Photon 2024

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IOP Institute of Physics

Welcome

On behalf of the organising committee of Photon 2024, we are delighted to welcome you to this 12th biannual conference covering optics and photonics.

During the event, participants will have the opportunity to hear from leading experts in the field, attend lectures from leading technology experts, and visit the exhibition profiling the latest in optics and photonics technology. The programme will consist of plenary and invited talks, as well as contributed presentations and posters. There will also be ample opportunity to network and explore collaborations with colleagues.

This multi-disciplinary conference is jointly organised by the Institute of Physics (IOP) special interest groups including Combustion Physics, Environmental Physics, Instrument and Science Technology, Optical, Quantum Electronics and Photonics, Quantum Optics, Quantum Information and Quantum Control and Medical Physics.

Information for Speakers

Plenary talks will be 45 minutes each, invited talks are 30 minutes, and contributed talks are 20 minutes. All presentation times are inclusive of approximately 5 minutes Q&A.

We would kindly ask that all presenters arrive in the break before their session and introduce themselves to the session chair and to test their presentation.

Plenary Speakers

Clare Elwell
University College London

Clare Elwell is a Professor of Medical Physics at University College London (UCL) and Vice Dean for Impact for UCL Engineering. She develops functional near infrared spectroscopy (fNIRS) technologies to image the human brain and her research projects include studies of acute brain injury, infant brain development, autism, migraine and malaria. She currently leads the Brain Imaging for Global Health (BRIGHT) project which delivered the first brain images of infants in Africa. In 2023 she was awarded a Brocher Foundation Fellowship to investigate the responsible use of neuroimaging in disorders of consciousness.

Clare is Past President of the International Society on Oxygen Transport to Tissue and hosted the 42nd Annual Meeting of the society in 2014 at UCL. Clare is also past President of the Society for Functional Near Infrared Spectroscopy. She is current President of the London International Youth Science Forum. She was a 2018 British Science Association Media Fellow at the Financial Times and is a Fellow of the Institute of Physics and of the Royal Society for Arts, Manufactures and Commerce. She is Founder and Trustee of the charity Young Scientists for Africa. She has won numerous awards for research, teaching and public engagement and is currently the academic lead for the UCL Festival of Engineering. In July 2024 she lead the UCL Festival of Engineering – Six Days to Change the World which attracted over 10,000 attendees of industry partners, policy makers, general public and school and community groups to engage with engineering innovations at UCL.

Daniele Faccio
University of Glasgow

Daniele Faccio is a Royal Academy Chair in Emerging Technologies, Fellow of the Royal Society of Edinburgh and Cavaliere dell'Ordine della Stella d'Italia (Knight of the Order of the Star of Italy). He joined the University of Glasgow in 2017 as Professor in Quantum Technologies where he leads the Extreme-Light group and is Director of Research for the School of Physics and Astronomy. Previously he was at Heriot-Watt University and University of Insubria (Italy). He worked in the optical telecommunications industry for four years before obtaining his PhD in Physics in 2007 at the University of Nice-Sophia Antipolis (France). His research, funded by the UK research council EPSRC, DSTL, The Leverhulme Trust, the EU and ERC, focuses on the physics of light, on how we harness light to answer fundamental questions and on how we harness light to improve society.

Andrei Faraon
California Institute of Technology

Dr. Andrei Faraon is the William L. Valentine Professor of Applied Physics and Electrical Engineering at California Institute of Technology. After earning a B.S. degree in physics with honors in 2004 at California Institute of Technology, he received his M.S. in Electrical Engineering and PhD in Applied Physics both from Stanford University in 2009. From 2009 to 2012 he was a postdoctoral fellow at Hewlett Packard Laboratories. During his PhD he was involved in seminal quantum optics experiments using single semiconductor quantum dots coupled to photonic crystal resonators. At HP, he pioneered quantum nano-photonic devices in single crystal diamond coupled to color centers.

Dr. Faraon left HP in 2012 for a faculty position at Caltech where he works on nano-photonic technologies for both classical and quantum applications including: optically addressable quantum bits, optical quantum memories, microwave to optical quantum transduction, metasurfaces and metamaterials for multi-functional imaging applications.

Dr. Faraon is the recipient of the 2018 Adolph Lomb Medal of Optica that recognizes a noteworthy contribution to optics made by a researcher who is still early in his or her career and was elected as Optica Fellow in 2020.

Paul French
Imperial College London

Paul French received his BSc in physics and PhD in laser optics from Imperial College London, where he joined the academic staff of the Physics Department in 1994, having previously worked at the University of New Mexico and at AT&T Bell Laboratories. Today his multidisciplinary research is also based in a satellite laboratory at the Francis Crick Institute, having evolved from ultrafast dye and solid-state laser physics to biomedical optics for applications in cell biology, drug discovery and clinical diagnosis. Current interests include the development and application of multidimensional fluorescence and quantitative phase imaging technology for assays of biomolecular interactions, super-resolved microscopy, automated high content analysis, endoscopy and tomography, with an emphasis on more accessible and sustainable instrumentation, including open-source approaches to modular hardware, data acquisition and analysis.

Ursula Keller
ETH Zurich, Switzerland

Ursula Keller, a tenured professor of physics at ETH Zurich since 1993, has shaped the field of ultrafast science. She led the NCCR MUST program from 2010 to 2022. Keller obtained her Diplom from ETH in 1984 and a Ph.D. from Stanford University in 1989. Between 1989 and 1993, she worked as a Member of Technical Staff at Bell Labs, initiating her independent research career. Keller co-founded Time-Bandwidth Products, which was acquired by JDSU in 2014, and K2 Photonics in 2023. She has served on Jenoptik's supervisory board since 2022. Her research focuses on advancing ultrafast science and technology through innovations in ultrafast solid-state and semiconductor lasers. She invented the semiconductor saturable absorber mirror (SESAM) for ultrashort pulse generation in solid-state lasers resolving the long-standing Q-switching problem. She pushed pulse generation into the one to two optical-cycle regime and pioneered carrier-envelope offset stabilization, full frequency comb generation and stabilization. Her contributions include establishing ultrafast solid-state lasers for scientific and industrial applications and inventing new multiplexing methods for dual-comb applications. Keller's pioneering work in attosecond science includes the attoclock technique, full electric field control for petahertz electronics, and groundbreaking attosecond photoemission time delays using coincidence detection and angular resolution. Her awards include the Swiss Science Prize Marcel Benoist (2022), the OSA Frederic Ives Medal (2020), the SPIE Gold Medal (2020), the IEEE Edison Medal (2019), the OSA Charles H. Townes Award (2015), the EPS Senior Prize (2011), and two ERC advanced grants. Keller has supervised 95 Ph.D. students, authored 519 journal articles, and has an h-index of 120 with over 55,000 citations according to Google Scholar. She recently authored "Ultrafast Lasers," a graduate textbook published by Springer Verlag in 2022.

Roy Taylor
Imperial College London

Scott Silburn
UKAEA

Scott Silburn is a senior viewing & infrared system expert at UK Atomic Energy Authority, who has worked with infrared & visible imaging systems on the flagship Joint European Torus (JET) fusion experiment between 2014 and the end of its operation in 2023. His areas of work include development and operation of imaging instrumentation and image analysis techniques for fusion plasmas, and participation in the UK and EUROfusion fusion science research programmes, focusing on using imaging data to address plasma-wall interaction and related areas of study. He completed his PhD research on “coherence imaging” spectroscopic imaging techniques for fusion plasmas with the Centre for Advanced Instrumentation, Durham University and UKAEA in 2014.

Oral Presentations

Active and Adaptive Optics

Optomechanical Tuning Metasurfaces via Reshaping Photosensitive Azobenzene-containing Polymers

Moujdi S[1], Zamani A[1], Momtazpour M[1], Ying C[1], Xu L[1], Rahmani M[1]

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An increasing interest in tunable metasurfaces has garnered significant attention, driven by their potential applications in multi-functional devices for imaging, sensing, and planar optics. Pursuing dynamic and adaptable metasurfaces has fuelled research into innovative tuning mechanisms, ranging from mechanically reforming the substrate and heating to magnetising and carrier injection. Each technique comes with its own cons and pros that limit it to different applications [1]. Therefore, today, there is a quest to find a universal, reliable, reversible and precise tunning technique. Our study introduces a pioneering approach for achieving tunable metasurfaces by integrating mechanically photoresponsive materials. These materials, also known as azobenzene-containing polymer films, have emerged as promising platforms for optomechanical manipulation [2]. They possess a unique capability to form a mechanically moving surface pattern upon UV/ Visible light exposure. This photoinduced surface patterning arises from the reversible light-induced mass movement of polymer chains triggered by the cyclic photoisomerisation of azo chromophores. Harnessing this property, we utilise azopolymer tunable metasurfaces by reversibly patterning polymer surfaces. These provide robust platforms for controlling and tuning the optical response of metasurfaces with exceptional flexibility and precision. We are particularly focused on opto-mechanical light steering devices, such as light detection and ranging (LIDAR) that can potentially eliminate the need for rotatable mirrors for wide angle fields of view [3].

References

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Improving the sensitivity of the measurements of fixational eye movements via adaptive optics retinal imaging by using a model eye

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The human eye is constantly in motion; even when we maintain our gaze on an object, the eye makes small fixational eye movements [1]. We are usually unaware of these movements, and yet they are critical to human vision. Fixational eye movements may be measured with unprecedented sensitivity using an adaptive optics scanning laser ophthalmoscope (AOSLO) [2][3] to image and track the retina. This is enabling new studies to understand and control their function, as well as how they may be disrupted by disease [4]. However, measurement of eye motion may be confounded by other sources of image motion, including vibrations and instabilities in the system, and these effects could affect our interpretation of the fixational eye movement characteristics.

We describe here a method of measuring system motion artefacts while the eye is imaged by simultaneously imaging a model eye on the optical bench. We show that in closed loop operation of the system, the imaging beam may be displaced by external motion sources, which could be incorrectly inferred as a movement of the eye itself. Using a model eye we can measure these deviations independently and account for them in the estimation of the eye motion. We also show how real-time correction of the eye's aberrations impacts the quality of the image of the model eye, which shares the same optical path through the system, and how this may be calibrated.

References:
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Utilizing Phase Diversity for Direct Zernike Coefficient Prediction and Aberrated Image Correction Using Deep Learning

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Optical imaging quality is severely degraded by wavefront aberrations with a detrimental effect through both system- and sample- induced factors. System aberrations stem from imperfections in optical elements and misalignment, which affect overall image quality. However, sample induced aberrations are specific to the sample and have complex spatial variability due to changing refractive indexes. These aberrations will increase with depth, further distorting the wavefront leading to a degraded imaging focus and consequently impose limitations on deep tissue imaging.
Existing adaptive optics systems typically rely on iterative search algorithms to correct for aberrations and improve images. These approaches can be slow which increases the risk of sample damage and makes several corrections per field of view not practical. With the advancement of computer vision, deep learning has emerged as a promising technique for addressing a range of image-based inverse problems. Researchers have applied deep learning approaches to perform aberration retrieval by either directly reconstructing the phase of the aberrated wavefront or by recovering the Zernike coefficients from input aberrated images.
This presentation demonstrates the application of convolutional neural networks to characterise the optical aberrations by directly predicting the Zernike coefficients from two to three phase-diverse optical images. Previous studies have primarily focused on simulated datasets and exhibited limitations in prediction accuracy. Our work directly predicts Zernike coefficients from distorted images in both simulated and experimental settings with high accuracy of ~1.5% and over a wide range of Zernike modes, from Z3 to Z27. We demonstrate that the deep learning network can be trained to determine wavefront aberrations from the aberrated point spread functions (PSFs) and 2D images using only 2 or 3 defocus planes as an input. Importantly our approach does not require any pre-processing of the data/images, works for many Zernike modes (≤Z27) and is applicable to severely aberrated images.

Advances in Optical Metrology and Measurements

Ultra-High-Speed Non-Contact Temperature Measurements: Advancements in Instrumentation and Metrological Applications

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The accurate measurement of rapid temperature changes in dynamic environments is crucial for advancements in various scientific and industrial fields. This research presents the development of an ultra-high-speed, non-contact temperature measurement system based on infrared radiation thermometry (IRT), enhanced with avalanche photodiodes (APDs) and field-programmable gate arrays (FPGAs). Traditional IRT systems are challenged by slow response times that are inadequate for capturing transient temperature phenomena occurring on microsecond or even nanosecond scales, such as in high-speed industrial processes or explosive materials testing.

Our work introduces a novel IRT configuration utilising APDs for enhanced sensitivity and response speed, coupled with FPGA-based digital electronics for rapid data processing. This system is calibrated against the International Temperature Scale of 1990 (ITS-90), ensuring metrological traceability and high measurement accuracy. The advanced IRT system can resolve temperature changes at speeds orders of magnitude faster than conventional systems, with applications demonstrated in combustion dynamics and explosive material characterisation.

Key results include the successful deployment of the system in capturing the rapid temperature dynamics of droplet combustion, with measurement capabilities significantly exceeding those of commercially available technologies. This advancement not only pushes the boundaries of thermal measurement but also opens new possibilities for research and industrial monitoring where fast and reliable temperature data are critical.

Furthermore, this research provides an overview of the technological innovations that drive the high-speed IRT system. It delves into its calibration and metrological considerations, as well as its applications in real-world scenarios. The implications of these advancements are profound for future research and industrial applications, promising enhanced safety, efficiency, and insight across a multitude of disciplines.

Spray-On Quantum Dot Chemical Sensor Metrology

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[1]The University of Sheffield

In the face of escalating climate challenges, high-quality sensor and instrumentation technologies are pivotal for acquiring scientific data that supports effective strategies towards achieving net zero emissions. Semiconductor solution-processed quantum dot-based sensors represent a revolutionary advancement in sensor technology, offering high sensitivity and selectivity for environmental monitoring, energy applications, and healthcare. These sensors exploit the size-tuneable optical properties of quantum dots and their capability for multiplexed chemical and biological detection.

Our project explores the integration of non-toxic quantum dots, such as transition metal dichalcogenide (TMD) semiconductors, including molybdenum disulfide and tungsten disulfide, and other nanomaterial, like carbon and graphene. These advancements pave the way for developing eco-friendly sensors tailored for net zero initiatives such as carbon sequestration, pollution monitoring, and biodiversity assessments.

This research utilises a cutting-edge "spray-on" technique to fabricate quantum dot sensors: aerosol jet printing (AJP). This method not only enables rapid prototyping and characterisation of bespoke sensors, but also presents a scalable solution conducive to mass production without the environmental burden of traditional sensor manufacturing processes.

Additionally, this work aims to establish a comprehensive methodology for integrating these quantum dot sensors with essential electronics and instrumentation. This includes the development of custom high-speed electronic circuitry and software for interfacing with devices such as spectrometers and radiometers, crucial for the practical deployment of these sensors in diverse applications.

The ultimate focal point of the research is the design and testing of a spray-on quantum dot chemical sensor for detecting CO2 and heavy metals in water. This sensor is designed to facilitate low-cost, efficient monitoring solutions essential for environmental conservation and sustainable practices. This research represents a significant stride towards innovative metrology in sensor technology, crucial for informed decision-making in our quest for sustainability.

Quantitative Simulation of Fringe Projection Profilometry Techniques Using Blender

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Fringe projection profilometry (FPP) is a widely used metrology technique involving structured light and cameras to reconstruct an object's form [1, 2]. Due to it being a non-contact technique and offering high-availability of data, it is increasingly popular in a wide range of fields such as clinical medicine [3] and additive manufacturing [4]. Evaluating the performance of a large number of different FPP setups is difficult due to a vast range of configurations and methodologies which exist: phase unwrapping and FPP calibration; configuration of projector-camera parameters; and distortion are just a small subset of these.

Our work aims to provide a process for producing large and easy-to-obtain result sets of simulated FPP setups to compare and contrast the performance of these. Blender [5] is an open-source program which includes three-dimensional (3D) modelling and rendering allowing for the simulation of optical processes. We explored the effectiveness of simulating FPP by comparing a virtual replica in Blender to the real life setup of a Raspberry Pi Camera Module v1.0 and an LG Minibeam PH150G projector. Furthermore, we explored the relationship between intrinsic and extrinsic parameters such as environmental background light, camera-projector resolution, and gamma response.

This work offers an insight into the performance of FPP setups and future implementation could include an optimisation framework for a given set of requirements (leading to a digital-twin concept). It also opens the window for large datasets to be obtained and used for deep-learning to accelerate the speed and accuracy of FPP [6, 7].

References:

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[3] https://doi.org/10.1016/j.phro.2023.100517
[4] https://doi.org/10.1016/j.addma.2019.100940
[5] Blender Foundation. Blender - https://www.blender.org
[6] https://doi.org/10.1364/OE.418430
[7] https://doi.org/10.1016/j.cviu.2020.103023

Non-contact real-time identification and classification of microplastics in flow using Raman spectroscopic techniques

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The global awareness of microplastic pollution in the marine environment has risen recently. While spectroscopic techniques have been widely used to identify plastics collected from the sea, these are time-consuming due to the need for separation from bio-organic particles and long measurement time. In this work, novel methods for non-contact direct identification and classification of microplastics in flow using Raman spectroscopic techniques are presented.

Firstly, focusing on in situ monitoring of microplastics in the sea, an integrated device of Raman spectroscopy and holography, called “RamaCam”, is reported. A collimated laser beam for both Raman spectroscopy and holography illuminates a flow cell (L20 × ϕ1 cm) where seawater flows through. As soon as a particle flowing into the cell is detected using holography, a volumetric imaging technique, the particle is trapped in the cell, and Raman spectroscopy, which needs ~10 s for the measurement, is performed on the same particle for chemical analysis. Different plastic pellets with a size of ~1 mm were successfully identified using the laboratory setup. In 2024, the in situ “RamaCam” device, as shown in Figure, was developed and deployed in the sea, and fully automated in situ measurements of marine particles were successfully performed at a water depth of 1000 m.

Secondly, for measurements of smaller microplastics (< 100 µm), a method based on coherent anti-stokes Raman scattering (CARS) is proposed. Microplastic and bio-organic particles (algae) with a size of 20-40 µm in fast flow (4 mm/s) were successfully detected and classified by simultaneous detection of CARS and two-photon excited autofluorescence (TPEAF) signals.

The proposed methods demonstrate the potential for non-contact continuous in situ monitoring of microplastics suspended in water without the need for collection/extraction, which is a game-changer for current sampling-based analysis and will contribute to the understanding of global-scale microplastic pollution in oceans.

Compact fluorescence-quenching sensors for trace pollutant detection using fluorescence lifetime imaging

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[1]University of St Andrews, [2]University of Edinburgh, [3]Swedish EOD and Demining Centre-SWEDEC, [4]Lightwater Sensors

Trace chemical detection for in-field environmental monitoring requires compact sensors that combine high sensitivity with sufficient specificity and low power operation. Thin-film fluorescent sensors offer an attractive optical solution for ppb-level detection of various pollutants (e.g. pesticides, pharmaceuticals, explosives) via fluorescence quenching by pollutant molecules absorbed into the film from the environment.

A challenge for these optical sensors is how to discriminate between quenching by different analyte molecules. Here we present an approach for selective detection combining a CMOS fluorescence lifetime imaging system with an array of fluorescent polymers that provide differing polymer-analyte interactions. We also study how molecular interactions and microscopic photophysics of fluorescence quenching in the microporous polymer PIM-1 determine sensing response.

The FLIM system is a custom 120x128-pixel time-gated SPAD array with integrated CMOS photon counting electronics, < 400 ps time resolution and 7 Hz frame rate. Simultaneous measurements of fluorescence lifetime and intensity were made for four fluorescent polymer films, photoexcited with 100 ps pulses at 379 nm [1]. During exposure to ppb-level vapours of different nitroaromatic explosives/pesticides, we observed characteristic changes in fluorescence intensities and lifetimes across the array that differ between analytes.

The characteristic optical responses arise from differences in polymer-analyte binding and photoinduced electron transfer quenching. To relate these processes to sensor response we undertook a combined experimental and theoretical study of nitroaromatic molecule sensing using the microporous polymer PIM-1. Films were contaminated with trinitrotoluene and dinitrotoluene, and absorption and fluorescence spectra measured before and after analyte exposure, and after thermal desorption, were compared with density functional theory calculations using Gaussian. We find good agreement in size of analyte binding energy and related spectral shifts for different analytes which provide insights to optical sensor kinetics, sensitivity, and potential for discrimination between target pollutants.

[1] A.B. Matheson et al., Opt. Lett. 48, 6015 (2023).

Optical access for tomographic in-combustor absorption imaging

Wright P[1], Kulkarni A[1], Blount C[1], McCann H[2], Johnstone W[3], Williams M[4], Carrotte J[4], Harding S[5], Brend M[4], Armstrong I[3], Ghosh A[1], Clark S[3], Lengden M[3]
[1]The University Of Manchester, [2]The University of Edinburgh, [3]University of Strathclyde , [4]Loughborough University, [5]Rolls Royce plc, [6]National Centre for Combustion and Aerothermal Technology

Optical absorption spectroscopy has long been used in the quantification of chemical species, especially gases. Recently, tomographic implementations of Tunable Diode Laser Absorption Spectroscopy (TDLAS) have been used by combustion researchers to investigate chemical species and temperature distributions in flames and exhaust flows, e.g. [1, 2]. This paper describes optical access methods intended to allow TDLAS-based tomographic imaging within an intermediate pressure (IP) combustor rig, with the ultimate goal of validating and improving combustion modelling. The challenges of implementing a spatially-dense grid of measurement paths in a pressurised, high temperature and space-constrained environment are considered, along with possible solutions. We then present our current approach, which combines fibre optic access to the pressure vessel with miniature optical elements. This approach allows a measurement grid comprising 128 beams to be implemented, with an expected spatial resolution of less than 3 mm. The system is intended for operation in the NIR (1800-2350 nm) region, providing access to high-temperature absorption lines of H2O, CO2 and CO. Recent single-path proof-of-concept measurements targeting H2O hot lines at 1963 nm and 1999 nm are presented. Good-quality path-integrated absorption spectra are obtained, even at the high (>10 kHz) spectrum acquisition rates needed for ‘frozen flow’ imaging of these highly dynamic combustion systems, provided sufficient optical power is available. The results indicate that, despite the use of fibre-amplified sources, the optical power budget is challenging, making reduction of optical insertion losses associated with not only the beam optics but also the fibre optic delivery critical to the system’s success.

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Astronomical and Space Instrumentation

Single and coupled-cavity spatial-mode-sensing schemes, using a diagnostic field, for quantum sensing.

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Precise optical mode matching is of critical importance in experiments using squeezed vacuum states. Automatic spatial-mode matching schemes have the potential to reduce losses and improve loss stability. However, in quantum-enhanced coupled-cavity experiments, such as gravitational-wave detectors, one must also ensure that the sub-cavities are also mode matched.

I will demonstrate a coupled cavity mode-sensing scheme with: no moving parts, nor tuning of Gouy phases. Instead a diagnostic field tuned to the HG20/LG10 mode frequency is used.

The error signals are derived to be proportional to the difference in waist position, and difference in Rayleigh ranges, between the sub-cavity eigenmodes. The two error signals are separable by 90 degrees of demodulation phase. I will discuss the theoretical basis for this work, as recently published [1]. I will then expand on the research conducted by Caltech & the LIGO gravitational-wave laboratory, expanding upon this work.

This work will facilitate a plethora of new quantum-sensing opportunities, where low loss photonic states can be trivially coupled between optical cavities and fibers.

[1] https://doi.org/10.1364/OE.502911

Temporal adaptive optics

Phillips D[1], Mididoddi C[1], Kilpatrick R[1], Sharp C[1], Horsley S[1], del Hougne P[2]
[1]University Of Exeter, [2]Univ. Rennes

The scattering of light impacts sensing and communication technologies throughout the electromagnetic spectrum. Overcoming the effects of time-varying scattering media is particularly challenging. We introduce a new form of adaptive optics that responds to temporal, rather than spatial, light distortion [1]. Our strategy is based on the observation that many dynamic scattering systems (such as turbulent air or living tissue) exhibit a range of decorrelation times -- meaning that over a given timescale, some parts of the medium may essentially remain static. We experimentally demonstrate a suite of new techniques to identify and guide light through these networks of static channels -- threading optical fields around multiple dynamic pockets hidden at unknown locations inside opaque media. We first show how a single stable light field propagating through a partially dynamic medium can be found by optimising the wavefront of the incident field. Next, we demonstrate how this procedure can be accelerated by 2 orders of magnitude using a physically realised form of adjoint gradient descent optimisation. Finally, we describe how the search for stable light modes can be posed as an eigenvalue problem: we introduce a new optical matrix operator, the time-averaged transmission matrix, and show how it reveals a basis of fluctuation-eigenchannels that can be used for stable beam shaping through time-varying media. These methods rely only on external camera measurements recording scattered light, require no prior knowledge about the medium, and are independent of the rate at which dynamic regions move. Our work has potential future applications to a wide variety of technologies reliant on general wave phenomena subject to dynamic conditions, from optics to acoustics.

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Biophotonics

Silicon oxy-nitride photonic integrated circuits for biosensing

Armstrong D[1,2], Ibrahim S[1,2], Naserikarimvand S[3], Whelan S[4], Guy O[3], Bennett A[1,2], Hadden J[1,2]
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During the recent COVID-19 pandemic a bottleneck in the delivery of polymerase chain reaction (PCR) testing led to increased numbers of false-negative test results[1]. Lateral flow self-testing kits were adopted to enable quick and easy at-home results; however, their sensitivity and reliability was poor[2]. There is therefore a growing need for simple, easily deployable biosensors that combine rapid results with high sensitivity and reliability to provide early detection of infectious diseases such as MRSA and coronavirus[3].

In this work, we present a proof-of-concept of a lab-on-chip bio-compatible biosensor using SiON-based photonic microring resonators and etched microfluidic channels, which can sense changes in the local environment. Using receptor-functionalised SiO2, the low loss of the SiON platform can enable ultra-sensitive detection of biomarkers in liquid around the waveguide which changes the group index[4] as seen in Figure 1. The performance of the biosensor will be discussed, commenting on its functionality against different test conditions, temperature, liquid, and optical probing parameters. We also make comment on the limitations of our current design, highlighting, where necessary, areas in which the sensitivity and performance of the sensor can be improved.

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Resolving action potentials in acute rabbit cardiac slices with 2-photon remote focusing microscopy

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[1]University of Glasgow, School of Physics and Astronomy, [2]University of Glasgow, Institute of Cardiovascular and Medical Sciences

Cardiac diseases are among the leading causes of death in the UK. Therefore, methods to investigate heart pathology in animal models are essential to develop diagnostic and therapeutic interventions. In the heart, action potentials (APs) travel through the tissue to orchestrate muscle contraction and make the organ an efficient pump. Electrophysiology can be investigated with two-photon fluorescence microscopy, which offers optical sectioning, high resolution and tissue penetration depth, revealing biochemical function. With voltage-sensitive dyes, APs were resolved as deep as 500µm in individual planes of rabbit ventricular wall [1]. However, transmural AP propagation across this wall has not yet been observed. In the rabbit heart, action potentials propagate from the endocardium to the epicardium with a conduction velocity of approx. 30cm/s. Therefore, a rapid vertical scan is necessary. In conventional microscopy, axial refocusing methods are slow or cause disturbances, as either the sample or the objective is moved. Remote focusing allows rapid axial refocusing by introducing an additional objective to create a virtual copy of the sample. This copy is then probed by actuating a lightweight mirror at the focal plane of the remote objective [2]. Here we present an implementation of a versatile remote focusing module, compatible with retrofitting to commercial two-photon microscopes and capable of 300Hz axial scanning over a range of 200µm in cardiac tissue without disturbing the sample or the sample objective. We discuss system optimization to compensate for pulse broadening, power losses and optical aberrations. Using Fluovolt-stained viable rabbit ventricular slice model [3], we present AP traces obtained in discrete longitudinal planes throughout the sample. Furthermore, we demonstrate fast cardiac structure imaging and preliminary transmural electrophysiological data acquired with 2-photon remote focusing microscopy. We believe that this method will allow us to investigate quantitatively and at cellular resolution how myocardial infarction scar impacts cardiac conduction.

