AN INTERNATIONAL
INTERDISCIPLINARY WORKSHOP ON

CORRELATED DISORDER, HYPERUNIFORMITY AND LOCAL SELF-UNIFORMITY

FROM BIOMIMETICS TO PHOTONIC INTEGRATED CIRCUITS

25-26 JUNE 2018

UNIVERSITY OF SURREY

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INTRODUCTION

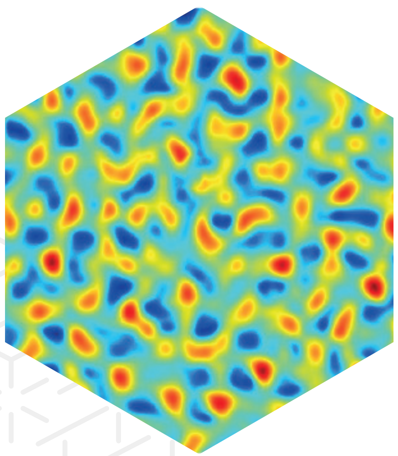
The subtle interplay between composition, morphology, topology and structural uniformity present in correlated disordered structures and in particular the newly introduced hyperuniform and local-self-uniform materials has a direct impact on a wide range of directions from more efficient solar-cell platforms and structure of amorphous silicon, to optical functionalities in avian feather barbs and butterfly wings.

The hyperuniformity and local self-uniformity concepts suggest a fundamental connection between structure and physical response and may offer a direct route towards engineering designer materials with on-demand, unprecedented physical functionalities. The impact of these new concepts on many different areas of fundamental and applied science appears to be important and yet our current understanding of these novel types of structuring is in early stages.

This workshop aims to bring together a diverse group of physicists, chemists, materials scientists, mathematicians and biologists to explore the consequences of hyperuniformity across diverse research fields and to unravel the fundamental impact of correlated disorder on biomimetic and nanophotonic applications.

Organisers:

Dr Marian Florescu, University of Surrey
Dr Riccardo Sapienza, Imperial College London
Prof Stephen Sweeney, University of Surrey



PROGRAMME

DAY 1 MONDAY 25 JUNE
WATES HOUSE, TREETOPS ROOM

8:30 am **Registration and coffee**

9 am **Welcome**
Stephen Sweeney, Head of the Physics Department, University of Surrey

Session 1 **Chair: Marian Florescu**

9:10 am Frank Scheffold, University of Fribourg, Switzerland
Band Gap Formation and Anderson Localization in Hyperuniform Disordered Materials

9:50 am Kurt Busch, Humboldt University & Max-Born Institute, Germany
Design of an Integrated Random Spectrometer

10:30 am Riccardo Sapienza, Imperial College London, UK
Lasing in Disordered Photonic Networks

10:55 am **Coffee**

Session 2 **Chair: Riccardo Sapienza**

11:30 am Guillaume Gomard, Karlsruhe Institute of Technology, Germany
Phase-Separated Disordered Nanostructures for Energy Saving Applications

12:10 pm Gabriel Lozano, Institute of Materials Science of Sevilla, Spain
Mie Glasses: Optically Disordered Materials for Optoelectronic Applications

1 pm **Lunch**

Session 3 **Chair: Kevin Vynck**

2 pm Salvatore Torquato, Princeton University, USA
Novel Physical Properties of Disordered Stealthy Hyperuniform Materials and Bounded-Hole-Size

2:50 pm Esther Alarcon Llado, AMOLF, Netherlands
Hyperuniform Disordered Structures for Solar Cell Applications

3:15 pm Alvaro Blanco, Institute of Materials Science of Madrid, Spain
Fano Resonance in Correlated Disordered Colloids

