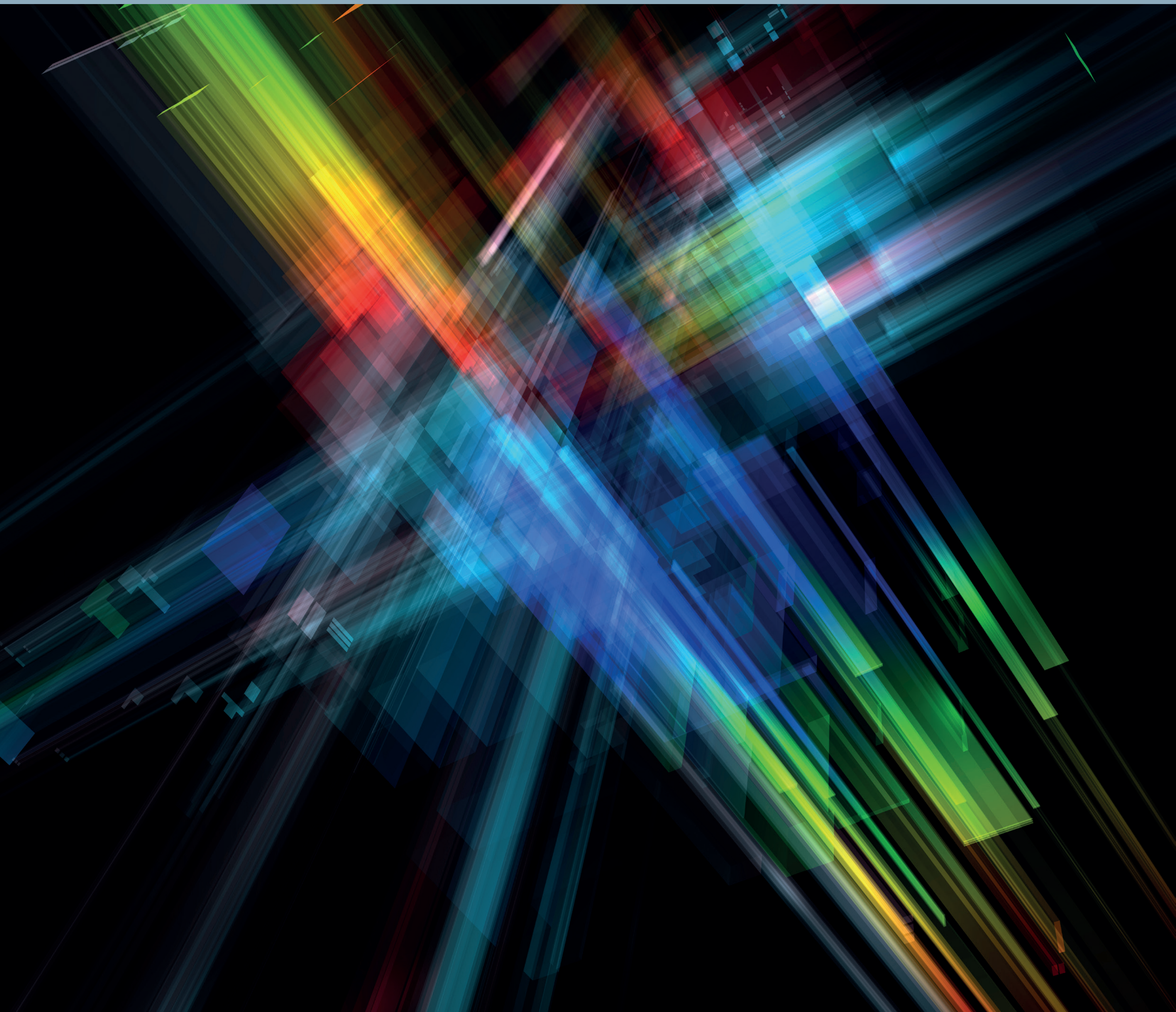
Abstract book



PHOTON 2018

3–6 September 2018
Aston University, Birmingham, UK

www.photon.org.uk

IOP Institute of Physics

Monday 3 September

(Plenary) Silica the Wonder Material

D Payne

University of Southampton, UK

The internet is perhaps the most important and life-changing invention of the 20th century. It required the invention of a new global communication medium capable of carrying vast quantities of information across trans-oceanic distances, reliably, cheaply and efficiently. This turned out to be the unpredictable, unlikely and extraordinary role of optical fibres made from the two most common elements of the earth's crust, silicon and oxygen (silica).

As the internet traffic grows by some estimates at 70%/annum there is constant pressure to find more fibre capacity, although at $8/km the option remains to simply install more fibre, rather than find better fibres. However, in some applications where small volume, reduced transit time or better phase stability is critical, there may be a role for advanced designs such as hollow-core or multi-core fibres.

With the huge increase in data traffic comes a headache in how to store the information for the requisite period of time that is often mandated by banks and government – up to several hundred years. A new storage medium based once again on silica appears a leading contender to replace today's tape units. The technique, known as 5D storage because of the way each bit can be written and read, provides both high storage density and extraordinary life time estimated at 1020 years. Once again this is related to the refractory nature of silica.

The parallel field of high-power fibre lasers also relies on silica fibre because of its thermal properties. This field has seen a revolution in industrial laser processing using fibre lasers and the market has grown to several $B/annum. Because of its robust, monolithic nature and its efficiency, the fibre laser is finding favour in defence applications as well.

Parallel Session 1: Novel and super-resolution microscopy I

(Invited) Back focal plane ptychography

M Somekh[1], T W K Chow[2] and H Zhuangyu[2]

[1]University of Nottingham, UK, [2]The Hong Kong Polytechnic University, Hong Kong

In recent years phase retrieval methods have had a very significant influence on microscopic imaging. After reviewing these methods, we will describe our recent work that demonstrates how similar methods can be applied to localized measurement.

It is well known that the back focal plane can be used to recover a great deal of sample information in terms of its response to light of different incident angles and polarisation. A significant limitation on back focal plane measurements is that the phase information is lost. It is, of course, possible to recover phase interferometrically, however, this can be instrumentally demanding and great care is necessary to ensure system stability. The success of phase retrieval methods in imaging has prompted us to try to apply these to recovery of the phase in the back focal plane, two methods have been successfully applied: ptychography and transport of intensity.

We report the results using these methods particularly emphasizing the results using ptychography. By applying an iterative algorithm between the back focal plane and the image plane we demonstrate excellent phase retrieval in both the image and back focal planes. The specific experimental conditions that must be met in terms of dynamic range are discussed.

We then demonstrate, how recovery of both the amplitude and phase in the back focal plane provides the data from which many other original measurements may be obtained purely by computation with no additional hardware. For instance, propagation vector, attenuation and coupling of surface waves can all be retrieved with this approach. The computational measurements are compared with hardware measurements using a spatial light modulator.

In summary, we show how phase retrieval in the back focal plane provides both an inexpensive, robust and highly flexible measurement approach for localized measurement of material properties.

Refractive index tomography using spherical optical transmission

J Maxwell and C Paterson

Imperial College London, UK

Brillouin scattering microscopy is a technique which promises to measure elastic stress properties in biological media, using high-precision spectroscopy on light scattered by optical phonons. However, there exists an ambiguity in spectral data between variations in the speed of sound – related to the elastic modulus – and variations in refractive index (RI). To alleviate this ambiguity, we present a novel tomographic system to measure RI variations in extended (>100μm) samples.

In contrast to many existing RI tomographic approaches, the specimens relevant to Brillouin microscopic studies are large – for example corneal tissue – affording new challenges to standard tomographic arrangements. Firstly, thicker samples pose greater diffraction and scattering issues. Secondly, tomographic reconstructionis complicated by the large transverse spatial extent of typical objects of interest.

In our approach we use a spherical optical field which probes the sampleat different angles before being collimated by a collection objective. A Mach-Zehnder interferometer is used to measure phase variation in the back focal plane of the objective. Additionally, while traditional RI tomography employs transmission through the object at multiple angles, here the beam is translated in position, allowing partial spatial regions to contribute to each interferogram.

A linear forward model has been constructed and used for reconstruction, using projections onto convex sets to invert the phase data into the RI distribution. We will present details of the experimental implementation and software reconstruction method, and present resultsfor sample RI test objects.

Adaptive optics for SLM-based STED microscopy

A Barbotin, J Antonello, S Galiani, J Rittscher, C Eggeling and M Booth

University of Oxford, UK

Super-resolution fluorescence microscopy is an invaluable tool to investigate cellular processes at the molecular level, but is particularly sensitive to optical aberrations. This is particularly the case in Stimulated Emission Depletion (STED) microscopy, which breaks the diffraction barrier through a combination of optical and photophysical effects. Aberrations can be corrected using adaptive optical elements, such as a Spatial Light Modulator (SLM) or a Deformable Mirror. We propose here new methods to implement SLM based aberration correction in STED microscopy. These methods seek to overcome previous limitations such as correction speed and excessive specimen exposure.

Multi-purpose SLM-light-sheet microscope

C Garbellotto and J Taylor

University of Glasgow, UK

Selective Plane Illumination Microscopy (SPIM) is becoming increasingly popular for live fluorescence imaging in developmental biology. Its particular illumination/detection geometry (excitation delivered by a light-sheet, imaged using a perpendicular imaging arm) gives SPIM important advantages over rival techniques such as confocal microscopy, including reduced photobleaching and rapid snapshot acquisition. Despite these advantages, a classical SPIM implementation also suffers from a number of issues, such as shadow artefacts, scattered out-of-focus background and limited field of view.

A variety of advanced techniques in light-sheet microscopy have been proposed to tackle these issues, and previous publications have shown how image quality can be improved by rejecting out of focus light (structured illumination and pencil beam scanning), reducing shadow effects (light-sheet pivoting), or increasing the effective field of view by moving the focus of the light-sheet across the imaging field of view (tiling).

We will present results from our SPIM design, in which a phase-only Spatial Light Modulator (SLM) has been integrated into the illumination arm. We will show how the SLM placed in a Fourier plane can be used to modulate the microscope's light-sheet in an easy and programmable manner, resulting in a versatile system able to perform all the above-mentioned techniques. The modular nature of our system also offers the possibility to choose between three different light-sheets, in thickness and height, which can be selected according to the characteristic of the sample and the imaging technique to be performed.

The proposed SLM-SPIM configuration is easy to build and use, and is flexible and versatile in terms of the advanced imaging techniques that can be implemented on it. To demonstrate this we will present and discuss the results obtained performing different imaging techniques on samples of fluorescent beads, Zebrafish (Danio rerio) embryos, and optically cleared whole mouse brain samples.

Parallel Session 1: Optical environmental sensing

(Invited) Optical remote sensing of the oceans: latest results from the ESA Sentinels

S Groom and S Sathyendranath

Plymouth Marine Laboratory, UK

Optical satellite remote sensing of coastal seas and oceans (or Ocean Colour) can provide information on in water constituents such as phytoplankton (the marine plant plankton at the base of the marine food chain) as well as suspended particulates in coastal environments. Individual satellite images provide a snapshot and can be used for operational applications like monitoring for rapid growth of phytoplankton in response to excess in-water nutrients or providing alerts of presence of harmful algal blooms around aquaculture sites. By contrast, global time-series are key to studying phytoplankton at seasonal and inter-annual scales, and understanding the role of phytoplankton in the global carbon cycle and the response of marine ecosystems to climate variability. Spectrally-resolved water-leaving radiance is recognised as Essential Climate Variables (ECV) by the Global Climate Observing System.

Retrieval of accurate water leaving radiance is complicated by the presence of the atmosphere which adds considerably to the satellite-detected signal, and on-board satellite sensor calibration needs to be complemented by vicarious calibration using in situ Fiducial Reference Measurements which also validate the retrieved radiances. Furthermore, generation of a long time-series of ocean-colour data is not a trivial task since there are a number of satellites, each with a finite life-span, and differing sensor characteristics, so data from the individual sensors need to be merged without introducing artefacts.

This presentation will introduce optical remote sensing of marine and coastal environments, and describe some of the activities at PML engaged in validation of satellite retrievals using FRM data, examples of operational ocean colour applications and efforts to produce global time series of ocean colour data.

Field Spectroscopy measurements of urban trees: initial results from the InfruTreeCity project

C Halios, S Smith, B Pickles and L Shao

University of Reading, UK

Urban trees and their interactions with other components of the urban fabric is one of the most important factors that control the urban microclimate. Recent research suggests that trees and green spaces have significant benefits on people's thermal comfort in exterior spaces, energy consumption of buildings, pollution and noise reduction. In particular, it has been indicated that infrared radiation that accounts for more than 50% of the solar radiation reaching the Earth, is important for the cooling process in trees; yet systematic research on this is still sparse.

The present study will present initial measurements of the urban trees thermal performance taken in the frame of the InfruTreeCity project which aims to advance the understanding of urban tree – built environment interactions, focusing on the infrared radiative energy exchange. Field spectrometry measurements will be taken with a spectrometer (Spectral Evolution, SM-2500) and thermal imaging will be acquired with an infrared camera (Optris PI 640) with a prototype experimental approach that has been particularly developed for measuring urban trees. The urban radiation environment is measured with a net radiometer (Apogee, SN-500) and the micro-meteorological conditions with a weather transmitter (Vaisala, WXT 356). Soil moisture conditions will be measured with soil moisture and temperature sensor (Meter Environment Decagon TM5), whilst the tree stress will be monitored with a combination of a Chlorophyll Content Meter (Arborcheck, ArbCm-01) and a Chlorophyll Fluorescence System (Arborcheck, ArbFl-01). For these measurements containerised common tree species will be selected. Initially, monitoring will be carried out using containerised small trees with dense foliage; larger trees of multiple species in varied urban environments will be studied later.

This study will shed new light in the understanding of the thermal processes that control the interaction between trees and the urban environment.

A novel hyperspectral imaging system

C Huntly, D Langstaff, M Gunn, R Cross, L Tyler and A Gay

Aberystwyth University, UK

The novel hyperspectral imager being developed in Aberystwyth, SPEC-I, is a windowing hyperspectral camera. It is fitted with two linear variable filters (LVF) each covering an octave of spectral range. These are in a linear actuator making it possible to cover a wide range of wavelengths in a small imaging system; SPEC-I covers 400 – 1000nm at a spectral resolution of ~10nm. The wide spectral range of SPEC-I coupled with fast acquisition times means that it is ideal for a range of different applications, including planetary sciences and precision agriculture.

The hyperspectral image from SPEC-I can be built up in two ways, by windowing-framing or windowing-pushbroom. The windowing-framing method is achieved by scanning the LVF across the optical path meaning the camera and subject can be stationary. For the windowing-pushbroom method the LVF is fixed over a wavelength range and the hyperspectral data is built up by either moving the camera system of the subject.

The advantage of using SPEC-I over traditional systems is the two-dimensional image taken at each frame has sufficient spatial detail to allow registration of images. This is important when using the camera for field work, especially in remote sensing applications. Initial testing of SPEC-I on reflectance standards has yielded data that aligns with manufacturer spectra. SPEC-I has also been assessed to demonstrate the suitability of the camera as a tool for precision agriculture with collaborators in IBERS. The results from this showed that SPEC-I is sensitive enough to perform as a plant diagnostic tool.

The calibration methods and initial test results from the camera will be presented.

The invisible rangefinder

S Frick and J Rarity

University of Bristol, UK

In this paper we present our work towards an “Invisible Rangefinder”. Conventional rangefinders use bright modulated laser light directed at an object (or “target”). A simple time of flight measurement then yields the distance to this target. However, the unique spectral and temporal signature of laser light makes this method of rangefinding easy to detect from the targets position.

Inspired by the idea of Quantum Illumination we can replace the bright laser light with light from a spontaneous parametric down-conversion (SPDC) source. Carefully engineering the poling structure of a periodically poled Potassium titanyl phosphate (ppKTP) non-linear crystal, enables a phase-matching condition that results in a broadband spectral structure of the down-converted photons. Such phase-matching leaves the two photons in a highly spectrally entangled state.

However, these entangled beams, when viewed singly, appear in a mixed state, as associated with spontaneous emission processes. Background is also effectively a broadband thermal state and hence our source, with suitable spectral shaping, could be made indistinguishable from background both temporally and spectrally, particularly when viewed from the target. This also means that the arrival time of returned photons alone contains no temporal information on target distance. However, since the two photons produced in SPDC are created at the same time, one of the photons can be kept locally while the other is sent towards the target. A histogram of start to stop events thus shows a peak at the time of flight revealing the distance to the target.

Lidar and wind energy assessments

P Clive

Wood Group, UK

Optical remote sensing of the environment using coherent heterodyne Doppler lidar is having a transformational impact on wind energy assessment procedures. Established wind measurement techniques rely on cup anemometry mounted on temporary meteorological masts (met masts). The limitations of these instruments have imposed a number of approximations and rules of thumb that have become embedded in industry standards and guidelines. This has created a barrier to the adoption of new methods that exploit the far more extensive capabilities of lidar. However, as the benefits of lidar, in terms of wind velocity vector field characterisation that at last provides a robust test for the physics parameterised and encoded in flow models, become apparent, these barriers are being overcome. It is now becoming possible to fully digitise wind energy assessment using optical sensors: where fibre Bragg gratings are used as strain gauges to validate wind turbine load models based on aeroelastic and finite element calculations, the wind flow models themselves can now be validated using lidar measurements, closing the loop. This allows a common and comprehensive understanding of wind project performance to develop and be shared by all stakeholders, overcoming friction that has hitherto existed at the interfaces between phases of project delivery due to different perspectives on incomplete information. In this presentation a number of case studies will be presented illustrating the contribution lidar data makes to successful wind power project delivery today.

Parallel Session 1: Metamaterials and plasmonics I

(Invited) Not every dipole is the same: the circular, Huygens and Janus sources

F J Rodriguez Fortuno, A Zayats and M Picardi

King's College London, UK

Near-field directionality of circularly polarized dipoles has opened the way to the design of novel devices such as integrated nano-polarimeters, polarization-based nano-routers, non-reciprocal optical devices, and quantum-optical readout of spin states. Here we generalize the concept of directionality of dipolar near-fields, uncovering novel directional sources beyond the circularly polarized emitter. These sources exhibit distinct symmetries and behaviors.

The directionality near-field properties of dipoles are revealed when a waveguiding structure is placed in close proximity to the dipole. When this happens, different dipoles may excite waveguide modes directionally. This can be described via a single equation, based on Fermi's Golden Rule, which describes the coupling of any dipole to any mode. For simplicity we started our analysis with planar waveguides, such as dielectric slabs supporting guided modes via total internal reflection, or metallic surfaces supporting surface plasmons. In this simplest case, the mathematical description of the equation is remarkably concise. The solutions of dipoles exhibiting perfect directionality become readily apparent: all possible directional dipolar sources can be written as a linear superposition of three elemental cases: (i) the circularly polarized dipole, which originally spawned interest on near field directionality and has given rise to many applications, (ii) the Huygens' dipole, which is a source known to exhibit far-field directionality, but can be generalized to the near field, and finally (iii) the Janus dipole, which shows a counterintuitive and rather unique face-dependent coupling; coupling to a waveguide, or not, depending on which side of the dipole is facing the waveguide.

Transformations, topology, and metamaterials

J Gratus[1], P Kinsler[1] and M McCall[2]

[1]Lancaster University, UK, [2]Imperial College London, UK

Topology has been embedded in transformation optics from the very beginning: mathematically, the cylindrical cloak represents a space with a missing point, a feature native to both the original conception by Dolin (1961) and the independent reinvention by Pendry et al (2006). Such a space is topologically non-trivial, and so technically Stokes' theorem, no longer holds. But what are the electromagnetic consequences of such a situation?

At the mathematical level, there are two guardians of charge conservation: Stokes' theorem, and the standing of the electromagnetic excitation fields D,H as fundamental fields. But since a non-trivial topology denies Stokes', and since D,H can be treated without approximation as being only gauge fields for the current, both guardians can be defeated.

As we will show, this has significant implications for the treatment of electromagnetism in spacetimes where black holes both form and then evaporate, as well as extending the possibilities for treating vacuum polarisation. Further, using the gauge freedom of D,H we can also propose an alternative to the accepted notion that a charge passing through a wormhole necessarily leads to an additional (effective) charge on the wormhole's mouth. Indeed, it is possible to construct a self-consistent electromagnetic solution where the wormhole only temporarily accommodates a passing charge.

Nevertheless, although the mathematical prescription for a cloak relies on a non-trivial topology, the native laboratory space it inhabits still contains the mathematically omitted point, and so is still topologically trivial - fortunately charge conservation is safe, even in the most advanced cloaking devices. Nevertheless, we will also consider the role topology plays in transformation optics, and discuss the potential implications for, possibilities or, and demands on metamaterial elements.

A bottom-up approach to lossless surface plasmon

H Deng

University of Exeter, UK

We show that pure surface effects could be utilized to systematically reduce the losses experienced by surface plasma waves (SPWs) supported on the interface between a metal and a dielectric (usually the vacuum). These effects occur in a double-fold way: first through a self-consistent treatment of the role played by surface in charge dynamics and then by means of translation symmetry breaking. A generic charge density wave theory is set up to take care of these aspects, with inlcusion of real-world complications such as inter-band transition and dielectric effects. Existing theories impose artificial boundary conditions at the surface and have totally missed such effects. A unified view of and a comparison among various existing models, including the classical Drude model, the hydrodynamic model and the specular reflection model as well as the semi-classical model, are presented in light of the theory. Some historical misconceptions are clarified concerning these models. Experimental consequences, in regard to the possibility of overcompensating for the energy losses suffered by SPWs, are exemplified for two common plasmonic materials: silver (Ag) and aluminum (Al). In both metals, the losses are argued to have been substantially reduced because of the surface effects but not overcompensated. In Ag, the inter-band transition effects significantly weaken such effects and make them unable to beat the losses, while in Al the loss rate is too high. Nevertheless, we find it possible to enhance the surface effects by replacing the vacuum with a moderate dielectric so that the losses can be overcompensated in Ag. This prediction calls for experimental scrutiny.

Self-induced trapping of quantum dots in nanocavities

V Pacheco-Peña[1], R A Alves[2] and M Navarro-Cia[2]

[1]University of Pennsylvania, USA, [2]University of Birmingham, UK

Nanocavities supporting plasmonic modes with extraordinary small mode volume are ideal systems for studying light–matter interaction and provide a natural platform for trapping quantum dots. It is only recently that the mapping of plasmon resonances in plasmonic nanostructures with more complex topology than spheres and cylinders (that can be described by Mie's theory) is viable owing to the noteworthy increase of computational power along with the advances in computational electromagnetics. Still, the modelling of complex nanostructures demands in some cases unaffordable computational burden. This problem can be alleviated by championing analytical tools such as transformation optics.

This communication reports the analytical (based on conformal transformation) and numerical study (based on finite element method) of a nanoemitter inside a bowtie nanocavity. The contribution shows the strong dependence that the non-radiative Purcell enhancement has on the actual geometry of the bowtie nanocavity, and the position and polarization of the emitter. The strong variances observed in the non-radiative Purcell enhancement is also mirrored in the self-induced trapping ability of a colloidal ZnO quantum dot located inside the bowtie nanocavity. We observe though that the trapping force exceed the Brownian motion along the perimeter of the bowtie nanocavity regardless of the quantum dot photoluminescence polarization. This work demonstrates the potential that conformal transformation has for modelling cost-effectively plasmonic nanostructures.

Enhancement of effective second- and third-order optical nonlinearities of graphene-based metasurfaces

Q Ren, J W You and N Coriolan Panoiu

University College London, UK

Using a new homogenization technique, we demonstrate that the effective second- and third-order nonlinear susceptibilities of graphene metasurfaces possessing a double-plasmonic-resonance feature can be enhanced by several orders of magnitude as compared to the corresponding intrinsic nonlinear susceptibilities. Specifically, the primary components of our properly deigned metasurfaces have plasmon modes both at the fundamental frequency and the frequency of the higher-harmonic (second- or third-order harmonics in our case). This nonlinearity enhancement is demonstrated in two generic cases, namely for a graphene-nanoribbon metasurface and a graphene-cruciform metasurface. In particular, we demonstrate that a double-plasmonic-resonance effect can be achieved in both cases by properly engineering the shape and size of the basic unit cells of the two graphene-based metasurfaces.

In order to quantify the nonlinearity enhancement facilitated by the graphene metasurfaces investigated in this study, we develop a novel homogenization technique based on the well-known effective-medium theory and apply it to determine the effective linear and nonlinear optical coefficients (electric permittivity and nonlinear susceptibilities) of the metsurfaces. The results of our analysis prove that local field enhancement induced by graphene plasmons leads to a giant effective nonlinear susceptibility and consequently a strong, resonant enhancement of nonlinear optical interactions in graphene-based metasurfaces. We also explore the implications of our work to the development of new active photonic nanodevices with new or improved functionalities.

Parallel Session 1: Quantum optics I

(Invited) On computer-designed Quantum Experiments

M Krenn

University of Vienna, Austria

Designing experimental setups for high-dimensional multipartite entangled states is a notoriously difficult feat. For that reason, we have developed the computer algorithm Melvin which is able to find new experimental implementations for the creation and manipulation of complex quantum states [1]. The discovered experiments extensively use unfamiliar and asymmetric techniques which are challenging to understand intuitively. Melvin autonomously learns from solutions for simpler systems, which significantly speeds up the discovery rate of more complex experiments. Several of the computer-designed experiments have already been successfully implemented in our laboratories [2-5].

By analysing Melvin's solutions, we were able to discover several novel techniques and surprising connections:

One technique is a well controlled generation of entanglement based on a technique introduced by the group of Leonard Mandel in 1991. Surprisingly, this technique only uses elements which were available already for 25 years, but it has been discovered only now by a computer algorithm. This shows that computer designed quantum experiments can be inspirations for new techniques [7].

Another surprising concept has uncovered using solutions from the computer: It is a deep connection between Quantum Experiments and Graph Theory [8,9], which among others has led to a new experimental methods for special-purpose quantum computing.

[1] Krenn, Malik, Fickler, Lapkiewicz, Zeilinger, Automated search for new quantum experiments. Physical Review Letters, **116**(9), 090405 (2016).
[2] Malik, Erhard, Huber, Krenn, Fickler, Zeilinger, Nature Photonics, **10**(4), 248 (2016).
[3] Erhard, Malik, Krenn, Zeilinger. arXiv:1708.03881.
[4] Babazadeh, Erhard, Wang, Malik, Nouroozi, Krenn, Zeilinger, Physical Review Letters, **119**(18), 180510 (2017).

Photon scattering in waveguide QED

D Hurst and P Kok

University of Sheffield, UK

Proposals for practical quantum devices such as a measurement-based quantum computer or a Quantum Internet require large entangled states of stationary qubits [1]. Optical photons, with their long coherence times and large velocities, form the ideal carriers of quantum information between these nodes and this means that understanding the light-matter interaction is of great importance. A possible route towards engineering this light-matter interaction involves coupling quantum emitters to the modes of a nanophotonic waveguide and there has been a great deal of recent experimental progress in this field [2].

We develop an approach to analysing light-matter coupling in waveguide QED based upon scattering amplitudes evaluated via Dyson series [3]. Unlike many previously reported procedures, our method fully specifies a combined emitter-optical state that permits investigation of matter-matter entanglement generation protocols. We find that for multi-photon input optical states, terms in the Dyson series increase in complexity and we develop a diagrammatic recipe for their evaluation. We find that our method extends readily to systems where the emitter has multiple ground states.

We conclude by discussing some practical limitations in the case where the emitters coupled to the waveguide are semiconductor quantum dots (QDs). We discuss recent experimental results [4], which show promisingly strong interaction between a single QD and light transmitted by a waveguide. However, even here, we operate away from the deterministic interaction limit and need to think carefully about how to improve this situation in the future.

[1] H. J. Kimble. “The quantum internet”. Nature 453.7198 (June 2008).
[2] P. Lodahl et al. “Chiral quantum optics”. Nature 541.7638 (Jan. 2017).
[3] D. L. Hurst and P. Kok. “Analytic Few Photon Scattering in Waveguide QED for Entanglement Generation”. ArXiv (May 2017).
[4] D. Hallett et al. “Electrical control of nonlinear quantum optics in a nano-photonic waveguide”. ArXiv (Nov. 2017).

Speed limits for quantum photonics

P Barrow

Heriot Watt University, UK

Optical quantum information processing requires the development of high purity single photon sources that operate with high brightness as well as detectors with detection efficiencies as close to unity as possible. Devices that meet these requirements are constantly being improved but for multi-photon protocols in particular there is always a question as to which regime they should operate under to achieve optimal performance. Here we present two methods that allow for signal-to-noise and absolute detection rates to be modelled under the conditions of imperfect number purity and detection efficiency. In order to to identify conditions for optimal performance we place focus on limitations provided by detector reset time, optical switching speeds and detection efficiency, we find that it is often beneficial to operate sources with clock rates that far exceed timing limits imposed by imperfect components. Our first model employs the use of combinatorics to calculate the probability of generation/detection of photons from a given single photon source providing us an insight into the sources characteristics whereas the second, a Monte Carlo-like method, allows for the analysis of more complex multi-photon schemes capable of taking advantage of multiplexing making it applicable to both quantum dot and parametric down conversion photon sources.

Two-way frequency conversion of photons between the Sr+ transition at 422 nm and the telecommunications C-band

T Wright[1], R J A Francis-Jones[2], C B E Gawith[3], J N Becker[2], P M Ledingham[2], P G R Smith[3], J Nunn[1], P J Mosley[1], B Brecht[2] and I A Walmsley[2]

[1]University of Bath, UK, [2]University of Oxford, UK, [3]University of Southampton, UK

Quantum networks enabling long-distance secure communication are reliant on the successful transfer of quantum states between nodes. However, no single quantum system currently displays suitable properties for both distribution and processing of information. Hybrid quantum networks, that store and process information with trapped ions or solid state qubits and distribute it via photons, provide a route by which a high-performance network may be established. However, one challenge of a hybrid network is that the short wavelengths at which fluorescence is emitted by candidate ions are not suitable for direct transmission over long lengths of optical fibre. Quantum frequency conversion, where individual photons are coherently shifted between frequency bands, addresses this obstacle by linking wavelengths as short as the ultraviolet, where many convenient ion transitions are located, to the infra-red telecommunications bands, enabling long-distance low-loss transmission in optical fibre.

We report a single-stage bi-directional interface capable of linking Sr^+ trapped ion qubits in a long-distance quantum network. Our interface converts photons between the Sr^+ emission wavelength at 422 nm and the telecoms C-band. Conversion was achieved in a magnesium-doped periodically poled lithium niobate crystal, where $\chi^{(2)}$ sum and difference frequency generation were used to achieve bi-directional conversion of an input photon. We achieved up- and down-conversion at the single photon level with efficiencies of 9.4 % and 1.1 % respectively. Furthermore, we demonstrate that the noise introduced during the conversion process is sufficiently low to implement high-fidelity interconnects suitable for quantum networking.

This is to our knowledge the lowest-noise single-photon-level frequency conversion reported to date, and the only bi-directional link between short-wavelength ion transitions and the C-band.

Bragg cavity enhanced narrowband four-wave-mixing sources in UV-written silica

D Smith[1], T Hiemstra[2], R H S Bannerman[1], W S Kolthammer[3], J C Gates[1], I A Walmsley[2] and P G R Smith[1]

[1]University of Southampton, UK, [2]University of Oxford, UK, [3]Imperial College London, UK

Creating high-quality photons for quantum information and communication is a long-standing problem in quantum optics; a further important problem is to make the source integrable. Here we present a new scheme for preparing photons in the C-band using telecommunications-compatible equipment.

In this scheme we use spontaneous four-wave mixing (SFWM) in silica as the light source—a process that is often broad-band and constrained by noise. Here we use cavity enhancement to promote SFWM in the noise-free region between the Brillouin and Raman bands, with the daughter photons spaced at a wavelength-division-multiplexing compatible 100 or 200 GHz either side of the pump.

The cavity is formed using Bragg gratings inscribed using direct UV writing into either planar silica chips or single-mode fibre. Silica, suitably prepared, is photosensitive to UV, permanently changing its refractive index. Using an interferometric setup and a 244 nm laser focussed to 5 µm, we can write arbitrarily apodised Bragg gratings.

Using carefully designed Bragg gratings for SFWM has several benefits: first, the mirrors are narrowband, such that only the three modes of interest exist, which makes the source truly narrowband; and secondly the cavity modes themselves can be engineered to enhance the spectral purity of the daughter photons. Most cavity-based sources have poor spectral purity due to energy conservation, while our Bragg gratings have been engineered to avoid this problem: the linewidth of the pump field mode is much wider than the daughter photons, substantially increasing spectral purity.

At this stage modelling and design is complete, and fabrication of devices is ongoing; early prototypes are being fabricated in fibre, while we plan on moving on-chip in future using the same design. We are experimentally testing the tradeoff between field enhancement and bandwidth to find the optimal Q for the pump and daughter photon cavities.

Parallel Session 2: Novel and super-resolution microscopy II

(Invited) Tip enhanced near-field optical spectroscopy of semiconductor molecules

A J Meixner, K Eitel, J Rogalski, X Wang, K Braun, A Horneber and D Zhang

Eberhard Karls University of Tübingen, Germany

Tip enhanced near-field optical microscopy is a scanning probe technique which reveals spectroscopic information about the chemical composition and morphology with nanometer spatial resolution. When a small gap between a sharp Ag or Au-tip and the sample is illuminated by a tightly focused laser beam, the field in the gap is enhanced and simultaneously the optical emission from the gap coupled into the far field [1]. In 2000 tip-enhanced Raman spectroscopy (TERS) with a side-illuminated AFM-tip was introduced independently by Zenobi et al. [2] and Kawata et al. [3].

In our approach, the antenna gap is in the focus of a parabolic mirror, exciting the tip, collecting the signal and reducing the background to a diffraction-limited confocal volume [4]. In this talk, the plasmonic coupling between the tip and the sample [5-7] and our progresses of using TERS to determine the nanometer-sized morphology in organic semiconductor films identifying molecular orientation changes [8,9] will be shown. We content that tip enhanced near-field optical microscopy has grown into an effective technique with wide applications.

[1] O.J.F. Martin, et. al., Appl. Phys. Lett., 70, 705 (1997).
[2] R.M. Stöckle, et. al., Chem. Phys. Lett., 76, 3130 (2000).
[3] N. Hayazawa et. al., Opt. Commun.183, 333 (2000).
[4] J Stadler, et. al.,Optics letters 33, 681 (2008).
[5] K. Braun et. al., Beilstein J. Nanotech., 6, 1100 (2015).
[6] X. Wang et. al., ACS Nano, 9, 8176, (2015).
[7] A. Horneber et. al., Phys. Chem. Chem. Phys., 17, 21288 (2015).
[8] X. Wang et. al., Adv. Func. Mater., 20, 492 (2010).
[9] X. Wang et. al., Phys. Chem. Chem. Phys., 8, 15919 (2016).

Spectral Fluorescence Lifetime Imaging at world leading rates using a novel CMOS SPAD line array

G Williams[1], E Bohl[2], A Erdogan[1], N Finlayson[1], R Henderson[1] and J Girkin[2]

[1]University of Edinburgh, UK, [2]Durham University, UK

We present an achromatic confocal optical scanning system including a novel complementary metal–oxide–semiconductor (CMOS) single photon avalanche diode (SPAD) line array capable of recording spectral fluorescence lifetime images (sFLIMs) at a world leading rate (>3 frames per second for a 128x128 image) by processing 16.5 Giga events per second and building lifetime histograms "on-chip". This overcomes the limitations of traditional time-correlated single photon counting (TCSPC) techniques which build a lifetime histogram on the PC, involving the transfer of large data packages from the detector to the PC greatly slowing down the acquisition of the image. Achromaticity of this imaging system, for a spectral range from 400-900nm, is achieved through the use of a reflective optics rather than relying on lens systems, except for the primary objectives. Initially two excitation sources have been integrated into the system with wavelengths of 485nm and 640nm, however, these sources can be interchanged with any pulsed, fibre coupled, laser source or a filtered supercontinuum. Our imaging system incorporates a galvo system which scan the laser beam over the sample with the capability of changing the Field of View (FOV) on the fly and up to 1.5x1.5mm. The image resolution is diffraction limited and the system can reach resolution of 0.5 µm in free space imaging which we demonstrated by fully resolving a negative US Air Force test target placed in front of a green-fluorescent chroma slide. Furthermore, sFLIMs of Microbeads labelled with fluorescein, NBD and Rhodamine have been acquired to demonstrate the system capability of distinguishing the various fluorophores spectrally as well as by their different fluorescence lifetimes.

Two-Photon excitation of nucleobase analogs with shaped laser pulses

D Nobis[1], R S Fisher[2], L M Wilhelmsson[3], A C Jones[2] and S W Magennis[1]

[1]University of Glasgow, UK, [2]University of Edinburgh, UK, [3]Chalmers University of Technology, Sweden

Fluorescent nucleobase analogs (FBA) can be incorporated into DNA as fluorescent markers without disturbing its native structure. Unlike external marker molecules which have to be attached with long linkers, FBA's can allow direct investigation of the local structure and dynamics of DNA. However, their low brightness and tendency to photobleach makes them unsuitable currently for single-molecule spectroscopy. Another disadvantage for in vivo application is their one-photon absorption maximum which is in the UV region [1, 2].

In this work we will address these issues by using two-photon (2P) excitation in a new home-built multiphoton single-molecule fluorescence microscope. This system deploys a pulsed Ti:Sapphire laser (bandwidth 135 nm FWHM) with subsequent pulse shaping to compensate for dispersive pulsebroadening, using the MIIPS-method [3, 4]. With this technique pulses shorter than 10 fs at the focal plane of the objective are achieved. The signal-to-background ratio is improved by further pulse shaping. As a fluorescent marker we use a new nucleobase analog, pentacyclic adenine (pA) which has unprecedented two-photon brightness for FBAs of 5.3 GM [5]. We will report our study of pA incorporated in DNA using two-photon fluorescence correlation spectroscopy.

[1] Wilhelmsson, M. L., Q Rev Biophys, **43** 159–183 (2010)
[2] Xu, W. et al., Nat. Chem., **9** 1043–1055 (2017)
[3] Coello, Y. et al., JOSA B, **25** A140-A150 (2008)
[4] Lane, R. S. K. et al., Opt. Express, **20** 25948-25959 (2012)
[5] Bood, M. et al., Chem. Sci., Advance Article (2018)

Parallel Session 2: Photonic systems and optical communications

(Invited) Limits of optical fibre communication systems

A Ellis

Aston University, UK

Understanding of the practical limits in the performance of optical transmission systems has been sought since the invention of the laser [1-2]. Due to the influence of nonlinearity, the phrase "nonlinear Shannon limit" [3-4] was introduced in 2009, and a consensus has begun to form regarding the actual maximum achievable performance. Such studies are of contemporary interest since the constant growth (40% per annum [5]) in traffic demand combined with a fundamental capacity limits gives rise to an optical "*capacity crunch*" [6-7]. Rather than armageddon [8], this necessitates a shift in the telecommunications business model for service providers. In this presentation, we will trace the evolution of performance limit predictions, and review their contemporary relevance for both directly and coherently detected systems. We will examine the different models, and extend the analysis to systems which compensate for nonlinear impairments.

[1] D. Matulka: Application of LASERS to Digital Communications, *IRE Transactions on Aerospace and Navigational Electronics*, vol. ANE-9(2), pp. 104-109, 1962.

[2] C. Kao and G. A. Hockham: Dielectric-fibre surface waveguides for optical frequencies, *Proc. of the Institution of Electrical Engineers*, vol. 113(7), pp. 1151-1158, 1966.
[3] J-C. Antona: Key technologies for Present and Future Optical Networks, presented at Topical Workshop on Electronics for Particle Physics 2009 (https://indico.cern.ch/event/49682/contribution/154).
[4] A.D. Ellis *et al.*: Approaching the non-linear Shannon limit, *J. Lightwave Technol.*, vol. 28, pp. 423–433, 2010.
[5] A.D. Ellis *et al.*: Communication networks beyond the capacity crunch, *Phil.Trans.R.Soc. A*, vol.374, pp.20150191.
[6] J. Richardson: Filling the Light Pipe, *Science*, vol. **330**(6002), pp. 327-328, 2010.
[7] Chraplyvy: The Coming Capacity Crunch, *in Proc. of ECOC 2009*, Vienna, Austria, Second Plenary Presentation. (http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5287305&isnumber=5286960)
[8] https://www.bild.de/digital/internet/internet/internet-am-ende-40813022.bild.html

Coherent transceiver transmitter-side skew calibration based on receiver-side DSP

P Skvortcov, C Sanchez-Costa, I Phillips and W Forysiak

Aston University, UK

To support the traffic growth in modern-day optical communication systems, higher-order modulation techniques and higher symbol rates are being deployed. Moving towards polarization multiplexed (PM) 64GBaud 64-QAM transmission, these systems become increasingly sensitive to timing skews. Thereby, the system performance can be severely degraded by uncompensated skews, particularly at the transmitter-side (Tx-side) [1]. Mitigation for the impact of IQ Tx-side skews at the receiver requires additional DSP processing [1]. Additionally, the impact of XY Tx-side skews is mixed with the impact of receiver-side (Rx-side) skews in a complicated way because of polarization rotation and PMD. In such cases DSP's ability to mitigate for both skew types is limited. Therefore, Tx-side skew calibration is required beforehand normal transmission operation.

A simple skew estimation technique based on Rx-side DSP is proposed. The technique requires the use of a calibrated (de-skewed) receiver as the “golden device” connected to the transmitter under test in a back-to-back configuration. Sub-picosecond accuracy of the method has been shown in numerical simulations and then proven experimentally . A 30GBaud PM 16-QAM transmitter has been characterized in terms of skews using a calibrated coherent receiver and offline DSP processing.

Key DSP blocks used for skew estimation are a polarization demultiplexer and a clock tone amplitude detector [2]. In the presence of IQ Tx-side skews the clock tone amplitude is degraded. By sweeping IQ skews at the Tx-side and maximizing the clock tone amplitude detected at the receiver, IQ skews can be estimated. Once IQ skew calibration is complete, XY skews can be estimated using a conventional approach for Rx-side skew compensation [2].

[1] C. R. S. Fludger et al, “Transmitter impairment mitigation and monitoring for high baud-rate, high order modulation systems,” ECOC 2016
[2] N. Stojanovic et al, “A Circuit enabling Clock Extraction in Coherent Receivers,” ECOC 2012.

Free-space optical systems employing space-division-multiplexing for high speed data connection in urban area

M Mansour Abadi, R E Alsaigh and M P J Lavery

University of Glasgow, UK

Developing a “plug-and-play” high speed data connection is an inevitable target for both research and industry communities. In particular, the long-term plans by countries such as the UK to equip all individual residences with high speed internet connection motivate active groups to face the challenges and develop various solutions. Among progressing and promising solutions, free-space optical (FSO) communication system has the potential to revolutionise the way we connect our cities, by providing dynamic untethered connections that can be redistributed as cities needs evolve in time. We will discuss our latest achievements in developing a "plug-and-play" FSO systems suitable for deployment in urban environments. Our design is enhanced with space-division-multiplexing techniques to increase the link capacity of the point-to-point link. Using passive optics, our system is designed to be inviable to modulation format using and will be compatible with state of the art passive optical networks (PON). Our system is designed to automatically align with other transceivers within a range of 200 m. We will present our experimental measurements including cross-talk as well as bit-error-rate (BER) to assess system performance. Further, we will provide an overview of the auto-align functionality we have developed. Results will be presented for a link comprising up to 19 spatial channels in various urban use-cases between 15m and 200m.

Fluorescent antenna for visible light communications

S Collins, A Riaz, H Chun, G Faulkner and D O'Brien

University of Oxford, UK

The popularity of WiFi means that it is becoming difficult to satisfy user demand. Consequently, a search is underway for electromagnetic frequencies that can provide additional data transmission capacity. One of the alternative sources of capacity that is being investigated is the visible light from LEDs.

One aim when developing a visible light communications system is to deliver 100Mbps inexpensively. Achieving this data rate using simple modulation schemes will require a specific signal-to-noise at a frequencies of 70MHz or higher. Inexpensive photodetectors whose bandwidths are 70MHz or higher have an area of less than 2mm^2 and in a typical room they would therefore typically capture less than 10^{-4}% of the light from a lighting LED. Compound parabolic concentrators could be used to concentrate light onto these photodetectors. However, etendue means that the resulting system would have an unacceptably limited field of view.

Recently it has been shown that fluorescence and total internal reflection can be exploited to create receivers for visible light communications that have a wide field of view and could potentially have vast input aperture. The 'fluorescent antennas' in these receivers are similar to luminescent solar concentrators. However, they only have to absorb a narrow range of wavelengths, but, the subsequent re-emission should occur as quickly as possible, hence the use of fluorophores.

Results will be presented which demonstrate that materials developed for high energy physics experiments contain fluorophores with time-constants which mean that they could be used in 'fluorescent antennas'. However, to achieve 100Mbps both these antennas and the lighting LEDs used to transmit data will need to be driven at frequencies that are higher than their 3dB frequencies. These results, together with the characteristics of lighting LEDs and photodetectors, will be used to predict the expected performance of future visible light communication systems.

Contour integrals approach for processing of degenerate or close solitonic eigenvalues for NFT-based transmission

A Vasylchenkova, J E Prilepsky and S Turitsyn

Aston University, UK

Nonlinear Fourier transform (NFT) has been actively studied during the recent years as a high-efficiency technique for nonlinearity mitigation in future optical transmission systems. In the NFT decomposition of a signal, the solitonic modes correspond to the discrete NFT spectrum part; this part includes the so-called solitonic eigenvalues and spectral amplitudes attributed to them. The former can be computed numerically as zeros of auxiliary spectrum function in the upper complex half-plane of the nonlinear spectral parameter (nonlinear frequency). The iterative methods that have been used in the overwhelming majority of existing works devoted to the eigenvalues location, are quite successful for some particular test profiles. However, in practical cases, we can likely have similar solitonic modes, which leads to the necessity to deal with closely-located or even coinciding eigenvalues. The iterative methods encounter a difficulty to process such cases successfully.

We describe a novel method for digital signal processing related to the solitonic eigenvalues detection, which is based on the contour integrals computation in the complex plane of nonlinear frequency parameter. For this method, the accuracy and runtime are almost independent of a number of eigenvalues and their closeness. In particular, we show a performance of this method for the profile involving highly degenerate eigenvalues, for a sequence of identical separated individual solitons (optical soliton train), and for a couple of relatively exotic combinations of these cases.

The application of the contour integrals approach adopts the advantages of NFT-based processing and allows us to perform the faster and more reliable analysis of complicated degenerate solitonic profiles.

Parallel Session 2: Metamaterials and plasmonics II

(Invited) Strongly coupled graphene-metamaterial hybrids

G Nash[1], I Luxmoore[1], P Liu[2], S Mikhailov[3], N Savostiyanova[3], F Valmorra[2], P Li[1] and J Faist[2]

[1]University of Exeter, UK, [2]ETH Zurich, Switzerland, [3]University of Augsburg, Germany

Research on metamaterials has progressed rapidly with substantial expansion of both the scope of novel functionalities and the operating frequency range enabled by different types of artificial structures. Many approaches are based on noble metals, but at mid-infrared wavelengths and longer the negative permittivity of noble metals means that the surface plasmons (SPs) are weakly bound to the metal-dielectric interface. Graphene has been shown to support tightly confined SPs in this spectral range, with the significant advantage that the SP resonance can be tuned by changing the conductivity of graphene, which can be modulated by two orders of magnitude using an applied gate voltage. In this talk, I describe a novel type of tunable hybrid metamaterial employing graphene plasmonic resonators strongly coupled to conventional metal based metamaterials [1].

The hybrid metamaterial acts to concentrate the electric field component of incident radiation along the edge of the graphene ribbon, significantly enhancing the interaction of light with a sample under test and therefore, for example, potentially enhancing the sensitivity and resolution of infrared spectroscopy. As a first step towards this we have been able to reproduce the infrared transmission spectrum of a very thin (~20nm) layer of test polymer by integrating this metamaterial with graphene photodetectors [2]. Features associated with the vibrational modes within the polymer molecules then appear as minima in the measured photo-voltage. This is a key step towards the realization of a fully integrated, high spatial resolution, surface enhanced sensor and the ultimately could form the basis of a spectrometer-on-a-chip.

[1] P. Q. Liu et al, “Highly tunable hybrid metamaterials employing split-ring resonators strongly coupled to graphene surface plasmons”, Nat. Commun. **6**, 8969 (2015).
[2] I. J. Luxmoore et al, “Graphene−Metamaterial Photodetectors for Integrated Infrared Sensing”, ACS Photonics **3**, 936 (2016).

Dual Colour Plasmonic Filters

A Clark, E Heydari, J Sperling and S Neale

University of Glasgow, UK

The ability to effectively separate discrete colors from white-light lies at the heart of how we record and view optical information; whether that be the arrangement of coloured inks in painting and printing applications, or the spectral filters that enable many modern image display and recording technologies. In each case, colour separation is typically provided by organic compounds; dyes and pigments that absorb and scatter particular wavelengths of light. Recently, structural colour systems based on engineered nanophotonic materials have emerged as an appealing alternative to absorptive dyes. Among these examples are color filters based on plasmonics materials. Plasmonic filters hold several dimensional and stability advantages over their dye-based counterparts. As a result, they have been positioned as new technological solutions for sub-wavelength colour printing, RGB splitting for image sensors, anti-counterfeiting measures, and optical data storage.

Here, we demonstrate a method for patterning full-colour images and codes, at subwavelength resolutions, that exhibit dual, polarization-dependent information states. Our individual pixels are comprised of asymmetric cross-shaped nano-apertures in a thin film of aluminum; each aperture engineered to exhibit 2 independent plasmonic color resonances that can be individually tuned across the sRGB spectrum. This enables us to encode 2 arbitrary information sets into the same unit area using the same array of nano-pixels. We show that using a standard optical microscope, color separation can be controlled down to 2x2 nano-pixels (approximately 370 x 370 nm), while retaining polarization selectivity. This, in turn, defines our maximum data storage capability; each 2x2 pixel area acting as a 2-state data bit that can be read optically. The maximum data density we can achieve using this technique is approximately 1.46 Gb/cm^2, with the added ability to further encode each of those pixels using the full visible-color spectrum.

Nanoscale light-confinement using J-aggregates

S Holder[1], S Núñez-Sánchez[2] and R Oulton[1]

[1]University of Bristol, UK, [2]Universidade de Vigo, Spain

J-aggregates are self-assembling dye molecules whose electronic orbitals couple together when assembled. This coupling produces delocalised Frenkel excitons spanning many dye monomers. Polymer films doped with J-aggregates have extreme dielectric permittivity due to the excitation of Frenkel excitons in the J-aggregate, giving rise to high reflectivity and negative real electric permittivity in a narrow wavelength range. These properties allow J-aggregate-doped polymer films to support surface exciton polaritons (SEP) analogous to surface plasmon polaritons in metals. Importantly, the J-aggregate films confine light without any metal present.

