Complex Nanophotonics
Science Camp

Preface

The aim of the 'camp' is to bring together ~60 early-career scientists in the field of photonics, but also science writers and editors, in an unconventional format, mixing contributed and invited talks, seminars and debates, to present and discuss the latest research and future directions of the field in an open atmosphere, and help developing the community of complex nanophotonics.

Sponsors

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Key Products: *Nanomaterials, Organic and Printed Electronic Materials, Lithium Ion Battery Materials, Materials for Energy and Electronics, Biomaterials, Graphene and 2D materials*

The Nanophotonic Science Camp

In the past years the number of fields influenced by photonics and nanophotonics have increased steadily.
And the boundaries between what is considered to be nanophotonics and what is not have become more and more fuzzy and difficult to define.

Nowadays disciplines like biophotonics, plasmonics, bio-sensing, optical imaging, quantum nanophotonics etc. are deeply interconnected with each other.
And the tendency is to go in the direction of increasing the interdisciplinarity of research. In this novel landscape a new generation of scientists is now emerging, carrying the necessity to rethink the traditional conference format, which are often showcases of career-long investigators.

The Complex Nanophotonics Science Camp is meant to break with the conventional schemes to engage the creativity of early-stage scientists and create new scientific connections, fostering critical thinking.

A Camp for Young Minds

The main target of this Science Camp are junior scientists, post-docs and PhD students.

The Poster Session

The poster session is a very important part of the Science Camp.
We think that a poster session is a magnificent occasion to discuss that must be exploited. In addition we will feature a "poster pitch" session. Everyone presenting a poster will be given the possibility to make a 60 second pitch, aimed at advertising the work and attract public to the poster.

Clarity and conciseness will have to be staple of the pitches. The time constraint will be strictly enforced.

Support & Prizes

We thank EPSRC for the kind support that makes this Science Camp possible.
In addition we acknowledge *Sigma Aldrich*, *University College London*, *Nature Communications*, *Elliot Scicentific*, *Merck* and *Zurich Instruments* for sponsoring the camp.
A prize for the best talks and posters will be awarded at the end of the Camp.

Evening Debate

There will be two open debates, on the first evening with Laurent Daudet and John Lincoln and on the second evening with Telma Carvalho and Nina Meinzer.

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Cumberland Lodge

The Camp will be held at Cumberland Lodge, a beautiful 17th Century country house in Windsor Great Park, close to London. The Lodge is now occupied by a education charitable foundation and holds a very diverse range of conferences, lectures and discussions.

-> **CUMBERLAND LODGE, THE GREAT PARK, WINDSOR SL4 2HP**
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Directions

BY PLANE The closest airport is Heathrow, at just 20 minutes by car. Gatwick airport is 40 minutes by car.

BY TRAIN The closest train station is Egham, that is well connected to both London Waterloo and Reading.

BY TAXI The appropriate fares to Cumberland Lodge are about £9 from Egham Station, £25 from Heathrow and £65 from Gatwick.

BY CAR Cumberland Lodge has plenty of free parking. Please note that for Crown Estate legal reasons, GPS SatNav Systems do not work within the Great Park. However, they do work for Bishopsgate Road, Englefield Green, TW20 0XU, which is just outside the Bishopsgate ntrance to the Park, and SL4 2JA is for drivers coming from the Windsor and Ascot direction using the Ranger's Gate entrance.

Historical Foundation

Cumberland Lodge is a former Royal residence in The Great Park at Windsor. In 1947 King George VI granted the Lodge to St Catharine's, a then newly established educational charitable trust. They would be given the opportunity to discuss important social and ethical issues and to reflect on the value of their academic work in relation to society.

The Grounds

There are two main buildings - the Lodge and the Mews. The dining rooms, lounges, chapel, library and administrative offices are housed in the Lodge, while the two conference rooms and four seminar rooms are located on the ground floor of the Mews.

Accomodation

All bedrooms have en-suite bathrooms and are primarily located on the higher floors of both buildings. New visitors are surprised to learn that there are no room keys. However, we are able to secure valuables in one of our insured safes by arrangement. Guests are asked to vacate bedrooms by 9.00 AM on the day of departure. Free Internet access is offered on PCs in the Mews and the basement of the Lodge, and both buildings have free Wi-Fi as well.

Recreational Facilities

Recreational facilities at the Lodge include a small gymnasium, tennis court, croquet, snooker, pool, table tennis and table football. We may also be able to provide a small number of bicycles, subject to availability. A wide variety of board games are available in the bar. There is an electronic organ in the Chapel and a grand piano in both the Drawing Room and Tapestry Hall.

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EXTREME PICOPHOTONICS: TRAPPING LIGHT TO THE ATOMIC SCALE

Watching electrons, atoms and molecules dynamics directly with light has been a dream for decades. I will show here how it is possible to use plasmonic metals to achieve extreme nano- and pico-photonics, where light is trapped below 1nm cubed, a billion-fold tighter than with any dielectric resonator. This provides access to optically-induced forces at the nanoscale, to watching anc controlling redox photochemistry, and to the realization of nano-machinery. These are important for a whole class of devices, from molecular sensing, understanding of surfaces, to new types of electronic information storage, as well as fundamental quantum science.

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LEVITODYNAMICS

I discuss our experiments with optically levitated nanoparticles in ultrahigh vacuum. Using both active and passive feedback techniques we cool the particle's center-of-mass temperature to 100 microKelvins and reach mean quantum occupation numbers of 15. I show that mechanical quality factors of one billion can be reached and that damping is dominated by photon recoil heating. The vacuum-trapped nanoparticle forms an ideal model system for studying non-equilibrium processes, nonlinear interactions and ultrasmall forces.

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SUPER-RESOLUTION IN DIFFRACTION MICROSCOPY: THE INTEREST OF COMPUTATIONAL IMAGING

The resolution of diffraction (i.e. marker free) microscopy is fundamentally limited by the elastic light-matter interaction which states that, in the single scattering regime, the far-field scattered by an object illuminated under propagative waves conveys information on the object permittivity spatial frequencies up to 2/λ at most (where λ is the illumination wavelength in the background medium). In addition, this information is poorly restored with conventional analogical microscopes (such as brightfield or confocal) as the observed standard resolution limit, seen as the full width at half maximum of a point-like object is usually about 0.6λ instead of the theoretical reachable diffraction limit of 0.3λ.

A widely explored solution for improving the resolution consists in taking advantage of evanescent waves for the illumination or the detection via near-field probes or metamaterial lenses [2-3]. These techniques ameliorate the resolution, albeit seldom beyond 0.3λ in practice, but at the expense of an increase in the experimental complexity and a restriction to surface imaging.

In this talk, we present another research avenue which consists in extracting the most out of the sample scattered field using numerical reconstructions based on an accurate model of the sample-light interaction. This quantitative imaging approach has been shown experimentally to achieve the best possible resolution of 0.3λ [4-6] in the single scattering regime and even much better for certain samples in the multiple scattering regime for which the diffraction limit does not hold [7].

In addition, quantitative imaging can take advantage of a priori information on the sample. The latter may be used to recover object spatial frequencies beyond the physically accessible domain. Hence, by imposing a binary behavior on the contrary permittivitya spectacular improvement of the resolution can be obtained on com-

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Invited Talks

Nicolas Bachelard

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COLLECTIVE MECHANISMS FOR THE SELF-ORGANIZATION OF DYNAMIC PHOTONIC AND PHONONIC CRYSTALS

Nicoas Bachelard, Chad Ropp, Yuan Wang and Xiang Zhang

In photonics the propagation of waves is typically shaped through a spatial modulation of the optical environment. For instance, in devices achieved by repeatedly stacking layers with different properties, like a photonic crystal, the propagation of waves can be forbidden over continuous energy bandwidths, known as bandgaps. Such systems are routinely manufactured either through top-down techniques—such as e-beam lithography—or bottom-up processes—such as chemical self-assembly. However, these structures are intrinsically static and arise in thermodynamic equilibrium. They form inherently rigid devices, thus difficult to reconfigure and very sensitive to inhomogeneity and imperfections.

The observation of Nature teaches that complex materials and systems can be obtained through alternative mechanisms. Flocks of birds or schools of fish are examples of systems of high complexity that spontaneously self-organize from “simple” elements. Through constant dissipation of energy and entropy production, individual elements are continuously attracted toward a collective steady state that resides far from thermodynamic equilibrium. This attraction provides the ensemble with the ability to adapt to environmental perturbations (e.g. to avoid predators) and to collectively create coherent motions despite important heterogeneities in its populations.

In this talk, we reproduce collective mechanisms to force the self-organization of wave devices far from thermodynamic equilibrium. We explain how an ensemble of dissimilar mobile particles can be driven to spontaneously form a coherent band-gap structure, which is able to self-heal or continuously adapt to its environment. Then, we demonstrate that similar mechanisms can be enforced to drive the emergence of coherent responses in solid-state platforms that are bestowed with resilience properties and complex nonlinear memory effects.

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TRANSIENT LIGHT IMAGING FUNDAMENTALS AND APPLICATIONS

Transient light imaging refers to the ability to capture or freeze light in flight. We will overview the basic technologies and approaches to transient light imaging, with particular emphasis on single-photon cameras. We will then look with more detail at some applications. Examples are imaging behind corners and imaging through complex/opaque materials.

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FRACTAL TEXTURES OF SILICON NANOWIRES: NEW ROUTE FOR UNIQUE OPTICAL PROPERTIES AND UNEXPECTED INTERFERENCE

Understanding the complex transport of light in disordered and strongly scattering media gives rise to a fascinating physics as well as to new smart applications. The development of highly functional materials for light emission and/or amplification is a research field in constant expansion; in particular, high-density semiconductor nanowires slabs represent promising systems attracting a considerable scientific interest for applications in light sources, sensing and photovoltaic devices [1]. The spatial arrangement of nanowires in new disordered textures can drive exciting optical phenomena. Here we report on the unique optical properties exhibited by a forest of vertically aligned thin Si NWs that are densely arranged in a 2D random fractal. This particular texture where light waves bounce back and forth before coming out is responsible for a very high light trapping [2] and multiple scattering events giving rise to interference phenomena that lead to a coherent backscattering cone. We explore the role of multiple scattering in the intense Raman emission from the Si NW material, surprisingly registering a Raman radiation arranged in a cone of enhanced backscattering. This occurrence demonstrates that CBS survives in the inelastic scattering regime and represents the first experimental evidence of an interference effect in spontaneous Raman scattering on a macroscopic scale. Raman CBS is the signature of the coherent nature of individual Raman scattering processes, typically occurring on the scale of the phonon coherence length and time. Furthermore, Raman scattering can be counted among the all-optical mechanisms able to broken reciprocity of the reverse light paths in an interesting way that depends on the material properties [3,4].