Single-Molecule Analysis of Ferritin Conformational Dynamics and Kinetics using Plasmonic Optical Tweezer

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Ferritin, a vital protein found across various organisms, controls cellular iron levels. Understanding its mechanisms is important in revealing cellular processes and diseases. Single-molecule techniques offer detailed insights into ferritin's behaviour, such as conformational changes and iron loading-unloading dynamics, which were previously difficult by bulk methods. However, conventional single-molecule methods like FRET and cryo-EM cannot track minor protein movements without chemical modifications in native ferritin. Consequently, ferritin's kinetic responses to diverse buffer conditions and pore-channel dynamics are largely unexplored at the single-molecule level.

The optical nanotweezers [1], a recent single-molecule approach, use nanostructures to confine optical fields into nanometre-scale hotspots, enabling individual protein trapping without tethering. Here, we employed gold double-nanohole structures (DNH) to generate field-enhancement for trapping single unlabelled ferritins (Figure 1a). The light transmitted through the DNH detects the refractive index in the hotspot, revealing the conformational changes of the trapped protein. We successfully trapped apo-ferritin and holo-ferritin separately and monitored their structural dynamics in real-time. Notably, we observed the dynamic process of iron loading in a single apo-ferritin as it converts to holo-ferritin in situ (Figure 1b) [2].

Additionally, the linear correlation between light transmission through the DNH and trapped particle size enables successful tracking of single-ferritin molecule disassembly in acidic environments. Results show stepwise disassembly kinetics characterised by cooperative interactions among subunits, highlighting the specific involvement of intermediate subunits [3].
These findings advance our understanding of ferritin's role in iron metabolism, aiding medical treatments and drug development.

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Figure 1. Trapping and analysing single-ferritin with optical nanotweezer.(a) Using DNH for trapping single ferritin.(b) Transmission signal through DNH with an apo-ferritin trapped while it undergoes iron biomineralisation.

Mesoscale light sheet microscopy to study post myocardial infarction alterations in rabbit cardiac structure

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Light scattering through tissue reduces depths at which optical imaging can be recorded. Mitigation techniques rendering the tissue transparent via optical clearing techniques allow imaging of mesoscale samples (mm3 to cm3). Light sheet microscopy is suited to image these cleared tissues due to its ability to produce isotropically resolved, large field of views images captured at relatively high speeds. By employing mesoscale light-sheet microscopy and optical tissue clearing protocols: we have imaged tissue slices excised from the left ventricle of healthy and scarred New Zealand white rabbit hearts to assess structural remodeling of the heart due to myocardial infarction.

On these samples we have applied cardiomyocyte optimized clearing protocols (CLARITY, CUBIC-L/RA) to afford high tissue transparency, structural preservation [1-3]. The tissues are sliced (thickness 400 - 2000 µm) following heart dissection and perfusion. The application of both protocols results in tissue expansion; thus specimens are placed in Polylactic Acid (PLA) 3D printed spacers to ensure warping-free, isotropic expansion in the slice plane. Once tissues are optically cleared, they are stained (Wheat Germ Agglutinin – Alexa Fluor 488) to label cell membranes. Tissues are then inserted into custom PLA 3D-printed sample mounts and imaged using an assembled open-source Mesoscale Selective Plane Illumination Microscope (mesoSPIM), designed to accommodate cleared samples to perform structural imaging studies over a 14mm field of view. Magnification obtained with Olympus MVX10 zoom body affords high-resolution imaging for smaller interest regions [4].

Here, we present detailed characterization of our mesoSPIM as well as clearing, staining, mounting, and imaging protocols for rabbit cardiac tissue slices used in this microscope. We compare results obtained from clearing protocols, and present preliminary data of tissue structure at a cellular level. It is believed these methodologies will be viable in obtaining reliable, accurate 3D tissue remodeling data in rabbit hearts post myocardial infarction.

A Multimodal fluorescence setup for probing Biochemical and Cellular Dynamics

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The conformational arrangement of biomolecules greatly affects their binding dynamics and activity. Force spectroscopy techniques have long enabled direct manipulation of biomolecular structures through the application of mechanical force. Optical tweezers are one of the most used and versatile techniques for single-molecule and supramolecular manipulation, as they allow the precise application of a wide range of biologically relevant forces (0.1-100 pN) with great spatial and temporal resolution.

Cell membrane curvature has been shown to regulate the localization and molecular conformation of cell membrane receptors and can be induced by the application of force through an optically trapped bead. To characterize the response of the cell membrane and its proteins to mechanical stress we have built a multimodal setup that combines optical tweezers with fluorescence microscopy. This setup includes widefield imaging with epi and TIRF illumination modes as well as fluorescence correlation spectroscopy (FCS) coupled with lifetime measurements. To evaluate its performance, we stained HEK293 cells with a fluorescent membrane tension probe (Flipper-TR), placed them under osmotic shock or mechanical stress and observed changes in Flipper-TR fluorescence lifetime as a function of cell membrane tension and curvature.

Side-lobe suppressed Bessel beams enhance contrast for wide field light-sheet microscopy

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The propagation-invariant nature of Bessel beams (BBs) has seen them implemented in a wide range bio-imaging in light sheet microscopy [1,2]. In contrast to Gaussian beams, BBs can capture larger fields of view of a specimen and retain high axial resolution across the whole image. However, the side-lobes of the BB produce out-of-plane fluorescence, which makes high-contrast imaging in one-photon mode difficult to achieve [3]. In this work, we demonstrate a side-lobe suppressed Bessel beam (SSBB) light-sheet system and provide a quantitative study of contrast improvement for biological imaging in comparison to BB light-sheet. A BB and a SSBB with equal radius (60 µm) are produced by projecting a phase mask onto a Spatial Light Modulator [4]. We show that SSBB carries less than 10% of peak intensity in the first-side lobe. We validate our approach by observing side-lobe suppression in the point-spread function (PSF) of a light-sheet microscopy approach using a SSBB. This lobe-suppression can also be seen in imaging of a scattering medium (phantom) at greater depth (up to 430 µm). Finally, we address the relatively unexplored question of the efficiency of SSBB for biological imaging. We report a two-fold enhancement in contrast-to-noise ratio when imaging labelled cellular eye structures and the notochord for fixed Zebra-fish larvae (4-5 dpf). Our results offer an effective approach to use a SSBB for light sheet imaging in biology, tackling previously unaddressed challenges related to enhancing contrast in for this modality whilst retaining a large field of view at high resolution.

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Snapshot hyperspectral imaging of intracellular lasers

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Micro- and nanolasers are emerging as powerful photonic tools enabled by their unique emission spectrum, high brightness, and narrow linewidth, making them a promising alternative to conventional fluorescent reporters. With the aid of spectral detection, these lasers can be used for long-term tracking and to sense local parameters, including cardiomyocyte contraction] and antigen-antibody binding with exceptional precision. Despite their promise, the limited detection speed of conventional spectral detection using point-scanning and push-broom scanning has challenged high-speed, widefield, and high-throughput applications.

In this study, we investigate the use of hyperspectral imaging with an integral field detector for rapid detection of multi-quantum well microdisk lasers in a single widefield snapshot acquisition. We quantify the sensitivity of our hyperspectral system and demonstrate rapid volumetric and widefield detection of microdisk lasers. We further discuss the advantages and challenges of snapshot hyperspectral imaging in the sparse and narrow linewidth context of microdisk emission. Our results demonstrate that snapshot hyperspectral imaging tailored to microdisk lasers has the potential for new and powerful applications.

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Design of high sensitivity plasmonic refractive index sensor for biomedical sensing

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We present theoretical study of a highly sensitive biosensor based on disc-on-mirror nanostructures, consisting of a gold disc with a diameter of 400 nm and a height of 200 nm on top of a silicon dioxide disc with a diameter of 200 nm and 10nm height. Leveraging the unique plasmonic properties of this nanostructure, localized surface plasmon resonance (LSPR) field enhancements and strong field confinement inside the nanogap region, enabled precise and sensitive detection of molecular interactions in the plasmonic gap, making it an incomparable platform for biosensing applications. Lumerical FDTD was used to optimize the structure parameter space, including the diameter of both discs, and the gap thickness, in order to achieve maximum sensitivity. This is illustrated through the detection of DNA hybridization and hepatitis antigen. For DNA hybridization (figure 1), a layer of silane with 1nm thickness has been used as a functionalization layer between the structure and DNA, followed by a 3 nm layer of ssDNA with refractive index of 1.456. Using Lorentz-Lorenz mixing rule, we then modulate the change in refractive index as a function of dsDNA concentration, allowing us to achieve sensitivity of 552.28nm/RIU (nm per refractive index unit) with LOD (0.0076). In parallel, for the hepatitis antigen detection (figure 2), the functionalize layer is protein A with thickness of 2 nm and refractive index of 1.48 followed by an antibody layer (ssDNA) with thickness of 3 nm and a refractive index of 1.456. A third layer is used as a blocking layer (bovine serum albumin) with thickness of 1 nm and refractive index of 1.59. Finally, a 4 nm of hepatitis antigen (HBsAg) constitutes the analyte with refractive index of 1.5. Using the same Lorentz-Lorenz mixing rule, the system was shown to reach a sensitivity of 248 nm/RIU for hepatitis antigen sensing, LOD (0.018).

Time-resolved Raman Spectroscopy using a CMOS SPAD array to separate Raman and fluorescent signals

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Many biological samples have a stronger fluorescent signal than Raman signal. Time-resolved Raman spectroscopy can separate Raman signals and fluorescent signals in the time-domain due to fluorescence occurring at longer time scales than Raman scattering [1].

Here, we separate Raman scattering and fluorescence by using a time-resolved 512 pixel single photon avalanche diode (SPAD) line sensor array with 512 pixels operating in time-correlated single photon counting (TCSPC) modality [2], configured as a spectrometer [3]. In this setup, the SPAD array measures the backscattered light from the sample as a function of time and wavelength. The arrival time of the photons are used in post processing to separate the Raman and fluorescence signal. The advantage of using a SPAD line array is that the integrated timing electronics allow for rapid and multiplexed single photon counting where numerous detectors measure the Raman and fluorescent signal. This increases possible count rate, therefore decreasing measurement time for practical application. In this work we typically use a measurement time of 30 s.

In Fig. 1. we show the separation of Raman and fluorescence signal in olive oil. Here it can be seen that the Raman scattering occurs at earlier time-bins compared to the fluorescent signal which occurs at later time-bins. This method will now be applied to biological tissue samples.

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Optically Manipulated Photonic Membranes for Biophotonics

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Traditional optical microscopy methods using microscope objectives limit the angles and distances at which we can interact with biological samples, hindering comprehensive analysis. Microlasers based on Whispering Gallery Mode (WGM) resonators offer powerful sensing capabilities when used in microfluidic environments, but their excitation is constrained by the limited angles of access.
In this study, we introduce a novel platform designed to transcend the limitations of traditional microlaser excitation methods. Our solution uses optically trapped micromirrors on flexible polymeric membranes to offer arbitrary excitation angles for WGM microlasers. This approach allows for precise environmental sensing along multiple well-controlled planes and facilitates light delivery and collection throughout a microfluidic chamber.

Our work delves into the development and application of this platform, highlighting the unique capabilities brought forth by optically trapped micromirrors. We first provide a comprehensive study of our ability to excite arbitrary WGMs to probe different environments. We then demonstrate the system's versatility through a time-resolved experiment, involving monitoring the spectral shift of the WGMs as we orbit a polystyrene bead around the microlaser, showcasing its potential for dynamic sensing applications.

Beyond extending the frontiers of refractive index sensing using WGM lasers, our utilization of optically trapped micromirrors presents a multitude of other use cases, including advanced imaging, light sheet microscopy using a single objective, and when combined with metasurfaces, the ability to send and collect conditioned light virtually anywhere in the sample plane.

Metabolic imaging of pre-implantation embryos using a phasor-based hyperspectral light-sheet microscope

Bruce G

Spatial mapping of cellular metabolic activity can reveal the health of cells and tissue. In particular, imaging the endogenous metabolic cofactors, nicotinamide adenine dinucleotide (phosphate) (NAD(P)H) and flavin adenine dinucleotide (FAD), can help to determine tissue and cell viability in a clinical environment. However, current imaging techniques are unable to achieve a high imaging speed at subcellular resolutions, leading to issues relating to photodamage.

In this poster, we achieve three-dimensional mapping of metabolism in pre-implantation murine embryos by constructing a phasor-based hyperspectral light-sheet microscope with a single UVA excitation wavelength. This choice of wavelength can simultaneously excite substantial NAD(P)H and FAD autofluorescence and the contribution of each is separated by using a hardware-based spectral phasor analysis. This approach avoids the need for multiple excitation wavelengths or multi-photon imaging, and is suitable for future clinical translation for noninvasive assessment of embryo viability.

Applications of Raman microscopy in breast cancer surgery: towards intra-operative assessment of surgical margins and sentinel lymph nodes

Notingher I

Breast cancer is the most frequent cancer among women, with 55,000 new cases diagnosed annually in the UK and 2.2 million worldwide. Surgery is the main treatment for breast cancer, aiming to remove the entire tumor while retaining as much healthy tissue as possible. Because sentinel lymph nodes are the first nodes to be involved when breast cancer metastasizes, it is a common practice for patients without preoperative diagnosis of positive lymph nodes to have sentinel lymph node sampling rather than axillary lymph node clearance. Raman spectroscopy is a powerful technique for analysing biological tissues at a microscopic level. Combining Raman spectroscopy with auto-fluorescence (AF) imaging, we developed selective sampling techniques that assess the whole surgical margins of excised tissue as well as detect positive sentinel lymph nodes. This dual-modality approach enables fast analysis of tissue (within 20-30 minutes for our first prototypes) with high sensitivity and specificity, without requiring extensive user training of subjective interpretation of images. With further development, the AF-Raman could help surgeons detect positive margins and positive lymph nodes in the first operation and could avoid second surgery for tumor re-excision or axillary lymph node clearance.

Integrated Photonics and Photonic Systems

On-chip III/V semiconductor graph lasers for neuromorphic computing

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We demonstrate the application of on-chip III/V semiconductor random graph lasers in neuromorphic computing tasks, where parts of the parameter space and processing of neural networks are offloaded to a physical system, with minimal post-processing required to obtain useful answers. The nonlinear interaction of lasing modes within our waveguide networks enables feature extraction and classification functionalities.

Our lasing system is a lithographically designed network of waveguides etched into a wafer-bonded layer of InP using Inductive Coupled Plasma Reactive Ion Etching. With InP providing gain, and the graph-like connected waveguides providing confinement, the network acts as a lasing medium, with many spatially overlapping modes competing for gain. Measuring the light scattered at the graph's nodes through a spectrometer allows us to observe the mode dynamics as we modify the gain landscape by patterning the pump laser's beam with a digital micromirror device (DMD). Fig 1 a) shows a schematic of this setup, with a spectrum from a part of the network and its LL curve shown in b) and c).

We can directly input image data into our system through patterned illumination and rely on the nonlinear competition between lasing modes to process it. Observing the lasing spectrum directly allows us to perform simple feature detection, and training a single regression layer on the spectra enables classification tasks. By scanning an image across the network to extract its features and projecting this data back onto the network to perform classification, we construct a two-layer photonic convolutional neural network, with 98.05% and 87.85% accuracies for MNIST and Fashion MNIST respectively.

While the system performs well without task-specific tuning, the top-down fabrication approach and the flexible input scheme allow for adjusting system parameters pre- and post-fabrication, and we explore how this affects the system's performance.

Cavity-Enhanced Fluorescence Detection for Single Molecules of Explosives

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With the increasing threat that explosives pose to national security, the importance of continual development of explosive trace detection (ETD) technologies cannot be overstated. In the present work, we demonstrate open-access microcavity-enhanced fluorescence detection of single molecules for use in ETD. 655nm quantum dot solutions are introduced into the optical cavity, where they undergo excitation by a 1 mW 475 nm continuous wave laser source. Subsequent fluorescent emission is detected using a single photon avalanche diode. Changing the key system parameters such as the cavity length, the radius of curvature of the cavity, and the flow rate, enables thorough characterisation of the detection system. For a detection time of 120 s, the concentration range of the input analyte solutions that enables successful single molecule detection is 1 × 10^-9 M to 1 × 10^-14 M; equating to approximately 300-0.003 ppt. The maximum signal to noise ratio achievable is ~220 at a cavity length of ~1 µm, owing to a signal enhancement by the Purcell effect. Successful detection of single molecules in the femtolitre sensing volumes occurs for a range of cavity lengths, providing multiple design options and combinations for a commercial device. Our findings show that this proof-of-concept device may have the potential to overcome sensitivity and selectivity issues associated with conventional methods of detection, thus establishing a foundation on which to realise the potential of such a sensor in developing commercial ETD devices.

Near-unity Raman β-factor of surface-enhanced Raman scattering in a waveguide

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To enhance the Raman scattering efficiency of photons by molecules, various techniques relying on either stimulated or surface enhanced Raman scattering (SERS) have been developed. But they are either limited by the poor control of scattered light, narrow bandwidth of resonance frequency, or restricted area of field enhancement. Here we present a unique waveguide approach to achieve broadband enhanced Raman scattering of molecules with precisely controlled propagation direction. We demonstrated 99% of the Raman photons can be coupled into the waveguide.

In this presentation, we will report directional broadband Raman scattering of light by molecules which are chemically coated onto plasmonic slot waveguide[1]. We spatially resolved the coupling in of the excitation laser and coupling out of Raman scattering, and investigated how the scattered Raman photons of molecules couple into the waveguide, propagate and couple out via the antennas. We have experimentally determined the fraction of spontaneous Raman scattering coupled into a plasmonic waveguide (β factor). The near-unity Raman β factor is due to the largely enhanced spontaneous Raman scattering rate into the waveguide mode. The enhancement mechanism can be understood analogously to fluorescence emission enhanced by the Purcell effect, due to increased vacuum fluctuations and increased density of states. While Raman scattering in highly localised metallic hotspots offers high enhancement factors for a few molecules, here, a plasmonic waveguide offers predictable broadband enhancement for many molecules with a greatly improved interaction volume compared to other SERS approaches. The ability of waveguide-SERS to direct Raman scattering is relevant to Raman sensors based on integrated photonics with applications in gas and bio-sensing[2].

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Electrically driven organic laser using integrated OLED pumping

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While organic light-emitting diode (OLED) technology is now well established, with OLEDs mass produced in smart phone displays and televisions, organic laser diodes have proven to be extremely difficult to demonstrate, despite significant research efforts over the last 30 years. Achieving direct injection lasing in an organic semiconductor is very challenging because the injected charges mostly form non-emissive triplet excitons that absorb light across the luminescence spectrum and quench the singlet population inversion. Here we address this grand challenge of organic photonics through integration of a thin-film polymer distributed feedback laser into the substrate of a pulsed blue OLED of exceptionally high light output [1].

The blue OLED was configured as an organic pin-diode structure on a flexible substrate, with electrodes designed to minimise series resistance while providing efficient light coupling through a semi-transparent silver anode. A 2nd-order distributed feedback laser based on poly(phenylenevinylene) derivative BBEHP-PPV was fabricated using UV-nanoimprint lithography before integration with the OLED via a parylene/$Al2O_3$/ZrO_2 multilayer stack.

Under electrical drive with pulses of a few nanoseconds the integrated device generates the highest peak power density ever reported for an OLED, with the electroluminescence internally pumping a population inversion in the BBEHP-PPV waveguide. Above a threshold peak current density of 2.8 kA/cm^2, the device emits laser light at 542 nm, in a double-lobed beam characteristic of the surface-emitting DFB laser cavity used, linearly polarized parallel to the grating grooves.

This result advances OLED technology into a new very fast and intense operating regime. Such bright, high bandwidth OLEDs can also be applied as Gbps data transmitters in optical wireless communications and may enable new integrated functions for communication and sensing in OLED displays.

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Gradient Calculation in Nonlinear Layers of Optical Neural Network using Amplitude Modulation and Lock-In Detection

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Optics provide a promising new platform for Artificial Intelligence hardware due to their inherent strengths in performing linear and parallel computations. Optical neural networks (ONNs) have shown progress in the inference stage, which typically consists of multiple linear layers followed by nonlinear activation function layers. While backpropagation is widely accepted as the most efficient way of training large Neural Networks (NNs), its application in optical implementations has been limited due to additional requirements.

Two approaches for gradient calculation in ONNs have been demonstrated experimentally to the best of our knowledge. Pai et. al. [1] demonstrated a way to calculate the gradient of the output with respect to the weight matrices using an integrated photonic platform and measuring the gradients via interferometry. This approach could not perform backpropagating through non-linear layers as finding an optical material that is nonlinear in its forward pass and linear in its backwards pass is non-trivial. Another approach demonstrated by Spall et al. [2] used a pump-probe process with a gas saturable absorber to optically calculated the gradient of the nonlinear layer with respect to its input using, however this method cannot be generalised to electronic activation functions.

We demonstrate a scheme that is applicable to both free space and integrated photonic schemes, for nonlinear gradient calculation across different nonlinear layers. By using lock-in amplifiers, capable of detecting very small AC signals, we measure the derivative of the nonlinear activation layer with respect to its inputs. This is achieved by amplitude modulating the input laser light at a given frequency, so that we can measure the derivative of the nonlinear activation layer with respect to its inputs synchronously during the forward pass.

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Engineering nonlinear nanowires via low-index materials

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In this study, innovative photonic nanowires are engineered utilising materials with a low refractive index and subsequently evaluated within the near-infrared spectrum to explore their nonlinear optical characteristics [1]. The research presents a compelling case for re-evaluating the conventional nonlinear figure of merit, proposing a recalibration in terms of the nonlinear phase shift and optical transmission over a specific propagation distance [2]. Utilizing this revised metric, the newly developed devices are shown to significantly surpass the performance of existing optical platforms, particularly within the linear dimension range of 50–500 µm, addressing a critical technological shortfall. Impressively, for ultra-short pulses of 85 femtoseconds at a carrier wavelength of 1480 nm and power levels below a micro-watt, these devices achieve a spectral broadening that surpasses 80% of the initial bandwidth within a mere 50 µm of propagation (see Figure) [3]. By harnessing CMOS-compatible technologies and leveraging well-established materials such as silicon, silica, and indium tin oxide, these devices offer considerable potential for the innovation of alternative all-optical devices. These devices are distinguished by their exceptional nonlinear performance within the specified range, paving the way for advances in photonic applications.

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Optics and Photonics at Extreme Wavelengths

Demonstration of High-Power Multi-Cycle Terahertz Pulses in Cryogenically-Cooled Lithium Niobate Wafer Stacks

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Lithium niobate wafers can be stacked to mimic periodically-poled crystals, providing a large-area source for laser-driven multi-cycle terahertz (THz) generation [1]. Stacking wafers allows for control over the number of cycles generated, with increasing numbers providing a higher energy and narrower bandwidth pulse [2]. However, the air/vacuum gaps between lithium niobate wafers act as Fabry-Pérot etalons, introducing a THz transmission loss and adding a phase-shift, which can alter the PPLN phase-matching condition and the generated THz frequency. These effects, alongside reabsorption of generated THz in the wafer stack, place a limit on the efficiency of the wafer-stacking method. We have demonstrated here that through cryogenic cooling of a wafer stack to 100 K, we can minimise the THz loss and greatly extend the number of wafers that can be stacked whilst maintaining a consistent THz electric field strength, as shown in Figure 1. Stacking up to 48 wafers, we produced 0.55 mJ THz pulses with 24 cycles, demonstrating an average power of 27.5 mW. The effectiveness of cryogenic cooling in reducing losses paves the way for stacks with even higher numbers of wafers, demonstrating the competitiveness of PPLN wafer stacks against traditional multi-cycle THz generation methods such as bulk PPLN crystals and complex setups employing chirped pulse beating and tilted pulse fronts. Alongside increasing the efficiency of the source, the change in temperature allows for tunability in the central frequency of the THz pulse. Among numerous potential applications, these narrowband pulses are particularly attractive for driving THz-based particle accelerators [3].

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Experimental Demonstration of Terahertz Spatiotemporal Wave Synthesis in Random Scattering Systems

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This work presents an experimental demonstration of achieving full-field control and manipulation of broadband terahertz (THz) pulses propagating through random scattering media[1]. By leveraging the time-domain nonlinear ghost imaging technique and genetic algorithm, we demonstrated that it is possible to synthesize an arbitrary field-defined spatiotemporal THz waveform at desired spatial positions within complex disordered systems.

The key innovation lies in the coherent detection of the scattered electric field at a specific target point, enabled by THz time-domain spectroscopy. Different from conventional optical approaches[2], our methodology facilitates direct waveform synthesis at the field level. This is achieved through the optimization of incident spatial patterns, either utilising genetic algorithms or by measuring transfer matrix, upon a nonlinear crystal– based on previous numerical work[3],[4]. The experimental results showcase remarkable spatiotemporal focusing and the ability to recover transform-limited pulses with null carrier-envelope phase and demonstrate control over the absolute time delay of the transmitted waveforms.

This work represents a paradigm shift in the THz domain and holds profound implications for various applications, including time-reversal control of optical waves and metamaterial analogue computing[5].

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Medical Applications of Light

Clinical translation of an early-photon imaging system for safe placement of feeding tubes

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Placement of nasogastric tubes (NGTs) is a routine medical procedure, yet the consequences of misplacement are dire (e.g. food entering the lungs, leading to death and/or disability from pulmonary complications). Current practice for NGT localisation relies on X-rays. This introduces delays to initiation of feeding (associated with worse patient outcomes) and increases burden on healthcare system resources and exposes patients and staff to ionising radiation. We have developed a compact bedside system with off-the-shelf componentry, capable of providing real-time guidance when placing NGTs. This device utilises an imaging implementation of time-correlated single-photon counting (TCSPC): early photons with a near direct path from a point source of light placed inside an NGT are detected by a time-resolved single-photon sensitive camera positioned outside of the patient. To date, we have validated device functionality, specifically differentiation between stomach and non-stomach NGT localisation, in porcine and human cadaver models. We shall shortly be commencing a first in-human clinical study at Edinburgh's Royal Infirmary.

Optofluidic Methods for Enhanced Pharmaceutical Purification Analytics

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During live-attenuated influenza virus (LAIV) vaccine production, it is necessary to test products after manufacture to verify the concentration of virus particles [1]. Typically, this is done using biochemical assays such as the fluorescent focus assay (FFA) [2]. FFA is cell culture based and requires 1-6 days to complete [3]. The significant time required for the analysis makes it impossible to use FFA and similar assays to monitor the vaccine production cycle in real time. As a result, there is currently no feedback on any process parameters during a production cycle, meaning yield is not necessarily optimal. Assays such as the enzyme-linked immunosorbent assay (ELISA) can be completed in under 3 hours [4]; however, given the dilute nature of impure samples, their sensitivity limits pose a challenge to the quantification of LAIV.

Here, we propose using fibre-enhanced fluorescence to provide purification analytics on dilute vaccine samples. The method employs optofluidic hollow-core photonic crystal fibres (HC-PCFs) that guide light by interference effect in a micro-structured cladding, permitting light guidance at the centre of a microfluidic channel [5,6]. By surface functionalising the fibres with antibodies, influenza viruses are immobilised onto the fibre surfaces and then fluorescently labelled. The fibre's waveguiding properties are then used to collect and guide the weak fluorescence of dilute samples, with the extended path length enhancing the overall sensitivity compared to that achieved in conventional fluorimetry methods. The HC-PCFs geometry also allows for continuous flow, potentially allowing in-line analytics in a pharmaceutical production setting. We anticipate that this alternative detection approach could lead to feedback within 3 hours with greater sensitivity than ELISA, increasing the yield and quality of products and thereby reducing the cost of accessing vaccination.

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Low-cost optical illumination, spectroscopy, and fluorescence lifetime systems for monitoring of photodynamic therapy

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Photodynamic therapy (PDT) is a light-based tumour treatment, often used alongside resection. A photoactivatable agent called a photosensitiser (PS) is either topically applied to the tumorous region or is introduced intravenously and localises in the malignant tissue. When illuminated at a PS specific wavelength, in the presence of oxygen, an excited singlet state of oxygen is produced causing localised cell death. Measuring the quantity of singlet oxygen produced is a method to monitor PDT dosing. Singlet oxygen production occurs through photon stimulated excitation of the PS to a triplet state, followed by energy transfer to oxygen molecules exciting the singlet state. Alternatively fluorescent decay of the PS is also possible, indirectly linking visible fluorescent emission to singlet oxygen generation. Studying the fluorescence emission of the PS gives insight into singlet oxygen production and PDT dosage.