The aim of this work is to show J-aggregates can be used as the building blocks for organic materials that confine light on the nanoscale. Different J-aggregates absorb at wavelengths spanning the visible and near-infrared. We chose three J-aggregates absorbing at 560nm, 590nm and 615nm, using each to create a densely-doped PVA film with metal-like reflectance. The optical properties of each film were determined using spectroscopic ellipsometry. The optical properties are dominated by the J-aggregate absorption, the material behaving like a dielectric at most wavelengths with the exception of the narrow region of negative permittivity close to the J-aggregate absorption. To show the capacity of these materials to confine light on the nanoscale, we demonstrated coupling to the SEP in each of the three films, using Fourier imaging spectroscopy in a prism-coupling configuration to collect light at specific angles. Each sample allowed coupling to the SEP in a different wavelength range controlled by the energy of the exciton transition of the J-aggregate.

Thus we demonstrate the ‘plasmonic’ capabilities of a new family of organic, disordered materials. This novel organic platform can exploit the fabrication tools of supramolecular chemistry, to control and design J-aggregates which give access to light-confinement at desirable new wavelengths across the visible and near-infrared.

Tailored optical response from nano-engineered metallic clusters in glass

A Abdolvand and S Zolotovskaya

University of Dundee, UK

Homogeneously distributed, embedded spherical silver nanoparticles (30 nm in diameter) in glass were uniformly reshaped into spheroids of bespoke aspect ratios using an ultrashort-pulsed laser system. The aspect ratios were theoretically estimated using Gans's extension of Mie theory for non-spherical particles [1], and experimentally verified via nonlinear response of the reshaped nanoparticles. We will present that by subsequent irradiation of the metamaterial with precisely chosen wavelengths, elongation effects greater than the values presented in the talk can be achieved, leading to higher scattering cross sections and effectively better nonlinear responses. Laser reshaping provides spectral selectivity, and more importantly the much-needed spatial selectivity, for fast and local processing of this class of matamaterials. This is particularly of interest since fabrication, structural modification and characterisation of nanostructured materials have gained a great deal of attention due to their distinctive properties and potential use in technological applications. Glass containing silver nanoparticles is routinely used as high-contrast optical polarisers [2]. It has been recently demonstrated as a promising medium for high-volume optical storage of information [3]. Strong second and third harmonic generation has been demonstrated [4] where the glass containing mechanically and laser reshaped nanoparticles were subjected to pulsed laser excitation, thus showing the potential of this class of metamateriasl as an effective nonlinear optical medium for nanodevice applications.

[1] Gans R, Über die form ultramikroskopischer silberteilchen Ann. Phys. **47** 270–84 (1915).

[2] https://codixx.de/en/home.html

[3] Stalmashonak A, Seifert G, Abdolvand A, Metal-glass nanocomposite for optical storage of information Appl. Phys. Lett. **99 (20)** 201904 (2011).

[4] Zolotovskaya S A, Tyrk M A, Stalmashonak A, Gillespie W A, Abdolvand A, On second harmonic generation and multiphoton-absorption induced luminescence from laser-reshaped silver nanoparticles in glass, Nanotechnology **22** 435703 (2016).

Quantum dots within a confined-Tamm Plasmon at telecomms Wavelength

M Parker[1], R Oulton[1], E Harbord[1], E Clarke[2], K Kennedy[3] and J Rarity[1]

[1]University of Bristol, UK, [2]EPSRC National Centre for III-V Technologies, UK, [3]University of Sheffield, UK

Tamm Plasmons (TPs) are optical surface modes between a distributed Bragg reflector (DBR) and a metal layer. Like similar modes at dielectric-metallic interfaces they can be used to create localized electric fields to alter the emission characteristics of fluorophores, but possess key differences from surface plasmons, such as lower absorptive losses and emission within the light cone. This makes TPs an attractive option for devices that require lossless manipulation of single emitters, such as quantum dots (QDs), for use in applications such as quantum repeaters.

Additionally, lateral confinement can be added by shaping the dimensions of the metal layer. We show that confining the mode results in a blueshift effect and explore the use of asymmetric structures to create polarized effects. Compared to other confining structures (e.g. micropillars), confined-TPs have simple structures and require no active layer etching (which can add charge noise to the QDs). The ability to shape the emission profile by tailoring the metal layer structure, such as to that of a fibre mode, can be used to greatly increase the direct-coupling efficiency for a Tamm-based single-photon source.

We have designed and fabricated GaAs/AlAs + gold Tamm Plasmon structures that are resonant at 1.3 um and measured the effect of metal thickness and confinement (disc diameter) on the emission characteristics. This wavelength was chosen for it potential for telecoms application, and are the highest wavelength confined-TPs reported [1]. We also successfully measure enhanced PL emission of QDs, and use FDTD simulations to explore the mode structure and effect of QD position under the metal disc.

[1] Parker M., et al. IET Optoelectron., 2018, Vol. 12 Iss. 1, pp. 11-14

Parallel Session 2: Quantum optics II

(Invited) Vector vortex beams in optics and atom optics

S Franke-Arnold, N Radwell, A Selyem, R Hawley and F Castellucci

University of Glasgow, UK

We all know it - but often ignore it when dealing with optical systems or light-matter interaction: electro-magnetic fields are vectors. Replacing scalar theories with a full vectorial treatment can sometimes reveal surprising results and offers access to otherwise unachievable parameter regimes. We generate light fields with spatially varying polarisation profiles, including vector vortex beams, using Fresnel cones as well as compact interferometric devices. We can quantify the non-classical correlations between polarisation and space contained in these vectorial light fields by measuring their concurrence. These non-classical correlations allow us to design novel polarimeters. Moreover, the interaction of vectorial light fields with cold atoms can generate magnetic dipole structures which act like an (expensive) atomic compass.

Quantum logic and photon steering with single cavity photons in integrated photonic circuits

A Kuhn[1], T Barrett[1], M Mohammed[1], N Holland[1], T Doherty[1], K Theophilo[1], A Rubenok[2], J Matthews[2], O Barter[1], D Stuart[1] and B Yuen[1]

[1]University of Oxford, UK, [2]University of Bristol, UK

We demonstrate quantum logic and quantum feedback using narrow linewidth photons that are produced with an a-priori non-probabilistic scheme from a single rubidium atom strongly coupled to a high-finesse cavity [1]. We use a controlled-NOT gate integrated into a photonic chip to entangle these photons [2], and we observe non-classical correlations between photon detection events separated by periods exceeding the travel time across the chip by three orders of magnitude. Furthermore we apply a quantum-feedback scheme in a two-photon interference setting that allows deliberate switching between bosonic and fermionic photon behaviour, thus steering the second photon in a Hong-Ou-Mandel type two-photon interferometer to an arbitrarily chosen output port [3]. This feature also demonstrates that any probabilistic cavity-based atom-atom entanglement scheme can be made deterministic. Next steps to be taken to push the present state-of-the-art to a fully scalable quantum network will be briefly mentioned, see e.g. [4], and explored in detail by some of the co-authors with their own contributions.

[1] A. Kuhn, Cavity Induced Interfacing of Atoms and Light, in Engineering the Atom-Photon Interaction, Springer (2015)
[2] A. Holleczek et al., Phys. Rev. Lett. 117, 023602 (2016)
[3] O. Barter et al., in preparation.
[4] D. Stuart and A. Kuhn, New. J. Phys. 20, 023013 (2018)

Observing a distinct facet of bosonic coalescence

A Dada[1], J Song[2] and B Gerardot[3]

[1]University of Bristol, UK, [2]Korea Institute of Science and Technology, South Korea, [3]Heriot-Watt University, UK

When two identical photons meet at a balanced beam splitter, they coalesce and exit in the same direction, a phenomenon known as “two-photon interference” or the Hong-Ou-Mandel (HOM) effect [1]. This manifestation of the bosonic nature of photons has been exploited in key schemes for the optical realization of quantum information processing [2, 3]. Here, we demonstrate a distinct and previously unobserved facet of the bosonic characteristic of light. Using single photons generated through resonance fluorescence of a bright, charge-tunable semiconductor quantum dot [4], we show experimentally that when a single photon meets with a coherent state (containing dozens of photons on average) at a highly-reflecting beam splitter (~99%), their interference can also cause the single photon to be transmitted with a greater probability than when the coherent state is absent, as though the single photon gets “sucked in” by the coherent state, while the reflectivity experienced by the coherent state itslelf is modulated by the single photon [5, 6]. This has allowed us to recover, from a continuous-wave stream of single photons, a visibility profile consistent with the temporal wavefunction of single photons emitted by the dot. This effect is fundamentally beyond the type of coalescence observed in two-photon interference experiments. Also, this phenomenon could be exploited for higher-success-probability implementations of non-Gaussian operations on coherent states and quantum sensing [5, 6], and will likely open up the possibility for novel quantum applications.

[1] K. Hong, Z. Y. Ou, and L. Mandel, PRL **59**, 2044 (1987).
[2] E. Knill, R. Laflamme, and G. J. Milburn, Nature **409**, 46 (2001).
[3] S. Aaronson and A. Arkhipov, (ACM, New York, New York, USA, 2011).
[4] A. C. Dada, et al., Optica **3**, 493 (2016).
[5] P. Seshadreesan, et al., PRA **91**, 022334 (2015).
[6] C. Radtke, et al., J. Phys. B: At. Mol. Opt. Phys. **50**, 215501 (2017).

Observation of One-way Einstein-Podolsky-Rosen steering

S Wollmann[1], N Tischler[2], T Baker[2], N Walk[3], A Bennet[2], H Wiseman[2], G Pryde[2] and J Matthews[1]

[1]University of Bristol, UK, [2]Griffith University, Australia, [3]University of Oxford, UK

Quantum entanglement is a key resource for quantum information and communication tasks, such as teleportation, entanglement swapping and quantum key distribution. Within the hierarchy of quantum correlations, Einstein-Podolsky-Rosen (EPR) steerable states are distinguished from both entangled and Bell-nonlocal states by their inherent asymmetry. These nonlocal correlations allow to observe ‘steering’ that is when measuring one system affects the measurement results on the other system. In principle, two parties (Alice and Bob) who share certain entangled states may be able to complete the protocol if Alice tries to steer Bob’s measurement outcomes, but not vice versa. This is known as one-way steering.

In previous work we proved and then observed one-way steerability of an experimentally accessible class of entangled polarisation states – so-called Werner states [1] -- for the general case of positive-operator-valued measures (POVM) [2]. While these specific states can be conclusively proven to be one-way steerable, we recently aimed to settle the remaining open question about one-way steerability by deriving a necessary condition for steerability of arbitrary two-qubit states with loss for general POVMs [3]. Testing our experimentally generated Werner-like states, having a 99% fidelity with a Werner state, against this practical necessary condition demonstrates the requirement for robustness of experimental data generated in a laboratory environment [3]. We experimentally addressed this requirement using a novel photon source which allows us to give a conclusive answer to one-way steerability of arbitrary two-qubit states for arbitrary settings [4].

[1] R. F. Werner, Phys. Rev. A 40, 4277 (1989).
[2] S. Wollmann et al., Phys. Rev. Lett. 116, 160403 (2016)
[3] T. Baker, S. Wollmann, H.M. Wiseman, and G.J.Pryde, J. Opt. 20, 3 (2018).
[4] N. Tischler et al., arXiv:1806.10279 (2018)

Quantum-to-classical transition in a highly excited quantum dot-microcavity system

T Allcock, E Muljarov and W Langbein

Cardiff University, UK

An effective two-level exciton-photon system present in a semiconductor quantum dot (QD) inside a microcavity is described well by the Jaynes-Cummings (JC) model [1]. Photons exciting this system are distributed between different rungs of the JC ladder. Low intensity four-wave mixing (FWM) excitations populate only the first two rungs of the ladder, with six optical transitions fully describing the dynamics of the system, as demonstrated by good agreement with experiment [1]. As the excitation power increases, higher rungs become important for the QD-cavity dynamics and need to be taken into account in the modeling of high-intensity experiments [2,3].

In this work, we calculate the FWM nonlinear response of the QD-cavity system at different excitation powers, taking into account up to 50 rungs of the JC ladder in the Lindblad dynamics of this system, and including all allowed transitions, which occur only between adjacent rungs. We show that the FWM spectrum consists of discrete polariton lines with the broadening increasing with the rung number. In the spectrum with a higher excitation intensity, these lines interfere and gradually transform the spectral profile from the lowest-rung polariton doublet towards the classical Mollow triplet [4]. Owing to the analytical solvability of this problem, we provide a detailed visualisation of this quantum-to-classical transition, tracing the individual rung contributions.

[1] J. Kasprzak et al., Nat. Mat. 9, 304 (2010).
[2] J. M. Fink et al., Nat. Lett. 454, 315 (2008).
[3] J. Kasprzak et al., New J. Phys. 15, 045013 (2013).
[4] B. R. Mollow, Phys. Rev. 188, 1969 (1969).

Parallel Session 3: Adaptive optics and laser manipulation

(Invited) Integrating biology, photonics, data processing and simulations to advance the Understanding of Life

J Girkin

Durham University, UK

It is clear that optics and photonics can provide significant help in enabling life scientists to answer complex biological questions through the development of new imaging methods and instrumentation. Indeed such collaborations aid both branches of science; it was through the development of early microscopes that Robert Hooke discovered the cellular structure of life and Abbe's work on improved microscopes led to a better understanding of the limit of optical resolution. However, this is only scratching the surface of the way that true multidisciplinary approaches can advance both biological and physical understanding.

In this presentation I will initially look at the challenge of understanding life as perceived by an optical physicist. The presentation will then use a study of the vascular endothelium (a single layer of connected cells that cover all blood vessels) as a model for a true multidisciplinary approach to biomedical problems. A novel optical method for imaging inside intact vessels will be presented alongside new techniques in data processing that together provide insights into cell signalling and the response to external stimuli. These experimental findings will then be linked to a simple mathematical model of cell response to pressure changes, which is subsequently proven using optical methods.

As well as presenting the most recent findings and optical methods being developed a strong narrative within the presentation will be on multidisciplinary research and how all parties can help lead to significant advances in understanding.

Single arm vibrational optical coherence elastography (OCE) for tissue mechanical properties characterization

D Zhang[1], J Wang[2], C Li[1], Z Huang[1] and Y Ling[1]

[1]University of Dundee, UK, [2]Tianjin University, China

Cancer, e.g. prostate cancer and breast cancer tends to alter the mechanical properties of tissue. The mechanical properties, especially tissue stiffness can served as a signature to diagnose as well as characterize of tissue suspected with cancer. Our team employ phase sensitive spectral domain optical coherence tomography (PhS-OCT) to characterize the elastic property of ex-vivo human tissue by applying axial vibration. Other than conventional dual arm OCT setup, we are also developing common path interferometry PhS-OCT to enhance the sensitivity, by which means vibration with lower amplitude is able to be detected and co-generated shear wave can be greatly reduced with lower stimulation power. The common path OCT utilize the lower surface of glass window to serve as the reference where the sample is below the window. Tiny displacements occurred from disturbance of nature in the common path setup will not add as much as noise when compared with conventional OCT, where displacements between two light paths is not likely to be the same, thus the sensitivity is enhanced. Hardware layout also offers its potential on complex in-vivo conditions as the probe can be manufactured in a tiny scale by coupling fibers as well as piezoelectric materials.

Optical Instrumentation for Imaging Inside Tubular Organs

P Lawton[1], C Saunter[1], J Girkin[1], J McCarron[2] and C Wilson[2]

[1]Durham University, UK, [2]Strathclyde University, UK

Many biological organs are tubular, creating the challenge of imaging a cylindrically-curved surface on a flat detector. We present an extension of a previous method of imaging inside intact and pressurised ex-vivo arteries with the addition of field-aberration quantification and correction.

The vascular endothelium is a complex single layered network of cells which signal via the release of Ca^{2+} ions; the study of endothelial cell function and interactions in response to stimuli provides useful information for medical research into, for example, hypertension, diabetes and heart failure. A side- viewing GRIN imaging system has previously been used to view calcium signalling in the endothelium [1] utilising a low numerical aperture GRIN rod and microscope objective to increase the imaging depth and image a large number of cells over the curved inner artery surface, at the cost of resolution.

In this work we investigate this important imaging challenge further with a view to compensating for both the cylindrically-curved geometry of the arteries and field- aberrations present in the optical system. The field aberrations in the imaging optics and resulting from the curved surface/planar sensor mismatch have been quantified and corrections made through introducing field curvature and aberration correction into the imaging path. This new instrumentation opens up the potential to image calcium signalling within large numbers of cells to try and understand the complex patterns which are produced in response to a range of stimuli.

[1] C. Wilson, C.D. Saunter, J.M. Girkin and J.G McCarron 'Pressure-dependent regulation of Ca^{2+} signalling in the vascular endothelium', J Physiol 593.24 (2015)

Imaging mitochondrial interactions with bacteria in macrophages after bacterial challenge

G Cairns[1], G Johnstone[1], D Dockrell[2] and B Patton[1]

[1]University of Strathclyde, UK, [2]MRC Centre for Inflammation Research, UK

Mitochondrial reactive oxygen species (mROS) have recently emerged as critical microbicidal factors employed by macrophages[1,2]. Our long term aim is to quantify the role of mROS in the clearance of internalised extracellular bacteria in alveolar macrophages, particularly Streptococcus pneumoniae, the most common cause of the inflammatory condition pneumonia[2]. Recently, colocalisation has been observed between mROS, generated in response to S. pneumoniae, phagolysosomes and the bacteria itself[2]. Advances in microscopy and image analysis offer new opportunities to quantify these interactions to allow future examination of our ability to pharmacologically enhance host responses against antimicrobial resistant bacteria. However, there are numerous challenges posed when trying to image mROS in macrophages, particularly when also trying to correlate mROS location and dynamics with specific host responses. We present here initial results comparing computational super-resolution and deconvolution approaches on data obtained on a conventional confocal microscope with aberration-corrected images from a custom-built adaptive-optics enhanced confocal system in the University of Strathclyde. These images are multi-colour, using appropriate stains for mitochondria, mROS and bacteria. Adaptive-optics requires the use of an adaptive correction element; in our system a deformable mirror (DM) is used for this.

Key words: Mitochondria, macrophages, confocal, multi-colour, adaptive optics.

[1] West, A. P. et al. TLR signalling augments macrophage bactericidal activity through mitochondrial ROS. Nature **472,** 476-480 (2011).

[2] Bewley, M. A. et al. Impaired Mitochondrial Microbicidal Responses in Chronic Obstructive Pulmonary Disease Macrophages. J. Respir. Crit. Care Med. **196**, 845-855 (2017).

Parallel Session 3: Photonic integrated circuits

(Invited) State of the art InP photonic integrated components for terabit optical transmission

S Farwell

Oclaro Technology Ltd, UK

In order to meet the data transmission demands of the modern world, industry has turned to coherent optical transmission technologies utilising complex modulation schemes employing all the available dimensions of amplitude, phase states and polarisation. Such systems require very high bandwidth transmitters and receivers with complex functionality to generate and decode these optical waveforms. Photonic integrated circuit (PIC) technology is a key enabler for such systems.

PIC technology in InP provides all the necessary functionality including wide spectral bandwidth tuneable light sources, high bandwidth modulation, signal detection, amplification, and attenuation. Using this building block approach large complex photonic integrated circuits can be designed, manufactured in volume and tested. In this talk we will show practical examples of how these circuits have provided the basis for complete coherent transmission components, including small form factor pluggable transceivers operating above 200Gb per second with low power dissipation.

The enabling technical advances in materials and photonic devices will be discussed.

Acknowledgement: The author would like to thank the whole Oclaro team for their contributions to the development of these technologies.

Microresonator isolators and circulators based on the intrinsic nonreciprocity of the Kerr Effect

L Del Bino, J Silver, M Woodley, S Stebbings, X Zhao and P Del'Haye

National Physical Laboratory, UK

Miniaturisation of optical circuits will play an important role in the realisation of future telecommunication networks and lab-on-a-chip devices. One challenge for the evolution of optical circuits is the difficulty in realising optical isolators overcoming the size limits of Faraday-based isolators and circulators.

Here we present a proof-of-principle setup for isolators and circulators relying on Kerr-effect-induced nonreciprocity in microresonators. This has the key advantages of being completely passive, chip-integrable and competitive with the isolation of Faraday-effect-based isolators and circulators.

Pumping a microresonator in opposite directions with enough power leads to symmetry breaking with the surprising result that light of a given frequency can only circulate in one direction. This effect can be explained by a Kerr-nonlinearity-mediated interaction between the counterpropagating light that splits the clockwise and counterclockwise resonance frequencies.

We exploit this to realise an optical diode by coupling light into a silica microresonator with enough power to induce a resonance splitting. This sets the resonator into a state in which it only transmits the forward direction, preventing any back-reflections from coupling back into the resonator.

Being based on a nonlinear effect implies that the higher the input power, the more efficient the isolator is. Isolation over 20 dB is achieved at high power with insertion losses are around 5 dB. Furthermore, the isolator's characteristics can be tuned for optimal isolation or optimal transmission, depending upon the requirements of the system.

Given the simple design, it should be straightforward to realise integrated devices with even higher isolation working with input powers as low as a few uW.

By using all the ports of the add-drop configuration it is also possible to extend the use of the device to a 4-port circulator with similar isolation and transmission figures.

Nonlinear optical properties of silicon waveguides over a temperature range of 5.5 to 300K

G Sinclair, N Tyler, D Sahin, J Barreto and M Thompson

University of Bristol, UK

The linear optical properties of silicon have been extensively studied over the previous decades, motivated by a wealth of silicon photonic applications. However, by comparison, studies of the nonlinear optical properties of silicon have been somewhat neglected. Here, we make the first measurement of the nonlinear optical properties of silicon at telecom wavelengths over a range of temperatures from 5.5 to 300 K. In our work, we are primarily motivated by integrated quantum photonic applications, where the use of superconducting single-photon detectors often necessitates the operation of devices at cryogenic temperatures.

We focus on measuring the nonlinear two-photon absorption and self-phase modulation in a silicon wire waveguide from 5.5 to 300K. The two-photon absorption coefficient is determined by measuring the transmission of a 4.9ps optical pulse at a wavelength of 1.55 micron and fitting the nonlinear coefficient by using the inverse transmission method. The refractive nonlinearity is determined by observing the spectral broadening of the pulse due to self-phase modulation. By using the Saxton-Gerchberg phase retrieval algorithm, we can deduce the peak phase-shift of the pulse as a function of the input pulse power, thus yielding the refractive nonlinearity.

From our measurements, the two-photon absorption is seen to reduce by approximately a factor of two from room temperature to 5.5K, whereas the refractive nonlinearity remains a constant. This suggests that key optical components, such as photon-pair sources for quantum information processing, should continue to operate well at cryogenic temperatures.

Integrated superconducting nanowire single photon detectors for scalable silicon quantum photonics

J Paul[1], K Erotokritou[1], R Heath[1], D Sahin[2], J Barreto[2], B Slater[2], S Miki[3], H Terai[3], G Sharp[1], C Klitis[1], M Sorel[1], M Thompson[2] and R Hadfield[1]

[1]University of Glasgow, UK, [2]University of Bristol, UK, [3]National Institute of Information and Communications Technology, Japan

Combining fast and efficient single photon detection with integrated optical components is essential for scalable quantum photonic applications such as quantum computing and secure communications [O'Brien, Science 318 1567 (2007)]. Superconducting nanowire single photon detectors (SNSPDs) offer exceptional efficiency and timing jitter and are ideally suited for this purpose. SNSPDs may be fabricated atop waveguides for evanescent light-coupling [Sprengers et al., Appl. Phys. Lett. 99 181110 (2011), Pernice et al., Nat. Comms. 3 1325 (2012)]. To this end, we present the design and fabrication of integrated linear passive optical components with SNSPDs: grating couplers connected through waveguides and on-chip optical components to evanescently-coupled superconducting nanowires fabricated on silicon-on-insulator (SOI) wafer.

To enhance the coupling efficiency, the etch depth of the grating coupler is optimised using FDTD simulation. The theoretical out-coupling efficiency is ~ 63 % when the device operating at telecoms wavelengths. Scanning and transmission electron microscopy analyses together with optical characterisation are presented, verifying design parameters along with the performance of fabricated devices. The optimised optical components culminate in evanescently-coupled NbTiN-based SNSPDs designed for single photon detection applications. Electrical and optical characterisation of these detectors verifying their efficiency and timing properties is presented. This builds on previous work fabricating waveguide-coupled detectors from MoSi [Li et al., Opt. Express 24 13931 (2016)].

This work is supported by the "EPSRC Programme Grant EP/L024020/1" Engineering Photonics Quantum Technologies.

High performance quantum random number generators in silicon

F Raffaelli[1], G Ferranti[1], P Sibson[1], J Kennard[1], D Mahler[2], G Sinclair[1], A Santamato[1], D Bonneau[1], M Thompson[1] and J Matthews[1]

[1]University of Bristol, UK, [2]Xanadu, Canada

Random numbers are an essential resource in science and technology. The number of different ways to realise quantum random number generators (QRNG), that explore the probabilistic nature of quantum mechanics, has rapidly grown in recent years. Many approaches have been developed, based, for example, on single photons, homodyne detection and phase fluctuations from lasers [1]. While achieving good performances in term of generation rate and unpredictability, most of the experiments so far have been performed in bulk optics, suffering limitations due to their size, such as optical stability and scalability. Moreover, QKD and Quantum Information Processing are moving towards integrated systems [2,3]. To help deployment and mass manufacture of QRNG, effort has turned to integrating them into monolithic structures, such as integrated photonics. This opens up the possibility of embedding the source of random numbers, for example, into the sender/receiver of an integrated QKD system. Here we report our latest results in silicon-on-insulator (SOI) QRNGs. First, we demonstrated a homodyne detector integrated on a SOI device, employed to generate high rate random numbers [4]. Then, the SOI platform was used to generate random numbers by exploiting phase fluctuations from a laser diode with a new device design [5]. Another promising approach is Indium Phosphide (InP) [6]. We will compare the performance characteristics of SOI and InP, and discuss future perspectives of integrating QRNGs into other quantum technologies, such as QKD systems.

[1] M. Herrero-Collantes et. al, Rev. Mod. Phys. 89, 015004 (2017).
[2] P. Sibson et al., Nat. Commun. 8, 13984 (2017).
[3] J. Wang et al., Science (2018).

Parallel Session 3: Topological photonics

(Invited) Topological metamaterials

S Zhang

University of Birmingham, UK

Metamaterials have attracted tremendous attention due to their exotic optical properties and functionalities that are not attainable from naturally occurring materials. In particular, metamaterials can be designed to introduce strong spin-orbit coupling for light and consequently nontrivial topological properties. In this talk, I will start with a brief introduction to the concepts of Berry curvature, Chern number and topological photonics. I will show that combination of chirality and hyperbolicity – an extreme form of anisotropy, can result in nontrivial topological orders in metamaterials and consequently topologically protected photonic surface states that are immune from scattering by defects and sharp edges. The Weyl points in such systems result from the crossing between the bulk longitudinal plasmon mode and the transverse circularly polarized propagating modes. The photonic 'Fermi arcs' were directly observed in the microwave regime, which showed Riemann-surface like helicoid configuration in the energy-momentum space. I will further introduce a metamaterial approach for realizing three dimensional Dirac points, each of which represents the merging of two Weyl points with opposite chiralities. Spin polarized Fermi arcs are supported at the surface of the Dirac metamaterial.

Singular field at anomalous Zero-Group-Velocity in non-symmorphic photonic crystal waveguides

M Sotto[1], K Debnath[2], A Khokhar[1], I Tomita[3], D Thomson[1] and S Saito[1]

[1]University of Southampton, UK, [2]Indian Institute of Technology Kharagpur, India, [3]National Institute of Technology, Gifu College, Japan

Symmorphic Photonic Crystal Waveguides (PCWs) support guided modes defined by their parities under mirror operation. Thus, the conservation of this discrete symmetry allows even and odd to intersect inside the bandustructure. Nevertheless, breaking the mirror symmetry, by translating one side of the photonic crystal along the propagation direction with respect to the other, induces a branch exchange between these modes. In a perturbative framework, quantitative analysis shows that the substitution of the mirror-symmetry by glide-plane axis induces repulsive coupling between these modes experimentally verified. It is also well-known to induce attractive coupling between modes with origanally same parity to ensure mandatory features imposed by the periodicity. Considering glide-plane axis as a degree of freedom to tailor the bandstructure can be beneficial to design PCW-based devices in order to control the transmitted mode bandwidth, the slow-light effect or implement anomalous Zero-Group-Velocity points. These peculiar points issued from the branch exchange between transverse electric modes with different parities, guidance mechanismes and orthogonal dominant polarisations (i.e. transverse and longitudinal) are predicted by 3D-FDTD simulations to display fields patterns with enhanced singularities. Firstly, circular polarisation points (Spin Angular Momentum (SAM) of light) overlapping high field intensity regions which can be used for chiral light-matter interactions by embedding quantum dots with spin dependant transition. This will inhibit the propagation in the opposite direction because it is associated with opposite handedness. Secondly, optical vortices (Orbital Angular Momentum (OAM) of light) around which the energy flow is rotating and the field acquire an extra-phase defined by the vortex winding. Complex patterns of singularities with opposite vorticities emerge and appear to be higly dependant of the glide-plane axis. Moreover the tailoring of the bandstructure, these singularities offer the possibility to impose the directionality of the light and carry more information by the means of topological charges on-chip.

Measuring the Berry curvature from the geometrical pumping of light

H Price[1], M Wimmer[2], I Carusotto[3] and U Peschel[2]

[1]University of Birmingham, UK, [2]Friedrich-Schiller-Universitat Jena, Germany, [3]University of Trento, Italy

Geometrical properties of energy bands underlie fascinating phenomena in a wide-range of systems, including solid-state materials, ultracold gases and photonics. Most notably, local geometrical characteristics, like the Berry curvature, can be related to global topological invariants such as those classifying quantum Hall states or topological insulators. Regardless of the band topology, however, any non-zero Berry curvature can have important consequences, such as in the dynamical evolution of a wave-packet. We experimentally demonstrate for the first time that wave-packet dynamics can be used to directly map out the Berry curvature over an energy band. To this end, we use optical pulses in two coupled fibre loops to explore the discrete time-evolution of a wave-packet in a 1D geometrical charge pump, where the Berry curvature leads to an anomalous displacement of the wave packet under pumping. This is a direct observation of Berry curvature effects in an optical system, and, more generally, a proof-of-principle demonstration that wave-packet dynamics can be used as a high-resolution tool for probing the geometrical properties of energy bands

No exceptional precision of exceptional point sensors

W Langbein

Cardiff University, UK

Recently, sensors with resonances at exceptional points (EPs) have been suggested to have a vastly improved sensitivity due to the extraordinary scaling of the complex frequency splitting of the n initially degenerate modes with the n-th root of the perturbation [1-3]. I show here [4] that the resulting quantum-limited signal to noise at EPs is proportional to the perturbation, and comparable to other sensors, thus providing the same precision. The complex frequency splitting close to EPs is therefore not suited to estimate the precision of EP sensors. The underlying reason of this counter-intuitive result is that the mode fields, described by the eigenvectors, are equal for all modes at the EP, and are strongly changing with the perturbation.

[1] J. Wiersig, Phys. Rev. Lett. 112, 203901 (2014).
[2] W. Chen et al., Nature 548, 192 (2017).
[3] H. Hodaei et al., Nature 548, 187 (2017).
[4] W. Langbein, arXiv:1801.05750

Spin-angular momentum coupling with optical Weyl point systems

E Goi, B Cumming and M Gu

RMIT University, Australia

The Weyl point (WP) systems considered in this work are an excellent platform to investigate topological bosonic states. These three-dimensional (3D) linear point degeneracies are topological monopoles of the quantized Berry flux in momentum space carrying a quantized topological charge defined by corresponding Chern numbers of ±1 and therefore carry chirality. A WP is absolutely robust in momentum space, as it can be generated or eliminated only pairwise with opposite topological charge. Due to their topological nature, WPs exhibit Fermi arc surface states, and they can be associated with many exotic phenomena. Moreover, WPs are the simplest possible topologically non-trivial 3D band structure, and therefore the ideal starting point for the study of 3D topological systems. In this work, we demonstrate the first experimental realisation of photonic WPs in the technologically important infrared regime in gyroid-based photonic crystals coated with layered-composite nanometric materials. In order to fulfil the symmetry and the refractive index (n) requirements to exhibit frequency isolated WPs, the photonic crystals were

fabricated using a symmetry-preserving two-photon laser direct fabrication method that accounts for the elongation of the focus and then coated with high-n Sb2Te3 thin films (~ 100 nm) by atomic layer deposition (ALD). We investigated the chiral nature of the WPs by coupling with spin-angular momentum carried by circularly polarised light. This WP-induced mechanism leads to reversed circular dichroism along the directions that intersect the oppositely charged topological photonic states. This new discovery provides an entirely new platform for developing topologically protected super-robust photonic devices in angular-momentum-based information processing, circular-dichroism-enabled protein sensing, spintronics and quantum optoelectronics can lead to the discovery of novel 3D topological physics in the optical frequency and new non-linear, non-Hermitian and quantum optical phenomena.

Parallel Session 3: Quantum optics III

(Invited) Structured light from quantized light rays

M Dennis

University of Birmingham, UK

I will describe an approach to structured light families, especially Laguerre-Gaussian and Hermite-Gaussian modes, using geometrical optics. The propagation characteristics define a 2-parameter family of light rays: self-similar Gaussian beam family can be constructed from hyperboloidal families of straight rays. These are weighted by complex amplitudes determined by quantization rules. For Gaussian beams, the ray families are described by paths on a sphere analogous to the Poincaré sphere of orbits of a classical two-dimensional harmonic oscillator, and the quantization is that of the Pancharatnam-Berry phase on the Poincaré sphere. This ray-based description also provides a simpleexplanation for many aspects of structured Gaussian beams, such as “self-healing” and the Gouy and Pancharatnam–Berry phases. If there is time, I will outline generalizations to other structured beam families, including Bessel beams and Airy beams.

M A Alonso and M R Dennis "Ray-optical Poincaré sphere for structured Gaussian beams" Optica **4**, 476-86 (2017)

Non-ergodicity in open quantum systems through quantum feedback

A Beige[1], L Clark[2], F Torzewska[1] and B Maybee[3]

[1]University of Leeds, UK, [2]University of Newcastle, UK, [3]University of Edinburgh, UK

It is shown that quantum feedback can dramatically alter the dynamics of open quantum systems. It can induce non-ergodicity and system dynamics of expectation values which depend forever on initial conditions. To illustrate this, we consider an optical cavity inside an instantaneous quantum feedback loop which can be implemented relatively easily in the laboratory [1].

Non-ergodic quantum systems like the one described here can be used to overcome the standard quantum limit in quantum metrology without having to create entanglement as a resource [2,3]. Moreover, quantum systems with feedback have interesting applications in quantum information processing [4,5]. Non-ergodicity is also needed to design quantum heat engines whose efficiency is not limited by the laws of equilibrium thermodynamics. Moreover, understanding how to induce non-ergodicity in quantum systems might shine some new light on the relationship between classical and quantum physics.

[1] L. A. Clark, F. Torzewska, B. Maybee and A. Beige, **Non-ergodivity of open quantum systems through quantum feedback**, arXiv:1611.03716 (2018).

[2] L. A. Clark, A. Stokes and A. Beige, **Quantum-enhanced metrology with the single-mode coherent states of an optical cavity inside a quantum feedback loop**, Phys. Rev. A **94**, 023840 (2016).

[3] L. A. Clark, A. Stokes and A. Beige, **Quantum Jump Metrology**, in preparation (2018).
[4] A. Monras, A. Beige, and K. Wiesner, **Hidden Quantum Markov Models and non-adaptive read-out of many-body states**, Appl. Math. and Comp. Sciences 3, 93 (2011).
[5] L. A. Clark, W. Huang, T. M. Barlow, and A. Beige, **Hidden Quantum Markov Models and Open Quantum Systems with Instantaneous Feedback**, ISCS 2014: Interdisciplinary Symposium on Complex Systems, Emergence, Complexity and Computation 14, p. 143, Springer (2015).

Multi-spatial-mode squeezed light for direct quantum imaging

P Petrov, J Hordell, E Fradgley, C Gill and V Boyer

University of Birmingham, UK

Squeezed light can be used to improve the performance of optical sensing in cases where the sensitivity is limited by the shot noise. Multi-spatial-mode (MSM) squeezing extends this benefit to imaging and spectroscopy techniques. For instance reduction of the quantum fluctuations on the relevant quadrature, amplitude for absorption imaging or phase for phase-contrast imaging, leads to smoother images. Squeezed light illumination can even deliver increased spatial resolution in super-resolution schemes, and is likely to play a role in those applications where the signal to noise ratio cannot be improved by simply increasing the amount of light shone on the object. This can be the case for fragile biological samples.

Four-wave mixing in hot atomic vapours has been shown to be an efficient way to produce MSM squeezed light. So far, most experiments have focused on the continuous detection of light, sacrificing resolution and operating at analysing frequencies high enough to avoid technical noise. Here we are reporting on the direct observation of spatial intensity-difference squeezing between twin beams with a CCD camera. We show that from shot-to-shot, the fluctuations of the photon numbers in any matching areas of the twin beams are identical with an uncertainty less than the shot noise, that is to say less than the square root of the mean photon number in these areas. To show this, we have developed a spectroscopy technique producing the spatial noise power spectrum of the intensity difference, as well as a wavelet analysis, which reduces the impact of overall technical noise on the twin beams. Together, these techniques inform us on the spatial structure of the squeezing produced by our device and ultimately help us determine the size and shape of objects that could be better detected with this form of quantum illumination.

Towards an efficient quantum network with defects in diamond coupled to open-cavities

S Johnson[1], L Weng[1], S Ishmael[1], P Hill[2], H Liu[2], R Leyman[2], B Green[3], C Stephen[3], P Salter[1], A Trichet[1], G Morley[3], E Gu[2] and J Smith[1]

[1]University of Oxford, UK, [2]University of Strathclyde, UK, [3]University of Warwick, UK

The negatively charged nitrogen-vacancy (NV) defect in diamond is well established as a prime candidate qubit in the solid state, displaying highly coherent electron spin properties, with optical read-out, and the facility for coupling to nearby longer-lived nuclear spins. Distributed quantum networks additionally require coherent photon emission for remote entanglement protocols. Here the NV is inhibited, as only ~3% of the emitted photons originate from its coherent zero-phonon line (ZPL). This situation can be rectified by coupling these defects to an optical microcavity, to selectively enhance the ZPL emission through the Purcell effect, and efficiently channel these photons into the network.

Here we present the development of an efficient spin-photon interface based on NV defects in pristine diamond membranes coupled to open-cavities. Focused ion beam milling used in fabrication allows these devices to offer ultra-small mode volumes down to $5\lambda^3$. The open-cavity consists of independent high-reflectivity mirrors in a planar-concave geometry allowing for in-situ optimisation of the emitter-cavity coupling. A critical component will be the ability to engineer high-quality NV defects in diamond. Nitrogen ion-implantation has been predominantly employed for these purposes. However, NVs generated through the newly-developed laser writing technique have recently been shown to possess highly coherent optical transitions with transform limited linewidths of 13 MHz. We will discuss our efforts towards integrating this technique with the open-cavity device. Finally, we present the operation of the open-cavity system in a bath cryostat at 4K. Single NV defects are individually and deterministically coupled to the cavity modes and leading to an increase in the ZPL photon emission rate at resonance.

Looking to the future, the application of these devices in quantum networks requires fully integrated microwave control to coherently manipulate the electron spin of the NV within the cavity, we show some of our preliminary efforts towards this.

Commissioning of a quantum-enhanced Raman spectrometer

P Bertier[1], E Cici Ginistrelli[2], J Gutjahr[2], C Muldoon[2] and A Kuhn[1]

[1]University of Oxford, UK, [2]VeriVin Ltd, UK

We aim at the development of a unique non-invasive wine analyser which is based on quantum-enhanced spectroscopic sensing of trace compounds in sealed containers. Our approach combines Raman spectrometry with optical Cavity-QED effects [1].

For the actual process, we have a narrow-band driving laser which excites a small sample of molecules placed inside an optical cavity. The latter leads to enhanced Raman scattering of photons into the cavity mode. The cavity is of asymmetric mirror reflectivity to send all the scattered light through the output coupler into a spectrometer. Furthermore, both free-spectral range and cavity finesse are chosen carefully to eventually observe the entire Raman spectrum. The spectrometer will serve to measure the spectra of various molecules of interest in wine (water, ethanol, acids, glycerol, sugars, tannins, etc.) in order to build up a library of spectra for characterisation. These spectra, combined with sophisticated analysis techniques, will be used to de-convolute the wine spectrum and detect the presence of particular molecules.

In parallel, we are working on a technique to measure the spectrum of wine in the bottle, at the glass-bottle interface, using the evanescent field resulting from the near total internal reflection of an excitation source incident on the glass at the critical angle.

[1] C. Muldoon: Non-invasive wine taint detector US patent number 9453826B2 (2016)

[2] A. Kuhn: Cavity Induced Interfacing of Atoms and Light. In: Engineering the Atom-Photon Interaction. A. Predojević and M. Mitchell (eds) Springer (2015)

Tuesday 4 September

(Plenary) Organic molecules coming of age in quantum optics

V Sandoghdar

Max Planck Institute for the Science of Light, Germany

Interaction of light and matter at the nanometer scale lies at the heart of quantum optics because it concerns elementary processes such as absorption or emission of a photon by an atom. Over the past decade, we have shown that direct coupling of a photon to a single two-level atom should be possible via tight focusing. However, because transitions in quantum emitters are typically not closed, laboratory demonstrations of this idea fall short of the theoretical prediction. In this presentation I shall report on recent achievements, where the branching ratio of a single organic molecule is improved by a substantial Purcell effect when coupled to a microcavity. Furthermore, we will discuss coherent linear and nonlinear experiments on molecules coupled to subwavelength waveguides on a chip. Together with their ability to generate narrowband stream of single photons, these developments make organic molecules viable candidates for integration in chip-based quantum optical circuits.

(Plenary) Nitride single photon sources

R Oliver[1], T Zhu[1], J Jarmann[1], C Ren[1], F Tang[1], C Kocher[2], T Puchtler[2], B Reid[2], T Wang[2], S Patra[3], S Schulz[3] and R Taylor[2]

[1]University of Cambridge, UK, [2]University of Oxford, UK, [3]Tyndall National Institute, Ireland

Single photon sources are a key enabling technology for quantum communications, and in the future more advanced quantum light sources may underpin other quantum information processing paradigms such as linear optical quantum computation. In considering possible practical implementations of future quantum technologies, the nitride materials system is attractive since nitride quantum dots (QDs) achieve single photon emission at easily accessible temperatures, potentially enabling the implementation of quantum key distribution paradigms in contexts where cryogenic cooling is impracticable.

However, nitride heterostructures grown along the polar c-axis typically exhibit large internal electric fields due to the polarisation mismatch between different alloys and to piezoelectric effects. Electrons and holes captured by a QD are separated by the field, reducing their probability of recombination and limiting the single photon source emission rate. Whilst a number of approaches are being explored to overcome this issue, utilisation of nitride QDs grown on non-polar surfaces is particularly attractive since not only are the internal fields expected to be greatly reduced, but also the emission should be polarised along a specific crystal direction due to changes in the valence band structure induced by the asymmetric strain state of the material.

We have developed various methods for the formation of non-polar InGaN QDs utilising self-assembled growth regimes on either planar non-polar surfaces or the non-polar sidewalls of nanorod structures. We demonstrate polarised single photon emission with short lifetimes from QDs grown by these various methods, and show that the properties of the QDs correlate well with the predictions of a model based on k.p theory. The most successful QDs exhibit polarised optically-pumped single photon emission up to 220 K, a temperature accessible by on-chip cooling, and we have also demonstrated highly polarised electroluminescence from a single photon light emitting diode.

Parallel Session 4: Biophotonics – quantitative digital microscopy

(Invited) Malaria microscopy & fibre alignment with open, printed optomechanics

R Bowman[1], A Patto[2], A Ambekar[2], J Sharkey[2], D Foo[2], Q Meng[1], R Jaques[1] and J Baumberg[2]

[1]University of Bath, UK, [2]University of Cambridge, UK

Consumer electronics and the growing hardware "hacker" movement mean that the sensors, actuators, and microcontrollers to create high-performance instruments are now cheap and readily available. One of the limiting factors on the performance of DIY instruments is the mechanical assembly to integrate all the components, which must often be positioned with micron precision. We have shown this is possible using inexpensive 3D printed plastic parts, opening up the possibility of high-performance devices that can be produced in any reasonably well equipped "maker space". This talk will detail the sub-micron performance we are able to achieve, and show the applications of this technology from malaria diagnostics to fibre alignment.

The Openflexure Microscope [1,2] is a highly customisable mechanical and optical design for a microscope, with options ranging from a modified $3 webcam up to oil immersion 100x objective lenses, including beamsplitters for fluorescence and full computer control. This makes it possible to replace a basic manual microscope with a robotic one, with exciting prospects for medical diagnostic microscopy. Its small size, low power consumption, and low cost make it ideal for parallelising experiments, and the open-source hardware and software have been designed for ease of customisation and integration into other experiments.

More general micromanipulation is also possible using 3D printed parts, and we will also present the Openflexure Block Stage [3], a monolithic plastic flexure stage with 2x2x2mm travel, sub-20nm step size, and mechanical performance that comfortably surpasses the requirements of auto-aligning single mode fibre.

[1] "A one-piece 3D printed flexure translation stage for open-source microscopy" Sharkey, Foo, Kabla, Baumberg & Bowman, Rev. Sci. Instrum. **87**, 025104 (2016); http://dx.doi.org/10.1063/1.4941068
[2] https://github.com/rwb27/openflexure_microscope/
[3] https://github.com/rwb27/openflexure_block_stage/

Measuring sub-nanometre thickness changes in supported lipid bilayers with quantitative differential interference microscopy

D Regan, B Williams, P Borri and W Langbein

Cardiff University, UK

Supported lipid bilayers are one of the most prolific model systems used to study the biophysical properties of phospholipid membranes [1]. Supported lipid bilayers are commonly imaged using fluorescence microscopy, which suffers from limitations including fluorophore saturation and photobleaching, as well as sample manipulation artefacts from insertion of the label. Alternatively, quantitative differential interference contrast microscopy (qDIC) is a phase technique that allows label free imaging of lipid bilayers, as well as the extraction of quantitative information about the layer thickness with high sensitivity [2].

Here we present our results on qDIC indicating that the chemical treatment applied to the substrate affects the thickness of the supported bilayer. When formed on a surface rendered hydrophilic using Caro's etch, a thickness difference of 3.3 Å between the first and second bilayers on the surface was observed, while no significant difference in thickness was observed in samples formed on non-etched glass. An effect of the osmolarity of the hydration medium was also observed, with bilayers formed in distilled water approximately 3 Å thicker than those formed in PBS buffer.

Quantitative DIC was also used to visualise different membrane phases without the use of fluorescent labels. When applied to measure the thickness difference between coexisting liquid-ordered and liquid-disordered domains, a thickness difference of 11 Å was measured, in good agreement with literature values. The gel-fluid phase transition was also studied with qDIC, finding that incorporation of fluorescently labelled lipids into the bilayer prolongs the fluid-gel phase coexistence period in a concentration dependent manner.

[1] Ralf P. Richter, Rémi Bérat and Alain R. Brisson. Formation of Solid-Supported Lipid Bilayers: An Integrated View. Langmuir, 22(8):3497 – 3505, 2006.

[2] Craig I. McPhee, George Zorinyants, Wolfgang Langbein, and Paola Borri. Measuring the lamellarity of giant lipid vesicles with differential interference contrast microscopy. Biophysical Journal, 105(6):1414 – 1420, 2013

Imaging Ellipsometry as a novel detection method for protein-protein interactions

J Tomes, D Langstaff, M Gunn and R Morphew

Aberystwyth University, UK

Proteins are the functional unit of the genome and as such the investigation of protein-protein interactions are of significant biological interest. Ellipsometry is a well-established optical technique for the characterization and determination of thin film thickness and offers the potential of a label free, real time method to quickly detect multiple biological analytes and monitor complex protein interaction processes.

While Previous studies of protein-protein interaction using imaging ellipsometry have been successful they rely on a null method requiring prior calibration of the protein layers via separate spectroscopic ellipsometry. We present an imaging ellipsometer that directly utilizes a radiometric data collection technique, coupled to scheimpflug optical alignment, to give a high resolution flat field of view providing label free detection of model protein interactions with a 2D lateral resolution of 11µm and thickness detection at a nanometre scale.

The research equipment is now being optimised to discover if protein interactions can be measured for key biomarkers from Fasciola hepatica, the common liver fluke, which is a global zoonotic parasite that currently infects up to 17 million people and costs global farming in excess of $3 billion annually.

The wider impact of this research is a novel approach to rapid diagnostic testing and can also offer opportunities for increased understanding of wider protein-protein interactions, protein function analysis and anthelmintic development.

qDIC – Extracting quantitative information from Differential Interference Contrast (DIC) Images

J Williams, D Regan, G Zoriniants, W Langbein and P Borri

Cardiff University, UK

Differential Interference Contrast (DIC) is a linear microscopy method which yields contrast proportional to the differential in optical path length in the shear direction. Owing to its simplicity, speed of acquisition in wide-field illumination and low light intensities, DIC microscopy is a widespread tool for observing transparent objects such as living cells and tissues. Recently, work from our lab (1) has shown that with appropriate acquisition an image analysis, DIC can be used as a quantitative technique (qDIC) to measure thicknesses with sub-nanometer precision.

In this work, we have further developed the quantitative image analysis software which integrates DIC contrast images to extract optical phases. The integration of contrast images is achieved through the use of the Fast Fourier Transform (FFT) and Wiener-like filtering to reverse the differential transform performed when imaging in DIC. We have introduced an apodization routine which creates a smooth window function around the image to reduce the effects of aliasing, and minimises the integration artefacts which otherwise appear at the edges of the retrieved phase images. An Energy minimisation framework is subsequently used in order to further penalise against integration artefacts that are introduced through the use of the Wiener-like filtering process whilst preserving phase edges.

Our qDIC analysis also includes polynomial background fitting, to minimise the effects of a slowly varying background across the image. Furthermore, a region exclusion filtering algorithm allows the user to filter out objects whose integration artefacts encroach on the retrieved phase signal of nearby objects of interest. This software also has the facility of integrating multiple images within stacks, to extract quantitative information from 3D objects.