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BRANCHED FLOWS

Wave propagation in random media — this might sound abstract but is in fact very tangible and almost omnipresent in science and everyday life. A common example of such random waves are surface water waves such as the wind driven ocean waves, but also light, sound, electrons, tsunamis and even earth quakes are waves that in a natural environment typically propagate through a complex medium. Due to its complexity, the medium is often best described as random but correlated. Examples include the turbulent atmosphere, complex patterns of ocean currents, semiconductor crystals sprinkled with impurities but also index of refraction fluctuation in biological tissue.

Intriguingly, even very weak fluctuations in a random medium, if they are correlated, lead to focussing of the waves in pronounced branch-like spatial structures and to heavy-tailed intensity distributions. These branches are closely connected with the occurrences of random caustics, i.e. singularities in the corresponding ray fields.

I will give an overview over the phenomenon of branching and the statistical characteristics of branched flows, discussing examples from ballistic electron transport in semiconductors to the random focusing of tsunamis waves, all with close analogies in photonic structures. I will also briefly address the role that the interplay of branching and nonlinearity plays in the rogue wave formation in the nonlinear Schrödinger equation.

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RANDOM LASERS: FUNDAMENTAL PHYSICS AND APPLICATIONS

Random lasers (RLs) were first theoretically introduced by Letokhov in 1968 as "quantum generator" of coherent light by a scattering medium with gain [1]. The feedback is given by the scattering mechanism and no external cavity is needed to obtain stimulated emission of light. A pioneering experimental evidence was reported in 1994 by Lawandy et al., who demonstrated the stimulated emission from a dye-doped colloidal solution as a drastic spectral narrowing of a featureless peak centered at the highest gain frequency with the threshold behavior of standard lasers [2]. Different disordered suspensions have been examined showing multiple sub-nanometer narrow peaks above the amplification line [3]. The wide variety of the spectral features reported in the last decades and the still debated emission properties are due to the fact that RLs are open systems where light can propagate in any direction in a disordered fashion instead of oscillating between well specific boundaries as in standard lasers.

The first part of my talk will be dedicated to an introductory description of RLs and the main results reported in literature, including interesting applications.

In the second section I will show our recent works on RLs in miniaturized systems. We will examine the role of geometrical confinement and morphology of the materials and the interplay between gain and light entrapment on the random laser performance and efficiency [4-7].

A last section will be devoted to statistical mechanics of RLs and the novelty of the application of the Replica Symmetry Breaking in disordered lasers [8].

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COMPOSITE LIGHT SCATTERING LAYERS FOR LIGHTING AND DISPLAY TECHNOLOGIES

Dominik Theobald, Shudong Yu, Benjamin Fritz, Yidenekachew J. Donie, Amos Egel, Jan B. Preinfalk, Bryce S. Richards, Zongtao Li, Hendrik Hölscher, Uli Lemmer

Polymeric matrices incorporating light scattering particles or pores are industrially relevant systems to improve light management in many optoelectronic devices. They indeed allow the use of high-throughput techniques such as printing methods, which additionally offer great flexibility in terms of design. This point will be first motivated by covering recent developments in the field of printed polymer:inorganic nanoparticles composites, whose volumetric light scattering properties are tailored to foster the outcoupling of waveguide modes in organic light emitting diodes.

Similar strategies can be employed to assist light conversion in polymer:quantum dots hybrid films excited by an external (UV/blue) light source. In this case, the design of the nanoparticles is more challenging: backscattering should be maximized for the converted light to promote its extraction in forward direction, and suppressed at the excitation wavelength to improve the in-coupling of the UV/blue light in the converting medium. For practical applications, high scattering efficiencies as well as minimal parasitic absorption losses are also demanded. These challenges can be addressed by properly engineering single-layered core-shell particles. This approach will be exemplified with T-matrix simulations accounting for an ensemble of 10 thousands of such randomly positioned particles.

An alternative method, taking advantage of the outstanding light scattering properties of polymer foams, will eventually be explored. By directly introducing the quantum dots in a micro- or nano-porous network, the exciting light absorption and down-shifted light extraction can be both improved, resulting in enhanced photoluminescence properties. The requirements of the microcellular foaming technique as well as the influence of the porous network morphology will be analyzed and discussed in the context of novel backlight sources for liquid crystal display panels.

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SUPER-RESOLVED IMAGING FOR PROBING SINGLE-MOLECULE/ ENVIRONMENT INTERACTIONS

G. Blanquer, B. Van Dam, D. Bouchet, S. Marguet, Y. De Wilde, I. Izeddin, V. Krachmalnicoff

Recent progress has been made in the fabrication and the characterization of nanostructured media to control light-matter interactions. Such interaction can be probed through measurements of the fluorescent decay rate of emitters in close proximity of the nanostructures [1] and requires the use of super-resolved techniques. The potential of scanning probe near-field microscopy has been widely explored for this. Unfortunately, such techniques demand a remarkable experimental knowhow and non-negligible implementation costs. As an alternative to scanning probe near-field microscopy, we have recently developed a far-field optical approach, by combining the simultaneous super-localization of stochastically activated individual fluorescent emitters with a high sensitivity camera, and the detection of their fluorescence decay rate with a time-resolved single-photon avalanche diode (SPAD) [2].

The technique enables fluorescent decay-rate imaging of a densely marked nanostructured sample with a spatial resolution in the order of 10 nm. In our current work, we further expand this framework by addressing the major limitation, i.e. the limited field of view (FOV) associated with the SPAD detector (in the order of 1 μm). For this, we replace the SPAD with an array of SPADs [3], effectively enhancing the FOV by more than a factor 10. We show that the super-resolved lifetime images reveal features at the nanometer length scale otherwise invisible on intensity-based super-resolution images. We use the technique to perform a deep study of the light-matter interactions along silver nanowires and in disordered arrangements of nanotriangles. Our technique offers not only applications in nanophotonics, but also in biological imaging in combination with techniques based on Förster resonance energy transfer.

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CONTROL AND MANIPULATION OF HIGH-DIMENSIONAL ENTANGLEMENT THROUGH COMPLEX SCATTERING MEDIA

Photonic high-dimensional entanglement in the spatial degree of freedom has recently emerged as a practical way to enhance the capacity of quantum information systems, as well as increase their robustness to noise. However, the transport and control of high-dimensional quantum states of light remains a challenge. In particular, methods for transporting such states over large distances and performing general transformations on them usually require free-space optical communication systems and complex networks of bulk optical elements. Due to their naturally large Hilbert space, complex scattering media such as multi-mode fibres present an intriguing platform for both transporting and manipulating such states. However, in order to do so, we need to develop methods to control their complex transmission matrix for quantum states of light, which presents a unique set of challenges different from the classical regime. In this talk, I will discuss efficient methods for generating and measuring high-dimensional entangled states of light, and steps towards manipulating and transporting them through complex scattering media such as multi-mode fibres.

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ORGANIC MOLECULES IN INTEGRATED QUANTUM DEVICES

Organic molecules of polyaromatic hydrocarbons were the first system in the solid state to show single photon emission [1,2]. However they are still considered unconventional sources of non-classical light. I will try to unveil part of the mystery behind such quantum emitters and show how they could effectively contribute to integrated quantum photonic platforms.

I will report on fluorescence coupling from a single molecule to a planar optical antenna [3] and a single-mode dielectric waveguide [4], discuss the integration of single quantum emitters into hybrid dielectric-plasmonic devices [5] and the coupling with 2D materials [6]. I will present our recent results about the fabrication of single-molecule doped nanocrystals, preserving the optical properties of the bulk system, i.e. negligible blinking and spectral diffusion [7]. Eventually, I will report on ultrafast time-resolved transient spectroscopy on a single molecule [8].

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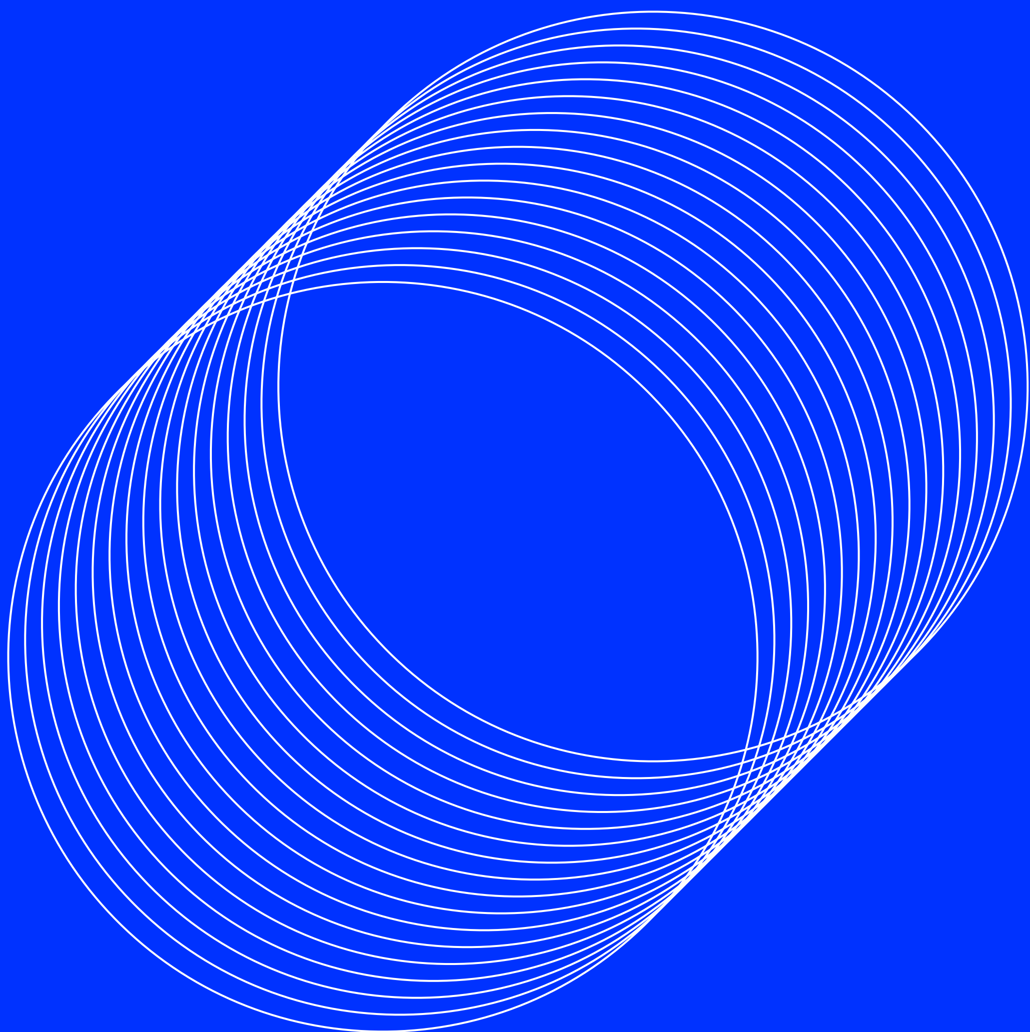
Contributed Talks