3:40 pm **Coffee**

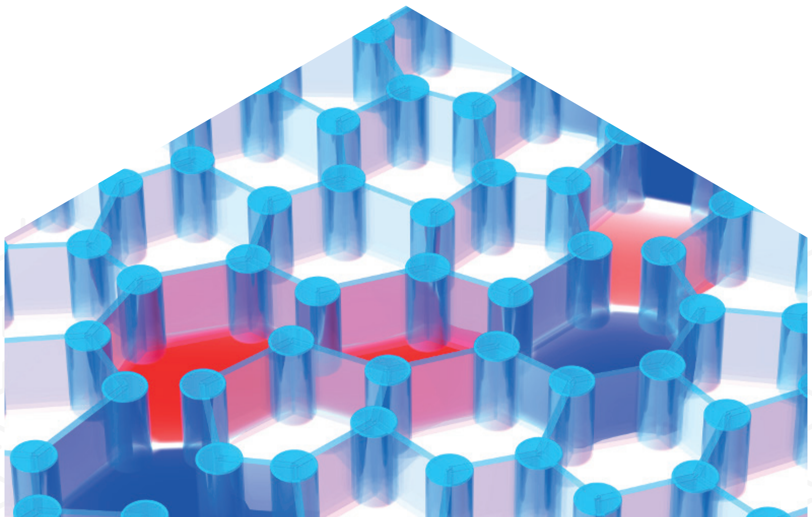
Session 4 **Chair: Alvaro Blanco**

4:20 pm Jose Anguita, University of Surrey, UK
Optical Structures with sp2 Carbon

4:45 pm Peter Keim, University of Konstanz, Germany
Experimental Realization of a 3D Isotropic Photonic Band Gap in the Microwave-Regime

5:10 pm **Poster session/Drinks (Wates House)**

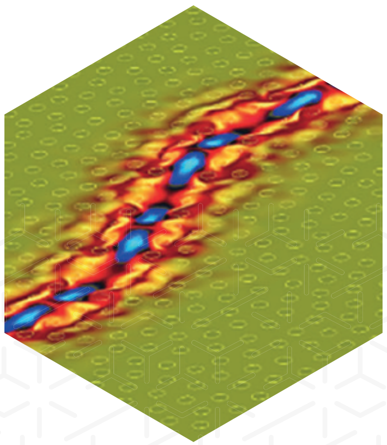
7pm **Dinner (Weyside, Guildford)**

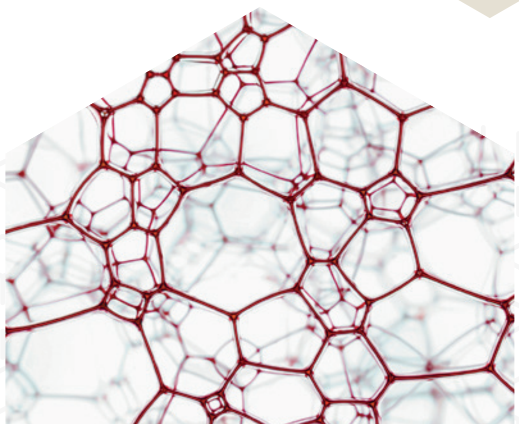


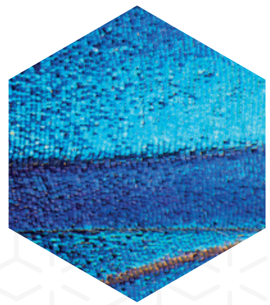
PROGRAMME

DAY 2 TUESDAY 26 JUNE
WATES HOUSE, TREETOPS ROOM

Session 5	**Chair: Weining Man**
9 am	Remi Carminati, Institut Langevin, France **Transparency and Enhanced Absorption in Hyperuniform Disordered Media**
9:40 am	Bodo Wilts, Adolphe Merkle Institute, University of Fribourg, Switzerland **Gyroid Photonic Crystals in Butterflies: Pigmentation, Order and Disorder**
10:20 am	Marian Florescu, University of Surrey, UK **Local Self-Uniform Photonic Networks**
10:45 am	**Coffee**
Session 6	**Chair: Remi Carminati**
11:30 am	Rémi Dreyfus, CNRS/UPenn/Solvay, France/USA **Hyperuniform Assembly of Colloidal Particles**
11:30 am	Alexander Sprafke, University Halle-Wittenberg, Germany **Self-Assembly of Nanoparticles into Nearly Hyperuniform 2D Structures**
1 pm	Lunch
Session 7	**Chair: Kurt Busch**
2 pm	Weining Man, San Francisco State University, USA **Experimental Studies of Hyperuniform and Local-Self Uniform Disordered Photonic Structures**
2:25 pm	Kevin Vynck, University of Bordeaux, France **Disorder Engineering in Complex Nanostructured Surfaces to Control Light Scattering and Trapping**
3:05 pm	**Coffee**
Session 8	**Chair: Guillaume Gomard**
3:45 pm	Luis Froufe, University of Fribourg, Switzerland **Light Transport Phase Diagram in Stealthy Hyperuniform 2D Materials**
4:10 pm	Milan Milosevic, University of Southampton, UK **Hyperuniform Disordered Silicon Photonics for the Next Generation of Photonic Integrated Circuits**
4:35 pm	**General Discussion / Future Directions**
7 pm	**Workshop Dinner (The Ivy, Guildford)**