Application examples of this qDIC image analysis platform will be presented, including single lipid bilayers and dielectric nanostructures.

[1] Craig McPhee, George Zoriniants, Wolfgang Langbein, and Paola Borri, Biophysical Journal, 105, 1414 (2013).

Simultaneous measurement of thickness and refractive index of lipid bilayers by interferometric reflectometry (iRef)

A Nahmad-Rohen, D Regan, P Borri and W Langbein

Cardiff University, UK

Measuring the thickness and refractive index of nanometre-scale layers with high lateral spatial resolution is a difficult challenge. We present a technique to address this challenge.

We describe a model to calculate the complex reflection coefficient of a sample consisting of an arbitrary number of parallel thin layers for arbitrary incident light and focus more closely on the case of a gaussian beam emerging from an objective of known numerical aperture.

Using a confocal interferometric reflectometry (iRef) microscopy setup, we measure the amplitude and phase of each of the two perpendicular linear polarisation components of a light field reflected from a sample and reconstruct the sample's complex reflection coefficient. Comparing this reflection coefficient to the one calculated for a sample consisting of several parallel thin layers, we determine the thicknesses and refractive indices of the layers.

We present iRef results for lipid bilayers such as those found in cellular membranes, for example. Our data allows the determination of the thermodynamic phase transitions of the bilayer in a noninvasive and nondestructive manner.

Parallel Session 4: Waveguide and fibre optic devices and sensors I

(Invited) Bi-doped fibre lasers and amplifiers: technology and applications

J Sahu

University of Southampton, UK

Recent developments of O- band amplifier, and CW and pulsed lasers in Bi-doped fibres are reviewed. A flat gain of 25 dB covering the wavelength region from 1320 to 1380nm using Bi-doped phosphosilicate fibres is presented and its application in optical fibre communication is demonstrated. Further, a CW laser with an average power of 100mW and a pulsed laser with a peak power of 1W are discussed.

Resonant state expansion applied to photonic crystal structures

S Neale and E Muljarov

Cardiff University, UK

The resonant state expansion (RSE) is a novel rigorous method for calculating resonant states (RSs) of a photonic system [1]. These are the eigensolutions of Maxwell's wave equation (MWE) with outgoing boundary conditions. Using a complete set of RSs of a simpler system as a basis, the RSE makes a mapping of MWE onto a linear eigenvalues problem, determining the full set of the RSs of the complex system.

In addition to higher numerical efficiency compared to other computational methods [2], the RSE provides an intuitive physical picture behind resonant phenomena and features observed in optical spectra. So far, the RSE has been applied to finite open optical systems of different geometry and dimensionality, as well as homogeneous and inhomogeneous planar waveguides [2]. Very recently the RSE has been used in first order perturbation for photonic crystal (PC) structures to describe refractive index sensing [3].

Here, we develop a PC-RSE, a new rigorous approach to accurately calculate RSs in planar PC structures using a homogeneous slab as a basis system. The periodicity of PC structures mixes all possible Bragg harmonics. Therefore, the basis RSs have to be taken with different in-plane wave numbers. As a result, the Green's function of MWE has branch cuts in the complex frequency plane, which have to be taken into account in the PC-RSE along with the RSs. This presents the major complication of the PC-RSE which we have dealt with by splitting the cuts into a series of discrete, artificial cut states added for completeness to the basis along with the RSs [2].

[1] E.A. Muljarov, W. Langbein, and R. Zimmermann, Europhys. Lett. **92**, 50010 (2010).
[2] S.V. Lobanov, G. Zoriniants, W. Langbein, and E.A. Muljarov, Phys. Rev. A **95**, 053848 (2017).
[3] T. Weiss et al., Phys. Rev. Lett. **116**, 237401 (2016).

CO_2-filled Kagome hollow-core fibres for compact laser frequency stabilisation systems and spectroscopy at 2051 nm

A Curtis[1], G Barwood[1], C Edwards[1], R Phelan[2], N Wheeler[3], T Bradley[3], M Petrovich[3] and P Gill[1]

[1]National Physical Laboratory, UK, [2]Eblana Photonics Ltd., UK, [3]University of Southampton, UK

Global monitoring of atmospheric trace gases, particularly those of specific interest in the study of climate change, requires a long-term solution. A space-borne method of active sensing of greenhouse gases has been proposed using DIAL (differential absorption lidar), with either one or a number of satellites in low-earth orbit. Of the various greenhouse gases currently under long-term observation, one of the most important is carbon dioxide (CO_2). Using DIAL to measure the atmospheric concentrations of CO^2 requires a high-power laser stabilised alternately to a CO_2 absorption line centre and then ~3 GHz away; the differential backscatter at these two frequencies is used to determine the CO_2 gas concentration.

We have developed a compact, low-power, cw, frequency-stabilised diode laser system at 2051 nm that demonstrates better than the required line-centre frequency stability of 100 kHz at 10 s averaging time and can also be offset in frequency by ~3 GHz. This low-power laser is planned as a reference for a high-power pulsed laser for DIAL applications. The reference laser system is based on CO_2 gas-filled Kagome hollow-core fibre, about 5 m in length, typically filled to a few hundred Pa pressure. A DFB fibre-coupled laser is coupled into the Kagome fibre and the observed linear absorption features are used to stabilise the laser output frequency using a Pound-Drever-Hall locking scheme. We characterize the frequency stability of the system by a beat frequency comparison against a reference laser using a free-space absorption cell. Results will be presented for the laser locked to the centre of the $^{12}C^{16}O_2$ R(30) transition, and for two methods to lock ~3 GHz from this line. We also show that these gas-filled Kagome fibres exhibit no observable change in gas concentration or pressure over a period of ~15 months.

PT symmetric coupled Raman fibre lasers

D Churkin[1], S Smirnov[1], M Makarenko[1], A Sukhorukov[2] and I Vatnik[1]

[1]Novosibirsk State University, Russia, [2]Australian National University, Australia

In this talk we will discuss the concept of fiber lasers coupled in the way they can generate in different PT-symmetric regimes and exhibit PT-transition between PT-symmetric and PT-broken generation regimes. We investigate 2 couple Raman fibre lasers connected to each other by means of two couplers. The coupling coefficient can be adjusted by changing the couplers' coupling ration. By managing the values of optical losses and raman gain in both fibre lasers, the system can be operated either of PT-symmetric or PT-broken solution. PT-symmetric generation regimes is characterized by equality of generated powers in both laser cavities despite only one cavity is active, while other cavity is passive (not pumped). We describe the system both theoretically and numerically, using different models. We demonstrate an effect using the simple discrete matrix model which also takes into account phenomenologically introduced nonlinear phase shifts. Then we make an analysis using a more sophisticated model based on coupled nonlinear Schrodinger equations considering the intrinsic phase noise in the system. We show the generation map how generation regimes of different PT symmetric properties depend on the parameters of the system, including how the generated power depends on the pump power ind different regimes. We also show that the PT-transition is affected by self-phase modulation inside the fiber cavity and investigate requirements that should be met in order to observe PT-transition experimentally despite Kerr effect that violates exact symmetry conditions.

Parallel Session 4: Nonlinear photonics I

(Invited) Silicon core fibers for nonlinear photonics

A Peacock

University of Southampton, UK

The nascent field of silicon core optical fibers is attracting increased interest as a means to exploit the optoelectronic functionality of the semiconductor material directly within the fiber geometry. Compared to their planar counterparts, this new class of waveguide retains many of the advantageous properties of the fiber platforms such as robustness, flexibility, and long waveguide lengths. Furthermore, by employing standard fiber post-processing procedures to reshape and recrystallize the core material, it is also possible to tailor the optical properties beyond what is achievable on-chip, of particular use for nonlinear applications. In this paper I will review our efforts regarding the nonlinear characterization of the silicon core fibers fabricated via different methods. Results of transmission measurements obtained for fibers with different core materials and geometries will be presented, and the potential to extend their application into the mid-infrared wavelength regimes discussed.

Long-term stability of breathers in arrays of optical wave-guides

G-L Oppo[1], L Chirondojan[1] and A Politi[2]

[1]University of Strathclyde, UK, [2]University of Aberdeen, UK

The propagation of light through arrays of optical wave-guides is well described by the discrete nonlinear Schrodinger equation (DNLSE) which couples the Kerr nonlinearity in one waveguide to that of the nearest neighbours [1]. The DNLSE is known to admit localised solutions, known as discrete breathers, which are discrete solitons with, sometimes, astronomically long life-times [2].

Most previous analytical attempts of describing the stability of breathers dealt with very small backgrounds characterised by a smallness parameter [3]. The novelty of the perturbation technique presented here consists in introducing a smallness parameter inversely proportional to the frequency of oscillation of the breather thus making our method independent of the scale of the background. This allowed us to implement a multiple time scale analysis (MTSA) and to average over fast frequencies. The MTSA proves that breathers are still perfectly stable in the DNLSE up to a high order of the smallness parameter. The MTSA can also separate perturbative diffusion of the light intensity in the background from catastrophic rare events that can drastically change the shape and location of the discrete breather.

Within the perturbative regime, we obtain an averaged effective Hamiltonian of the breather that allows for fast numerical integrations through the elimination of the fast frequency components. This effective Hamiltonian can then be employed in hybrid integration algorithms resulting in computational simulations that are 5 to 10 times faster than the direct integration of the DNLSE.

[1] A. Sukhorukov, Y. Kivshar, H. Eisenberg and Y. Silberberg, "Spatial Optical Solitons in Waveguide Arrays", IEEE Journal Quantum Electronics **39**, 1 (2003)

[2] R. Franzosi, R. Livi, G.-L. Oppo and A. Politi, "Discrete Breathers in BEC", Nonlinearity **24**, R89 (2011)

[3] M. Johansson and S. Aubry, "Existence and stability of quasiperiodic breathers in the discrete nonlinear Schrodinger equation", Nonlinearity **10**, 1151 (1997)

A spontaneous symmetry breaking of light in ring resonators

L Hill[1], M Woodley[2,3], G-L Oppo[1], J Silver[2] and P Del'Haye[2]

[1]University of Strathclyde, UK, [2]National Physical Laboratory, UK, [3]Heriot-Watt University, UK

The Lugiato-Lefever (LL) equation [1] has been used to model a variety of nonlinear optical systems [2]. One of its major successes has been in describing light propagating in fiber loops and micro-ring resonators. A system of two coupled LL equations can be used to describe the interaction of either two circularly polarised fields [3] or two counter-propagating fields circulating in micro-ring resonators. The latter was experimentally studied in [4].

We show that a symmetry breaking bifurcation of the equal amplitude homogeneous stationary state may occur, as in [5], when increasing the input pump. The emergence of this symmetry breaking bubble however depends on the cavity detuning being above a threshold value. We provide a wide analysis of the dependence of the symmetry breaking from the parameters that characterise different experimental realizations of micro-ring resonators. Practical applications of these devices, such as frequency comb generation, Sagnac interferometry, chip-based nonreciprocal operation, optical gyroscopes, isolators and circulators based on the Kerr effect, require careful predictions about the onset of the symmetry breaking bifurcation.

[1] L. A. Lugiato and R. Lefever, Spatial Dissipative Structures in Passive Optical Systems, Physical Review Letters 58, 2209 - 2211 (1987)

[2] Y. K. Chembo, D. Gomila, M. Tlidi and C. R. Menyuk, Theory and applications of the Lugiato-Lefever Equation, European Physical Journal D **71**, 299 (2017)

[3] J. B. Geddes, J. V. Moloney, E. M. Wright and W. J. Firth, Polarisation patterns in a nonlinear cavity, Optics Communications **111**, 623 - 631 (1994)

[4] L. Del Bino, J. M. Silver, S. L. Stebbings and P. Del'Haye, Symmetry Breaking of Counter-Propagating Light in a Nonlinear Resonator, Scientific Reports **7**, 43142 (2017)

[5] A. Kaplan and P. Meystre, Directionally asymmetrical bistability in a symmetrically pumped nonlinear ring interferometer, Optics Communications **40**, 229-231 (1982).

Frequency comb solitons in microresonators with quadratic nonlinearity

A Villois and D Skryabin

University of Bath, UK

Microring resonators made with materials possessing quadratic nonlinearities open novel exciting avenues for precision spectroscopy and information processing applications and also for blue sky research in the area of frequency combs and soliton formation. Using of quadratic nonlinearity provides an important opportunity for developing comb self-referencing on the same photonic chip and using the same material platform as for the comb generator itself. Quadratic nonlinearity removes the necessity for bright soliton operation in the anomalous dispersion range and allows generation of stable bright soliton combs in the range of normal dispersion, which is more readily accessible for a broad range of input wavelengths, through the engineering of effective defocusing Kerr nonlinearity. In this work we report bright comb solitons and transition to the soliton combs in microresonators with normal dispersion and cascaded nonlinear effect. Our findings greatly extend a bulk of existing research on microcombs relying on bright solitons due to an interplay between anomalous dispersion and self-focusing Kerr nonlinearity.

Parallel Session 4: Quantum communication

(Invited) Advances in continuous-variable quantum key distribution

C Lupo, C Ottaviani, P Papanastasiou and S Pirandola

University of York, UK

Quantum Key Distribution (QKD) is the most advanced among quantum technologies, whose goal is to exploit quantum physics for communication security. Due to compatibility with existing telecommunication infrastructure, a compelling architecture for QKD is the one based on continuous variables (CV) of light, e.g., quadrature and phase. Here I review recent notable progresses and open challenges in the security analysis and implementation of CV QKD protocols. I will put particular emphasis on the Measurement-Device Independent (MDI) framework, which has been introduced as a robust way to protect against side-channel attacks on detectors.

Wide-angle receiver for long-distance free-space quantum key distribution

R Donaldson, A Maccarone, G Buller and A Fedrizzi

Heriot-Watt University, UK

Performing quantum key distribution in fibre-optic networks over long distances is challenging due to inherent losses in fibre-optic cable and the inefficiency of quantum amplifier and repeater technology. To enable global quantum key distribution it is widely recognised that free-space channels between ground stations and airborne high-altitude platforms or satellite nodes is the fastest approach. Research initiatives around the globe are already performing proof-of-principle studies and field trials, for instance in China, Japan, Singapore, Europe, Canada, and other international partners.

Wavefront distortions and intensity fluctuations due to atmospheric turbulence can lead to pointing-and-tracking errors during the quantum key sharing process in free-space quantum communication. These resultant errors can significantly increase the qubit error rate for time-bin quantum key distribution protocols due to a reduction in interferometric visibility with the changing angle-of-incidence.

Here we present a time-bin optical receiver, designed to be robust to turbulent multimode free-space channels as well as pointing-and-tracking errors [1]. The receiver implemented a novel single-photon avalanche diode 2D array allowing us to measure the qubit time-bin information and incident position simultaneously. This allows us the

possibility to reduce the complexities of conventional pointing and tracking for future demonstration. A wide aperture telescope was included in the design to enable a wide range of angles-of-incidence to be demonstrated. The presentation will include the concept design of the wide-angle receiver, and show operation performance for single and multimode free-space channels for a range of angles-of-incidence.

[1] Jin, J. et al. Efficient time-bin qubit analyzer compatible with multimode optical channels. arXiv **4,** 10 (2015).

Quantum Communications Hub

J Rarity

University of Bristol, UK

I will report progress from the UK quantum technologies communications hub.

Quantum key distribution for nanosatellite-to-ground application

D Lowndes[1], D Oi[2], L Mazzarella[2] and J Rarity[1]

[1]University of Bristol, UK, [2]University of Strathclyde, UK

Quantum key distribution (QKD) using satellites to exchange keys over global distances is a candidate for extending QKD networks beyond fibre optic metropolitan scale without the need for quantum repeaters.

In order to minimize the issues of limited coverage, we propose a nanosatellite swarm rather than a smaller number of larger and more expensive satellites. This requires development of free space optical components which are compatible with the size, weight and power (SWaP) of the nanosatellite platform (<10l; <10kg; <10W).

We present a low SWaP acquisition, pointing and tracking (APT) system which is necessary for establishing the quantum channel and counteracting atmospheric turbulence and platform instability to the few microradian pointing level. The APT system comprises of a small telescope, MEMS mirror, dichroic beamsplitter and NIR optimised CMOS camera. An 850nm beacon laser is imaged onto the camera after reflecting from the mirror. A feedback loop controls the mirror to move the beacon image to set-point, hence steering the counter propagating quantum signals.

This system has been tested over a 750m terrestrial link between two buildings at the University of Bristol. The performance of the link was then evaluated with a QKD source coupled into the APT system via the dichroic beamsplitter and a QKD receiver similarly situated alongside the beacon.

The APT + QKD system is designed to be compatible with a 6U or 3U cubesat but the low SWaP requirements also mean the system would be suitable for other free space optical (FSO) deployment such as on drones or in fixed links where fibre connection is not practical.

State comparison amplification

J Jeffers[1], U Zanforlin[2], D W Canning[2], G Tatsi[1], R J Donaldson[2], L Mazzarella[1], R J Collins[2] and G S Buller[2]

[1]University of Strathclyde, UK, [2]Heriot-Watt University, UK

Quantum mechanics imposes constraints on the amplification of an unknown quantum signal. Deterministic amplification always implies the addition of noise, but probabilistic linear noiseless amplification is allowed [1,2].

The state comparison amplifier (SCAMP) [3] amplifies a set of coherent states of unknown phase. The amplification process is: Alice picks an input state uniformly and at random, passes it to Bob, who mixes it with one of two (or more) suitable guess coherent states at a beam splitter in an attempt to achieve destructive interference in one output arm. The lack of trigger at an APD detector in this output is an imperfect indication that Bob's guess is correct and that the other output contains the correct amplified state. If, however, the detector fires Bob knows that his guess was wrong and he can correct the output at a second identical amplification stage via a feed-forward loop. Successful amplification occurs when both the detectors do not fire or when state correction is performed.

Figures of merit compare favorably with other schemes: e.g. the success probability-fidelity product [2] of the SCAMP is larger than for a USD based amplifier [2].

The SCAMP requires only classical resources and fast switching and is suitable for on-chip implementation. Without state correction it has achieved high-gain, high fidelity and high repetition rates [4, 5]. It could be used as a recovery station to counteract signal degradation due to propagation in a lossy fibre or across the turbulent atmosphere, or as a quantum receiver.

[1] T.C. Ralph & A.P. Lund, Proceedings of the 9th QCMC Conference 2009.
[2] S. Pandey, et al., Phys. Rev. A 88, 033852 (2013).
[3] E. Eleftheriadou et al., Phys. Rev. Lett. 111, 213601 (2013).
[4] R. Donaldson et al., Phys. Rev. Lett. 114, 120505 (2015).
[5] R. Donaldson et al., in preparation.

Parallel Session 5: Biophotonics – raman scattering and OCT

(Invited) Raman Spectroscopy Using Spatial Light Modulators

Z Liao, F Sinjab, H Elsheikha and I Notingher

University of Nottingham, UK

Raman micro-spectroscopy (RMS) is a powerful technique for highly specific molecular imaging of samples in 3-dimensions (3D). While RMS allows sensitive and chemically specific hyperspectral imaging, acquisition times for measurements in 3D are often lengthy, due to the weak spontaneous Raman scattering cross-section of many materials. The addition of a pinhole also typically comes at the cost of optical throughput for RMS detection, further increasing the acquisition times.

Multi-foci confocal Raman hyperspectral imaging is a promising strategy to improve Raman imaging speed while maintaining good depth resolution. In this paper we compare the depth-discrimination and speed performance of multi-foci Raman mapping with the reference standard of a single laser point confocal Raman mapping. A liquid crystal spatial light modulator (LC-SLM) is employed for the generation of multi-foci laser beams, and a digital micromirror device (DMD) is used as a software-configurable reflective pinhole array. The patterns of the laser-foci and pinhole array can be rapidly changed without requiring any hardware alterations. Here, three confocal patterns with different distance-to-size ratios (i.e. confocal period) are tested and compared for depth-discrimination performance. After optimisation of the laser foci pattern, we demonstrate the feasibility of using the multi-foci Raman instrument for recording depth-resolved Raman maps and optically-sectioned Raman maps of biological cells (Acanthamoeba castellanii trophozoites). Micrometric depth resolution and short acquisition times (20 minutes for single plane confocal image) is achieved.

Information theoretic resolution limit for raman spectroscopy and optical coherence tomography

A Dhakal and N Uprety

Phutung Research Institute, Nepal

We revisit Rayleigh-Shannon-Kosarev resolution limit [1-2] and discuss its implications for Raman spectroscopy and optical coherence tomography. In particular, contrary to common assumption, we show that the resolution for

Raman spectroscopy and optical coherence tomography (OCT) can be improved indefinitely by enhancing signal-to-noise ratio (SNR) and increasing sampling frequency, regardless of the spectral bandwidth of the excitation source. We will discuss the interplay between SNR, spectral bandwidth, sampling frequency and signal resolution, and propose a deconvolution method to retrieve Raman signal (or, equivalently, the OCT axial-scan/A-scan) by analyzing the scattered light collected from a sample when excited by a broadband source of a given bandwidth. For example, our preliminary calculations and simulations indicate that in the shot-noise-limited case, when a sample is excited with a light-emitting diode (LED) with Full-Width-at-Half-Maximum (FWHM) of 20 nm centered at 633 nm, a SNR of at least 30dB is needed in order to identify the Raman peaks narrower than 80 cm^{-1} using a spectrometer with spectral resolution 0.5 nm/pixel.

[1] C. E. Shannon, "Communication in the presence of noise." Proceedings of the IRE 37 **1** 10-21 (1949).
[2] E. L. Kosarev, "Shannon's superresolution limit for signal recovery." Inverse problems 6 **1**, 55 (1990).

Imaging of lipids and lipid metabolism in mouse oocytes and early embryos

J Bradley, I Pope, W Langbein, K Swann and P Borri

Cardiff University, UK

Many promising techniques proposed to monitor gamete developmental potential and quality are invasive and not realistically useful in clinical practise. Recent studies show mammalian oocyte and embryo viability are closely associated with their metabolic profile, relying entirely on their mitochondria as a source of ATP[1]. Fatty acids, stored in intracellular lipid droplets (LDs), are an important source of ATP. We recently demonstrated the use of the emerging technique Coherent Anti-stokes Raman Scattering (CARS) microscopy to allow chemically-specific, non-invasive imaging of lipid droplets within the living egg[2], with high three-dimensional spatial resolution. Here, we used a home-built single-source CARS microscope[3] featuring high spatial and spectral resolution, to examine the number, size, and 3D spatial distribution of LDs in mouse eggs and embryos. Quantitative analysis showed statistically significant differences during oocyte maturation and embryo development from two-cells through to blastocyst stage. We were also able to investigate how the LD conformation reflects their metabolic profile, in oocytes that had been subjected to alterations in mitochondrial metabolism. We find that a more dispersed LD conformation relates to an increased capacity for fatty acid metabolism, while a more clustered arrangement reflects diminished use of fatty acids for ATP. Furthermore, we are able to use deuterium-labelling of fatty acids to dynamically investigate the turnover of fatty acids from LDs.

Metabolic assays are also used to determine the contribution of β-oxidation to mouse oocyte/egg redox state and ATP production. This work hopes to establish new methods for non-invasive assessment of oocyte or embryo quality which could be used in clinical IVF or animal reproductive technologies.

[1] Sturmey RG et al. (2009) Reprod. Dom Anim 44, (Suppl 1) 50-58
[2] Bradley J et al. (2016) Development 143 2238-2247
[3] Pope I et al. (2013) Optics Express 21, 7906-7106

Evaluation of corneal wound healing process using a in-vitro 3D corneal model and optical coherence elastography

Y Ling[1], C Li[1], Y Yang[2] and Z Huang[1]

[1]University of Dundee, UK, [2]Keele University, UK

When cornea is exposed to damages, such as injuries, scratches, laser surgery and chemical reagents, it usually heals on its own after minor injuries. However, deeper injuries can cause corneal scarring, which will result in a haze on the cornea that impairs vision. In vitro studies of new ophthalmic drugs selection are usually performed using excised cornea from slaughtered animals or laboratory animals. To avoid the use of animal experiments, reconstructed in vitro models proved to suit better for the rapid testing of the uptake or metabolism of drugs in corneal cells based on tissue engineering techniques. In this study, lesion with different size and depth will be created with Ferric Chloride on a in-vitro 3D epithelium-stroma model for the drug uptake. Mechanical characterization of the corneal equivalents plays an essential role in studying the wound healing process and effects of new ophthalmic drugs as the pathological process is usually associated with the mechanical properties of the cornea. Optical coherence elastography (OCE) is a novel and non-invasive optical imaging technique aiming at early detection of subtle stiffness changes in diseased tissues. To evaluate the effect of new ophthalmic drugs, optical coherence elastography will be applied to monitor stiffness alteration of normal and injured cornea. The success of this project is of great clinical significance to understand the cell behaviour in vivo after injury and the therapeutic effectiveness of regenerative medicine.

Skin angiography using multi-functional OCT system based on improved SDV (complex differential variance) algorithm

Y Ji, C Li, Z Huang and Y Ling

University of Dundee, UK

The characteristics of subsurface capillary network has been proved to have a close correlation with skin diseases, e.g. skin cancer. However, the absence of a comprehensive and non-invasive imaging device make it difficult to view the full pattern of micro-vascular mapping in region of interest for in vivo diseases evaluation quantitatively, e.g. blood vessel density and curvature, etc. Fully characterization of morphology and structure of micro vascular would help to realize some skin diseases essentially and further to differentiate the lesion and normal skin tissue. Also has further significant for the skin disease progression and treatment.

Optical coherence tomography angiography (OCTA) is currently a popular technology for non-invasively image the high resolution micro-vascular distribution. We have developed an improved SDV algorithm not only to achieve higher vascular contrast, but also suppress the bulk motion noise and sparkling noise from instrument synchronization errors. Current system contains accurate acquisition of number of vascular trees (NT), vascular density (VD) and number of branching nodes (NB), etc. These parameters are significant to judge the feature of blood vessel quantitatively for some specific skin disease.

Parallel Session 5: Waveguide and fibre optic devices and sensors II

(Invited) Silicon photonic waveguides using nanoscale LEGO® blocks

S Saito[1], M Sotto[1], J Byers[1], K Debnath[2] and I Tomita[3]

[1]University of Southampton, UK, [2]Indian Institute of Technology, Kharagpur, India, [3]Gifu College, Japan

Silicon photonics is revolutionising optical communications by integrating both passive and active circuities similar to the complexity to electronic counterparts, opening up the era for the photonics-electronics convergence on a chip. The fundamental building blocks is the waveguide made of single-crystalline silicon layer bonded on top of the buried oxide layer. The state-of-the-art nano-electronics tools are used to pattern the silicon layer, however, the line-edge-roughness ultimately caused by just one molecule affects the scattering loss. The loss is especially critical for quantum communications and computations, since researchers are treating single photon to manipulate entangled states. Here, we introduce our attempts to use atomically-flat interface for fabricating silicon photonic waveguides using anisotropic wet etching. The technique was well-known to make Micro-Electro-Mechanical-Systems, and we have refined the process to apply for photonic waveguides by preparing a special silicon-on-insulator substrate with silicon (111) crystal plane aligned perpendicular to the substrate. We confirmed the loss of sub-1dB/cm for the waveguide, fabricated in the Southampton Nano-fabrication Centre at the Zeplar Institute, which is comparable to the result from industries. The challenge to utilize this substrate is to design combinations of the limited geometries with the flat-interface, like LEGO® blocks, while the circular bending can be included by the proper masking during the wet etching. We have also fabricated slot-waveguides with the slot width of 100nm and the record-low loss of 4.1dB/cm, which will be useful to various sensing applications and electro-optic modulators. These waveguides are also useful to novel metal-oxide-semiconductor based optical modulators, operated by carrier accumulations. We have also applied the technique to new designs of photonic crystals, where we could manipulate polarizations by intentionally breaking a mirror symmetry to allow the opening of the new photonic band-gap, which will be useful for realising strongly correlated photonic crystals for future quantum simulations.

Planar ultra thin glass seals for tamper protection of safety critical hardware components

G Flachenecker, J Koch, M Thiel and W Schade

Fraunhofer Heinrich Hertz Institute, Germany

Optical seals consisting of waveguide Bragg grating sensor structures in ultra thin glass transparencies have been developed to cover security relevant objects like cryptografic communication units for detection of unauthorized access.[1] For generation of individual optical signatures in the seals, femtosecond laser pulses were used. The optical seals were connected with an optical fiber to enable external read out of the seal. Thus the seal can be proved from time to time by external mobile reading system consisting of a broad band light source and a high resolution spectrometer (both connected via fiber optic coupler to the seal) and a notebook. Different attack scenarios for getting undetected access to the object, covered by the seal, were proven and evaluated. The results presented here, verify a very high level of security. An unauthorized detaching and subsequent replacement by original or copy of the seals for tampering would be accompanied with a very high technological effort, posing a substantial barrier towards an attacker. Environmental influences like temperature effects have a strong but reproducible influence on signature, which can be clearly distinguished from tamper attacks. In order to enable a permanent autonomic supervision of the state of integrity, the optical reading system has to be miniaturized drastically and resided together with the safety critical hardware under the seal. A miniaturization is possible by writing via femtosecond laser technology a dispersive coupling element into the ultra thin glass seal. This new approach for miniaturization of next generation seals system will be presented here too, as well as concepts for evaluation of data for recognition of tamper attacks.

Thiel, M. et al. Planar ultra thin glass seals with optical fiber interface for monitoring tamper attacks on security eminent components. Opt. Lasers Eng. **98,** 89–98 (2017).

A micro-optical assembly for scalable addressing of ion microtrap arrays

M Day[1], Z Chaboyer[2], K Choonee[3], M Thompson[1], S Gross[2], M Withford[2], A Sinclair[3] and G Marshall[1]

[1]University of Bristol, UK, [2]Macquarie University, Australia, [3]National Physical Laboratory, UK

Trapped ions are a useful resource for quantum information processing, quantum-enhanced sensing, and precision spectroscopy. Scaling to large numbers of ions remains an open, technological challenge that would advance the functionality and utility of the systems. Ion microtrap arrays, fabricated using MEMS techniques, have provided a key component to this scaling challenge. Of equal importance is a scalable optical interface, which will deliver the necessary laser beams for control of the ion's quantum states, as well as collection of the state-dependent fluorescence. We have developed some of the essential building blocks with which a scalable optical interface could be created; this is based on laser-written waveguides and continuous-relief diffractive optics.

The application of laser-written waveguides to trapped ions required the development of single-mode waveguides at blue wavelengths. We present a fabricated 10-waveguide chip suitable for delivering blue (422 nm) and near-IR (1033, 1064 nm) wavelength single-modes to two separate ion microtrap segments. The performance of a diffractive micro-optics array fabricated using grayscale electron beam lithography coupled to the waveguide chip will be outlined, detailing total system efficiencies and background scattering away from lens foci. The suitability of using the assembly for trapped ion addressing will be discussed.

Intracavity laser spectroscopy with controlled introduced optical losses for studying of waveguiding structures

A Shulga, A Khomchenko and I Shilova

Belarusian-Russian University, Belarus

A new technique of intracavity waveguide spectroscopy for studying of thin-film structures is proposed. This approach is based on recording and processing of the spatial intensity distribution (angular spectrum) of the light beam reflected from the prism coupler in the case of excitation of a guided mode in thin-film structures by the intracavity radiation of low-gain laser. The incident laser beam is coupled into a planar waveguide by the parallelepiped coupling prism, in which the intracavity radiation enters the input faces of the prism at the Brewster angles and undergoes double internal reflection in the prism. Excitation of the waveguide at the weak coupling of the prism with the waveguide structure makes it possible to reduce the influence of the coupling prism that increases the measurement precision. As a waveguide sample the low-loss ion-exchanged waveguide supporting five guided modes at λ = 632.8 nm was used. The Brewster coupling prism (n = 1.65708) with a low-loss planar waveguide was placed in the laser cavity consisting of two spherical mirrors – high reflector and output coupler – between the output coupler and the tube of the laser. The air gap thickness was controlled by means of the adjustable pressure. Precise angular positioning of the prism coupler was provided by the motorized rotation stage. It was shown that controlled introduced losses (diffraction, Fresnel) increase the round-trip threshold gain of the laser cavity and make the technique more sensitive to the waveguide losses.Thus, it is shown that the proposed technique can be used to measure optical losses in thin-film structures less than 5 cm^{-1}.The reflection spectra of “extracavity” radiation had no resonance dips which were observed only at strong pressure of the test waveguide to the coupling prism. This fact confirms the advantage of the intracavtiy technique when recording low waveguide losses at weak coupling.

Parallel Session 5: Nonlinear photonics II

Fiber-Optic Reservoir Computing

M Sorokina, S Sergeyev and S Turitsyn

Aston Institute of Photonics Technologies, UK

Machine learning and, in particular, Recurrent Neural Networks open novel possibilities for signal processing. Reservoir computing (RC) or Echo state networks provide implementation architecture for RNNs. It is realized by randomly connected nonlinear nodes, "neurons," while the training is achieved by the signals at each state being collected and processed to compute optimum weights. The system can be demonstrated by employing "reservoir" network requiring only one nonlinear node and delay line. Optical implementation of RC enables high-speed optical signal processing and can provide new generation of hardware devices. One of the first demonstrations of an all-optical RC utilizing GHz bandwidth was based on a semiconductor laser.

Here, we propose all-optical fiber implementation of RC. Specifically, we investigate the efficiency of signal processing on a non-linear prediction task for THz bandwidth signals. The system utilizes a spool of highly nonlinear fiber, attenuator and pump to achieve the desired nonlinear response. The feedback loop is used to achieve multiple nodes functionality. The simple design enables high performance processing of optical signals with high bandwidth. The resulting nonlinear node enables to approximate sine-transformation over the amplitude. The performance of the reservoir was demonstrated on the standard Mackey-Glass prediction task. We demonstrated that the scheme can operate at THz bandwidth.

Spiral bandwidth of four wave mixing in rubidium vapour

R Offer[1], D Stulga[1], E Riis[1], S Franke-Arnold[2] and A Arnold[1]

[1]University of Strathclyde, UK, [2]University of Glasgow, UK

Laguerre-Gauss (LG) beams, and more generally the orbital angular momentum of light (OAM), provide valuable research tools for optical manipulation, processing, imaging and communication, in both classical and quantum domains. In order to fully realise this potential, methods of frequency converting, manipulating and generating classical and quantum OAM states are required.

In this talk I will explore the high-efficiency frequency conversion of OAM in a four wave mixing process in rubidium vapour. Conservation of the OAM contained in the two pump beams determines the total OAM shared by the generated light fields at 420 nm and 5.2 μm – but not its distribution between them.

We find that a small pump OAM is transferred almost completely to the 420 nm beam – allowing efficient frequency conversion of the OAM state. However, increasing the total pump OAM broadens the OAM spectrum of the generated light, indicating OAM entanglement between the generated light fields. We experimentally investigate the available spiral bandwidth of the generated light modes as a function of pump OAM. This clears the path to high-efficiency OAM entanglement between widely disparate wavelengths.

Multi-parameter optimisation of dual-pump NALM fibre laser using machine-learning approaches

S Boscolo[1], I Gukov[2,3], S K Turitsyn[1,4] and C Finot[5]

[1]Aston University, UK, [2]Moscow Institute of Physics and Technology, Russia, [3]Skolkovo Institute of Science and Technology, Russia, [4]Novosibirsk State University, Russia, [5]UMR 6303 CNRS-Université de Bourgogne Franche-Comté, France

Recently, a new design of a model-locked all-fibre Figure-8 laser employing a nonlinear amplifying loop mirror (NALM) with two active fibre segments and two independently controlled pump-power modules has been proposed and experimentally demonstrated. This laser layout combines the reliability and robustness of conventional Figure-8 lasers with the flexibility of nonlinear-polarisation-evolution (NPE) lasers, providing access to a variety of generation regimes with a relatively wide adjustment range of the pulse parameters. Moreover, it enables reliable and reproducible live electronic adjustment of the lasing regimes, which is practically impossible to do by adjusting fibre-based polarisation controllers in NPE lasers.

The general issue of reaching a target mode-locked laser regime with a setup featuring many adjustable parameters can be intelligently addressed by using machine-learning techniques. Here, we apply predictive regression to find optimum operating regimes in the NALM laser that are accessible through independent control of the pump powers in the gain segments, $P_{p,1}$, $P_{p,2}$, and the laser output coupling ratio β. We use a piece-wise propagation model for generating data that characterises the laser. In the fibres, propagation follows a standard modified nonlinear-Schrödinger equation including gain saturation and spectral response for the active segments. The gain coefficient amplitude is dependent on the average signal and pump powers, the average power dynamics being described by standard rate equations. We have trained a gradient boosted tree algorithm on our dataset to identify high-energy, stable mode-locked solutions across the full variation range of the total pump level delivered to the active fibres, $P_{p,tot}$, the ratio $P_{p1}/P_{p,tot}$, and β (tens of thousands of points). The algorithm has quickly handled the whole parameter space. Our approach paves the way for alternative approaches to the optimisation of nonlinear cavity dynamics, and can be generalised to other complex systems and higher degrees of freedom.

Quasi-phase-matching sinusoidally-tapered waveguides for third-order parametric interactions

M Saleh

Heriot-Watt University, UK

Periodically-tapered-waveguides (PTWs) technique is an emerging potential route to achieve robust quasi-phase-matching (QPM) platforms in third-order nonlinear media, analogue to periodic poling, for on-demand optical parametric four-wave mixing processes. In this work, I will explain using Fourier-series analysis how the phase-matching condition is satisfied in PTWs, where both the linear and nonlinear properties are simultaneously longitudinally varied. Without loss of generality, I have studied as a practical example the enhancement of third-harmonic generation in dispersion oscillating fibres (DOFs), which are silica solid-core sinusoidally-tapered microstructured fibres made of stack of capillary tubes.

The novelty of this research is in obtaining the right conditions that allow a DOF (or in general a PTW) to be employed as an efficient QPM structure. In periodically-poled microstructures, there is a single phase-mismatching component that will be counteracted by one of the Fourier harmonics of the periodic nonlinear coefficient by choosing the right poling period. Whereas in a DOF, both the nonlinear coefficient and propagation-constants are periodically varying. Therefore, there are multiples phase-mismatching Fourier components of a single nonlinear process due to the periodic nature of the waveguide. By proper adjustment of both the tapering period and modulation amplitude, all the Fourier components of the nonlinear coefficient can simultaneously balance these multiple mismatchings, and the QPM condition is satisfied. A 50 dB enhancement in the third-harmonic generation parametric process can be obtained in DOFs in comparison with a uniform fibre that has an average diameter and same length.

QPM periodically-poled microstructures have remarkably boosted second-order nonlinear-based optical frequency-conversion applications in bulk and integrated platforms. Therefore, I envisage that this work could revolutionise the applications of integrated nonlinear optics using materials, such as silicon that are incompatible with periodically-poling techniques.

Dissipation induced instabilities in nonlinear optics: applications to mode-locked lasers and amplifiers

A M Perego[1], S Turitsyn[1] and K Staliunas[2]

[1]Aston University, UK, [2]Universitat Politecnica de Catalunya, Spain

We present the most recent results about the novel research topic of dissipation induced modulation instabilities in nonlinear optical systems. Such counterintuitive instabilities exploit a selective spectral damping, that applied to some spectral modes leads to energy transfer from the pump field to the damped modes themselves (gain-through-losses process). We comment both on the theoretical and on the experimental studies performed in this field with special emphasis about the demonstration of harmonically mode-locked fibre lasers operating, thanks to dissipative Faraday instability, with a pulse repetition rate in the GHz range. We provide an example of how dissipation induced instabilities, through the peculiar gain-through-losses process, could be practically engineered in order to design fibre amplifiers with tunable amplification spectral window, and how flexible amplification schemes could be obtained by a direct mapping of dissipation profile into the gain one (imaging of losses into gain). A further application of the dissipation induced instabilities include externally driven passive fibre resonators where tunable frequency combs and pulse trains could be generated, but also optical parametric oscillators where asymmetric losses for signal and idler waves may lead to amplification even when standard phase-matching conditions are not satisfied.

Thermo-optical pulsing in a micro-resonator based laser

M Rowley[1], B Wetzel[1], L Di Lauro[1], J S Totero Gongora[1], H Bao[1], J Silver[2], L Del Bino[2], P Del'Haye[2], M Peccianti[1] and A Pasquazi[1]

[1]University of Sussex, UK, [2]National Physical Laboratory, UK

The presence of complex and chaotic phenomena in dynamical systems has been widely reported across many fields. Here we report on thermo-optically induced chaos from a laser system consisting of a high-Q (>10^7) micro-resonator nested in a fibre-loop cavity. The micro-resonator high-Q factor significantly enhances various nonlinear optical phenomena– including the thermo-optical effect [1]. Thermal oscillators have been investigated in whispering-gallery mode resonators starting from works by Il' Chencko and co-workers [2], including effects like regenerative self-pulsing [3] and giant self-pulsation [4], with applications, for instance, in sensing [5].

In our dissipative laser system, the main-cavity loop comprises a narrow band-pass filter, along with polarisation control elements to adjust the losses as well as an optical amplifier to regulate the system gain. By adjusting these parameters, we investigate the dynamics that arise from thermo-optical effects in the micro-resonator. In particular, we observe the generation of 'slow' pulsing dynamics such as stable pulses at a 100 kHz repetition rate (corresponding to approximately 700 laser-cavity roundtrips).

In addition, by suitable adjustment of gain and losses in the laser system, we report a wide variety of dynamics, including the transition from stable to chaotic pulsed regimes, along with hysteresis and more complex multi-stability dynamics.

The reported results are also qualitatively confirmed by numerical simulations, underlining that such complex dynamics mainly arise from thermo-optical effects in the micro-resonator and can be controlled by acting on static parameters of the laser, such as gain and losses.

[1] Ilchenko and Gorodetskii, Laser Phys. 2, 1004–1009 (1992).
[2] Fomin, et al. , J. Opt. Soc. Am. B 22, 469 (2005).
[3] Park and Wang, Opt. Lett. 32, 3104–3106 (2007).
[4] Diallo, Lin and Chembo, Opt. Lett. 40, 3834-3837 (2015).
[5] Deng, Liu, Leseman and Hossein-Zadeh, Opt. Express 21, 4653-4664 (2013).

Parallel Session 5: Optical and quantum metrology

(Invited) Sub shot noise absorption measurement and microscopy with correlated photons

J Matthews

University of Bristol, UK

The quantum fluctuations of a given light field ultimately limits the precision with which physical parameters can be measured with that light. The lowest noise light source used in measurement is the laser, which when performing ideally is limited to performing at the optical shot noise limit of parameter estimation. This in turn defines limits in the quality of data collection in applications such as spectroscopy, microscopy and interferometry. In this talk, we will review work conducted in my group to demonstrate use of quantum states of light to measure absorption beyond the optical shot noise limit. We will discuss efforts to start performing such methods at different wavelengths and different photon fluxes in order to adapt to different future applications. We will report using these approaches for microscopy to observe weakly absorbing sample features.

Noise-dependent optimal strategies for quantum metrology

Z Huang[1], C Macchiavello[2] and L Maccone[2]

[1]University of Sheffield, UK, [2]University of Pavia, Italy

Quantum metrology describes strategies which allow the estimation precision to surpass the limit of classical approaches. When the system is sampled N times, there are different strategies which will allow one to achieve the Heisenberg limit, where the variance of the estimated parameter scales as $1/N^2$. All of these are equivalent when the systems are noiseless. However, in the presence of noise, these strategies are shown to be inequivalent, where entanglement and the use of ancillas are shown to improve the precision of the estimation.

For phase estimation using qubits, we show that for some noise channels, the optimal entanglement-assisted strategy depends on the noise level. We note that there is a non-trivial crossover between the parallel-entangled strategy and the ancilla-assisted strategy - in the former the probes are all entangled, the latter the probes are entangled with a noiseless ancilla but not amongst themselves. The transition can be explained by the fact that, separable states are more robust against noise and therefore are optimal in the high noise limit, but they are in turn outperformed by ancilla-assisted ones.

Phys. Rev. A.97.032333

High-resolution depth profiling using a range-gated CMOS SPAD quanta image sensor

P Connolly[1], X Ren[1], A Halimi[1], Y Altmann[1], I Gyongy[2], R Henderson[2], S McLaughlin[1] and G Buller[1]

[1]Heriot-Watt University, UK, [2]University of Edinburgh, UK

Light detection and ranging (LiDAR) based 3D imaging using single-photon detection is an emerging technology capable of high-resolution 3D profiling, and is now being used with sparse single-photon data. Typical single-element systems employ time-of-flight (ToF) measurements using time-correlated single-photon counting (TCSPC) techniques for high-resolution ranging, which are typically combined with an optical scanning system to reconstruct depth profiles. By comparison, it is possible to have practical scanless alternatives with use of image sensors, which offer reduced measurement time, enabling rapid single-photon depth imaging. This work presents a time-gated depth imaging system using a 256x256 element CMOS single-photon avalanche diode (SPAD) array, whose absence of timing electronics allows a high (61%) fill-factor. The device operates as a quanta image sensor (QIS), which allows raw photon data to be treated digitally by reducing the output from a single detector to the binary “0”: no photons, and “1”: at least one photon. This digital representation facilitates a binary frame output at high speed (up to 100k frames per second in this case) with negligible read out noise. Depth and intensity estimates are obtained by analysis of timing histograms generated from a sequence of oversampled time-gated binary frames of 10 ns gate width, advanced through the target in 10 ps step increments. A new clustering-based image restoration method has been developed which utilises binomial photon statistics and non-local spatial correlations within the target scene. This bespoke method is able to improve the estimates and reconstruct millimetre resolution depth and intensity profiles from as few as two binary frames per delay step, containing sparse photon data. Our imaging approach has potential uses in wide-ranging fields including defence and exploration, autonomous vehicle navigation, gaming and augmented reality, and underwater imaging, where high efficiency detectors are required for 3D imaging.

Extracting maximum information from limited data

J Rubio Jimenez and J Dunningham

University of Sussex, UK

Empirical data constitute our primary source of information to construct theories that explain the world around us, and to develop the necessary technologies that help us to accomplish that task. However, the quality of this information is restricted in practice by factors such as the number of experiments that we can perform or the energy employed by the experimental arrangement. This is particularly relevant for cases where we are interested in studying a fragile system, or when we can only have access to a few observations before the system under study is out of reach. In this talk we discuss a methodology to develop quantum-enhanced metrology protocols that are suitable for these scenarios. In particular, we study phase estimation in a Mach-Zehnder interferometer that operates in the non-asymptotic regime of limited data and moderate prior information. Our methods combine different Bayesian techniques to provide quantum lower bounds on the uncertainty associated to different quantum probes in this new regime. We show that our results constitute a non-trivial generalisation with respect to those that are obtained when the Fisher information is used instead, although the latter emerge asymptotically in our calculations. In addition, we explore the possibility of approaching these bounds with experimentally feasible operations, and we discuss the properties of those probes – such as their quantum correlations – whose performance is the best. Our results have important implications for theory and experiments in quantum metrology when the available data is limited.

Twin beam sub-shot-noise raster-scanning microscope with a hybrid detection scheme

J Sabines[1], A McMillan[1], P-A Moreau[2], S Joshi[1], J Rarity[1] and J Matthews[1]

[1]University of Bristol, UK, [2]University of Glasgow, UK

Traditional imaging techniques relying on classical optics, particularly microscopy, have a long history of development and are now standard tools across a broad range of scientific disciplines. For biomedical research in particular, high resolution images of structures such as cells continue to be invaluable. In recent years, there has been increasing awareness of the advantages of incorporating quantum states of light in imaging systems. Some well-known examples of beneficial quantum imaging effects include ghost imaging, super resolution and imaging without detection. In particular sub-Shot-noise imaging is of interest when dealing with delicate photosensitive samples where increasing the probe intensity may improve the signal-to-noise ratio and imaging quality, but it could also damage the sample under investigation. In any case, the precision with which optical parameters of a sample, such as absorption, can be measured is limited by the stability of the light source used as the probe, and even the most stable classical source (an ideal laser) suffers from unavoidable shot-noise.

Twin-beams from a spontaneous parametric sources can suppress noise beyond the shot-noise limit improving the precision per photon exposure when estimating absorption. Here we have constructed a raster-scanning microscope where illumination is provided by a correlated twin-beam source, we have incorporated feed-forward and the use of a hybrid detection scheme combining an APD and a CCD camera. Feed-forward allows us to reject uncorrelated photons into the sample whilst the CCD camera provides high detection efficiency.

We have recorded an image and performed an analysis that evidences sub-Shot-noise performance. We have obtained a precision ratio of 1.56 ±0.2 when comparing our results to an ideal coherent direct imaging scheme, and 1.76 ±0.2 when compared to a coherent scheme measured with the same detector efficiency as in our setup.

Parallel Session 6: Biophotonics – fluorescence & nanoparticle microscopy

(Invited) Correlative Light Electron Microscopy via Four Wave Mixing imaging of gold nanoparticles

I Pope[1], F Masia[1], L Payne[1], K Arkill[2], H Tanner[2], W Langbein[1], P Verkade[2] and P Borri[1]

[1]Cardiff University, UK, [2]University of Bristol, UK

Correlative Light Electron Microscopy (CLEM) combines the advantages of live cell imaging from light microscopy (LM) with the sub-nanometer spatial resolution of electron microscopy (EM) into one experiment. CLEM is however seriously hampered by the availability of robust probes. It is questionable whether most bimodal probes using both a fluorophore (for LM) and gold nanoparticles (for EM) attached to the protein of interest actually show the same protein pool. This is a serious drawback that needs to be addressed.

In this work, we show a novel CLEM workflow using only a single probe; gold nanoparticles (GNPs). To visualise GNPs within cells using LM, we use a novel optical imaging technique developed in our lab, based on the nonlinear four wave mixing (FWM) response at the surface plasmon resonance of GNPs [1]. This provides highly sensitive, specific, and quantitative particle detection without relying on fluorescence readouts, and is background-free even in highly scattering environments.

As a marker protein, we used Epidermal Growth Factor coupled to either 10 or 20nm GNPs, bound to the surface of HeLa cells grown on sapphire discs and subsequently high-pressure frozen. The samples were then freeze substituted into Lowicryl HM20; 300nm sections were analysed by FWM microscopy and TEM and the images registered together. We found a perfect match between gold particle signals from both modalities, with mean position deviations in the 10nm range. Notably, as expected from our model of the FWM response [2], the cross-polarised FWM amplitude correlates well with the GNP ellipticity measured in TEM, and the phase correlates with the NP orientation.

In short, this novel CLEM method alleviates major issues around multimodal probes and generates a more reliable CLEM workflow with one-to-one translation of the markers.