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SPIN HALL EFFET OF LIGHT IN RANDOM MEDIA

Tamara Bardon-Brun, Dominique Delande, Nicolas Cherroret

A current exciting question in physics research deals with the realization of photonic systems allowing to reproduce phenomena encountered in solids or in quantum systems in general. Recent examples include the observations of light superfluidity in nonlinear materials and of optical Hall effects or Anderson localization of light, and even the realization of topological insulators.

An interesting phenomenon shared by electrons and photons is the spin-orbit interaction (SOI). In optics, it is defined as the coupling between the spatial and the polarization degrees of freedom. One of its manifestations is the optical Spin Hall effect which refers to an helicity dependent sub-wavelength shift of a beam. This phenomenon arises naturally in inhomogeneous media and is well-known for beams crossing interfaces (Imbert-Fedorov effect) or propagating in a gradient-index material (optical Magnus effect).

A presently open problem is whether SOI of light can be achieved in a (statistically homogeneous) random medium. A positive answer would be appealing, because this might help, for instance, to engineer new types of gauge fields for photons or to realize exotic symmetry classes for disordered optical insulators. We have theoretically demonstrated that optical beams propagating in transversally disordered media experience a spin Hall effect as soon as they deviate from paraxiality (i.e. have a nonzero transverse wave vector). This phenomenon, never reported so far, is to our knowledge the first clear-cut manifestation that SOI of light do arise in disordered systems. I will present its theoretical description and properties, and show that it could be experimentally observed under realistic experimental conditions.

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RANDOM PLASMON SCATTERING FOR SINGLE PARTICLE SENSING

Joel Berk, Matthew R. Foreman

Electromagnetic surface modes have long been used in biosensing, most notably in surface plasmon resonance (SPR) based techniques. In particular, the confinement of surface plasmons at a metal-dielectric interface allows biological processes occurring at a surface to be studied. For example, binding of biological molecules to surface-bound receptors can be monitored using shifts in the plasmonic resonance, in turn enabling measurements of binding rates. Importantly, such measurements can be performed without labelling of biological molecules. SPR sensing however suffers from limited sensitivity due to losses within the metal which has hitherto meant single particle sensitivity has remained elusive.

In this work, we propose an alternative biosensing modality which exploits random scattering of surface plasmons propagating on a rough surface. The proposed technique therefore retains the surface confinement advantages of SPR, whilst additionally leveraging interference effects which can exhibit greater sensitivity to small configurational changes, such as binding of a single particle, than conventional SPR techniques. In particular, by monitoring changes in the speckle pattern seen within the leakage radiation originating from surface plasmon propagation on a rough metal surface, single particle binding can be detected.

With this method in mind, we present a theoretical study of the changes in the properties of the speckle pattern resulting from scattering of surface plasmons from a rough metallic surface when a single scatterer is introduced near the surface. The sensitivity of a number of sensing signals is quantitatively assessed and compared to conventional SPR techniques to assess the achievable performance gains.

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NUMERICAL DIPOLES METHOD FOR LIGHT SCATTERING BY COMPLEX RESONANT NANOSTRUCTURES

Maxime Bertrand, Alexis Devilez, Jean-Paul Hugonin, Philippe Lalanne, Kevin Vynck

Large disordered ensembles of resonant nanoparticles deposited onto or incorporated into layered media provide a very rich panel of optical features, such as frequency-selective wide-angle light absorption [1], controlled light coupling between free-space modes and guided modes in an optical stack [2] and strong light localization [3]. This richness comes from the nanoparticles themselves, their interaction with interfaces and their mutual interaction with neighboring nanoparticles.

Theoretically or numerically predicting the optical properties of such "complex nanostructured surfaces" has however remained elusive due to the difficulty to simulate coherent phenomena occurring both at the individual nanoparticle and at the ensemble scales. Nanoscale phenomena are typically investigated using brute force Maxwell's equations solvers (FDTD, FEM, ...), but these approaches can hardly deal with large volume ensembles. This problem may instead be tackled with T-matrix methods, which become very limited as soon as strong near-field interactions (between nanoparticles or between a nanoparticle and an interface) take place. Efforts are currently undergoing to overcome this limitation [4].

Here, we propose a novel numerical method where we find a small set of fictitious electric and magnetic dipoles that can reproduce the near field scattered by an arbitrary nanoparticle for any excitation at a given wavelength [5]. The polarizability tensor describing the set is obtained by solving a numerical inverse problem. This allows us to model multiple scattering in complex nanostructured surfaces, including in cases with strong near-field interactions, using a Green tensor formalism.

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ENTANGLED PHOTON-PAIRS SPATIAL CORRELATIONS STUDY USING PUMP BEAM SHAPING

P. Boucher, H. Defienne, S. Gigan

We demonstrate experimental generation of spatially-entangled photon-pairs by spontaneous parametric down conversion (SPDC) using wavefront shaping on the pump beam. Properties of down-converted photons, including their degree of entanglement or the number of entangled modes, are set by the crystal parameters and the pump wavefront. By shaping the pump beam, we wish to investigate how these properties are influenced by the amplitude spectrum of the pump beam and transfer to the downconverted photons. In particular, by going beyond the usual frame of the gaussian approximation for the amplitude spectrum of the pump beam we can study a variety of Schmidt decomposition of the biphoton amplitude at the output of the crystal. We measure the full joint probability distribution of the entangled photons using a recently developed measurement scheme for EMCCD cameras.

Entanglement between transverse spatial modes allows to work in high-dimensionality Hilbert spaces. In this regard, such a system should prove an interesting platform for the implementation of highly multimode quantum communication protocols and quantum computation in complex media.

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INFORMATION-DRIVEN OPTIMIZATION OF LIGHT SCATTERING BASED ON WAVEFRONT CONTROL

Dorian Bouchet, Allard P. Mosk

Imaging inside a strongly scattering medium is a challenging task due to light absorption and scattering, which respectively lower the collected intensity and shuffle its spatial distribution. Yet, in many situations, measuring highly-resolved images is not a final goal, as these images are then used to estimate key parameters of interest, such as critical dimensions of semiconductor nanostructures. For such applications, the amount of information enclosed in the scattered light about any parameter characterizing the system can be formally assessed using the Cramér-Rao lower bound, which corresponds to the ultimate precision that can be achieved by any unbiased estimator.

We introduce two different strategies for tailoring the excitation field in order to increase the amount of information enclosed in the scattered intensity based on wavefront shaping. Firstly, we show that it is possible to identify a wavefront that is optimally shaped to estimate one or several critical parameters characterizing a scattering medium. This approach reveals that the localization precision of a dipole is fundamentally related to the local density of states at its position. Secondly, we show that the principal modes of a non-Hermitian generalization of the Wigner-Smith operator are also good candidates for parameter estimation in complex media, as they allow to easily build an efficient estimator based on intensity measurements using only a bucket detector. This theoretical analysis is supported by numerical simulations using the coupled dipole method, which is an exact formulation for a set of dipole scatterers. The approach, which can easily be adapted for any method of electromagnetic simulation, opens new perspectives for the characterization of complex scattering materials with quantitative imaging techniques.

output of the crystal. We measure the full joint probability distribution of the entangled photons using a recently developed measurement scheme for EMCCD cameras.

Entanglement between transverse spatial modes allows to work in high-dimensionality Hilbert spaces. In this regard, such a system should prove an interesting platform for the implementation of highly multimode quantum communication protocols and quantum computation in complex media.

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OPTICAL NANO-IMAGING USING SCATTERING METASURFACE SENSORS

RD Buijs, G Gerini, AF Koenderink, E Verhagen

Optical microscopes are fundamentally limited in their spatial resolution by diffraction of light. Imaging at the nanoscale thus requires advanced techniques. However each of these techniques, prominently scanning probe microscopy and electron microscopy, has significant drawbacks in the form of throughput or requirements on samples. We study in theory and experiment a new method of nano-optical imaging, based on multiple scattering between the sample of interest and a metasurface patch ('sensor'). In this technique, we aim to extract nanoscale spatial information about samples from the combined scattering profile of the sample and the sensor. Our initial experiments focus on localising a fine perturbing probe with respect to a sensor composed of plasmonic antennas without moving the sensor. We investigate how a single plasmonic antenna may be used to localise a point perturbation by studying laser scattering in real, reciprocal and frequency space. More complex metasurfaces, composed of multiple interacting scatterers, are expected to produce more intricate field patterns and thus encode more intricate spatial information in their scattering profiles. This would allow reconstruction of more complex perturbations. The inverse problem of retrieving a localised permittivity distribution from its scattering profile may be solved more readily through the use of additional degrees of freedom. Theoretical analysis using a discrete dipole model shows how reconfiguration of incident polarisation can help increase resolution and eliminate blind spots in imaging. Reconfiguring of such optical parameters may provide a sufficient basis for resolving arbitrary nanoscale spatial permittivity distributions.

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COLOUR OF LIGHT AT NANOSCALE MIXING WITH MOLECULES

How to 'see' things at nanometer scales with light? Can the visible light be focused down to single-molecule and atom? How to control and tailor the properties of single molecules and atoms, using light? By designing and developing novel nano-architectures using tiny metallic particles, I will show how it is possible to trap light in extremely tiny 'gaps', making the interaction of light and matter extremely strong. I will also show how to use it to probe and manipulate the dynamics of molecules at the level of single entities. This opens new avenues to control over the physical and chemical dynamics of elements which constitutes the building blocks of life.