We present multiple portable low-cost systems developed to monitor the fluorescent emission of the PS, targeting accurate dosing during PDT treatment. Utilising low-cost laser diodes we have developed fibre-based systems to allow monitoring of fluorescence spectra during PDT. The small, portable systems can be transported and implemented in various lab spaces, as well as being tailored to clinical needs. Swapping the laser diode component allows practical wavelength matching to PS. We further target low-cost frequency-based fluorescence lifetime monitoring. Deploying a MOKU:Go, and an InGaAs photodetector the laser diode is modulated up to 20MHz, a phase shift in returned fluorescence corresponds to varying lifetime. Both systems use the same 400µm core fibres; a handheld fibre probe allows directed and controlled illumination over fluorescent samples. Using a common PS, Rose Bengal, these systems have been characterised for both fluorescence spectroscopy and frequency domain fluorescence lifetime. We are applying these techniques to investigate novel photosensitisers currently in development.

Non-invasive assessment of the developmental potential of embryos using digital holographic microscopy

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Embryo quality is a crucial factor affecting live birth outcomes. However, an accurate diagnostic for embryo quality remains elusive in the in-vitro fertilization clinic as current approaches for assessing embryo quality are subjective (morphology) and invasive (biopsy), and not predictive of live birth. Determining physical parameters such as the refractive index of the embryo may offer key information for this purpose. Elevated intracellular lipid causes a shift in refractive index in other cell types and in embryos, is associated with poor quality.

Here, we demonstrate that digital holographic microscopy (DHM) can rapidly and non-invasively assess the refractive index of embryos grown in conditions known to negatively impact quality. Murine embryos were cultured in either low- or high-lipid containing media and digital holograms recorded at the 2-, 4-, 8-cell, morula- and blastocyst-stages of development. The phase of the recorded hologram was numerically retrieved, from which the refractive index of the embryo was calculated. We confirmed that culture in high-lipid media significantly increased intracellular lipid compared to the low-lipid group. We show that the results obtained with DHM agree with intracellular lipids quantified with BODIPY staining.

For the first time, we have demonstrated that changes in refractive index may be non-invasively measured in the embryo in the complete absence of exogenous stains. As elevated intracellular lipids compromise embryo health, DHM may prove beneficial in developing an accurate diagnostic of embryo quality.

Machine Learning Estimate the Optical Properties of Tissue

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Estimation of the optical properties of scattering media such as tissue is important in diagnostics as well as in the development of techniques to image deeper. There are many well-accepted methods of measurement, but they all have their own set of shortcomings. The Integrating Sphere Spectrophotometry method is the first choice for the ex-vivo measurement, however, the impact of water loss cannot be ignored. For in-vivo measurement, Diffuse Reflectance Spectroscopy and Spatial Frequency Domain Imaging are well-accepted methods for measuring optical properties, but both methods require specialist equipment, careful calibration, the recovered values are highly dependent on the validity of the optical model used, and measurements are sensitive to ambient light. Moreover, in most cases, these methods do not reveal the anisotropy factor, g.

Machine learning has been proposed by several authors as a means of recovering optical properties from either the backscattered or the transmitted light. We train a general-purpose convolutional neural network RESNET 50 with simulated data based on Monte Carlo simulations. Compared with previous work, our approach gives comparable or better reconstruction accuracy when training on a much smaller dataset. Moreover, by training on multiple parameters such as the intensity distribution at multiple planes or the exit angle and spatial distribution of the photons one achieves improved performance compared to training on a single input such as the intensity distribution captured at the sample surface. Currently, our best model can measure the reduced scattering coefficient within a 2.14% error and the absorption coefficient within a 3.43% error. In the next step, we are aiming to train a network able to separate the scattering coefficients and anisotropy g in certain scattering regions.

Development of an Optical Fibre Sensor for measuring Venous Refill Time under a Compression Bandage

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Leg ulceration is a costly condition for the healthcare system. Annually, its treatment is estimated to cost the National Health Services (NHS) approximately £2 billion and is mainly caused by Chronic Venous Insufficiency (CVI) [1]. One of the treatments is to use a compression bandage to enhance blood circulation inside the veins.

Venous Refill Time (VRT) is a quick and inexpensive approach for the screening of CVI. It involves using a Photoplethysmography (PPG) measurement with IR light on the leg, where the refill time of venous blood is monitored after a calf exercise is performed. The refill time is considered 90% of the baseline after the exercise. If the VRT is less than 18 seconds, it shows the venous pump is abnormal [2].

In this study, data were collected from healthy volunteers to assess VRT utilising an optical fibre sensor. It involved obtaining two PPG signal measurements using a fabricated sensor. First, measurements were acquired without a compression bandage, and subsequently, another measurement was taken while the compression bandage being applied. During the test, the sensor was positioned 10 cm above the ankle and the dorsiflexion exercise was performed ten times.

Results will be presented comparing VRT with and without compression bandaging in healthy volunteers. Future research may investigate the effect of the compression bandage on the VRT in participants with venous ulcers.

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Metamaterials and Plasmonics

A reprogrammable metasurface for LiDAR applications

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Reprogrammable metasurfaces enable active modulation of light at subwavelength scales. Operating in the microwave, terahertz, and mid-infrared ranges, these metasurfaces find applications in communications, sensing, and imaging. Electrically tunable metasurfaces operating in the near-infrared (NIR) range are crucial for LiDAR applications [1-2].

Achieving a NIR reprogrammable metasurface requires individual gating of nano-antennas, emphasizing effective heat management to preserve device performance. To this end, here we propose an electrically tunable Au-vanadium dioxide (VO2) metasurface design on top of a one-dimensional Si-Al2O3 photonic crystal (PC), positioned on a SiC substrate. Each individual Au-VO2 nano-antenna is switched from an Off to ON state via Joule heating, enabling the programming of the metasurface using 1-bit (binary) control. While operating as a nearly perfect reflector at λ0=1.55 µm, the materials, thickness, and number of the layers in the PC are carefully chosen to ensure it acts as a thermal metamaterial. This enables efficient heat transfer from the Au nano-antennas to the SiC sink. Moreover, with high optical efficiency (R~40% at λ0), appropriate thermal performance, and feasibility, the metasurface also enables broadband programmable beam steering in the 1.4 µm-1.7 µm range for a wide steering angle range. This metasurface design also offers active control over NIR light transmittance, reflectance and absorptance in the wavelength range of 0.75 µm-3 µm. These characteristics render the device practical for LiDAR and active filtering.

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All-dielectric qBIC-based metasurface for sensing

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Traditional plasmonic metasurfaces face limitations due to low Q-factors, high ohmic losses, and decreased specificity [1]. In contrast, all-dielectric metasurfaces exhibit lower ohmic loss [2] and excel at controlling light's direction, amplitude, and phase [3]. These characteristics also enable enhanced multiplexing capabilities, making all-dielectric metasurfaces a versatile and efficient option for next-generation sensing technologies.

To achieve both high Q-factors and external field enhancement concurrently, our structure employs the use of quasi-bound states in the continuum (q-BIC). These sharp resonances can be manufactured in all-dielectric metasurfaces by introducing a small degree of asymmetry to a resonator or resonator pair. These qBICs, characterized by sharp Fano resonances with long optical lifetimes, are achieved by incorporating slight asymmetry into the design of nanoresonators. The fabrication and control of these resonances offer unique opportunities for creating high-quality sensors.

In this study, our novel design for an all-dielectric nanoresonator with qBIC resonances has been adapted to use Si3N4, transferred onto a fused silica substrate and submerged in a water based medium as the sensing envirnment. This results in a practical design supporting a high Q-factor and field enhancement external to the structure. The results from the fabrication and characterization of these metasurfaces are presented and compared with simulations. The realized design provides resonances that are robust, highly tubeable and ideal for multiplexed sensing in the visible and near-infrared regions.

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A reprogrammable metasurface for LiDAR applications

Bradley L

Reprogrammable metasurfaces enable active modulation of light at subwavelength scales. Operating in the microwave, terahertz, and mid-infrared ranges, these metasurfaces find applications in communications, sensing, and imaging. Electrically tunable metasurfaces operating in the near-infrared (NIR) range are crucial for LiDAR applications [1-2].

Achieving a NIR reprogrammable metasurface requires individual gating of nano-antennas, emphasizing effective heat management to preserve device performance. To this end, here we propose an electrically tunable Au-vanadium dioxide (VO_2) metasurface design on top of a one-dimensional Si-Al_2O_3 photonic crystal (PC), positioned on a SiC substrate. Each individual Au-VO_2 nano-antenna is switched from an Off to ON state via Joule heating, enabling the programming of the metasurface using 1-bit (binary) control. While operating as a nearly perfect reflector at λ_0=1.55 µm, the materials, thickness, and number of the layers in the PC are carefully chosen to ensure it acts as a thermal metamaterial. This enables efficient heat transfer from the Au nano-antennas to the SiC sink. Moreover, with high optical efficiency (R~40% at λ_0), appropriate thermal performance, and feasibility, the metasurface also enables broadband programmable beam steering in the 1.4 µm-1.7 µm range for a wide steering angle range. This metasurface design also offers active control over NIR light transmittance, reflectance and absorptance in the wavelength range of 0.75 µm-3 µm. These characteristics render the device practical for LiDAR and active filtering.

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Tunable metasurfaces for generating meta-pixels and sensing applications

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Active and reversible tunning of metasurfaces has attracted significant attention for applications such as meta-lenses, polarisation converters, nano-sensors, and nano-switches [1]. Tunable metasurfaces offer substantial capabilities by employing various external stimuli, such as mechanical, electrical, and optical means. Here, I briefly review our recent achievements in exploiting various tools to tune the metasurfaces [2-4]. First, I demonstrate electrically tunable metasurfaces driven by the thermo-optic effect of silicon [2]. As shown in Fig. 1, our metasurface encapsulated by a transparent localised heater enables modulation rise-time of < 625 µs, leading to programming the spatially individual metasurfaces on demand [2]. Furthermore, I show how phase-change materials, such as antimony trisulfide (Sb2S3), can further improve the tunability of metasurfaces for broader tunability. Alongside these, I demonstrate a mechanically moving surface pattern upon light exposure by the photoisomerisation of polymers [3]. Finally, I will demonstrate practical applications, such as generating meta-display, ultra-sensitive detection of biochemical constants, and light steering devices [2-4].

Figure 1. (a) SEM of the Si hole-array metasurface embedded in ITO and (b) Picture of the printed circuit board. (c) Transmission intensity, indicating the switching rise-time and (d) tuning of individual metasurface pixels by controlling the micro-heaters.

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All optical switching of magnets in a magnetic metasurface with a low power cw laser.

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All-optical magnetic switching represents a next-generation class of local magnetisation control, with wide-ranging technological implications. 75% of all data is stored magnetically and the predominant current recording technology uses power-consuming magnetic fields with plasmonic focusing of laser heating for Heat Assisted Magnetic Recording (HAMR). Existing (field-free) all-optical switching schemes are unsuitable for device integration, typically requiring power-hungry femtosecond-pulsed lasers and complex magnetic materials. Here, we demonstrate deterministic, all-optical magnetic switching using a low-power, linearly polarised continuous-wave laser in magnetic metasurface consisting of nanos-scale bar magnets in a square array made from simple earth abundant ferromagnetic alloys (Ni81Fe19, Ni50Fe50) and dielectrics. We use an optical interference effect to dramatically enhance absorption in the nanomagnets, enabling high fidelity writing at powers as low 3 mW. Isolated and densely packed nanomagnets are switched across a range of dimensions, laser wavelengths and powers. All artificial spin ice vertex configurations are written with high fidelity, including energetically and entropically unfavourable `monopole-like' states inaccessible by thermalisation methods. No switching is observed in equivalent structures with pure Co magnets, suggesting multi-species interactions within the nanomagnet play a role. The results presented here point to the potential of low-cost, low-power optically controlled devices with applications in data storage, neuromorphic computation and reconfigurable magnonics.

Almost-Periodic Time-Varying Media

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Within the realm of time-varying media, we demonstrated in Ref. [1] the temporal analogue of an archetypal photonic structure, a Bragg grating, wherein the relative permittivity is a periodic function of time rather than space. Waves falling inside the first-order momentum bandgap, formed in the corresponding Brillouin diagram, are apparently parametrically amplified, rather than attenuated as in spatial gratings. By contrast to the latter, where the refractive index profile may be written using well-established technologies, such as phase-mask illumination of femtosecond pulses of UV light, time-modulation requires the nonlinear response of certain photonic time-crystals (e.g., ITO). Consequently, imperfections in phase or amplitude modulation, impurities, and further defects in the temporal unit cellular structure are inevitable. Acknowledging the inherent challenges of temporal modulation, we examine the optical response of a 'time-slab' of a medium with an almost-periodic permittivity, aiming to bridge the gap between ideal temporal Bragg gratings and those likely to be implemented in the laboratory. Introducing a temporal version of vectorial coupled-wave equations, we identify a sub-critical regime wherein, remarkably, parametric amplification outperforms periodic counterparts, even leading to significant amplification for sub-harmonic resonances, particularly in the epsilon-near-zero regime. Therefore, contrary to conventional wisdom, structural defects and phase fluctuations in the temporal medium paradoxically enhance performance, as demonstrated through a detailed analysis of wave propagation, offering insights into potential advancements in the field.

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Laser written volumetric metamaterials for multi-plane light conversion

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Multi-plane light converters (MPLCs) are emerging 3D beam shaping devices capable of transforming a basis of input light modes to a different target basis of output modes [1,2]. This process can be understood as a high-dimensional basis rotation - a widely sought after yet challenging to achieve operation in photonics, with applications spanning optical communications, computing, and imaging, in both classical and quantum regimes. MPLCs consist of a series of inverse-designed diffractive elements separated by free-space. They have so far been realised through a few different means, for example, using multiple reflections from spatial light modulators or lithographically etched phase masks and metasurfaces. In this work we investigate how millimetre-scale MPLCs can be manufactured within a glass chip using single-step direct laser writing. Irradiating fused silica glass with femtosecond laser pulses can lead to self-forming nanogratings, which are birefringent and deterministically imprint controllable geometric phase onto light propagating through them [3] (see image below for an example of light shaping with one such laser-written structure). These features make such nanogratings promising candidates for creation of the diffractive elements in a glass-imbedded MPLC. Here we present proof of concept experiments demonstrating light shaping and spatial mode sorting with transmissive several-plane MPLCs.

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Nanophotonics and Nanoscale Quantum Optics

Quantum bistabilty in nanolasers

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Quantum dot nanolasers are very promising for on-chip and inter-chip communications because they have minimal footprint and thermal load; from a fundamental point of view, a consequence of their size is that light emission in nanolasers is dominated by quantum effects. We model these nanolasers by including quantum correlations between photons and emitters, which allow us to determine the nature of the emission and the presence of superradiance. In contrast to the predictions of semi-classical theories, we find mixed states with co-existing coherent and incoherent emission. Furthermore, the onset of lasing requires finite amplitude fluctuations of the coherent field (green, cyan and blue curves in figure 1) and at threshold the coherent state is a squeezed state. Correlations between emitters lead to superradiance and increase the stimulated emission threshold (blue line), but this effect is strongly reduced by phonon scattering (cyan line). The difference between lasing and non-lasing solutions can be detected by measuring the first-order coherence, g (1) . Our predictions provide a tool for a correct interpretation of experimental measurements at the onset of lasing and open the way to the generation of quantum light with nanoscale sources.

Enhancing NV Center Emission Using Localized Plasmon Hotspots in Gold Nanofoam Substrate

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The quantum revolution requires advanced quantum emitters capable of emitting coherent photons that can be controlled, triggered on demand, and integrated into photonic circuits. Diamond-based solid-state emitters such as Nitrogen-Vacancy (NV) centers hold great promise due to their stable emission properties and compatibility with various environments without degradation. However, their photon emission rate is slow (lifetime: 20 ns-30 ns), limiting the bandwidth of their utility in quantum technologies. Altering the proximity environment around the emitter offers a non-deteriorating method to control the transition rate between energy levels of an emitter, potentially increasing photon emission efficiency. We propose a method to enhance the light-matter interactions of NV centers using a gold (Au) nanofoam substrate. The substrate is fabricated through chemical etching of an Au-Ag (Silver) alloy, where the Ag is selectively removed, leaving behind a network of randomly distributed Au ligaments and pores with a few 10s of nanometers width. The nanodiamonds containing NV centers are coupled with such interconnected ligaments that provide numerous attachment sites owing to high surface area-to-volume ratio. The disordered structure creates diverse electromagnetic field hotspots through surface plasmon localization, boosting light-matter interactions [1]. Our results demonstrate that the Au-nanofoam enhances photoluminescence (PL) and accelerates emission rates of NV centers. It is found that there is an average 5 times reduction in the NV's emission lifetime. The findings hold great promise for the practical utilization of such systems in various quantum technologies and sensing applications. The current approach is based on the randomly distributed emitters coupled with Au-nanofoam. However, surface functionalization or directed deposition techniques can selectively position emitters at desired locations, enabling precise control over their coupling with selective field hotspots.

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Third-harmonic chiroptical scattering in hybrid metamaterials

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We demonstrate the third-harmonic chiroptical scattering effect in hybrid (plasmonic/dielectric) nanohelices.

Chiral nanotechnology is of interest for negative refractive index materials, nanorobotics and molecular sensing. Accurate determination of chirality is essential for bio/nano-machinery and chiral photochemistry. It was recently discovered that third-harmonic chiroptical scattering can reveal the chirality of metal (silver) nanohelices, dispersed in water [1]. Similar scattering was reported from semiconducting (CdTe) nanohelices [2]. However, such an effect has never been shown in hybrid metamaterials. These materials can mitigate the individual disadvantages of both plasmonic and dielectric resonances. They offer broadband spectral and intensity tunability across the UV, visible and near-IR spectrum [3]. Moreover, previous work on Ag nanohelices focused only on right-handed scattering, leaving the forward scattering process unexplored.

Figure 1 displays the forward scattering signals of left- (L) and right-handed (R) nanohelices and silver nanohelices under left-handed circularly polarized (LCP) and right-handed circularly polarized (RCP) light, at 1095 nm. Cubic functions ($y=Ax^3$) are excellent fits to the experiment data. As expected, the chiroptical contrast reverses between L and R nanohelices, see Figure 1a and 1b. In our presentation, we will show how this forward scattering compares to right-handed scattering intensity and we will identify the scattering regime. We will also present our first results from hybrid plasmonic/dielectric metamaterials and discuss their significance.

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Local tuning of Rydberg exciton energies in nanofabricated Cu2O pillars

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Rydberg excitons within Cu2O exhibit remarkable optical nonlinear characteristics [1]. Leveraging these properties for quantum applications necessitates confinement sizes matching the Rydberg blockade, which in case of Cu2O, could extend up to a few microns. In this study, we demonstrate a top-down approach to achieve exciton confinement through focused-ion-beam etching of micropillars on a polished bulk Cu2O crystal, while preserving their excitonic properties. By etching the crystal to micron sizes, we were able to have localized and precise tuning of Rydberg exciton energies via optically induced temperature changes. The tunablity is also driven by the size of the micropillars [2]. These findings lay the groundwork for utilizing the substantial nonlinearities of Cu2O Rydberg excitons within micropillars to create non-classical light sources. Additionally, the ability to finely tune emission energies provides a viable avenue for constructing a scalable photonic quantum simulation platform.

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Probing Efficiency and Enhancement of FRET by Local Density of States in Tailored Plasmonic Nano-gaps

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Understanding Förster Resonance Energy Transfer (FRET) is crucial for various applications in fields ranging from biophysics, nanotechnology, and materials science. FRET relies on the non-radiative energy transfer between a donor and acceptor fluorescent molecules, a process which is greatly influenced by both the surrounding environment and the local density of states (LDOS). This theoretical study explores FRET enhancement within plasmonic nano-gaps formed between extended 100 nm thickness film of gold and 100 nm diameter gold nano-particle (Figure 1). Using FDTD simulations, and treating the donor and acceptor as classic electric dipoles, the impact of the plasmonic nano-gap size on the LDOS and power transferred from donor to acceptor, normalized to the power in free space, is investigated.

Plasmonic nano-gaps of varying thicknesses (4 nm, 6 nm, 8 nm, 10 nm, 15 nm, 20 nm, and 30 nm) were modelled, introducing high LDOS for both the donor and acceptor dipoles, which, in turn, leads to enhanced Förster Resonance Energy Transfer (FRET). Our calculations demonstrate that changing the plasmonic nano-gap thickness allows us to control the LDOS and enhances the FRET rate over orders of magnitude. Additionally, the donor-acceptor separation, (r(DA)), inside the plasmonic nano-gap resulted in very different impact on the FRET rate and FRET efficiency depending on the nano-gaps thickness. In small gaps (4 nm), varying (r(DA)) from 1 nm to 20 nm resulted orders of magnitude modifications of both the FRET rate and efficiency, while in larger gaps (30 nm), both remained largely unchanged. This illustrates the versatility of plasmonic nano-gaps in controlling FRET processes.

Two-photon-polymerization as a method to place a single quantum dot near a single Au bipyramid to achieve room temperature strong coupling

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The investigation of semiconductor quantum dots (QDs) interacting with plasmonic structures in photonics has garnered substantial interest due to its potential as a source of single photons for quantum applications, opening avenues for innovative optical effects relevant to sensing, imaging, quantum information processing. A significant challenge in this context pertains to determining an effective approach for precisely situating the QD in proximity to the plasmonic structure. To address this challenge, researchers have previously used the plasmon-induced two-photon polymerization method to place nanoemitters within the plasmonic hotspots near nanocubes [1]. Nanocube have multiple hotspots. Au bipyramids (BPs), in contrast, present a single hotspot at substrate surface. Furthermore, BPs are distinguished by their pronounced electric field enhancements at the sharply pointed tips, resulting in distinctive and sharp plasmon resonances that lead to a substantial increase in electric field intensity.

For the precise localization of QDs in close proximity to the Au BPs, we employed the two-photon polymerization method, utilizing QDs dispersed in a polymer hosts. By utilizing a laser operating at a power level below the polymerization threshold, we exclusively achieved polymerization and the positioning of QDs in regions adjacent to the Au BPs, where the intensity had been enhanced due to the plasmonic effect. Using this method, the QD-plasmon interaction can enter the strong coupling regime. Clear Rabi splitting is observed in the dark field scatter spectra for single QD-Au BP pairs. There are only a few examples of experimental strong coupling with a single plasmonic nanoparticle reported to date.

The results presented validate this approach for fabrication of strong coupling components. Further characterization of the strongly coupled exciton-plasmon pair will also be presented.

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Calculation of the light scattering and completeness of eigenmodes in the resonant-state expansion

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We present an eigenmode based method to calculate the scattering-matrix and the optical cross-section of resonators. The eigenmodes of the system of interest are calculated via perturbation of an analytically solvable basis system using the resonant-state expansion (RSE) [1]. The eigenmodes form a complete set, and one can construct the Green’s function as a Mittag-Leffler series. The scattering-matrix can be uniquely linked to the Green’s function, and from it the cross-section can be found [2]. The non-resonant contribution to the scattering-matrix is fully taken into in the Green’s function, thus there is no need for further fitting or other approximations [3]. This method eliminates the overlap integrals between the excitation and the mode fields used in other approaches, making it computationally highly efficient. For illustration, the cross-section of a dielectric sphere and a cylinder is calculated over a broad frequency range. The perturbed modes form a complete set inside the basis system, both inside and outside of the resonator. The impact of this on the scattering calculation and on other applications is also discussed.

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Stable single photon emitters with large Debye-Waller factor in silica

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Single photon emitters in wide bandgap materials are a promising platform for the achievements of many quantum applications, such as quantum photonics devices and scalable quantum information architectures etc [1,2]. Although a plethora of single-photon emitters have been identified in diamond and silicon carbide (SiC) [2,3], diamond and SiC are not good materials for photonic structure fabrication which is a hindrance for on-chip quantum devices developments. Thus, it has still a need to find out the spin defects in other materials with well-established photonics structure fabrication methods, such as nitride materials and silica.

Here, we report on a new unknown single photon emitter in silica. The spectrum of the emitter shows a clear zero-phonon line at around 580 nm followed by two small phonon sidebands, one at around 590 nm and the other one at about 630 nm, as shown in Figure 1(a). The second-order autocorrelation function measurements of the defects show a dip well below 0.2 at g(2)(0), indicating that the defects are single photon emitters and high single photon purity (see Figure 1(b)). Moreover, the Debye-Waller factors of the reported single photon emitters were measured to be between 0.5 and 0.74. These large Debye-Waller factor values are not common, and it provides great advantage to improve photon entanglement efficiency. The spin dynamics of the emitters was investigated and it can be described by standard three-level system model. The excitation power dependent photoluminescence (PL) measurements show that the saturated PL intensity is up to 45.2 kcounts/s. We also demonstrate that the fluorescence is linear polarized.

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Realization of Z2 topological photonic insulators based on bulk transition metal dichalcogenides

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Recently a new field of nanophotonics based on bulk transition metal dichalcogenides, two-dimensional materials with weak van der Waals bonding between layers, has emerged. These materials possess high oscillator-strength excitons and can be transferred repeatedly on various substrates, enabling tunable heterostructures for novel optical devices. Their high refractive indices (up to n=5) and a variety of transmission windows allow the fabrication of nanophotonic structures with a tightly localised electromagnetic field and hence strong nonlinear effects.[1]

We demonstrate topologically distinct photonic crystals on slab waveguides of thin exfoliated films of WS2. The spin-Hall hole lattice structures are fabricated via electron beam lithography and reactive ion etching with flake alignment and shape optimization (Fig. 1a). Topological photonic devices are essential for various nonlinear and quantum applications, since they have unidirectional photonic edge states at their interface, which have inherently low scattering losses and topologically protected backscattering-immune transport.[2] A symmetric lattice (R=R0) has a Dirac cone at Γ point, but perturbations open a gap, producing a topological photonic insulator. At the domain interface a topological interface states appear in the gap, confirmed with direct angle-dependent reflectance measurements and band structure simulations (Fig. 1b,c). Unidirectional propagation confined in the slab waveguide controlled with the handedness of circular polarization is observed in emission, and confirmed with simulations of the same structure (Fig. 1d,e).

Fig. 1. a) SEM of hole lattices in 71 nm WS2 on SiO2/Si. b) Measured angle-dependent reflectance of the interface in a). c) Corresponding simulated density of states near Γ (ky=0). d) Real-space propagation at the domain interface, 881 nm excitation. e) Corresponding simulation of integrated electric field in the flake.

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Nonlinear Photonics

Comprehensive study of nonlinear harmonic generation in low-index media

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Research into conductive oxides has increasingly captured the attention of the photonics community, due to their distinctive linear and nonlinear optical properties [1]. Although recent experimental works have shown promising results for high harmonic generation from oxides thin films, a comprehensive understanding of their electro-optical behaviour at the nanoscale remains elusive, primarily due to the absence of a robust theoretical framework [2,3]. In our study, we specifically target aluminium zinc oxide, as representative low-index material, optically pumped in its epsilon-near-zero spectral region with femtosecond laser pulses. This excitation results in relatively efficient frequency up-conversion, yielding both even and odd harmonics up to the seventh order (see Figure). To analyse these phenomena, we employed a modified hydrodynamic-Maxwell model that considers linear and nonlinear dispersion, nonlocal effects, surface contributions, magnetic, and bulk nonlinearities [4]. This comprehensive model covers a broad spectral range, extending over two and a half octaves from the ultraviolet to the near-infrared region. Our findings significantly advance the understanding of the fundamental material parameters that govern optical nonlinearities in conductive oxides. The insights gained from this research are crucial for the future development of these materials in applications across sensing, ultra-fast physics, and spectroscopy.

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Parametric Interaction of Laser Cavity-Solitons with an External CW Pump

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Laser cavity-soliton microcombs are robust and controllable [1-3], but have not been mixed so far with external sources. Multi-source pumping has been explored in externally-driven microcomb configurations as a tool to enhance cavity-soliton states in a variety of ways, including conversion efficiency [4], stability and studying new types of soliton [5]. We present a study of the first such interaction of a laser cavity-soliton microcomb with an externally coupled, co-propagating tunable CW pump, observing parametric Kerr interactions which lead to the formation of both a cross-phase modulation and a four-wave mixing replica of the laser cavity-soliton.