[1] Francesco Masia, et al., Opt.Lett. 34, 1816(2009) and Phys.Rev.B 85, 235403(2012).
[2] George. Zoriniants, et al., Phys.Rev.X 7, 041022(2017).

Quantitative Coherent Anti-Stokes Raman Scattering Microscopy on Single Nanodiamonds

R Lewis, I Pope, P Davies, O Williams and P Borri

Cardiff University, UK

Nanodiamonds (NDs) have great potential for biomedical applications, for example as non-toxic drug delivery vehicles. NDs have predominantly been studied by exploiting the existence of fluorescent defects for imaging. Recently it has been shown that non-fluorescent NDs exhibit a strong coherent anti-stokes Raman scattering (CARS) signal at the sp3 carbon resonance, eliminating the need for fluorescent defects or tags. However, previous work on CARS imaging on NDS [1] has been limited to NDs sizes larger than 100 nm radii. This was due to poor surface quality on the NDs, containing large quantities of non-diamond carbon, resulting in NDs becoming optically and structurally unstable at smaller sizes. On the other hand sizes <100nm are more suitable for cellular uptake. In this work, surface non-diamond carbon of small NDs has been minimised. We verified that NDs down to a size of 20 nm are stable under CARS imaging conditions. The CARS signal strength of individual NDs has been quantified as a function of the ND size, using correlative CARS and differential interference contrast.

[1] I. Pope, et al., Nature Nanotechnology, 2014, 9, 940-946

Inverted SPIM with implemented beam shaping and imaging adaptive optics

V Morozov and J Girkin

Durham University, UK

In this study we built custom two-level system with translation stage, sample tank and brightfield illumination optics on the lower level and excitation and imaging arms on the upper one. We have implemented adaptive optics in both arms to correct aberrations in the excitation and detection light paths to improve the imaging quality at depth.

SPIM in general is a fluorescent-based imaging technique the main concept of which is to illuminate a specimen from the side in a well-defined volume using a thin sheet of light, while the axis of detection is orthogonal to the illumination. The illumination plane, the light sheet, is aligned to be at the focal plane of detection objection lens and the specimen is located at the point at which these two axes intersect. The thin sheet of light, typically around 1-2 microns in depth, is created in the simplest configuration by using a cylindrical lens such that the back aperture of the excitation objective (of a reasonably low NA ~0.3) is illuminated with a line of light.

Inverted SPIM (iSPIM) is a modality which was introduced in 2011 by Wu et al. It provides a more traditional way of mounting the sample by placing it horizontally while illumination and detection optical axis are aligned above it at an angle of 45° to the coverslip plane. This approach has several advantages; one of which is that the sample is less likely to subside compared to mounting inside a vertical capillary as it is already in a resting state. However, the optical system is more mechanically complicated as it has to extend vertically from the table.

In the presentation the practical design of the system will be discussed and results presented showing the improvements in image quality due to the beam shaping and imaging adaptive optics.

High Speed Fluorescence Lifetime Imaging through Optical Fibre Imaging Bundles

E Bohl[1], G Williams[2], A Erdogan[2], N Finlayson[2], R Henderson[2] and J Girkin[1]

[1]Durham University, UK, [2]University of Edinburgh, UK

The traditional time-correlated single photon counting (TCSPC) techniques build a lifetime histogram on the PC which involves the transfer of large data packages from the detector to the PC greatly slowing down the acquisition of the image. Our advanced detector arrays, which are capable of performing lifetime histogram generation on-chip, can process over 16.5 Giga events/s enabling extremely fast lifetime data acquisition. We present an achromatic optical scanning microscopy system including a novel complementary metal–oxide–semiconductor (CMOS) single photon avalanche diode (SPAD) line array capable of recording spectral fluorescence lifetime images (sFLIMs) through an imaging fibre at a world leading rates. The presented imaging system enables us to resolve features as small as 3 μm through an imaging fibre of 8100 fibre cores[1]. We present both proof of principle data in the form of negative US Air Force test target for resolution along with demonstration of the system for imaging relevant biological systems ex-vivo as a precursor to in-vivo translation of the technology. We demonstrate the advantages of sFLIM through the use of Microbeads labelled with fluorescein, NBD and Rhodamine which clearly demonstrate the system capability of distinguishing the various fluorophores spectrally as well as by their different fluorescence lifetimes. The imaging fibre bundle enables the application of the system in medical research applications where it can be used for example in conjunction with a standard bronchoscope to reach alveola space in the distal lung. Further applications of this system can be in medical imaging of any endoscopically accessible organs.

[1] J. M. Stone, H. A. C. Wood, K. Harrington, and T. A. Birks; Optics Letters Vol. 42, Issue 8, pp. 1484-1487 (2017)

A fluorescent calibration specimen for the characterisation of optical microscopes

A Corbett[1], P Salter[2], M Booth[2], M Shaw[3] and T Wilson[2]

[1]University of Exeter, UK, [2]University of Oxford, UK, [3]National Physical Laboratory, UK

Fluorescence microscopy is an essential tool in nearly all fields of scientific discovery. It is therefore all the more surprising to find that there are no widely adopted standards for the calibration of fluorescent microscopes. Calibration provides a wide range of information relating to microscope performance. Without calibration, images taken on two separate microscopes cannot be directly compared as they may have differing magnifications, illumination intensities or detector sensitivities. As the range of microscopy techniques capturing 3D information continues to increase the need for standardization becomes ever greater.

Widely used methods for determining microscope performance are currently limited to basic techniques such as fluorescent beads, which don't form a regularly spaced pattern and reflective etched gratings, which are limited to being two-dimensional and require changes to the microscope filter sets.

Laser processing of plastic substrates has shown that it is possible to generate bright fluorescent patterns which meet many of the criteria needed to develop a fluorescent calibration standard in optical microscopy. The new standard will be able to quantify a range of parameters that determine microscope performance. For example, spatial distortions within the field of view can be quantified by a regular array of bright fluorescent points. Other patterns can determine factors such as detector linearity, field flatness and changes in the point spread function across the field of view and over depth.

Parallel Session 6: Fibres and propagation physics

(Invited) Mode Multiplexers for Space-Division Multiplexed Communications

N Fontaine

Nokia Bell Labs, USA

Mode multiplexers or mode sorters take spatially separated optical fields and combine them into spatially overlapped modes in free-space or of a multi-mode fiber. Building a device that can losslessly excite 100s-1000s modes would enable diverse applications including ultra high capacity space division multiplexed communication systems and imaging in multimode fiber.

Scaling towards 100s-1000s of modes without incurring loss is challenging. These multiplexers should also be able to interface with single mode fiber systems – that is the demultiplexed beams should be diffraction limited Gaussians such that they can couple into a small detector or interface with a single mode fiber.

We study two technologies: all-fiber photonic lantern spatial multiplexers and multi-plane light conversion (MPLC). Photonic lanterns are adiabatic tapered fiber bundle-like structures, and MPLC devices comprise alternating free space propagation with phase manipulations. Both have their own strengths and weaknesses. MPLC uses inverse design algorithms to determine the phases masks and therefore have the freedom to produce almost any spatial field. Photonic lanterns are all fiber devices, and the refractive index profile of the taper is constrained to the available fibers and capillary. Therefore lanterns do not have as much control over the field, but due to the all fiber construction, they are very low loss.

Our primary use of these mode multiplexers are to encode information onto each spatial mode of a fiber supporting 100s of modes and transmit 1000s of km. We will present our progress towards a 45 spatial mode communications system in standard graded index fiber and progress towards spatial multiplexers supporting 1000s of modes.

Low-frequency suppression of classical laser fluctuations using hollow-core fibre

E Allen[1], G Ferranti[1], D Mahler[1], K Rusimova[2], P J Mosley[2] and J Matthews[1]

[1]University of Bristol, UK, [2]University of Bath, UK

Reduction of classical laser amplitude noise can be advantageous for a number of optical applications, including Raman scattering microscopy and quantum squeezed light generation. Classical laser noise is particularly prevalent in doped fibre-based lasers, which are popular due to their relatively low cost, compact size and environmental stability compared with optical parametric oscillator (OPO) lasers. One technique to reduce classical fluctuations for pulsed laser systems involves the combination of the pulsed laser train with a delayed version of itself, which suppresses noise at a particular frequency. This mixing is performed via an asymmetric Mach-Zehnder interferometer where the asymmetry, L, is related to the suppression frequency, f, via $L=c/(2nf)$, where c is the speed of light and n is the refractive index of the delay medium.

This scheme presents practical challenges when suppressing at low frequencies as free-space propagation becomes difficult when longer delays are required. Conventional fibre propagation is also undesirable as effects in the fibre (self-phase modulation spectral broadening, dispersion) degrade both the effectiveness of the noise suppression scheme and decrease the usefulness of the light after noise suppression.

Here we circumvent both of these issues by implementing the delay using hollow-core free-boundary fibre. The fibre consists of six 33 μm resonators surrounding a 45 μm core with an outer diameter (fibre O.D.) of 160 μm, and provides single-mode propagation at 1550 m with 0.06 dB/m attenuation. We demonstrate a reduction of classical noise to within 0.2 dB (< 5%) of the shot-noise limit at 4.5 MHz using a 35 m hollow-core fibre delay. The fibre system provides considerable practical and stability improvements over free-space delays and in principal could be completed in an all-fibre system. This implementation paves the way for noise suppression techniques at frequencies previously unattainable without the significant challenges of building long free-space delay lines.

Slow light propagation through a Moiré grating at the zero dispersion wavelength

T Maybour, P Horak and D Smith

University of Southampton, UK

The reduction in the group velocity of a light pulse, or ‘slow light’, has many practical applications including optical switching and buffers. We investigate slow light propagating near the band edge of a Bragg grating. At the Bragg wavelength a resonance occurs in the reflection spectrum creating a photonic band gap. At wavelengths close to the band edge light is transmitted through the grating and a reduction in group velocity is observed, but also an increase in group velocity dispersion (GVD) leading to large pulse broadening preventing any practical use. We present a possible resolution to this problem.

We analyse single period Bragg gratings using coupled mode theory. For a pulse with a given carrier frequency and desired group velocity, there exist two grating periods for a chosen AC grating modulation which produce a band gap above and below the carrier frequency respectively. In both cases, as the group velocity tends to zero the GVD diverges causing substantial pulse broadening. One grating period produces normal and the other anomalous GVD, suggesting that a Moiré grating that superimposes both grating periods could be used to create a zero dispersion wavelength at the carrier frequency. To simulate pulse propagation through such a grating, we employ matrix transfer methods and numerical optimisation to find the grating parameters which produce the smallest group velocity and GVD for a given pulse bandwidth.

Our initial results demonstrate a group velocity reduction by a factor of 4 with negligible pulse broadening. We are currently examining the use of apodisation which will provide an improvement in the grating transmission spectrum and increase the allowable pulse bandwidth. With this we expect to achieve group velocity reduction by a further two orders of magnitude whilst minimising pulse broadening.

Neural Network classification for intensity imaging through multimode optical fibres

P Caramazza, R Murray-Smith and D Faccio

University of Glasgow, UK

The need for endoscopic imaging has stimulated research, both scientific and technological, on optical fibres. In particular, multimode fibres represent an ideal means for their capacity to transmit different light modes simultaneously. However, strong distortions arise due to mode dispersion and mode-coupling phenomena. Nonetheless, recent results have highlighted that the light field evolution is in principle deterministic and, therefore, it is possible to find a relation between input and output of the fibre. Different techniques have been proposed such as phase conjugation and transmission matrix (TM) measurements. However, the main limitations are related to the necessity to measure both amplitude and phase (TM), and for no bending of the fibre, and a static object plane. Here, we explore the possibility given by artificial neural networks for image transmission through multimode fibre. A first step in this direction is the demonstration
of neural networks to classify images coupled into the fibre. In our experimental setup, gray-scale images (28 × 28) are generated, by means of a CW laser source (λ = 532) and a spatial light modulator, and coupled into a multimode step-index fibre (1m-long, core diameter = 105μm and NA = 0.22). The output of the fibre is imaged onto a CMOS camera, so that just the amplitude is measured. Remarkably, a supervised neural network algorithm could classify correctly over 90% of speckle patterns corresponding to hand-written digits (and similarly with the Fashion MNIST dataset). A second step would be the implementation of a deep complex-weighted encoder to solve the inverse problem, in order to retrieve the original image. We will report progress with this approach and on the possibility to also determine the robustness with respect to bending of the fibre and longer cables.

Imaging temporally resolved optical fibre modes with a single-pixel camera

S Johnson, M Edgar and M Padgett

University of Glasgow, UK

Single-pixel cameras with temporal resolution can produce 3D images. We present a single pixel camera that has a temporal resolution of 200 picoseconds, enabling us to resolve the modes from a few-mode optical fibre. This resolution is achieved by utilising single-pixel imaging that uses a bucket detector to collect the light from selected areas of the image, in our system the light emitted from the fibre is incident on a digital micro-mirror device (DMD) that displays a known pattern and those parts of the image are reflected into our bucket detector. From the measurements of many patters a full image can be reconstructed.

We coupled a high repetition-rate pulsed laser into the optical fibre. The different eigen-modes in an optical fibre travelled at different group velocities depending on the characteristics of the fibre. The relative velocities of these eigen-modes within the fibre caused a temporal separation of the modes, where the separation was proportional to the length of the fibre. To view the output mode of the fibre we displayed a series of Hadamard patterns on the DMD, for each pattern a time-resolved measurement was made. Our bucket-detector was a photomultiplier tube with 200 picosecond time resolution, we used time-correlated single photon counting electronics to determine the arrival time of the photons at our bucket detector. An image was calculated from the intensity measurements and the Hadamard patterns for each time bin.

The 3D image of the optical modes showed the changing temporal picture of the dispersed laser pulse with different modes appearing though time. The modes could be separately imaged if the temporal spacing was greater than 200 picoseconds.

Parallel Session 6: Quantum dots I

(Invited) Metallic nano-rings to improve light extraction from single quantum dots

L Sapienza[1], O J Trojak[1], C Woodhead[2], J D Song[3] and R Young[2]

[1]University of Southampton, UK, [2]Lancaster University, UK, [3]KIST, Korea

We report on a broadband device based on metallic nano-rings deposited on the sample surface in correspondence to single quantum emitters. These allow increasing the extraction of light from single InAs/GaAs quantum dots (QDs) of up to a factor 20 [1]. By combining the nano-ring with a deterministically placed super-solid immersion lens (super-SIL), a further increase of up to a factor 10 in the brightness is measured [2]. The combined nano-ring-super-SIL device allows reaching single-photon fluxes as high as ~1MHz from a QD in bulk. Such a device is scalable and relatively easy to fabricate: the positioning of single QDs can be carried out in an automated system, the dimensions of the rings are compatible with photolithography and nano-imprint, and the super-SIL deposition requires only optical microscopy tools. Furthermore, the combined enhancement effect of the nano-ring and the super-SIL is wavelength insensitive, therefore broadband, and compatible with any kind of solid-state emitter of classical and quantum light.
We have also developed a new class of droplet QDs with ultrathin capping layer (~10nm) [3]: the proximity of the emitters to the sample surface is expected to allow the interaction with plasmonic fields excited in the metallic nano-rings, thus opening the path to controlling the QD spontaneous emission rate via QD-plasmonic coupling.

[1] O.J. Trojak, S.I. Park, J.D. Song, L. Sapienza, "Metallic nanorings for broadband, enhanced extraction of light from solid-state emitters", Applied Physics Letters **111**, 021109 (2017).
[2] O.J. Trojak, C. Woodhead, S.I. Park, J.D. Song, R.J. Young, L. Sapienza, "Combined metallic nano-rings and solid-immersion lenses for bright emission from single InAs/GaAs quantum dots", arxiv.org/abs/1801.07210 (2018).

A nuclear spin quantum memory in an InGaAs quantum dot system

J Hinchliff[1], P Androvitsaneas[1], D McCutcheon[1], A Young[1], T Nutz[2], J Rarity[1] and R Oulton[1]

[1]University of Bristol, UK, [2]Imperial College London, UK

An excess electron spin in a quantum dot (QD) is a two-level spin qubit, much like an atom. However, QDs contain 10^5 atoms, all with spin, each with a strain-dependent coupling to the electron spin, creating an effective, varying magnetic field, which decoheres the electron spin state. We propose to polarise the spin bath along the axis of a small (<200mT) external magnetic field in the Voigt geometry by applying laser pulses along the optical axis, driving the electron spin such that the nuclei align into a stable configuration and their effective field becomes constant. Varying the pulse power and detuning introduces asymmetry in the direction of alignment of the nuclei, giving control over the effective field magnitude, so the electron precesses according to the sum of the external and effective field components.

To create a nuclear spin quantum memory, we need the electron to interact with a single nucleus. Many nuclei will have 9/2 spin, and quadrupolar coupling, A_Q dictated by strain. Modeling the distribution of A_Q shows a 5MHz region with high probability of containing a single nucleus. We can initialise this nucleus into the electron spin plane using a radiofrequency pulse with 5MHz linewidth, (equivalent to 100ns). The electron and nucleus then evolve according due to their hyperfine coupling. If the effective field is set to negate the external field, the electron and nuclear spin states swap periodically. Maximal entanglement between the spins occurs when the system takes the form of the $\sqrt{SWAP}$ operation. At this point, the electron spin state is mapped onto the nuclear spin. Applying a $\pi/2$ pulse to the electron disentangles it from the nucleus, which retains its spin state. We can read out this state by performing a quantum non-demolition measurement on the nucleus using an ancilla photon.

High beta factors and directional coupling of InAs/GaAs quantum dots to photonic crystal waveguides determined by direct spectral imaging

L Scarpelli[1], B Lang[2], F Masia[1], D Beggs[1], A Young[2], C Schneier[3], S Hofling[3], R Oulton[2] and W Langbein[1]

[1]Cardiff University, UK, [2]University of Bristol, UK, [3]University of Wurzburg, Germany

Quantum dots (QDs) embedded in photonic crystal waveguides (PCWGs) are promising systems to implement quantum circuits. A fundamental requisite of any network based on PCWGs is that all the spontaneous emission (SE) from the emitter couples to a single waveguide mode only. The probability that a spontaneously emitted photon couples to the waveguide mode is given by the beta factor β. Previous works have used the lifetime to estimate β [1],[2]. This approach approximates the free space emission as constant, which we show creates significant errors. In this work, we image the SE of the QD along the WG onto the input slit of a high resolution imaging spectrometer, at T=5K. The SE is measured both spatially resolved along the waveguide and spectrally resolved. The SE guided by the PCWG and coupled by the bottom and top grating couplers to free space is measured together with the direct QD free space emission. The β factor can be, for the first time, directly determined, using the relative emission intensities. By introducing an external magnetic field, directional emission is demonstrated, as previously observed [1]. Using the collected emission intensities, we can directly quantify the directionality of the emission, and consequently the mode circularity at the QD site. Evaluating the mode circularity versus beta factor, we find that high beta factors are only found for small mode circularities, and vice versa, with beta factors > 97.5% outside of the slow light regime. By measuring the propagation wave vector for different energies, simulations are accurately calibrated to the experimental data. This allows us to determine the position of the QDs within the lattice unit cell from their beta factors and mode circularities.

[1] M. Arcari et al., Phys. Rev. Lett., **113**, 093603 (2014).
[2] A. Laucht et al., Phys. Rev. X, **2**, 011014 (2012).

Phonon induced dephasing in a quantum dot-microcavity system

A Morreau and E Muljarov

Cardiff University, UK

A quantum dot (QD) embedded within a solid-state optical microcavity constitutes a fundamental system in cavity quantum electrodynamics. Kasprzak et al. [1] employ the Jaynes-Cummings (JC) model to calculate the optical linear response of such a system, but consider only an idealised case in which the influence of the phonon environment is neglected. Whilst this model provides some insight, there is significant evidence to suggest that exciton-phonon coupling plays a crucial role in the system response [1-5].

One approach to the task of incorporating phonon dephasing within a QD-microcavity model is to make a Born-Markov approximation [2] (suitable only for weak exciton-phonon coupling). Another approach is to apply a polaron transformation followed by a perturbative treatment of the phonon-dressed exciton coupling to the cavity mode [3-5] (suitable only for strong exciton-phonon coupling). Notably, all such approaches are valid only if the phonon memory time is short in comparison to the period of the polariton Rabi oscillations.

We present an exact solution to the problem of the phonon-induced dephasing in a QD-microcavity system, alongside simple analytic approximations. Central to our approach is a Trotter decomposition of the full system Hamiltonian into two exactly solvable parts: (i) a phonon-free JC model part and (ii) an independent boson model part. Crucially, our approach is valid for all exciton-phonon coupling strengths. Further, it takes the effects of the exciton-photon and exciton-phonon coupling on equal footing, thereby providing access to regimes of comparable polaron and polariton timescales.

[1] Kasprzak et al., Nature Materials **9**, 304 (2010).
[2] A. Ramsay et al., Phys. Rev. Lett. **105**, 177402 (2010).

[3] I. Wilson-Rae and A. Imamoğlu, Phys. Rev. B **65**, 235311 (2002).
[4] D. McCutcheon and A. Nazir, New J. Phys. **12**, 113042 (2010).
[5] G. Hornecker, A. Auffèves, and T. Grange, Phys. Rev. B **95**, 035404 (2017).

Disentangling spectral diffusion and blinking from intrinsic line-shapes in single QD photoluminescence by non-negative matrix factorization

F Masia, L Scarpelli, D Harlow and W Langbein

Cardiff University, UK

The emission line-shape of single quantum dots (SQDs) under optical excitation is often strongly affected by random charging and fluctuating local charges. The fluctuating local charges provide a fluctuating local electric field, which affects the emission energy of the exciton transition via the quantum-confined Stark effect. Charging strongly modifies the transition energy via exchange and correlation energies, and the fine structure. The combination of these effects, which occur on a sufficiently fast timescale to limit the number of collected photons during a stable emission shape, hinders the determination of the intrinsic line-shapes. At present, time dependent spectra are typically manually selected during times of low jitter, or fitted with model functions. In this work, we present a novel method to analyse the SQD spectro-temporal emission, using non-negative matrix factorization (NMF).

The SQD PL spectra are factorized into a product of the probability of the SQD being in a particular state and experiencing a particular local field and the corresponding emission spectrum. Since the spectral jitter is mostly a rigid shift of the emission line-shape, we use in the NMF iteration a grouping step which collects component spectra of similar shape into equal spectra with rigid shifts, in this way providing a common line-shape free from spectral wandering beyond the acquisition time step, and the spectral shift. The analysis is unsupervised, i.e. it does not use prior knowledge of the emission line-shapes. The line-shapes are determined with a high signal to noise, using all photons detected during the measurement sequence.

Optionally, the spectral jitter can be constrained by a charging model using a few charge traps, each creating a specific spectral shift upon occupation. This allows to extract from the observed spectral jitter the charge dynamics of the traps.

We will present analysis examples for emission of colloidal and epitaxial SQDs.

Parallel Session 6: Ultrafast optics

(Invited) Leveraging novel nonlinear devices for compact modelocked laser-based gigahertz frequency combs

A Mayer

University of Vienna, Austria

We will summarize recent work on compact gigahertz frequency combs based on SESAM-modelocked solid-state lasers carried out in the Ultrafast Laser Physics group at ETH Zurich in Switzerland. A special emphasis will be placed on how to leverage novel chip-scale devices to enable nonlinear processes at very low pulse energies.

We will present examples including three different nonlinear platforms.

As a first example, we will discuss supercontinuum generation results obtained in silicon nitride waveguides that led to efficient carrier-envelope-offset (CEO) detection and stabilization of a 1 GHz Yb:CALGO solid-state laser.

As a second example, we will show how the resulting supercontinuum was further used in combination with waveguides made of periodically poled lithium niobite (PPLN) to generate an offset-free mid-infrared frequency comb with 1 GHz comb line spacing. We will discuss how the waveguide structure can be leveraged to strongly enhance the nonlinear interaction, hence allowing the mid-IR comb to be generated using the 1-GHz Yb:CALGO laser oscillator output without any external amplifiers.

As a third example, we will discuss our successful efforts to scale the repetition rate of Yb:CALGO lasers into the 10-GHz regime. We will present a novel approach to solve the Q-switching damage issue in SESAM-modelocked lasers at high repetition rates by using cascading of second-order nonlinearities in a PPLN device. This method allowed us to achieve femtosecond Watt-level modelocked operation at 10-GHz repetition rate directly from a 1.5 cm-long straight cavity.

The talk will be concluded by an outlook on work that is being carried out at the author's current lab, the Christian Doppler Laboratory for Mid-IR Spectroscopy and Semiconductor Optics led by Dr. Oliver Heckl at the University of Vienna in Austria.

Parallelized spatiotemporal focusing: overlapping ultrafast pulses in space and time

P Salter[1], B Sun[1], C Roider[2], A Jesacher[3], J Strauss[2], J Heberle[2], M Schmidt[2] and M Booth[1]

[1]University of Oxford, UK, [2]Friedrich-Alexander-University Erlangen- Nuremberg, Germany, [3]Innsbruck Medical University, Austria

Simultaneous spatio-temporal focusing (SSTF) describes the technique of spectrally dispersing an ultrashort pulse to increase it's duration, before recombining all the spectral components to reform the short pulse at the focus of a lens. This has several advantages for optical applications using ultrashort pulses, enabling a focus with large lateral extent but displaying much greater axial confinement than with conventional focussing. Meanwhile non-linear propagation inside samples is also minimised. We extend the technique to generate multiple SSTF focal spots via holography. In contrast to previous implementations, a phase hologram is placed in the ultrafast beam while it is spatially chirped. Thus, we show that it is possible to create multiple focal spots formed by SSTF arranged in three dimensions. Demonstrations are given for ultrashort pulse laser machining on the surface and inside glass. Furthermore, due to the strong pulse front tilt exhibited by an SSTF spot, we show how multiple spots can be stitched together in space and time to generate extended intensity distributions. Spatially overlapped regions can be separated in time using the property of pulse front tilt such that holographic arrays of SSTF spots can be created with apparently no spatial separation.

Fibre optic devices with integrated carbon nanotubes for generation of ultra-short laser pulses and gas sensing

A Rozhin, M Al Araimi, I Chernikov, M Chernysheva and T Allsop

Aston University, UK

Single Wall Carbon Nanotubes (SWNT) have a unique combination of optical and structural-surface properties making them promising for ultrafast optical switching, sensor and bio imaging applications [1]. SWNTs are characterised by excellent processing in aqueous and organic solvents, which make it possible to obtain stable dispersions with a controlled size of nanotube bundles or isolated tubes, and carry out selection by chirality and electronic type of SWNTs [2]. Subsequently, the SWNTs dispersion can be used to produce reinforced, conductive and nonlinear optical composites, or to develop a nano-ink for printable plastic electronics and photonics.

In this report, we will demonstrate development of SWNT's based nano-inks for simple and effective integration of uniform SWNTs layers with optical devices such as single mode and D-shape optical fibre. Consequently, we can contro the printing resolution and the number of printable SWNT's layers on the optical surface, which will clearly define the optical properties of the resulted nanomaterial- photonic devices. Then, such devices will be integrated into the laser resonators and will serve as a mode-locker in order to generate femtosecond (fs) laser pulses [3]. In another approach, the SWNT nano-ink will be applied to the localised surface plasmon structure deposited on the D shape optical fibre, whicwhich can be exploited as selective gas sensor [4].

[1] T. Hasan, et al., Adv. Materials 21, 3874 (2009).
[2] D. Janas, Mater. Chem. Front. 2017, DOI: 10.1039/c7qm00427c.
[3] M. Al Araimi, et al., APL Mat. 2018 submitted.
[4] T. Allsop, et al., Light S&A 5, e16036; doi: 10.1038/lsa.2015.36 (2016).

Location of peak intensity autocorrelation of ultrashort pulses around the focal point of a mirror with aberrations

M Rosete-Aguilar, S Anaya-Vera, O G Rodríguez-Herrera, J A Moreno-Larios and J Garduño-Mejía

Universidad Nacional Autónoma de México, Mexico

Time-domain measurements of ultrashort pulses based on two-photon absorption (TPA) autocorrelation is one of the techniques used in nonlinear microscopy. With this technique, an estimation of the pulse duration can be obtained from the intensity autocorrelation measured at the focal region of the microscope objective. In this work we model the intensity autocorrelation of femtosecond pulses at the focal region of a spherical mirror which introduces aberrations but no dispersive effects into the focused pulse by using the scalar diffraction theory. The peak value of the intensity autocorrelation is plotted as a function of relative focal position. In our model we remove the approximation used in the literature that the wavenumber of the frequencies of the pulse is approximated by the frequency of the carrier in order to calculate the pulse duration, the spot size and the peak value of the intensity autocorrelation of pulses around the focal point. We show that for a few-optical-cycle pulses, the position for the shortest pulse duration, the position for the minimum spot size and the position for the peak intensity autocorrelation are not coincident and that pulse duration changes along the optical axis. For longer pulses, the duration of the pulse does not change along the optical axis and within the Rayleigh range. We show results for pulses with carrier wavelengths of 400nm, 800nm and 1550nm. Finally, we compare some of our results with experimental results presented in the literature.

Dark-bright soliton generation in ring fibre laser with semiconductor optical amplifier gain medium at 1,55 μm

I Kudelin[1] and M Chernysheva[2]

[1]Bauman Moscow State Technical University, Russia, [2]Aston University, UK

Nowadays, ultrashort pulse generation in mode-locked fibre lasers is of great demand in many modern fields of science and industry. Generation of mode-locked laser radiation makes it possible to obtain various unique pulses of ultrashort durations, in particular dark solitons, i.e. the generation of ultrashort dip in the intensity of a stable background continuous wave radiation. Dark solitons have big potential for application in x-ray spectroscopy, comb generation, optical communications, coherent quantum control of optical transitions in atoms, nonlinear optics research and Bose – Einstein condensation. Dark solitons feature zero intensity at its centre and a sharp ð phase shift at its density minimum. The formation of dark solitons in mode-locked lasers has been extensively investigated numerically, however majority of experimental results have been poorly researched. Here we present ring fibre mode-locked laser with SOA gain medium with output central wavelength at 1,55 μ The application of SOA in fibre ring laser cavities is quite unique, though it ensures proper intracavity nonlinearity and dispersion favourable for dark-solitons formation. Our results demonstrate features of dark and dark-bright solitons propagation, interaction and generation in laser resonator consisted SAO. During the experiments, we observed generation of dark solitons and dark-bright soliton pairs at fundamental repetition rate with ~18 MHz with signal-to-noise ratio ~35 dB and to ~120 harmonics at ~2.191 GHz by varying the SOA pump current and net cavity birefringence.To reveal the nature of dark soliton pulses formation we also provided phase measurement and real-time measurements. We anticipate that our experiments will help to establish a base for compact and stable dark pulsed laser sources with high repetition rate for various ultrafast applications.

Wednesday 5 September

(Plenary) Merging nanophotonics and materials science for future optical technologies

A Boltasseva

Purdue University, USA

The advent of nanophotonics has redefined contemporary thought for controlling electromagnetic radiation and invigorated a generation of scientists and engineers to broaden the horizon of future optical technologies. As the breadth of potential applications grows, it has become evident that the development of new material platforms is pertinent to the field of nanophotonics and requires a synergistic approach between optical and material science. In this talk, I will discuss state-of-the-art material platforms which have shown exceptional promise for optical applications, including transparent conducting oxides, transition metal nitrides, oxides, and carbides, as well as novel two- and quasi-two-dimensional materials. I will discuss and demonstrate the unique advantages of these materials over conventional platforms and address their relevance for fundamental science and future optical devices across the fields of on-chip optoelectronics, sensing, and energy conversion.

(Plenary) Quantum simulations with photonics

A Laing

University of Bristol, UK

Modelling the dynamics of quantum mechanical systems, including molecules, is generally intractable to classical computational techniques. Such computational overheads may be overcome by utilising quantum simulation techniques, in which a well-controlled quantum system is programmed to mimic the quantum behaviour of another. Recent progress in integrated photonics has seen the advent of high fidelity on-chip processing of photonic quantum information and fully programmable circuitry to establish devices that are universal for linear optics. Progress has also been made in the integration of photon sources and single photon detection, which together with high-speed and low-loss photonic switches, enable a versatile class of photonic quantum simulators. It is hoped that the demands on error correction for specialised quantum simulators could be much lower than those for universal digital quantum simulators. Here we discuss proof-of-principle experimental demonstrations of quantum photonics as a simulation platform for molecular quantum dynamical behaviour. Using the analogy of optical modes in miniaturised waveguides for vibrational modes and single photons for quantised vibrational excitations, we simulate the dynamics of molecular systems, including time evolution for a range of different molecules, evolution of multiple excitations, anharmonics, thermalisation, and demonstrate applications including machine learning algorithms that identify disassociation pathways.

Parallel Session 7: Medical applications of light I

(Invited) Optical coherence tomography ographies and their applications

D Sampson

University of Surrey, UK

Often, we are faced with a dilemma in optical coherence tomography – we do not have the contrast or resolution at the necessary imaging field of view for a given application. Do we push for higher resolution, with all of its technical demands and limitation in axial depth range, or do we simply sacrifice field of view (in all three spatial dimensions), or do we try for an alternative contrast source, of which there are many? Once we have volumetric imaging data, we may choose from attenuation, various polarisation contrasts, such as birefringence or axis orientation, mechanical properties, such as stiffness or viscoelasticity, and motion, to deduce fluid flow, usually blood, but also lymph. In this talk, I will consider these options in more depth, highlighting examples of different resolutions and contrast mechanisms, and attempt to shed light on this intriguing question. Ultimately, though, we would prefer to "have our cake and eat it too" – resolution and alternative sources of contrast in combination provide the best case.

Fibre-grating sensors of curvature for respiration monitoring In non-invasive mechanical ventilation

J Petrovic[1], M Ivanovic[1], A Savic[1], G Gligoric[1], M Miletic[1], M Vukcevic[1], B Bojovic[1], L Hadzievski[1], T Allsop[2] and D Webb[2]

[1]University of Belgrade, Serbia, [2]Aston University, UK

Mechanical ventilation is one of the most commonly applied techniques in the treatment of patients who cannot match the level of respiratory effort required to maintain a proper breathing cycle. Critical to successful ventilation are the synchronization patient-ventilator and the volume of air provided to the patient. Commonly used non-invasive sensors detect the patient's respiratory effort from a change in pressure or airflow in the ventilatory circuit at the end of the neuro-ventilatory coupling sequence, thus exhibiting an intrinsic delay with respect to the initiation of breathing. Moreover, all pneumatic-triggering variables may be affected by air leaks, which play a major role in generating time lag in the feedback to the ventilator. The estimated lag reaches 500 ms. Significant efforts have been invested into explorations of non-invasive respiration monitoring alternative to pneumotachography. However, triggering accuracy surpassing the current clinical standard has not been demonstrated.

In an attempt to find a non-invasive triggering mechanism that precedes pneumatic triggering in the neuro-ventilatory coupling sequence, we have developed a new method based on the measurement of chest-wall motion. The measurement apparatus comprised a single fibre-grating sensor in a monochromatic interrogation scheme. A comparative study was performed on 34 healthy volunteers. We first show that the change in curvature of the chest-wall during breathing is linearly correlated with the tidal volume (the volume of air moved into or out of the lungs within each breath) [Biomed. Opt. Express 5, 1136 (2014)]. We further show a consistent fibre-grating signal advance with respect to the standard pneumatic signal by (230±100) ms in both the inspiratory and expiratory phases [Physiol. Meas. (2018), doi:10.1088/1361-6579/aab7ac]. The results indicate that the proposed measurement technique may lead to a more reliable triggering decision and, hence, has good prospects for application in clinical non-invasive ventilation.

Pilot study of polarisation sensitive optical coherence tomography as a biomarker for fibrosis in systemic sclerosis

E Marjanovic, G Dinsdale, M Berks, T Moore, J Manning, V Sharma, S Leggett, M Dickinson, A Herrick, R Watson and A Murray

The University of Manchester, UK

Patients with systemic sclerosis (SSc) develop skin and internal organ fibrosis (scarring). Skin fibrosis is assessed by the Rodnan skin score from subjective palpation(pinching). This pilot study investigated a commercial non-invasive imaging technique, polarisation-sensitive optical coherence tomography (Ps-OCT, Thorlabs Inc) as an objective biomarker for skin fibrosis. Ps-OCT takes an image ('optical-biopsy') up to 3mm into tissue.

31 patients with SSc and 27 healthy controls participated in the study. Rodnan skin score was obtained at the site of imaging (forearm, patients only). Ps-OCT provides a structural image into the skin tissue (allowing measurement of skin-thickening associated with fibrosis) and a birefringence image (a measure of skin heterogeneity and therefore possibly fibrosis). Measurements of epidermal thickness were extracted from structural images, and intensity from corresponding birefringence images. A subset of 10 from each group underwent 4mm punch biopsy at the site of Ps-OCT imaging for histological analyses to assess fibrosis including: pricrosirius red staining for

fibrillar collagen content and organisation; and in situ zymography to assess the presence of gelatinase and collagenase (essential enzymes for the remodelling of collagenous extracellular matrices).

Epidermal thickness measured by Ps-OCT was significantly larger in patients ($p=0.012$). There was significant correlation between Ps-OCT and histology-measured epidermal thickness ($r= 0.79$, $p<0.001$) and a strong relationship between the intensity in birefringence images and gelatinase ($r=0.69$, $p=0.02$).

Non-invasive Ps-OCT measurements of epidermal thickness correlate with histological measurements and show increased skin thickness in patients with fibrosis. Birefringence intensity images correlate with measurements of gelatinase (indicative of the formation of scarring). This was a small pilot study; consequently further work is required to fully understand the relationships between Ps-OCT and histology. Our findings suggest that Ps-OCT has the potential to provide non-invasive measurements of skin thickening, as well as insights into pathophysiology, for application in longitudinal and in cross-sectional studies.

Structural characterization of the skin tissue treated with an ablative fractional laser by using Optical Coherence Tomography

K Feng[1], K Zhou[1], Y Ling[1], P O'Mahoney[2], E Ewan[2], S Ibbotson[2], C Li[1] and Z Huang[1]

[1]University of Dundee, UK, [2]Photobiology Unit, NHS Tayside, UK

Ablative fractional skin lasers are applied for an amount of applications of medical skin conditions, such as the cosmetic field and to achieve topical drug delivery. The influence upon the skin caused by lasers has been studied before through using invasive excision and biopsy with microscopy. However, these invasive modalities are possible to raise distortion of the skin and just snapshots at a single time point post-treatment. To measure and characterise the damage induced by lasers to tissues, Optical Coherence Tomography (OCT), a novel and non-destructive imaging method is utilised to overcome those issues, and has the ability of monitoring the change of structure of tissues irradiated by the laser. The entire measurement is completed based on Phase sensitive Optical coherence tomography (PhS-OCT) system. OCT system provides high-resolution, cross-sectional images of tissue microstructures. Therefore, the aim of this study is to measure the change to the skin tissue treated with ablative fractional laser by using OCT, exploring how the laser treatment impose an influence over the geometry of skin surface.

Feasibility study of photoacoustic imaging for measurement of finger vessel structure in healthy controls and patients with systemic sclerosis

A Murray[1], J Cummings[1], S Zafar[1], S Morscher[2], T Moore[1], J Manning[1], G Dinsdale[1], M Berks[1], C Taylor[1], M Dickinson[1] and A Herrick[1]

[1]The University of Manchester, UK, [2]Ithera Medical, Germany

Systemic sclerosis (SSc) is a multisystem connective tissue disease affecting the structure and function of the small blood vessels (microvasculature). One of the main features of SSc is finger ischaemia (lack of blood flow), which can lead to ulceration causing extreme pain, loss of hand function and a severe reduction in quality of life. Multi-wavelength photoacoustic imaging, a combination of optical and ultrasound techniques, offers a non-invasive method for assessing vascular structure and oxygenation. This feasibility study aimed to assess a commercial prototype photoacoustic imager (iThera-Medical, multispectral optical tomography [MSOT]): (1) as a method to quickly and easily identify severity of finger ischaemia in clinical practice, and (2) as a potential outcome measure in clinical trials.

Photoacoustic images were obtained in 32 healthy controls and 21 patients with SSc. Images were taken on the dorsal aspect of the middle finger joint on all 8 fingers. The system resolution of 30 microns allowed visualisation of digital arteries and larger microvessels. Images were post-processed and analysed for vascular volume and baseline oxygenation

The intravascular volume of the digits was not found to be significantly different between healthy controls and SSc groups for any of the 8 fingers (e.g. non-dominant ring finger: control, mean volume 148 [SD 52.0] mm^3; SSc, 96 [29.8]; p = 0.24). The baseline saturated oxygenation (mean for all the fingers) did not differ between the two groups (control, 0.38 [0.02] arb units; SSc, 0.37 [0.02].

The patients with SSc in this study do not appear to have significantly occluded finger arteries, lower finger microvascular volume or baseline oxygenation. Data on oxygenation under finger occlusion (with a pressure cuff) and vascular volume in those with severe finger ischaemia was also collected but is not yet analysed; this may provide further insight into suspected peripheral vascular abnormalities in SSc.

Parallel Session 7: Strong light matter interactions and laser processing

(Invited) Laser material interaction effects in laser material processing

S Williams and W Suder

Cranfield University, UK

Laser are very attractive as an energy source in laser material processing due their ultimate capability for being controlled both spatially and temporally. However the interaction between the laser light and the material is complex due to many factors such as coupling effects, plasmas and thermal transfer. In this talk new laser material processing applications in both additive manufacture and welding using lasers will be highlighted. The exploitation of the laser light controllability and the complex interaction with materials will be demonstrated.

Application of high power Nd:YAG laser for surface decontamination

G Greifzu, T Kahl, W Lippmann and A Hurtado

Technische Universität Dresden, Germany

Lasers have proven their suitability for material processing in a wide variety of applications, e.g. high precision drilling, cutting and structuring. Upcoming interest in application of lasers arises in the field of nuclear decontamination due to prospected reduction of secondary nuclear waste production and dust formation as well as reduction of exposure time for the staff. Successful decontamination requires removal of radioactive particles below clearance limit. These radioactive particles can infiltrate or cover surfaces like oxides or protective paints. In this work we present the results of surface decontamination using a pulsed 1,064 nm Nd:YAG laser. The removal of contaminated iron oxide and epoxy paint surfaces from carbon steel has been studied varying laser processing parameters (pulse fluence, pulse length, repetition frequency). Important radionuclides for decommissioning like Cobalt-60, Caesium-137 and Strontium-90 have been substituted using their stable isotopes for the investigation of surface contamination. Incorporation of radioactive particles into bulk metal during laser treatment is prevented using laser fluences below ablation threshold of 3.5 J/cm^2 for carbon steel. The modifications of steel surface and grain structure by laser processing have been characterized using laser scanning microscopy and scanning electron microscopy. The decontamination effect has been investigated using X-ray fluorescence analysis before and after laser treatment. A high decontamination factor, approximately 100 in case of Caesium, has been achieved. Optimal combination of laser parameters for high decontamination factors on iron oxide and epoxy paint surfaces have been determined. Ablated contaminated particles and aerosols were extracted in filters, their composition and quantity was determined using inductively coupled plasma mass spectrometry. The harsh conditions at decommissioning sites favor robust tools. The concept and practical implementation for a mobile decontamination system including the modified laser head and peripheral equipment will be presented together with the results of the successful surface decontamination using laser ablation.

Laser engineered metal surfaces with suppressed total secondary electron yield

A Abdolvand, D Bajek and S Wackerow

University of Dundee, UK

Secondary electron emission (SEE) is induced by primary electron impingement on solid surfaces. Suppression of the secondary electron emission has been identified to be one of the major factors leading to the degradation of system performance in accelerators [1], satellites [2], and Hall thrusters [3]. The secondary electron yield (SEY) is frequently used to quantitatively characterise the SSE properties of a given material, and it is defined as the ratio of the number of all the emitted electrons to the number of incident primary electrons. We introduced surface structures exhibiting low SEY that were produced by short pulsed lasers [4]. Recently, we have also demonstrated the practical application of surfaces with extremely low SEY in particle accelerators [5]. The latter were produced using ultra-short pulsed lasers. The aim here is to present the light-matter interaction mechanism for the formation of the laser engineered structures leading to the suppression of the SEE from surfaces.

[1] M. A. Furman, M. T. F. Pivi, Probabilistic model for the simulation of secondary electron emission, Phys. Rev. Spec. Top.–Accel. Beams 5, 124404 (2002).

[2] V. Nistora et. al. Multipactor suppression by micro-structured gold/silver coatings for space applications, Appl. Surf. Sci. 315, 445–453 (2014).

[3] J.-P. Boeuf, Tutorial: Physics and modeling of Hall thrusters, J. Appl. Phys. 121, 011101 (2017).

[4] R. Valizadeh, O. B. Malyshev, S. Wang, S. A. Zolotovskaya, W. A. Gillespie and A. Abdolvand, Low secondary electron yield engineered surface for mitigation of electron cloud, Appl. Phys. Lett. 105, 231605 (2014).

[5] S. Calatroni, E. Garcia-Tabares Valdivieso, H. Neupert, V. Nistor, Ana Teresa Perez Fontenla, M. Taborelli, P. Chiggiato, O. Malyshev, R. Valizadeh, S. Wackerow, S. A. Zolotovskaya, W. A. Gillespie and A Abdolvand, First accelerator test of vacuum components with laser-engineered surfaces for electron-cloud mitigation, Phy. Rev. Spec. Top.–Accel. 20, 113201 (2017).

Low-loss optical-lattice-like waveguides in lithium niobate by high-repetition-rate femtosecond laser inscription

T Piromjitpong[1], M Dubov[2] and S Boscolo[1]

[1]Aston University, UK, [2]Optoscribe Ltd., UK

Tightly focused femtosecond laser pulses of 11-MHz repetition rate and 790-nm wavelength were used to fabricate a set of waveguides in a lithium niobate ($LiNbO_3$) crystal. To establish the inscription conditions for optimal low-loss waveguides, within each sample we varied the laser pulse energy, the speed and direction of translation stage movement, and the focus depth of the laser beam. We deployed two new approaches to enhance the inscription results: 1) increase of the laser pulse energy with increasing focus depth inside the material to compensate for the corresponding decrease of the refractive-index contrast between exposed and unexposed areas, and 2) decrease of the laser energy for the modification tracks closer to the waveguide's core region to reduce the scattering losses due to high-laser-energy driven waveguide's non-uniformities. All waveguides had an optical-lattice-like hexagonal packing geometry with a track spacing of 10 μm (optimised for effective suppression of high-order modes). Each structure comprised 84 single-scan Type-II-modification tracks, aligned with the crystalline X-axis of the $LiNbO_3$ wafer. As observed through the optical microscope, the diameters of core and outer cladding of the waveguide were approximately 24 μm and 95 μm, respectively. After thermal annealing at 623K for 3 hours, the minimum attenuation coefficients of (0.4±0.1)dB/cm and (3.5±0.3)dB/cm for the ordinary and extraordinary light polarisation states, respectively, were achieved at the 1550-nm wavelength. These low-attenuation waveguides were obtained with an inscription energy varying between 50.6 nJ and 53.6 nJ and a translation speed of 10 mm/s. The corresponding refractive-index contrast of individual tracks was $-(1.55\pm0.04)\times10^{-3}$. The waveguides also showed low attenuation in the visible and near-infrared portion of the spectrum (from 532 nm to 1456 nm).

Our results offer promising means for the development of low-loss, preserved-nonlinearity waveguides that are suitable for several applications, including telecommunications, nonlinear integrated optics and quantum optics.

Laser processing inside diamond with ultrashort pulses

P Salter

University of Oxford, UK

Recent advances in the manufacture of synthetic diamond are creating new opportunities for diamond as a material for advanced technology. Laser writing with femtosecond pulses enables 3D fabrication of a variety of components inside diamond for a range of applications. Focusing at high numerical aperture inside the diamond, with adaptive optics used for aberration correction, non-linear absorption leads to a perturbation of the diamond structure on a scale less than a micrometre, without any damage to the surrounding material or surface. Working in different fabrication regimes, it is possible to generate in the same system electrically conductive wires, optical waveguides and coherent colour centres. New results are presented here on structural characterisation of the laser modifications within diamond. These include the extraction of a cross-section from a laser written wire using a focused ion beam, which is subsequently thinned and analysed by transmission electron microscopy (TEM). This reveals the internal structure of the laser written features, crucially showing that there is no bulk conversion of the diamond and sp2 bonded carbon is only formed within small 100-nm scale clusters. The sp2 clusters are accompanied by micro-cracks in the principal diamond cleavage plane which mediate the generated stress. In addition, quantitative polarization microscopy is employed to measure the birefringence generated around laser written inclusions, thereby inferring the induced stress field.

Parallel Session 7: Quantum dots II

(Invited) Epitaxial quantum dots as tunable sources of single and higly-entangled photons

A Rastelli

Johannes Kepler University, Austria

Semiconductor quantum dots (QDs) obtained by epitaxial growth are regarded as one of the most promising solid-state sources of triggered single- and entangled-photons for applications in emerging quantum technologies.

The limited control on the structural properties of individual QDs - which produces random fluctuations of their electronic and optical properties - represents a major hurdle towards the use of QDs in applications relying on multiple sources.

In this talk I will report on our efforts towards the realization of scalable sources of quantum light based on QDs. In particular I will focus on the combination of initially unstrained GaAs QDs and post-growth strain-engineering as a flexible technological platform to obtain QDs with precisely tailored light emission properties. On one hand, strain allows reshaping the selection rules of optical transitions in GaAs QDs [1,2] and controlling their emission wavelength - which may be useful for integrated quantum photonic circuits. On the other hand, it allows restoring the excitonic level degeneracy and obtain wavelength-tunable sources of polarization-entangled-photon-pairs [3] with nearly unity degree of entanglement [4] for free-space quantum optics experiments and applications.

[1] Y. Huo et al. Nature Phys. 10, 46 (2014)
[2] X. Yuan et al. arXiv:1710.03962

[3] R. Trotta et al. Phys. Rev. Lett. 114, 150502 (2015); Nature Comm. 7, 10375 (2016)
[4] D. Huber et al. Nature Comm. 8, 15506 (2017); arXiv:1801.06655

A quantum light emitting diode for the standard telecom window around 1550 nm

T Muller[1], J Skiba-Szymanska[1], A Krysa[2], J Huwer[1], M Felle[1], M Anderson[1], M Stevenson[1], J Heffernan[2], D Ritchie[3] and A Shields[1]

[1]Toshiba Research Europe Ltd, UK, [2]University of Sheffield, UK, [3]University of Cambridge, UK

Quantum communication networks are expected to enable new applications, such as cryptography secured by physical laws, distributed quantum computing. An essential building block for all these applications is a source of pure single photons and entangled pairs, compatible with the low-loss fibre telecom window around 1550 nm. Previous work based on gallium arsenide quantum dots, colour centres in diamond or single atoms has been largely limited to wavelengths unsuitable for long distance fibre quantum network applications. While efforts have been made to use standard gallium arsenide based quantum dots for these applications by extending their operating wavelength range, electrically driven quantum light emission from quantum dots in this ideal telecommunication window has not been possible yet.