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STUDY OF THE PROPAGATION TIME OF WAVES INSIDE STRONGLY SCATTERING MEDIA

Mathieu Durand, Rémi Carminati, Sébastien Popoff, Arthur Goetschy

We present an analysis that reveals how we can control the transit time and the storage energy of waves inside strongly scattering media by wavefront shaping. This is done by studying numerically and analytically the eigenvalue distributions and the eigenstates of the Wigner-Smith operator. We found that the scattering dynamics is bounded by a minimum and maximum delay times, which are, respectively, much lower and much larger than the mean time spent by waves inside the medium. We also show that the dwell-time operator (Wigner-Smith operator) allows to build robust wavefronts that can store more energy that the so-called open channels of the disordered medium. Finally, we demonstrate the utility of this operator to focus selectively on resonant targets buried inside the sample.

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OPTIMAL MICROMANIPULATION WITH STRUCTURED LIGHT FIELDS

M. Horodynski, M. Kühmayer, A. Brandstötter, K. Pichler, Y.V. Fyodorov, U. Kuhl and S. Rotter

A recent and very promising trend in micromanipulation is to make use of the technological advances of spatial light modulators to create light fields that are tailor-made for each desired purpose [1]. The techniques developed in this context so far rely mostly on iterative optimization schemes in order to calculate the best wave front for the problem at hand. This has the disadvantage, however, that the convergence to the global optimum in the iteration is not assured, as one may get stuck in some local minimum, preventing one from reaching optimal micromanipulation [2].

Here, we introduce and experimentally demonstrate a novel approach to micromanipulation based on a generalization of the well-established Wigner-Smith time-delay operator [3-6]. Using this procedure, we reduce the problem of finding the optimal scattering state for micromanipulation to a simple eigenvalue problem based only on scattering amplitudes that are experimentally available in the far-field of a system.

We implement a corresponding experimental demonstration of this approach in a microwave waveguide containing a disordered medium and show that we can transfer the largest possible momentum to a target embedded in the disorder, exert a maximum torque on it or optimally control the applied pressure. Our approach is generally applicable and should be readily transferrable to the optical regime, where it would open up the way for the generation of tailor-made light fields for optimal micromanipulation of targets with a complex shape or in a complex environment.

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PROGRAMMING LINEAR QUANTUM NETWORKS WITH A MULTIMODE FIBER

Saroch Leedumrongwatthanakun, Luca Innocenti, Hugo Defienne, Thomas Juffmann, Alessandro Ferraro, Mauro Paternostro, Sylvain Gigan

The ability to implement reconfigurable linear optical networks is a fundamental building block for the implementation of scalable quantum technologies. Currently, integrated linear optics are the most popular platforms to implement such networks. However, their scalability is significantly limited by the fabrication process. Here, we present an alternative way to implement the networks in a multimode fiber by harnessing its complex connectivity and an ability to control light propagation with wavefront shaping techniques. We program linear transformations involving spatial and polarization modes of the fiber and experimentally demonstrate their accuracy and robustness by deterministically manipulating two-photon interferences between multiple ports of various networks. In particular, we illustrate the reconfigurability of our platform by emulating a tunable coherent absorption experiment, where two-photon survival probability at outputs of interest can be controlled. By demonstrating complex, reprogrammable, reliable, linear transformations, with the potential to scale, our results highlight the potential of complex media driven by wavefront shaping for quantum information processing.

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SILICON NANOWIRES FOR PHOTONICS AND BIOSENSING

M. J. Lo Faro, A.A. Leonardi, D. Morganti, P. Musumeci, B. Fazio, F. Priolo, A. Irrera

The recent rise of semiconductor nanowires opens new opportunities due to the unique one-dimensional structure with remarkable electrical and optical properties. Particularly, as one of the most earth-abundant materials, silicon nanowires (NWs) represent one of the most promising resources to be employed in modern nanodevices although their fabrication is still challenging. We demonstrated the fabrication of a dense array of vertically aligned Si NWs with tunable aspect ratio by a low-cost, maskless approach compatible with the current Si technology. The synthesis of Si NWs was properly engineered for the realization of 2D random fractal systems by using a fractal gold layer above the percolation threshold. We demonstrated control over the optical properties of the system through the optimization of different fractal geometries1. Strong in-plane multiple scattering and efficient light trapping related to the fractal structure were observed with perspective for photonics and photovoltaics2. Moreover, NW achieved by this technique exhibited a very bright room temperature luminescence under both optical and electrical pumping, tunable with NW size in agreement with the occurrence of quantum confinement effects. An innovative label-free optical Si NW biosensor was realized by exploiting the PL quenching upon the selective capture of target proteins or genome. A low cost selective sensor for the C-reactive protein (CRP), the major biomarker for heart-failure pathology, has been realized showing a high sensitivity of a few fM across a broad concentration range for non-invasive analysis in saliva3. By changing the functionalization protocol, we realized a label- and PCR-free NW optical sensor for the selective detection of few copies of Hepatitis B virus without amplification4, demonstrating their potential as optical biosensors for primary health care diagnosis.

1 Light Sci. Appl. 5, 4, 2016

2 Nat Photonics 11, 170, 2017

3 ACS Photonics 5, 2, 2018

4 ACS Sensors 3, 9

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OPTICAL COMPLEX MEDIA AS UNIVERSAL RECONFIGURABLE LINEAR OPERATORS

Maxime Matthes, Philipp Del Hougne, Julien De Rosny, Geoffroy Lerosey, Sébastien Popoff

Performing linear operations using optical devices is a crucial building block in many fields ranging from telecommunications to optical analogue computation and machine learning. For many of these applications, key requirements are robustness to fabrication inaccuracies, reconfigurability and scalability. We propose a way to perform linear operations by using complex optical media such as multimode fibers or scattering media as a computational platform driven by wavefront shaping. Given a large random transmission matrix (TM) representing light propagation in such a medium, we can extract any desired smaller linear operator by finding suitable input and output projectors. We demonstrate this concept by finding input wavefronts using a Spatial Light Modulator (SLM) that cause the complex medium to act as a desired complex-valued linear operator on the optical field. We experimentally build several 16x16 operators and discuss the fundamental limits of the scalability of our approach. It offers the prospect of reconfigurable, robust and easy-to-fabricate linear optical analogue computation units.

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GLOBULAR MULTILAYER BLUE: THE STRUCTURALLY COLOURED FRUIT IN YOUR GARDEN.

Rox Middleton, Miranda Sinnott-Armstrong, Yu Ogawa, Edwige Moyroud, Paula Rudall, Michael Donoghue, Beverley Glover, Silvia Vignolini

The use of structural colour avoids the need for energetically costly and sensitive pigments by producing colour by constructive interference from periodic nanostructures. The phenomenon is widely observed in nature, including more recently in a growing number of plant species. Many of the examples of structural colour in plants are blue-reflecting, congruous with the difficulty for biological organisms of producing blue pigment molecules, which has made true blue plant tissues a rare and much sought-after target.

Structural colour in blue fruits has previously been reported in tropical and subtropical species, and in flowers. This is the first description of a European-native species with structural coloured fruit, with apparent convergent evolution to produce a similar effect to distant species. Viburnum tinus is a widespread garden shrub with attractive shimmery metallic blue fruits. We demonstrate its structural colour mechanism through optical polarisation microscopy, staining, TEM and numerical staining, and compared a similar structural colour also in its close relative, native to China, V. davidii. Colour is reflected in both cases from a non-uniform globular biphasic multilayer in the highly thickened cell wall.

This analysis demonstrates a biomaterial with potential to inspire new artificial structural colour materials, combining reflective and scattering effects with semi-disordered multilayers.

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READOUT OF WIDE FIELD FLUORESCENCE FUNCTIONAL SIGNALS THROUGH HIGHLY SCATTERING TISSUE

Claudio Moretti, Sylvain Gigan

Fluorescence represents nowadays an irreplaceable tool to non-invasively probe neuronal activity in the mammalian brain. However, when neurons are very deep, fluorescent light propagation through the upper layers of tissues scatter and scramble seemingly beyond recovery the original information. This problem can be circumvented in many ways, however a non-invasive method to record fluorescent functional activity from several sources simultaneously, in the multiple scattering regime, is still lacking. Our work is based on recent signal processing insight, indicating that multiple scattering of light does not destroy its information content. We generate temporally varying fluorescent sources, emulating signals from neuronal calcium activity reporters, and we let the light go through a highly scattering mouse skull. We demonstrate we can retrieve the temporal traces of individual neurons in such regime. Importantly, we do not rely here on ballistic light, nor on the presence of speckle correlation across the field of view.

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MODE SELECTIVE MIRRORS

David Phillips & Simon Horsley

Multiple scattering systems are capable of performing high-dimensional optical transformations - potentially offering new functionality beyond existing optical devices. For example, the ability to efficiently reshape light in complex yet predetermined ways finds applications in a variety of fields, including optical computing, imaging, and optical communications. However, both designing and fabricating scatterers that behave as we hope is challenging. Simulation of fully 3D scattering systems demands high computational overheads, and fabrication requires significantly sub-wavelength tolerances in 3D.

Here we explore a more tractable approach, by course graining a scattering system into a series of partially reflective plates, separated by free-space. Each plate is capable of imparting a spatially varying phase delay to the light that is transmitted through or reflected from it. We demonstrate an iterative design strategy to optimise the phase profiles, so that the ensemble performs a desired optical transformation. Using this approach, we design a selective mode mirror - a device capable of selectively reflecting or transmitting monochromatic light based on the incident spatial mode (i.e. light pattern). We investigate the multiplexing capability of the mode mirror, and demonstrate how a single sequence of plates can efficiently perform engineered transformations on multiple incident light modes simultaneously. Analysis of the reflection and transmission eigenchannels of these selective mode mirrors reveals that we have engineered the high eigenvalues to be spatially localised and resemble the light fields we wish to transform. In line with recent studies on random media, we find that the energy density associated with reflected modes exponentially decays through the structure, while peaking towards the centre in the transmitted case. Our work paves the way towards the fabrication of artificial scattering systems with predetermined optical transform capabilities.