INVITED TALKS

NOVEL PHYSICAL PROPERTIES OF DISORDERED STEALTHY HYPERUNIFORM MATERIALS AND BOUNDED-HOLE-SIZE PROPERTY

Salvatore Torquato
Department of Chemistry, Department of Physics, Princeton Institute for the Science and Technology of Materials and Applied & Computational Mathematics,
Princeton University, USA

Disordered stealthy hyperuniform materials are shown to possess many unique thermodynamic and nonequilibrium physical properties, including negative thermal expansion behavior, complete isotropic photonic band gaps comparable in size to those of a photonic crystal, transparency even at high densities, and nearly optimal transport properties. We describe how these novel physical properties of disordered stealthy hyperuniform materials are partly related to the fact that they cannot possess arbitrarily large "holes" in the infinite-volume limit. We also discuss how this bounded-hole-size property is related to short-range correlations and/or hyperuniformity at large length scales in these systems.

TRANSPARENCY AND ENHANCED ABSORPTION IN HYPERUNIFORM DISORDERED MEDIA

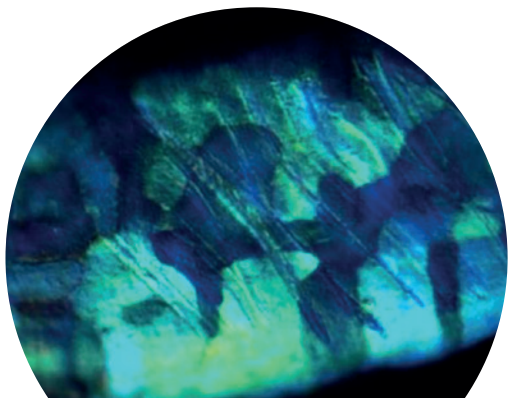
Remi Carminati
Institut Langevin, ESPCI Paris, CNRS, PSL Research University, Paris, France

We will discuss some photonic properties of correlated disordered materials made of scatterers distributed on a stealth hyperuniform point pattern (a pattern for which the structure factor S(q) vanishing in the neighborhood of q=0). Such materials can be transparent, at densities for which a fully disordered material would be opaque due to scattering. In the single scattering regime, transparency is a direct consequence of the vanishing of the structure factor S(q). Interestingly, we will show that transparency can survive in the multiple scattering regime under a general condition ensuring that the effective scattering mean free path remains larger than the system size. We will also discuss the potential of correlated disordered materials for the production of strong absorbers of light (and more generally waves) over a broad spectral and angular range. We will demonstrate the existence of an upper bound for the absorbed power and discuss the underlying physical picture. Based on this picture, we will propose a strategy to engineer disorder materials with optimized absorption and show that hyperuniform structures emerge as an interesting class in this context. Hyperuniform disorder may offer the possibility to produce materials with blackbody-like absorption. The interest in the production of hyperuniform disordered materials with peculiar photonic properties is supported by the possibility to fabricate such materials using self-assembly techniques.

TRANSPARENCY AND ENHANCED ABSORPTION IN HYPERUNIFORM DISORDERED MEDIA

Frank Scheffold
Department of Physics and Fribourg Center for Nanomaterials, University of Fribourg, Switzerland

Structured dielectric materials with a sufficiently high refractive index contrast can display partial or full photonic band gaps. This leads to dramatic changes of the optical transport properties with a strong spectral dependence. The latter is responsible for the transparency of the cornea to visible light, the iridescence of opal gems and structural colours in biology. The lowered density of states may also result in increased lifetimes for embedded light emitters such as fluorescent molecules. Interestingly, it appears that many of these unique properties are not tied exclusively to crystalline structures. In a recent numerical study Florescu et al. demonstrated that particular disordered materials can also display full photonic band gaps. Mapping hyperuniform point patterns with short-range geometric order into tessellations allows the design of interconnected networks that give rise to photonic properties in two and three dimensions. Here we report on the fabrication and characterization of such photonic network structures in three dimensions and for optical wavelengths in the shortwave infrared. We first discuss the fabrication of polymer templates of the network structures using direct laser writing (DLW) lithography. Next the mesoscopic polymer networks are converted into silicon by infiltration and double-inversion. The resulting hyperuniform materials display a pronounced photonic gap in the optical transmittance at λ=2.5µm. To obtain a deeper understanding of the physical parameters dictating the properties of amorphous photonic materials we investigate band gaps, and we report Anderson localization in hyperuniform structures using numerical simulations of the density of states and optical transport. Our results show that, depending on the frequency of incident radiation, a dielectric material can transition from photon diffusion, localization to a bandgap crossing an intermediate regime dominated by tunnelling between weakly coupled states.