We compare and explain the dependence of the microcomb spectra from both the cavity-soliton and pump parameters, demonstrating the ability to adjust the microcomb externally without breaking or interfering with the soliton state. The parametric nature of the process agrees with numerical simulations. The parametric extended state maintains the typical robustness of laser-cavity solitons.

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Broadband Infrared Imaging Governed by Guided-Mode Resonance in Dielectric Metasurfaces

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Nonlinear metasurfaces have experienced rapid growth due to their potential in related applications, including infrared imaging and spectroscopy [1,2,3]. Current research has been devoted to improving conversion efficiency under moderate input intensities to exploit metasurfaces as a practical imaging platform. To date, nonlinear metasurfaces have focused on employing high-Q resonances to increase efficiency. However, this limits the range of operating wavelengths. Here, we overcome this issue by introducing a new nonlinear imaging platform utilising a pump beam to enhance signal conversion through four-wave mixing (FWM), whereby the metasurface is resonant at the pump wavelength rather than signal or nonlinear emissions [4]. As a result, we demonstrate broadband nonlinear imaging for arbitrary objects using metasurfaces. By introducing a silicon disk-on-slab metasurface, we exhibit a guided-mode resonance at the pump wavelength, enabling direct conversion of a broad IR image ranging from 1000 to 4000 nm, into visible. Importantly, adopting FWM substantially reduces the dependence on high-power signal inputs or resonant features at the signal beam by utilising the quadratic relationship between the pump intensity and the FWM emissions. Our results unlock the potential for broadband infrared imaging capabilities with metasurfaces, making a promising advancement for all-optical infrared imaging techniques with chip-scale devices.

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Infrared imaging with nonlinear silicon resonator governed by high-Q quasi-BIC states

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Infrared to visible up-conversion serves to expand the purview of imaging technologies which can pose widespread impacts in medicine, spectroscopy, night vision, and broadband imaging [1,2]. The ability of resonant dielectric nanoantennae to enhance nonlinear light-matter interactions whilst minimising optical losses has proven them to be a promising platform for carrying out frequency conversion. Their Mie-type resonances exhibit strong field confinement which can be controlled through the careful design of antenna geometry and/or excitation using structured light beams [3]. By constructing resonances with precise multipolar compositions, methods for boosting nonlinear interactions such as quasi-bound states in the continuum (BICs) have been proposed [4,5].
By enhancing the four wave mixing (FWM) process in a silicon nanodisk supporting a pair of high-Q quasi-BIC resonances, we demonstrate how NIR to VIS images can be captured even in the presence of low signal powers, approximately 1mW, by addition of an externally applied pump at 10mW [6]. The high-Q resonances were formed via the suppression of leaky modes at the point of anticrossing between high and low order multipoles at two different frequencies culminating in two distinct quasi-BIC states: one for each of the pump and signal. Using a point scan imaging system, images of an arbitrary target were reconstructed using third harmonic generation and FWM signals. Notably, we convincingly show how, owing to a quadratic dependence on pump power, FWM provides an additional degree of freedom for boosting conversion efficiency in low light conditions where harmonic processes are severely hindered.

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Remote Focusing via Dispersion Compensation in a Temporally Focused 2-Photon Microscope

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Temporal focusing (TF) spatially separates the constituent wavelengths of the excitation laser by introducing a grating in a conjugate imaging plane [1], elongating the pulse temporally. Subsequently, the beam is focused by the microscope objective where the shortest pulse is confined to the geometric focal point and temporally broadened above and below. In doing so, high temporal photon density is achieved only at the focal plane, thus optical sectioning is made possible. In the absence of strong spatial focusing, TF provides a regime suitable for wide-field multi-photon microscopy in depth [2].

Previous work demonstrated both theoretically and experimentally the possibility of shifting the location of the TF focal plane by altering the phase of the initial laser pulse [3]. To date, the few systems that demonstrate remote temporal refocusing employ spatial light modulators [4-7], acousto-optical modulators [7] or electrically tuneable lenses [2] that can be costly and complex to align.

We demonstrate a TF setup in combination with simple dispersion management to axially shift the temporal focus. We present direct measurements of the pulse duration as a function of axial position by employing a custom built inline autocorrelator [8], capable of measuring laser pulses with a high degree of divergence, post objective. Using this, we directly measure the change in pulse duration introduced by the temporal focusing. Exploiting our home-built pulse compressors dispersion compensation and that of our commercial Ti:Sa laser, we translated the temporal focus remotely by 30µm using a change in pre-compensation of 8Kfs2. Therefore we have demonstrated our ability to remotely shift the focal plane of our microscope. Future work will involve increasing GDD induced refocusing speed, expanding into 3-photon microscopy and 3-dimensional imaging.

Second harmonic generation enhancement in hybrid Mie-plasmonic modes in metasurfaces made from WS2 dielectric nanoantennas on gold

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Achieving efficient second harmonic generation and high nonlinearity is an important long-standing goal for a variety of modern photonic applications. Surface nonlinearity of noble metals can be significantly boosted by plasmon-induced field enhancement. However, the intrinsic material losses of metals are a central bottleneck for plasmonics. Recently, a range of dielectric nanostructures have been demonstrated using van der Waals materials, showing a wealth of distinct optical resonances that offer many opportunities for nonlinear photonic applications [1,2,3].

Here we report second-harmonic generation (SHG) from a metasurface consisting of a square lattice (period 900nm) of dielectric WS2 nanoantennas (nanoantenna radius: 360nm, thickness: 80nm) placed on a gold substrate (Fig.1a) and the enhancement of the SHG signal in resonance with the optical modes of the metasurface. The reflectance contrast (RC) of the nanostructure shows a series of hybrid Mie-plasmonic modes (denoted P1, P2, P3 in Fig.1b) and a bound state in the continuum (BIC) (Fig.1b). The nature of these states is confirmed from detailed angle-resolved RC measurements. The metasurface gives rise to a clear SH signal while no SHG is observed from the unetched WS2 flake (Fig.1c), as the bulk WS2 is a centrosymmetric crystal. By scanning the excitation wavelength, we show a strong resonant SH behaviour for excitation around 790 nm (Fig.1d) into the resonance observed in the RC spectrum. Our results provide a novel route for SHG in hybrid dielectric-metallic metasurfaces, emphasizing the role of van der Waals materials for nonlinear nanophotonic applications.

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Novel and Super-Resolution Microscopy

Interferometric Gated Off-Axis Reflectometry (iGOR) - ultrasensitive label-free tracking of nanoparticles and suspended membranes in three dimensions

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To unravel dynamic processes underpinning key functions in cell biology, it is essential to develop imaging technologies able to track the movement of individual bio-nano-objects under physiologically relevant conditions, hence at high speed (ms) and in 3D. Many methods of particle tracking [1] only capture motion in two dimensions, while cells have an inherently 3D structure. Additionally, the reliance of many techniques on fluorescent labelling limits the observation time due to photobleaching.

Here, we demonstrate a new method, named Interferometric gated off-axis reflectometry (iGOR), suitable to investigate suspended membranes and nanoparticles in 3D. iGOR detects the back-scattered light of the structure of interest using an external off-axis reference, to measure amplitude and phase of the detected field. Employing coherence time-gating by femtosecond pulses, the axial extension of the detected volume is controlled, and spurious signals from other regions and surfaces are supressed. The measured field can be digitally refocussed to extract the position of single particles moving in the volume, as in transmission holography [2]. Notably, due to the reflection geometry, the phase of the scattering provides an axial position resolution in the sub-nanometer range, an improvement of one to two orders of magnitude compared to transmission detection. We show tracking of single gold nanoparticles with 10nm diameter, freely diffusing in volume, at 3ms dwell time. Notably, from these measurements we can quantify the particle hydrodynamic size and its geometrical morphometry (size and non-sphericity) independently.

We investigate the spatiotemporal dynamics of suspended single lipid bilayers, in the form of giant unilamellar vesicles and droplet interface bilayers. We show that the membrane thickness can be measured with 0.1nm precision, and the membrane axial position with 0.5nm precision, at 3ms dwell time.

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High-efficiency digitally scanned light-sheet fluorescence lifetime microscopy (DSLM-FLIM)

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Time-correlated single-photon counting (TCSPC) array cameras hold great potential for accelerating acquisition in fluorescence lifetime imaging. The application of CMOS based arrays consisting of single-photon avalanche diodes (SPAD), each coupled with a time to digital converter (TDC), allows for widefield array-based lifetime imaging. However digitally-scanned light-sheet microscope (DSLM) and two-photon microscope systems present significant technical barriers, which have to date prevented full and efficient use of the capabilities of SPAD arrays. Because the frame rate of array cameras (many kHz is faster than achievable DSLM scan rates, only a very small fraction of the SPAD pixels can be illuminated at a given moment. The tension between the efficient use of a widefield SPAD camera array (taking advantage of its ability to record times of arrival for over 108 photons per second) and the need for spatially-concentrated instantaneous laser excitation (for efficient two-photon microscopy) means that the full potential of SPAD cameras is yet to be realised for two-photon and DSLM-based FLIM.

We present a new optical design based around astigmatic imaging optics, ensuring a more even instantaneous distribution of photons across the whole SPAD-TDC array, and thus enabling rapid and efficient acquisition of fluorescence lifetime imaging data. We demonstrate our system with both one- and two-photon excitation sources, validate performance with lifetime reference beads, and demonstrate separation of similar fluorescence emission spectra in biological samples via lifetime contrast. Our approach paves the way for optimal co-deployment of TCSPC SPAD cameras and DSLM illumination, with either one- or two-photon excitation. Thus we anticipate that our approach will open up a new application space of high-speed fluorescence lifetime imaging using TCSPC SPAD cameras.

Hyperspectral Super-Raman microscopy

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Raman scattered signals from advanced materials and biological systems are highly reliable fingerprints and it is a label-free non-destructive process. However, the conventional confocal Raman microscopy is severely limited by small imaging area (~diameter of laser beam focused on sample) and resolution is diffraction limited as well. The efforts to scale up the area via point-by-point scanning yields poor resolution Raman maps and the process itself is further hindered by the slow speeds of mapping. Advancements like tip-enhanced Raman spectroscopy (TERS) manage to resolve the spatial resolution issue but it is again a slow scanning process with its own set of limitations viz. probe vulnerability, planarity of sample required, high technical/instrumentation complexity and costs. Thus, a technique which can provide better resolution and larger area maps without caveats of high complexity and costs is highly desirable.

We introduce WISER (Wide-field Imaging with Super-resolution Enabled by Raman Signals) with an aim to resolve the above-mentioned issues. The issue of wider area Raman maps is addressed by employing a wide-field Raman technique in place of conventional confocal Raman. Wide-field Raman in conjunction with imaging interferometer enables high speed Raman mapping. The image acquisition process is an optoelectronic one and thus does not suffer from slow speeds and imperfections introduced by the mechanical movement of stage/beam in conventional Raman mapping. Super-resolution Raman maps are enabled by utilizing structured illumination approach where a digital mirror device is used to modulate the incident wide-field laser illumination. The Raman maps of diverse samples (nanodiamonds, 2D MoS2) acquired using WISER technique show improvements as high as 40% in spatial resolution over conventional approach. Our approach of combining the structured illumination microscopy with hyperspectral Raman thus promises wider area Raman maps of better resolution in comparison to conventional Raman microscopy.

Full field displacement estimation in microscopy using deep learning

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Biological tissues are highly dynamic and motion is critical to their form and function. As such, imaging of live samples at high spatiotemporal resolutions and over long term is coming to the fore in revealing a host of functional biophysical processes. This emerging domain of imaging is accompanied by new challenges, such as the accurate estimation of motion from biological images or videos at high spatial and temporal resolutions required to quantify biophysics. Here, we present an open-source deep-learning method, termed Displacement Estimation FOR Microscopy (DEFORM-Net), that outperforms traditional digital image correlation and optical flow methods, offering simultaneous high accuracy, spatial sampling, and speed. DEFORM-Net is experimentally unsupervised and does not require experimental ground truth. Instead, it relies on displacement simulation based on a random fractal Perlin-noise process and training loss functions that are optimised to match biophysical and microscopy processes. We demonstrate its performance on real biological videos of beating mouse cardiomyocytes and pulsatile cells in Drosophila pupae, and in various microscopy modalities. We provide DEFORM-Net as open source and demonstrate inference in the ImageJ/FIJI platform for rapid evaluation, which may empower new quantitative applications in biology and medicine.

The Exeter Multiscope: High throughput imaging of cardiac activity using semi-coherent light

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The Exeter Multiscope: When designing an imaging system, a trade-off has to be made between magnification and field of view. To read out images from 96 well plates typically means a choice between a low resolution, low magnification image of the entire plate or mechanically moving a high magnification objective to each well, compromising temporal resolution. The Exeter Multiscope (based on the RAP microscope design [1]) avoids this trade off by forming a high magnification imaging path around each individual well. Using a parabolic mirror to converge the light from all imaging paths onto the same camera, it is possible to read out an entire plate at cellular resolution in less than a second. In this paper we exploit the optical properties of micro-LEDs to track phase changes in biological samples ranging from cells to whole embryos.

Micro-LEDs development: LED technology has advanced greatly in the last decade. Emitters have become smaller, more efficient and now cover a broader spectral range. One consequence of the smaller emitter area is that the spatial coherence of the source is increased [2]. Spatially coherent light passing through a living fish larva undergoes multiple scattering, producing an interference pattern at the detector. Monitoring changes in this pattern allows the cardiac cycle of an entire killifish larva can be accurately tracked at the frame rate of the camera. As a brightfield method, signal is high even at low light dose and produces minimal phototoxicity.

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Motion and microscopy - customisation, automation, sharing

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Flexure-based translation stages offer particularly smooth motion at small step sizes. Using the flexibility of thin plastic sheets, together with the rigidity of thicker plastic bars, enables this high performance translation geometry to be constructed in a single monolithic structure with 3D printing. The OpenFlexure project (openflexure.org) uses open development of modular and parametric designs of 3D printed translators, together with motorisation and optical systems, to realise high performance laboratory translation stages and microscopes. A translation stage with a step size of less than 10nm allows incremental motion to be resolved with 60nm resolution, with a mean drift of 1.6µm over 16 hours and bi-directional repeatability at the same level. The complete microscope is diffraction-limited with 100× objectives and includes autofocus, slide scanning, image stitching and sequence scripting. Integration of hardware and software gives additional benefit for a system to automatically map position and focus, account for drift and backlash, and monitor its own optical and mechanical performance. Changes to performance can be flagged to the user. Modularisation is important for customisation and flexibility, but when a system is physically built from modular parts it increases complexity and construction time. Modularisation of hardware at the program level, in conjunction with 3D printing, allows custom devices that still benefit from the stability of a monolithic structure. Accounting for the actual diameter, back focal length and thickness of lenses in a design yields optical systems that need minimal alignment. We shall present examples of customisation of the OpenFlexure Microscope, including modifications made by the core team in response to the needs of end users, together with customisations by researchers who have built and used the microscope in over 50 countries and on all continents. These include structured illumination, polarisation microscopy, modifications for cell biology in incubators and many more.

Optic Materials for Applications in Quantum Technology

LED-Driven Quasi-Continuous-Wave Operation Room-Temperature Pentacene Maser

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The MASER (Microwave amplification by stimulated Emission of Radiation), analogous to a laser but operating in the microwave range, was first pioneered in the 1950s and achieved by manipulating spin states within paramagnetic impurities. In 2012, a critical advancement in the field developed the world's first room-temperature maser [1]. This paper presents the longest recorded room-temperature quasi-continuous-wave pentacene maser signal spanning over 5 ms at 1.45 GHz. Traditional masers have faced limitations due to high vacuum, cryogenic conditions, and complex optical pumping mechanisms. Our study overcomes these challenges with a novel compact LED-driven luminescent concentrator system [2], leveraging LEDs' low cost, scalable power output, and long lifetimes. The extended lifetime, which reveals phenomena like Rabi oscillations, plays a crucial role in advancing the frontier of quantum technologies.

By replacing conventional high-power lasers [1] and xenon lamps [3] with a safer, more economical, and thermally efficient LED pump system, we demonstrate a significant reduction in operational complexity and resource requirements. The Luminescent concentrator supported by the introduction of a Cerium-doped Yttrium Aluminium Garnet (Ce: YAG) crystal luminescent concentrator is pumped by 288 blue 455 nm LED chips, which concentrates and delivers the optical power necessary to induce masing in pentacene. Using the simulation software CST Microwave Studio Suite, we optimize the geometry of the microwave cavity and the placement of the gain medium, ensuring maximum efficiency of the masing operation. These simulations allow precise adjustments and enhancements in the mode volume and Q-factor of the cavity, facilitating the efficient mode coupling at room temperature.

This work represents a technological leap in extending the lifetime operation of masers, reducing costs, and streamlining operation size. Such advancements broaden masers applications in quantum technologies and pave the way for their advancements in quantum computing, precise frequency standards in metrology, and deep-space communication systems.

Emission enhancement of erbium in a reverse nanofocusing waveguide

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Since Purcell's seminal report 75 years ago, electromagnetic resonators have been used to control light-matter interactions to make brighter radiation sources and unleash unprecedented control over quantum states of light and matter. Indeed, optical resonators such as microcavities and plasmonic antennas offer excellent control but only over a limited spectral range. Strategies to mutually tune and match emission and resonator frequency are often required, which is intricate and precludes the possibility of enhancing multiple transitions simultaneously. Here we report plasmonic devices for nano-focusing and nano-defocusing light to the 10 nm scale, capable of drastically enhancing interactions between light and matter over a broad bandwidth[1]. We demonstrate this capability using technologically relevant Er3+ ions on a hybrid silicon plasmonic waveguide platform. Our reverse nanofocusing device gives rise to 300-fold shorter Er3+ ion emission lifetimes accompanied by an enhancement of >338x in luminescence efficiency when compared to non-plasmonic control devices. Efficient collection of the enhanced luminescence is achieved by exploiting photonic to plasmonic nanofocusing methods, but in reverse. All plasmonic devices were found to produce more photons than photonic control devices. The extraordinary enhancements of this system are further underpinned by the observation of multiple enhanced Stark-split electric dipole transitions across the Er3+ telecommunications emission band. This demonstrates the capability to strongly dress multiple atomic transitions simultaneously using a one-dimensional mode continuum at room temperature.

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Waveguide-integrated coherent spins in diamond

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Nitrogen vacancy (NVs) in diamond are excellent candidates for use as room temperature coherent spins for Quantum Technologies. The NV is susceptible to changes in the local environment's temperature, strain, electric and magnetic field. Moreover, optical detected magnetic resonance (ODMR) is an efficient tool to initialize, manipulate and read out the NV's quantum state. These outstanding properties have established NVs as robust, high-sensitivity and high-resolution sensors. However, it's challenging to fabricate high coherence NVs in photonic structures - a crucial requirement for hybrid quantum networks and enhanced quantum sensing applications.
Recently, femtosecond laser writing emerged as a versatile tool for creation of photonic waveguides integrated with quantum emitters in diamond [1]. In this work, we investigate single waveguide integrated NVs (WGINVs) in type IIa chemical vapor deposition (CVD) diamond and ensemble WGINVs in type Ib high-pressure-high-temperature diamond [2]. We use standard pulsed ODMR protocols to probe spin coherence, including inhomogeneous dephasing time T2*, spin transverse relaxation time T2 and longitudinal relaxation time T1. We show single WGINVs in IIa diamond with spin coherence properties (T2 ~ 0.5 ms) comparable to native NVs (Fig. 1). Additionally, in Ib diamond, we demonstrate creation of ensemble WGINVs with up to 900 times intensity enhancement resulting in a sub 26 nT · Hz−1/2 photon-shot-noise-limited DC magnetic field sensitivity. Thus, fs-laser writing provides a cost-effective way to create photonic-integrated quantum sensing devices based on economical type Ib diamond.

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Optical Trapping and Manipulation

Backaction suppression in levitated optomechanics using reflective boundaries

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Optically levitated nanospheres in vacuum are an exciting platform for fundamental and applied sciences. Recent experiments have demonstrated cooling of their motion to the lowest possible quantum mechanical state [1,2]. The impressive sensitivity necessary for this quantum feat has found application in ultra-sensitive force measurement, and there are hopes for technologies from gravitational wave detectors to matterwave interferometers. However, these trapped particles scatter light, and when this contains position information it necessarily introduces noise on the motion of the particle, known as backaction. In free space, this is associated with the momentum recoil of scattered photons.

We present a theoretical proposal which mitigates backaction and elucidates the deep connection with information theory, and we describe a feasible experimental scenario [4]. (There is related work which seeks to mitigate backaction by supplementing the trapping light with specially crafted quantum light field [5].)

Reflective boundary conditions are known from Purcell to affect the rate of spontaneous processes. Rayleigh scattering rates are also affected, as was exploited in some of the recent cooling experiments. We show, using stochastic electrodynamics in combination with the formalism of scattered information, that a hemispherical reflective boundary with a nanoparticle at the centre can fully suppress backaction noise and is experimentally feasible. We find, surprisingly, that the backaction suppression condition coincides with maximum scattering because, under these conditions, the scattered light contains no first-order position information.

This new approach offers a way to engineer information availability and backaction in levitated experiments and mitigate noise and the associated quantum decoherence. We anticipate more interesting geometries, beyond the simple hemisphere, when motion is restricted, light is confined in waveguides or cavities, or with shaped particles such as nanorods or disks.

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Single-beam grating-chip 3D and 1D optical lattices

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Ultracold atoms are crucial for unlocking truly precise and accurate quantum metrology, and provide an essential platform for quantum computing, communication and memories. One of the largest ongoing challenges is the miniaturization of these quantum devices. Here, we show that the typically macroscopic optical lattice architecture at the heart of many ultra-precise quantum technologies can be realized with a single input laser beam on the same diffractive chip already used to create the ultracold atoms. Moreover, this inherently ultra-stable platform enables access to a plethora of new lattice dimensionalities and geometries, ideally suited for the design of high-accuracy, portable quantum devices.

Optical trapping and manipulation of whispering gallery mode microlasers for precision controlled cellular delivery

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Integrating micro- and nanolasers into living system is a rapidly evolving frontier in biotechnology. This innovative approach facilitates non-invasive probing and labelling with unparalleled precision and information density. Among these, Whispering Gallery Mode (WGM) lasers stand out for their exceptional brightness, narrow linewidth, sensitivity to refractive index changes and their ease of biointegration, opening exciting possibilities for biosensing applications. They have been used to sense specific target molecules [1], measure single cardiac cell contractility [2] and to label single cells and track their migration [3,4].

Despite recent advancements, achieving precise single-cell delivery remains a significant challenge. Traditional methods like microinjection often result in cellular damage, while the current delivery of microlasers is primarily stochastic, relying on chance encounters between microlasers and cells for uptake. To address this limitation, we show that by using optical trapping of microlasers, we can carefully position them, gaining control over delivery and engulfment to selective cells, improving uptake statistics without causing cellular damage. In addition, the output WGM microlaser spectra reveals distinct optical responses influenced by refractive index distribution changes during the process of cellular engulfment. Thus, valuable information such as uptake time and intracellular refractive index can be measured and monitored.

In summary, optical trapping provides unparalleled control over the positioning and delivery of microlasers to specific cells, enhancing uptake efficiency without compromising cellular integrity. Furthermore, the spectral output can be monitored during uptake and microlaser-cell interactions and provide valuable insights into cellular dynamics.

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Quantum Communication

A cost-effective and rack-mountable time-bin entangled biphoton source for quantum networks

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Quantum networks, distributing qubits among user nodes via quantum channels, will play a vital role in future quantum communication [1]. Among the different degrees of freedom available, time-bin entanglement has advantages for maintaining stability over long-distance fibre links [2].
A rack-mountable fibre-based source, generating time-bin entangled photon pairs in the telecom C-band, was developed. It utilises second harmonic generation (SHG) and spontaneous parametric down-conversion (SPDC) processes in a single type-0 periodically poled lithium niobate (PPLN) waveguide. Continuous-wave (CW) pump light at 1550.22 nm undergoes SHG in transiting the waveguide; the SHG light is then reflected back through the same waveguide to generate photon pairs by SPDC.

The experimental setup is shown in Fig. 1(a). Laser light is amplified to pump the waveguide, generating correlated photon pairs with high coincidence count rates and coincidence-to-accidental ratios. Three different correlated photon pairs were extracted, occupying six DWDM ITU channels. 50 MHz double pulses of ~120 ps duration separated by 1 ns are carved out of the initial CW laser light to generate time-bin entangled biphoton states. Time-bin entanglement was verified by projection measurements using two unbalanced Mach-Zehnder interferometers (UMZIs) with path difference of 1 ns. Fig. 1(b) shows typically observed interference fringes. The obtained visibility was 80.2% (maximum achievable 85.7% because of unequal path loss in the UMZIs), exceeding the CHSH inequality entanglement threshold value of 70.7% [3].

The source has a broadband SPDC spectrum that can yield up to 27 correlated photon pairs on a 100 GHz DWDM grid, and thus has promising potential for implementing quantum networks.

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Finding an optimal combination of wavelength and bandwidth for quantum communications systems.

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Quantum Communications systems are now developing towards real world scenarios [1,2]. However, there is no consensus on the optimal choice for the wavelength of photons. Typically, either the C-Band or the O-Band are used for transmission through current deployed fibre infrastructure. We present a detailed simulation study to conclusively answer the debate on the optimal wavelength and extend the arguments into what bandwidth is optimal for different choices of wavelength. Based on entanglement-based quantum key distribution [3], this work defines the optimal choice of the wavelength and bandwidth as a function of the measurement jitter and the distance of transmission through different optical fibre types [4,5]. We then present simulations towards future fibre infrastructure to see in what combination of wavelength, bandwidth, and distance through current fibre infrastructure have comparable performances to next generation optical fibre [6].

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Quantum Computation

Quantum error cancellation in photonic systems - undoing photon losses

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Real photonic devices are subject to photon losses that can decohere quantum information encoded in the system. In the absence of full fault tolerance, quantum error mitigation techniques have been introduced to help manage errors in noisy quantum devices. In this work, we introduce an error mitigation protocol inspired by probabilistic error cancellation (a popular error mitigation technique in discrete variable systems) for continuous variable systems. We show that our quantum error cancellation protocol can undo photon losses in expectation value estimation tasks. To do this, we analytically derive the (non-physical) inverse photon loss channel and decompose it into a sum over physically realisable channels with potentially negative coefficients. The bias of our ideal expectation value estimator can be made arbitrarily small at the cost of increasing the sampling overhead. The protocol requires a noiseless amplification followed by a series of photon-subtractions. While these operations can be implemented probabilistically, for certain classes of initial state one can avoid the burden of carrying out the amplification and photon-subtractions by leveraging Monte-Carlo methods to give an unbiased estimate of the ideal expectation value. We validate our proposed mitigation protocol by simulating the scheme on squeezed vacuum states, cat states and entangled coherent states.

Quantum transport in AC+DC Double Finger-Gate Devices

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Gallium arsenide (GaAs) semiconductor devices have garnered significant attention due to their unique properties and potential applications in various fields. GaAs, characterized by a direct bandgap semiconductor with high carrier mobility, offer advantages over silicon in optoelectronic and high-frequency applications. The material system of GaAs stands out for its quantum functionalities, enabling single-photon generation, manipulation, and detection, all integrated on the same chip. The integration of AC+DC biasing in GaAs semiconductor devices offers a promising avenue for exploring new functionalities and improving device performance. This research incorporates an N-type AC+DC finger gate device system using GaAs material. In this system, various DC potential energy addition values are used as parameters to study their effect on the system's total conductance result. The result of this study reveals that in addition to the formation of quasi-bound states due to the AC bias, a peak structure is also formed by the DC bias. Furthermore, the results also show that when the DC potential energy value exceeds the AC potential energy, the total conductance becomes highly suppressed as the structure of the quasi-bound state becomes very low in electron resonance. This research provides insights into the dynamic behavior of GaAs devices under combined AC and DC electrical fields, revealing potential instabilities and chaos phenomena that may emerge in such systems.

Reconfigurability of generation, manipulation and detection of frequency-encoded qu-d-its: boosting networks in entanglement-based quantum cryptography

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Quantum networks enhance quantum communication schemes by linking multiple users. Harnessing high dimensional quantum states, qu-d-its, allows for a denser transfer of information with increased robustness to noise compared to their binary counterparts [1], usually at the expense of the simplicity of the hardware.