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NONLINEAR LIGHT GENERATION IN DISORDERED MICRO-BALLS

Romolo Savo, Andrea Morandi, Fabian Kaufmann, Flavia Timpu, Marc Reig Escalé, Michele Zanini, Lucio Isa and Rachel Grange

Disordered photonic materials offers original strategies to overcome phase-matching limitations in nonlinear optical generation. In particular, polycrystalline structures with random distribution of the crystalline domains can produce a globally incoherent nonlinear light generation with relaxed phase-matching conditions. This effect is known as random quasi-phase matching (RQPM) and its distinctive feature is the linear scaling of the nonlinear light intensity with the number of domains. RQPM has been exclusively investigated in transparent polycrystalline films generating a second-harmonic signal, with domains size of the order of the coherence length (few tens of microns). However, RQPM is expected for any size of the crystal domains, down to the nano-scale, but no evidence has been produced so far, because of material and fabrication limitations.

Here, we employ bottom-up assembly of noncentrosymmetric metal-oxide nanoparticles to realize disordered micro-spheres that generate random quasi-phase matched second harmonic. Despite the intrinsic inhomogeneity (40% porosity) the micro-spheres are surprisingly transparent in the visible range and can also sustain Mie resonances. Under near-infrared femtosecond laser illumination the second harmonic generation appears as a speckle pattern, confirming the random nature of the nonlinear generation. We investigated several tens of structures of growing size and observe a robust linear scaling of the generated second harmonic with their volume, remarkably over three orders of magnitude. As far as we know, this is the first evidence of random quasi-phase matching in nanostructured systems. Very interestingly, on top of the pure volume dependence, we observe highly peaked second harmonic signal for some specific sphere sizes, suggesting resonant effects stemming from the outer geometry.

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NON-LINE-OF-SIGHT IMAGING USING ARTIFICIAL NEURAL NETWORKS

Ilya Starshynov, Alejandro Turpin, James Fitches, Daniele Faccio

It is well known that under certain conditions it is possible to reconstruct an image carried by a light field after it undergoes a single or even multiple scattering. Despite numerous suggested reconstruction methods, this still remains a practically challenging problem. The ultimate solution is measuring the S-matrix of the scattering object, which allows the perfect reconstruction of the input distribution given the output one. However, such a method is often infeasible since the number of relevant modes can be very high, sometimes not all of them are accessible and finally, this method requires the measurement of the relative phases of the output modes. Recently a number of novel reconstruction methods have been suggested, based on the machine learning approach. Instead of directly measuring the scattering matrix these methods estimate the input-output relationships by training an artificial neural network without requiring complex field measurements. Here we apply this approach to the problem of tracking, classification, and imaging of the objects hidden from direct observation in a scattering enclosure.

We consider a moving object placed into an enclosure with scattering walls. We illuminate this object with coherent light and measure the speckle patterns escaping the enclosure, simultaneously tracking its position. We then use this data to train an artificial neural network and show that it is able to successfully retrieve the position of the object by only using the observed speckle patterns. We discuss different variants of the geometry of this experiment and the possibility to reconstruct the 3D shape of the object placed into the enclosure.

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TRANSMISSION EIGENCHANNELS IN A WIDE MULTIPLE-SCATTERING SLAB

Transmission eigenchannels are building blocks of coherent wave transport through multiple-scattering media. High transmission eigenchannel can have near unity transmittance. Wavefront shaping techniques have been developed to selectively couple light into such channels to enhance light transmittance through multiple-scattering media [1,2]. It has been shown that coupling light into high-transmission channels not only enhances the transmittance, but also modifies the depth profile of energy density inside the medium.

We discover that the transmission eigenchannels of a wide multiple-scattering slab exhibit transversely localized incident and outgoing intensity profiles, even in the diffusive regime far from Anderson localization [6]. Such transverse localization can be understood with optical reciprocity, local coupling of spatial modes, and non-local intensity correlations of multiply-scattered light. Experimentally, we observe transverse localization of high-transmission channels with finite illumination-area. Transverse localization of high-transmission channels enhances optical energy densities inside and on the back surface of the turbid media, which will be important for imaging and sensing applications.

We further demonstrate that selective coupling of light into a single transmission eigenchannel modifies the range of angular memory effect. High-transmission channels have a broader range of memory effect than a plane wave or a Gaussian beam, thus will provide a wider field-of-view for memory-effect-based imaging through multiple-scattering media.

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SCATTERING OF LIGHT BY CORRELATED SURFACE AND VOLUME DISORDER

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Light scattering by combined randomly rough surface and bulk dielectric fluctuations has been little studied in the literature. Little is known for example about regimes of predominance of surface and volume scattering depending on parameters of the system such as the wavelength, the correlation lengths of the surface and dielectric fluctuations, the rms roughness, and the rms permittivity. Furthermore, most of the works dealing with the scattering problem by the combined surface and volume disorder make the assumption that the two types of disorder are uncorrelated. One often observes that the resulting intensity pattern for the combined system can be well approximated by summing incoherently the intensities of the sub-systems where only one type of disorder is present at a time. This is known as the splitting rule. A specific regime where the splitting rule holds exactly, is that of single scattering for uncorrelated surface and volume disorders. The present study aims at (i) revisiting the problem of combined surface and volume scattering to map a diagram of regimes in terms of the parameters defining the scattering system, and (ii) exploring the effects of cross-correlation between the surface roughness and the volume dielectric fluctuations.

The study is carried out by means of a general volume scattering framework. In this first step, we have focused on single scattering, and the study will be extended to multiple scattering in a future work. Different regimes of surface and bulk dominated scattering are identified for different length scales of the surface and bulk disorders. In particular, we have identified two configurations of bulk disorder, namely the genuine volume configuration and the surface-like configuration, which respectively couples weakly or strongly to surface scattering via surface-bulk correlations. We also illustrate how the control of the surface-bulk correlation can be used to control interference pattern in the diffusely scattered light.

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IMPACT OF DISORDER ON THE SCATTERING PROPERTIES OF CELLULOSIC CHOLESTERIC LIQUID CRYSTALS

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Hydroxypropyl cellulose (HPC) is a low-cost, non-toxic cellulose derivative that can self-assemble in water into a cholesteric liquid crystal. At the nanoscale, its structure consists in helicoidally arranged polymer chains that twist around the helical axis, at a periodicity called the pitch[1]. The cholesteric structure selectively reflects light around a wavelength that is proportional to the pitch and depends on the angle of incidence, giving rise to bright iridescent colours[2].

When the orientation of the cholesteric structure is uniform, the region of reflected wavelength is narrow. However, on macroscopic samples, a multitude of domains of various orientations coexist in the mesophase and their contribution broadens the reflection peak[3,4]. Here we study how an increase of disorder impacts the scattering properties of the mesophase and we relate this to properties of the polymer.

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MEASURING GENERALIZED EIGENSTATES OF AIR AND A STRONG SCATTERING MEDIUM

Jeroen Bosch, Pritam Pai, Matthias Kuehmayer, Stefan Rotter, Allard Mosk

A strong scattering medium completely scrambles the transmitted wavefront of an incident light beam. However, this is not true for every incident wave: it is possible to find generalized eigenstates of the system, which are waves that are transmitted with the same spatial profile through the sample as through air. Effectively, the material is invisible for these specific waves. We have experimentally generated such waves and propagated them through strongly scattering nanoparticle layers. We find a substantial correlation between waves propagated through the sample and through an equivalent thickness of air.

Additionally we also demonstrate wavefront shaping with these states, where we are able to create a focus simultaneously through both materials.

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FLUORESCENCE-BASED NON-INVASIVE LIGHT FOCUSING INSIDE SCATTERING MEDIA VIA SPECKLE VARIANCE OPTIMIZATION

Antoine Boniface, Baptiste Blochet, Jonathan Dong, Sylvain Gigan

Propagation of coherent light through a scattering medium generates a speckle pattern, which is detrimental for imaging applications. Since 2007, various wavefront shaping techniques have emerged to control this very complex figure of interference. In particular, they can be used to focus light behind scattering media. Still, all of these approaches require some feedback signal from the targeted focal point. Usually, the feedback is either measured with a detector placed behind the scattering medium, or recovered from implanted guide stars. Both approaches are invasive and thus not directly applicable when it comes to imaging at depth. To go beyond this major limitation, wavefront shaping has recently been combined with techniques such as acoustics or nonlinear optics. However, focusing non-invasively on extended fluorescent objects with linear excitation remain to date unresolved.

Here we report on a new method allowing focusing inside a scattering medium using an incoherent linear optical signal as feedback, for instance fluorescence, in an epi detection geometry. Our technique does not rely on speckle correlations and is also efficient in the multiple scattering regime. We use an optimization procedure to find the incident phase correction that maximizes the spatial variance of the linear fluorescence speckle, retro-reflected by the medium. The speckle pattern variance is the product of the contrast and the intensity of the speckle, meaning it is maximal when all the excitation light is focused on a single fluorescent target, since fluorescent signals emitted by multiple targets are summed incoherently. Experimentally, we demonstrate diffraction-limited focusing of light scattered after propagation through multiple layers of parafilm using the variance of the fluorescence speckle pattern as a feedback signal. This approach should be adaptable to several microscopy techniques and linear optical signals.

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INTEGRATION OF CHALCOGENIDE MATERIALS WITH PHOTONICS FOR RECONFIGURABLE CONTROL OF LIGHT

Matthew Delaney, Kevin Vynck, Philippe Lalanne, Otto Muskens, Dan Hewak

By layering a thin film of phase change material (PCM) on top of an multimodal interference device (MMI), the propagation of light could in principle be manipulated to create a reconfigurable optical demultiplexer. In this project we are exploring the properties of the PCM required for low loss and efficient operation. Using a laser, a pixel pattern of crystalline and amorphous regions can be written into the thin film PCM, creating an effective index throughout the MMI. Pixel patterns that provide a strong coupling into one output have been optimised using different techniques - a neural network was tested for an inverse design approach, whereas using Lorentz reciprocity provided the fastest brute force approach. Experimentally it has been found that a pixel pattern can be used to change the coupling efficiency of an MMI, however the PCM explored so far are not suitable for this application due to an increase in absorption when crystallised. This causes any pixel pattern to increase the loss more than the increased transmission from the guiding pattern. Novel materials are being explored to address this problem.