Here, we develop indium phosphide based quantum dot devices to address this gap. Recently, it has been shown that QD growth using metalorganic vapour phase epitaxy (MOVPE), which is the industry favoured growth method, can create droplet QDs with low fine structure splitting (FSS). We now extend this growth scheme to produce the first optoelectronic devices for single and entangled photon emission in the 1550 nm telecom window. We show single photon emission with multi-photon events suppressed to 0.11±0.02. From the biexciton cascade, we further obtain entangled light with a maximum fidelity of 0.87± 0.04 sufficient for the application of error correction protocols. We can further extend the device working temperature up to 93 K, allowing operation with liquid nitrogen or simple closed-cycle coolers. Our quantum photon source can be directly integrated with existing long distance quantum communication and cryptography systems, and provides a new material platform for developing quantum network hardware.

Ultrafast charge transfer in quinone functionalised CdTe/CdS quantum dots for biosensing applications

R Ahumada-Lazo[1], A J Harvie[2], C T Smith[1], L Jeuken[2], M Califano[2], R S Bon[2], S J Hardman[1], D J Binks[1] and K Critchley[2]

[1]The University of Manchester, UK, [2]University of Leeds, UK

Colloidal quantum dots (QDs) have found numerous applications in biomedical research, ranging from in vitro biosensing to intracellular and in vivo imaging, due to their bright, size-tuneable, spectrally-narrow and photo-stable emission. The sensitivity of QDs to organic ligands and to the chemical environment allows them to be functionalised for tracking specific biochemical processes and the diagnosis of diseases [1,2]. In particular, QD conjugates can be used for intracellular redox-sensing, the effectiveness of which depends on the efficiency of the switchable electron transfer event that leads to luminescence quenching.

In this work, the excited state dynamics in CdTe/CdS core/shell QDs with electron accepting quinone (Q2NS) ligands attached to the surface were studied under oxidised and reduced conditions, using ultrafast laser spectroscopy techniques. These results, along with atomistic modelling of the system, enabled us to determine that the electron transfer pathway is a multistep process incorporating ultrafast (2-8 ps) trapping of hot electrons. The efficiency of this hot-trapping step enables the QD-quinone system to achieve redox detection with a small number of sensor molecules per QD, which preserves their colloidal properties and allows for further functionalization to expand its application. The new insight into the excited state properties and the possibility of ultra-fast charge transfer will have important implications for the study of charge extraction from quantum dots.

[1] Medintz, I.L., et al., Nature materials, 2005. 4(6)
[2] Algar, W.R., et al., Anal. Chim. Acta, 2010. 673(1)

Single organic molecule coupling to a hybrid plasmonic waveguide

S Grandi[1], M P Nielsen[1], J Cambiasso[1], S Boissier[1], K D Major[1], C Reardon[1], T F Krauss[2], R F Oulton[1], E A Hinds[1] and A S Clark[1]

[1]Imperial College London, UK, [2]University of York, UK

The integration of versatile nano-structures with efficient single photon sources will enable many quantum technologies. The coupling of solid state single photon sources with dielectric structures, while showing promising results, is limited by the mode confinement imposed by the diffraction limit. Here we present a hybrid dielectric–metal approach in coupling a single dibenzoterrylene (DBT) molecule to an optical mode in an integrated planar device. We designed and fabricated a hybrid plasmonic waveguide (HPW) consisting of a titanium dioxide slab with a nanoscale gap patterned in gold on the surface. Confinement and propagation of the mode are controlled by the width of the gap: when this is <100 nm the mode is mainly between the two gold slabs, providing strong confinement; but when the gap is wider the mode decouples from the gold and propagates mainly in the TiO2, with low loss.

We deposited DBT-doped anthracene crystals on the surface using a supersaturated vapour growth technique. Using confocal fluorescence microscopy we found a DBT molecule positioned near the gap, and measured its saturation intensity and lifetime. Under CW excitation we measured the second-order correlation function g(2)(τ) of the light emitted directly into the microscope. This showed clear anti-bunching with g(2)(0) = 0.25(6) proving this to be a single molecule. By detecting photons simultaneously from the microscope and from the grating coupler we measured g(2)(0) = 0.24(6), demonstrating that this single molecule was emitting into the waveguide mode. By measuring the optical losses in our setup we calculated the coupling efficiency from the molecule to the HPW to be ~ 12%. This method provides a route to building waveguide sources of photons in planar integrated quantum photonic circuits for applications in quantum technology.

Rare earth doped MoS2 for photonics applications

C Maddi[1], Aparna P[2], Adarsh Kv[2] and A Jha[1]

[1]University of Leeds, UK, [2]IISER Bhopal, India

Two-dimensional transition metal dichalcogenides (TMDCs) are the focus of intense experimental and theoretical research, because of a unique 2D- physical structure, that is potentially compatible with graphene for designing a range of optoelectronic and photonic devices [V. P. Pham, et al., 2016 and M. Onga, et al., 2017]. Recently, the 2D layered materials grown by pulsed laser deposition technique have become attractive in a wide range of device applications [Z. Yang, et al., 2016].

Here, we present the results of the characterization of femto-second (fs) pulsed laser deposited thin-films of undoped and Yb^{3+}- rare-earth-ion doped MoS_2 films. For deposition the Ti-sapphire laser with 100 fs pulse duration and 1kHz repetition rate, which was mode-locked at 800 nm wavelength, was used for forming the layered MoS_2 films. The deposited films were characterized by Raman spectroscopy which clearly showed the characteristic A_{1g} and E^1_{2g} modes. The separation between the two Raman modes is 23 cm^{-1}, which translates it into the ~ 4-6 number of layers. Strikingly, when these few layer MoS_2 are doped with Yb^{3+} ions, the Raman modes were shifted to higher frequencies, implying the possible effect of Yb^{3+} doping and/or defects on 2D MoS_2 structure. Further confirmation of number of layers formed and doped structure analysis have been investigated using transmission electron microscopy (TEM) and X-ray photoelectron spectroscopy (XPS). Nonlinear optical properties of undoped and doped MoS_2 films were studied using open aperture Z-scan technique. In Yb^{3+} doped films, enhancement in saturable absorption (SA) at room temperature was observed, which important for applications in nano-photonic devices, such as the passive modelocking and optical switches. Our results on fs-pulsed laser deposition technique offers an opportunity for materials fabrication and device engineering using novel multi functional rare-earth doped 2D materials.

Parallel Session 7: Quantum photonics

(Invited) Machine learning for the development of quantum technologies

R Santagati, A Gentile, S Paesani, J Wang, B Flynn, S Knauer, J O'Brien, J Rarity, M Thompson and A Laing

University of Bristol, UK

Machine learning algorithms with their noise-resilience properties and flexibility have found a wide range of applications. Recent progress has shown how their use in quantum technologies can enhance the performance of quantum algorithms in non-error-corrected quantum computers [1], enable the efficient characterisation of quantum systems [2] or provide noise resilience for the simulation of quantum systems [3].

In this talk, we will review some of our most recent progress in the characterisation and optimisation of quantum systems and technologies using Bayesian inference.

[1] Paesani, Gentile, Santagati, Wang, Wiebe, Tew, O'Brien, Thompson. Experimental Bayesian Quantum Phase Estimation on a Silicon Photonic Chip - Physical Review Letters 118, 10 (2017)

[2] Wang, Paesani, Santagati, Knauer, Gentile, Wiebe, Petruzzella, L O'Brien, G Rarity, Laing, Thompson. Experimental quantum Hamiltonian learning - Nature Physics 1, 149 (2017)

[3] Santagati*+, Wang+, Gentile+, Paesani, Wiebe, McClean, Short, Shadbolt, Bonneau, Silverstone, Tew, Zhou, O'Brien, Thompson. Witnessing eigenstates for quantum simulation of Hamiltonian spectra - Science Advances 4, eaap9646 (2018)

Generation of high-dimensional entanglement in frequency-encoded photonic qubits via engineered parametric down-conversion

F Graffitti[1], A Branczyk[2] and A Fedrizzi[1]

[1]Heriot Watt University, UK, [2]Perimeter Institute for Theoretical Physics, Canada

Photonic quantum technologies rely on the deterministic preparation of qubits encoded in single-photons degrees of freedom. While polarisation, orbital angular momentum and path have been routinely used since the early days of photonic quantum information, the last few years have seen an increasing interest in the frequency-time encoding [1,2,3]. Indeed, the possibility of generating high-dimensional states, combined with the compatibility of frequency modes with standard optical components, makes the spectral degree of freedom suitable for enhancing the efficiency of quantum protocols, spanning from quantum communication (where higher channel capacity means higher transmission rates) to optical quantum computation (that would benefit larger amount of exploitable quantum information without a reduction in the detection rate).

Here we present a new scheme for generating frequency-entangled photon pairs in parametric down-conversion (PDC) processes. By means of our novel non-linearity engineering technique [4,5], we deterministically choose the orientation of each ferroelectric domain of a poled crystal to tailor its phase-matching function as a multi-peaked function. The photons produced in such crystals emerge in a coherent superposition of orthogonal spectral Schmidt modes, and depending on the chosen phase-matching function's shape it is possible to generate two-photons entangled states in an arbitrarily high-dimensional Hilbert space.

Our technique can easily be implemented as requires no additional components respect to a standard bulk PDC setup, it's highly compatible with other degrees of freedom encodings such as polarisation and orbital angular momentum, and can be adapted with small overhead to integrated waveguide sources for integrated quantum photonics applications.

[1] B. Brecht et al., Phys. Rev. X 5, 041017 (2015).
[2] J. M. Lukens et al., Optica 4, 8-16 (2017)
[3] M. Kues et al., Nature 546, 622–626 (2017)
[4] F. Graffitti et al., Quantum Sci. Technol. 2, 035001 (2017)
[5] F. Graffitti et al., accepted for publication by Optica (2018)

High-dimensional entanglement with large-scale integrated optics

S Paesani[1], J Wang[1], Y Ding[2], R Santagati[1], P Skrzypczyk[1], A Salavrakos[3], J Tura[4], R Augusiak[5], L Mančinska[6], D Bacco[2], A Acín[3], K Rottwitt[2], L K Oxenløwe[2], J L O'Brien[1], A Laing[1] and M G Thompson[1]

[1]University of Bristol, UK, [2]Technical University of Denmark, Denmark, [3]Institut de Ciencies Fotoniques, Spain, [4]Max-Planck-Institut für Quantenoptik, Germany, [5]Polish Academy of Sciences, Poland, [6]University of Copenhagen, Denmark

The ability to control multidimensional quantum systems has interesting applications for the investigation of fundamental science and for the development of advanced quantum technologies. However, so far experimental approaches for the generation and processing of multidimensional quantum systems have presented significant limitations in terms of controllability, precision and universality, which represent bottlenecks for further developments of multidimensional technologies and the experimental investigation of high-dimensional systems. We present a novel approach based on multidimensional integrated quantum photonics for the generation, processing and analysis of high-dimensional quantum entanglement. In particular, we report a programmable bipartite entangled system with dimension up to 15 × 15 realized on a large-scale silicon-photonics quantum circuit. The device monolithically integrates more than 550 photonic components on a single chip, including an array of 16 identical photon-pair sources based on spontaneous four-wave mixing. We verify the high precision, generality and controllability of our multidimensional technology, and further exploit these abilities to demonstrate key quantum applications experimentally unexplored before, such as quantum randomness expansion and self-testing on multidimensional states. Our work provides a prominent experimental platform for the development of multidimensional quantum technologies.

Gaussian quantum illumination with jamming protection

H Yang, W Roga and J Jeffers

University of Strathclyde, UK

Quantum illumination promises enhancements to sensitivity and trustfulness of traditional radar systems or any imaging system where the observer provides a signal to probe an object with. Originally stated in [1], quantum illumination relies on non-classical correlations - entanglement between the signal state and the ancillary state, in order to improve the distinguishability of detection results between two possible scenarios: noise (nothing) or a return signal (something). This has been experimentally verified by [2]. Here, we study an entire host of scenarios with different noise surroundings and probe signals under the Gaussian state formalism [3], unite an energy constraint, before extending to the secure imaging protocol in [4].

[1] S. Lloyd, Science (80). **321**, 1463 (2008).
[2] E. D. Lopaeva, I. Ruo Berchera, I. P. Degiovanni, S. Olivares, G. Brida, and M. Genovese, Phys. Rev. Lett. **110**, 1 (2013).

[3] C. Weedbrook, S. Pirandola, R. García-Patrón, N. J. Cerf, T. C. Ralph, J. H. Shapiro, and S. Lloyd, Rev. Mod. Phys. **84**, 621 (2012).
[4] W. Roga and J. Jeffers, Phys. Rev. A **94**, 1 (2016).

Quantum simulation with reconfigurable Silicon photonic devices

A A Gentile[1], R Santagati[1], J Wang[1], S Paesani[1], N Wiebe[2], S Knauer[3], C Granade[2], J McClean[4], J O'Brien[1] and M Thompson[1]

[1]University of Bristol, UK, [2]Microsoft Research, USA, [3]UNSW Sydney, Australia, [4]Google Inc., USA

We present here recent advances in silicon quantum photonics for quantum information processing and simulation. The devices presented here integrate several essential components, such as spontaneous four wave mixing photon pair sources, over 40 reconfigurable phase shifters and around 100 optical components.

The chip is capable of entangled state preparation and of implementing arbitrary controlled unitary operations up to CU(4). We observe high visibility quantum interference, high-fidelity quantum state preparation and measurements, thus enabling the implementation and test of a range of quantum information protocols.

Firstly, a quantum simulation approach called WAVES (Witness Assisted Variational EigenSolver), capable of finding ground and excited states of physical Hamiltonians via an intrinsically quantum property, the “eigenstate witness”. This requires the measurement of only the control qubit emerging from a controlled unitary (CU) operation, independently from the size of the Hamiltonian simulated [Santagati et al. Sci.Adv. 4 (1) 2018]. This variational bootstrap is shown to boost the performances of subsequent application of the Iterative Phase Estimation Algorithm (IPEA).

We introduce Rejection filtering protocols applied to phase estimation (RFPE), providing additional robustness to noise and infidelity in the operations, when compared to traditional IPEA implementations [Paesani et al. PRL 118 (10) 2017]. To do so, we leverage upon the stability and controllability of our photonic chip to study algorithm performances under various types of realistic noises.

Finally, the application of quantum Hamiltonian learning to learn with our photonic quantum simulator the Hamiltonian describing the dynamics of a quantum system [Wang et al. Nat. Phys. 13 (6) 2017]. In particular, we focus about experiments involving NV-centres in diamond and prove the capability of our simulator to retrieve online crucial physical properties of these systems.

This work provides a flexible, robust platform for the systematic investigation of a wide range of toolsets developed for pre-threshold quantum devices.

Parallel Session 8: Medical applications of light II

(Invited) Fibre-based sensing of physiological parameters with time-resolved single photon spectroscopy

K Ehrlich, R R Thomson and M G Tanner

Heriot-Watt University, UK

In the age of antimicrobial resistance, there is an unmet need for fast, accurate and less invasive diagnostic methods for lung diseases. The EPSRC-IRC Proteus project attempts to fill this gap, seeking to develop minimally invasive methods of identifying pulmonary infections and inflammation for patients in critical care in vivo. This is enabled by combining novel optical fibres with advanced detector technologies.

We present a system for endoscopic sensing in size restricted regions such as the alveolar space of the distal lung consisting of a miniaturised single optical fibre probe and an in-house made CMOS SPAD line sensor for time-resolved single photon detection. The line sensor offers simultaneously read-out of 256 single photon detector pixels for fast time resolved spectroscopy. The system is exemplified for pH sensing with both fluorescent markers in the visible spectral range and functionalised surface enhanced Raman scattering (SERS) reporters in the near-infrared spectral region. pH is a key physiological parameter and tightly regulated in the body but can be locally changed in inflammatory and cancerous environments.

Fluorescence emission and Raman scattering are normally influenced and superposed by various unwanted background signals, especially the fibre background in miniaturised endoscopic sensing. We demonstrate addressing these problems with time-resolved detection. For fluorescence-based sensing, the local environment is investigated via changes in the fluorescence lifetime, which is less sensitive to fluorophore concentration, photobleaching and tissue autofluorescence than simple fluorescent amplitude. For SERS applications, we demonstrate complete recovery of the usually weak Raman signal from the unwanted fibre background through time-gating.

Fibre-based time-resolved spectrometry is an extremely versatile technique, we will discuss further adaptation to a variety of applications in the field of Raman and fluorescence spectroscopy.

K. Ehrlich et al., "pH sensing through a single optical fibre using SERS and CMOS SPAD line arrays," Opt. Express **25**, 30976-30986 (2017)

Multispectral fibre imaging of lung disease

H Parker[1], J Stone[2], R R Thomson[3], K Dhaliwal[1], N Krstajić[1] and M G Tanner[1,3]

[1]University of Edinburgh, UK, [2]University of Bath, UK, [3]Heriot-Watt University, UK

Respiratory diseases are prevalent throughout the world and include a range of conditions such as pneumonia, tuberculosis, and many others. In the clinic, we see there is an unmet need for quick and accurate diagnosis of lung infection and inflammation in intensive care.

The Proteus project (www.proteus.ac.uk) aims to improve the detection and diagnosis of pulmonary infection and inflammation by employing targeted fluorescent molecules (Smartprobes) to visualise bacterial burdens in the distal lung. Sometimes the signal from the Smartprobes is difficult to detect on a background of lung tissue, which is brightly fluorescent due to the abundance of collagen and elastin. In addition to resolving probes from intrinsic fluorescence, multiple probes may have overlapping emission spectra. This is particularly true for many well-established fluorophores that reside in the green region of the spectrum. If imaging with fluorophores that have distinct emission spectra is not possible or desirable, then spectral sorting of the signals can be carried out.

Here we present a simple coherent fibre bundle based[1] widefield ratiometric imaging system consisting of a single colour LED illumination source (480nm) that is capable of enhancing the contrast between similar spectra of pathologically relevant fluorescence signals without complex spectral unmixing. To visualise disease, Smartprobes are delivered into the lung through capillary channels down a novel, cheap, and disposable fibre bundle developed by the University of Bath. The bundle features an imaging fibre which consist of 8100 cores with a 450µm corner to corner field of view.

Contrast enhancement is carried out on dual images of the same field of view from different parts of the spectrum by post processing of the images. This enables us to interpret better the images produced both in autofluorescence and molecular imaging contexts.

[1] A Perperidis, H E Parker et al, Optics Express 25 (10), 11932, (2017)

Early arriving photon imaging for locating optical endomicroscopy fibres and medical devices

M G Tanner[1], T Choudhary[1], T Craven[2], B Mills[2], M Bradley[2], R Henderson[2], K Dhaliwal[2] and R Thomson[1]

[1]Heriot-Watt University, UK, [2]University of Edinburgh, UK

Optical fibre based endoscopes are increasingly used for imaging and sensing within the human body without navigational guidance of the miniaturised fibre probe. Meanwhile, medical device placement is a standard procedure in clinic. We demonstrate successful imaging of optical device location with centimetre resolution in clinically relevant models, in a realistically lit environment, achieved through the detection of early arriving photons with a time-resolved single photon detector array.

This prototype has been developed within the UK-EPSRC Proteus project, moving advanced research technologies towards clinical implementation.

Short (~100ps) laser pulses are transmitted from the endoscope tip at 785nm in the “optical window” where attenuation is less severe. Most photons passing through tissue undergo much scattering from the disordered structures providing little location determination of the light source. However, some photons probabilistically undergo less scattering, or travel in an almost straight line, exiting the body sooner than the highly scattered light.

A camera based upon a 32 × 32 array of Single Photon Avalanche Photodiode Detectors (SPADs) is used to image the small number photons exiting the tissue. The time resolution capabilities of such a single photon detector (50ps time bin resolution, 200ps jitter) allows separation of the early arriving photons from the highly scattered light, revealing the endoscope location.

This compact packaged system with aggressive optical filtering is demonstrated in a normally lit room to determine optical endomicroscope location in a whole ventilated ovine lung as well as tissue models including bone structure. At the limit of capabilities of this prototype, demonstration through an entire human torso is shown. System improvements and the potential of the next generation prototype in development will be discussed, offering the potential for real time (sub second) imaging of device location for application in standard medical procedures.

Tanner et al, Biomedical Optics Express 8, 4077 (2017)

Printing holograms on contact lenses (wearable biosensors)

H Butt

University of Birmingham, UK

The key challenge for producing nanostructures based commercial applications is the scaling up of the fabrication process. We present the fabrication of dye based nanostructures by using the fast and commercially viable method of holographic laser ablation. In this method we use a single beam of a nanosecond laser, which after reflecting from a mirror self-interferes. This results in an interference pattern which can be used to ablate a well-ordered gratings in thin films. The period of the grating is determined by the incident wavelength (λ) and tilt angle (θ) of the sample with respect to normal incidence. In this manner we recorded various holographic nanopatterns onto transparent substrates, such as glasses and commercial contact lenses. Using this quick, scale and economical method we produced several wearable contact lens sensors. [1,2] These contact lens based holographic sensors can be used for monitoring the eye curvature and pressure of glaucoma patients. The holograms can also be functionalized to sense glucose concentrations in the tears of diabetic patients.

The findings have been reported in highly reputable journals [1,2] and have also received a lot of media attention. The approach was also extended into 3D patterning by ablating 3D assemblies of Ag nanoparticles within polymer media (10μm thickness).[3] Through laser ablation, ordered 3D geometries/patterns were written within the polymer layers. These reconfigurable geometries act as holographically recorded optical devices.

[1] AlQattan, A. K. Yetisen, H. Butt, Direct Laser Writing of Nanophotonic Structures on Contact Lenses, **ACS Nano (In Press)**

[2] Elsherif, M.U. Hassan, A. K. Yetisen, H. Butt, Glucose Sensing with Phenylboronic Acid Functionalized Hydrogel Based Optical Diffusers, **ACS Nano, DOI: 10.1021/acsnano.7b07082 (2018)**

[3] Montelongo, Y., Yetisen, A. K., Butt, H. & Yun, S.-H. Reconfigurable optical assembly of nanostructures. **Nat Commun 7, doi:10.1038/ncomms12002 (2016).**

A multimodality hybrid gamma-near infrared (NIR) fluorescence camera for intraoperative cancer surgery

A Almarhaby[1], J E Lees[1], S L Bugby[1], M S Alqahtani[2], L K Jambi[2], N S Dawood[1], W R McKnight[1], B S Bhatia[3] and A C Perkins[4]

[1]University of Leicester, UK, [2]King Khalid University, Saudi Arabia, [3]Imaging Clinical Group, Sandwell and West Birmingham NHS Hospital Trust, UK, [4]University of Nottingham, UK

Recently, intraoperative hybrid gamma-near infrared (NIR) fluorescence imaging system has emerged as a new clinical technique for real-time visualisation of lymphatic system and tumour delineation. This complementary multimodal surgical guidance combines the attractive penetration ability of the radio-labelled colloid with the superior spatial resolution of NIR fluorescence probes. ICG-^{99m}Tc-nanocolloid, for example, is already being used for sentinel lymph node identification in head and neck cancer, melanoma and oral cavity lesions surgeries. Currently, gamma detection is carried out using a separate hand-held gamma camera or with a non-imaging probe. NIR fluorescence surgical guidance requires a dedicated NIR imaging system, several of which are available commercially.

We have developed a novel hand-held hybrid NIR-gamma camera, capable of displaying co-aligned images from both modalities, which can be combined into one image or viewed separately. This work evaluates the performance of two NIR fluorescence imaging systems for use in the hybrid camera including; phantom studies, different fluorophores and different setups. The minimal detectable concentrations of ICG and 800CW dyes were investigated for both fluorescence imaging cameras. A bespoke micrometastatic lymph node phantom with tissue-like scattering layers was constructed to evaluate detection capability.

ICG dye could be detected at minimum concentrations of 1 μM using both cameras. The lower threshold for reliable 800CW dye detection were about 10^{-2} μM for both systems. The maximum imaging distance to detect targets as small as 0.5 mm diameter ranged between 5 and 15 cm. Both cameras were unable to detect micro scale targets under 3 mm depth of scattering materials, but were able to identify larger targets as deep as 7 mm.

Both imaging systems have demonstrated their ability to detect NIR-fluorescence targets with different concentrations and volumes. Further improvement will combine one of these systems with the hand-held hybrid gamma camera for intraoperative imaging.

Parallel Session 8: Optomechanics

(Invited) Search for quantum gravity signatures with optomechanical systems

I Pikovski

Harvard-Smithsonian Center for Astrophysics, USA

Most phenomena on the interface between quantum physics and gravity are beyond experimental reach. Nevertheless, some experiments can shed light on the interplay between the two theories and can test behavior that might be expected from a full theory of quantum gravity. In this talk, I will discuss how low-energy quantum systems, and optomechanical systems in particular, can be used to test models and aspects of quantum gravity. After giving an overview of the field I will focus on proposals to probe quantum gravity models with a modified commutation relation.

Observation of Brillouin optomechanical strong coupling with an 11 GHz mechanical mode

G Enzian[1], M Szczykulska[1], J Silver[2], L Del Bino[2], S Zhang[2], I A Walmsley[1], P Del'haye[2] and M R Vanner[1,3]

[1]University of Oxford, UK, [2]National Physical Laboratory, UK, [3]Imperial College London, UK

We report the observation of strong coupling between an optical cavity field and a high frequency (11 GHz) mechanical whispering gallery mode of a fused silica microresonator via spontaneous Brillouin scattering. Using an optical heterodyne detection scheme, frequency-upconverted light backscattered from the resonator (anti-Stokes scattering) is observed. Normal mode splitting and an avoided crossing, which are unambiguous signatures of strong coupling, are observed in the recorded heterodyne spectra. The optomechanical coupling strength reaches values as high as $G/2\pi=39$ MHz through the use of an auxiliary pump resonance, where it dominates both optical ($\kappa/2\pi=3$ MHz) and mechanical ($\gamma/2\pi=21$ MHz) amplitude decay rates. In this talk, our experimental setup and results will be described in detail. This observation creates significant potential for the development of new optomechanical quantum technologies, such as nonreciprocity, quantum memories, and transducers. Moreover, this new platform opens a promising route for studies of non-classicality at a macroscopic scale.

Laser refrigeration of levitated nanocrystals

A T M A Rahman and P F Barker

University College London, UK

Levitated optomechanics has seen significant progress over the last ten years. While a considerable control over the centre-of-mass motion has been achieved, the internal temperature of levitated particles remains at best at room temperature. Here we report on the demonstration of internal cooling of levitated ytterbium doped yttrium lithium fluoride (Yb^{3+}: YLF) nanocrystals. Using anti-stokes laser refrigeration we demonstrate that trapped particles can be cooled from room temperature to 130 K. By controlling the amount of trapping power, and exploiting the interaction between polarised light and the particles natural birefringence, we demonstrate that the Yb^{+3}: YLF nanocrystals can be aligned along the direction of the trapping laser's electric field enhancing the refrigeration. We show that both the spectral emission from the levitated particle induced by the trapping laser and a modification to the damping rate of the particle in the trap, can be used to determine the temperature of the levitated particle.

Rotational Optomechanics

J Millen[1], S Kuhn[2], M Arndt[2], B Stickler[3] and K Hornberger[3]

[1]King's College London, UK, [2]University of Vienna, Austria, [3]University of Duisburg-Essen, Germany

Optomechanical systems may well be key devices in quantum technology, by storing and transducing quantum signals, and generating entanglement between optical and mechanical modes. By levitating the mechanical element, dissipation is drastically reduced, promising long-lived quantum states, high-fidelity signal processing, and even the potential to test the limits of quantum physics.

By working with levitated objects it is possible to access rotational degrees of freedom, which is impossible in a clamped system. Rotation is fundamentally different to vibration, both in the classical and quantum domains. We have optically trapped [1], driven [1] and frequency-locked [2] the rotation of nanoscale levitated cylinders. We predict it will be possible to cool the motion of these nano-objects to the quantum ground state [3] using high-performance optical micro-cavities [4], and even at modest temperatures we predict the observation of orientational quantum revivals [5].

Rotational optomechanics promises unparalleled, potentially quantum-enhanced rotation and torque sensitivity [2, 5] with micrometre spatial resolution in a compact package, that could even be circuit integrated [6], as well as the potential to look for quantum signatures in the motion of mesoscopic objects [5].

[1] Kuhn, Kosloff, Stickler, Patolsky, Hornberger, Arndt & Millen Optica 4, 356-360 (2017).
[2] Kuhn, Stickler, Kosloff, Patolsky, Hornberger, Arndt & Millen Nature Communications 8, 1670 (2017).
[3] Stickler, Nimmrichter, Martinetz, Kuhn, Arndt & Hornberger Physical Review A 94, 033818 (2016).
[4] Kuhn, Wachter, Wieser, Millen, Schneider, Schalko, Schmid, Trupke & Arndt Applied Physics Letters 111, 253107 (2017).
[5] Stickler, Papendell, Kuhn, Millen, Arndt & Klaus Hornberger arXiv:1803.01778
[6] Goldwater & Millen arXiv:1802.05928

Quantum measurement and control of levitated nano-particles

L Walker, G Robb and A Daley

University of Strathclyde, UK

Over the past few years, considerable developments have been made in controlling quantum systems through a combination of measurement and feedback. Any measurement in general will naturally disturb the system through direct interaction with it. However, if we can characterise the resulting disturbance and appropriately interpret the measurement information, then we can determine how to perform feedback in such a way as to drive the system into low-temperature and potentially highly non-classical states [1].

We have been interested specifically in using feedback to prepare and manipulate quantum states of motion of levitated nano-particles. Recently there has been experimental development in nanomechanical systems, in which magnetic traps are capable of creating sufficiently large trapping potentials for levitated nanospheres and nanodiamonds about a micron in diameter [2]. We have been theoretically exploring this parameter regime, which differs from previous work with trapped ions or nanomechanical resonators in high-frequency trap systems. In particular, we typically need to control these large systems on a timescale faster than the trap frequency, to avoid adverse effects of heating and coupling to the environment. We have explored several possible measurement and feedback schemes that can be useful for cooling these particles. By combining measurements of position and of momentum, we further develop ideas for creating non-classical states in a new generation of quantum control technologies immediately appropriate for implementation in these experiments.

[1] H. M. Wiseman and G. J. Milburn, Quantum measurement and control, Cambridge University Press, 2010
[2] Hsu, J., et al., Cooling the Motion of Diamond Nanocrystals in a Magneto-Gravitational Trap in High Vacuum, Scientific Reports, 2016

Parallel Session 8: Nanophotonics I

(Invited) PicoPhotonics: Extreme Nano-Optics with single molecules and monolayers

J Baumberg

University of Cambridge, UK

Coupling between coinage metal ‘plasmonic’ nano-components generates strongly red-shifted optical resonances combined with intense local light amplification on the nanoscale. I will show how we now create ultralow volume plasmonic cavities trapping light to <1nm^3. This allows us to routinely watch individual molecules and bonds vibrating. Using DNA origami we can now couple 1-4 dye molecules together optomechanically, and produce strong-light matter coupling that changes their quantum emission properties. We also watch redox chemistry in real time, watching single electrons shuttle in and out of single molecules, as well as 2D materials confined in the same gap. Prospective applications range from (bio)molecular sensing to fundamental quantum science.

[1] Nature 491, 574 (2012); Revealing the quantum regime in tunnelling plasmonics,
[2] Nature Comm 5, 4568 (2014); Threading plasmonic nanoparticle strings with light

[3] Nature Comm 5, 3448 (2014); DNA origami based assembly of gold nanoparticle dimers for SERS detection
[4] Nature 535, 127 (2016); Single-molecule strong coupling at room temperature in plasmonic nanocavities
[5] Science 354, 726 (2016); Single-molecule optomechanics in picocavities
[6] Nature Comm 8, 994 (2017); Plasmonic tunnel junctions for single-molecule redox chemistry
[7] Nature Comm 8, 1296 (2017); Strong-coupling of WSe2 in ultra-compact plasmonic nanocavities..
[8] Nano Letters 18, 405 (2017); Mapping.. single-molecule emitters in plasmonic nanocavities using DNA origami

Efficient excitation of a single molecule for photon generation

R Schofield, K D Major, S Grandi, S Boissier, E A Hinds and A S Clark

Imperial College London, UK

A reliable photon source is an integral component of many quantum technologies. Organic molecules are a candidate for building such a source as they have desirable properties such as near unity quantum yield, a large range of emission wavelengths, and photostability even at room temperature [1]. For a molecule to deliver a photon on demand it must be prepared efficiently in an excited state. At low temperature this can be achieved [2], however at room temperature this is not always possible due to phonon-induced dephasing causing spectral overlap between the zero- and higher-vibrational levels of the excited state, leading to competition between stimulated emission and excitation. We have developed a simple model to predict this behaviour, which we have then experimentally verified [3]. To do so, dibenzoterrylene (DBT) molecules were embedded in an anthracene (Ac) crystal [4] and a confocal microscope was used to identify and excite a single molecule at room temperature. The fluorescence from the molecule as a function of pump intensity and wavelength was monitored. We found a maximum excited state population of ~75%, matching our model. DBT/Ac crystals were then cooled in a cryostat and the dephasing was measured as the temperature was increased by monitoring the dispersed spectrum of the fluorescence. In line with our prediction, at liquid nitrogen temperature (77K) we measured over 99% population inversion, recovering the ability to build an efficient photon source [3].

[1] C. Polisseni et al., *Optics Express* 24, 5615 (2016).
[2] J.-B. Trebbia, H. Ruf, Ph. Tamarat, and B. Lounis. *Optics Express* 17, 23986-23991 (2009).
[3] R. C. Schofield et al., arXiv:1803.10115 (2018).
[4] K. D. Major et al., *Review of Scientific Instruments* 86, 083106 (2015).

Photonic network random lasers

D Saxena[1], M Gaio[1], J Bertolotti[2], D Pisignano[3], A Camposeo[3] and R Sapienza[1]

[1]Imperial College London, UK, [2]University of Exeter, UK, [3]Istituto Nanoscienze-CNR, Italy

Random lasing systems based on disordered architectures are alternate means to generate laser light. Compared to conventional lasers, they offer several advantages such as robustness against disorder and low spatial coherence, which makes them attractive for applications such as speckle-free imaging and bio-sensing. In recent years, designed-disordered architectures for random lasing systems have attracted much attention, as they can achieve better control over spectral emission and directionality, as well as achieve efficient lasing action.

We present a new architecture for designing and fabricating random lasers based on photonic networks. The photonic networks are built from a planar mesh of interconnected subwavelength polymer nanofibers doped with Rhodamine-6G dye. The networks sustain random lasing action when optically pumped and present lasing thresholds and optical properties which are determined by the network topology. We show that the network lasing modes are Anderson-localised, and can be designed via the network connectivity/topology and modelled by a graph description of Maxwell's equations.

The photonic network random lasers are promising for on-chip sensing applications, as they are planar and have a large surface-area-to-volume ratio. In addition, these lasers could potentially be used in photonic integrated circuits, as photons confined in the network can be easily routed on-chip and be easily out coupled to external waveguides for integration with other photonic components.

Mapping of ultrafast plasmon control and dynamics by PEEM

J Lin and B Ji

Changchun University of Science and Technology, China

In recent years, ultrafast plasmon, which can be realized by concentrating ultrashort femtosecond laser pulses in a subwavelength structure, has been intensively explored. Coherent control of the near field in a nanostructure could be realized by selectively exciting the localized surface plasmon (LSP) mode. The ability to engineer a plasmonic system providing a desired ultrafast response in a predetermined nanostructure is crucial, thus it is necessary to understand the temporal evolution of ultrafast plasmon mode and to manipulate optical near field in a given nanoscale volume. Obviously, towards this direction a technique that is capable of imaging plasmons and characterizing the ultrafast plasmon dynamics with nanometer and femtosecond spatiotemporal resolution is imperative. Photoemission electron microscope (PEEM) assisted with femtosecond time-resolved interferometric technology is an ideal tool to mapping ultrafast plasmons with ultrahigh temporal-spatial resolution.

In this talk, we demonstrate subwavelength imaging of plasmonic dynamics evolution and control of the localized near-field distribution in gold bow-tie and nanoring nanostructure through ultrafast nonlinear photoemission electron microscopy. A series of images of the evolution of local surface plasmon modes on different tips of the bowtie are obtained by the time-resolved three-photon photoemission electron microscopy, and accordingly different localized near-field dynamics are disclosed within a bow-tie nanostructure. In particularly, dephasing time of the hot spots in the bowtie has been obtained based on the PEEM measurement and simulation from plasmon oscillator. Subwavelength imaging of the plasmon control on bowtie at resonant and off-resonant conditions are given, and near-field distribution imaging between the structure with sharp corners (bow-tie) and the one without (nanoring) is compared, and the underling physics responsible for the PEEM difference is discussed.

This project was supported by National Natural Science Foundation of China under Grant Nos. 11474040, 61605017 and 61775021.

Parity symmetry and Strong Coupling spatio-temporal dynamics in plasmonic nano-cavities

A Demetriadou[1], N Kongsuwan[2], J Hamm[2], J Baumberg[3] and O Hess[2]

[1]University of Birmingham, UK, [2]Imperial College London, UK, [3]University of Cambridge, UK

Plasmonic nano-cavities provide the ideal conditions to strongly-couple emitters and plasmons, due to the high-field enhancement associated with the plasmon excitation and the radiative nature of higher-order modes that suppresses quenching. This unique combination of properties allows for a single molecule to strongly-couple with a plasmon mode at room temperature, which opens the route to bring in ambient conditions quantum information systems.

In this work, we explore the coupling of emitters with the multiple type of modes that are present in plasmonic structures. We show that external radiation excites both the even and odd bonding modes of a plasmonic dimer, which are simultaneously exciting and exchanging energy with QEs. We demonstrate that both types of modes, exhibit identical coupling strengths, despite the different field enhancement, Q-factor and mode volume of the two sets of modes.

Additionally, we show that parity symmetry in plasmonic nano-cavities dominates the spatio-temporal dynamics of the plasmon-excitons. By tailoring the illumination set-up of the plasmonic structure, we can dynamically control the hybrid states of the strongly-coupled system, and therefore specifically adapt the dressing of molecules with light.

Parallel Session 8: Optical quantum information

(Invited) New frontiers for light storage at room temperature

O Firstenberg

Weizmann Institute of Science, Israel

We study two new schemes for quantum memories in warm alkali vapor. In one scheme, we map the optical field onto the superposition between electronic orbitals in a ladder level scheme. Our fast ladder memory (FLAME) demonstrates high bandwidth, long lifetime, and low noise, and is thus highly suitable for quantum network synchronization. Potentially, FLAME can be performed in miniature vapor-cell devices incorporating optical waveguiding, and it can be integrated with Rydberg-level excitations for quantum nonlinear-optics applications. In the second scheme, we achieve a record 150-millisecond memory lifetime at room-temperature by mapping the optical field onto ground-state spin orientation, which is insensitive to spin-exchange collisions. This scheme paves the way towards hour-long memories using rare-gas nuclear spins.

Quantum memory verification with minimal assumptions

A Pickston[1], M Ringbauer[1], F Graffitti[1], P Barrow[1], M Proietti[1], D Kundys[1], D Rosset[2] and A Fedrizzi[1]

[1]Heriot-Watt University, UK, [2]National Cheng Kung University, Taiwan

Implementing quantum memories is important in quantum information processing (QIP), particularly in quantum networks, photonic quantum computing with linear optics, and quantum repeaters [1-3]. Verifying whether a quantum memory is capable of storing quantum information rather than transferring classical information between measuring an input state and preparing an output to be sent at a subsequent point in time, is equally as important in QIP. The later is known as an entanglement-breaking (EB) channel and does not store any quantum information, it only transfers classical information. There are various methods to determine if a channel is EB or not, each of which place different constraints on the trust required in preparation and measurement devices. For example, performing a process tomography requires full trust on preparation and measurement, whereas a violation of a Bell inequality would verify if a certain channel is EB without any trust.

In this work we demonstrate an experimental realisation of a measurement device-independent (MDI) approach to quantum memory verification that addresses the limitations of other methods, theoretically described in D.Rosset et al [4]. This method consists of a semi-quantum signalling game which is played between someone who wants to buy a quantum memory and a seller, whose aim is to convince the buyer that they have a quantum memory. The game proposed only requires trusted measurement devices (a minimum for practical quantum channel verification), and is faithful (can verify any channel that is not EB). The results show that this method wins in detecting that entanglement has been preserved over other methods, even in the presence of losses and noise.

[1] Kimble, H. Jeff. Nature 453.7198 (2008): 1023.
[2] Knill, Emanuel, Raymond Laflamme, and Gerald J. Milburn. Nature 409.6816 (2001): 46.
[3] Briegel, H-J., et al. Physical Review Letters 81.26 (1998): 5932.
[4] D.Rosset et al, arXiv:1710.04710v2.

A new method for multi-bit and qudit transfer based on commensurate waveguide arrays

J Petrovic[1], J Krsic[1], A Maluckov[1] and P Veerman[2]

[1]University of Belgrade, Serbia, [2]Portland State University, USA

Parallel transfer of bits, qubits and qudit states on optical chips is essential for building efficient optical computers. Whereas ever increasing link capacity puts strict demands on dense packaging and scalability of optical interconnects, thereby increased cross-talk between waveguides induces signal distortions that impede perfect transfer. Here, we propose a method that leverages on a suitably engineered cross-talk between waveguides to achieve the perfect transfer of classical and quantum states. The method is based on the full state revivals in linearly coupled waveguide arrays with commensurate eigenvalues. The commensurability enforces periodicity of light dynamics, resulting in the phase and amplitude revivals of the initial state. The key design challenge is to find ratios of the waveguide coupling coefficients that render such eigenspectra, which belongs to a class of non-trivial inverse eigenvalue problems. Such problems are analytically solvable in a small number of cases and are, in general, of polynomial complexity. We have reported analytical solutions for symmetric arrays composed of 4 and 5 optical waveguides with possible applications in signal routing [Opt. Lett. 40, 139 (2015)]. Here, we present analytical solutions for arrays with up to 9 waveguides and use them to design commensurate WGAs that are accessible to modern fabrication techniques, such as direct laser writing [Ann. Phys. 392, 128 (2018)]. We discuss scaling of the link capacity with the number of waveguides and possible sources of dephasing that may impact the transfer fidelity.

Measuring incompatible properties of a photon deterministically

A Dada[1], W McCutcheon[1], A McMillan[1], E Andersson[2], B Gerardot[2], J Rarity[1] and R Oulton[1]

[1]University of Bristol, UK, [2]Heriot-Watt University, UK

It is well known that joint measurements of non-commuting quantum observables are possible at the cost of increased measurement uncertainties. Impressive efforts have been made in this direction, and the few experiments reported so far have utilized different approaches, including weak measurements [1,2] and optimal quantum cloning [3]. However, amongst other limitations, realizations of such approaches until now have relied on postselection. This imposes inherent loss which fundamentally limits their scalability and applicability in quantum information and communication scenarios.

Here, we use a previously untested approach inspired by a scheme for optimal joint measurement of two spins and the operational locality principle [4] to experimentally demonstrate the possibility of a joint quantum measurement of non-commuting quantum observables that is both optimal and non-postselective. We implement a genuine single-quantum realization using a heralded single-photon source and experimentally verify the quantum-mechanical relation that governs the measured variances to demonstrate quantum-limited performance of the positive-operator-valued-measure (POVM) scheme.

This work offers a fresh experimental perspective on joint quantum measurements and demonstrates how to implement them more scalably and with less quantum resources. It will likely have broad implications for state estimation, quantum control, and for probing foundational ideas in quantum theory [1,2,4], in all of which joint measurements continue to play a pivotal role.

[1] J. S. Lundeen, et al., Nature **474**, 188 (2011)
[2] S. Kocsis, et al., Science **332**, 1170 (2011); M. Ringbauer, et al., PRL **112**, 020401 (2014); F. Piacentini, et al., PRL **117**, 170402 (2016).
[3] G. Thekkadath, et al., PRL **119**, 050405 (2017).
[4] P. Busch, Phys. Rev. D **33**, 2253 (1986); P. Busch, et al., Operational Quantum Physics (Springer, 2001); E. Andersson, et al., Phys. Rev. A **72**, 042104 (2005).
[5] S. Hacohen-Gourgy, et al., Nature **538**, 491 (2016); L. A. Rozema, et al., PRL **109**, 100404 (2012).

Protecting multi-qubit graph states from phase-damping noise

M Proietti[1], M Ringbauer[1], F Graffitti[1], A Pickston[1], P Barrow[1], D Kundys[1], A Fedrizzi[1], R Chaves[2], D Cavalcanti[3] and L Aolita[2]

[1]Heriot-Watt University, UK, [2]Universidade Federal do Rio Grande do Norte, Brazil, [3]ICFO, Spain

Entanglement is a fundamental resource in many quantum information applications, however its usefulness in any real experimental implementation is restricted by the presence of noise [1]. Already existing quantum error correction codes successfully provide full robustness of entangled states by encoding logical qubits with many physical qubits, nevertheless this solution is experimentally very demanding, in particular as the system's dimension increases, therefore limiting the usefulness of the method.

We present, an experimental demonstration, of an entanglement protection protocol [2] providing full robustness without requiring any further encoding than unitary rotations on each single qubit. Both a 4-qubit Greenberger–Horne–Zeilinger state (GHZ) and a linear cluster state are prepared and encoded according to our protocol before undergoing a dephasing channel, here used to reproduce phase-damping noise. Multi-qubit entanglement measures as well as coherence measures, are thus performed on the channel's output state successfully showing and demonstrating the desired protection against the degrading effect of the noise.

Beside this already important result, we apply the method proposed in a typical Quantum Metrology task: the phase estimation [3]. It is known indeed that using entangled states as resources for parameter estimation it is possible to go beyond the classical precision. However, this advantage is lost if noise is present making the entangled resource useless for the phase estimation. We show that using our simple protocol phase estimation is now still possible even in the full-strength noise case, yet quantitatively proving this enhancement via Fisher information analysis.

[1] Aolita, L., et al. "Scaling laws for the decay of multiqubit entanglement." Physical review letters100.8 (2008): 080501.
[2] Chaves, Rafael, Leandro Aolita, and Antonio Acín. "Robust multipartite quantum correlations without complex encodings." Physical Review A 86.2 (2012): 020301.
[3] Giovannetti, Vittorio, Seth Lloyd, and Lorenzo Maccone. "Quantum metrology." Physical review letters 96.1 (2006): 010401.

Parallel Session 9: Active and adaptive optics

(Invited) Using AO retinal imaging in the living human eye to study the dynamics of visual sampling

L Young[1], T Morris[2], C Saunter[2] and H Smithson[1]

[1]University of Oxford, UK, [2]Durham University, UK

When we fixate on an object our eyes are not completely still, but make fine jittering motions that move the image over several photoreceptors. These movements are important for preventing visual fade and there is evidence that they may also be important in fine spatial tasks. By studying the relationship between eye stability and carefully manipulated properties of a stimulus we can better understand the feedback mechanisms that work to maintain fixation.

Adaptive optics scanning laser ophthalmoscopy (AOSLO) produces high-resolution in vivo images of the retinal mosaic. Due to the scanning nature of the instrument, eye motion introduces distortions in AOSLO images. By comparing the distorted images to a stationary reference frame, eye movements can be measured on the scale of the photoreceptors and at very high speed.

We have developed a new-design AOSLO for studying healthy and diseased retina. Using AOSLO eye-tracking measurements, combined with an exact record of an observer's particular photoreceptor mosaic, allows us to estimate the spatio-temporal stimulation of the photoreceptors as the eyes move over a stimulus. We have characterised the accuracy with which we can measure eye movements using a simulation of the data capture from a realistic model retina.

Versatile Adaptive Optics Module for Multiphoton Microscopy

K Hampson, J Wang, Qi Hu and M Booth

University of Oxford, UK

Multiphoton microscopy techniques rely on the simultaneous combination of photons within the sample. The advantage of such techniques is enhanced depth resolution as the emitted light is generated only at the focus of the laser. However when light travels through a specimen, inhomogeneities in the refractive index induce aberrations that prevent the light being focused at a single point. This reduces the effectiveness of the technique and impedes image quality. The aberrations can be corrected for using adaptive optics. However, the optimum wavefront sensing strategy varies with sample. We have developed an adaptive optics module that combines both sensor-based (Shack-Hartmann) and sensorless wavefront sensing. This allows for the aberrations of a wider variety of samples to be corrected. Aberrations are corrected using a deformable mirror. The adaptive optics system is inserted into the microscope using a flip mirror and so causes minimum disruption to an existing microscope design. The effectiveness of the module is demonstrated on a scanning two-photon microscope. As it can be flexibly incorporated into existing microscope designs it will have future applications in other microscopy techniques.

Demonstration of an adaptive optics assisted 4Pi Microscope

J Wang, M Phillips, J Antonello, I Dobbie, C He and M Booth

University of Oxford, UK

4Pi microscopy is a far-field fluorescence microscopy technique that uses two opposing objective lenses to allow coherent detection on biological samples. By combining 4Pi microscopy with single molecule switching microscope techniques, significantly improved spatial resolution and collection efficiency can be achieved. Although 4pi microscopy is known to be capable of imaging thick samples such as whole cells, even a moderate sample thickness will inevitably introduce aberrations that effect the performance of the system, especially the focusing properties. More importantly, the aberrations induced in the two imaging directions, will be different due to the nature of 4Pi imaging. Adaptive optics have been proven capable of compensating for sample-induced aberrations in a range of microscopy techniques. In this report, we experimentally demonstrate an adaptive optics scheme that uses two deformable mirrors and sensorless wavefront sensing in a 4Pi microscope to compensate for sample induced aberrations and restore the spatial resolution and sensitivity of the system.

A unified approach to image based indirect wavefront sensing for adaptive microscopy

Q Hu, K Hampson, J Wang and M Booth

University of Oxford, UK

Image based indirect wavefront sensing is widely used in adaptive optics microscopy. Three major approaches – modal, zonal and F-Sharp – have previously been proposed and implemented in two-photon fluorescence microscopy. Whilst different in concept, we show that these methods have significant similarities and can be considered as variations on the same theme. We tested and compared the three methods in theoretical modelling and through practical implementation on a multiphoton microscope. The results can help us to develop more optimal customised methods for indirect wavefront sensing.