Frequency encoding enables access to a high dimensional Hilbert space where qu-d-its are manipulated with off-the-shelf fibered devices such as Electro-Optic Modulators (EOMs) and Programmable Filters (PF) [2]. Frequency encoding is robust against phase or polarization fluctuations and compatible with telecom fiber infrastructure.

In this work, we use Bell states of dimension d=2 (qubits) and d=3 (qutrits) to implement a frequency-domain proof of concept of entanglement-based quantum key distribution [3] protocol. We build on reconfigurability of our simple implementation to boost the network and protocol performances. Using a silicon microresonator parametric photon pair source, via Four Wave Mixing (FWM), we access up to 70 frequency modes in, and independently manipulate 15 frequency-bin entangled qu-d-its, interconnecting up to 6 users [4]. We benchmark and optimize the source (via pump power), the signal processing (via coincidence window size) and qu-d-it encoding (d=2 or 3) with a single hardware depending on interconnection lengths.

We thus propose an adaptive strategy to exploit reconfigurability to increase the transmitted secret key rate at short distances, taking advantage of the dense encoding capacity of a qutrit, 1.5 higher than qubit, and benefiting from the higher signal to noise ratio afforded by qubits at distances longer than 220km. This demonstration paves the way for larger dimensionality implementations deployed on metropolitan fiber links.

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Large-scale silicon quantum photonics for quantum walk simulations and applications

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Integrated quantum photonics provides a promising approach for robust and exquisite control of quantum information processing by allowing the generation, manipulation, and detection of photons on a single chip. Silicon photonics holds greater capability for large-scale quantum photonic circuitry, because of its strong third-order nonlinearity, high component density and CMOS compatibility, and it shows a feasible path for implementing large-scale and programmable quantum walk (QW) simulations and QW-based applications.

Here we present a list of our works in silicon quantum photonic chips for QW simulations and applications [1-4]. The chips integrated with up to ~1000 photonic components can generate and manipulate photons on the same device. Using these chips, we implemented various QW simulations, including discrete-time QW simulations on a universal two-qubit photonic quantum processor [1], and continuous-time QW simulations on a fully programmable photonic quantum processor [2] --- which for the first time allows full control over QW parameters such as the particle properties, initial state, graph structure, and evolution time. Furthermore, we implemented a series of QW-based applications, such as searching marked vertices in graphs, measuring the node centrality of networks, distinguishing the non-isomorphic graphs, measuring the similarity of graph pairs, and simulating the topological phases of higher-order topological insulators [3]. These results show that silicon quantum photonics combined with QWs paves a viable path to bring quantum photonics to fruition in applications of practical interests soon.

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Exciton Dephasing by Phonon-Induced Scattering between Bright Exciton States in InP/ZnSe Colloidal Quantum Dots

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Colloid chemistry methods enable quantum dots (QDs) to be formed as nanocrystals dispersed in a liquid solution [1] which offer versatility in semiconductor materials and sizes and shapes. Of these, CdSe-based QDs are prominent and have been shown to be single-photon emitters [2]. The spin-flip from the bright to the dark states results in exciton dephasing times up to about 100ps [3]. III-V semiconductors such as InP avoid the toxic Cd, and the bright-to-dark spin flip time was found to around 1ns [4], which raised the prospect of a slower exciton dephasing.

We report on exciton dephasing in InP/ZnSe core/shell QDs, using transient four-wave mixing (FWM) spectroscopy in heterodyne detection [5]. We can describe the radiative decay rate of the exciton by assuming thermal equilibrium between a dark and a bright state, split by about 6meV. The variation of the dephasing time with temperature, from 23ps at 5K, is described by phonon-induced transitions between exciton states split by a mere 0.32meV. Notably, such an energy difference is consistent with the splitting between the 3 states of the nearly isotropic exciton in InP/ZnSe QDs suggesting that dephasing in InP/ZnSe QDs is determined by phonon-induced scattering within the triplet of bright exciton states. Micro-photoluminescence of individual InP/ZnSe QDs at 5K show emission lines down to 50ueV spectral width, consistent with the measured dephasing time. We conclude that phonon-induced scattering between bright exciton states is the dominant dephasing mechanism in colloidal III-V InP/ZnSe QDs at low temperatures, and that single InP/ZnSe QDs can show emission spectra with a dephasing-limited linewidth.

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Insights into Electronic and Excitonic Properties of site-controlled GaAs Quantum Dots – First Steps Toward Multi-Dimensional Photonic Cluster State Generation

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Advancement of quantum information processing and quantum computing hinges on the scalability of systems to large numbers of qubits. Multi-dimensional photonic cluster states (PCS) have emerged as a potential solution to this scalability issue when used as a substrate for quantum computations [1]. Semiconductor quantum dots (QDs), notably site-controlled [111]-oriented GaAs QDs, exhibit exciting prospects for PCS generation, owing to their superior structural control [2] when compared to [001]-oriented Stranski-Krastanov (SK) QDs. Nonetheless, significant challenges persist in general for using [111]-oriented dots to generate multi-dimensional PCS. Theoretical studies can help to pave the way for such applications, and understanding the electronic and excitonic properties plays an important role. However, understanding from well-studied [001] QDs cannot be carried over to these site-controlled structures given fundamental differences in, for instance, the underlying symmetry of the systems.

Here, we investigate the electronic and excitonic properties of experimentally relevant [111]-oriented site-controlled GaAs QDs using a symmetry adapted 8-band k.p model, including strain and polarization fields. The model preserves the underlying C3v symmetry which is crucial for an accurate description. Our electronic structure calculations reveal several bound hole states and minimal electron confinement, thus in stark contrast to [001] SK QDs. Notably, the first excited hole state exhibits a large pz-like orbital character, indicative of a light-hole-like state, which, again is not seen in typical [001] systems.

By employing configuration interaction calculations based on the obtained single-particle states, we explore excitonic and biexcitonic properties of [111]-oriented GaAs QDs. We identify both "heavy-hole" (X10) and "light-hole"-like (X01) excitonic states. The obtained excitonic features align well with experimental studies, serving as an ideal starting point for exploring the properties of site-controlled QDs for multi-dimensional PCS generation.

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Nitrogen-Vacancy Centres in Nanodiamonds as Single Emitter Standard Candles

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The search for stable, pure quantum sources is an active area of research for use in photonic quantum computing, such as qubit transmission nodes and quantum logic gates[1]. In the past decade, several types of single emitters have been studied, from colloidal quantum dots[2], embedded quantum dots in nanowires[3] to laser written defects in bulk crystals[4]. Yet, quantitative comparison between these materials remains challenging due to lack of a suitable reference when considering the variables of experimental equipment. This is addressed by using reference single emitters as a benchmark with known properties – specifically the second order degree of coherence, g(2)(t) – which exhibits a g(2)(0)<0.5 and emits at a known countrate at saturation as a robust source of brightness, i.e. a ground truth standard candle.

An ideal candidate for this is the nitrogen-vacancy (NV-) colour centre in diamond, due to their stability, ease of fabrication and room-temperature emission.[5] This work aims to explore the feasibility of using NV centres in nanodiamonds (NDs) in a cross-laboratory study to identify single emitting NV centres that emit at a known countrate at saturation. Thousands of NDs were identified with a Hanbury Brown-Twiss (HBT) confocal microscopy setup (NPL), and narrowed down to candidates containing single NV centres with g(2)(0)<0.5. The character of these candidate NDs were recovered at a second laboratory (UoM) through correlating g(2)(0), saturation power and countrates using different experimental apparatus, thus verifying the approach of using NV- centres as reference emitters. As a result, we propose the use of stable NV- centres in nanodiamonds as a reference material for less stable and/or novel quantum materials.

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Optimization and coupling of perovskite nanocrystals with optical nanofibers for efficient integrated single-photon sources

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Achieving pure single-photon emission is essential for various applications in the field of quantum technologies, from optical quantum computing to quantum key distribution. Various materials systems have been investigated as candidates for single photon emission, such as single atoms and ions, as well as solid-state emitters such as organic molecules, color centers in diamonds and quantum dots. Among them, colloidal lead halide perovskite nanocrystals have gained significant attention owing to their unique structural and optical properties, rendering them appealing single-photon sources. However, their practical application has been hindered by environment-induced photo-emission instabilities. I will present a study of Zn-doped $CsPbBr_3$ perovskite nanocrystals showing efficient single photon generation, increased photostability under illumination and dilution and reduced blinking on sub-millisecond time scale.

Their integration with photonic structures, such as waveguides and optical fibers, represents a significant challenge in boosting their practical applications. I will present the first coupling of a single perovskite NC with a tapered optical nanofiber. Through near-field interaction, a significant fraction of the emitted light is coupled into the nanofiber, providing a proof of principle for a compact and integrated single photon source. To further enhance the emission properties of the nanocrystals and increase the collection efficiency of the emitted single photons, we explore a non-conventional fabrication method based on Electron Beam Induced Deposition (EBID). This method, employed for the first time to fabricate metallic nano-antennas directly on the tapered optical nanofiber, provides deterministic and precise control over the composition, location, and geometry of the nanostructure. This technique is easily adaptable to fabricate dielectric structures onto the nanofiber and a strong enhancement of the coupling of the emitted photons inside the nanofiber is expected (up to 60%). The successful implementation of this approach offers promising prospects for realizing a compact, efficient, and high-brightness integrated single-photon device.

Spin memory in the photoluminescence of room temperature vertical-cavity quantum dot gain structure

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Spin-optoelectronics promises to provide extra functionalities in communication and spectroscopy via ultrafast polarization modulation. We are addressing the question of spin memory in InAs/GaAs quantum dots (QD) used as gain structures for vertical-external cavity lasers (VECSELs), whereas most previous investigations focused on monolithic VCSELs. VECSELs offer possibilities for power scaling and additional flexibility as polarization controlling elements can be introduced into the free space sections.

We report on a systematic study of optimizing excitation conditions for a high spin polarization by exciting the samples at 852 nm, 915 nm, 980 nm, and 1070 nm. The sample consists of 5 groups of 3 InGaAs/In0.12Ga0.88As dot-in-a-well (DWELL) layers separated by GaAs barriers and spacers [1]. The sample is excited using a pump laser at 30° from normal and the resulting normal photoluminescence (PL) is collected and its Stokes parameter S3 characterizing helicity determined.

Emission of the QD is centred at 1290-1300 nm. The spin polarization in PL obtained for spin polarized pumping (S3,pump = ±1) is between 0.01 ≤ |S3,PL| ≤ 0.05. The effective spin lifetime deduced from that assuming a carrier lifetime of 770 ps is between 10 and 40 ps. The best result is obtained for 980 nm with a spin polarization of 5% and a lifetime of 40 ps. This wavelength provides also a good overall pumping efficiency [1]. The large variations are tentatively attributed to the different excitation channels. The 980 nm pump is probably exciting mainly the heavy holes of the quantum well with good spin efficiency, whereas the other wavelengths excite a combination of light and heavy hole states, or as barrier, respectively high-level quantum dot states. The investigations illustrate the importance of the choice of wavelength for optical pumping of spintronic devices.
[1] S. S. Alharthi , et al., Appl. Phys. Lett. 107, 151109 (2015).

Optical microcavity coupling with two-dimensional WS2

Qian J

Light-matter interaction can be enhanced resonantly when suitable material is placed in a small volume with confined light, which can generate exciton-polaritons, quasi-particles comprising superposition states of photons and excitons in semiconductors. Here we have studied the coupling of WS2 monolayers and optical microcavities at room temperature. Hemispherical features have been fabricated with a focused ion beam to build optical microcavities with small mode volumes in order to maximise polariton density. We have measured transmission spectra of both uncoupled and coupled cavities and have observed typical anti-crossing behaviour that indicates the strong coupling and formation of polaritons. The experimental results agree well with the finite-difference time-domain (FDTD) numerical simulations. This demonstrates the consistent tunability of multiple cavity modes over a wide range with a mode kept in strong coupling with excitons. Pumping the cavities off-resonantly with a continuous-wave laser, we have captured nonlinear behaviour of light emitting from excitons coupled to multiple cavity modes including both fundamental and higher-order transverse modes. After modelling the coupled cavities using a set of rate equations and Jaynes–Cummings Hamiltonian, we argue that the nonlinearity may come from transitions between polaritons from multiple cavity modes. This study has shown the strong coupling between WS2 monolayers and hemispherical metallic microcavities and the presence of multiple cavity modes leading to novel non-linear behaviour of exciton-polaritons.

Quantum Information and Foundations

Measurement Back-Action causes the difference between Classical and Quantum Counterfactual Effects

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The presence of an absorber in one of the paths of an interferometer changes the output statistics of that interferometer in a fundamental manner. Since the individual quantum particles detected at the output have not been absorbed, any non-trivial effect of the absorber on their path is a counterfactual effect. Here, we quantify counterfactual effects by evaluating the information about the presence or absence of the absorber obtained from the output statistics. We quantify the difference between classical and quantum counterfactual effects. We show that there is a counterfactual gain in quantum counterfactual communication, which quantifies the effect it has above and beyond any classical counterfactual effect. We show that this counterfactual gain can be separated into a semi-classical term related to the amplitude blocked by the absorber, and a Kirkwood-Dirac quasiprobability assigning a joint probability to the blocked path and the output port. When this Kirkwood-Dirac term is positive or zero, these counterfactual effects can only distribute probability more equitably over the set of outputs of the interferometer; however, if this Kirkwood-Dirac term is negative, blocking can cause output probability to focus on a specific output. Based on this analysis, we show that non-classical statistical effects are not sufficient to explain quantum counterfactual effects (we cannot explain quantum counterfactual effects simply by removing detection events), and identify the precise form of the back-action that describes the effects of the absorber on particles in other paths.

Electronic Maxwell's equations and the 8x8 electromagnetic Dirac equation

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The electron exhibits many wave-like properties that are similar to an electromagnetic wave. Here we shall show that this analogy can be exploited for understanding electromagnetic wave propagation in materials. Indeed, the Dirac equation - the relativistic first-order differential equation for the electron (fermion) – has several established and notable parallels with Maxwell's equations [1,2]. Using quaternion algebra, we can make this parallel almost perfect, obtaining both the electronic Maxwell equations [3] (the Dirac equation in the exact form of Maxwell's equations) and the 8x8 electromagnetic Dirac equation [4] (the Maxwell equations in the exact form of the Dirac equation).

We find that the difference between these two equations, namely the non—vanishing mass in the Dirac equation and the four—current in the Maxwell equations, leads to a difference in the properties of these two particles under Lorentz transformation.   Furthermore, when understood through the lens of electromagnetism, the electronic wave has longitudinal components, which are always zero in an electromagnetic wave. This critical difference of the longitudinal components plays an important role in determining the spin of the particle.

With this parallel description, some notable similarities between the electronic field and the electromagnetic field can be found, such as the temporal oscillations of the Poynting vector compared to the Zitterbewegung of the electron [4]. We shall also show that this theory can be applied to understand the properties of electromagnetic materials for a different perspective, viewing the refractive index as a potential energy and the impedance as the 'mass' of the electromagnetic wave.

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Quantum Metrology, Imaging, and Sensing

Enhancing Quantum Imaging with Undetected Photons: Balance, Seeding and High-Gain

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Infrared (IR) imaging and spectroscopy is invaluable to many disciplines for its ability to probe molecular responses, from material analysis to diagnostic medicine. However, these techniques are often limited by inefficient, noisy and expensive detectors/cameras. Nonlinear interferometers (NLI) offer an alternative route to IR sensing and imaging: visible-IR photon pairs within an interferometer enable a change in the IR path (due to an object to be sensed, for example) to be observed as a change to the interference of photons in the visible path. The IR photons need not be detected, hence “imaging with undetected photons” [1]. This technique completely circumvents the requirement for underdeveloped infrared detection technologies. We will introduce our implementation of compact Michelson-style NLIs based on periodically poled Lithium Niobate. We will discuss the operation of these setups in the context of a comprehensive model, exploring the influence of internal losses, inefficient detection, IR seeding, and parametric gain on interferometer fringe amplitude and visibility. These results show that interference performance can be enhanced, enabling sensing with few attowatt levels of illumination or imaging with undetected photons of low transmission samples even in the presence of significant experimental losses. The increased brightness under high gain or via IR seeding is also crucial for improving signal-to-noise ratios or reducing acquisition times.

We will finally introduce a novel sensing mode based on a combination of nonlinear interferometer modalities that has further implications for matching the interferometer type to the sample under test.

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Fundamental limits for parameter estimation of monitored noisy quantum emitters : a tensor-network approach

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Monitored driven-dissipative quantum systems are ubiquitous as platforms for quantum technologies, including optical clocks, quantum thermometry, and quantum imaging. In this submission, I will provide general recipes to evaluate fundamental limits of estimation of parameters corresponding to the open system of interest (for example, lifetimes of single quantum emitters or transition frequencies of clock atoms) using the (continuous or otherwise) measurement record gained from the monitoring. This is accomplished by casting the state of modes arriving at the detector as matrix product states[1], borne out of a collisional model view of system-probe interaction. This, in turn, allows for efficient many-body variational techniques to be brought to bear to calculate Fisher informations that set estimation error limits[2]. As an illustrative example, I will show that the proposed method can be used to evaluate fundamental limits for estimating Rabi frequencies of a driven atom that is also coupled to other, non-radiative dissipative modes (or equivalently, monitored using inefficient detectors), allowing us to evaluate the optimality of distinct monitoring strategies (such as photodetection, or homodyning) in estimating the Rabi frequency. Finally, I will also show that meaningful bounds to the quantum Fisher information quantity can be obtained in more efficient, non-variational approaches, setting the stage for studying fundamental limits of parameter estimation in more complicated contexts, such as quantum spectroscopies of complex systems[3,4].

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Time-frequency quantum metrology

Descamps E

Hong-Ou-Mandel interferometry takes advantage of the quantum nature of two-photon interference to increase the resolution of precision measurements of time delays. Relying on few-photon probe states, this approach is applicable also in cases of extremely sensible samples and it achieves attosecond-scale resolution, which is relevant to cell biology and two-dimensional materials. Here, we theoretically analyze how the precision of Hong-Ou-Mandel interferometers can be significantly improved by engineering the spectral distribution of two-photon probe states. In particular, we assess the metrological power of different classes of biphoton states with non-Gaussian time-frequency spectral distributions, considering the estimation of both time and frequency shifts. We find that time-frequency grid states, characterized by a periodic structure of peaks in the chronocyclic Wigner function, can outperform standard biphoton states in sensing applications.

After discussing the spectral engineering of photon pairs, we will discuss the use of more general quantum states possessing a higher number of photons for estimating time shifts using the presented intrinsic multimode quantum metrology approach. We will show that the particle-number and time-frequency degree of freedom are intertwined for quantifying the ultimate precision achievable by quantum means. Increasing the number of photons of a large entangled EPR probe state actually increases the noise coming from the frequency continuous variable hence deteriorating the precision over the estimation of a time shift.

Optimising Simple Quantum Illumination

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Quantum illumination uses quantum correlations to improve the ability to detect target objects in the presence of high background noise. Early schemes required a joint measurement of two modes. A common alternative, which is experimentally simpler, is to use a threshold detector to measure one mode, the idler, which conditions the signal mode that is sent to the target. Another threshold detector can be used to measure any light reflected from the target. Due to the typically low reflectivity of the targets in, for example, quantum lidar systems, it is commonly assumed that the most efficient detectors are the most effective. We investigate the optimization of such direct measurement schemes. We focus on optimising each of the three main components of such a system in turn: the detectors, the light beam parameters and the information processing protocol.

Surprisingly, we find that there can be an advantage to having a signal detector whose quantum efficiency is significantly less than perfect. This advantage does not vanish in the limits of low object reflectivities or low signal strengths. We also show that decreasing the separation between pulses, while keeping the rate of photons transmitted fixed to retain the same degree of covertness, can dramatically improve the performance of target detection. Finally, we show that post-selecting on the idler detector firing simply throws away information and does not improve the performance of the protocol.

Precision enhancement with bright squeezed light for static-loss microscopy

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For absorption imaging, optical noise can be a key limiting factor [1]. Photon counting experiments using correlated photon pair sources can achieve sub-shot noise imaging but are not scalable to high brightness [2]. Here, we demonstrate using bright Kerr-squeezed light to enhance the precision for absorption microscopy for optical power of ∼200 μW. The squeezed state is generated by propagating a coherent beam within a non-linear interferometer which incorporates a photonic crystal fibre as a non-linear medium, mediating the Kerr-effect for self-phase modulation and implementing squeezing. Subsequently, the probe is modulated in time between two optical paths to translate a static-loss measurement to a higher frequency bandwidth where the laser and detectors are shot noise limited. A sample is raster-scanned between two lenses in a confocal configuration, while measurement of the power at the frequency sideband is used to estimate the loss induced by the sample.

As the noise reduction from squeezing increases (see Fig(a)), the variance of the measurements decrease, leading to precision enhancement in the sample absorption estimate. For an optical noise reduction of –0.88 dB, the variance reaches the quantum noise limit (QNL), corresponding to the smallest variance achievable for a similar probe power of a shot-noise limited light source. Fig(b) demonstrates raster-scanned imaging with a squeezed source, where an enhancement of 1.13±0.01 in the variance is demonstrated for a noise reduction of –0.62 dB when compared to similar measurements for the same light source with no squeezing.

Finally, we have identified that the present performance is limited by our detection scheme. Higher efficiency detector with lower electronic noise will enable sub-shot noise imaging, corresponding to a precision which can only be achieved with quantum states of light.

[1] doi: 10.1021/jz101426x, 2010
[2] doi: 10.1364/OE.27.030810, 2019

Time-frequency quantum metrology

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Hong-Ou-Mandel interferometry takes advantage of the quantum nature of two-photon interference to increase the resolution of precision measurements of time delays. Relying on few-photon probe states, this approach is applicable also in cases of extremely sensible samples and it achieves attosecond-scale resolution, which is relevant to cell biology and two-dimensional materials. Here, we theoretically analyze how the precision of Hong-Ou-Mandel interferometers can be significantly improved by engineering the spectral distribution of two-photon probe states. In particular, we assess the metrological power of different classes of biphoton states with non-Gaussian time-frequency spectral distributions, considering the estimation of both time and frequency shifts. We find that time-frequency grid states, characterized by a periodic structure of peaks in the chronocyclic Wigner function, can outperform standard biphoton states in sensing applications.

After discussing the spectral engineering of photon pairs, we will discuss the use of more general quantum states possessing a higher number of photons for estimating time shifts using the presented intrinsic multimode quantum metrology approach. We will show that the particle-number and time-frequency degree of freedom are intertwined for quantifying the ultimate precision achievable by quantum means. Increasing the number of photons of a large entangled EPR probe state actually increases the noise coming from the frequency continuous variable hence deteriorating the precision over the estimation of a time shift.

Novel technologies for greenhouse gas sensing

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In this talk I will discuss our innovative methods for greenhouse gas sensing in real-time for continuous environment monitoring. They involve compact devices capable of measuring methane and carbon dioxide levels in a gas cloud from distances up to hundreds of meters away and identifying sources with high spatial resolution. The higher technology readiness level technique [1] is based on differential absorption lidar (DIAL), which consists of probing gas with a tunable short-wave infrared (SWIR) laser and collecting the light backscattered from a solid background to determine the concentration of methane in a gas plume. However, the sensitivity of this method is constrained by the weak absorption of methane at this spectral band.

Recently, some new methods leveraging nonlinear optical phenomena have shown the potential to surpass the capabilities of the current state-of-art DIAL sensors. One of them [2] is based on a nonlinear interferometer that exploits light sources generated by stimulated parametric downconversion to probe methane with mid-infrared (MIR) light, a region with strong absorption lines, and detect SWIR light which is compatible with photon counting technologies. Moreover, this method can be implemented on silicon integrated photonic chips using four-wave mixing sources for short-range detection and increased stability. Another method harnesses sum frequency generation using a high-efficiency periodically poled lithium niobate waveguide to upconvert light from MIR to near infrared. This approach enables the development of a new highly sensitive carbon dioxide sensor and potentially to use aerosol as the backscattering target, enhancing the versatility of the sensors.

[1] - J. Titchener, et al., “Single photon Lidar gas imagers for practical and widespread continuous methane monitoring,” Appl. Energy 306, 118086 (2022).

[2] - A. C. Cardoso, et. al., “Methane sensing in the mid-IR using short wave IR photon counting detectors via non-linear interferometry,” Opt. Con. 3, 5 823-832 (2024).

Quantum Optics

Photon thermalization and indications for condensation in broad-area VCSELs

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The intriguing concept of photon condensation originally demonstrated in microcavities filled with dyes [1] has been more recently extended to monolithic [2,3] and discrete [4] semiconductor microcavities. For a more systematic understanding of equilibrium and non-equilibrium phenomena, I am investigating electrically pumped broad-area vertical-cavity surface-emitting lasers (VCSELs) with a circular diameter of 200 µm using a microscope objective with NA 0.8 to image the spatial Fourier spectrum. An exponential decay of the strength of the photoluminescence vs modal energy is found, indicating thermalization of modes. For low injection currents, fits to the Boltzmann tail yield temperatures close to or somewhat above ambient temperature (280-340 K). For higher injection currents, fitting with the complete Bose-Einstein distribution is required and yields an increase of the fitted temperature to about 500 K at 400 mA. This might be related to a thermalization of carriers at plasma temperature but an incomplete thermalization of the electron-hole plasma with the lattice temperature. A change of the temperature by more than a factor of two (in K) was also observed in a much smaller device at much smaller current (up to 10 mA) in [4], however, the absolute temperature is lower than the lattice temperature.

A higher currents a structure appears in the photoluminescence spectra at small but non-zero energy. Its amplitude increases faster than the total photon number but less fast than one would expect for a true BEC. This is accompanied by a strong, but not complete saturation of the inferred chemical potential. This indicates a tendency towards photon condensation.

[1] J. Klaers et al., Nature 468, 545 (2010)
[2] S. Barland et al., Opt. Exp. 29, 8368 (2021)
[3] M. Pieczarka et al., arXiv: 2307.00081 (2023)
[4] R.C. Schofield et al., arXiv: 2306.15314v1 (2023)

Direct integration of Bragg gratings into photonic crystal fibre photon-pair sources.

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Heralded single photons are a key resource for photonic quantum technologies. Currently source performance – in particular state purity and success probability – limits their usefulness in scalable quantum technologies. Robust, single-photon sources have been created by heralding from photon pair generation by parametric down-conversion, however the second-order nonlinear materials required for this process typically incur high loss when coupled to fibre. One way forward to reduce this integration loss with existing optical networks is to generate the photons directly in fibre.

We pursue this approach here, using photonic crystal fibre (PCF) as a medium for photon-pair generation by four wave mixing (FWM). The annihilation of two photons from a bright pump laser pulse create nondegenerate photon pairs. The properties of the photon pairs can be engineered through control of the PCF dispersion, which is itself set by the size and separation of air holes that form the PCF cladding. This flexibility is an attractive feature of the platform, but these fibre sources often suffer from noise induced by unwanted nonlinear processes and failure to eliminate residual pump light from the guided mode.

We present experimental results of photon-pair generation in PCF designed to enable fibre Bragg gratings (FBGs) to be written directly into the core for optimised pump rejection. We achieve sufficient photosensitivity for FBG inscription by UV exposure by introducing a germanium-doped core. We discuss FWM phase matching and FBG inscription in this type of PCF and report our results demonstrating photon pair generation.

Towards a parametric oscillator in photonic crystal fibre for squeezed vacuum generation

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Squeezed light sources are crucial components of emerging quantum technologies for computing, communications, and measurement. The direct generation of squeezed light inside optical fibre is of particular interest due to minimal material loss, desirable mode properties and compatibility with long-distance optical networks.

Here, we report progress towards an all-fibre vacuum squeezer operating in the CW regime at O-band wavelengths. Our device is based on a Fabry-Perot cavity formed by two high-reflectivity fibre Bragg gratings (FBGs) written directly into a single section of photonic crystal fibre (PCF). This cavity is resonant for the intermediate wavelength of a dual-pump degenerate four-wave mixing (FWM) interaction and is transparent at the two pump wavelengths. This configuration creates a singly resonant optical parametric oscillator (OPO) inside a single section of fibre.