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LARGE-SCALE RESERVOIR COMPUTING USING LIGHT SCATTERING

Jonathan Dong, Mushegh Rafayelyan, Florent Krzakala, Sylvain Gigan

In complex media like fog or biological tissue, light does not go straight but gets scattered as it encounters inhomogeneities. The resulting interference pattern, commonly called speckle, is conveniently described by a Transmission Matrix linking the electric field before and after propagation in the complex medium. Thanks to the large amount of scatterers, the dimension of this Transmission Matrix is very large, typically more than a million. It means that we have access in optics to a multiplication by a random matrix of very large dimension. Using fast Spatial Light Modulators (SLMs), such as Digital Micromirror Devices or Liquid-Crystal SLMs, we use optics to efficiently perform random projections, at very large scale, for applications in Machine Learning.

In this work, we implement Reservoir Computing algorithms, where a Recurrent Neural Network with fixed random weights is trained to perform time series prediction. The network is able to succesfully predict the dynamics of chaotic partial differential equations like the Mackey-Glass or Kuramoto-Sivashinsky equations. Digital Micromirror Devices can only turn pixels on or off, while Liquid-Crystals SLMs commonly modulate phase of the electric field. For both cases, we analyze how to encode information on the SLM so that it does not degrade the prediction of the Reservoir. We show that this optical computing strategy can outperform electronic implementations by two orders of magnitude and scale to very large dimensions that we cannot obtain in electronics due to memory limitations.

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CORRELATIONS IN SURFACE PLASMON RANDOM SCATTERING

Matthew R. Foreman

Wave propagation in disordered media can result in a number of interesting physical phenomena such as coherent back scattering and Anderson localisation. Fundamentally these phenomena derive from phase or intensity correlations between scattered waves that persist despite the random nature of scattering in such systems. Correlations in random fields have thus been extensively researched in the optical domain. In recent years it has been recognised that evanescent field contributions can significantly affect the properties of fields inside a random medium, or at small distances from its exit surface and thus must be carefully considered in modern nano-photonic applications. Resonant surface waves, most notably surface plasmon-polaritons, can also affect the properties of random optical fields and can therefore have strong consequences for emission from fluorophores and information fidelity in plasmonic devices. Study of random plasmonic fields to date has largely focused on localization effects, however, in this work we report on the statistical properties of random surface plasmon fields, or plasmonic speckle patterns. Using fully rigorous analytic expressions for the correlations present in the roughness induced field fluctuations, derived using a Green's tensor approach, we present a number of analytic results pertaining to the near field polarization and coherence properties of random plasmonic fields. Dissipation effects in the metal can ultimately produce non-universal behaviour offering opportunities for particle sensing and near field imaging.

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BIOMIMETIC PHOTONIC CELLULOSE FILMS

Axel Fouques, Bruno Frka-Petesic, Laurent Heux and Silvia Vignolini

Helical assemblies of cellulose are the “go-to” evolutionary choice of plants willing to optimize a combination of mechanical and optical properties. These assemblies can be reproduced with cellulose nanocrystals: nanorods that form a stable suspension in aqueous media and further arrange into a cholesteric liquid crystalline phase above a critical concentration. Such structure behaves as a 1D colloidal photonic crystal, displaying iridescence if the pitch of the helix is on the order of the wavelength of visible light.

The optical response of the helices is usually determined by their polydomain structure, whereby the orientation of the helix h is not controlled and leads to a pixelated and polychromatic aspect. Although chemical and physical methods have both been used to control their optical response, the use of external fields, e.g., electric and magnetic, has been limited to only a few examples. Recently, the two groups Vignolini and Heux have demonstrated the possibility of using magnetic and electric fields to shape the optical response of photonic cellulose-based structures.

Finally, the ordering can be preserved in solid films through the drying of aqueous suspensions or polymerization of organic suspensions and lead to a strong reflection of the left polarization of light at a specific wavelength.

In this talk, I will discuss how electric and magnetic fields can be synergistically employed/engineered to generate various degrees of orientation of the cholesteric domains and how it shapes the resulting optical response of cellulose

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EXTRAORDINARILY TRANSPARENT COMPACT METALLIC METAMATERIALS

Metals are highly opaque, yet we show that densely packed arrays of metallic nanoparticles can be more transparent to infrared radiation than dielectrics such as germanium, even for arrays that are over 75% metal by volume. Despite strong interactions between the metallic particles, these arrays form effective dielectrics that are virtually dispersion-free, making possible the design of optical components that are achromatic over ultrabroadband ranges of wavelengths from a few microns up to millimetres or more. Furthermore, the local refractive indices may be tuned by altering the size, shape, and spacing of the nanoparticles, allowing the design of gradient-index lenses that guide and focus light on the microscale. The electric field is also strongly concentrated in the gaps between the metallic nanoparticles, and the simultaneous focusing and squeezing of the electric field produces strong 'doubly-enhanced' hotspots which could boost measurements made using infrared spectroscopy and other non-linear processes over a broad range of frequencies, with minimal heat production.

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BUILDING A REFLECTIVE RIG TO REVEAL THE DIM SPECTRA OF PLASMONIC NANOSTRUCTURES

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Metallic nanostructures exhibit interesting resonant interactions with light, analogous to radio antennae. Plasmonic materials are an emerging research area, and have benefitted applications such as sensing, communications, and quantum optics. One of the most utilized applications is surface enhanced Raman scattering (SERS). This enables label-free chemical sensing, potentially with single-molecule sensitivity.

Plasmonic modes of sparsely distributed nanostructures are typically studied using an optical microscope. However, the resonant spatial modes may not necessarily overlap with the point-spread function of the microscope. This is usually overcome by using optical spectroscopy to determine the frequencies of the plasmonic resonances. Our work focuses on revealing the 'dim modes' of plasmonic nanostructures. We are building a new design of reflective microscope that enables us to collect light emitted into spatial modes that do not radiate perpendicular to the substrate, over a uniquely wide range of wavelengths. This allows us to capture the spectra in ranges that would typically be very noisy. Exploring 'dim' radiated modes using reflective optics, instead of commercially available objectives, will allow for deeper experimental insights into nanoparticle systems.

Of particular interest is a dimer of two closely-spaced spheres of noble metal, each tens of nanometers in size, spaced around one nanometre apart. In the inter-particle gap, the electric field is strongly enhanced. Molecules can be placed in this region enabling sensitive optical detection and characterisation. We present early experimental studies of a well-understood system of gold spheres on a gold surface, in order to evaluate our microscope system.

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STRUCTURAL COLOUR IN FLAVOBACTERIUM IRIDESCENT 1

Gea T. van de Kerkhof, Villads E. Johansen, Yu Ogawa, Colin J. Ingham and Silvia Vignolini

Some of the brightest colours in nature arise from constructive and destructive interference of light, cause by the interaction of light with nano-sized structures [1]. Such mechanisms for structural colours are widely researched in higher order organisms, but remain largely unknown for prokaryotes [2,3]. A better understanding of the mechanisms underlying structural colour in prokaryotes could not only greatly add to our understanding of the function of structural colour in nature, but also create opportunities for applications such as biological pigments or biosensors. Here, we present the structurally coloured bacteria strain Flavobacterium Iridescent 1 (F. IR1).

By means of a gliding mechanism, these rod-shaped bacteria organise into a two-dimensional photonic crystal with hexagonal lattice. This configuration causes a colony of F. IR1 to selectively reflect certain wavelengths, giving the colony a vivid colourful appearance.

We present a study on the optical properties of IR1. We relate this to the morphology of the bacteria crystal, giving an in-depth understanding of the relation between the organisation of F. IR1 colonies and their colourful appearance.

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COLLECTIVE MODES OF HYPERUNIFORM RESONANT MEDIA

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We present an analysis of the collective modes of finite-size systems made of coupled resonant dipoles. The transition between crystalline structure and fully disordered samples is explored by tuning the degree of hyperuniformity of the point patterns. We build a wave transport phase diagram that accounts for the system size, the density and the degree of spatial correlation. Our analysis reveals in particular that the degree of stealth hyperuniformity allows to tune the system from a ballistic phase to a diffusive or localized phase. The effect of the vector nature of the field on this phase diagram is also discussed.

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TOWARDS HOT ELECTRON NANO SENSING WITH QUANTUM DOTS

Sergii Morozov, Evangelina L. Pensa, Stefano Vezzoli, Sandro Mignuzzi, Emiliano Cortes, Stefan A. Maier, Iwan Moreels and Riccardo Sapienza

We study the potential of giant-shell CdSe/CdS quantum dots [1] for local sensing of hot electron ejection from plasmonic nanostructures. Quantum dot emission dynamics (lifetime and blinking statistics) depend on the charge state of the semiconductor nanocrystals, and electron-accepting surface sites have the potential to trap hot electrons [2]. Therefore, a quantum dot placed in the vicinity of a plasmonic antenna can respond to hot electrons generated in its proximity. We test this hypothesis by recording individual quantum dot photoluminescence dynamics while controlling their degree of charging in an electrolytic cell. The CdSe/CdS quantum dots show outstanding photostability and can outline many

charge-discharge cycles. We report the experimental signatures of different charged excitonic complexes (trions), which are characterised by different quantum yield, lifetime and emission spectrum. As a next step, we suggest detecting hot electron ejection from plasmonic nanostructures by observing changes in the quantum dot photodynamics.

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REDUCING AND ENHANCING THE INTERACTION BETWEEN LIGHT AND SCATTERING MEDIA

Pritam Pai, Jeroen Bosch, Matthias Kuehmayer, Stefan Rotter, Allard Mosk

We present the generation of light fields that interact with strongly scattering media in special ways. Open channels are fields that are highly transmitted even through a thick scattering sample, and we experimentally show almost 50% transmission through an optically thick sample of zinc oxide nanoparticles. A key question is whether light-matter interaction is reduced in these strongly transmitted states, e.g. because the complex light field avoids the scattering centers, or enhanced, as in resonant transmission through an optical cavity. To address this question we also study generalized eigenstates, which retain the same wavefront whether they are transmitted through the scattering sample they are matched to or through clear glass. Both types of states are generated either from transmission matrix data or from iterative phase conjugation procedures.