DESIGN OF AN INTEGRATED RANDOM SPECTROMETER

Kurt Busch
Humboldt Universität zu Berlin, AG Theoretische Optik & Photonik; Max-Born-Institut, Germany

Compact spectrometers based on disordered planar waveguides exhibit a rather high resolution with a relatively small footprint as compared to conventional spectrometers. This is achieved by multiple scattering of light which – if properly engineered – significantly enhances the effective optical path length.

In the first part of this talk, a design study of random spectrometers for TE- and TM-polarized light is presented that combines the results of Mie theory, multiple-scattering theory and full electromagnetic simulations. It is shown that the performance of such random spectrometers depends on single scattering quantities, notably on the overall scattering efficiency and the asymmetry parameter. Further, the study shows that a well-developed diffusive regime is not required in practice and that a standard integrated-optical layout is sufficient to obtain efficient devices even for rather weakly scattering systems consisting of low index inclusions in high-index matrices such as pores in planar silicon-nitride based waveguides. This allows for both significant reductions in footprint with acceptable losses in resolution and for device operation in the visible and near-infrared frequency range.

The actual realization and experimental characterization is the subject of the second part of the talk. Specifically, novel fiber couplers are presented which serve at terminations of the input- and read-out-waveguides. The characterization of the resulting complete integrated random spectrometer devices demonstrates their excellent spectral resolution and also a very good agreement with the results of the theory/simulations. These devices may be equipped with superconducting single photon detectors, thus allowing the spectrometry of quantum light.

HYPERUNIFORM ASSEMBLY OF COLLOIDAL PARTICLES

Rémi Dreyfus
Centre National de la Recherche Scientifique, Compass Laboratory, UMI 3251, CNRS/UPENN/Solvayy

Colloidal complex fluids are suspensions of tiny particles of diameter ranging from tens of nanometers to tens of microns. When the particles are driven out of equilibrium, they can adopt a specific structural organization. This structural organization is what usually sets the macroscopic properties of the fluid. For this reason, studying the suspension structure is of importance. In this talk, we present the resulting structure of colloidal fluids as the suspension is driven out of equilibrium, either by jamming or in a flow. Two and Three-dimensional systems of micrometer-sized colloids were considered and characterized by studying their structure factor using microscopy and static small-angle light scattering. We found that suspensions tend to organize in a so-called hyperuniform organization, a type of organization that has attracted interest over the past decade due to its potential exciting photonic properties.

Our work evidences novel ways of assembling hyperuniform materials from colloidal suspensions, opening new routes for bottom-up assemblies of new functional materials.

GYROID PHOTONIC CRYSTALS IN BUTTERFLIES: PIGMENTATION, ORDER AND DISORDER

Bodo Wilts

Adolphe Merkle Institute, University of Fribourg, Fribourg, Switzerland

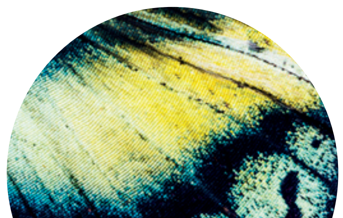
The existence of biophotonic gyroid material in buttery wing scales presents an exceptional feat of evolutionary engineering of functional nanostructures. Gyroids in butterflies can be found in a variety of families, e.g. Parides sp. or Callophrys sp. Gyroid photonic structures have unique properties: it is a complex, chiral 3D periodic structure and as such should invoke circular polarisation. I will discuss how pigmentation in different gyroid-carrying butterflies alters this phenomenon. I will furthermore show an unusual hierarchical ultrastructure in a Hairstreak buttery that allows high-resolution 3D microscopy. In T. opisena, the gyroid occurs in isolated facetted crystallites with a pronounced size-gradient rather than the conventional polycrystalline space-filling arrangement. This special arrangement is interpreted as a sequence of time-frozen snapshots of the morphogenesis and thus provides insight into the formation mechanisms of the nanoporous gyroid material. Interestingly, the same butterfly has disordered chitin networks on other wing regions with different optical properties.