Bragg grating inscription is realised using small-spot direct UV writing at 213 nm. Conventional PCF is composed entirely of silica which lacks the photosensitivity for FBG writing using UV. We therefore fabricate specialist PCF with a germania-doped core, which provides the required index susceptibility. The fibre is phase-matched for a $\chi(3)$-nonlinear interaction, degenerate FWM, to be pumped by amplified narrowband lasers at frequencies ωp (λp~1560 nm) and ωq (λq~1090 nm) . The interaction annihilates one photon from each pump and generates a photon pair at the intermediate frequency $\omega s=(\omega p+\omega q)/2$. Phase matching is assured by controlling fibre dispersion through the design of the PCF waveguide.

Here, we report on the design, fabrication and potential applications for this device, and present our most recent results for the characterisation of a PCF Bragg cavity and nonlinear performance.

Negative refraction in atomic arrays

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Negative-index media offer unique control of light with potential applications ranging from perfect lenses to cloaking devices and beyond. However, existing bulk metamaterials suffer from significant loss, a lack of tunability, and difficulty of numerically simulating the complex elements exactly. In this work, we propose arrays of trapped atoms as a platform for realising and investigating negative refraction. We first establish a formalism allowing for the exact calculation of optical response and transmission of beams through many-layered arrays. With our formalism we theoretically demonstrate negative refraction – enabled by cooperative interactions – through the atomic medium with high transmission and over a wide range of incident field angles. We further analyse negative refraction through the lens of collective resonances, and develop a simple description relating the beam transmission statistics to the group velocities and collective linewidths of the in-plane polarisation Bloch modes. We finally demonstrate robustness against realistic lattice imperfections. Our work suggests atomic arrays as a flexible platform for realising high quality refraction and exploring light propagation in unconventional media.

Continuously Sustained Bose-Einstein Condensate of Photons in a Semiconductor Quantum Well Open Microcavity

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Bose-Einstein condensates (BECs) of light are widely studied systems, however until now all photon BEC systems have used organic dyes [1], which imposes several limitations. Namely, long-lived dark states that require low repetition rate pulsed operation, molecular degradation over time, and weak photon-photon interaction. Here we report the first observation of photon condensation using an inorganic semiconductor quantum well [2].

Our device incorporates a GaAs/AlAs DBR mirror on which a single InGaAs quantum well was grown, with peak emission at 925 nm. A second commercial cut-down spherical DBR mirror completes the microcavity. The quantum well was optically excited off-resonance and tuned to the low energy Urbach tail of the quantum well from 930-960 nm. We observe broadband multimode fluorescence at low excitation intensity I_p, referred to as a thermal cloud of photons, and the generation of a bright, stable condensate at higher power when we cross the critical intensity I_crit, as shown in the spectra in Fig. 1. (a). We distinguish our system from a laser in several ways: thermalisation is observed below the critical intensity, with a spectral distribution corresponding to 300 K; condensation is observed where the absorption tail and cavity loss balance to produce good thermalisation, as shown below 955 nm in the phase diagram in Fig. 1. (b).

Our semiconductor open microcavity system sustains a stable photon condensate continuously and indefinitely over a large intensity range. This opens the possibility for probing photon BEC properties, such as coherence or non-equilibrium condensation, shown in Fig. 1. (b), over a large parameter range. Semiconductor mediated photon BEC also shows potential as a small, single mode, high power coherent light source.

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Measuring photon correlation using imperfect detectors

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The ability to reliably count photons is foundational to many demonstrations of quantum optics and photonic quantum technologies. However, all single-photon detectors are insensitive to subsequent photons after a detection, which limits their maximum count rate and efficiency [1]. Over tens of nanoseconds, as detection efficiency recovers, a fraction of incident photons are not detected [2], depending on the source photon statistics. This effect presents important implications for optical quantum technologies which ultimately require high detection rates.

In this work we present a model to describe the rate-dependent detection efficiency of a single-photon detector with finite deadtime for the three statistical distributions of light – bunched, Poissonian, and anti-bunched [3]. The temporal efficiency recovery for superconducting nanowire single-photon detectors is experimentally verified with photon counting, and the detected rate is numerically simulated based on the waiting time distribution for each detection channel. The impact of the temporal efficiency recovery on the second-, third- and fourth-order correlation function is modelled, and experimental data shows how high photon rates can suppress the detector's ability to accurately measure the correlation of bunched light sources.

This work presents an easily-implemented but impactful analysis method, which will be of increasing importance in photon counting experiments as higher rate correlated-photon sources are developed. In particular, the measurement of high photon rate correlations for bunched light sources is essential for verifying entangled photon pairs in quantum information processing applications.

Figure : Different rates for a bunched light source affect (a) the second-order correlation function and (b),(c) the third-order correlation function.

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Lie algebraic invariants in linear quantum optics

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Linear quantum optics is a promising candidate for obtaining a quantum computational advantage. However, linear optics without post-selection is not powerful enough to produce any quantum state from a given input state, which limits its computational capabilities. Thus, we need a deeper understanding of linear optical evolution. In this work, we use the Lie algebra of passive linear optical Hamiltonians to find conserved quantities in the evolution of a mixed quantum state. We obtain the invariants by projecting the density matrix onto this Lie algebra and taking the norm and the spectrum of the projected density matrix. This gives us invariant quantities along the passive linear optical evolution. Thus, if two input and output states have different invariants, it will be impossible to design a linear optical experiment that evolves one into the other. These invariants allow us to narrow the search when trying to prepare entangled resources useful for quantum computation, like Bell or noon states, from easy-to-prepare states, like Fock states. Using the invariants, we prove the impossibility of the following state preparations: 1) a Fock state from another Fock state (except by permutation of modes); 2) a perfect Bell state from a Fock state; 3) a noon state from a Fock state; 4) a W state from a GHZ state. We conclude that future state preparation algorithms will need to take into account the necessary conditions given by our invariants to weed out impossible linear optical evolutions.

Giant microwave–optical Kerr nonlinearity via Rydberg excitons in cuprous oxide

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We report on our recent experimental progress in using Rydberg excitons in Cu_2O for microwave-optical conversion [1,2]. In this material, we measure a microwave-optical Kerr coefficient of 0.022 ± 0.008 m/V^2 which is several orders of magnitude larger than other systems [2]. The key to this extreme nonlinearity is the exploitation of high-lying Rydberg states of excitons, whose large spatial extent leads to extremely high electric polarizability [3,4]. In contrast to Rydberg atoms, the nonlinearity is broadband covering at least 0.1 to 20 GHz due to the non-radiative broadening of the excitonic states. The results are in good agreement with a model for the nonlinear susceptibility based on the Wannier-Mott model [2]. As Rydberg excitons are inherently compatible with ultracold environments [5,6] the giant nonlinearity could be used as an optical readout for superconducting circuits, and we are in the process of integrating Cu_2O with a superconducting resonator. The giant Kerr coefficient highlights the potential of solid-state Rydberg systems for nonlinear optics and forms the basis for a microwave–optical frequency converter based on Cu_2O.

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Ambient Quantum Light Sources in Aluminium Nitride

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Solid-state quantum light emitters are being extensively investigated for applications in quantum technologies. To date, several material systems have been investigated in the context of single-photon generation, including semiconductor quantum dots and colour centres in wide-bandgap materials such as diamond and silicon carbide [1].

In this paper, we discuss a new family of quantum emitters based on colour centres in aluminium nitride [2]. Using time-resolved photon counting and spectral measurements we probe the optical properties of the emitters. Light emission dynamics are explored with power-dependent second-order correlation measurements, revealing a complex multi-energy-level system [3]. Polarisation-resolved photon-counting measurements show no preferential absorption dipole angle [4], which is surprising considering the crystallographic nature of the material.

In addition, we enhance the light collected from the emitters, which is inherently limited by refraction at the high refractive index contrast at the surface of the sample. Using an index-matched solid immersion lens on top of the sample, the detection rate was shown to approach one million photons per second at room-temperature [5].

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Figure 1 - Optical properties of emitters in aluminium nitride. i) Confocal scan map revealing the presence of point-like emitters. ii) Spectral measurement of the highlighted emitter in (i). iii) Second-order correlation measurement showing anti-bunched photon statistics at low optical pump power.

Towards fast, high-efficiency optical switching in rubidium vapour: Enhancing performance via a transfer cavity lock.

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Active multiplexing techniques enable the conditional routing of heralded single photons through switch networks, facilitating scalability in photonic quantum computation. To realise these techniques, a fast, low-loss optical switch is essential. However, achieving both high speed and high efficiency in the same device is challenging.

We show that cavity-enhanced light-matter interactions are a promising route to achieve high-speed single-photon switching in a low-loss platform. We utilise the strong two-photon absorption in warm rubidium vapor to mediate a controlled phase shift interaction with near-degenerate energy states in the atom's three-level ladder system. Our approach involves two counter-propagating laser fields, a signal and a control, interacting with atoms in an isotopically pure Rb vapor cell. By confining the fields to a resonant ring cavity, we enhance light-matter interactions and extend interaction times. We present data taken with the recent addition of a scanning transfer cavity lock, which enables the control field to be detuned from the atomic transitions. This detuning reduces absorption of the control field by the atoms, increasing the switch efficiency. The transfer cavity allows us to compare the switching results in both the on and off resonant regimes simultaneously and resolve the switching contrast. We demonstrate the capability of our system to achieve high-speed low-loss port switching suitable for implementing single photon multiplexing techniques.

Spontaneously sliding multipole spin waves in cold atoms

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We are reporting on the observation of a spontaneously sliding combined dipolar and quadrupolar spin density wave in the ground state of laser-cooled Rb atoms, where spontaneous magnetic ordering is obtained via light mediated interactions [1]. Spin density waves (SDW) and quadrupolar charge density waves (QDW) in condensed matter systems are stationary but translation is a (soft) Goldstone. However, in real materials SDW and QDW are pinned by inhomogeneities of the material and a finite amplitude parity breaking is needed for depinning and creating a sliding SDW [2]. The observation of spontaneous drift in a non-equilibrium version of magnetic ordering is expected to provide also insight in the question of time crystals and dissipative time crystals as ground state of many-body systems in general.

The scheme is based on a laser-cooled atomic ensemble irradiated by a linearly polarized laser beam detuned to the F=2 to F'=3-line of the 87Rb D2-line. Most of the light is retro-reflected by a plane feedback mirror. If a transverse magnetic field is applied parallel to the polarization vector of the pump light, a spatio-temporal structure emerges beyond a pump threshold. Analyzing the contrast of the transmitted light vs integration time of the camera shows a behaviour consistent with a drifting structure. For a stripe period of 78 µm and magnetic fields between 0.1 and 0.7 G, drift velocities are between 8 and 70 m/s.
Numerical simulations show that there is spontaneous symmetry breaking for the drift direction and the chirality. The magnetization vectors form a left-handed screw in space, if magnetic field and drift direction are parallel to each other, and a right-handed screw, if they are anti-parallel.

Quantum Technologies for Fundamental Physics

Electrical levitation of microparticles as a platform for fundamental physics

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The variations in large ensembles of particles are governed by the statistical properties of thermodynamics. However, as the associated length scale is reduced the characteristic energy scale of a system becomes comparable to thermal fluctuations. These play an important role in the operation of biological machinery and describe the shortcomings of nanoscale electronics [1]. While standard thermodynamics can be extended to this regime through the use of fluctuation theorems it remains challenging to verify them computationally. Here, we make use of electronically levitated nanoparticles to probe this regime known as mesoscopic physics.

The advantage of levitated systems over tethered systems comes predominantly in their decoupling from the environment. The lack of a physical connection to the surrounding system not only allows for access to the underdamped regime but it also offers higher Q factors due to the lower damping rates [2]. Coupled with the exceptionally large trapping depth offered through electronic levitation we can create a single-particle heat engine with enormous temperature ratios; with hot bath temperatures exceeding 100,000 K. This provides the ideal testbed to study the role of thermal fluctuations for reduced length scales. Such experiments cement this system as a viable platform for the study of fundamental physics.

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How similar are laser light and a single photon?

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Semiconductor quantum-dot devices (QD) are excellent and versatile quantum light sources due to their in-fibre single-photon brightness above 0.5 [1], their ability to produce controllable photon-number superpositions [2], and the very strong single-photon level nonlinearities they exhibit [3]. With these assets, they constitute potential and promising light sources for continuous-variable (CV) quantum information processing, where a crucial technique is homodyne detection, relying on the optimal mean-wavepacket-overlap M between classical laser light and quantum light [4].

We demonstrate two experimental methods to optimise and assess M in polarisation, timing, frequency, spatial and spectral-temporal distribution. Both methods are based on second-order-correlation measurements of a Local-Oscillator (LO, a pulsed laser/coherent state $|\alpha\_LO\rangle$ with mean-photon-number $\mu\_LO=|\alpha\_LO|^2$) combined with single-photons (SP, $|1\rangle$) generated from a QD in a micropillar cavity. Both are combined in a fibre-beam-splitter (FBS) with transmissivity (reflectivity) $T\simeq0.5$ (R) and analysed in auto- and cross-correlation configurations (Fig_Top_Setup).

For the auto-correlation configuration (Fig_Blue_Correlator_Box), we send one FBS-output into a Hanbury-Brown-Twiss setup including two single-photon detectors (SPD), D_1 and D_2. The normalised second-order-correlation function $g^2\_auto(\tau=0)$ shows an anti-bunching-to-bunching transition dependent on the mean-photon-number $R\mu\_LO$ (Fig_Blue_Plot_Box). This is observed for several overlap values M_auto, controlled by adjusting the LO-polarisation. Maximising the value of $g^2\_auto(\tau=0)$ to 1.243±0.002 at the optimal LO-polarisation increases M_auto to a maximal value of 0.76±0.02.

We confirm the values of M_auto independently in the cross-correlation configuration (Fig_Red_Correlator_Box), where both FBS-outputs are correlated in SPDs D_2 and D_3. M_cross is quantified using the modified Hong-Ou-Mandel visibility relation from [5]. This requires the correlation measurement $g^2\_cross(\tau=0)$ of the interference (mixing) between states of parallel (orthogonal) polarisations, and is independent of the mean-photon-number μ_LO (Fig_Red_Plot_Box). Our results represent an important milestone for observing non-Gaussianity of optical quantum states.

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Symmetry-informed quantum metrologies: a new path to measurement optimality

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Combining quantum and Bayesian principles leads to optimality in metrology, but exact solutions can be hard to find in practice. In this talk I show that searching for good measurement strategies often amounts to identifying which symmetry leaves a state of maximum ignorance invariant, irrespective of error bounds. For quantities that are isomorphic to location parameters, this allows the optimal strategy to be written in closed form for any parameter range, prior information, state, or sample size. I further demonstrate the practical potential of this framework for the estimation of a wide range of parameter types, including decay rates, photon losses, temperatures, locations, and speeds. This approach reduces the number of metrological calculations needed in practice and enables the rigorous application of quantum metrology to fundamental physics, where symmetries play a key role.

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Symposium: Solitons, Nonlinear and Quantum Photonics in Resonators and Waveguides

Interactions Between a Soliton and a Blue-Detuned State in a Microcomb Laser

Cutrona A

Cavity-solitons generated within a microresonator-filtered fibre laser [1] exhibit self-emergence and recovery facilitated by the interaction of slow nonlinearities within the system [2,3]. Nonlocal nonlinear effects like thermal detuning [4] and gain saturation [5] play a pivotal role in shaping the overall characteristics of these systems [6]. These effects operate on slower timescales compared to fast phenomena such as the Kerr effect, offering potential enhancements to the robustness of solitary regimes.

In this work (see Figure), we explore the nonlinear emergence and recovery of a bonded state consisting of a soliton and a continuous wave (CW), with the soliton being red-detuned and the CW blue-detuned relative to the microcavity resonance slopes. Our findings demonstrate that the blue-detuned CW and soliton emerge in distinct regions of the erbium laser spectrum, where the slow resonant nonlinearity of the amplifier exhibits a different sign. The physics underlying this state is notably complex, and our real-time measurements, conducted using Dispersive Fourier Transform (DFT), reveal an elastic bonding between the two states mediated by the system's modal structure and the slow nonlinearities.

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Continuous adiabatic frequency conversion in whispering gallery resonators

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One of the most promising domains benefiting from nonlinear photonics is optical frequency conversion. This process is essential for tasks as diverse as industrial machining and astronomical observation. Here, optical microresonators emerge as key players, elevating the performance of optical frequency converters through their unique ability to amplify optical nonlinearity. However, achieving high conversion efficiency necessitates both high light intensities and the provision of phase matching.

An alternative resonator-based mechanism modifying the frequency of laser light is adiabatic frequency conversion (AFC). It is based on changing the eigenfrequency of an optical resonator on a time scale smaller than its decay time. In contrast to its nonlinear-optics based counterpart, this mechanism is efficient even at the single-photon level. Furthermore, there are no phase-matching restrictions.

So far, experiments mainly focused on discrete frequency shifts, highlighting AFC's potential for fast and efficient frequency tuning. Our study introduces continuous frequency changes through electro-optically driven adiabatic frequency conversion using a lithium-niobate microresonator with 10^8 quality factor. Here, a voltage signal that varies over time is applied to the resonator and transformed into a corresponding temporal frequency modulation. Through this technique, we showcase frequency chirps with a slope of 10 GHz/µs and nonlinearities lower than 1 %. Moreover, this approach enables to convert nonlinear voltage signals into corresponding frequency signals with minimal nonlinear distortions. As a proof-of-concept, we have applied the linear frequency chirps for measuring distances up to 10 m via frequency-modulated continuous-wave LiDAR.

Our results show that electro-optically driven adiabatic frequency converters transform an arbitrary voltage signal into a corresponding frequency change on timescales far below 1 µs. Electronics and on-chip integration will enable 100 GHz frequency tuning in under 1 ns, broadening applications like ultrafast spectroscopy. Additionally, AFC is notable in quantum photonics for its efficiency without high light intensities.

Synchronisation and chaotic dynamics of dissipative breathing solitons

Boscolo S

Multi-color frequency combs in a single Si3N4 microresonator

Donegan J

Recent progresses in fiber Fabry-Perot resonators for frequency comb generation

Mussot A

Transitions of Temporal Talbot Effect in Fibres: From Linear Light Propagation to Soliton Crystals and Talbot Solitons

Zajnulina M

Ultrafast and Strong Light-Matter Interactions

Reveal molecular chirality with light: left or right?

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Chirality has been proven to play a vital role for living nature, emphasising the importance of its study across sciences with one of the key problems being chiral recognition – the creation of methods telling apart right-handed molecules from their mirror, left-handed, companions. As an illustration of this massive campaign of chiral study spread, it has recently become an emerging frontier in ultrafast physics, with vivid progress achieved in the strong laser field interaction with chiral molecules.

We introduce a new effect from the realm of ultrafast physics – chiral Stark shift. We theoretically show that the common Stark shift can be turned into its chiral counterpart if a chiral molecule is illuminated by synthetic chiral light [1]. This opens a way to turn Stark-shift-based phenomena into enantiosensitive, or chiral, ones. We demonstrate it within the example of free-induction decay steered by synthetic chiral light in the shape of a tricolour chiral (TRICC) field structured in space and time. We show that an excited chiral molecule accumulates an enantiosensitive quantum phase due to perturbative interactions with the TRICC field. The resulting spatial phase gradient steers the free-induction decay (FID) beam in opposite directions for left- and right-handed enantiomers, revealing the chirality of the molecule – the scheme we call FID labelling of enantiomers (FIDLE).

We show in the figure TRICC FIDLE simulations of the enantiosensitive quantum phase (a) and far-field FID beam (b) for the methyloxirane molecule, showing a clearly visible chiral steering of the FID emission [2].

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Strong coupling between quasi-bound states in the continuum and excitons based on WS2/Si3N4/fused silica hybrid metasurfaces

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All-dielectric metasurfaces supported quasi-bound states in the continuum (q-BICs) provide a pathway to develop a new paradigm for trapping and confining resonant optical modes due to the high quality factors (Q-factors) in q-BIC, low loss in dielectric metasurfaces, as well as broad spectral tunability and strongly enhanced near-fields for boosting both surface-driven and material-intrinsic processes in the field of nanophotonics [1]. Q-BIC can be obtained by breaking the in-plane symmetry of the structure, and the ultrahigh Q-factor resonance modes in the q-BIC can be readily tuned by the degree of asymmetry [2]. A machine learning (ML) algorithm has been developed to target a specific resonance energy based taking account of the specific materials and conditions. A slotted disk q-BIC designs are achieved with the tuneable resonance from 590 nm to 640 nm. The q-BICs are used to enhance the light-matter interaction with a WS2 monolayer, with strong coupling observed even at room temperature. A Rabi splitting energy of 29 meV is observed in a WS2/Si3N4/fused silica structure.

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Optical tunnelling without a barrier?

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Tunnel ionization is a central phenomenon of strong-field physics and it is involved in essentially all intense laser-matter interactions. Strong-field ionization in the tunnelling regime takes place as discrete events which the strong-field approximation describes via saddle points that give rise to the well-established formalism of quantum orbits.

In this work we consider the nonadiabatic above-threshold ionization of a 1D model atom by a bichromatic field. We pose the question of what happens to these ionization events (i.e., saddle points of the action) when we gradually replace a monochromatic beam with its second harmonic. Over this replacement, the number of ionization events per cycle of the fundamental changes from two to four. We therefore ask: Which ones are new? And, how did they get there?

The transition comprises two interesting features. Firstly, we identify configurations in which the saddle points describing ionization
events coalesce into a caustic and form a branch point. Here, continuous labelling of saddle points becomes impossible, the saddle point approximation breaks down, and novel uniform approximations have to be employed in its stead.

More remarkably, we find that the new saddle points start contributing to the ionization yield long before the field changes sign. In other words, we present a tunnelling ionization event which occurs when the instantaneous electric field is zero, and hence at a time when there is no barrier. This results purely from a nonadiabatic picture of tunnelling, and presents a situation which cannot be modelled within the semi-classical and quasi-static pictures of optical tunnel ionization.

How They Walk: Distributed Polymer Optical Fibre Sensing for Shape and Deformation

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Recent activities in distributed sensing using step index polymer optical fibre (POF), will be presented, combined with modern signal processing and data analysis, facilitating remote and unobtrusive measurements of person and animal motion for shape and deformation sensing, with applications in healthcare, agriculture and biometrics.

Smart Mats exploit embedded POF inside a carpet composite, to classify human motion characteristics, by applying Artificial Intelligence and Machine Learning algorithms to the raw signal generated by an optical fibre grid illuminated by LEDs and interrogated by photodiodes, when deformed by a person walking on the mat. This enables periodic walking patterns to be monitored, and significant signal features to be automatically extracted to relate early subtle changes in an individual’s walking pattern, to initial changes in molecular biomarkers that may indicate prodromal stages of Alzheimer's or Parkinson's disease (Deep and Frequent Phenotyping Study-Dementia Platform UK). Gait and mobility indicate neurological conditions such as preclinical dementia that affect executive brain function and mobility.

Applications include monitoring/analysis of patients affected by mobility problems, requiring rehabilitation; and tracking degenerative conditions such as musculo-skeletal diseases (MSD) and arthritis, as well as identifying individuals from "how they walk" for security applications, including age and sex of the subject. Further applications include predicting falls in elderly, retail footfall analysis in large spaces: and people monitoring in smart homes and cities.

Other beneficiaries include silent patients unable to communicate their condition, such as animals and babies. A smart mattress detected neonatal movement in premature babies via an embedded non-contact POF sensor, to identify neonatal startle reflex movements, to implement a care unit noise reduction strategy to improve the environment for sick babies. Similar smart mats was used to improve conditions for animal farming, facilitating detection of feeding patterns, hoof infections and monitoring pregnancy weight gain in pigs.

Modelling gas flow in long antiresonant hollow-core optical fibres using OpenFOAM

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Hollow-core fibres (HCFs) guide light in a gas-filled core, enabling many exciting properties and wide-ranging applications, from telecommunications to high-sensitivity gas detection. As the gas present in the fibre has a direct effect on an HCF's optical properties [1], including attenuation, the dynamic changes that occur during deployment due to gas exchange with the environment or during active gas filling/purging are important to understand, such as the gas-filling time and resultant pressure/concentration distribution.

Typically, a simple cylindrical tube model has been used to simulate the pressure distribution inside the core of an HCF [2], replacing the Navier-Stokes equations with a single one-dimensional differential equation. This model works well for photonic bandgap and Kagomé HCFs, where the core is well-approximated by a cylinder. However, more recent designs, such as nested antiresonant nodeless fibres (NANF, Fig. 1), have complex core shapes requiring the use of an effective core diameter correction [3]. As this correction is likely to be specific to the fibre geometry, full 3D modelling is required to investigate realistic situations.

Here, we expand an approach from [4], using OpenFOAM to simulate gas flow in a 435m length of NANF pressurised for ~50 hours. We compare the results of numerical simulations to the tube model and experimental results obtained by OTDR [3] to determine the suitability of this modelling approach.

Fig. 1 SEM image of a NANF with a core diameter Dc = 35 µm. Blue: approximation of the core with a cylinder; red: the area of the full complex core shape.

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Low loss multi-core anti-resonant hollow core fibre

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We report the fabrication and characterisation of a low loss anti-resonant fibre with multiple hollow cores. Within an outer diameter of 200 µm, three cores of 24 – 25 µm inscribed diameter are formed by stacking separate single-core canes, each with 7 tubular resonators, Fig. 1(a). In contrast to previous anti-resonant multi-core fibres [1,2], the cores do not share a common anti-resonant microstructure. The systematic variation in resonator size, with more inflation towards the outer regions of the fibre, seems to be due to temperature gradients from the drawing furnace into the fibre, together with the offset of the cores from its centre. When similarly drawing a single cane from the same batch (centred in its preform), this does not occur.

The transmission spectrum for near-infrared and visible light, Fig. 1(b), indicates a resonator wall thickness of ~ 700 nm, with very similar transmission through all three cores. A cutback measurement from 47.7 m to 8.9 m of a single core gave a minimum loss of 0.03 dB/m at 610 nm and 0.08 dB/m at 1000 nm. We observed little core-to-core coupling, which we attribute to the large physical separation of the cores.

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Multi-mode deep ultraviolet hollow core fibre

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Anti-resonant hollow core fibres (AR-HCFs) guide where solid-silica counterparts have high attenuation or photo-darkening [1]. Fabricating AR-HCFs in the deep ultraviolet (UV) (< 280 nm) is challenging due to the difficulty in maintaining non-contacting thin resonator structures. The guidance mechanism of AR-HCFs depends on the thin glass walls of the resonators, where thicknesses are of the order of the wavelength to be guided [1]; thinner walls mean the fibre is more susceptible to deformities during fabrication [2]. We recently reported a single mode fibre that guided to a wavelength of 190 nm, where the inscribed core diameter was ~12 µm [3]. However, for mode insensitive applications such as signal collection in sensing or spectroscopy, high throughput is preferred over single-mode guidance, especially if broader guidance than UV is desired as the small core becomes an unsuitable waveguide at long wavelengths. We report the fabrication of a multi-mode AR-HCF which guides light to the deep UV, with a core diameter over 2.5x that previously reported [3].

Figure 1. Attenuation from 14 m to 4 m. (Inset image): A near-field optical micrograph from a colour Si camera showing white light transmission through a length of 1 cm. The inscribed core diameter is ≈ 33 µm. (Square inset): A near field image captured with an InGaAs camera where white light has been coupled to a 4 m length of fibre.

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Tunable near-degenerate frequency conversion using doped photonic crystal fibe

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Large-scale quantum networks comprise various components such as photon sources and transmission lines, which operate at diverse wavelengths. The optimal transmission window through solid silica optical fibre is around 1.55 um, while efficient single-photon sources based on GaAs quantum dots operate in the range of 900-950 nm. Additionally, high indistinguishability between photons is needed to realise many quantum information technologies, but any two GaAs quantum dots seldom produce photons at the same wavelength.