Nanodiamonds and adaptive optics for deep tissue microscopy

G Johnstone, G Cairns and B Patton

University of Strathclyde, UK

Diamond presents much promise for biological applications, its stability means it is biocompatible and does not photobleach, unlike most dyes. Nanoscale sized particles of diamond have been shown to be small enough to allow endocytosis. Furthermore, the presence of optically active defects in the diamond structure, such as the nitrogen-vacancy (NV) defect, allow optical addressing of individual nanodiamonds. There is much interest in using the NV centre as a nanoscale sensor for biologically generated electromagnetic fields. We are developing superresolution microscopes to allow characterisation of the optical properties of nanodiamond in living tissue, such as the sensitivity of the optically active defects to small electromagnetic fields. We will also explore the more general use of diamond as an in-vivo fluorescent marker.

Our microscope is an adaptive optics enhanced, stimulated emission depletion (STED) microscope. Multi-colour excitation means that it is not only suitable for nanodiamonds, but can also simultaneously image a number of the other more conventional fluorophores, including STED-compatible near-infrared dyes such as ATTO 647N and Abberior Star 635. A deformable mirror and spatial light modulator correct for the sample-induced optical aberrations that are inevitable when imaging biological samples. An advantage of these AO components is that they allow high quality images from deep in the tissue of biological samples without the need for additional refractive index matching protocols.

Our microscope is currently under development and this presentation will demonstrate the state of play of the instrument, including the effect of the adaptive optics on conventional confocal imaging and on the integration of the STED-enabling components into the system. We will also present our most up-to-date work on developing nanodiamonds as fluorescent labels for biological samples.

Parallel Session 9: Advances in THz technology

(Invited) Graphene-enabled terahertz devices

C Kocabas

University of Manchester, UK

Advances in terahertz (THz) research and technology, has bridged the gap between radio-frequency electronics and optics. More efficient control of THz waves would highly benefit noninvasive, high-resolution imaging and ultra-fast wireless communications. However, lack of active materials inTHz, hinders the realization of these technologies. Graphene, 2d-crystal of carbon atoms, is a promising candidate for reconfigurable THz optoelectronics due to its unique electronic band structure which yields gate-tunable broad-band optical response. In this talk I will present our experimental work on graphene based devices for controlling intensity, phase and polarization of terahertz waves. These new modulation mechanisms could pave the way for developing active THz optoelectronic systems.

Optically Excited Terahertz Plasmonic Metasurfaces in Black Silicon

L Peters[1], J Tunesi[1], J S Totero Gongora[1], A Pasquazi[1], A Fratalocchi[2] and M Peccianti[1]

[1]University of Sussex, UK, [2]King Abdullah University of Science and Technology, Saudi Arabia

Plasmonic metasurfaces are intensely researched due to the remarkable control over the optical response that can be achieved through adjusting the properties of the surface. By engineering the system response, it is possible to finely tune the amplitude, phase and directionality of impinging optical fields, leading to the realization of advanced functionalities such as ultrathin lenses and beam-shapers.

This approach is intrinsically static and narrow-band because of the fabrication-fixed resonant nature of plasmonic metasurfaces. Although, abrupt changes of conductivity and other physical changes can be triggered in nanostructured semiconductors via ultrafast optical pumping. In appropriate injection regimes, this approach leads to a transition from a purely dielectric structure to a resonant metallic surface, whose optical properties can be controlled by an excitation pump.

We present evidence of optically-induced dynamic metasurfaces in the framework of terahertz (THz) photonics. Specifically, our demonstration exploits the THz emission of black silicon (B-Si) surfaces. B-Si is composed of a random distribution of silicon nanopillars that dramatically increases the absorption of optical light. While it has been demonstrated that B-Si emits THz radiation under ultrafast excitation, very little investigation focused into revealing the complex nonlinear field-matter dynamics. B-Si is 'complex' in the optical sense, i.e. the random distribution is characterized by widely different spatial scales which could lead to collective-resonant behaviours.

By observing the THz emission from B-Si surfaces under different photo-excitation conditions, we demonstrate a photocarrier activated plasmonic response that resembles typical resonant metasurface behaviour, including a phase-shift (up to π) and nonlinear conversion enhancement. Our results suggest that this response is compatible with a nonlinear coupling between the THz generating pump and a surface plasmon-polariton wave induced by the excitation pump. We believe that this result reveals a new class of ultrafast-activated metasurfaces, providing an extra degree of control over their properties.

Magnetic-field patterning of a spintronic source for arbitrary terahertz polarisation control

M Hibberd[1], D Lake[1], A Johansson[1], T Thomson[1], S Jamison[3] and D Graham[1]

[1]The University of Manchester, UK, [2]Science and Technology Facilities Council, Daresbury Laboratory, UK

Spintronic terahertz (THz) emitters utilise the laser-induced electron spin properties in magnetic multi-layers to produce high-field strength (300 $kVcm^{-1}$ [1]), gap-free broadband (1-30 THz [2]) THz radiation. They have the unique property that the generated THz radiation is independent of the pump laser polarisation but polarised perpendicular to the moment of the magnetic structure [3], requiring an applied magnetic field on the order of 10 mT to saturate the magnetic structure. We exploit this dependence by applying a magnetic field pattern to our spintronic emitter ($Ni_{80}Fe_{20}$ (2 nm) / Pt (2 nm) bilayer on a MgO substrate), aligning the magnetic domains of the $Ni_{80}Fe_{20}$ layer to the local field direction and enabling us to directly tailor the transverse polarisation profile of the emitted THz radiation. By placing the emitter between two magnets oriented with either aligned or opposing polarity, we were able to generate THz radiation of either linear or quadrupole-like polarisation, respectively. Our results demonstrate the potential in using magnetic-field patterning of spintronic emitters for high-field strength, arbitrary THz polarisation control, with applications employing both standard and unconventional THz beam polarisation envisaged in THz spectroscopy, coherent control [4] and THz-particle beam interactions [5].

[1] T. Seifert et al., Appl. Phys. Lett. **110**, 252402, (2017).
[2] T. Seifert et al., Nat. Photonics **10**, 483, (2016).
[3] D. Yang et al., Adv. Optical Mater. **4**, 1944, (2016).
[4] T.L. Cocker and R. Huber, Nat. Photonics **7**, 678, (2013).
[5] M.J. Cliffe, D.M. Graham and S.P. Jamison, Appl. Phys. Lett. **108**, 221102, (2016).

Broadband, rotatable terahertz polarisation control for the spectroscopy of anisotropic materials

C Mosley[1], M Failla[1], D Prabhakaran[2] and J Lloyd-Hughes[1]

[1]University of Warwick, UK, [2]University of Oxford, UK

The accurate determination of the optical properties of anisotropic materials in the terahertz range is important for the design of optical components for polarisation control, and for fundamental physical research.

We introduce the method of rotatable polarisation terahertz time-domain spectroscopy (RP-THz-TDS), which provides a accurate and precise probe of the behaviour of anisotropic materials at THz frequencies, based on rotating an interdigitated photoconductive emitter [1]. We obtained the orthogonal electric field components of THz pulses directly via electro-optic sampling, resolving the full THz polarisation state (defined by the polarisation angle, ψ and ellipticity, χ), without requiring the extra components, assumptions and data analysis required by ellipsometric methods. We show that this approach allows broadband polarisation rotation, with linearly polarized THz pulses that can be rotated to arbitrary angles (accuracy <1.0°, precision <0.1° in ψ), and exhibiting a small ellipticity (accuracy <0.75°, precision <0.1° in χ), across a frequency range of 0.3-2.5 THz.

The method does not rely upon THz waveplates, and is therefore broadband, and does not require wire-grid polarisers, circumventing the problem of their poor extinction ratio. We demonstrate the applicability of this technique by investigating anisotropic materials that included a wire-grid polariser, uniaxial and biaxial oxide crystals. Our approach allowed the orientations of the eigenmodes of propagation to be identified as the orientation angles that produced a transmitted THz pulse with zero ellipticity, and the birefringence to be quantified.

Rotating the THz polarization state has benefits in spectroscopy as it not only allows convenient access to the anisotropic optical properties at cryogenic temperatures, but also ensures that the same area on the sample is probed at each angle, solving both of these issues related to rotating the sample.

[1] C. D. W. Mosley, M. Failla, D. Prabhakaran and J. Lloyd-Hughes, Scientific Reports **7**:12337 (Sept 2017)

Developing a terahertz-driven dielectric-lined waveguide for electron beam manipulation

V Georgiadis[1], A Healy[2], M Hibberd[1], G Burt[2], S Jamison[3] and D Graham[1]

[1]The University of Manchester, UK, [2]Lancaster University, UK, [3]The Cockcroft Institute, Sci-Tech Daresbury, UK

Intense ultrafast terahertz (THz) pulses are extremely promising for the future design of high-energy, compact particle accelerators. THz radiation can provide accelerating field gradients on the order of multi-GVm^{-1}, exceeding the breakdown threshold limiting conventional radio frequency-based schemes. The key challenge in utilising THz radiation for particle acceleration and manipulation is in obtaining the sub-luminal phase velocities required to match the velocity of the particle beam. This can be achieved using a dielectric-lined waveguide to reduce the THz phase velocity below the speed of light and was recently demonstrated by accelerating non-relativistic 60 keV electrons by 7 keV, using high-field strength THz radiation focussed into a cylindrical waveguide [1]. However, the waveguide dispersion limited the interaction length to only 3 mm, demonstrating that characterising the dispersion of the waveguide is essential for developing an effective particle accelerator.

We report both experimental measurements and simulation results of the effect of waveguide dispersion on an input single-cycle THz pulse. We used a 10 mm long rectangular waveguide lined at the top and bottom with 240 μm-thick fused-quartz, leaving a 200 μm free space aperture for electron propagation, designed to operate at 0.5 THz. THz radiation was generated from a spintronic source and focussed into the waveguide with an off-axis parabolic mirror, using a tapered horn structure to improve the coupling efficiency. A 2 mm-thick ZnTe (110) crystal was placed at the exit of the waveguide and used in a back-refection geometry to measure the amplitude and phase of the transmitted THz radiation through electro-optic sampling. Furthermore, we will show how the THz polarisation mode generated by the spintronic source can easily be tailored to maximise the accelerating field in the waveguide.

[1] E.A. Nanni et al., Nat. Commun. 6, 8486, (2015)

Parallel Session 9: Nanophotonics II

(Invited) Nonlinear metamaterials for ultrafast polarisation control

A Zayats

King's College London, UK

Metamaterials make possible precise engineering not only linear optical properties and dispersion but also nonlinear response. Anisotropic hyperbolic metamaterials, in particular those based on plasmonic nanorod composites, provide wealth of exciting possibilities in free-space and integrated nonlinear optics offering epsilon-near-zero properties advantageous for enhancing nonlinear response, uniaxial anisotropy for polarization control, increased density of states for spontaneous emission acceleration and many others. Such metamaterials also combine strong Kerr-type and coherent second-order nonlinearities for efficient all-optical control of second-harmonic generation. Together with dielectric-based nonlinear metasurfaces, plasmonic metamaterials and metasurfaces, which enable engineering of resonant optical response of meta-atoms and coupling between them, establish a new platform for free-space and integrated nonlinear photonics applications. In this talk, we will discuss ultrashort pulse propagation in hyperbolic nonlinear metamaterials and nonlinear control of polarisation of propagating light.

Nanolaser optimization through statistical optoelectronic analysis

J A Alanis and P Parkinson

The University of Manchester, UK

Due to their characteristic elongated shape and reflective end-facets, semiconductor nanowires can be used as Fabry-Perot resonators to fabricate nanolasers. As a way of studying the key elements for lasing operation in these devices, we have developed and successfully employed a large scale optical technique to study interwire functional inhomogeneity. Taking advantage of this novel method we are able to locate and optically study a large number of nanolasers by -Photoluminescence. Through a statistical comparison, different parameters such as nanowire length, material inhomogeneity, lasing wavelength etc. are correlated to identify which mechanisms contribute to low-power lasing. We discuss two applications of this approach; nanowires with multi-quantum-well GaAs/AlGaAs active region [1], and p-doped GaAs nanowires [2]. Both studies allowed us to assess the lasing yield of ∼1000 nanowires and identify nanolasers operating at very low threshold. Through establishing the critical parameters, sub-populations can be simply identified with high room-temperature lasing yield (>80%). This approach is of industrial value, as well as providing identification of best operating nanolasers for the fabrication of devices for fundamental study.

[1] J. A. Alanis, D. Saxena, S. Mokkapati, N. Jiang, K. Peng, X. Tang, L. Fu, H. H. Tan, C. Jagadish, and P. Parkinson, Nano Lett., vol. 17, no. 8, pp. 4860–4865, Jul. 2017.
[2] T. Burgess, D. Saxena, S. Mokkapati, Z. Li, C. R. Hall, J. A. Davis, Y. Wang, L. M. Smith, L. Fu, P. Caroff, H. H. Tan, and C. Jagadish, Nat. Commun., vol. 7, no. May, p. 11927, Jun. 2016.

A metal-dielectric parabolic antenna to direct single photons

S Morozov, M Gaio, S A Maier and R Sapienza

Imperial College London, UK

Quantum emitters radiate light omni-directionally, making it hard to collect and use the generated photons. Here we propose a 3D metal-dielectric parabolic antenna surrounding an individual quantum dot as a source of collimated single photons which can then be easily extracted and manipulated. Compared to conventional nano-antennas, our geometry does not require near-field coupling and it is therefore very robust against misalignment issues, and minimally affected by absorption in the metal. The parabolic antenna provides one of the largest reported experimental directivities and the lowest beam divergences, which results in more than 96% extraction efficiency, offering a practical advantage for quantum technological applications.

Controlling spontaneous emission rate of dye molecules confined in a single nanofiber via humidity

B Gökbulut and M N Inci

Boğaziçi University, Turkey

Intrinsic properties of a Polyethylene Glycol (PEG) nanofiber is utilized for the first time to alter the spontaneous transition rate of the Boradiazaindacene (BODIPY) dye molecules, which are doped in PEG nanofibers. The dye doped nanofibers are produced by electrospinning, which is an efficient and cost-effective technique to fabricate almost uniform nanofibers with desired diameter. The physical mechanism affecting the spontaneous emission rate of the encapsulated BODIPY dye molecules within a single nanofiber is investigated through studying inhibition and enhancement in their lifetimes using a time resolved fluorescence lifetime imaging method. Nanofibers are excited with 470 nm picosecond light source while they are exposed to relative humidity (RH) from 40% up to 80%. Results show that the inhibition and enhancement occurring in the spontaneous emission rate of the dye molecules exhibit an oscillatory manner, arising from the humidity induced variations in the refractive index and diameter of the PEG nanofibers upon swelling. Varying the RH alters the spontaneous emission rate of the dye molecules almost periodically, which directly affects the Purcell factor to demonstrate a similar characteristics between 1.25 and 2.52. This oscillatory behavior of the Purcell factor, originating from the distinct characteristics of the single nanofiber cavity's mode volume and the steep increase of the quality factor, are also due to the humidity induced changes in the index of refraction and the fiber diameter. Such dynamical mechanism might be a useful candidate as an optical switch for the environments where the relative humidity is desired to be stringently controlled.

Wide-field imaging of single nanoparticle extinction with sub-nm^2 sensitivity

P Borri, L Payne and W Langbein

Cardiff University, UK

Small nanoparticles (NPs) in the sub-10nm size range are increasingly important for many applications ranging from optoelectronic devices exploiting quantum confinement at the nanoscale, to drug delivery and diagnostics. In this context, their optical response offers many opportunities in imaging and sensing. Increasing attention has been devoted recently to develop methods capable of detecting single NPs, since their properties can significantly differ from the ensemble average owing to inhomogeneities in NP size and shape. However, many NPs of widespread use are weakly or non-fluorescent, for example metallic NPs, making their optical detection in the sub-10nm size range specifically challenging.

We report a highly sensitive wide-field imaging technique for quantitative measurement of the optical extinction cross-section σ_{ext} of single nanoparticles [1]. The technique is simple and high-speed, and enables simultaneous acquisition of hundreds of nanoparticles for statistical analysis. Using rapid referencing, fast acquisition, and a deconvolution analysis, a shot-noise limited sensitivity down to 0.4nm^2 is achieved. Measurements on a set of individual gold nanoparticles of 5nm diameter using this method yield $\sigma_{ext} = (10.0 \pm 3.1)$nm^2, consistent with theoretical expectations, and well above the background fluctuations of 0.9nm^2. The method has thus a sensitivity competitive with more complex laser- and modulation-based techniques, while at the same time enabling rapid acquisition of σ_{ext} on many individual particles at once. This is particularly important, considering that NPs are often fabricated with large size and shape distributions. Notably, the method is applicable to any NP (including dielectric or semi-conducting), and can be easily and cost-effectively implemented on a conventional wide-field microscope. Thus it paves the way toward a much simpler, yet quantitative, sensitive, and high-throughput single particle optical characterization.

[1] L. M. Payne et al., Phys. Rev. Applied **9**, 034006 (2018).

Parallel Session 9: Quantum coherent control

(Invited) Photonic Quantum State Transfer between Disparate Quantum Nodes

H de Riedmatten

ICFO, Spain

Quantum networks (consisting of matter quantum nodes and quantum communication channels) hold promise for new capabilities compared to their classical counterparts. They could for example enable perfectly secure data transmission or enhanced data processing via distributed quantum computing. While it is generally agreed that photons are the best choice to transmit quantum information, the optimal matter system for building the quantum nodes is still an open question, as each system provides different functionalities. Therefore, the implementation of a hybrid network has been proposed, searching to combine the best capabilities of different material systems.

In this talk, I will present our recent results demonstrating photonic quantum communication between two very distinct quantum nodes functioning at very different wavelengths placed in different laboratories, using a single photon as information carrier. The emitting node was a laser-cooled cloud of Rubidium atoms and the receiving node a crystal doped with Praseodymium ions. We transmitted a qubit from one system to the other, using quantum frequency conversion techniques. The results of the study have shown that two very different quantum systems can be connected and can communicate by means of a single photon.

Cavity-assisted adiabatic transfer techniques for higher-order optical Fock state generation using nitride QDs embedded in micropillars

G Slavcheva[1,2], M Koleva[1,3], S Schulz[4,5], R Oliver[6] and R Taylor[5]

[1]Quantopticon Ltd., UK, [2]Johannes Kepler University Linz, Austria, [3]King's College London, UK, [4]Tyndall National Institute, Ireland, [5]University College Cork, Ireland, [6]University of Cambridge, UK, [7]University of Oxford, UK

The fabrication of reliable, integrated sources of non-classical light on a chip is a critical requirement for next-generation quantum technologies. Semiconductor quantum dots (QDs) are examples of non-classical light emitters: photons are 'antibunched', i.e. emitted one by one, in a manner described by sub-Poissonian statistics. In contrast coherent states, which are produced by lasers, are characterised by random delays in the emission of consecutive photons. Single photons can currently be routinely generated using semiconductor QDs with fidelity exceeding 95%. If a quantum system is prepared so as to emit a specified number of photons, one can speak of a 'Fock state'. Since any coherent state can be constructed as a superposition of Fock states, deterministic Fock-state generation is thus a prerequisite for complex 'mesoscopic' non-classical light states. Progress in this direction would benefit linear optical quantum computation, long-distance quantum communications, state teleportation and entanglement swapping. However, on-demand generation of high photon-number Fock states is challenging. One of the main difficulties stems from the lack of high-fidelity protocols for Fock-state preparation.

With a view to devising a scalable system by inter-coupling QDs coupled to micropillar cavities, we study adiabatic state-transfer techniques [1] to manipulate the QD-cavity systems into the desired Fock states. We exploit the fine excitonic structure [2] in nitride QDs to engineer integrated sources of optical Fock states of the cavity field. The system dynamics are modelled by our quantum-stochastic Maxwell-pseudospin-Langevin model [3-5] which describes multiple optical transitions between discrete levels in a realistic, driven-dissipative QD-cavity system. We design QD-cavity geometries specifically optimised for Fock-state generation and optimise the control pulse parameters. We compute the quantum dynamics and photon statistics of the emission from different output states and identify the most promising high-fidelity schemes for quantum light-state preparation. The ultimate goal is to fabricate on-chip arrays of Fock-state sources.

Theory of ultrahigh gain thin films

J Jeffers

University of Strathclyde, UK

Coherent perfect absorption [1-4] allows the degree of absorption of a lossy material to be controlled by adjusting the input mode of the light. The effect was first suggested theoretically for lossy beam splitters at the quantum level [1], and later developments in the field allowed it to be observed, first with classical light [2-4]. Many experimental and theoretical papers have explored the effect since then. It has been measured with both single photon [5] and two photon inputs [6], showing that at the quantum level loss is not always the random deletion of photons. The effect is striking for optically thin, high refractive index films, whose optical thickness is much smaller than the wavelength of light. One superposition mode can be completely absorbed and one fully passed by the absorbing device [1].

Detailed modeling of dielectric slabs [7] shows that the same theory applies to amplifying thin slabs. There is one crucial difference, however. One superposition mode of the slab is passed essentially unchanged by the amplifying device, the other, rather than being fully absorbed, is fully (i.e. infinitely) amplified. In practice the gain will be limited by practical considerations, but in the low input intensity limit ultrahigh gains could be achieved. The implications of this for optical generation will be considered.

[1] J. Jeffers, J. Mod. Opt. **47**, 1817 (2000).
[2] Y.D. Chong et al, Phys. Rev. Lett. **105**, 053901 (2010).
[3] W. Wan et al., Science **331**, 889 (2011).
[4] J. Zhang et al, Light: Sci. Appl. **1**, e18 (2012)
[5] T. Roger et al, Nat. Commun. **6**, 7031 (2015).
[6] T. Roger et al, PRL **117**, 023601 (2016).
[7] R. Matloob et al., Phys. Rev. A **55**, 1623 (1997).

Fine tuning of adiabatic potentials and control of the internal dynamics of alkali atoms using RF and MW fields

G Sinuco and B Garraway

University of Sussex, UK

Controlling the potential energy landscape and the internal dynamics of ultracold atomic ensembles is crucial for the advance of atomic quantum technologies. Fine control of both dynamical aspects can be achieved by combining inhomogeneous distributions of static magnetic field with radio-frequency (RF) or microwave (MW) fields, as it has been demonstrated experimentally [1] and theoretically [2,3]. In this work, we explore how bichromatic driving provides an extremely flexible mechanism for manipulating alkali atoms, taking 87Rb as a case of study.

We study the dynamics of the ground state of alkali atoms under the simultaneous influence of static, RF and MW radiation. We introduce an analytical approximation using a double-rotating frame approximation, and a fully numerical description applying the multimode Floquet approach. Using this framework, we explain how to evaluate the adiabatic potential landscape emerging from the interaction of atoms with MW and RF fields, as well as the time-evolution of the internal states of driven atomic systems.

As one application, we evaluate how MW radiation can fine-tune the potential landscape generated by RF-dressing of atoms in a magnetic field distribution. Using typical parameters of atom-chip experiments, we study conditions under which MW fields reduce the inhomogeneity of RF-dressed adiabatic potentials resulting from spatial variations of the field distribution.

We also study the internal dynamics of RF-dressed 87Rb irradiated by a microwave pulse and apply our theoretical and numerical frameworks to explain recent experimental results of microwave spectroscopy of dressed 87Rb [4]. Finally, we highlight the relevance of our findings for other experimental platforms pursuing applications in quantum technologies.

[1] C. L. Garrido Alzar, et. al. PRA **74**, 0534131 (2012).
[2] G.A. Sinuco-Leon, et al., Nat. Comm. **5**, 5289 (2014).
[3] G. A. Sinuco-Leon and B.M. Garraway, NJP **18**, 035009 (2016).
[4] W. von Klitzing, et al. in preparation (2017)

Polarised single-photons from a cavity-enhanced atom-light interface in photonic quantum networks

T Barrett[1], O Barter[1], D Stuart[1], A Rubenok[2], J Matthews[2], A Kuhn[1] and B Yuen[1]

[1]University of Oxford, UK, [2]University of Bristol, UK

Entanglement is a key resource for quantum information processing (QIP). Mutually entangled cluster states are inherently more robust than pairwise chains of entangled qubits, however it is particularly difficult to create these in non-local networks where bringing together distant nodes is often impractical. Instead quantum networks of interlinked stationary (typically single atoms or ions) and flying (photonic) qubits offer a scalable route to bridging these physical distances [1], but necessitate a reliable interface between these quantum elements. A single atom strongly coupled to a single mode of the electric field, where the internal spin state of the atom is entangled to the emitted photon polarisation, is then an ideal architecture for realising such a system. Probabilistic entanglement of distant atoms can be achieved by entanglement swapping acting on photons emitted from both atoms [2,3].

Here we discuss the essential first step, an a priori non-probabilistic source of polarised single-photons, that utilises the unparalleled control over the photonic states provided by the cavity-enhanced interaction with a single ^{87}Rb atom [4]. In particular we consider novel effects of non-linear Zeeman shifts on this system and the operation of a 4x4 multimode interferometer integrated onto a photonic chip [5] with pairs of cavity-photons.

[1] S. Ritter, C. Nolleke, C. Hahn, A. Reiserer, A. Neuzner, M. Uphoff, M. Mucke, E. Figueroa, J. Bochmann, and G. Rempe, Nature, **484**, 195 (2012).
[2] D. Moehring, P. Maunz, S. Olmschenk, K. Younge, D. Matsukevich, L.-M. Duan, and C. Monroe, Nature, **449**, 68 (2007).
[3] S. Olmschenk, D. Matsukevich, P. Maunz, D. Hayes, L.-M. Duan, and C. Monroe, Science, **323**, 486 (2009).
[4] A. Kuhn, Cavity Induced Interfacing of Atoms and Light; in Engineering the Atom-Photon Interaction, Springer (2015).
[5] A. Peruzzo, A. Laing, A. Politi, T. Rudolph, and J. L. O'Brien, Nature Communications, **2**, 224 (2011)

Thursday 6 September

(Plenary) Wider, Faster, Deeper: New perspectives for wide field imaging in biophotonics

K Dholakia

University of St Andrews, UK

Optical imaging has seen exceptional advances in the last two decades. In this talk I will describe routes for obtaining wide field images that minimise photodamage and enable deeper penetration into tissue. As an example I will describe light sheet microscopy using propagation invariant light fields, particularly Airy and Bessel beams. These fields offer exceptional advantages for this form of imaging. Recent work extending their use for the first time to the case of three photon imaging will be described where we will describe the advantages over two photon imaging.

More recent work from our team has shown how using attenuation compensated light fields can be used with both Airy, Bessel and potentially lattice light sheet modes. This offers a powerful new method for overcoming sample attenuation and scattering in a remarkably simple manner. The talk will conclude with some new concepts for wide field multiphoton imaging that avoid the direct use of aberration correction and allow imaging at depth without needing to resort to characterisation of the scattering tissue or media.

These advanced photonics based approaches offer exciting opportunities for optically visualising processes in neuroscience and developmental biology.

(Plenary) Single-Molecule Sensing with Optoplasmonic Microcavities

F Vollmer

University of Exeter, UK

My laboratory is developing a new class of nanophotonic architectures by combining optically resonant dielectric microcavities with plasmonically resonant metal nanostructures to enable detection at the nanoscale with extraordinary sensitivity.

Parallel Session 10: Trapping and manipulation

(Invited) Mechanical inequivalence of spin and orbital linear momentum of light: an optical centrifuge

S Simpson, V Svak, O Brzobohaty, M Siler, P Jakl, J Tragardh and P Zemanek

Institute of Scientific Instruments of the CAS, Czech Republic

The mechanical action of circularly polarized light beams is commonly associated with the rotation of absorbing on non-symmetric particles [1,2]. Here, we take a fresh look at this effect by considering the motion of a non-absorbing sphere in a circularly polarized vacuum trap.

We observe behaviour that, in many respects, is the opposite of that which is familiar. For example, increasing the power in our trap results in the bead moving more freely, rather than being more tightly confined. Above a well defined power - analogous to a lasing threshold - the motion becomes coherent, with the spontaneous formation of deterministic orbits. For yet higher powers, the bead is violently thrown from the trap. We present experimental results and corroborating theory to illustrate these phenomena. The non-equilibirium behaviour of our probe particle is directly attributed to the influence of the spin component of the Poynting momentum [3,4], a contribution previously thought virtual.

[1] NB Simpson, K Dholakia, L Allen, MJ Padgett, "Mechanical equivalence of spin and orbital angular momentum of light: an optical spanner", Optics Letters (1997).
[2] RA Beth, "Mechanical detection and measurement of the angular momentum of light", Physical Review (1936).
[3] MV Berry, "Optical Currents", Journal of Optics A (2009).
[4] KY Bliokh, AY Bekshaev, F Nori, "Extraordinary momentum and spin in evanescent waves", Nature Communications (2014).

Observing lipid raft formation in an optically stretched giant vesicle using Raman spectroscopy

L Collard[1], F Sinjab[2] and I Notingher[1]

[1]University of Nottingham, UK, [2]University of Tokyo, Japan

Cell membranes are made from a material called a lipid bilayer. Lipid vesicles consist of a lipid bilayer encapsulating a fluid; they are often used to model lipid interactions within a membrane. The intercalation of cholesterol to the lipid blend disrupts the local packing order of the bilayer. In a bilayer enriched with cholesterol, ordered microdomains (lipid rafts) form and float freely across the largely disordered bilayer. Lipid rafts are postulated to be involved in cell signalling and trafficking.

Optical methods have previously been used to investigate the stretching of lipid vesicles and red blood cells. The deformability of a red blood cell is linked to the oxygenation process and sickle cell disease. Fluorescence experiments have shown that for a stretched vesicle, ordered microdomain formation is favoured in the region of lower curvature. Raman spectroscopy can be used as a label free method to monitor local packing order in a lipid vesicle.

Holographic optical tweezers provide an opportunity to trap and deform a single lipid vesicle using a tightly focussed laser beam and spatial light modulator (SLM). Our optical tweezers have been integrated with a Raman spectrometer and digital micromirror device (DMD) allowing Raman spectra to be taken at several points on an optically trapped vesicle. The C-H stretching region can be used to distinguish between ordered and disordered regions of an optically trapped lipid vesicle.

In this work, a giant vesicle (diameter ~ 10 μm) was optically trapped and stretched using two optical traps. Raman spectra were then taken in regions of high and low curvature to show a higher degree of local packing order in the region of low curvature. Spectra were also taken for different values of separation between the two optical traps.

Holographic optical trapping Raman micro-spectroscopy for non-invasive measurement and manipulation of interacting live cells

I Notingher[1], F Sinjab[1], G Gibson[2], M Padgett[2], A Ghaemmaghami[1] and H Elsheikha[1]

[1]University of Nottingham, UK, [2]University of Glasgow, UK

We present a new technique combining holographic optical tweezers (HOT) and confocal Raman spectroscopy allowing fast, flexible and interactive manipulation and molecular measurement of multiple interacting live cells. Each laser beam created with a spatial light modulator is simultaneously used for optical trapping and confocal Raman spectroscopy measurements. To enable Raman measurements with high spectral resolution, a digital micro-mirror device (DMD) was used to generate reflective pinholes matched to each laser trap. Raman spectra with spectral resolution from diffraction limited points were able to be obtained from multiple trapped objects simultaneously in arbitrary locations in the field of view, with high temporal resolution. We show the general applicability of such an instrument, from measuring yeast, blood and mammalian immune cells, to pathogens such as bacteria and intracellular parasites. We present examples of interacting cell systems, including human dendritic cells and T cells forming immunological synapses, and Toxoplasma Gondii parasites interacting with human micro-endothelial cells. The combination of the technique with amino-acid isotope-labelled provides unique data on molecular transport and communication during these interactions. The results highlight the unique capabilities of the HOT-Raman instrument: ability to manipulate cells to initiate complex biological interactions between multiple cells whilst non-invasively acquiring high-quality Raman spectroscopic readout of the processes with high spatial and temporal resolution.

Hydrodynamic micromanipulation driven by optically actuated flow controllers

D Phillips[1], U Būtaitė[2], G Gibson[2] and J Taylor[2]

[1]University of Exeter, UK, [2]University of Glasgow, UK

Optical tweezers have proven to be an exceedingly versatile tool to manipulate mesoscopic objects. However, the use of optical forces place constraints on the types of materials that can be optically tweezed. In general, optically trappable particles consist of non-absorbing dielectric material, and are transparent to the trapping wavelength. In contrast to forces derived from light-matter interactions, hydrodynamic forces exerted by fluid flow can be used to manipulate particles completely independently of their composition. In this work we demonstrate how optical tweezers can be used to sculpt dynamic flow fields capable of precisely manipulating free-floating particles without directly illuminating them. Our method relies on a simple principle: when an optically trapped particle is moved, it displaces the surrounding fluid in a highly predictable manner, resulting in controllable hydrodynamic forces exerted on nearby objects. Therefore, manipulation of free-floating target particles can be achieved by orchestrating the motion of a set of optically trapped 'flow micro-actuators', themselves controlled automatically using holographic optical tweezers. We describe how this allows us to suppress Brownian fluctuations of target objects to a standard deviation of below 100nm; demonstrate the controlled translation of individual particles at over 10um/s; and precisely choreograph the motion of multiple particles simultaneously. Our work expands the capabilities of optical tweezers systems, providing a new route to the simultaneous control of multiple microscopic objects of arbitrary material and shape, and a new minimally invasive technique to stabilise and study biological systems while avoiding their irradiation with intense laser light.

Optical tweezers for neutral atoms: the key to a reliable atom-photon quantum interface

N Holland, D Stuart, K Theophilo and A Kuhn

University of Oxford, UK

A deterministic and coherent interface between atomic excitations and photonic states is a fundamental building block for hybrid quantum computation in a scalable quantum network. We aim to implement a novel single-atom single-photon interface via a high-finesse optical cavity [1]. To make the process deterministic, the atoms are trapped in microscopic dipole traps (optical tweezers), which may be dynamically reconfigured using a spatial light modulator (SLM) [2].

The optical tweezers are holographically generated - we discuss the physical setup used to realise this, along with a number of algorithms that may be used to calculate the holograms required to be displayed on the SLM [3]. We present our results in trapping arrays of single atoms in arbitrary configurations, and our current work towards moving these trapped single atoms to arbitrary locations. Finally, we discuss the possible integration of these techniques with the fibre-tip cavities also under construction in our group, and the significance of this to the field of quantum computation.

[1] A. Kuhn, Cavity Induced Interfacing of Atoms and Light. Ch.1 in: Engineering the Atom-Photon Interaction. Springer (2015).
[2] D. Stuart and A. Kuhn, New Journal of Physics, 20, 023013 (2018).
[3] N. Holland et al., pre-print, arXiv:1711.07845 (2017).

Parallel Session 10: Computational photonics

(Invited) Hyper-uniform and local self-uniform photonic structures

M Florescu, R Spalding and C Wan

University of Surrey, UK

The fundamental connection between geometrical and topological characteristics of structured photonic materials and advanced photonic functionalities is central to the design of novel photonic materials. Here, we introduce new metrics, hyperuniformity and local self-uniformity as measures of the structural order of photonic network structures. The hyperuniformity concept is built upon the properties of the structure in the reciprocal space, whereas local self-uniformity characterises the intimate connection between uniformity on local and global length scales. Despite their distinct characteristics, both metrics provide novel design strategies for achieving advanced photonic functionalities in non-periodic materials. Here, we will introduce computational approaches employed to generate these novel disordered structures. We then explore the connection between the hyperuniformity and local self-uniformity and the photonic band gap formation and introduce a novel photonic-network architecture, the amorphous gyroid network or triamond. We demonstrate that all architectures displaying large photonic band gaps, be they periodic or disordered, are characterized by large values of the newly introduced disordered metrics. We then explore computationally through both band structure calculations and finite-difference-time domain simulations their photonic properties: photonic band gaps, localisation and waveguiding, and photon transport. A comparison between their predicted properties and recent experimental results will also be provided. In the end, a series of applications of the new disordered photonic networks will be discussed including novel structuring for solar cell absorbers, wing-scale structuring in the butterfly Pseudolycaena marsyas and new designs for photonic integrated circuits and micro-opto-mechanical filters and modulators.

Non line of sight single pixel camera

G Musarra, A Lyons, M P Edgar, M Padgett and D Faccio

Glasgow University, UK

Non-Line-of-Sight (NLOS) imaging is the term applied to imaging a scene that cannot be directly viewed as happens for objects hidden behind an occluder such as a wall. This technique typically involves a pulsed laser beam pointed on a scattering surface, producing a sphere of light propagating into the hidden scene. When the first scattering hits the hidden object, the light is scattered back towards the scattering surface. Collecting the third bounce echo scattered from the hidden object permits to reconstruct the shape of the hidden scene by reconstruction imaging algorithms. Since the multiple back-scattered signal is typical weak and this technique requires computational algorithms and considerable memory resources, imaging NLOS scenes with high resolution and high-speed cameras is still a challenge. One of the main limitations of current NLOS imaging systems is the temporal resolution, which determines the ability to reconstruct 3D images.

We investigate the reconstruction in the IR spectrum of NLOS scenes by detection of the back scattered light with a time resolved 2D single pixel camera. A single pixel camera consists of reflecting the light from the scene with a digital mirror device (DMD) whose mirrors can be individually tilted. By controlling the tilt of each mirrors and by applying specific patterns to the collected light, this method allows to reconstruct the entire image using only one pixel sensor as opposed to many pixels detector.

This approach allows us to use a single pixel detector such as a photomultipler tube that is not only sensitive to single photons but also has one of the highest temporal resolutions on the market, with an impulse response function of just 17 ps quoted by the company (Becker\&Hickl) (but measured in our system 27 ps). This technique provides a readily reliable method to image NLOS scenes with full 3D information.

Strong light confinement in rod-connected diamond photonic crystals

D Ho, M Taverne, X Zheng, L Chen, C-H Fang and J Rarity

University of Bristol, UK

We show that it is possible to confine of light in a volume of order 10^{-3} cubic wavelengths using only dielectric material. Low-index (air) cavities are simulated in high index rod-connected diamond (RCD) photonic crystals. These cavities show long storage times (Q-factors $>10^6$) even at the lowest volumes. Such a high-Q cavity with ultra-small mode volume could be used to demonstrate strong coupling at elevated temperatures while coupled cavities of this type could form broad bandwidth, lossless, wavelength scale optical circuits in a fully 3D photonic crystal microchip. Additionally, these microchips could allow the development of ultrasensitive gas sensing chips guiding and confining light in air or low refractive index material and find applications in solar energy trapping and harvesting.

Calculating light propagation in large anisotropic materials

T Vettenburg[1], J Bertolotti[2] and S A R Horsley[2]

[1]University of Dundee, UK, [2]University of Exeter, UK

The interaction of light with a highly scattering material is interesting both from a theoretical and from an experimental viewpoint [1]. It has direct implications for optical microscopy of optically thick and heterogeneous biological tissue. Even though light scattering is typically considered to be a stochastic process, it has been shown that fine control can be exerted over the scattered light transmission [2]. Ensemble-average analytic solutions cannot provide more than general predictions for experiments on a specific scattering material. In principle, numerical calculations could bridge this gap; however, determining the field distribution for a specific heterogeneous material is an extremely demanding computational problem. This is compounded by the fact that most materials of interest exhibit some form of anisotropy or chirality. Label-free polarization microscopy images the birefringent structures in biological cells. In addition, scattering experiments on non-biological tissue often involve highly birefringent materials such as rutile powder (TiO_2).

Here we present an efficient method to determine the light fields for arbitrary anisotropic materials. Recently an algorithm was proposed was proposed to solve the Helmholtz equation specifically for heterogeneous materials [3]. Although this method can be extended to vector waves [4], it is restricted to isotropic non-magnetic materials. We demonstrate how the electromagnetic wave propagation can be calculated efficiently in complex birefringent, chiral, and even magnetic materials.

[1] Rotter, and Gigan. Rev. Mod. Phys. **89** (2017).
[2] Vellekoop, Lagendijk, and Mosk. Nature Photonics **4** (2010).
[3] Osnabrugge, Leedumrongwatthanakun, and Vellekoop. J. of computational physics **322** (2016).
[4] Krüger, Brenner, and Kienle. Optics Express **25** (2017).

Diffraction problems on two-dimensional complex domains: dusts, triangles, and carpets

J Christian and H Middleton-Spencer

University of Salford, UK

We consider a class of problem involving the scattering of plane waves by domains that are complex in the sense of being rough or (in the limit) scale-free. One instructive example is the von Koch snowflake, where a simple initiator-generator algorithm is used to gradually build-up a self-similar closed shape from a hierarchy of equilateral triangles. This abstraction may be used to model either a multi-scale aperture in an opaque screen (of principal interest in physics), or an opaque multi-scale screen surrounded by otherwise-empty space (often of greater interest in applied mathematics). Alternatively, one might be interested in scatterers that possess an interior structure such as the Cantor dust or the Sierpinski triangle.

Here, two methods will be discussed for attacking two-dimensional complex-domain problems in the classic geometries of optics experiments. Attention is first paid to a Fresnel level of description wherein the diffraction integral over the area of the aperture is transformed into a circulation around its boundary [1]. However, the Fresnel approximation tends to break down fairly abruptly when faced with the complementary screen. We thus also propose a more refined technique based on Rayleigh-Sommerfeld (RS) diffraction integrals. A crucial physical feature of this second approach is that it is free from the assumption of paraxiality which ultimately hinders any Fresnel-based solutions. Another is that, after some manipulation, the RS circulation can be expressed as a linear superposition of edge waves that are fully-nonparaxial generalizations of their counterparts from Fresnel optics [2]. Both of these highly desirable properties suggest that the RS formulation offers some distinct advantages, particularly in near-field regimes. We conclude with a selection of diffraction patterns from pre-fractal iterations of the dust, triangle, and carpet.

[1] J. H. Hannay, J. Mod. Opt. **47**, 121 (2000)

[2] J. G. Huang et al., J. Opt. Soc. Am. A **23**, 2768 (2006)

Parallel Session 10: Mid-IR photonics

(Invited) Infrared materials and fiber optics

J Sanghera[1], W Kim[1], C Baker[1], S Bayya[1], V Nguyen[1], D Gibson[1], G Villalobos[1], M Hunt[1], J Myers[1], B Shaw[1], R Gattass[1], J Frantz[1], L Busse[1], D Rhonehouse[1], S Bowman[1], J Friebele[2], M Kotov[2], I Aggarwal[2], F Kung[3], B Sadowski[3], R Miklos[3] and C McClain[3]

[1]Naval Research Laboratory, USA, [2]KeyW Corp, USA, [3]University Research Foundation, USA

We are developing infrared glasses, ceramics and optical fibers for many active and passive applications.

(i) Chalcogenide glasses: Compositions tailored to control refractive index and dispersion, as well as diffusion to produce graded optics, thereby enabling new multiband optical lens materials leading to huge savings in weight (>2X) for multiband imaging systems.
(ii) Chalcogenide fibers: Demonstrated light-pipes for remote chemical sensor systems, exo-planet discovery, scanning near field optical microscopy and aircraft protection systems. Hollow core fibers demonstrated with loss 100X lower than the material loss in the infrared. The high optical nonlinearity has been exploited to generate broadband IR supercontinuum sources and Raman wavelength shifters. Rare earth doping used to create bright IR sources for dynamic IR scene projection systems. IR fiber combiners fabricated for coupling the output from several QCLs in the IR into a single output fiber, thereby enabling efficient power and wavelength scaling.
(iii) New ceramic materials: Spinel ceramic with superior thermal and mechanical properties for window and dome applications. High purity powder utilized to demonstrate ultra-low absorption loss. Rare earth doped Lutetia and Yttria nano-powders hot pressed into transparent ceramic laser materials with record high slope efficiencies.
(iv) Nano-particle doping of silica fibers: Select rare earth doped nano-particles dispersed in silica fibers to mitigate issues associated with clustering, multiphonon quenching and stimulated Brilluoin scattering. Slope efficiencies for silica fiber lasers of 74% and 85% now demonstrated for Er at 1.6 µm and for Ho lasers operating beyond 2µm.
(v) Single crystal fiber lasers: Grew flexible, cladded single crystal fibers and demonstrated amplification.
(vi) Antireflective (AR) moth eye surfaces: Demonstrated optical components with very reflection losses (0.02%), large bandwidth, and high laser damage thresholds (~100J/cm^2).
The fabrication, properties and applications will be described in detail during the presentation.

Modelling of resonantly pumped mid-infrared Pr^{3+}-doped chalcogenide fibre amplifier with different pumping schemes

M Shen[1], D Furniss[1], Z Tang[1], L Sojka[2], S Sujecki[2], T Benson[1] and A Seddon[1]

[1]University of Nottingham, UK, [2]Wroclaw University of Technology, Poland

Narrow-band mid-infrared (MIR) sources covering the spectral range from 2.5 μm to 9.5 μm, are of great interest for applications in the fields of biomedical sensing, gas and chemical detection, and environmental monitoring. Robust, high power, high efficiency, near-diffraction limited MIR amplifiers and lasers are consequently required for these applications. Previous numerical modelling has demonstrated that a resonantly pumped Pr^{3+}-doped chalcogenide fibre is a promising route for realizing narrow-band MIR lasers beyond 4 μm. However, the near-infrared (NIR) photoluminescence (PL) which has been experimentally demonstrated recently was not included in this previous work. Thus a more general numerical model that considers both MIR and NIR amplified spontaneous emission (ASE) is required.

In this paper, a numerical model of a 4.1 μm resonantly pumped Pr^{3+}-doped chalcogenide fibre amplifier is developed, which includes excited state absorption and the full spectral ASE spanning from 2 μm to 6 μm. Based on this numerical model, the observed MIR and NIR PL generated from Pr^{3+}-doped chalcogenide fibre is explained for the first time. Then the output properties of a 4.1 μm resonantly pumped Pr^{3+}-doped chalcogenide fibre amplifier are simulated in both co- and counter-pumping schemes. Results show that the 4.1 μm counter-pumped fibre amplifier can achieve a power conversion efficiency (PCE) of over 62.8 % for signal wavelengths in the range 4.5 μm to 5.3 μm. This is, to our best knowledge, the highest simulated PCE for a Pr^{3+}-doped chalcogenide fibre amplifier.

Graphene-metamaterial mid-infrared thermal emitters

P Vadegadde Dakappa, C Shi, N H Mahlmeister, I J Luxmoore and G R Nash

University of Exeter, UK

There is a continuing need for the development of cost-effective and sustainable mid-infrared emitters for applications such as gas sensing. Over the last few years, there has been much recent interest [1] in the use of graphene as an incandescent source emitting in the visible, an effect which exploits the ability of graphene to sustain extremely large current densities. We have recently assessed the potential of using graphene based thermal emitters as an alternative, less complicated, approach to mid-infrared semiconductor LEDs [2],where the low thermal mass of graphene offers the potential for high frequency modulation [3]. Encapsulation of the emitting layer with hexagonal boron nitride(h-BN) allowed devices to run continuously in air for over 1000 hours [4],with the emission spectrum covering the absorption bands of many important gases. The h-BN encapsulation also allows the incorporation of a frequency selective surface metamaterial layer. The metamaterial, consisting of ring resonators, acts to tailor the broadband thermal emission into a dual band radiation, with measurements of both reflection and emission spectra agreeing well with simulations [5].In this work, we will discuss how the addition of a conductive layer beneath the emitting layer, separated from it by a thin dielectric layer, enhances the resonances of the metamaterial and we will present preliminary device results.

[1] Young Duck Kim, Hakseong Kim, Yujin Cho et al, Nat. Nanotechnol. **10**, 676 (2015).
[2] M. Lawton, N. H. Mahlmeister, I. J. Luxmoore, and G.R. Nash, AIP Adv. **4**, 087139 (2014).
[3] H. Mahlmeister, L. M. Lawton, I. J. Luxmoore, and G. R. Nash, Appl. Phys. Express **9**, 012105 (2016).
[4] R. Barnard, E. Zossimova, N. H. Mahlmeister, L. M Lawton, I. J. Luxmoore, and G. R. Nash, Appl. Phys. Lett. **108**, 131110 (2016).
[5] Shi, N. H. Mahlmeister, I. J. Luxmoore, and G. R. Nash, Nano Res, (2017) https://doi.org/10.1007/s12274-017-1922-7.

Design of metamorphic In(N)AsSb/AlInAs mid-infrared light-emitting diodes

C Broderick[1], R Arkani[2], E Repiso[3], P Carrington[3], A Krier[3] and E O'Reilly[2]

[1]University College Cork, Ireland, [2]Tyndall National Institute, Ireland, [3]Lancaster University, UK

Conventional GaSb- or InAs-based mid-infrared light-emitting diodes (LEDs) or diode lasers operating between 3 and 5 μm are typically limited by the ability to achieve heterostructures having suitable band structure properties in this challenging wavelength range. As such, many existing devices rely on quantum wells (QWs) having non-ideal type-II band alignment. Additionally, strain-thickness limitations present practical challenges for the growth of such structures.

Both of these issues can be overcome by a combination of (i) introducing relaxed AlInAs metamorphic buffer layers (MBLs), and (ii) growing on a GaAs substrate. InAsSb/AlInAs structures grown on GaAs substrates exhibit type-I band alignment, with large band offsets providing good carrier confinement and high optical efficiency. Furthermore, this material combination allows for the development of strain-compensated or strain-balanced structures, making it possible to achieve QWs having high structural quality.

We report on theoretical calculations and experimental measurements of the electronic and optical properties of InAsSb QWs grown on AlInAs MBLs. We validate our theoretical model by comparison to experimental measurements on prototypical devices grown by molecular beam epitaxy, where we find good, quantitative agreement between theory and experiment. We undertake a systematic analysis in order to define a design template for strain-balanced structures emitting at 3.3 μm emission. Our analysis quantifies the main trends in the device properties as functions of the alloy composition and structural properties, and identifies optimised structures of the realisation of high-performance 3.3 μm LEDs.

We also discuss the ability to achieve emission at wavelengths up to and beyond 4 μm using dilute nitride In(N)AsSb/AlInAs structures, where incorporation of dilute nitrogen concentrations (~1 - 2%) allows for control over the QW strain and emission wavelength, opening up further opportunities for band engineering to deliver high-performance LEDs.

Metamaterial-enhanced attenuated total reflection spectroscopy

C Shi, P Callum, P Jacqueline, P Gowda, I Luxmoore and G Nash

University of Exeter, UK

Infrared spectroscopy is a powerful analytical technique, and the use of attenuated total reflection (ATR) systems allows solid or liquid state samples to be characterised directly without particular sample preparation. In an ATR system evanescent waves, generated through total internal reflection, excite molecular vibrations within the sample. In this work, we explore the use of mid-infrared metamaterials to enhance the interaction between the molecular vibrations and the evanescent waves. A complementary ring-resonator structure was patterned onto Si/SiO_2 substrates, and the spectral properties of the structure was characterised using a Fourier transform infrared spectroscopy (FTIR) ATR system. Several resonant features were observed, corresponding to the resonance of the metamaterial and coupling to phonons in the substrate, in good agreement with simulations. Preliminary experiments, using mixtures containing trace amount of butyl acetate diluted with oleic acid, suggest that such an approach could be used to enhance the sensitivity of ATR measurements.