MIE GLASSES: OPTICALLY DISORDERED MATERIALS FOR OPTOELECTRONIC APPLICATIONS

Gabriel Lozano
Institute of Materials Science of Sevilla, Universidad de Sevilla, Spain

Mie glasses are inhomogeneous solids that behave as solid dispersions of light scatterers. A novel demonstration of a Mie glass synthesized by solution-processing methods and comprising a mesoporous TiO_2 matrix in which crystalline TiO_2 monodisperse nanospheres are dispersed in a random manner is reported. A full optical characterization of this optically disordered material, whose behavior can be predicted prior to fabrication based on single particle considerations using Mie theory, is performed to attain the key parameters that describe light propagation in random media, i.e. scattering and transport mean free paths.

Herein we discuss the potential of these inhomogeneous solids for optoelectronic applications. In particular, we show that Mie glasses are able to boost light harvesting and thus power conversion efficiency in bifacial dye-sensitized solar cells when the porous matrix is sensitized with a dye. Also, we prove that soaking the optically disordered material with fluorescent dye molecules yields brighter color conversion layers, which we attribute to a combination of resonant excitation and a better out-coupling of the emitted light.



DISORDER ENGINEERING IN COMPLEX NANOSTRUCTURED SURFACES TO CONTROL LIGHT SCATTERING

Kevin Vynck
Light in Complex Nanostructures, Institut d'Optique d'Aquitaine, France

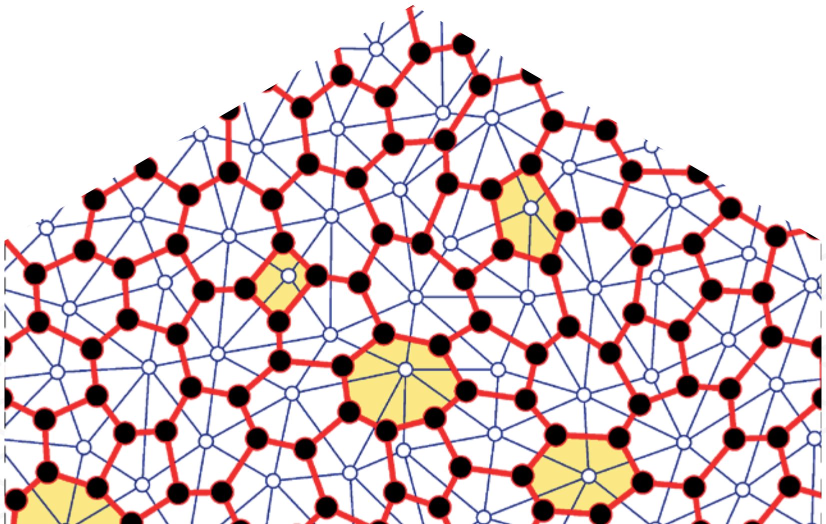
Multiple light scattering in disordered media is a topic of paramount importance for the optical spectroscopy of complex media like biological tissues, the improvement of photovoltaics or lighting technologies at low costs, and the fundamental study of mesoscopic wave phenomena such as light localization. It is well known that light propagation is strongly influenced by spatial correlations in the microstructure of disordered media. Recent years have witnessed a growing interest in the use of photonic structures with a controlled disorder, as to explore new opportunities in the control of light scattering and trapping. The emerging concept of "disorder engineering" is however still in its infancy and much remains to be explored on the potential of this approach for practical purposes.

This talk aims at showing how structural correlations can be exploited to control the very rich optical properties of "complex nanostructured surfaces", i.e. large disordered ensembles of scatterers (e.g. air holes, resonant nanoparticles) deposited on or incorporated in a stratified geometry. We will discuss the theoretical formalisms that can be used to describe the interaction of light with such complex systems, as well as the related physical concepts, and illustrate them with practical examples. In particular, we will see that short-range correlations can lead to a very effective tuning (i) of the light coupling/decoupling process between free-space modes and guided modes in the stratified medium, (ii) of the in-plane light transport and localization, making it possible to move from a weakly scattering to a strongly localizing regime very easily, and (iii) of the scattered intensity radiation diagram, thereby leading to sharp angular and spectral features. Structural correlations in complex nanostructured surfaces may thus be engineered to enhance light absorption and extraction in thin-film solar cells and organic LEDs, augment light-matter interaction for, e.g., sensing purposes and design the visual appearance of objects.