Parametric nonlinear processes, such as Bragg-Scattering four wave mixing (BS-FWM), enable frequency conversion of photons while preserving their quantum properties [1,2]. We present a BS-FWM scheme using bespoke germania-doped photonic crystal fibre that was fabricated in-house as a third-order nonlinear platform. Our scheme enables tunable conversion between telecommunications wavelengths (~1.55 um) and the operation range of GaAs quantum dots (~920 nm), as well as tunable conversion over a much smaller, few-nm wavelength range to and from wavelengths around 920 nm with up to 78% internal conversion efficiency, which could be used to interface dissimilar dots. To provide both required pump fields, we use a single commercially available fibre amplifier, seeded with a two-tone signal in the telecoms C-band; an innovation which considerably reduces the experimental cost and complexity of FWM-based frequency conversion. Finally, we show how cascading this frequency conversion can be used to generate a frequency comb.

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Posters

P1. Imaging of fast-moving single cells with adaptive single pixel detection

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The study of cells has led to a profound and extensive understanding of biology in the past century that was previously inconceivable. With numerous technological innovations in the last decade, analysis on a single cell level is now possible, which has enabled various discoveries that have advanced our understanding of the complex, dynamic processes that govern life.

Flow cytometry is at the forefront of such technologies in cell biology, used for the study of cell populations and of other single-celled biological particles, with state-of-the-art instrumentation allowing the detection and characterisation of up to 100,000 particles/s. Detection and characterisation are generally based on labelling targeted proteins, which require staining panels that have been carefully designed with prior, subjective knowledge of marker expression patterns. To empower more channels of detection, several other experimental approaches have been published on the topic of label-free cytometry [1]. The proposed solutions are mostly based on Raman spectroscopy, which allows the differentiation of certain cell types, but does not provide quantitative molecular information on the composition of cells and the current limit of detection also renders the achievable throughput incomparable to that of labelled techniques.

There are therefore strong incentives for a new disruptive method which would allow for untargeted, high throughput multi-omics analysis of cells in a flow cytometry setup. In this vein, we propose a novel means of high-speed, label-free cell analysis in a flow cytometer that leverages the high bandwidth of single pixel detectors (i.e. photodiode) and the high-speed motion of the droplet. Specifically, the photodiode signal is measured as the droplet traverses a region with spatially modulated light intensity.

Biophysical information (e.g. shape, size) of the cell is encoded by the light modulation, and therefore can be extracted by an analysis of the collected signal. Here, results from initial work are presented, showing the results from machine learning algorithms which were trained to determine the presence or absence of a cell in flow cytometry droplets. Critically, the trained algorithm is resilient to defocus, thereby removing any need for costly microfluidic devices to keep the cells to in focus.
The positive outcomes obtained motivate future work on further signal analysis, machine learning or otherwise, to extract useful biophysical information from the collected signal, as well as the optimisation of the utilised light modulation as part of the algorithm training, so as to boost the algorithm performance. Finally, as the method is nondestructive, the extracted information could be combined with other downstream investigations, such as mass spectrometry, for a wider and more comprehensive study of single cells.

P2. Application of strongly coupled plasmonic excitation for sensing of dye-labelled Bovine Serum Albumin

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The property of surface plasmons (SPP) to confine electric field into small volume (overcoming diffraction limit) leads to enhanced sensitivity to refractive index changes near the sensing surface, as a result paving way for SPP application for optical biosensing. However, the SPP-based detection of adsorbed surface mass is limited due to high energy losses in metals, therefore solutions to increase the sensitivity are needed.

The losses can be reduced (SPP sensitivity enhanced) by the application of strong coupling. Strong light-matter interaction based photonic nanostructures, supporting plasmons, recently gained interest due to their possible use in ultra-sensitive optical sensing [1], control of chemical reaction rates, lasers and quantum computing. If the conditions for strong light-matter coupling are reached a new hybrid mode is created and the energy exchange between hybrid mode components are lossless. It has been demonstrated that two strongly coupled plasmonic excitations of different nature can be used for enhanced biomolecule sensing [2]. This can also be achieved between plasmonic excitation and excitons of fluorescent dye-labelled proteins.

In this study, a simple structure of thin metal (40 nm Au/Ag) and CF680 dye labelled Bovine Serum Albumin (BSA) layer are modelled with different CF680/BSA concentrations. At high coverage of metal layer with CF680/BSA an apparent splitting of hybrid SPP-exciton mode can be observed. With the Rabi gap between the components of a hybrid mode acts as a direct indicator of the number of dye-labelled proteins attached to the sensing surface. The relation between the number of particles participating in the coupling (in this case emitters attached to the protein) demonstrated near linear relationship between the protein concentration and Rabi gap.

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P3. Asymmetrical temporal dynamics of topological edge modes in Su-Schrieffer-Heeger lattice with Kerr nonlinearity

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Asymmetrical phases, such as optical bistability and oscillation phases, can be observed in a Sagnac interferometer and a single-ring resonator made of Kerr nonlinear materials. In the Kerr nonlinear medium, the light intensity modulates the refractive indices. Similarly, a 1D array of coupled ring resonators with Kerr nonlinearity can exhibit asymmetrical dynamic phase. In this work, we construct a theoretical model for a nonlinear photonic Su-Schrieffer-Heeger lattice, as shown in Fig. 1, to demonstrate the bifurcation and various dynamic phases of topological edge modes [1]. By considering the envelope amplitude of each ring resonator, we show that the formalism based on temporal-coupled-mode theory can be written in a form similar to the Lugiato-Lefever equation but with additional coupling terms. Furthermore, we show how the Kerr nonlinear effect causes overlapping between the topological edge mode and some of the bulk modes leading to periodic and chaotic switching between clockwise and counter-clockwise intensity modes.

P5. Charging quantum batteries

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The challenge of storing energy efficiently and sustainably is highly prominent within modern scientific investigations. Due to the ongoing trend of miniaturization, the design of expressly quantum storage devices is itself a crucial task within current quantum technological research. Here we provide a transparent analytic model of a two-component quantum battery, composed of a charger and an energy holder, which is driven by a short laser pulse. We provide simple expressions for the energy stored in the battery, the maximum amount of work which can be extracted, both the instantaneous and the average powers, and the relevant charging times. This allows us to discuss explicitly the optimal design of the battery in terms of the driving strength of the pulse, the coupling between the charger and the holder, and the inevitable energy loss into the environment. We anticipate that our theory can act as a helpful guide for the nascent experimental work building and characterizing the first generation of truly quantum batteries.

P7. Circular Bragg Grating Cavities for Solid-State Photonic Systems

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A variety of solid-state colour-centres demonstrate narrow-band, fast and repeatable single-photon emission. Their solid-state nature enables integration with mature photonic platforms required for some quantum computation and networking schemes [1, 2]. Additionally, centres such as the diamond nitrogen-vacancy center, erbium-doped silicon and silicon T-Center demonstrate optically-accessible spin states, enabling use in quantum sensing, networking and computational schemes [3-6]. The latter two are of particular interest due their their emission into the telecommunication bands and silicon integration.

For implementation, challenges such as poor collection-efficiencies, low branching-ratios to the coherent zero-phonon line (ZPL) and low emission-rates must be overcome. Cavity integration is one way to do this. By structuring the electromagnetic environment of the center, it's emission can be modified via the Purcell Effect [2]. This enables the rate and ZPL branching ratio of the emission to be increased. Additionally, by choosing specific cavity designs, improved collection efficiencies can be achieved.

Here we will present the design, fabrication and characterisation of Circular Bragg Grating, or `Bullseye', cavities for telecom-emitting centres. The cavity consists of a central disk and 12 concentric rings in a Silicon-on-Insulator platform. These cavities produce a Gaussian-shaped vertically-leaky mode, enabling a large percentage of emission to be captured. With careful design of the cavity parameters, a moderate Purcell enhancement of the emission can also be achieved. The planar-nature of this cavity makes it suitable for ion-implantation techniques and as such is compatible with T-center and erbium-defect emitters.

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P8. Optoacoustic Imaging with Droplet Beams for Early Alzheimer's Disease Diagnosis

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A major challenge in optoacoustic microscopy is its restricted depth of field caused by the focused nature of Gaussian beams [1]. This limitation hinders capturing high-resolution images from uneven surfaces and acquiring quality 3D (volumetric) data without repeatedly scanning along the depth (z-scanning). To address this, we propose utilizing droplet beams, essentially side-lobe suppressed Bessel-like beams [2], in optoacoustic microscopy. These beams offer a significantly extended depth of field, approximately eighty times greater than the Rayleigh length of a Gaussian beam. We generate these beams using a modified Mach-Zehnder-type interferometer, equipping each arm with lenses of different optical powers. Demonstrating the advantages of droplet beam illumination through imaging fluorescent beads, we observe a 50% enhancement in image contrast compared to conventional Bessel beam illumination. Notably, the generation scheme for these droplet beams is readily adaptable to existing microscopy and bioimaging setups, requiring only standard optical components. Our optoacoustic microscopy approach excels at imaging 2.5 mm deep into the posterior cavity of mice eyes. This advantage arises from the designed illumination beam, possessing a depth of focus comparable to the ultrasound detector used in the optoacoustic imaging process. By facilitating the measurement of choroidal layer thickness, a potential early indicator of Alzheimer's disease, it offers opportunities for earlier disease detection.

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P9. Controlled Generation of Volumetric Poincaré Beams

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Emerging methods for generating structured light are finding applications across a spectrum of research fields, spanning free-space optical communications, thermal processing, remote sensing, particle manipulation, and high-resolution imaging. In this work, we present a method for the controlled generation of polarization-structured beams, encompassing both complete and partial polarization states, referred to as 'volumetric Poincaré beams' [1]. This is accomplished by manipulating spatial coherence by placing a rotating transmissive diffuser at the front focal plane and a spatially varying wave plate (SWP) at the back focal plane of a lens in a 2f geometry. SWP embeds the desired polarization distribution while ensuring a uniform degree of polarization across the beam's profile. Volumetric Poincare beams with controlled spatial coherence are generated by varying the beam size at the rotating ground glass diffuser. The far-field characteristics of volumetric Poincaré beams exhibit compelling features, including customizable irradiance profiles, polarization distributions, and degree of coherence distribution [2]. Notably, these beams display optical field singularities, which manifest as phase, polarization, and coherence singularities, with their interpretation contingent upon the beam parameters and the observation methodology utilized.

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P10. Leveraging the Fano Resonance in a Dielectric Array for Near-Field Trapping of Nanoparticles

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Near-field optics offers a solution to surpass the diffraction limit by generating strong optical gradients that facilitate nanoparticle trapping [1]. However, achieving efficient and stable trapping devoid of thermal effects presents a formidable challenge. While dielectric structures have been proposed for this purpose, they typically offer a weak trap stiffness. In this work, we leverage the Fano resonance effect in an all-dielectric quadrupole nanostructure to achieve a twenty-fold enhancement in trap stiffness (compared to the off-resonance case). We achieve a high effective trap stiffness of 1.2 fN/nm for 100 nm diameter polystyrene nanoparticles with 4.2 mW/µm2 illumination. Notably, the trap stiffness achieved with the quadrupole array surpassed non-resonant Si nano-antennas [2] by a remarkable factor of 25. Furthermore, the quadrupole array configuration allows for the simultaneous trapping of multiple individual particles. Such a system may be of relevance for Raman spectroscopic or other analyses of trapped nanometric particles (e.g., viruses).

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P11. Continuous Variable Distributed Quantum Sensing in Integrated Photonics

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Advances in nanofabrication techniques have permitted the rapid development of integrated photonics, a promising platform for efficiently scaling up quantum technologies, including quantum sensing. Quantum sensing with quantum probe states allows parameters to be estimated with a precision below the standard quantum limit imposed by classical physics [1]. When extending parameter sensing to estimating a linear function of distributed parameters, entangled quantum probe states allow the precision to be enhanced beyond what can be achieved using separable states [2][3]. Distributed quantum sensing is yet to be implemented on a photonic chip to the best of our knowledge. Entanglement-enhanced sensing of parameters in a fine spatial distributions would benefit measurements of photosensitive bio-samples.

Here, we present experimental plans and data for sensing the average of four spatially-distributed integrated phase shifters with entanglement enhanced precision. Continuous variable (CV) squeezed vacuum is generated deterministically off-chip and coupled onto the chip to be used as the quantum probe. Entanglement is deterministically generated using on-chip linear optics for the single mode squeezed probe, which can be routed through the chip in a reconfigurable manner. Parameter estimation, state detection and entanglement verification can all be performed on-chip with an array of four integrated homodyne detectors, demonstrating the scalability of CV integrated photonics. Figure 1 shows measurements of squeezed vacuum on two integrated homodyne detectors with simultaneous traces, with a trace of vacuum included for comparison. The measured quadrature changes from squeezed to anti-squeezed under thermal phase rotations in fibre.

This work demonstrates on-chip reconfigurable photonic networks for routing squeezed light probes, an essential endeavour for integrated quantum metrology and sensing.

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P12. Development of a modular ion microtrap apparatus

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The Ion Microtraps team at the National Physical Laboratory (NPL) is developing scalable microfabricated ion traps for applications in quantum information processing, quantum metrology and fundamental physics research. A new apparatus is being constructed to enable faster characterisation of the performance of the NPL microfabricated ion traps and support their ongoing development.

This new apparatus uses computer-aided design (CAD) to create a more compact and modular system. The CAD approach sets the position and alignment of all optical components at the design stage and increases the speed and ease of apparatus setup. Extensive use of fibre optic systems reduces the effect of beam drift inherent to free-space optics. RF device and experimental control is being implemented using the ARTIQ (Advanced Real-Time Interface for Quantum physics) system.

Lasers at several wavelengths are used to control the electronic states of trapped ions, including for laser cooling and manipulation of the qubit transition. The vacuum chamber housing the trap chip, along with the apparatus's laser systems, are mounted on individual custom-designed breadboards. From the laser breadboards, light is coupled into fibres for delivery to the microtrap chip. The beam delivery optics to the trap are mounted in modules that can be easily fitted or changed if modifications are required. Ion state measurement is carried out using high numerical aperture lenses mounted close to the vacuum chamber. These collect ion fluorescence, which is then detected by an EMCCD (electron multiplying charge coupled device) camera and PMT (photomultiplier tube).

P13. Cutting-Edge Infrared Thermometry: InAsSb Photodiode Fiber Optic Sensors for High-Speed, Near-Ambient Temperature Monitoring

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Infrared radiation thermometers (IRTs) overcome many of the limitations of thermocouples, particularly responsiveness and calibration drift. However, fast and reliable temperature measurements close to room temperature remains a challenge. A novel IRT sensitive to wavelengths between 3 µm and 11 µm was developed and evaluated in a laboratory setting. It is based on an uncooled indium arsenide antimony (InAsSb) photodiode, a transimpedance amplifier, and a silver halogenide fibre optic cable transmissive in the mid- to long-wave infrared regions. The prototype IRT demonstrated the ability to measure temperatures between 35 °C and 100 °C at an integration time of 5 ms and a temperature range between 40 °C and 100 °C at an integration time of 1 ms, with a root mean square (RMS) noise level of less than 0.5 °C. The thermometer was calibrated against Planck's law using a five-point calibration, leading to a measurement uncertainty within ±1.5 °C over the aforementioned temperature range. The thermometer was tested against a thermocouple during drilling operations of polyether ether ketone (PEEK) plastic to measure the temperature of the drill bit during the material removal process. Future iterations of the thermometer are intended to be used as a thermocouple replacement in high-speed, near-ambient temperature measurement applications, such as electric motor condition monitoring; battery protection; and machining of metals, polymers and composite materials, such as carbon-fibre-reinforced plastic (CFRP).

P14. Evaluation of Photonics Integration for Gas Sensing

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Global warming has emerged as an urgent issue due to its adverse impact on human and other life forms on Earth, including extreme weather events, glacial melting, and land degradation. This phenomenon is exacerbated by the accumulation of greenhouse gases (GHGs) such as carbon dioxide and methane. Prior to mitigating climate change by reducing GHG emissions, it is imperative to accurately track their concentrations for informed decision-making. Optical detection has proven to be an effective method for detecting gas leaks. However, existing systems are cumbersome, heavy, and power-hungry, limiting their practicality for real-world applications. To address this challenge and enhance Size, Weight, and Power (SWAP) efficiency, there is growing demand for photonic integration of bulk platforms for future applications, such as handheld or drone-mounted sensing. While photonic integrated circuits offer reduced size and weight compared to bulk optical systems, precise evaluation of each chip-on-submount component is essential due to their constrained design freedom.

In this study, QLM TECHNOLOGY LTD (Company) has developed a bulky gas leak detection camera, leveraging single-photon sensitivity with relatively low optical power, and facilitating rapid identification of GHG leaks through the use of commercial off-the-shelf (COTS) components. In our laboratory, we have undertaken the development of a semi-integrated platform, investigating a chip-on-submount Distributed-feedback (DFB) laser device and a Booster Optical Amplifier (BOA) device separately. Through free-spacing coupling from the DFB chip to the BOA chip (Fig.1), the absorption of a pure methane gas cell has been detected by the developed system using the differential absorption method. Building upon these initial findings, we propose the development of a fully integrated system utilizing Photonic Integrated Circuit (PIC) technology. This transition holds the promise of not only enhancing efficiency but also represents a significant step towards realizing the practical application of this gas sensing technology on a large scale.

P15. Ghost Displacement: imaging by measuring nothing

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Ghost imaging is a well-established technique that allows an image of an object to be sifted from twin-beam intensity correlations. One feature of the image is that the light that is detected to form it has not interacted with the imaged object. Only the correlated, unimaged beam does so – hence the term ghost imaging. The technique works with both quantum correlated and with split pseudo-thermal beams of light.

Here we describe a new form of ghost imaging, which we call ghost displacement, in which one of the correlated beams is first displaced coherently, before passing through an object and then being detected. When the detector does not fire, the beam that does not interact with the object receives a nonlocal displacement, despite not interacting with a coherent beam, but only at the transverse spatial locations corresponding to where the object in the other arm is transparent. The detection of this beam in coincidence with the other detector not firing allows an image to be formed. The method has previously been used in single mode fiber to transfer amplitude and phase information nonlocally and covertly [1].

We introduce a simple experimental method for performing imaging in a ghost displacement set-up. Our light source is an 842.2 nm VCSEL, pulsed to allow for simple timing correlation information. We use this to generate pseudo-thermal light via amplitude and phase modulation and obtain correlated twin beams using a beam splitter. We will show some preliminary results of our set-up.

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P17. High Throughput Characterization of Functional Nanomaterials using a Microfluidic Platform

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Microfluidic technology offers tremendous benefits for performing liquid phase characterization of functional nanomaterials, including reduced sample preparation time, on-line measurement, lower analysis costs, smaller sample consumption, multiplexed operation, and high throughput measurement. We present a novel microfluidic platform to study optoelectronic nanomaterials using optical methods. The platform consists of a microchannel possessing dimensions of 20 µ×25 µm, and a length of 50 mm. A pressure-driven system is used to drive a water-dispersed flow of micro and nano particles. Photoluminescence emission is measured following excitation at 405 nm and synchronized images and spectra of the particles are recorded at 90 Hz frame rates. The platform is calibrated by characterizing several hundred 0.5 µm fluorescent microspheres at ∼ 1 Hz, to correlate emission properties with geometric and dynamic properties. We show how this can be used for semiconductor nanomaterials towards high-throughput studies for low yield-materials.

P18. High-Efficiency Opto-Electrical Tuning of Sb2S3 Phase-Change Metasurfaces

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Metasurfaces, composed of precisely engineered nanostructures, offer a unique opportunity to control light at the subwavelength scale, shaping the wavefront of light with spectral selectivity,enabling various optical functionalities crucial in fields such as sensing and imaging [1]. Active control of these metasurfaces, driven by external factors like temperature [2] or light [3], holds promise for diverse real-time applications. This work investigates the tunability of antimony trisulfide (Sb2S3) depicted in Figure 1(a) as an all-dielectric phase change material (PCM) utilising indium tin oxide (ITO) film as a local heater [4] to crystallise the metasurface and an IR femtosecond laser for re-amorphisation.

The process involves heating the α-spot over the glass transition point by the ITO film at 275°C, followed by slow quenching for crystallisation of the metasurface (erasing). Then, amorphisation of c-film (writing) is achieved by heating the spot region to the melting point at 550°C and rapid quenching with femtosecond laser pulses. A significant contrast of optical properties such as refractive index between amorphous and crystalline states of Sb2S3 holds promise for active, reversible, non-volatile tuning of the proposed structure in the visible spectrum with ~180nm resonance shift. Our work suggests Sb2S3 metasurfaces are a powerful platform for high transmission efficiency, active wavefront manipulation, and developing integrated metasurfaces for beam deflectors, sensors, meta-lenses, and meta-displays.

Figure 1: a) Scanning electron microscopy (SEM) image of Sb2S3, b) simulation results for transmission in amorphous state, and c) the experimental results of transmittance in the same state.

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P19. Interoperable Mobile Ground Station for Quantum Kety Distribution

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Quantum Key Distribution (QKD) allows a cryptographic key to be distributed between two parties with information theoretically perfect security because it is physically impossible to copy an unknown quantum state without introducing errors. Thus, QKD is susceptible to losses as no amplifiers are available. At global distances the lowest loss path betwen two actors to share keys is with a trusted node satellite.

As part of the OS2 Volt (ESA) and SPOQC (UK) satellite missions, we present our efforts towards a mobile optical ground station that is interoperable with many of the currently planned international QKD satellite missions. To avoid adverse weather effects and maximise year-round key generation and test multiple potential sites to have the receiver infrastructure as close to population centres as possible, we have made our OGS mobile and easily deployed from a commercial van in a matter of hours. We also present our telescope agnostic design of the back-end QKD optics that can be readily adapted to a wide range of telescopes.

P21. Is the terahertz emission from spintronic structures enhanced by Cu alloying?

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Spintronic terahertz (THz) emitters are promising laser-driven THz radiation sources, that can provide gap-free, broad-bandwidth spectral emission with applications in material spectroscopy and industrial monitoring, amongst others. These emitters utilise the inverse spin hall effect (ISHE) in a nanometer scale heavy metal layer to convert ultrafast spin-polarised currents, generated in a nanometer ferromagnetic layer, into charge currents which act as the source for the radiation [1]. The parameter that characterises the efficiency of the ISHE is the spin hall angle (SHA). Recent research has focused on introducing dopants into the heavy metal layer with the aim of increasing the SHA. These include Au [2], MgO [3] and O [4] and have observed ~20%, ~100% and ~170% increases in THz emission respectively. These increases are attributed to a bulk increase throughout the layer and an 'interface effect'.

A set of CoFeB/Pt bilayer emitters with the Pt layers doped with Cu concentrations varying from 0% to 46%, were fabricated. The largest bilayer amplitude increase was found to be ~7%, for a Cu concentration of 18%. Additionally, W/CoFeB/Pt trilayer emitters doped with Cu in the Pt and W layers were produced and had a ~27% emission increase. However, there are other factors that could potentially cause an increase in emission. Here we will present an investigation into the possible origins for this increase, exploring the changes in layer thickness and the dependence on the photoexcitation conditions. Thus, highlighting the danger of simply attributing increased THz emission to material properties without careful consideration of all the parameters that affect the THz emission.

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P22. Laser Functionalisation of Flexible Polymer-Carbon Composites for Medical Sensing

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The project "Laser Functionalisation of Flexible Polymer-Carbon Composites for Medical Sensing" aims to utilise laser irradiation to convert polyimide into graphene enabling the creation of conductive circuits tuneable to sensing applications. Through direct laser writing (DLW), precise spatial confinement of conductive structures within insulating polymers will be achieved, facilitating the sensing of pressure, temperature, moisture or pH changes. The innovation involves creating three-dimensional graphitic structures within the bulk of polymers, advancing beyond the highly investigated area of surface modification. By focusing on micron scale sensors, the project seeks to enable the incorporation of sensors into catheters and stents, enhancing smart medical procedures and implants.

Key to the project is the exploration of light polarisation effects on size and quality of sensing structures, employing a spatial light modulator (SLM) for dynamic polarisation modification. Building on prior research demonstrating polyimide's suitability for three-dimensional graphene conversion in the picosecond regime [1, 2], the current work aims to optimise DLW parameters for structure size, porosity, and conductivity, while developing a process model for industrial scale-up.

The use of customised ytterbium-doped fibre laser (80 MHz repetition rate, adjustable pulse length 2 ps to 80 fs) was informed by Biswas et al.'s thermal model showing successful graphitic structure generation [3]. By streamlining graphene manufacturing into a single-step digital process, the project aims to revolutionise sensor production, offering flexible, scalable manufacturing solutions compatible with Industry 4.0 principles. This approach aligns with the new medical device regulation (MDR), necessitating enhanced safety and performance characteristics by 2026-2028, thus potentially offering a solution for meeting regulatory requirements and advancing medical device technology.

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P23. Lithium niobate microresonators for frequency comb generation

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Microresonator optical frequency combs provide a precise spectral ruler for applications ranging from spectroscopy and optical clocks to telecommunications and quantum information processing. Typically, the microresonator comb generator relies on third-order optical nonlinearity χ(3), but material platforms possessing quadratic nonlinearity χ(2) are growing in importance. Since lithium niobate ($LiNbO_3$) has large values of both these and low optical losses, it is an ideal platform for linking infrared with visible and mid-infrared spectral ranges [1,2].

We will report our progress with fabricating, periodic poling, and characterising ring microresonators at telecommunication wavelengths. We use a thin-film $LiNbO_3$ platform on SiO_2/Si with HSQ as a negative resist for electron beam lithography and a physical dry etch process with Ar plasma.

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P24. Low-Cost Hyperspectral Imaging for Environmental Monitoring

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Environmental monitoring is critical to our understanding of the impacts of climate change across a broad range of diverse ecosystems. As technologies have developed, hyperspectral imaging approaches have been increasingly applied across these environments, enabling more detailed non-invasive analyses. However, whilst these techniques are effective, they are often limited by high costs and bulky instrumentation significantly restricting their widespread application, particularly within more extreme environments. There is, therefore, a significant need for more accessible cost-effective hyperspectral imaging instrumentation within these contexts. This work discusses the development and application of two innovative hyperspectral imaging instruments designed for robust low-cost environmental monitoring. These instruments are: a smartphone-based portable hyperspectral imager and a laboratory-based high-resolution hyperspectral instrument. Both instruments have been designed to overcome specific limitations associated with conventional systems.

The smartphone-based instrument represents an ultra-low-cost, fully portable hyperspectral imager enabling the capture of hyperspectral datasets with a standard smartphone camera. This instrument is designed to promote accessibility and ease of use across a broad range of challenging field conditions. The high-resolution instrument enables detailed spatial and spectral resolution datasets to be captured using a low-cost, semi-portable laboratory-based instrument. This instrument is capable of analysing environmental features at a millimetre scale with a spectral resolution of < 1 nm.

Extensive testing across various environmental applications and real-world scenarios demonstrates that these devices can match the performance of high-end commercial systems, providing new monitoring opportunities for less well-resourced research teams. Furthermore, the smartphone-based instrument enables accessible and affordable data capture across more challenging and difficult to access environments. By lowering the financial barriers to hyperspectral imaging applications within environmental monitoring we aim to provide a step towards the democratisation of this analytical technique, providing more opportunities for data acquisition and improving our understanding of the impacts of climate change.

P25. Low-cost Ultra-thin Endoscopes for Improved Cancer Detection

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There is a clinical need for a cost-effective imaging device capable of detecting pancreatic cancer at early stages [1]. Spatial Frequency Domain Imaging (SFDI) is a low-cost imaging technique that works by projecting light fringes over a sample and measuring the diffuse reflectance, from which optical properties that serve as cancer indicators can be calculated: the absorption and reduced scattering coefficients. This technique is non-invasive and has the potential of producing near real-time results, making it ideal for clinical use, but existing systems are bulky and cannot be used inside the body [2]. Crowley and Gordon developed the smallest ultra-miniature SFDI imaging prototype (3mm diameter) that utilises dual-wavelength (515 and 660nm) to provide the absorption, reduced scattering and 3D shape of a sample [3]. However, the projection patterns must be changed manually which can take several minutes, making it unfit for a fast-paced clinical setting.

We will present a second iteration of this prototype that will have incorporations geared toward clinical use. To automate the system, we introduce a Spatial Light Modulator (SLM) device, and we develop a corresponding software to allow it to swap between patterns within seconds. The SLM also achieves less power loss and improved image quality. We also introduce a third wavelength (450nm) to perform a second imaging technique called Narrow-Band Imaging (NBI), which provides enhanced image contrast of blood vessels by sequentially projecting light at wavelengths that are similar to the absorption peaks of hemoglobin [4]. To validate the system’s performance, we test the prototype on 16 calibrated phantoms that span over a range of absorption and reduced scattering coefficients, and we use these findings to improve the image processing. These results show the potential of the prototype to produce near real-time measurements of cancer indicators.