Parallel Session 10: Quantum Optics IV

(Invited) Nonlocal control of single-photon metasurface images

D Faccio[1], C Altuzarra[2], A Lyons[1], G Yuan[3], C Simpson[1] and T Roger[1]

[1]University of Glasgow, UK, [2]Texas A&M Unversity, USA, [3]Nanyang Technological University, Singapore

Correlation detection of photons is a fundamental technique in quantum optics allowing, for example, demonstration of nonlocal interactions between entangled pairs of photons. Metasurfaces have been demonstrated to have use in quantum optical applications – for instance, they can control output based on input properties such as polarisation. Here, we combine a metasurface's polarisation sensitivity with correlated photon imaging.

The metasurface has two images superimposed, but each responds only to one of two orthogonal polarisations of the input light – horizontal or vertical. By generating entangled pairs of photons that are always orthogonally polarised we can visually demonstrate the non-local control of a signal photon's properties via the associated herald photon.

Using a classical pair of photons instead scrambles the images – both are always present regardless of the herald state. This promises to allow characterisation of the entangled state via imaging, plus applications in quantum information and communication.

Developing indistinguishable single photon sources in silicon photonics

I Faruque, G Sinclair, D Bonneau, J Rarity and M Thompson

University of Bristol, UK

High visibility quantum interference between single-photons from multiples indistinguishable sources is a key prerequisite for linear optical quantum computing and relevant technologies. Numerous experiments have investigated the interference between multiple on-chip silicon photonic sources, but all have been restricted to the generation of a single path-entangled photon pair as 2-fold coincidences. Interfering heralded single-photons generated from independent sources as 4-fold coincidences---a true measure of indistinguishability---has been limited to waveguide sources with off-chip interferometers. However, the indistinguishability of heralded single photons from micro-ring resonators has not been measured in any photonic platform including silicon. Resonant enhancement in micro-ring resonators naturally enables brighter, purer and more indistinguishable single-photon production without any tight spectral filtering compared to waveguide sources. Here we report on-chip indistinguishability measurements of heralded single-photons at telecom wavelengths from independent micro-ring resonator sources. We take an important step in the realization of integrated linear optical quantum computing by combining on-chip generation, spectral demultiplexing and interference of heralded single-photons from independent sources. Tuneable on-chip filters are used to spectrally demultiplex the photon pairs for off-chip detection for heralding purpose. On-chip interference of the heralded photons is performed using an integrated Mach-Zehnder interferometer. We measured the raw heralded two-photon interference fringe visibility as 72±3% from the 4-fold coincidences. A joint spectral intensity measurements estimate the upper bound of the purity to be 96% which is in agreement with the simulations. We found that the multi-pair emission is the primary cause of visibility degradation. In addition, we have measured the purity and indistinguishability of the waveguide sources as a function of spectral filtering achieving 86±8% raw indistinguishability. Using these measurements, we compared and identified pathways to improve nanowire waveguides and micro-ring resonators single photon sources in terms of brightness, purity and indistinguishability.

Parametric resonances in spontaneous down conversion and difference frequency generation

P Main, A Gorbach and P Mosley

University of Bath, UK

Quasiphasematching of waveguides with second order nonlinearity has long been standard in quantum optics for a wide range of applications. These micron level waveguides use periodically modulated second order nonlinearity to allow for the interaction and generation of photons in different frequency modes. Classically these systems are well known to contain parametric resonances, however, the periodic Hamiltonians which describe these systems on a single photon level have yet to be fully explored.

In this work we apply Flouquet theory to spontaneous down conversion (SPDC) and coherent difference frequency conversion (CDFC) with periodically varying nonlinear coefficient. This analysis allows the dynamics of the system to be fully determined by numerically solving the Schrodinger equation over a single period. By studying the eigenmodes of the Flouquet propagator we determine conditions for Rabi oscillations of CDFC photons and pair generation states in SPDC. The fundamental resonance corresponds directly to known quasiphasematching, however we also predict an additional series of parametric resonances where the modulation period is an odd integer multiple of the phase-detuning between the interacting photons. This effect should be evident in currently available Lithium niobate and KTP waveguides. We predict new SPDC frequency regimes by solving our equations with known dispersion of the phase-detuning and a square modulation profile of the nonlinearity to more specifically represent existing waveguides.

This work opens the possibility of greater flexibility in frequency conversion using available waveguides or the use of materials currently prohibited by achievable poling lengths.

De-excitation of dipole emitters in a finite array of nanowires on a material surface

A Kamli[1], X Zhang[2] and M Babiker[2]

[1]Jazan University, Saudi Arabia, [2]University of York, UK

It is well established that nanoscale periodic structures can be utilized to control the radiative properties of dipole emitters [1-3]. Here we focus on a novel structure consisting of a finite array of nanowires periodically deposited on the planar interface separating two media: vacuum and dielectric. This electromagnetic environment would influence the radiative properties of dipole emitters localised in the vicinity of the structured interface. In order to quantify the effects, a transfer matrix method is developed and used to determine the dispersion relation and the corresponding quantised fields which lead to the evaluation of the deexcitation rate for an emitter localized in the structure. The rate depends critically on various parameters, including the position of the emitter, the nature of the wires, their separation and their number as well as the kind of dielectric substrate on which the wires are deposited. Emitters in the vicinity of structured surfaces are envisaged to be the basis of quantum architectures leading to the realisation of scalable quantum information processing.

Room-temperature single photon sources using solid-state emitters and open-access microcavities

S Adekanye[1], P Dolan[1], A Trichet[1], S Johnson[1], T Tran[2], I Aharonovich[2] and J Smith[1]

[1]University of Oxford, UK, [2]University Technology Sydney, Australia

A robust triggered single photon source operating at room temperature has potential for use in sensing, metrology and communication. The embedment of solid-state emitters within the optical microcavity platform provides an attractive route towards such a device. These microcavities offer enhancement of the spontaneous emission rate, tunability of the emission spectrum and increased light collection. Such a device has the potential for high efficiencies and single photon purities.

Here we present developments in room-temperature coupling of single defects in both nanodiamonds and hexagonal boron nitride (hBN) to open-access microcavities. Our ultra-small focused ion beam milled cavities are of a planar-hemispherical geometry, providing mode volumes down to λ^3. We report enhancements in the spectral density of photons into a single cavity mode, combined with improved single photon purities. It will be shown that the NV-cavity system provides a ~3% single photon emission efficiency with purities of up to 96%. The hBN-cavity system provides count rates >1Mcts/s into a single cavity mode with single photon purities up to 97%.

Poster session 1

(P01) Beyond terahertz surface nonlinear emission limits

L Peters, J Tunesi, J S Totero Gongora, A Pasquazi and M Peccianti

University of Sussex, UK

Nonlinear optical to terahertz (THz) conversion at semiconductor surfaces has received a huge amount of attention due to the surprisingly large conversion efficiencies over extremely short effective interaction lengths, paving the way towards ultrathin THz emitters.

At semiconductor surfaces, the source of the nonlinearity is a competition between several different interaction mechanisms. Specific to this investigation, narrow-bandgap III-V compounds (e.g. Indium Arsenide) are considered the benchmark of THz surface emission. For above bandgap excitation, typical of these systems, THz emission is known to be related to photocarrier drift and includes contributions from the photo-Dember effect and surge current emission within the semiconductor surface field region. All these mechanisms, however, are known to be strongly saturated at high excitation energies. In InAs, however, at high-fluence optical ultrafast excitation the surface emits THz radiation primarily via a surface field-induced optical rectification (SOR). SOR relies on the static surface electric field at the surface which arises because of the semiconductor surface states pinning the Fermi level above the material conduction band. This results in the formation of a depletion region extending into the bulk of the material.

We present a novel experimental investigation into the dynamics of this surface emission physics by employing a pump-probe methodology we refer to as Optical Pump Rectification Emission (OPRE). This modulates the surface field with an ultrafast injection of photocarriers and this modulation is then directly observable in the emitted THz waveform. Via this approach, we can provide insight into the specific mechanism responsible for the emission saturation. A most relevant finding is that fundamentally there isn’t any hard saturation in the SOR THz emission. We further demonstrated that in these systems the typical role of the material dopants, which has a significant effect on the surface field dynamics, can be mimicked by properly injected photocarrier bursts.

(P02) The role of leaky-waves in high-performance extraordinary THz transmission quasi-optical filters

M Navarro-Cia[1], V Pacheco-Peña[2], S A. Kuznetsov[3] and M Beruete[4]

[1]University of Birmingham, UK, [2]University of Pennsylvania, USA, [3]Novosibirsk State University, Russia, [4]Universidad Pública de Navarra, Spain

The need of micrometer features over cm size areas for high-performance THz frequency selective surfaces and other components has proven to be a major challenge for the field. Direct metal milling usually does not meet resolution requirements for THz quasi-optical filters. Advanced microfabrication based on SU-8 or Silicon such as deep reactive ion etching does meet all the requirements at the expense of complexity (multi-step process) and cost. In the light of this, photolithography has emerged as the preferred choice in most cases, but it is not adequate for thick meshes and, more importantly, involves the need of a dielectric substrate that introduces additional losses. Electroforming is a cost-effective fabrication technique to meet tolerances while dielectric substrates are avoided.

In this contribution we report a systematic analysis of extraordinary THz transmission subwavelength hole arrays fabricated by photolithography and electroforming with varying experimental conditions; namely, array matrix size (i.e., number of holes) and beam-waist of the interrogating Gaussian beam, in addition to the substrate effect. This extensive analysis is underpinned by the use of two different spectroscopy techniques (CW and time-domain) and three different commercial instruments (ABmm millimetre-wave vector network analyser, and TERA K15 and TPS Spectra 3000 time-domain spectrometers). The contribution demonstrates that the periodic nature of the array favours the existence of leaky-waves that play a major role in the resonant phenomenon. Indeed, the contribution establishes undoubtedly that the important parameter for a strong extraordinary THz transmission is the total number of holes explored by the leaky-waves rather than the illuminated area. The contribution also reports an unprecedented 0.04 dB insertion loss for a free-standing quasi-optical filter with central frequency ~0.58 THz.

(P03) Hyperspectral Terahertz Microscopy with Nonlinear Ghost Imaging

J S Totero Gongora, L Olivieri, A Pasquazi and M Peccianti

University of Sussex, UK

The full-wave characterisation of complex field distributions is an ambitious challenge in Photonics with a wide range of potential applications. In this context, imaging devices operating at Terahertz (THz) frequency have been subject of intense research, as in this frequency range both amplitude and phase are experimentally accessible. One of the major challenges in this field, however, remains the limited availability of two-dimensional field-sensitive detectors. An intriguing alternative to conventional devices is provided by single-pixel imaging, also known as ghost-imaging (GI), which employs a single bucket detector and a set of pre-determined patterns to sequentially reconstruct the sample under investigation. While field-sensitive single-pixel detectors are currently available at THz frequencies, one of the current limitations in achieving time-resolved, full-wave GI lies in the realisation of THz structured light. In fact, spatial-light-modulators (SLM), which are readily accessible at optical frequencies, cannot be easily extended to the THz domain. While researchers have recently employed indirect patterning schemes (essentially masking devices), these are characterised by several conceptual and practical drawbacks. Such limitations, which descend from the stringent physics of deeply sub-wavelength apertures, strongly affect the amplitude and phase profile of the structured THz beam.

To address these limitations, we propose an entirely new approach, providing a full-reconstruction through time-resolved, coherent single-pixel imaging. This approach, conceptually outperforming standard GI implementations, is based on the direct generation of THz structured light through the nonlinear conversion of an ultrafast optical pattern. Our results show that this Nonlinear GI (NGI) can reconstruct without ambiguities the morphology and the full light-matter response of the sample, both in terms of amplitude and temporal delay. Although our case of study builds up within the THz imaging, our work conceptually impacts all the wave domains and, in particular, all the frameworks in which the access is enabled by nonlinear transformations.

(P04) WITHDRAWN

(P05) Intense broadband multi-terahertz pulses of 280 MV/cm for gaseous medium nonlinearity

Y Bai and P Liu

Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, China

We produce the extremely bright multi-terahertz pulses with a tunable frequency of 20 - 43 THz through difference frequency generation. Optimization of beam quality and beam focus results in an intense multi-terahertz pulse that spatio-temporally confined in the lambda-cubic volume. Near planar wavefront is achieved through the pump wavefront curvature manipulation in three-wave mixing process. As a result, spectrally and spatially coherent multi-terahertz pulses are produced at the frequency of 30THz with the peak field of 280 MV/cm and the intensity exceeding 100 TW/cm^2, estimated from measured pulse energy, spatial and temporal pulse profiles. Interaction of such an intense field with noble (Xe and Kr) gas forms plasma and generates supercontinuum in visible spectrum.

(P09) Photonic Hilbert transformer based on phase-modulated fiber Bragg grating in transmission

X Liu[1], X Shu[2], A Gbadebo[3] and L Zhang[3]

[1]Aston University, UK, [2]Huazhong University of Science and Technology, China, [3]Aston Institute of Photonic Technologies, UK

All-optical first-order Hilbert transformer is demonstrated with phase-modulated fiber Bragg grating (PM-FBG) in transmission for the first time. The profile of the designed PM-FBG for Hilbert transformation is obtained using numerical optimization algorithm.

(P10) Numerical simulations of speckle to extract surface roughness parameters from random rough surface scattering

A Lotay and J Girkin

Durham University, UK

We focus on the long-standing issue of electromagnetic wave scattering from randomly rough surfaces. We discuss the physical origin behind speckle pattern formation as a result of multiple scattering of coherent light from a rough surface. Some phenomena such as: enhanced backscattering, forward scattering enhancement (specular peak), coherent effects and certain non-linear effects are of interest to this study. We explore different modelling techniques and assess these with respect to their range of validity, accuracy, and applicability. Given the complexity of this problem we apply a set of approximations to find a solution for the intensity patterns resulting from certain structures. Using simple approximate scattering models we demonstrate that through the use of two parameters, σ and T, we can characterise a rough surface. We generate a series of rough surfaces and calculate the expected speckle pattern, for a specific experimental geometry, from those surfaces. The results demonstrate that a spatial-averaging algorithm applied to a speckle image enables the retrieval of the surface parameters of the surface under observation. The simulation is validated against some experimental data.

(P11) Investigation of low-index waveguiding in inverse rod-connected diamond photonic crystals

M Taverne, D Ho, C-H Fang, X Zheng, L Chen and J Rarity

University of Bristol, UK

In 2D photonic crystal waveguide designs, in-plane guidance is achieved through total internal reflectance and low loss guides are made of a higher refractive index than the surrounding medium, while losses from out-off plane scattering restrict the finesse (or Q-factor) achievable in cavity structures. In contrast, 3D photonic crystals can provide confinement in all directions due to their complete photonic band-gap (PBG) potentially providing lower loss structured waveguides, low radius bends, full 3D circuits and higher Q-factor cavities. Here we investigate such waveguides in 3D crystals, in particular the 3D direct rod-connected diamond (RCD) photonic crystals (PhCs). We exploit the similarity of the Γ-L plane in a 2D hexagonal crystal slab and the inverse RCD crystal to transfer existing waveguide designs from 2D to 3D.

Our preliminary numerical results report the efficiency and flexibility of waveguides based on low index coupled-air-defect-cavities in inverse RCD PhCs. These coupled-cavity waveguides guide electromagnetic fields via the overlapping of evanescent Bloch modes between adjacent optical defect cavities. We simulated an inverse RCD photonic crystal with size ~20×10×7 unit cells. The waveguide is introduced by using air-filled spherical defect cavities and distributing those defects in the crystal.

We will report the single-line air waveguide and 1×2 beam splitter created along the Γ-K direction, where the defects truncate the centres of dielectric rods. Such a configuration allows the light to be guided primarily in air (or other low-index material), with the possibility of 120° bends along the various Γ-K directions. FDTD simulation results

show transmittance values up to 96%. These waveguides can be coupled to high-Q cavities (Q~*10**^5 *-*10**^7 *) with coupling efficiencies up to 99%. Such a waveguide-cavity system could be arranged as multi-channel add drop filters while the high Q-factors could allow the creation of ultra-sensitive photonic sensors.

(P12) Indirect- to direct-gap transitions in Ge(C,Sn) group-IV semiconductor alloys: mechanisms and implications

C Broderick[1,2], M Dunne[1], A Kirwan[1], E O'Halloran[1], D Tanner[1], S Schulz[1] and E O'Reilly[1]

[1]Tyndall National Institute, Ireland, [2]University College Cork, Ireland

While silicon (Si) and germanium (Ge) are the mainstay of microelectronics, their indirect band gaps make them inefficient emitters/absorbers of light. Despite significant progress in passive Si-based photonic components, there remains a capability gap associated with the unavailability of suitable direct-gap materials to realise active Si-based components such as LEDs and lasers. This limitation derives from the material band structure, mandating a new materials-based approach.

There is growing interest in the group-IV alloys GeSn (containing tin) and dilute GeC (containing carbon). Initial research has demonstrated that incorporating ~1% C or ~10% Sn in Ge is generate a direct band gap. The 2015 demonstration of a GeSn-based laser has verified the feasibility of this approach. Despite a surge in activity to develop Ge(C,Sn) materials and devices, there remains a lack of fundamental understanding of the material band structure and its implications for technologically important material properties.

We present a multi-scale analysis of the electronic properties of Ge(C,Sn) alloys. Using hybrid density functional theory (HDFT) calculations we identify and quantify the mechanisms responsible for the indirect- to direct-gap transition. HDFT calculations for disordered alloys highlight the role played by alloy microstructure in determining the material properties. Based on HDFT calculations we derive a tight-binding (TB) model, allowing acces to much larger length scales, permitting direct analysis of a disordered Ge(C,Sn) alloys and realistically-sized nanostructures. The TB model provides a useful basis to further investigate ordered alloys: using supercell calculations we derive and parametrise model Hamiltonians describing the key roles played by C-localised impurity states and Sn-induced band mixing in determining the nature of the perturbed Ge(C,Sn) conduction band structure.

Our analysis reveals the mechanisms responsible for the indirect- to direct-gap transition, quantifies the evolution of the band structure, and highlights the implications of the unusual Ge(C,Sn) electronic properties for practical applications.

(P13) Scattering of waves by pre-fractal Cantor-set apertures: nonparaxial formulation and numerical analysis

H Middleton-Spencer and J Christian

University of Salford, UK

The scattering of plane waves by distributions of bars that mimic increasing iterations of the Cantor set has been known for many years in optics [1]. Experiments and analyses have often been conducted in the far field under the conditions of Fraunhofer diffraction, and the observed patterns may then be described quite simply in terms of Fourier transforms. More recent investigations of fractal-type gratings have been based on the Fresnel integral with principal emphasis placed on understanding self-imaging phenomena [2].

Here, we formulate wave scattering in a more elementary way by discarding the paraxial approximation entirely and instead retaining the greater generality of the underlying two-dimensional Helmholtz equation. The scatterer of interest corresponds to pre-fractal (that is, a finite number of) iterations of the Cantor-set initiator-generator algorithm and where the constituent bars may be envisaged as being cut out of an opaque screen of infinite extent. A formal solution in the forward half-plane can be written down which involves a convolution between the incident field and the free Green's function (strictly, its derivative normal to the screen). This approach corresponds to a Rayleigh-Sommerfeld (RS) diffraction integral and it renders subsequent analyses predominantly numerical rather than mathematical.

In addition to the proposed nonparaxial formulation, we will present a selection of computed diffraction patterns and intensity power spectra from new physical regimes of illumination wherein the waveform incident on the pre-fractal scattering obstacle is, itself, also pre-fractal. It will be seen that the RS approach is a natural one to adopt when considering problems involving illumination with multi-scale waves. The broad spatial bandwidth of the outgoing waves is a key feature but it is not always handled satisfactorily by treatments based on Fresnel optics.

[1] C. Allain and M. Cloitre, Phys. Rev. B **33**, 3566(R) (1986)
[2] J. Wang et al., Appl. Opt. **53**, 2105 (2014)

(P14) On generalizing the knife-edge problem for fractal waves: the Weierstrass-Lamb solution

J Christian and H Middleton-Spencer

University of Salford, UK

One of the classic configurations in electromagnetic theory is describing how a plane wave scatters from a screen of semi-infinite extent. By anticipating that the screen is perfectly conducting and has zero thickness, one can obtain an exact continuous-wave solution to the boundary-value problem that follows from Maxwell's equations. While Sommerfeld first solved the knife-edge problem towards the end of the nineteenth century [1], our interest is with the subsequent and more elegant approach devised by Lamb [2] who considered the screen as the limit of a parabolic cylinder.

Here, Lamb's solution is generalized to regimes wherein the incident wave has spatial structure across many scalelengths. The Weierstrass function is one obvious candidate model for multi-scale illumination. It comprises a linear superposition of N cosine-type waves defined by a spatial-frequency spectrum whose constituents are geometrically separated (distinct from the uniformly-spaced frequency combs that tend to characterize Fourier decompositions), and in the limit $N \to \infty$ has the intriguing property of being everywhere continuous but nowhere differentiable. In electromagnetics, one is going to be concerned with finite-N (or "pre-fractal") scenarios since we do not expect to find an infinite number of pattern scalelengths in any physically-meaningful field; such a truncation of the Weierstrass summation helps simplify some of the subsequent mathematical and computational considerations. We will detail our recently-derived Weierstrass-Lamb solution to describe the scattering of a pre-fractal incident waveform. This fully-vectorial solution to Maxwell's equations captures both transverse-electric and transverse-magnetic polarization states, satisfies the boundary conditions everywhere on the screen (which are of the Dirichlet and Neumann type, respectively), and holds throughout all space. In the relatively narrow window of validity prescribed by the slowly-varying envelope approximation, a solution to the paraxial diffraction equation emerges asymptotically.

[1] A. Sommerfeld, Math. Ann. **47**, 317 (1896)
[2] H. Lamb, Proc. Lond. Math. Soc. **4**, 190 (1907)

(P16) Singlet Oxygen Luminescence Dosimetry with a fiber-coupled Superconducting Nanowire Single-Photon Detector

K Tsimvrakidis[1], N Gemmell[2] and R Hadfield[1]

[1]University of Glasgow, UK, [2]University of Sussex, UK

The detection of a single photon at 1270 nm wavelength allows the direct monitoring of Singlet Oxygen ($^1O_2$), making Singlet Oxygen Luminescence Detection (SOLD) a powerful dosimetry technique for photodynamic therapy in the treatment of cancer [1]. However, the direct detection of $^1O_2$ emission at 1270 nm wavelength is extremely challenging as the $^{1}O_2$ à $^{3}O_2$ transition in biological media has very low probability (~10^{-7}) and short lifetime (<<1 μs) due to high reactivity of singlet oxygen with biomolecules. Recent advances in high efficiency, low noise superconducting nanowire single-photon detectors (SNSPDs) are an important innovation in the development of a practical SOLD system for eventual clinical use [2, 3].

Here we present a compact fiber coupled SOLD system, using a supercontinuum pump source to precisely target exact photosensitizer absorption peak wavelengths and a SNSPD for detection. Both pump laser and detector are intrinsically fiber coupled making them ideally suited for the development of practical singlet oxygen sensor head. Measurements were made in Rose Bengal, Methylene Blue and Eosin Y – well characterized model photosensitizers – in distilled water, ethanol and methanol, acquiring time-correlated $^{1}O_2$ emission photon counts histograms using various photosensitizer solutions and mass concentrations.

[1] Jarvi et al., Photochem. & Photobiol., 82, (2006), 1198
[2] Nathan R. Gemmell et al., Optics Express, 21, (2013), 5005
[3] Nathan R. Gemmell et al., J. Biophotonics, 10, No 2, (2017), 320-326

(P17) Measurement of blood oxygenation in nailfold capillaries; a feasibility study in patients with systemic sclerosis and healthy controls

M Berks, G Dinsdale, S Peytrignet, T Moore, J Manning, S Legett, J Murray, J Clark, C Cooke, C Taylor, M Dickinson, A Herrick and A Murray

The University of Manchester, UK

Systemic sclerosis (SSc) affects the smallest blood vessels (capillaries). Nailfold capillaroscopy is a well-established technique for imaging characteristic structural capillary abnormality in SSc. This study assessed the feasibility of measuring oxygenation in the nailfold capillaries using adapted nailfold capillaroscopy.

The absorption spectra of oxy- and deoxy-haemoglobin are very different enabling differential calculation of oxygenation levels in blood vessels. Dual-camera, simultaneous capillaroscopy was performed with two bandpass-filtered cameras (560 and 530nm; 10nm bandwidth). Filters were chosen to capture images of 1) large; and 2) negligible intensity difference with changes in oxygenation. The intensity ratio of these images provides false-colour capillary oxygenation maps. Imaging was performed in single vessels only. Participants underwent imaging before (baseline), during (after 1 minute, and at release) and 1 minute post finger occlusion (2 minutes, 200 mmHg). A two-sample t-test with unequal variances was used to compare baseline oxygenation between patients with SSc and healthy controls (HC), and changes between time-points.

Twenty sets of images were analysed: 7 (35%) HC and 13 (65%) SSc. At baseline, the mean oxygenation was 2.8 (SD 8.9) arbitrary units in HC and -0.6 (SD 8.4) in SSc ($p=0.416$). During occlusion, oxygenation dropped in all but one HC. The mean change in oxygenation was -12.1 (SD 8.1) for HC and -14.4 (SD 6.3) for SSc ($p=0.522$). The mean change upon release was 14.2 (SD 2.9) for HC and 13.7 (SD 6.8) for SSc patients ($p=0.840$).

This feasibility study confirms that the system is sensitive enough to measure, in individual capillaries, changes in oxygenation due to occlusion. In this small study, no differences were detected between HC and patients with SSc. Further work is required to establish whether oxygenation variations exist in abnormal vessels in SSc.

(P18) The OPTA device: A novel miniature optical probe to evaluate tissue atrophy

A Lotay and J Girkin

Durham University, UK

In this presentation we will outline the optical principles, design, production and usage of the OPTA device: an Optical Probe to evaluate Tissue Atrophy. We will present a portable profiling system capable of directly interrogating the integrity of human skin in-vivo. The device utilises laser speckle and imaging modalities to form a suite of physical parameters, in particular surface roughness and blood oxygenation. We relate these measurements to a subject's perception of skin pathologies. We will first discuss the technical information relating to the design and assembly of the OPTA probe and then describe the techniques used to characterise our novel system; specifically the optical element configurations (e.g. use of polymer optical fibres and miniature cage system). Then, we will present the practical use of this device using our results of a pilot study that trial the OPTA device, in house.

(P19) WITHDRAWN

(P20) A concept of pixellated optics for low vision aids: Telescope Windows

C Bourgenot[1], E Cowie[2], L Young[1], G Love[1], J Courtial[2] and J Girkin[1]

[1]Durham University, UK, [2]University of Glasgow, UK

A Telescope window (TW) is a novel concept of transformation-optics consisting of an array of micro-telescopes, in our configuration of a Galilean type. When the array is considered as one multifaceted device it acts as a traditional Galilean telescope with distinctive and attractive properties such as compactness and modularity. Each lenslet, can in principle, be independently designed for a specific optical function.

In a standard Galilean telescope, consisting of 2 single continuous lenses, an increase in the system aperture usually comes at the price of an increase in the system dimension as one normally wishes to keep the element's F number constant in order to maintain the optical resolution. This is not the case for Telescope Windows where larger apertures are simply obtained with larger arrays of the same compact, and light, sub-elements. There is, consequently no limit in the aperture dimension extending the possibilities offered by afocal systems, in a range of application.

We report on the design, manufacture and prototyping, by diamond precision machining, of 2 distinctive concepts of telescope windows, and discuss both their performances and limitations with a view to use them as potential low vision aid devices to support patients with macular degeneration.

(P21) Imaging ellipsometry as a novel detection method for protein-protein Interactions.

J Tomes, D Langstaff, M Gunn and R Morphew

Aberystwyth University, UK

Proteins are the functional unit of the genome and as such the investigation of protein-protein interactions are of significant biological interest. Ellipsometry is a well-established optical technique for the characterization and determination of thin film thickness and offers the potential of a label free, real time method to quickly detect multiple biological analytes and monitor complex protein interaction processes.

While Previous studies of protein-protein interaction using imaging ellipsometry have been successful they rely on a null method requiring prior calibration of the protein layers via separate spectroscopic ellipsometry. We present an imaging ellipsometer that directly utilizes a radiometric data collection technique, coupled to scheimpflug optical alignment, to give a high resolution flat field of view providing label free detection of model protein interactions with a 2D lateral resolution of 11μm and thickness detection at a nanometre scale.

The research equipment is now being optimised to discover if protein interactions can be measured for key biomarkers from Fasciola hepatica, the common liver fluke, which is a global zoonotic parasite that currently infects up to 17 million people and costs global farming in excess of $3 billion annually.

The wider impact of this research is a novel approach to rapid diagnostic testing and can also offer opportunities for increased understanding of wider protein-protein interactions, protein function analysis and anthelmintic development.

(P22) WITHDRAWN

(P27) Structure and optical properties of Er^{3+}-doped gallium lanthanum sulfide (GLS) thin films prepared by femtosecond pulsed laser deposition

K Albarkaty[1], J Chandrappan[1], C Craig[2], E K Barimah[1], S Ganapathy[2], D Hewak[2] and G Jose[1]

[1]University of Leeds, UK, [2]University of Southampton, UK

Thin films of Er^{3+}-doped gallium lanthanum sulfide (GLS) glass were deposited on a single crystal Si(100) substrate using femtosecond pulsed laser deposition (fs-PLD) process. The film thickness, crystallinity and composition was studied as a function of substrate temperature. The deposited films were characterised by TEM- energy-dispersive X-ray spectrometry, X-ray diffraction, Raman, and Photoluminescence spectroscopy at room temperature. The results show that by increasing the substrate temperature the deposited layer thickness increases and crystallinity of the material changes. Increasing the substrate temperature enhances the crystallisation process. It is also observed that that amorphous and crystalline films with varying optical quality can be precisely engineered by careful variation in the fs-PLD process parameters. The room temperature photoluminescence spectrum and lifetimes of the $^4I_{13/2}\rightarrow{}^4I_{15/2}$ transition of Er^{3+} were measured at 1.54µm under 980 nm laser excitation.

(P37) Modulational instability and soliton dynamics in Lithium Niobate nano-waveugides

A Gorbach, D Skryabin and W Rowe

University of Bath, UK

Interplay between dispersion and nonlinearity is well-known to be the driving mechanism between a plethora of nonlinear phenomena in waveguides in fibres. To date, the research in this area is mainly focused on cubic (chi3) nonlinearity, typical for glass fibres and semiconductor nano-waveguides. Recent advancement of full wafer technology for single-crystaline Lithium Niobate on isulator (LNOI) thin films open exciting perspectives of bringing quadratic (chi2) nonlinear functionality onto the scale of integrated optical components. Recently we demonstrated that strong geometrical dispersion of such LNOI nano-waveguides not only represents a powerful tool to arrange and tune phase-matching, but also enables matching of group velocities of interacting fundamental and second harmonics in remarkably broad wavelengths ranges [2,3].

In this work we present a comprehensive analysis of Modulational Instability (MI) and chi2 temporal soliton dynamics in chi2 nano-waveguides. We explore the range of MI gain and two-colour soliton solutions existence in the parameter space of group velocity mismatch and relative dispersion of the fundamental and second harmonics. We also study chi2 interaction with dispersive waves and emission of Cherenkov radiation. We apply our analysis to realistic LNOI waveguide geometries and discuss possibilities of experimental observation of these effects.

[1] G. Poberaj et al., Laser Photon. Rev. 6, 488 (2012)
[2] A. V. Gorbach and W. Ding, Photonics 2, 946 (2015)
[3] L.T. Cai et al., in Conf. Lasers Electro-Optics CLEO (OSA, Washington D.C., 2017), p. SM3M.6

(P38) WITHDRAWN

(P39) WITHDRAWN

(P40) Nonlinear Fourier transform analysis of a mode-locked fibre laser

M Kamalian Kopae, S Sugavanam, Y Prylepskiy and S Turitsyn

Aston University, UK

Nonlinear Fourier transform (NFT) is a mathematical approach to solve some nonlinear partial differential equations. Based on the concept of NFT and due to its previously proven effectiveness in fibre optic communication, a new analysing tool to uncover the underlying nonlinear dynamics of a mode-locked fibre laser is introduced. In this way, the time-domain waveform of the output of the laser is used to calculate its so-called nonlinear spectrum consisting of invariant and variable parts representing the solitonic and dispersive components, respectively.

The nonlinear spectrum can unravel some complex and nonlinear dynamics of laser which can hardly be identified by traditional methods. Distinguishing coherent structures and investigating their interactions, as well as formation and disappearance, are of the important tasks of implementing NFT for lasers.

One of the challenges of utilising NFT for such system is that it requires the phase information of the output of the laser with rather a high sampling frequency. Here the real-time full-field characteristics of the laser are reconstructed via heterodyne detection of the in-phase (I) and quadrature (Q) components of its output. Another critical point to address is the integrability of the partial differential equations governing the light evolution in laser. For those equations for which the NFT can find solutions, hence, integrable, the nonlinear spectrum has a linear evolution as opposed to the signal and its linear spectrum. However, this is not in general true for a fibre laser. Therefore, the extent to which one can interpret the nonlinear spectrum as the solitonic and dispersive component of the signal needs to be argued. In this work, we consider this problem and discuss the practicable interpretations of the nonlinear spectrum and their implications in studying lasers.

(P41) Nonlinear regimes governed by parametric interaction in micro-cavities

L Di Lauro[1], J Li[2], D J Moss[3], R Morandotti[4], S T Chu[2], M Peccianti[1] and A Pasquazi[1]

[1]University of Sussex, UK, [2]City University of Hong Kong, Hong Kong, [3]Centre for Microphotonics, Swinburne University of Technology, Australia, [4]INRS-EMT, Canada

Micro-cavities, fabricated either in bulk design or as integrated platforms, exhibit a small modal volume and ultra-high quality factor, with strong enhancing of the circulating optical field. These features make cavities suitable for many applications in metrology, biosensing and quantum optomechanics [1,2]. In a third-order nonlinear material, the high-modal confinement stimulates intensity-dependent effects at very low power levels, which may produce interesting nonlinear dynamics. For instance, optical bi-stability, oscillatory instability and chaotic response can be observed [3]. In particular, the ratio between Kerr and thermo-optic coefficients, that can assume positive or negative values, is fundamental in regulating the above regimes.

Within the framework of the coupled-mode theory (CMT), we present an approach that allows governing nonlinear dynamics in micro-cavities exploiting FWM [4], in presence of Kerr and thermo-optical nonlinearities. We demonstrate that a weak signal can control and transfer dynamical regimes between cavity modes, even at very low signal powers. This work provides a practical understanding on how the signal intensity can modulate thermal instabilities, chaos. Moreover, it show that new strategies are possible for designing efficient micro-cavity-based oscillators and sensors.

[1] V. Lefêver-Seguin, S. Haroche, “Towards cavity-QED experiments with silica microspheres”, Mater. Sci. Eng. B-Solid **48** (1997) 53–58.

[2] M. Karpov, M. H. P. Pfeiffer, J. Liu, A. Lukashchuk, T. Kippenberg, "Photonic chip-based soliton frequency combs covering the biological imaging window", Nature Commun. **9**, 1146 (2018).

[3] 4. T. Carmon, L. Yang, and K. J. Vahala, "Dynamical thermal behavior and thermal self-stability of microcavities," Opt. Express **12**, 4742 (2004).

[4] L. Di Lauro, J. Li, D. Moss, R. Morandotti, S. Chu, M. Peccianti, and A. Pasquazi, "Parametric control of thermal self-pulsation in micro-cavities," Opt. Lett. **42**, 3407-3410 (2017).

(P42) Giant multiphoton absorption for THz resonances in silicon hydrogenic donors

H N Le[1], M van Loon[2], N Stavrias[2], K Litvinenko[1], T Greenland[3], C Pidgeon[4], K Saeedi[2], B Redlich[2], G Aeppli[5] and B Murdin[1]

[1]University of Surrey, UK, [2]Radboud University, Netherlands, [3]University College London, UK, [4]Heriot-Watt University, UK, [5]ETH Zurich, Switzerland

The wavefunction of the excess electron orbiting a phosphorous donor in silicon is around 100 times larger than that of Hydrogen due to the screening of the donor core's potential and the small effective mass. This suggests an extremely large enhancement in the dipole matrix element and hence the N-photon absorption (NPA) rate. We observed 1PA, 2PA and 3PA in Si:P with a terahertz free-electron laser and extracted the absorption cross sections from a photothermal ionization spectroscopy measurement. The 2PA coefficient for 1s–2s at 4.25 THz was 400,000,000 GM (4 x 10^{-42} cm^4s), many orders of magnitude larger than is available in other systems (Nature Photonics 12, 179–184). Such high cross-sections allow us to enter a regime where the NPA cross-section exceeds that of 1PA, and open new prospects for controlling dopant and photonic qubits in silicon. We described an effective mass theory for multiphoton processes of shallow impurities in semiconductor which gives an excellent agreement with the experimental result.

(P43) Light-sheet microscopy beam path miniaturisation using optical MEMS

R Bauer, S Bakas and D Uttamchandani

University of Strathclyde, UK

Light-sheet microscopy (LSM) as 3D fluorescence imaging tool has shown impressive growth over the last decade, specifically with open-source and application tailored systems in mind. By structuring the fluorescence excitation light to only illuminate a thin sheet of the sample in the active focal plane of an orthogonal imaging path, low light doses and fast 3D imaging can be achieved. In this work, we present digital control of the light-sheet creation, positioning and imaging using Microelectromechanical Systems (MEMS) micromirrors and the use of their inherent miniaturisation potential.

The micromirrors used for active control were fabricated using a commercial silicon-on-insulator process with device layer thicknesses of 10µm or 25µm and apertures between 0.7mm and 1.7mm. Multiple actuation mechanisms were employed for control of different excitation and imaging beam parameters. Electrostatic actuation allowed for >25kHz scan speeds to create the light-sheet, electrothermal control of a 2D tilt mirror allowed for its positioning in 3D space, and bimorph electrothermal control of a mirror surface curvature allowed for positioning of the focal plane of the imaging path. The MEMS were controlled using an Arduino microcontroller and a custom amplifier circuit to create the drive signals. The optical design of the LSM beam paths use off-the-shelf singlet and doublet lenses to allow flexibility and low-cost, with an overall foot-print of 130x60mm for the excitation path and 160x50mm for the imaging path, including fibre-coupled delivery of the fluorescence excitation lasers.

Our latest results showcasing the 3D positioning accuracy, light-sheet characteristics and imaging performance will be presented. This includes both the miniaturisation of larger field-of-view and higher resolution systems, allowing their tailoring for varying imaging applications. A further focus will be on the integration and characterisation of full

3D imaging, using the synchronisation of all MEMS devices and the inclusion of flexible auto-focus and -positioning potentials.

(P48) Developments in low cost laser detection

D Benton and M Zandi

Aston University, UK

Low cost, portable and bright diode lasers are now widely available and have proven to be an issue of concern to aircraft, which are regularly dazzled around airports. Laser warning systems developed in the '90s have proven ineffective at detecting these relatively low power CW lasers. A low cost approach based on detecting coherence properties has been developed which has shown great promise as it detects weak laser sources against bright incoherent background illumination (e.g solar background). This system can also determine the laser wavelength. We report developments beyond a limited staring system to provide a 360 degree azimuthal acceptance angle. Techniques to locate the direction of origin of the incoming laser source are presented. We also report on methods to assist efficiency of wavelength determination using tunable spectral filters.

(P49) Limits on Mueller-polarimeter errors using the eigenvalue calibration method

N Bruce[1], O G Rodríguez-Herrera[1], J M López-Téllez[2] and O Rodríguez-Nuñez[1]

[1]Universidad Nacional Autonoma de México, Mexico, [2]University of Arizon, USA

Polarimetry is being used in many applications, such as remote sensing, imaging, microscopy and metrology. Traditional polarimeters can use rotating fixed retarders to create signals that can be Fourier analyzed to extract Stokes or Mueller parameters of a light beam or sample. Rotating polarization components can cause vibrations in optical systems and have speeds limited by mechanical restrictions. Non-rotating polarization components, such as electro-optic cells or liquid crystals, which have changes in retardance with changes in applied voltage are being used in polarimetry. Liquid crystal cells have some advantages over other methods: small size and weight, fast response and small controlling voltages (typically in the range of 0-10V). However, these cells are sensitive to changes in temperature or errors in the applied voltage or retardance axes positions. Because of this, calibration techniques have been developed, using known samples, such as polarizers or retarders, to calculate and remove the effect of these errors. We have built a Mueller polarimeter based on four liquid crystal variable retarders (LCVRs) and we have found that the eiegenvalue calibration scheme is robust and reliable for correcting many of the errors in the polarimeter. However, it is clear that the any calibration method will not work if the random measurement errors and/or the systematic polarimeter errors are too large. In this work a numerical study is carried out to find the experimental conditions necessary for the eigenvalue calibration procedure to work correctly in a liquid-crystal variable retarder Mueller-matrix polarimeter. Using the error between the simulated experimental Mueller matrix in a polarimeter with errors and the expected ideal Mueller matrices for 4 calibration samples, the maximum systematic experimental errors are estimated for different error levels in the final Mueller matrix. It is found that the retarder axes orientations have smaller permitted errors than the retardation values.

(P50) Investigation into the effects of direct radiation interactions in a detector's PMT

Ali McLean

AWE, UK

A scintillation detector system has been designed for use in very intense radiation fields. During detector trials it was observed that, in some circumstances, radiation interactions in the photomultiplier (PMT) appear to produce an unwanted signal of a similar magnitude to that produced by the scintillator. Preliminary laboratory experiments have indicated that gamma rays interacting with a material in the region of the PMT window is responsible for producing the unwanted signals. The latest results of experimentation will be presented along with hypotheses regarding the underlying physics causing this effect.

(P54) 3D-printed double lenslet array for wide-angle static concentrating photovoltaics

R E Alsaigh[1], R Bauer[2] and M P J Lavery[1]

[1]University of Glasgow, UK, [2]University of Strathclyde, UK

Concentrating photovoltaic (CPV) are widely utilised to lower the costs of harvesting and generating solar energy. To further reduce the system costs, static concentrating photovoltaic can be employed to replace the expensive mechanics in traditional CPV. However, the solar collection of conventional static concentrating photovoltaic designs falls dramatically at extreme angles, that is >50°. Innovative optical designs offer a key solution to the wide-angles constraint and enhance its collection capabilities. The use of secondary optics is also a promising solution to improve the solar collection angles [1]. However, costs associated with conventional manufacturing techniques of optics still hinder a feasible deployment of these designs as static concentrators.

We present a thin low-cost innovative optical prototype that employs two lenslet arrays arranged with their curved faces touching. The optical arrangement is based on two opposite 1mm hemispheric optics, where this arrangement leads to a field of view (FOV) of 80° allowing for very wide-angle solar collection [2]. A cost-effective sub-micron-precision Stereolithographic 3D-Printer is used to fabricate and print the lenslet arrays. The lenslet arrays are bonded to a 58.1x48.6mm amorphous silicon solar panel. The open circuit voltage of the solar panel was measured with and without the concentrator, achieving a total increase of 7% in solar collection across the whole solar zenith angles (0°- 90°) when material losses are factored out. The material loss of the 3D prints was also measured to be 5.69%. When manufactured through injection moulding and with addition of an antireflection coating these losses will be minimised and produce an effective optical layer that will yield substantial gains in optical collection efficiency.

[1] Katie Shanks, S. Senthilarasu and Tapas K. Mallick 2016 Renewable and Sustainable Energy Reviews 60 394–407

[2] M. Rezaei, I. H. Nia, A. Bonakdar and H. Mohseni 2016 Applied Optics 55 8752-8756

(P55) Mitigation of noise-induced corruptions for nonlinear Fourier-based optical transmission methods.

M Pankratova[1], J Prilepsky[1], A Vasylchenkova[1], S Derevyanko[2], D Shepelsky[3] and S Turitsyn[1]

[1]Aston University, UK, [2]Ben-Gurion University of the Negev, Israel, [3]B.Verkin Institute for Low Temperature Physics and Engineering, Ukraine

The throughput of current-generation optical fibre transmissions systems is believed to become almost exhausted within the next 5-7 years [1-3]. This problem has largely emerged due to the detrimental effect that the fibre nonlinearity has on the line's capacity, and while the efficacious methods of linear impairments have been already successfully implemented, the nonlinearity now remains the main source of transmission degradation. Among the other nonlinearity mitigation techniques, the so-called nonlinear Fourier transform (NFT) based methods have been actively studied recently [2]. At the same time, the optical noise arising due to the amplification process sets additional limits to the achievable transmission quality. Dealing the NFT-based transmission implies that we have to be able to assess the signal corruptions occurring due to the optical noise, and paramount goal is then to optimise the signal parameters inside the NFT-domain, the task which differs considerably from the optimisation methods used in the "ordinary" space-time domain.

The noise inside the NFT domain itself has been the subject of increased interest [1, 3]. In our talk we will present the data concerning the properties of effective noise arising inside the NFT channel and noise's characteristics (correlation properties) dependence on signal power, bandwidth, type of modulation used, and transmission distance. Finally we propose the ways of how to diminish the noise-induced data corruption inside the NFT domain.

[1] S. A. Derevyanko, J. E. Prilepsky, S. K. Turitsyn, Nat. Commun., Vol. 7, 12710 (2016).
[2] S. K. Turitsyn, et al, Optica, Vol. 4, 307 (2017).
[3] V. Aref, S. T. Le, H. Buelow, J. Lightwave Technol., Vol. 36, 1289 (2018).

(P56) The loglog growth of channel capacity for nondispersive nonlinear optical fiber channel in intermediate power range. Extension of the model

I Terekhov[1], A Reznichenko[1], A Chernyh[1] and S Turitsyn[2]

[1]Novosibirsk State University, Russia, [2]Aston University, UK

In our previous paper (Phys. Rev. E,Vol. 95, p. 062133(2017)) we considered the optical channel modelled by the nonlinear Shr\"{o}dinger equation with zero dispersion and additive Gaussian noise. We found per-sample channel capacity for this model. In the present paper we extend this model by introducing the output signal detection procedure and the initial signal dependence on time. The proposed model is the more closer approximation of the realistic communications link than the per-sample model where there is no dependance of the initial signal on time. For our channel we found the conditional probability density function (PDF), entropy of the output signal, conditional entropy, and mutual information. Maximizing the mutual information we found the optimal input signal distribution, channel capacity, and their dependance on the form of the initial signal in the time domain for the intermediate power range.

(P57) Single photon counting receivers for visible light communications

S Collins, L Zhang, Z Ahmed, H Chun, G Faulkner and D O'Brien

University of Oxford, UK

Visible light is already employed to provide wireless communications channels in some specific situations. However, it is now being considered as a way to provide wireless communications channels that can augment WiFi when it is struggling to satisfy user demand.

A key component of these visible light communications systems is the photodetector within the receiver. Then like, other communications systems, the capacity of the visible light communications system depends upon both the bandwidth and the signal to noise ratio of the receiver. The most sensitive photodetectors that have been available are avalanche photodiodes (APDs). However, excess noise in these devices, rather than Poisson (shot) noise, limits their sensitivity.

Arrays of single photon avalanche diodes (SPADs) have just become available, with output pulses that are consistent with OOK data rates of up to 500 Mbps. Recently, it has been suggested that if arrays of SPADs have a photon detection efficiency of more than 15% they could be used to create receivers that are more sensitive than receivers containing APDs. Results from experiments on a commercially available array of SPADs, operating in ambient light, will be presented that confirm this prediction. The signal to noise ratio of a receiver containing this array of SPADs will then be compared to the Poisson or shot noise limit.

One method of increasing the data rate of a visible light communications is to use more sophisticated modulations schemes. The simplest modulation scheme that increases data rate is pulse amplitude modulation and so Poisson statistics have been used to determine the transmitted power levels needed to represent the symbol levels need by pulse amplitude modulation. These theoretical results will be compared to the levels that are needed to transmit data to a receiver containing an array of SPADs from a blue laser diode.

(P58) Low cost camera based laser detection.

S Tipper

DSTL, UK

A novel low cost camera based method of detecting Continuous Wave (CW) lasers has been developed at the Defence Science and Technology Laboratory (DSTL), with the capability to measure the laser wavelength and the power collected by the lens. The method uses a defocused camera to detect and distinguish lasers from other sources, whilst taking advantage of the monochromatic nature of lasers and the fundamentals of colour cameras to determine laser wavelength and collected power. Combining power, wavelength and lens size allows for comparisons of the sampled irradiance with the Maximum Permissible Exposure levels, thus indicating whether a laser exposure is above the eye safe level. A prototype is under development and will be assessed in realistic handheld laser engagement scenarios.

(P60) Low loss dielectric mirrors for cavity based single photon emission

Najwa Sidqi[1,2]

[1]Helia Photonics, UK, [2]Heriot Watt University, UK

Quantum Key Distribution (QKD) or quantum cryptography is a hot topic in the communication field as a safe and completely secure way of exchanging data. Cavity-based single photon emission possesses a very high potential for future quantum networks and quantum communication systems.

Fabry-Perot cavities especially, are a good candidate for these applications, thanks to a circular mode profile emission and low-lasing threshold. These properties are related to the small volume of the active region and the use of highly reflective Distributed Bragg mirrors (DBRs). The reflectivity R of the DBRs is related to the *finesse* F of the cavity, which represents the number of round trips performed by a photon before being lost by the transmission of one of the cavity mirrors. In order to assure a strong coupling in the cavity, a high *finesse* is required and therefore a reflectivity value as high as 99.9999%.

Achieving such high goal faces many technical challenges and limiting parameters such as optical losses (scatter and absorption) and other limitations related to thin film coating technologies. The control of the mirror fabrication and losses and relevant measurements to the cavity *finesse* will be addressed in this poster.

Key words:

Quantum cryptography, Single photon emission, High-Finesse cavities, High reflectance mirrors, thin film fabrication, losses

(P66) Evaluating the propagator in quantum field theory

L Ucho[1] and E Aiyohuyin[2]

[1]Ekiadolor-Benin, Nigeria, [2]University of Benin, Nigeria

Quadratic divergencies are encounted in evaluating the propagators of scalar, spinor and vector fields. This problem of quadratic divergencies has led to the formulation of alternative theory of particle physics.