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LIGHT-CONTROLLED PATTERNING OF STRUCTURAL COLOUR

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In the quest for more sustainable sources of colour, Nature provides inspiration for new designs and an abundant supply of raw materials. The helicoidal photonic structures found in plants such as Pollia condensata can be re-created in vitro using cellulose nanocrystals (CNCs), which undergo evaporation-induced self-assembly to produce dazzling structural colour [1]. However, progress toward large-scale use of CNC photonic films is hindered by a lack of precise control over the resulting colour and an incomplete understanding of the self-assembly process [2].

In this work, the coalescence and gelation of chiral nematic liquid crystal domains in CNC suspensions is controlled by adding a UV-sensitive surfactant and applying structured illumination during the drying process. The surfactant can be reversibly isomerised by applying near-UV or blue light, rapidly changing the local surface tension and thereby generating Marangoni flows. The resulting colour pattern of the films can thus be determined by the illumination strategy, as previously demonstrated with polystyrene microspheres [3].

This novel approach provides a new tool for understanding the self-assembly of CNCs and paves the way towards facile patterning of structural colour for applications such as anti-counterfeiting designs.

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HIGHLY SCATTERING POLYMER FILMS VIA A WATER VAPOR-INDUCED PHASE SEPARATION METHOD

L Pattelli, W Zou, J Guo, S Yang, M Yang, N Zhao, J Xu, DS Wiersma

The scales of Cyphochilus beetles are known for having a bright white appearance in spite of their low thickness and refractive index contrast. This outstanding scattering efficiency stems from a disordered, anisotropic ultrastructure made of chitin filaments that raised a lot of interest in several application fields where thin and opaque coatings made of common polymeric materials would be highly desired. To date, however, little is known regarding the topological properties of its structure, its spatial and angular correlations, or even its natural growth and formation process.

Here, we explored a bio-compatible self-assembly process that can take place under mild environmental conditions and give rise to anisotropic bi-continuous network structures similar to that of the Cyphochilus beetle. In particular, we use a simple water-vapor induced, one-step phase separation process to create highly turbid, thin polystyrene films. Optical characterization based on a Monte Carlo inversion procedure reveals an outstanding scattering strength, with a sub-µm transport mean free path at a wavelength of 500 nm for a film thickness of just 3.5 µm. The broadband reflectivity of these films results from a complex interplay between the scattering mean free path and the asymmetry factor, resulting in a scattering "fingerprint" of the material which sheds light on its underlying scattering mechanisms and provides a figure of merit for the comparison to other similar structures.

Preliminary numerical results on modeled bi-continuous scattering structures reveal the prominent role of just two basic parameters, namely the network volume density and its degree of structural anisotropy. Indeed, we show that even very unrefined architectures with a simple tuning of these two sole parameters can still deliver superior broadband reflectivity at a comparable or lower weight than the Cyphochilus beetle.

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CAVITY ENHANCED RESONATORS FOR TERAHERTZ DETECTION

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Spanning frequencies from 300 GHz to 10 THz, the Terahertz domain lays within a region of the electromagnetic spectrum that is often difficult to generate and detect.

This work looks at the progress towards the creation of a Terahertz detector similar to that of a golay cell. A golay cell functions using an absorbing layer and a gas cell with a membrane wall. The absorbing layer absorbs incoming infrared radiation and deposits it into the gas cell. The gas in the cell then expands causes the membrane wall to warp, this warping is measured and can be used to determine the energy of the incoming infrared radiation.

By creating a metamaterial structure for near perfect absorption within the Terahertz domain, the metamaterial can replace the absorbing layer of the golay cell to create a Terahertz detector.

The metamaterial designed for use in the golay cell consists of a layer of split ring resonators which have a resonance response at close of 550GHz. By placing these split ring resonators close to a gold layer, the resonance response is enhanced due to the mirroring of charges within the gold. By adjusting the separation of the gold and metamaterial layers the response can be tuned. By tuning the resonators response, the golay cell can be used across multiple frequencies within the THz domain.

The effect of the enhancement of the split ring resonators from the gold surface was seen by measuring the reflected THz from the cavity with and without the gold layer. The cavity without the gold layer reflected THz only at the resonance with a relative maximum reflection having an increase of 6dB. When the gold layer is added, the cavity reflects THz across the spectrum except at the resonance with a decrease in the reflected light of 45dB at the resonance.

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RECURRENCES IN AN ISOLATED QUANTUM MANY-BODY SYSTEM

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Out-of-equilibrium dynamics in complex quantum many-body systems is a vast topic of research, touching many different areas of physics. One of the most versatile experimental platforms to investigate these effects are ultracold atoms, due to their flexibility and easy isolation from the environment. In this context, we investigate the non-equilibrium dynamics of one-dimensional (1d) Bose gases, realized with ultracold Rubidium atoms on an atom chip.

To bring the system out of equilibrium, we initialize two parallel 1d gases in a phase coherent state by coupling them through a tunneling barrier, before suddenly ramping the coupling to zero. The subsequent dynamics is monitored by matter-wave interferometry, providing access to the relative phase field between the gases. After an initial dephasing dynamics we observe multiple revivals of coherence due to a rephasing of the underlying excitations. Within a low-energy description of the system, these revivals constitute a full return of the initial state and, therefore, can be seen as recurrences. Further analyzing the damping of the return fidelity allows us to detect otherwise elusive scattering effects between excitations, opening a new window into the long-term dynamics of these systems.

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FAR-FIELD WAVEFRONT OPTIMIZATION OF THE OPTICAL NEAR-FIELD IN NANOSCALE DISORDERED PLASMONIC METASURFACES

Sebastien Bidault, Sylvain Gigan, Samuel Gresillon

Plasmonic nanoantennas featuring nanoscale gaps exhibit strongly enhanced optical near-fields that have been extensively used in surface enhanced spectroscopy (Raman and Fluorescence) and in biosensing. However, deterministic nanostructures do not provide enough degrees of freedom to control optically these local field enhancements. By comparison, wavefront shaping techniques in disordered scattering media provide numerous degrees of freedom to control light focusing in space and time. To associate local field enhancements and far-field wavefront control, we use disordered plasmonic surfaces close to the percolation threshold that feature hotspots and delocalized plasmon modes. In this presentation, we demonstrate how controlling the phase of an incoming femtosecond laser on a disordered gold surface allows us to optimize the two-photon induced luminescence (TPL) at a chosen position. Importantly, the TPL signal has been shown to provide a far-field image of local field enhancements in nanoantennas. Our results therefore indicate a far-field optimization of the optical near-field in disordered plasmonic metasurfaces. In practice, the surface of a spatial light modulator is conjugated with the sample plane using a high numerical aperture inverted microscope in order to spatially modulate the phase of the incoming femtosecond source while preserving a homogeneous intensity. The emitted TPL is then imaged in parallel on a CMOS camera. A random optimization process of the incoming wavefront is then performed in order to enhance the TPL signal at the centre of the image. Comparing the distribution of TPL signals before and after optimization we observe a typical two orders of magnitude enhancement of the measured signal. These results demonstrate a strong enhancement of the nonlinear luminescence at any chosen position of the sample, at the diffraction limit; indicating an optimization of the near-field in disordered plasmonic metasurfaces by far-field wavefront shaping.

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ALL-DIELECTRIC HYBRID SILICON-GST RECONFIGURABLE META-DEVICES WORKING IN THE NEAR INFRARED

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High refractive index dielectric metasurfaces are a most promising platform for light control at the nanoscale. In contrast to plasmonic devices, the effective magnetic response in dielectric nanoantennas is not driven by conduction currents, but rather by displacement currents. Thus, high refractive index dielectric nanoantennas not only provide improved scattering efficiency, but can also support both strong magnetic and electric resonances that can be exploited to yield new, high-efficiency functionality in terms of the manipulation and control of light.

To date, silicon has been mainly used for dielectric metasurfaces, due to its high refractive index, negligible dielectric losses in the near and mid infrared, and low cost. However, the optical response in most of these approaches is fixed by design, meaning that they cannot be used for applications where light needs to be dynamically manipulated. Combining phase-change materials with optical metasurfaces is one way to introduce dynamic reconfigurabilty, and several plasmonic metasurface concepts that incorporate phase-change materials have been reported in recent years. However, the combination of phase-change materials with all-dielectric meta-structures remains relatively unexplored. In this work, therefore, we present a novel reconfigurable metasurface which is based on the combination of all-dielectric arrays of silicon nano-disks with deeply subwavelength-sized GST inclusions (<lambda/100). We show (both theoretically and experimentally) how, by locating the GST inclusions in the electric field antinodes, our structures can provide high efficiency and separate control of the electric and magnetic modes supported by the array. We believe that the proposed reconfigurable metasurface provides the pillars for a wide range of new possibilities and design degrees of freedom towards the realisation of novel tuneable and highly efficient meta-devices.

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DESIGNING FIBRE PROBES FOR HOLOGRAPHIC MICROENDOSCOPY

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Multimode fibres (MMFs) have recently emerged as prospective minimally invasive microendoscopes for in vivo imaging. Light is delivered through a hair-thin probe, resulting in an endoscope with a very small footprint. When compared to conventional fibre-based endoscopes, MMFs offer a reduced footprint and improved resolution. Although light propagating through an optical fibre is seemingly chaotic, the process can be described in terms of a transmission matrix (TM), linking the input and output fields of the fibre probe. If the TM is known, imaging is still possible through wavefront shaping.

In practical settings, bending of the MMF significantly modifies its optical properties, resulting in image distortion. Although imaging can still be performed by correcting the TM, a precise knowledge of the fibre bending is required.

We propose a new microendoscopic design that enables imaging even when the fibre is bent during image acquisition. The microendoscope consists of an optical fibre bundle with a central multimode fibre for imaging, surrounded by six all-grating single mode fibres for curvature sensing. Image reconstruction can be achieved by providing real-time fibre curvature information to an algorithm which predicts the TM in real-time, based on detailed modeling of light propagation through a multimode waveguide. Such a fully flexible microendoscope could provide new insights in the study of motile and freely-behaving animal models, with minimal perturbation of their motor and functional activities.

While the damage induced by the insertion of a single MMF in biological tissue is vestigial (<50 μm), the flat tip of the fibre can be engineered to reduce the damage even more. We propose a less invasive fibre termination, which could also offer a 360° view inside the tissue, instead of the usual imaging in front of the fibre tip. This new kind of fibre termination could allow the study of structures even less affected by the fibre probe.