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P26. Metabolic imaging of pre-implantation embryos using a phasor-based hyperspectral light-sheet microscope

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Spatial mapping of cellular metabolic activity can reveal the health of cells and tissue. In particular, imaging the endogenous metabolic cofactors, nicotinamide adenine dinucleotide (phosphate) (NAD(P)H) and flavin adenine dinucleotide (FAD), can help to determine tissue and cell viability in a clinical environment. However, current imaging techniques are unable to achieve a high imaging speed at subcellular resolutions, leading to issues relating to photodamage.

In this poster, we achieve three-dimensional mapping of metabolism in pre-implantation murine embryos by constructing a phasor-based hyperspectral light-sheet microscope with a single UVA excitation wavelength. This choice of wavelength can simultaneously excite substantial NAD(P)H and FAD autofluorescence and the contribution of each is separated by using a hardware-based spectral phasor analysis. This approach avoids the need for multiple excitation wavelengths or multi-photon imaging, and is suitable for future clinical translation for noninvasive assessment of embryo viability.

P27. Micro- and Nano-Patterned Metallic Surfaces for High Temperature Solar Thermal Absorbers

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Solar energy converters based on thermal processes require the maximum incident solar energy to be absorbed and converted into heat. Ideal solar absorbers therefore need to have excellent selective surface properties, absorbing all incident electromagnetic energy whilst minimising re-radiation [1]. It has been shown through electromagnetic modelling that surface nanopatterning can dramatically alter the optical response of an interface and that it can be tailored to enhance broadband absorption across the solar spectrum [2][3]. This paper studies laser patterning of molybdenum surfaces that can be achieved over large areas using low cost laser processing. We have previously investigated this topic with lower laser powers [4] but here by using a higher power laser we have obtained much improved performance obtaining “Black” molybdenum with a particular laser recipe. This work investigates the nature of the surface using Fourier Imaging, Scanning Electron Microscopy and Energy Dispersive X-ray analysis.

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P28. Microscopy with propagation-invariant beams: addressing the deconvolution challenge

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Advanced microscopy imaging using propagation-invariant beams, such as the Airy and the Bessel beam, offers powerful opportunities for achieving high-resolution imaging over an extended depth of field, as well as higher penetration into scattering media via their self-reconstructing properties. However, their use in microscopy is far from ubiquitous. Beyond the obvious challenges in engineering the beam shape, the spatial content in such images is encoded by a complex point-spread function that is often non-trivial to deconvolve. This often limits the sensitivity and resolution and fails to meet the expectation posed by theory. In this poster, we explore these trade-offs in optical microscopy and describe various methods to approach the problem of deconvolution. Importantly, recent deep learning methods have breached many limitations of conventional deconvolution methods. We show that a deep-learning method that is guided by prior knowledge of the physics of the imaging system and sample content can breach the limitations in sensitivity and resolution. By solving the problem of deconvolution effectively, the use of propagation-invariant beams could become a staple in many microscopy designs.

P30. Multi-laser spectroscopy of atomic ladder transitions

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Multi-laser spectroscopy of atomic ladder transitions

Eesa Ali, Hannah Seabrook, Frederic Leroux, Rowan A. Hoggarth, and Alex S. Clark

Ladder- type atomic transitions are a promising platform for noise- free quantum memories [1] which can be integrated with single-photon sources [2]. Due to the higher- lying excited state Rb manifold, a variety of wavelengths for photon storage can be implemented. In particular, the 5P3/2 to 4D5/2 transition is at 1529 nm which is a widely used telecommunication wavelength, compatible with existing optical fiber networks. Photon storage at this wavelength has been demonstrated using the ORCA scheme [3] but photon storage at 780 nm (D2 line in Rb) has not. Storage at 780 nm is of interest due to compatibility with single photon emitters, such as Dibenzoterrylene molecules [4], and compatibility with other types of quantum memories [5]. This would also pave the way for single photon frequency conversion between 780nm and 1529nm and vice versa.

These memory experiments require robust locking of narrow linewidth lasers. For the 780 nm lasers, polarisation spectroscopy [6] is used followed by tunable beat-note locking for other lasers. Two-photon spectroscopy using 1529 nm and 780 nm lasers can produce a DROP [7] or polarisation spectroscopy signal which can be used to lock the 1529nm laser. I will present an investigation of two-photon spectroscopy over a range of frequency detuning across the hyperfine manifold of the 5P3/2 to 4D5/2 energy levels. This has application in laser locking and the optimal operating ranges for a ladder memory.

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P31. Nanofabrication of complex and chiral flat optics via multi-exposure laser interference lithography

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Nanofabrication has advanced significantly with the integration of laser interference lithography (LIL), a method particularly adept for fabricating nanostructures over cm areas in a few minutes [1-2]. In this study, we experimentally demonstrate the capability of LIL for creating complex and chiral structures on a nanoscale. We have designed and developed a home-built LIL setup that can utilise a series of patterned exposures where the angle, phase, and polarisation of interfering laser beams are precisely controlled. As a result, we have managed to construct complex, three-dimensional chiral optical structures with high spatial resolution and repeatability, as can be seen in Figure 1. The experimental setup consists of a coherent laser source split into multiple beams that interfere at the substrate, with the interference pattern being modulated through controlled variations in exposure parameters. This approach allows for the realisation of arbitrary complex hierarchical patterns that can be tuned to achieve specific optical effects. Our results demonstrate the successful fabrication of chiral nanostructures with sub-wavelength features which are not easily achievable with traditional fabrication techniques. The ability to produce such intricate structures opens opportunities for the development of sophisticated flat optics that exhibit unique optical properties, such as polarisation control and phase manipulation, which are crucial for applications in imaging, sensing, and communication technologies. Future work will focus on refining the control over the interference patterns and exploring the limits of chiral geometries that can be achieved.

Figure 1: Microscopy Image of Hierarchical 3D Patterns Created by an a) 3 b) 8 and c) 16 Exposure Rotation, the finest structure is 1μm.

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P32. On the role of multiple scattering in speckle sensitivity, and the optimal way to quantify speckle change

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Speckle patterns are well known random interference patterns. Although sometimes seen as a nuisance, they can be used as a powerful measurement tool. Countless speckle-based methods have been developed, generally allowing high sensitivity and simple setups.

An essential task in this field is to assess speckle sensitivity to a given measurand of interest. To this end, different metrics are used in the literature, some of which suffer flaws that were only recently identified. I will present the optimal metric of speckle change.

It was also recently found that the performance of speckle-based techniques can be improved by several orders of magnitude by using speckle patterns resulting from the multiple scattering of light, rather than single scattering. I will present our work on modelling speckle patterns which explains this empirical observation. Intriguingly, our work also shows that multiple scattering offers no improvement for certain measurands. The improvement is either considerable or null. We formulate a general criterion which allows one to determine whether multiple scattering is beneficial for a given metrology task. This provides a valuable guide for the optimisation of experimental designs.

P33. Proscope: a multimodal colonoscope for early detection of colorectal cancer

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Colorectal cancer (CRC) is the second most common cause of cancer death in Europe. A contributing factor is that current colonoscopy, i.e. white-light video, is inadequate for in-vivo detection and characterisation of the various types of (pre-) cancerous lesions found in the colon. It is crucial that early detection of these lesions is enhanced as this improves survival rates.

Proscope is a EU wide collaboration which aims to provide a unique combination of label-free, non-ionising, proven optical imaging modalities that provide higher sensitivity and specificity compared to current colonoscopy.

Proscope aims to combine Raman spectroscopy, Optical Coherence Tomography (OCT) and Two Photon Light Sheet Microscopy (TPLSM) into one common imaging platform.
In the near future we plan to run clinical trials with the whole Proscope system though our EU partners.

Further information on the wider Proscope project can be found at https://proscope-h2020.eu

P34. Respeckle: a deep learning approach for speckle metrology

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Laser speckle is formed by the multiple interference of coherent light through a disordered medium, such as an integrating sphere, reflecting disc, multimode fibre, transmissive diffuser. Using integrating spheres, speckle meteorology has demonstrated exceptional sensitivity, achieving precision at the attometer level for wavelength [1], one part in a billion for refractive index [2], and picometer precision in displacement measurements [3]. However, heating of the integrating sphere by the laser causes mechanical changes and decorrelation of the speckle leading to short periods of time (on the order of a few minutes) when well-resolved data can be taken. To alleviate this concern, we present a deep learning denoiser, Respeckle.

Respeckle uses a convolutional neural network, UNET, to denoise images of unresolved, low power speckles into high power, well-resolved images of speckles. This allows for measurements to be taken at low power for longer periods of time without decorrelation occuring.

We show that Respeckle can denoise unresolved speckles at several wavelengths to near ground truth level, with typical values of similarity of ~0.9. Training of Respeckle can be undertaken on a consumer level GPU, and typically takes less than several hours to complete. Denoising of an image typically takes on the order of seconds to minutes depending on the image size.

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P35. Quantum Interconnected Devices for Distributed Quantum Computing

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Distributed quantum computing offers a potential advantage in communication complexity, since qubits can encode complex amplitudes that would otherwise require an exponential number of classical bits to be transmitted.

We propose a proof-of-concept setup to realise a distributed quantum computing task between two parties; where Alice prepares an arbitrary two-qubit photonic quantum state, and Bob performs an arbitrary two-qubit gate and samples from the resulting state in an arbitrary basis.

This could be generalised to any matrix-vector multiplication using techniques such as the singular value transformation or unitary block-encoding, and potential applications include distributed linear regression.
A novel approach based on a generalisation of the post-selected fusion gate to qudits of different dimensions was developed to transfer Alice's state into Bob's graph and realise the computation. The computation is performed in the measurement-based quantum computing framework using a suitable graph state prepared on Bob's side. All states are generated in a post-selected way using spontaneous photon pair sources and qudit path encoding, and the single qubit operations and measurements are realised with standard interferometry and photo-detection.

This proposal can readily be implemented using photonic integrated circuits, and we believe that it is a non-trivial protocol that can help understanding and developing new methods in post-selected quantum information processing, as well as stabilisation techniques between two separate integrated photonic circuits.

P36. Radio clock characterisation capability at NPL's Advanced Quantum Metrology Laboratory

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Highly stable and accurate radio and microwave frequency signals are critical for precise timing in several research and industrial settings, including telecommunications, navigation, and high frequency trading. Characterising devices which produce such signals requires reference signals whose stability and accuracy surpasses the device's performance. At the National Physical Laboratory (NPL), we maintain the UK time scale UTC(NPL) as the highest point of reference for time and frequency signals in the UK, based on a frequency-steered active hydrogen maser. UTC(NPL) is disseminated directly to NPL's new Advanced Quantum Metrology Laboratory (AQML), which has been equipped with the instrumentation to perform radio and microwave frequency characterisations traceable to UTC(NPL). We will present how we are using phase comparison measurement techniques to evaluate frequency accuracy, frequency stability and phase noise for signals in the range 7 kHz to 20 GHz, as well as stability for 1 pulse per second timing signals. We will show the measurement limits of these characterisations, with an Allan deviation below 2 x 10^(-13) at 1 s averaging time. We will also show how we are improving the limits for phase noise measurements by developing an ultra-low phase noise microwave reference based on an ultrastable laser down-converted to 10 MHz by an optical frequency comb. Characterisations of radio and microwave frequency devices can be integrated with the AQML's measurement capability for optical frequencies, forming part of a wider quantum test and evaluation capability which has already been exploited by several projects beginning this year. We will conclude by discussing future options for integration of next-generation optical frequency standards using the ytterbium lattice clock being built at the AQML.

P37. Resolution enhancement in extreme ultraviolet ptychographic imaging using structured asymmetric probes.

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Ptychography is emerging as the leading variant of coherent diffractive imaging. In ptychography, a coherent probe beam is scanned across an object, and the scattered light, collected at different probe beam positions, is processed by algorithms to reconstruct an image without the use of lenses. Ptychography allows high-resolution imaging with coherent EUV radiation produced using high harmonic generation[1].

Image reconstruction using ptychography typically uses data measured in the Fourier plane, linking resolution with experimental signal to noise, as the highest spatial frequencies in the scattered light have the lowest signal levels and are most affected by experimental noise. In this paper we describe ptychography in the extreme ultraviolet using structured probe beams with high M^2 and low rotational symmetry and show that the resolution of the resultant images is improved compared to that seen when using circular apertures, and also directional. The figure shows (a) a reconstructed image of 1µm PMMA spheres taken using 29 nm radiation, and the x- and y-direction Fourier correlations[2] of images reconstructed from data taken (b) with a structured probe, and (c) with a circular probe. The improvement in resolution and the observed directionality arise from the increased extent of the probe's angular spread in the Fourier plane. The use of a probe beam with a large extent in Fourier space can also increase resolution beyond the diffraction limit and compensate for missing regions in the scattered light data caused by, for example, beam stops or detector gaps. Optimisation of the structure of the probe beam will be an important direction in improving the performance of ptychography for water-window X-ray microscopy.

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P38. Single Molecule Analysis of Ferritin Disassembly using Solid-State Nanopores

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Solid-state nanopore offers a label-free single-molecule technique for characterising DNA, RNA and proteins in liquid solution1. This technique involves a nanometre sized pore in a thin membrane connecting two compartments filled with electrolytic solutions. By applying electrical voltage across the pore channel, an ionic current flow through the pore, and is detected by the amplifier. This ionic current drop when there is an object passing through and the current drop is associated with the size and volume of the passing objects 2. In this study, we employed polymer coated SiNx nanopores to monitor the ferritin disassembly process in acidic solution in real time. When ferritin is fresh mixing in electrolyte of pH 2, its subunits initiate to detach from the shell and start disassembly. This process leads to a reduction in the size of the passing protein over time, and the process lasts longer than 30 min3. To enable the tracking of the full disassembly process, we utilised a self-assembled monolayer of PLL-g-PEG polymers to prevent proteins adhering to the nanopore wall during their translocation4,5. This long-term measurement allows us to track the disassembly process of ferritin. Through the analysis of current blockade and dwell time correlated to the translocated ferritin's volume and shape, we could detect critical ferritin subunit sizes during ferritin disassembly.

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P39. Size-Dependent Chiral Dichroism and Enhanced Hyper Rayleigh Scattering in Plasmonic Chiral Helicoid-III

Choi H

Plasmonic nanoparticles (NPs) have attracted significant attention in various research fields due to their unique optical properties arising from localized surface plasmon resonances (LSPRs). The advancements in nanofabrication techniques have enabled the creation of complex plasmonic NP designs with tailored sizes, shapes, materials, and arrangements, opening up a wide range of applications. The optical properties of plasmonic NPs are highly dependent on their surface size and shape, with surface effects becoming more prominent due to the low volume-to-surface ratio. These unique properties have led to the development of novel applications in fields such as sensing, imaging, catalysis, and photonics.

In this study, we employ Hyper Rayleigh Scattering (HRS) to investigate the size-dependent chiral nonlinear optical responses in D-handed chiral plasmonic gold helicoids-III. HRS is a powerful technique for probing the nonlinear optical properties of nanomaterials, as it is highly sensitive to the orientation and symmetry of nanoparticles. By comparing the HRS response of gold helicoids with diameters of 100 nm and 180 nm, we found the relationship between size and the linear and nonlinear dichroism exhibited by these nanostructures.

Here, we report a clear size dependence of the chiral dichroism in gold helicoid nanoparticles. The larger nanoparticles, with a diameter of 180 nm, exhibit a more pronounced dichroism compared to their 100 nm counterparts, both in the linear (λ) and Hyper Rayleigh Scattering (HRS) regime (1/2λ). Remarkably, we observed a strong nonlinear g-factor of 0.55 from the 180 nm diameter gold helicoids, indicating their exceptional nonlinear optical properties.
The outcomes of this study advance our understanding of chirality at the nanoscale and its impact on nonlinear optical phenomena. Exploiting the size-dependent chiral dichroism and its correlation with the HRS response paves the way for developing novel chiroptical sensing techniques and efficient nonlinear optical materials. The outstanding nonlinear g-factor of the 180 nm gold helicoids opens up possibilities for their integration into highly sensitive systems. Our work provides new avenues for future research in chiral nanophotonics and showcases the potential of HRS in investigating chiral nanomaterials.

P41. Datacentre-scale entanglement distribution

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Nu Quantum is building the quantum networking infrastructure essential to scaling quantum computers. Quantum computers must go from hundreds to hundreds of thousands of qubits in order to achieve transformational impacts. Our approach is to interconnect many smaller cores using a Quantum Networking Unit (QNU) capable of efficiently scaling discrete Quantum Processing Units (QPU) to form a larger and more useful quantum computer.

Nu Quantum is uniquely positioned to deliver a flexible platform that is adaptable to all qubit modalities, while delivering order-of-magnitude improvements in rate and fidelity over the current state-of-the-art.

We are creating full hardware solutions to create entangled qubit networks, including a unique high-efficiency qubit interface, photonic switching fabric, and control systems to build towards multi-core quantum supercomputers and quantum data centres. Partnering with leading quantum companies, governments and research groups, we are accelerating quantum out of the lab and into real world use.

We will present an overview of our vision for a networked quantum computer, and highlight the challenges that we are addressing in order to make this vision a reality. This will include the distributed architecture, implementing a Bell state measurement scheme which allows a single QNU to entangle multiple distal QPUs. We'll present details of the QNU which are critical to achieve the requisite performance, and note progress in both components-off-the-shelf and photonic integrated circuit (PIC) solutions. We will also discuss the role of the light matter interface, and its role as a source of loss alongside detection and transmission losses.

Figure 1. Nu Quantum architecture of four quantum processing units (QPUs) connected to a single quantum networking unit (QNU).

P43. Surface Plasmon Coupled Emission of Rhodamine 6G Dye in Strong Coupling Regime

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Surface plasmon coupled emission (SPCE) has emerged as technology for fluorescence detection in biological sciences, biotechnology and medical diagnostics. New approach of SPCE technology allows to significantly increase collection efficiency of fluorescence signal by transforming normally isotropic emission of fluorescence dyes into directional[1] due to plasmon emission at resonance angle. This is achieved by coupling fluorescence signal from molecular dyes into resonant plasmonic modes and typically is performed by placing the emitters in the near field of plasmonic nanostructures. While SPCE typically resembles that of free space emission, difference being the decay lifetime of coupled emission due to Purcell effect, the spectrum remains the same[2].

In this work we have investigated emission from samples exhibiting strong coupling dynamics. Experimental techniques involving spectroscopic ellipsometry and Fourier space microscopy were performed on Rhodamine 6G fluorescent dye layers formed on silver based plasmonic nanolayers. Directional emission was observed for samples, along with modified spectrum due to Rabi splitting. Further experiments involving measurements of strongly coupled Rhodamine lifetime could indicate considerable reduction in decay times. Fluorescence lifetime imaging at picosecond scale[3] could have huge benefits from reduced decay times increasing the visibility of the quantum Hong-Ou-Mandel interference

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P45. Towards Monolithic Integration of Continuous Variable Quantum Sources and Detectors on Silicon Photonics

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The ability to efficiently generate and detect squeezed light is integral to developing technologies based on quantum continuous variables (CV), including large scale implementation of photonic quantum computing for which the CV platform shows great promise [1]. With integrated photonics providing a clear route to scalable implementations, there has been efforts to develop and refine the required building blocks for CV applications. This includes integrated homodyne detectors capable of measuring at the quantum level [2] along with advances in on-chip sources of squeezing [3]. However, uniting these components in a single chip is still a challenge. We present progress in monolithically integrating sources of squeezing and homodyne detectors on a single silicon-on-insulator photonic chip to further demonstrate the scalability this platform.

The layout of the photonic chip is shown in attached figure. Single-mode squeezing is generated by a pulsed dual pump spontaneous four wave mixing scheme in a spiral waveguide; a method that has provided indirect observation of generation of squeezed states in silicon waveguides [4] . The pumps are spectrally filtered before the squeezed state is detected by on-chip homodyne detectors of the type reported in [5]. We extend the operation of these detectors into the pulsed regime to facilitate the extraction of high levels of squeezing obtained by pulsed generation. This device has been engineered to enable future work with non-gaussian light, required for universal CV photonic quantum computing [6], to realise a path to large scale CV quantum applications.

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P46. Towards non-contact time-domain diffuse optical tomography

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Near-infrared light has good contrast in scattering and absorption across different tissue types [1], diffuse optical tomography (DOT) leverages this by using computational techniques to reconstruct volumetric images of tissue absorption and scattering coefficients [2]. Rich data available in time-domain (TD) measurements enables high quality reconstructions but is victim to extremely long computation times, bottlenecked by finite-difference methods [3]. Non-contact methods [4] also suffer from this as the modelling amounts to a ray-tracing problem. Current DOT methods require specialised hardware to be worn by the patient [5] or the use of an intralipid to fill void space [6] which attenuates signal and can be uncomfortable for the patient. Non-contact DOT methods could realise a similar modality to CT and MRI which is familiar to both patients and clinicians. This enables multimodal approaches using structural priors [7], and compact single photon avalanche diodes (SPADs) could be easily integrated into such a system.

Therefore, we present Diffuse Optics by Graphics Processing Unit Parallelisation (DOGPUP). A MATLAB toolkit which takes advantage of the parallel architecture of GPU hardware and the new CUDA support in MATLAB to enable fast simulation of non-contact TD-DOT detections, by decomposing the signal into a Fourier series [8] and using highly parallelisable Plücker coordinate ray-triangle intersection tests [9]. We compare this to experimental data with a line scanning camera using a time-resolved CMOS SPAD [10].

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P47. Towards Non-Local CNOT Gates on Photonic Integrated Circuits: Enabling Quantum Network Advancements

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Distributed quantum computing presents the future of the quantum internet, promising the sharing and processing of quantum information on remote devices. One way to achieve this is through the teleportation of entangled qubit pairs, combined with information processing, at different nodes in the network [1,2]. We propose the integration and distribution of non-local Controlled-NOT (CNOT) gates across an entanglement-based many-user quantum network, such as the 8-user network demonstrated in Ref. [3]. The platforms we choose for this integration are silicon photonic integrated circuits due to their scalability and subwavelength stability, aiming to achieve a photon detection success probability of 1/4 using ancilla Bell states [4], compared to previously demonstrated chip-scale CNOT gates with 1/9th success probability [5,6]. In this poster, we present our work towards practical implementations of these concepts by considering resource allocations of the gates and their efficiencies. This experiment will be the first demonstration of on-chip remote CNOT gate operations across a reconfigurable multi-user network to show the feasibility of distributed quantum computing.

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P48. Wafer-scale correlated morphology and carrier lifetime in uniformly grown GaAs/AlGaAs core-shell nanowires.

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Efforts to merge optically active materials with silicon substrates span decades [1]. Integrating III-V semiconductors into silicon electronics promises more efficient electronic-photonic functionality and a clear route to commercialisation of on-chip photonics [2]. However, epitaxially growing III-V semiconductors on Si is challenging due to differing crystal structures and thermal expansion coefficients [3]. The growth of nanowires can mitigate these effects by decoupling the nanowire properties from the growth substrate [4]. This approach is promising, and recent advances in self-catalyzed MBE growth have facilitated uniform wafer-scale growth of high-quality intrinsic III-V GaAs nanowires on Si (111) [3]. These nanowires demonstrate strong absorption of incident light and are therefore promising for solar energy harvesting applications. In this study, we take an important step towards this application, by demonstrating the uniform wafer-scale growth of p-doped GaAs/AlGaAs core-shell nanowires.

To examine the uniformity of the growth we use a multi-faceted high-throughput experimental approach [5] that correlates the density and quality of the nanowires at both wafer and micron-scales [Figure 1]. Scanning electron microscopy was used to determine the nanowire density [Figure 1(a,b)]. A conventional assessment of nanowire quality would be to measure the emission intensity across the wafer. However, this approach is sensitive to fluctuations in the nanowire density. Instead, we use time-correlated single photon counting (TCSPC) to measure maps of the carrier lifetime at wafer and micron-scales [Figure(c,d)]. This mapping provides a measure of the carrier recombination efficiency, an important metric for device performance, decoupled from the nanowire density.

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P49. Effect of skin colour on optical properties and associated Inequality in Medical Technologies

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Understanding the effect of skin colour on optical medical technologies is important e.g. COVID-19 highlighted this with pulse oximetry unreliably determining oxygen saturation levels in people from black and ethnic minority backgrounds[1]. Furthermore, increased use of other optical medical wearables reliant on light penetration of skin measuring other vital signs including heart rate/blood pressure, and photodynamic therapies to treat skin cancers, require thorough understanding of the effect skin colour on light penetration. However, most studies assess optical medical technologies only in light skin; barely ~1% assess skin colour effects[2].

Skin colour affects its optical properties and light penetration. Our recent literature reviews on the optical properties of skin show that reported values for absorption coefficients of dark skin are up to 74% greater than light skin and, beyond 600 nm, reduced scattering coefficients of dark skin are up to 48% greater than light skin[3], [4]. However, published data has variations of up to 98% in reduced scattering and 81% in absorption coefficients when comparing different skin colours[3]. Compilation of published data suggests that wavelengths beyond 940 nm are most useful for all skin colours because light transmission and transport mean free path are maximal. However, published data beyond 1000 nm is limited.

Data derived from skin of a diverse population and understanding interactions of a broad spectrum of light is required to fully understand limitations of optical medical technologies. To address this we created a transmission device to measure transmission of light through skin of volunteers with varying skin colour. This system combines a supercontinuum white light source (450-1700nm) and optical fibre delivery with a portable pulse oximeter-like clip for transmission measurement. Our poster summarises findings from our literature reviews plus our experiments measuring transmission of light through skin across a wide wavelength range in a diverse volunteer group.

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P50. Retrodictive state estimation for informationally incomplete measurements

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In standard quantum mechanics, prepared states evolve forwards in time and are sometimes said to collapse at the measurement device. In quantum retrodiction, measurement produces a retrodictive state that evolves backwards in time and could be thought to collapse at the preparation device. This formalism sheds light on the nature of quantum measurement and collapse. It has also proven useful for analysing experiments in quantum imaging and quantum communication. Here we apply multi-shot quantum retrodiction to the problem of quantum state estimation. This approach has the advantage that the evolution of the retrodictive state matches the flow of information within the estimation problem. The formalism naturally incorporates prior information into the estimation procedure.

We illustrate the approach by looking at examples of state estimation with non-informationally complete measurements. Such measurements are unable to distinguish perfectly between possible prepared states for a single shot of the experiment. In particular, we look at the problem of using a projective measurement to discriminate between three and four equiprobable qubits, which are symmetrically distributed about a plane of the Bloch sphere. We find that one can correctly estimate the state with high fidelity, provided the correct measurement is used, where this measurement is deduced from the formalism. We then apply the formalism to states of the optical field, such as Fock states and optical implementations of previous three qubit states, where we encode the qubits in the polarisation of single photons and coherent states. One surprising result is that when discriminating between optical states, it can help to use detectors with quantum efficiencies that are less than one. This is true both for discriminating between Fock states and the polarisation of coherent states.

P52 - Hyperspectral Imaging of Electrochemically Controlled Photoluminescence and Raman Scattering of Single Layer MoS2 in Widefield

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Single layer molybdenum disulphide (MoS2) is extensively investigated two-dimensional materials for their remarkable optoelectronic attributes in contrast to the bulk material [1]. This makes them appealing for diverse applications such as photocatalysis and sensing. However, considerable heterogeneity in these properties has been observed due to the presence of defects and discontinuities at the edges [1,2].

In this study, we investigated this spatial inhomogeneity using photoluminescence (PL) and Raman spectroscopy within an electro-spectrochemical configuration. Hyperspectral imaging was employed, capturing spectral features from each pixel across a broad field of view rather than individual points. The findings reveal a 34% enhancement in average PL intensities within the range of -2 V to 2 V, demonstrating notable change in exciton densities. Such a change is likely to stem from charge trapping at defect sites which varies across a layer. Moreover, two distinct electrolyte solutions, NaCl and PBS, were utilised to further explore the influence of ions in this phenomenon. Thus, this study paves way for real time and large-scale monitoring of electrochemical and optically active sites of MoS2 and similar materials and is significant from perspective of their application in electrocatalysis as a future scope.

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