The path integral formulation of quantum mechanics is adopted in this work. In this formulation, the evolution of a system is calculated by evaluating the quantum mechanical overlap amplitude. The amplitude is evaluated as a path integral.

The expectation of operators that are time-ordered can also be evaluated via a path integral. The path integral involves summing together all possible ways with appropriate weight of going from an initial state to a final state.

In this work, all infinite quantities cancel in a well defined way provided d<&(infinity)

(P71) Design and fabrication of versatile optical cavities for quantum networks

T H Doherty, M Mohammad, N Holland, K Theophilo, D Stuart, A Kuhn and B Yuen

University of Oxford, UK

A scalable quantum network will require an effective interface between light and matter. A high finesse optical resonator, which strongly couples a single atom to a photon, forms a key element. The application of these systems has been demonstrated in multiple studies [1,2], including as scalable source of bespoke single photons. However, the techniques used to fabricate optical cavities have remained largely unchanged since their introduction. A variety of engineering challenges have prevented the production of highly curved, perfectly reflecting, mirrors. This has resulted in insufficient access to persistently trap an emitter in a cavity, weak atomic coupling and perturbing polarization dependent effects.

However, with the continual development of modern manufacturing processes, such as laser ablation [3] and focussed ion beam milling [4], these challenges can now be overcome. A new generation of resonators are being constructed with stronger atomic coupling, a reduction to birefringence and greater access to the cavity mode. We review the state-of-the-art in the techniques which make this possible, the potential applications of these resonators and their position in a future quantum network.

[1] Kuhn, A. Engineering the Atom-Photon Interaction, Chapter 1, Springer International PU (2016).
[2] Reiserer, A. & Rempe, G., Reviews of Modern Physics, **87**, 1379-1418 (2015).
[3] Hunger, D. et al., New Journal of Physics **12**, 065038 (2010).
[4] Dolan, P. et al., Optics Letters **35**, 3556 (2010).

(P72) Excimer laser nano-structuring of SU-8 using silica micro-spheres

Q Al-jarwany and C Walton

University of Hull, UK

Nano and micro-sphere lithography can be used to pattern a wide range of materials. In some applications spheres self-assemble on substrates into desired patterns or and in other cases optical tweezing techniques can be adopted for positional purposes. Spheres may shield an underlying substrate or the inverse approach can be utilised and light is focussed to enhance the intensity of light at the sphere interface. In this work, we compare experimental results with computational simulations. Ultra violet radiation (UV) emitted from a 193 nm excimer laser is used to illuminate dielectric micro-spheres that are typically 1 micron in diameter. Lumerical™ a finite difference time domain (FDTD) software is used to simulate the electric field intensity in the sphere SU-8 substrate system. In addition, COMSOL™ a finite element method (FEM) is adapted to calculate the system temperature. Experimentally, we characterise the surface modified substrate with atomic force microscopy (AFM) and scanning electron microscopy (SEM) measurements. The microsphere's act as small ball lenses that focus pulsed, 11 ns (FWHM) UV radiation beneath the particle resulting in the formation of 200 nm diameter holes and smaller. Analysis of the results are used to discuss the light-matter interaction process, separation of the spheres from the substrate and the resulting resolution and surface topology.

(P75) Sintering different concentrations of iron doped calcium phosphate biomaterials using femtosecond laser for tissue engineering

E Alsubhe, A Anastasiou, E M Raif and A Jha

University of Leeds, UK

Calcium phosphate minerals (CaPs) have been widely used for scaffold manufacturing through Selective Laser Sintering (SLS) due to their compositional and structural similarity with the mineral of human ard tissues. Although hydroxyapatite $Ca_5(PO_4)_3(OH)$ (HA) is one of the most popular CaP mineralit was found to have a low resorption rate that hinders the formation of new bones. Recently, iron doped calcium phosphate (β-pyrophosphate β-$Ca_2P_2O_7$ phase) minerals have been investigated to be an attractive option for manufacturing scaffolds for bone regeneration, using SLS. β-pyrophosphate has an excellent resorption rate comparing to HA and in a recent work we demonstrated that doping with iron can greatly improve the laser sintering process. Therefore, this study aims to evaluate the suitability of the iron doped pyrophosphateas the main constructive material for scaffolds and other medical devices related to bone regeneration.

In this respect, various concentrations of Fe^{3+} (0%, 5%, 10%, 20%, and 30%) doped brushite mineral ($CaHPO_4.2H_2O$) synthesized and characterized using x-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), fourier transform infrared spectroscopy (FTIR). In order to simulate the phase transformations induced by laser irradiation, the samples were heat treated at 1000^{o}C for 5hrs. The sintered Fe-β-pyrophosphate showed high mechanical properties (1.2GPa for 10% Fe) than undoped materials (0.3GPa for 0%Fe). For the materials with Fe concentration above 30% the dominant phase was iron phosphate ($FePO_4$). Cell viability and proliferation assays (extract ATP and contact assays) were applied, the sintered samples did not induce any adverse biological reaction to the cells even at high concentrations of doping (i.e. 30%mol).

(P76) Simulation and observation of the Talbot effect in cylindrical symmetry based on the orbital angular momentum

N Al muhawish, D Friday, A Selyem and S Franke-Arnold

University of Glasgow, UK

The Talbot effect, first discovered in 1836, is an example of periodic self-imaging which can be observed in the near field diffraction pattern of any period structure. Today's availability of coherent light sources and more recently reconfigurable diffraction gratings allows us to observe the Talbot effect for a broad range of periodic light structures. Here we concentrate on gratings and light fields with cylindrical symmetry, including beams that carry orbital angular momentum. We model and observe the resulting Talbot hyper-carpets (three dimensional light structures) that occur at the Talbot length and fractions thereof. We do this by performing tomography based on light scattered from a resonant atomic medium, as well as by direct observation with a movable camera.

(P77) Broad-band impulsive vibrational spectroscopy to detect raman signal of molecules at time domain

C Li, Y Long and A Monkman

Durham University, UK

Thermally activated delayed fluorescence (TADF) emitter materials for organic light-emitting diode (OLED) promise efficient and long-lifetime performance without any heavy metals. Recent study shows that the reverse intersystem crossing (rISC) between singlet and triplet charge transfer (CT) states in TADF molecules is mediated by one of the local triplet states of the donor or acceptor [1]. The vibronically coupling between the CT triplet and the local triplet is crucial for the rISC process, so we believe it is important to study the vibronic states of the excited electronic states in TADF molecules. We are building a broad-band impulsive vibrational spectroscopy setup (BBIVS) that was proved to be a powerful technique to record the vibrational spectra of excited states in the time domain [2]. We will present the home-made non-collinear optical parametric amplifier (NOPA) with ~10 fs output pulses that used as the impulsive pump in the BBIVS, the setup of two-beam BBIVS and the test measurement on acetonitrile solvent, silicon carbide, etc. In the future, a third actinic pump will be introduced into the system to pump TADF materials to excited states for which the vibronic coherence can be probed.

[1] Marc K. Etherington, Jamie Gibson, Heather F. Higginbotham, Thomas J. Penfold, Andrew P. Monkman, Nat. Commun., 2016, 7, 13680.
[2] Matz Liebel, Philipp Kukura, J. Phys. Chem. Lett., 2013, 4, 1358-1364.

Poster session 2

(P06) A low cost open source pressure myograph system

P Lawton[1], M Lee[2], C Saunter[1], C Wilson[2], J McCarron[2] and J Girkin[1]

[1]Durham University, UK, [2]Strathclyde University, UK

Measuring changes in vascular dimensions as a result of modulated blood pressure or chemical stimuli is important in understanding a wide range of circulatory diseases. We have developed a real time measurement system based upon low cost cameras and miniature computers, as an alternative to commercially available myograph systems with more customisability for specific applications.

Contractions in the smooth muscle layer outside arteries cause an increase or decrease in the cross-sectional artery diameter. This is caused by pressure and flow changes through the artery. Pressure myograph systems are used to study this function under the effects of vasoactive compounds. We have utilized the availability of low cost USB cameras to build a biologist friendly system for making such measurements that can easily be attached to any commercial microscope. By measuring the diameter along these vessels using images from a camera in response to near-physiological pressure and flow conditions, it is possible to monitor the geometry of blood vessels in real time. In this work, an open source, easily modified program for this purpose has been developed using an Arduino controlled pressure sensor and using the Python language to measure artery diameter, and to record and plot all measurements in real time. Results will be presented illustrating the core image analysis methods behind the new instrument along with recent results obtained on a range of samples.

(P07) WITHDRAWN

(P08) Auto-phase-locked time-gated luminescence microscope for background-free upconversion biological imaging

Z Zhu and X Shu

Huazhong University of Science and Technology, China

Time-resolved technique is widely used in biological detection and imaging for the observation of functional and molecular recognition events, since this technique can eliminate the background signals from scattering and short-lived autofluorescence and greatly increase the signal-to-noise ratio. For most time-gated luminescence measurements, a pulsed excitation source and a gated detector are the basic requirements in relative apparatus. Although some high-speed cameras, such as ICCD (Intensified Charge-Coupled Device), EMCCD (Electron-Multiplying CCD) or stream camera, can photograph with a delay time from nanosecond to microsecond, they are prohibitively expensive. Besides, all these systems require that the phase of each excitation and detecting shutter are precisely synchronized with both the excitation source and the detector acquisition state. This requires complex electronic phase matching circuitry and control systems. In addition, phase jitter of mechanical chopper and circuit delay should be avoided to reduce the scattering signals. These directly make the instrument expensive to implement and maintain.

Herein, we developed a simple method to realize the detection of time-gated luminescence. By adjusting the exciting and detecting optical paths to pass through the same chopper wheel, only one mechanical chopper was needed, which simultaneously acted as pulse generator and detecting shutter. The phases of each excitation and time gate can be synchronized and locked automatically as the optical paths fixed. Therefore, no complex electronic phase matching circuitry or control system was needed. The pulse cycle and gate time can be adjusted to approximate values by setting the speed and duty ratio of the chopper to detect the delayed luminescence. And this method can effectively reduce the scattering signals even if the chopper frequency jitters. This simple assembled system equipped with a 980nm CW laser was successfully used for true-color time-gated luminescence imaging of cell with no background interference.

(P15) Simple model of self-phase modulation spectral patterns in optical fibres

S Boscolo[1], C Finot[2] and F Chaussard[2]

[1]Aston University, UK, [2]UMR 6303 CNRS-Université de Bourgogne Franche-Comté, UK

Self-phase modulation (SPM) has been extensively studied for several decades in optical fibers. This phenomenon manifests itself by a change of the frequency spectrum of a pulse, owing to the nonlinear index variation that follows the temporal evolution of the pulse. In the general case, the spectrum of the transmitted pulse cannot be calculated analytically and only approximate or rms expressions giving the bandwidth of the transmitted spectrum are used.

In this paper, we present a novel theoretical treatment of SPM based on a spectral interference model. We show that a two-wave interference process is sufficient to describe the main features of the SPM-broadened spectra of initially Fourier-transform limited pulses or pulses with an initial positive linear chirp, and to accurately predict the extreme values of the spectra. The latter provide a more plausible measure of the spectrum extent than the rms width. Simplified but fully tractable closed formulae are derived for the positions of the outermost peaks of the spectra, which are particularly relevant to several recent applications of SPM. In the case of negatively chirped input pulses, the description of the SPM spectral patterns requires the inclusion of a third wave in the interference model.

Our spectral interference approach can also help better understand qualitatively the genesis of peculiar spectrum shapes of laser pulses, such as the batman ear spectra observed in all-normal dispersion lasers or Mamyshev oscillators. While the present discussion focuses on SPM, the concept can also be applied to other nonlinear modulations of the phase of a pulse, such as the modulation generated by cross-phase modulation or an external modulator.

(P23) Unexpected constitutive properties in electromagnetism and metamaterials

P Kinsler[1], J Gratus[1] and M McCall[2]

[1]Lancaster University, UK, [2]Imperial College London, UK

Metamaterials allow us a great freedom to implement material properties that cannot be found in nature. However, most such explorations consider the standard constitutive tensor approach, which is restricted to 35 possible couplings between the Maxwell fields (E,B) and the excitation fields (D,H) -- but in fact there can be up to 55 possible couplings. We will show how to generate these novel responses using a standard constitutive tensor, but find that to do this requires the help of metamaterials that are inhomogeneous, dispersive, and/or non-local. Now that these new parameters have been exposed, it should only be a matter of time before researchers can design materials with these new and exciting properties.

We explain the origin of these new constitutive possibilities with an elegant recasting of electromagnetism which enables us to condense the Maxwell-Ampere equation and the constitutive relations into a single equation. The key feature is the introduction of a first order operator that combines the role of the derivative and the constitutive tensor, so that the resulting theory dispenses with any need for the (D,H) excitation fields entirely. Even in the restrictive case of a homogeneous, non-dispersive, and local medium, we now have 20 new constitutive parameters to investigate. We will show that 4 of these new degrees of freedom are axionic, and that the other 16 relate differentials of the electromagnetic field to the charge and current in new ways.

We will categorize the new possibilities, and give analytic and numerical examples of their roles and behaviours, both as intrinsic media and as the consequence of deliberate metamaterial design. We will also ask how electromagnetic radiation propagates in such new types of media, and what happens at the interface between such a medium and the vacuum.

(P24) Shaping longitudinal electric field profiles using wire metamaterials

T Boyd, P Kinsler, J Gratus and R Letizia

Lancaster University, UK

We show how to use wire metamaterials to achieve detailed wavelength-scale tailoring of the profile of an electromagnetic field - i.e. how that field varies through space. By means of a lattice of parallel dielectric wires with radius modulated along the wire axis, we can show that the electric field experiences a spatially varying plasma-like dispersion relation. It is the effect of this varying dispersion relation that is the key to our success, and it allows a wide range of profiles to be selected, such as flat-topped, triangular, peaked, and other profile shapes.

One remarkable feature of our wire metamaterial medium and its plasma-like dispersion is that it supports field modes that are not only carefully shaped, but that also are dominated by regions where the electric field is longitudinal, i.e. parallel to the wires. This suggests potential applications in particle beam dynamics, with the particles experiencing carefully calibrated field profiles along the beam path.

We will describe how our field sculpting process works, which is highly efficient and does not require extensive numerical iteration over design possibilities. By modelling our material using a one dimensional spatially dispersive model it was possible to develop a method for relating a desired profile with a function for the variation of the radius of the wires in our material. If this radius variation was replicated in our material then a field with the desired profile should also be present. We were again able to validate this approach using numerical simulations for a variety of different profiles and dielectric constants. We have also extended these numerical results from idealised models of infinite lattices to four by four arrays of dielectric wires in a metal encasing.

(P25) Resonant state expansion generalised to magnetic, chiral, and bi-anisotropic open optical systems and metamaterials

E Muljarov[1] and T Weiss[2]

[1]Cardiff University, UK, [2]University of Stuttgart, Germany

We have generalised the resonant state expansion for open optical systems containing arbitrary reciprocal bianisotropic materials or metamaterials, including those having magnetic and chiral optical activity, as well as circular dichroism. The resonant state expansion is the most efficient and intuitive computational approach for treating open optical systems, as demonstrated in numerous publications [1-4]. The present theory [5] has the widest spectrum of applications, ranging from modeling and optimisation of chirality sensors to accurate description of the optics of magnetic and metamaterial systems.

[1] E.A. Muljarov, W. Langbein, and R. Zimmermann, Europhys. Lett. **92**, 50010 (2010).
[2] M. B. Doost, W. Langbein, and E. A. Muljarov, Phys. Rev. A **90**, 013834 (2014).
[3] T. Weiss, M. Mesch, M. Schäferling, H. Giessen, W. Langbein, and E. A. Muljarov, Phys. Rev. Lett. **116**, 237401 (2016).
[4] S.V. Lobanov, G. Zoriniants, W. Langbein, and E.A. Muljarov, Phys. Rev. A **95**, 053848 (2017).
[5] E. A. Muljarov and T. Weiss, arXiv:1801.08883, Opt. Lett., in press (2018).

(P26) The multiphysics solution to maxwell-hydrodynamic equations for modeling terahertz generation from plasmonic metasurfaces

W E I Sha[1], M Fang[2], Z Huang[2] and X Wu[2]

[1]University College London, UK, [2]Anhui University, China

The interaction between electromagnetic fields and plasmonic nanostructures leads to both the strong linear and nonlinear responses. In this work, the time-domain Maxwell-hydrodynamic model is adopted for describing the motion of electrons in plasmonic nanostructures, in which both the surface and bulk nonlinearities are fully considered. The coupled Maxwell–hydrodynamic system capturing the full-wave physics and free-electron dynamics is numerically solved with the parallel finite-difference time-domain method. The validation of the proposed multiphysics model is presented by simulating a plasmonic metasurface consisting of single layered split-ring resonator array. The linear response is compared to the Drude dispersion model; and the nonlinear terahertz emission from a difference-frequency generation (rectification) process is theoretically analyzed. The results show that the nonlinear metasurface enables us to generate broadband terahertz radiation free from the quasi-phase-matching condition. The work is fundamentally important to design nonlinear plasmonic nanodevices, especially for efficient and broadband THz emitters.

(P28) Three dimensional (3D) photonic crystal composites with high refractive index thin films

X Zheng[1], K Morgan[2], D Y-L Ho[1], M Taverne[1], L Chen[1], C-C Huang[2], D Hewak[2] and J Rarity[1]

[1]University of Bristol, UK, [2]University of Southampton, UK

To achieve modification of photonic band structures and realise dispersion control for functional photonic devices, composites of photonic crystal templates with high refractive index material are fabricated. This is not a new idea since people find high refractive index contrast could tune photonic bands, open and enlarge bandgaps and control the dispersion of photonic crystals. Some studies have been made using one-dimensional (1D) photonic crystal and in natural photonic crystals (eg butterfly wings).

Here, polymer-high refractive index composites are fabricated by coating polymer three-dimensional (3D) woodpile structures with thin molybdenum disulphide (MoS_2) films. A two-step process is used: 3D polymer woodpile templates are fabricated by the direct laser writing (DLW) method followed by chemical vapour deposition (CVD) of MoS_2. The optical properties of the composite structures are examined by measuring reflection spectra change after each thin film coating via our angle-resolved Fourier imaging spectroscopy (FIS) system. In this conference, we demonstrate that red shifts of photonic bandgap can be observed after each deposition with results confirmed by plane-wave expansion (PWE) calculations. Furthermore, the simulation results also suggest that by coating the polymer structure with an appropriate thickness of the high refractive index material, the bandgap size can be optimized.

(P29) Towards a full 3D photonic bandgap structure in the near infrared region via back-filling of polymer templates

L Chen[1], K Morgan[2], X Zheng[1], M Taverne[1], D Y-L Ho[1], C-C Huang[2], D Hewak[2] and J Rarity[1]

[1]University of Bristol, UK, [2]University of Southampton, UK

A three-dimensional full photonic bandgap structure is desirable for its ability to block photon propagation in all directions. This ability results in applications extending beyond 1D and 2D photonic crystals such as in sensing, controlling light emission and enhancing light matter interactions. However, the successful realization of 3D bandgap structures represents a fabrication challenge either based on complex layered 2D lithography, or on backfilling of low index templates made by self-assemble or 3D laser lithography. Here we discuss our progress towards a single backfill scheme filling a polymer templates with high index material at near room temperature

(<40C°). We highlight that a low fill factor of the high index material, required in large bandgap structures, leads to a more easily fabricated high fill factor polymer template, thus a higher tolerance in the fabrication. Here the template is based on a rod-connected diamond structure designed to have a 10% bandgap ratio in the near infrared wavelength (in the range of 1-3um) in its inversed structure. It is fabricated via direct laser writing (Nanoscribe). A high index (n~2.2 @1.5um) chalcogenide material, SnS, is then deposited inside the structure using a homemade CVD process. Using a focused ion beam, the CVD layer is cut to reveal the top polymer layer, thus enabling a full removal of the polymer using oxygen plasma etching. In the presentation we will demonstrate the whole process in detail and include optical measurement results in the near infrared region.

(P30) Direct laser ablation based diffractive polymer surface

R Ahmed[1], J-M Romano[1], S Alamri[2], S Dimov[1] and H Butt[1]

[1]University of Birmingham, UK, [2]Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS, Germany

Direct laser interference which is a mask-free lithography technique that allows to process one/two-dimensional micro/nano-patterns at fast, low-cost, and large scale compare with others established nanofabrication methods (e-beam, chemicals etching or photolithography etc.). Here, two-beam laser interference technique have been used to produce surface-relief structures on a flexible, transparent polymer sheet. Diffraction grating, two-dimensional patterns (square, rectangle structures), and micro-lens were fabricated as a demonstration. Well-orders far-field one/two-dimensional diffraction patterns were observed and measured with angle-resolve setups. Semicircular micro lens array show diffractive light focusing at a hexagonal arrangements. Optical characterization results ensured uniform microstructure fabrication that followed with computation modeling. Therefore, two-beam laser interference based flexible polymer devices may have suitable applications on wearable sensors and actuators.

(P31) Bio-inspired microstructures for surface functionality applications

R Ahmed, J-M Romano, H Butt and S Dimov

University of Birmingham, UK

Sub-wavelength microstructures based on metal, semi-metal, and topological insulators are able to control optical and surface properties at nanometer scale. Here, fs-direct laser ablation method have been used to modify meta-surface that mimic microstructures of collembola insect. Bio-inspired triangle structures are organized at hexagonal order and showed far-field hexagonal diffraction patterns at broadband and monocromatic light illumination. Surface functionalization based on manufacturing parameters (laser fluence/energy, processing speed etc.) were also performed to control optical and surface-relif properties. Finally, wetability and anti-bectarial application were also demonstrated. It is anticipated that bio-mimic trinagular meta-structures may have applications in color filters, holography, and smart sensors.

(P32) The coherent random lasing based on PM597 laser dye doped-azobenzene polymer vesicles

Z Hu and Y Li

Hefei University of Technology, China

In the work, we study the characteristics of the dye doped vesicals in the solution system and random lasing emission. The dye doped azobenzene polymer vesicles are self-assembled in the water and tetrahydrofuran with a volume ratio of 5: 3. The vesicle is a double-walled structure with two parts - a hydrophiliffdc part and a hydrophobic part. Both inside and outside of the vesicles are hydrophilic and the wall is the hydrophobic part. The location of PM597 dye dopant is in the vesicle wall and as a gain group. The coherent RLs are obtained under the pump of a 532nm pulse laser for the vesicals solution in the glass tube.

(P33) Quantitative correlative light-electron microscopy of single plasmonic nanoparticles

Y Wang, A Zilli, L Payne, P Borri and W Langbein

Cardiff University, UK

Metallic nanoparticles (MNP) are attracting increasing interest for many applications in photonics, ranging from optoelectronic devices to bioimaging and biosensing. An advantage of these systems is that their optical properties, governed by their localized surface plasmon resonance, are widely tunable with the nanoparticle shape and size, and can easily be controlled via e.g. colloid synthesis. In that context, it is very important to develop accurate experimental methods able correlate the size and shape of a single MNP, measured with nanometric precision, with the optical properties of the same nanoparticle.

In this work, we investigated three different MNP systems, namely commercially-available Ag nanocubes of 75nm edge, in-house fabricated Ag decahedrons in the 50nm size range, and Ag nanodimers in-house developed via controlled self-assembly of polymer linkers onto commercial quasi-spherical Ag nanoparticles of 40nm diameter. An experimental protocol for correlative optical/transmission electron microscopy was developed and optimized, comprising reproducible deposition of these silver nanoparticles onto TEM grids, their optical characterization via polarization-resolved high-resolution dark-field and extinction micro-spectroscopy, and subsequent TEM tomography of the same particle. Notably, the same nanoparticle was characterized optically in different dielectric environments, namely a high refractive index medium (n=1.52) and air (n=1), and its scattering and extinction cross-section was determined in absolute nm^2 units using an in-house developed quantitative measurement protocol. These studies pave the way toward an in depth understanding of the relationship between geometrical and optical properties of MNPs of non-trivial shapes, which in turn have the potential to be exploited in innovative bioimaging and biosensing platforms.

(P34) WITHDRAWN

(P35) WITHDRAWN

(P36) WITHDRAWN

(P44) Calibration phantoms for optical coherence tomography

Y Lu[1], N Gordon[1], D Robinson[2], B Coldrick[3], V Mezentsev[1], F Menduni[1], A Fratini[1] and K Sugden[1]

[1]Aston University, UK, [2]Arden Photonics Ltd, UK, [3]Optimec Limited, UK

In recent years, optical coherence tomography (OCT) has received significant interest in the medical field, and has been used in areas such as ophthalmology, dermatology, as well as contact lens metrology. Currently, there is no standard method used to calibrate and compare the performance between different OCT systems. With the increasing use of OCT systems, it is necessary to have such an optical device acting as an optical ruler such that the performance of OCT systems can be quantitatively measured and any errors calibrated out.

A curved OCT phantom developed at Aston University, in collaboration with Arden Photonics, has been used to confirm the validity of post-processing algorithms that are implemented to correct the distortion caused by the nature of the curved structures, however there were some features that required further development to improve ease of use.

Here we present an improved OCT phantom to assist in distortion correction. The 3D embedded phantom is inscribed in a plano-convex fused silica substrate using a femtosecond laser. The phantom consists of a series of X and Y lines that make a 250µm grid in a plane parallel to the flat surface of the lens. The first grid is inscribed at 200µm in apparent depth below the flat side of the lens. Further grids are fabricated at different depths such that there are 8 grid layers in total with a layer separation of 50µm in the Z-direction. In addition, there are also landmarks located above the first layer to show the exact location such that the position within the lens can be easily identified when viewing the phantom through the OCT system. This OCT phantom is characterised using an optical microscope and OCT systems.

(P45) Passive broadband polarimeter based on a Fresnel cone

R Hawley, J Cork, S Franke-Arnold and N Radwell

University of Glasgow, UK

Fresnel cones - glass cones with a 90 degree peak angle - have been shown to generate light with polarisation structure. These so-called vector vortex beams have received interest for their ability to produce focal fields below the diffraction limit and have been investigated as information carriers. Here, instead of harnessing these properties to generate useful beams, we instead use them to measure the polarisation state of the incoming light beam. This method is shown to be a direct spatial analogue to the popular rotating quarter wave-plate technique, and is in addition broadband and requires no moving parts. We show that we are able to recover the full Stokes vector and our results show an average overlap between observed and expected Stokes vectors of 99.5% and 98.9% for an input polarisation state generated using a half wave and quarter wave plate rotation respectively. The analogy with the well-known rotating quarter wave plate technique allows the use of previous error analysis research, which is discussed with regards to retardance optimisation and number of measurements. In addition to being intrinsically broadband, our single-shot polarimeter is robust and cost-effective.

(P46) Micro-scale optical profilometry with fiber optic Lloyd's mirror

G Kösoğlu[1], A İnanç[2], M N İnci[2]

[1]Marmara University, Turkey, [2]Bogazici University, Turkey

The purposed technique enables measurements of three-dimensional rigid-body shapes by using a fiber optic Lloyd's mirror at the micron scale with a resolution of 4 µm. A fiber optic Lloyd's mirror assembly is basically a technique to create an optical interference pattern using the real light point sources and their images and in this application, this assembly is combined with an ordinary optical microscope for high magnification at micron –scale. The generated fringe pattern thanks to this technique is deformed when it is projected on an object's surface and this deformation is placed right above the objective of the microscope. CCD camera is positioned on the vertical axis of the eyepiece tube of the microscope. Fringe positioning, fringe width, and the separation are easily adjusted by modifying the distance between the optical fiber and the mirror. The phase analysis of the acquired image is carried out by One Dimensional Continuous Wavelet Transform for which the chosen wavelet is the Morlet wavelet and the carrier removal of the projected fringe patterns is achieved by reference subtraction. The experimental setup is a simple and low cost to construct and is insensitive to the ambient temperature fluctuations and environmental vibrations that cause unwanted effects on the projected fringe pattern. This basic experimental setup enables a reliable and high precision optical topography measurement method in micro-scale without any high-cost equipment or optical apparatus.

(P47) Measurement of optical cross-talk in time domain multiplexed derivative sensing techniques

J M De Freitas

Independent Consultant, UK

One of the main issues influencing the performance of time domain multiplexed (TDM) reflectometric fibre-optic sensing arrays is optical cross-talk. Reflectometric techniques have been used extensively in the Defence and Oil & Gas sectors (De Freitas, *Meas. Sci. Technol.* **22** (2011) 052001), however, the number of sensors that can be attached in line on a single fibre branch is limited by optical cross-talk. Moreover, the maximum phase-based signal amplitude is inversely proportional to the signal frequency, a consequence of the Nyquist sampling limits in terms of phase, often referred to as signal overscaling. To overcome over-scaling, a new derivative measurement scheme was developed (US8564786B2). The TDM derivative technique involves the use of two frequency shifted pulses that are much shorter than conventional TDM schemes and are not mixed remotely in the interferometer. This leads to smaller phase amplitudes and results in the time derivative of the main sensor signal. This paper reports the first measurements on optical cross-talk in conventional TDM reflectometric systems, signal over-scaling limit, and the derivative response and cross-talk. These results will be useful for large-scale fibre-optic sensor array designs for the Defence, Oil & Gas and the Climate Change sectors.

(P51) Optomechanical self-structuring of a Bose-Einstein Condensate

G Robb[1], G-L Oppo[2] and T Ackemann[2]

[1]University of Strathclyde, SUPA, UK

Supersolid phases are intriguing as they combine spatial structure with superfluidity. Early claims of observation in helium or cold atoms were controversial, but recent experiments demonstrated progress in 1D systems or intersected cavities [1].

We consider a genuine 2D configuration based on the single-mirror feedback scheme (see e.g. [2,3]). A detuned laser beam drives an expanded Bose-Einstein condensate (BEC) at T=0. Most of the light is retro-reflected by a plane feedback mirror at some distance d behind the BEC. A modulation of the BEC density will cause a phase modulation of the transmitted optical field. Diffraction in the feedback loop leads to conversion of phase-to-amplitude modulation on length scales $\sim \sqrt{(\lambda d)}$. This amplitude modulation leads to BEC density modulation via dipole forces. Above some threshold, the density modulation and the optical lattice form spontaneously and sustain each other. For thermal atoms, this was demonstrated in [2].

A first treatment in [3] based on a Gross Pitaevskii equation with optical feedback confirmed the instability in quantum degenerate matter for vanishing atomic interactions and indicated a non-zero threshold even at T=0 due to the finite ground-state energy. Further analysis shows that repulsive atomic interactions hinder the instability whereas attractive ones enhance it. Numerical simulations in 1D [3] and 2D yield structured states in the atomic density, i.e. a supersolid phase. If the induced lattice is strong enough to hinder tunneling, the resulting phase would be a highly interesting spontaneous Mott insulator.

[1] R. Li et al., Nature **543**, 91 (2017), J. Leonard et al., Nature **543**, 87 (2017).
[2] G. Labeyrie et al., Nature Photonics **8**, 321 (2014).
[3] G. R. M. Robb et al., Phys. Rev. Lett. **114**, 173903 (2015).

(P52) Optomechanical self-structuring instabilities involving orbital angular momentum

G Baio, G Robb, A Yao and G-L Oppo

University of Strathclyde, UK

The spontaneous emergence of spatiotemporal order is a prominent feature of physical systems driven far from equilibrium. In optical systems the self-sustained structures are generally encoded in the internal excitations of an optical medium.

When considering cold atomic ensembles, the optomechanical coupling between light and atoms is also known to lead to spatial instabilities. In the quantum degenerate case this is interpreted as a quantum phase transition.

Generally speaking, density redistribution effects can provide positive feedback leading to the appearance of patterns in cold atomic clouds and this was shown theoretically and experimentally.

Moreover, due to their potential applications in optical and information related technologies, spatial light structures carrying orbital angular momentum (OAM) are of central interest in quantum optics.

In this work we consider a cold atomic cloud within a planar ring cavity geometry, interacting with a Laguerre-Gaussian mode carrying non-zero net OAM. Additionally, optical molasses are assumed to provide strong momentum damping to the atoms.

(P53) Development & field testing of an automated portable optomechanical accelerometer

Y L Li and P Barker

University College London, UK

The exquisite detection of mechanical motion in optomechanical systems can be used to create ultrasensitive inertial sensors that look to surpass current standards. We have demonstrated an optomechanical accelerometer capable of measuring micro-g accelerations (g=9.81 m/s^(2)) due to a dispersive and dissipative coupling between a whispering gallery mode (WGM) resonance and the centre-of-mass motion of the WGM cavity itself. This optical system is suitable for applications such as navigation or gravity gradiometry but will become invaluable for calibrating & stabilising quantum sensors which have inherently low bandwidths and sampling rates. The development of a portable WGM accelerometer prototype is also described. Results from both the lab and successful outdoor field trials are analysed to characterise the sensor performance.

(P59) Lindblad dynamics of quantum walkers in optical lattices

B Longstaff and E-M Graefe

Imperial College London, UK

The quantum counterpart of a classical random walk is known as a quantum walk. Typically a quantum system is open and the control of indistinguishable quantum particles requires an account of environmental influences on the system. In the Markovian approximation a system weakly coupled to its environment can be described by the Lindblad equation. Here we consider continuous time quantum walks of ultracold atoms in an optical lattice, where the unitary dynamics are generated by the one-dimensional Bose-Hubbard Hamiltonian. This poster will illustrate how the presence of losses, together with the on-site interaction, influences the quantum dynamics.

(P61) Nano-cathodoluminescence and Carrier Dynamics in All-inorganic Perovskite Nanocrystals

R Ahumada-Lazo[1], J T Griffiths[2], F Wisnivesky-Rocca-Rivarola[2], N J L K Davis[2], W Y Fu[3], F J De La Pena[2], M Price[2], J A Alanis-Azuara[1], P Parkinson[1], D J Binks[1], A Howkins[4], I Boyd[4], C Humphreys[2], N Greenham[2] and C Ducati[2]

[1]The University of Manchester, UK, [2]University of Cambridge, UK, [3]University of Hong Kong, Hong Kong, [4]Brunel University, UK

Nanocrystals of caesium lead halide perovskites ($CsPbX_3$, X = Cl, Br, and I) have emerged recently as a promising new type of optoelectronic material offering bright emission across the visible spectrum [1]. An understanding of carrier dynamics and recombination in these materials and their dependence on nanocrystal structure and composition will be essential to their exploitation and development.

In this study, we apply nano-cathodoluminescence in a scanning transmission electron microscope to characterise the nanoscale structure of individual $CsPbCl_3$ and $CsPbI_3$ nanocrystals, and relate it to their emission properties. We also compare these nanoscale optical properties to those of ensembles of the same nanocrystals and investigate the carrier dynamics by fluence-dependent transient absorption (TA) and photoluminescence (PL) spectroscopies, and quantum yield measurements.

It was found that all of the $CsPbI_3$ nanocrystals studied, which were of regular shape and had a narrow size distribution, exhibited efficient CL. In contrast, a larger size distribution was observed for the $CsPbCl_3$ nanocrystals with irregular shapes and higher aspect ratio nanocrystals; of these, only the larger, more regular nanocrystals exhibited efficient CL. Ensembles of these nanocrystals exhibited PL with a similar fluence-dependence; in both cases, the quantum yield initially grew as the fluence was increased before reducing again. This behaviour was attributed to the initial saturation of defect-related non-radiative recombination followed by the onset of Auger recombination, which occurs when the absorption of more than one photon per nanocrystal per excitation pulse becomes probable. Trapping and Auger recombination lifetimes were extracted from the TA transients and their scaling with the nanocrystal volume was used to explain why the CL efficiency is so sensitive to nanocrystal size.

[1] Protesescu, L. et al. Nano Lett. 15, 3692–3696 (2015).

(P62) WITHDRAWN

(P63) Ultrasensitive Time and Spectrally-Resolved Microscopy of Single Multiple Quantum Well Nanowire Lasers

S Skalsky[1], J Alanis[1], M Lysevych[2], D Saxena[3], H Tan[2], C Jagadish[2] and P Parkinson[1]

[1]University of Manchester, UK, [2]The Australian National University, Australia, [3]Imperial College London, UK

Over the past two decades, semiconductor nanowires have emerged as a promising candidate for nanophotonic applications, primarily due to their wavelength-scale dimensions and a facile route to growth on silicon. More recently, the ability to easily tune the lasing wavelength of multiple quantum well nanowires (MQW NWs) through radial design modification as well as proven operation at room temperature [1] has motivated significant research towards enabling applications incorporating this architecture. While efficient as light sources, difficulties in studying nanowire lasers arise due to their typically low-total-power optical output and susceptibility to degradation under high excitation conditions. In this research, we present a study of MQW NWs via a novel high-throughput, single-photon-sensitive, spectrally and time-resolved technique which provides unique information about photoluminescence lasing output with time. We demonstrate that this technique has the potential to provide new insight into dynamical processes occurring within nanoscale systems in the presence of degradation, enabling future optimisation of the fabrication procedure towards applications.

[1] J. A. Alanis et al., “Large-scale statistics for threshold optimization of optically pumped nanowire lasers,” Nano Lett., vol. 17, no. 8, pp. 4860–4865, 2017.

(P64) Molecular single photon sources

R C Schofield, S Boissier, S Grandi, K D Major, E A Hinds and A S Clark

Imperial College London, UK

Photons lie at the heart of many quantum technologies; however, they are difficult to generate and collect with high efficiency. I will present the use of organic molecules for generating single photons. When dibenzoterrylene (DBT) is embedded in anthracene it is photostable and forms a two-level system which when excited will emit a photon at a wavelength of ~780 nm. Room temperature fluorescence from DBT can be used for communication and sensing, however I will show that it is difficult to efficiently and fully populate the excited state of DBT in these conditions. By cooling to liquid nitrogen temperature, we can achieve almost 100% population inversion in DBT, and therefore efficiently generate photons. Further cooling is used to generate coherent, lifetime-limited photons. I will show our work in characterising a single molecule at temperatures down to 4 K and show that coherent Rabi oscillations are then seen in the excited state population. Clearly DBT can efficiently generate photons, but the next challenge is to collect them. I will present an overview of our recent work to couple the emission from single molecules into optical fibres using a microcavity and into photonic and plasmonic waveguides using nano-fabricated devices.

(P65) Luminescent carbon nanodots directly grown on Si-based substrates by chemical vapor deposition

R Huang, Z Lin and J Song

Hanshan Normal University, China

In this paper, we report on a novel approach in which carbon nanodots can be directly grown on Si-based substrates by chemical vapor deposition. It is clarified by combining Raman, Atomic Force Microscope (AFM), and X-ray photoelectron spectroscopy (XPS) measurements that the carbon nanodots with the controlled diameters are uniformly distributed on the substrates. Photoluminescence (PL) measurement reveal that the carbon nanodots feature a sharp blue light emission. The PL peak position is almost independent of the nanodot size. This suggests that the photoluminescence of carbon nanodots should not originate from quantum confinement effect but from the surface effect of nanodots. Our work provides a promising simple approach to obtain luminescent carbon nanodot for practical applications.

(P67) A new explanation for the color variety of photons

G Saleh, M Faraji, R Alizadeh and A Dalili

Saleh Research Centre, Iran

This new explanation is based on Wave-Particle Duality and Newtonian Laws and represents a unique definition of a three-dimensional motion for the photon, whose dual behavior is partly explained by the double-slit experiment of Thomas Young [1], who represents the photon's motion as a wave, and by the Photoelectric effect [2,7], in which the photon is considered as a particle. However, for scientists, the photon's true motion is unclear. In this article, we define a new type of motion for photons to solve both this ambiguity and the difficulty of presenting a three-dimensional trajectory for the photon's motion, and present a new formula to calculate its energy. In addition, because we believe in the helical motion of photons, where r is the gyroradius, we believe that their color is an effect of the order of magnitude of r. We present real examples that prove our energy formula

(P68) Entanglement indicators for arbitrary number of modes optical fields

B Woloncewicz[1], M Zukowski[1], J Ryu[2], M Marciniak[1] and M Weisniak[1]

[1]University of Gdansk, Poland, [2]National University of Singapore, Singapore

We present a sufficient and necessary condition for entanglement detection via polarisation measurement for squeezed singlet involving Normalized and Traditional Stokes parameters. We generalize our approach for arbitrary number of modes optical fields. Our entanglement condition is independent of detector efficiency and has high noise resistance.

(P69) Nonlocal coherent perfect absorption

J Jeffers

University of Strathclyde, UK

Coherent perfect absorption [1-4] allows the degree of absorption of a lossy material to be controlled by adjusting the input mode of the light. The effect was first suggested theoretically for lossy beam splitters at the quantum level in 2000 [1], but it was a further 10 years before the developments in the field allowed it to be observed, first with classical light [2-4]. Many experimental and theoretical papers have explored the effect since then. It has been measured with both single photon [5] and two photon inputs [6], showing that at the quantum level loss is not always the random deletion of photons.

We propose an experiment that is an extension of one performed in [6], in which a pair of photons in a state |2,0> - |0,2> is incident on an optically thin plasmonic film from both input directions. Exactly one of the photons is absorbed.

Here we show a similar effect survives even if the two photons are incident in one input arm of each of two independent lossy devices in an interferometric set-up. We have the curious situation in which a pair of photons interacts with the same lossy device – but one of them can be absorbed by two separate devices.

[1] J. Jeffers, J. Mod. Opt. **47**, 1817 (2000).
[2] Chong, Y. D. et al, Phys. Rev. Lett. **105**, 053901 (2010).
[3] Wan, W. et al., Science **331**, 889 (2011).
[4] J. Zhang et al, Light: Sci. Appl. **1**, e18 (2012)
[5] T. Roger et al, Nat. Commun. **6**, 7031 (2015).
[6] T. Roger et al, PRL **117**, 023601 (2016).

(P73) Optimisation and quality control of optical trapping in bespoke hydrogels

J James, A Wright, A Thompson, C Merry and K Arkill

University of Nottingham, UK

Haematopoietic stem cells (HSCs) are the stem cells that reside within the bone marrow, and possess the ability of limitless self-renewal in addition to the ability to produce all mammalian blood cells. However, recent findings have suggested stem cells are not limited to healthy tissues or organs; leukaemic stem cells (LSCs) are able to evade chemotherapy, leading to disease relapse. Within the leukaemic micro-environment, cellular behaviour is controlled by a combined influence of biochemical and biophysical cues. The highly complex matrix and multi-cellular nature of the normal and leukaemic bone marrow micro-environment creates particular challenges to interpret such cues that guide HSC and LSC fate decisions. Here, we have designed and built a fully-defined and tunable synthetic hydrogel combined with holographic optical trapping to enable step-by-step evaluation of micro-environment components. By use of triple focal-spot optical trapping, combined with fluorescence microscopy, we have the

capability to accurately and non-invasively interact with cellular behaviour at a single cell scale in the 3D micro-environment. Here, we use a leukaemic cell line model (U937s) to demonstrate the ability to trap and precisely manipulate cells within the defined 3D hydrogels. We combine optical trapping with fluorescent microscopy and perform cellular viability studies comparing various laser powers of single and triple focal-spot trapping. Through these methods we intend to obtain an improved mechanistic understanding of cell-cell interactions, with future work aimed at characterisation of HSC and LSC interaction with the bone marrow micro-environment.

(P74) Levitated electromechanics

J Millen[1] and D Goldwater[2]

[1]King's College London, UK, [2]University College London, UK

Nano- and micro-scale particles levitated in vacuum are of great interest due to their minimal coupling to the environment, enabling ultra-sensitive force sensing and explorations of quantum physics. Typically, such particles are optically levitated and cooled through their interaction with an optical cavity or via active feedback. These methods are limited by optical absorption leading to significant heating, instabilities when operating in high vacuum, and the recoil noise of the trapping light. A limited range of materials can be optically trapped in vacuum, with materials such as metals or nanobiological objects not possible due to heavy absorption. Here we analyse a scheme which avoids these issues, by electrically cooling charged particles levitated in a quadrupole ion trap. Through simulations, we investigate both passive resistive cooling and active feedback cooling, and explore cooling limits in the presence of realistic noise. Working in cryogenic environments would allow cooling to the quantum level. This all-electrical cooling and detection platform will complement existing optomechanical schemes, act as pre-cooling for quantum applications, and enable state-of-the-art force-sensing with an electrically-networked system.

Goldwater & Millen
arXiv:1802.05928

(P78) High resolution SAW elastography for ex-vivo porcine skin specimen

K Feng, K Zhou, C Li and Z Huang

University of Dundee, UK

Surface acoustic wave (SAW) elastography has been proven to be a non-invasive, non-destructive method for accurately characterizing tissue elastic properties. Current SAW elastography technique tracks generated surface acoustic wave impulse point by point which are a few millimeters away. Thus, reconstructed elastography has low lateral resolution. To improve the lateral resolution of current SAW elastography, a new method was proposed in this research. A M-B scan mode, high spatial resolution phase sensitive optical coherence tomography (PhS-OCT) system was employed to track the ultrasonically induced SAW impulse. Ex-vivo porcine skin specimen was tested using this proposed method. A 2D fast Fourier transform based algorithm was applied to process the acquired data for estimating the surface acoustic wave dispersion curve and its corresponding penetration depth. Then, the ex-vivo porcine skin elastogram was established by relating the surface acoustic wave dispersion curve and its corresponding penetration depth. The result from the proposed method shows higher lateral resolution than that from current SAW elastography technique, and the approximated skin elastogram could also distinguish the different layers in the skin specimen, i.e. epidermis, dermis and fat layer. This proposed SAW elastography technique may have a large potential to be widely applied in clinical use for skin disease diagnosis and treatment monitoring.

(P79) Optical fibre sensing of pH, temperature, turbidity and chemical species for nuclear industry applications

J Hyde[1], P Scully[1], B T Brown[1] and J Hastings[2]

[1]The University of Manchester, UK, [2]National Nuclear Laboratory, UK

A two dimensional multisensory net of optical fibres is under development for use in the nuclear industry focusing on the evanescent field sensing approach. The sensor will be used in a high pH Magnox pond at the Sellafield site in which legacy waste has been stored for a long period of time and has corroded forming sludge. The sensor will be tailored to monitor pH 9-12, temperatures of approximately 15°C and will detect the levels of oxygen, carbon dioxide and magnesium in the pond as well as turbidity levels. The information from this sensor will provide in situ measurements from multiple points, 0.5 metres apart, in the pond cheaply, allowing specific clean up processes to be monitored more closely and bulk data to be obtained, so modellers can predict the behaviour of the pond more accurately. Individual probes have been deployed in the pond previously; however, they have only been used in small numbers due to the expense.

A second sensor has also been proposed for use in Sellafield's sea tanks, the final storage tanks after the effluent treatment plants, where the water is released out to sea, in order to monitor the pH of the water and check it falls within government guidelines.

We will present irradiation tests performed on a range of optical fibres along with a test of fibre robustness when exposed to pH 12 sodium hydroxide solution to allow the selection of one which would be suitable for our application. Initial tests of a range of dyes, focusing mainly on the pH and temperature sensors, will also be presented including comparative tests of two possible immobilisation methods for attaching sensitive dyes to the fibre surface.

(P80) A fibre-tip Fabry-Pérot cavity for deterministic, strong atom-photon interactions

M Mohammed, T Doherty, N Holland, K Theophilo, D Stuart and A Kuhn

University of Oxford, UK

Optical fibre-tip Fabry-Pérot cavities [1] can be used for strong coupling of an atom's electronic state and the cavity's photon state, allowing for a reversible and controllable quantum interface. Besides the benefit of coupling the light directly to the fibre, the small fibre-tip diameter allows for optical access with numerical apertures as strong as 0.6, making possible the use of tightly focused dipole traps that hold single atoms at cavity standing-wave anti-nodes [2]. Our symmetric confocal fibre cavity is formed of two single-mode fibres, with a finesse of 100,000 and a predicted co-operativity of 29. Whilst there are constraints on the mode-matching efficiency and mirror parameters of these cavity types, we are developing novel designs and mirror
ablation techniques that will overcome these. The deterministic nature and strength of the atom-photon interaction will be particularly useful for photonic quantum networks.

[1] D. Hunger et al., New. J. Phys. **12**, 065038 (2010).
[2] C. Muldoon et al., New. J. Phys. **14** 073051 (2012).

(P81) Controlled-phase manipulation module for orbital-angular-momentum photon states

F-X Wang[1], J Wu[2], W Chen[2], Z-Q Yin[2], S Wang[2], G-C Guo[2] and Z-F Han[2]

[1]University of Science and Technology of China, China, [2]USTC, China

Phase manipulation is essential to quantum information processing, for which the orbital angular momentum (OAM) of photon is a promising high-dimensional resource. Dove prism (DP) is one of the most important elements to realize the nondestructive phase manipulation of OAM photons. DP usually changes the polarization of light and thus increases the manipulation error for a spin-OAM hybrid state. DP in a Sagnac interferometer also introduces a mode-dependent global phase to the OAM mode. In this work, we implemented a high-dimensional controlled-phase manipulation module (PMM), which can compensate the mode-dependent global phase and thus preserve the phase in the spin-OAM hybrid superposition state. The PMM is stable for free running and is suitable to realize the high-dimensional controlled-phase gate for spin-OAM hybrid states. Considering the Sagnac-based structure, the PMM is also suitable for classical communication with the spin-OAM hybrid light field.

(P82) Grating array based zonal wavefront sensor with enhanced spatial resolution

B Pathak[1] and B R Boruah[2]

[1]University of Oxford, UK, [2]Indian Institute of Technology Guwahati, India

In this paper, we introduce a scheme which can effectively improve the spatial resolution of a grating array based zonal wavefront sensor (GAWS) to a significant extent. A quick display of several laterally shifted binary grating patterns is made possible due to the use of a fast response ferroelectric liquid crystal spatial light modulator (FLCSLM) device. The proposed scheme shows the enhancement in spatial resolution at a frame rate equivalent to the standard refresh rate of the video signal or even at a faster rate. We illustrate a proof-of-concept experiment to implement the proposed spatial resolution enhancement scheme. We also provide numerical simulation results that demonstrate and quantify the enhancement in spatial resolution.

(P83) A zonal wavefront sensor with improved centroid detection accuracy

B Pathak[1] and B R Boruah[2]

[1]University of Oxford, UK, [2]Indian Institute of Technology Guwahati, India

In this paper, we propose a scheme to improve the accuracy of centroid detection in a grating array based zonal wavefront sensor (GAWS) by using more than one digital camera via a beam splitting mechanism. We present experimental results that demonstrate describing each of the focal spots over a larger detector subaperture area. The proposed scheme shows improvement in centroid detection accuracy without any post acquisition processing of the data. We also show that the same experimental arrangement can enhance the dynamic range of the sensor and reduce the possibility of crosstalk between adjacent zones.

Institute of Physics
76 Portland Place, London W1B 1NT, UK
Telephone: +44 (0)20 7470 4800
www.iop.org/conferences