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LARGE-AREA 3D NONLINEAR WOODPILE PHOTONIC CRYSTAL WITH BARIUM TITANATE NANOPARTICLES

Viola. V. Vogler-Neuling, David Pohl, Nicholas R. Hendricks, Lukas Lang, Maria Timofeeva, Barbara Schneider, Felix Richter, Flavia Timpu, Serge Monneret, Fabian Starsich and Rachel Grange

Nonlinear photonic crystals are one of the potential candidates for enabling photonic circuits, as they allow the control of light with light. Most of the current top-down fabrication approaches are time consuming and are restricted to small surface areas. Common nonlinear materials are either bulk materials or thin films bonded to a rigid substrate, impeding the integration with other platforms. Furthermore, they are difficult to etch in terms of quality, sidewall angle and anisotropy.

Here, we use UV-soft nanoimprint lithography, a bottom-up fabrication technique, together with solution processing of barium titanate (BaTiO3) nanoparticles to create large-scale nonlinear photonic crystals. We demonstrate 3D woodpile photonic crystals with up to eight layers over a surface area of 1.0 cm2. The band gap lies around 564 nm with a minimum transmission of 7 % for the seven-layer sample. We measure the second harmonic generated (SHG) signal from the 3D woodpile photonic crystals over the full visible range from 380 nm to 700 nm. The SHG signals match the results of the linear band gap in this regime. Polarization dependent SHG measurements show that for an unpatterned thin film the SHG response is circular whereas the SHG response for a single layer woodpile is dipolar with the long axis perpendicular to the rods. For consecutive layers, the SHG response becomes quadrupolar because the dipolar shapes for the individual layers are adding up.

In addition to second-order nonlinearity, BaTiO3 exhibits electro-optic, elasto-optic and thermo-optic effects. Therefore, it is especially suited for future active photonic crystal devices. Since the woodpile structure has the advantage that it can be fabricated layer-by-layer, our fabrication method is suitable for roll-to-roll fabrication, which can be easily adapted for industrial fabrication.

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DESIGN OF METAMATERIAL PERFECT ABSORBER BY DEEP LEARNING

Wei Xiao, Peter R. Wiecha, Kai Sun, C.H. de Groot, Otto L. Muskens

Metamaterial perfect absorber (MPA) is a kind of artificial nanostructures with near unity absorption in selective wavelength range [1], the applications include IR camouflage and radiation cooling [2].

However, the conventional way of designing MPA is based on simulating a serial of different geometries, and then solving the Maxwell's equation by commercial numerical software (COMSOL and FDTD), which is complicated and inefficient. Recently, with the advance of the computational techniques, Deep Learning (DL) is becoming a powerful computational tool to boost the development like face recognition [3] and optical information storage [4]. Therefore, applying deep learning on nanophotonics design provides a way to increase its efficiency.

Here, we will show a proof-of-principle study on using deep learning to predict the optical response of metarefelctor by given design parameters and predict the design parameter with a given spectral response (inverse design). Inverse design of a given optical spectrum fits well with the input design parameters. Moreover, other suggested structure parameters with more compact design by deep learning shows similar absorption spectrum, which is promising for the design of ultracompact nanophotonics device.

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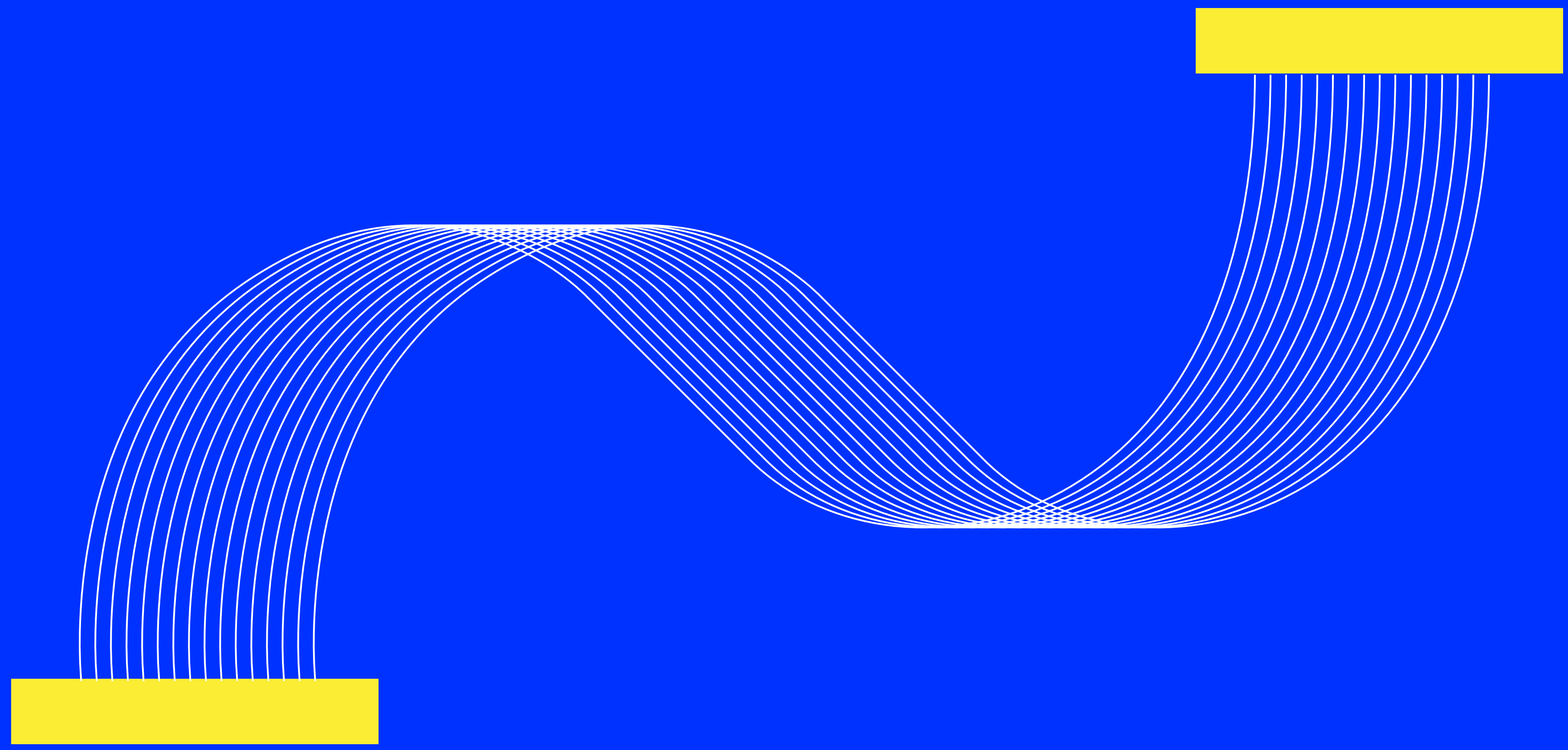
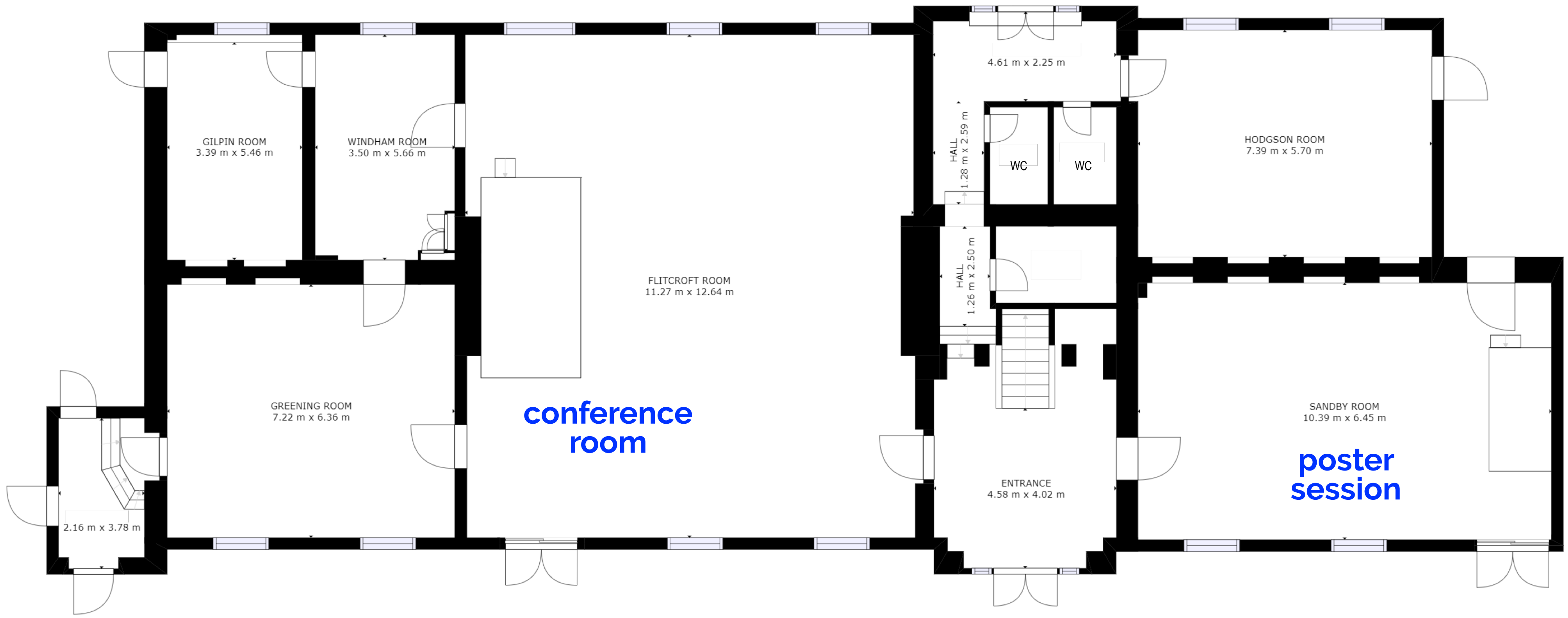


The Mews Floorplan



Ground Floor
Cumberland Lodge
The Mews

Gross Internal Area
Ground Floor: 437 m2; 1st Floor: 150 m2
Excluded Areas (Reduced Headroom Below 1.5m): 4 m2
Total 587 m2
Sizes and dimensions are approximate, actual may vary.

Cumberland Lodge
exchanging views, inspiring minds