SELF-ASSEMBLY OF NANOPARTICLES INTO NEARLY HYPERUNIFORM 2D STRUCTURES

Alexander Sprafke
Institute of Physics, Martin Luther University Halle-Wittenberg, Germany

Tailoring optical structures according to the needs of specific application remains a challenging task, in particular where throughput and cost are of the essence, e.g. in solar cells and large area solid state lighting. Self-assembled colloidal structures are candidates for such techniques as they fulfil the key requirement of scalability. In numerous literature examples, the tendency of monodisperse colloidal particles to form well-ordered structures in two dimensions (hexagonal gratings) and three dimensions (opals) has been exploited for use optoelectronic devices (e.g. solar cells). However, recent numerical studies show that structures with a tailored degree of disorder outperform ordered structures due to their better broad band response. Hyperuniform disordered materials are a particular sub-class of disordered materials. In contrast to previous studies of ordered colloidal structures, the here presented solution based technique allows us to generate particle deposits of nearly hyperuniform disordered patterns at an interface which can be used directly as a scattering layer or as templates for further processes. A more detailed investigation of the particle deposition process leads to the development of a deposition model that allows us to predict particle patterns fabricated by our presented deposition technique. This semi-phenomenological version of the well-known random sequential adsorption (RSA) model obviates the need for tedious trial-and-error experiment in order to optimize a certain structure. Examples are discussed for which the response of a predicted particle pattern is compared to angular resolved scattering measurements.

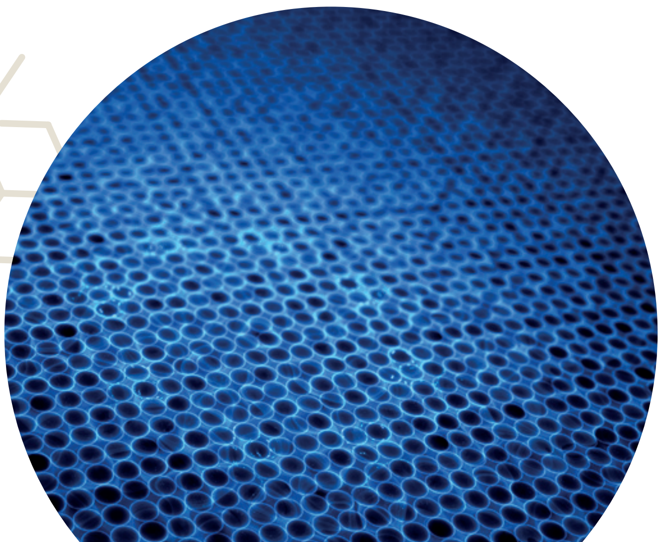


CONTRIBUTED TALKS

LIGHT TRANSPORT PHASE DIAGRAM IN STEALTHY HYPERUNIFORM 2D MATERIALS

Luis S. Froufe-Pérez
Department of Physics, University of Fribourg, Switzerland

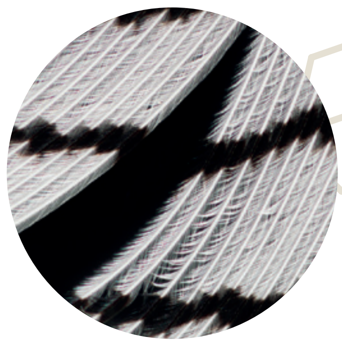
Photonic stealthy hyperuniform (SHU) disordered materials are dielectric structures defined though their structural properties in reciprocal space. Their distinctive characteristic is the lack of density fluctuations above a certain threshold length scale. In the reciprocal space this translates into a vanishing structure factor all the way from zero wavenumber to a critical value kc. SHU materials, despite being disordered, share many characteristics with photonic crystals: at low frequencies they show transparency while, depending on the exact geometric properties and materials, at higher frequencies they present a full isotropic photonic bandgap. Here, we propose a light transport schematic phase diagram in two-dimensional SHU systems. Depending on the frequency and degree of correlation (or 'stealthiness') of the sample, SHU photonic materials display regions of transparency, photon diffusion, Anderson localization and tunneling transport regimes. We demonstrate, through extensive statistical electromagnetic simulations, the transport characteristics of the different regimes in the correlation-frequency plane. Moreover, we present first preliminary experimental results on microwave transport through SHU two dimensional systems.



RECENT PROGRESS IN EXPERIMENTAL STUDY OF HYPERUNIFORM AND LOCAL-SELF UNIFORM DISORDERED PHOTONIC STRUCTURES

Weining Man
Department of Physics and Astronomy, San Francisco State University

Disordered photonic band gap materials not limited to crystalline nor quasicrystalline symmetry have be widely studied. Some of them have shown inherent advantages associated with the isotropy of the structures, offering unprecedented freedom for functional defect designs impossible to achieve in photonic crystals. Beyond our previous work in experimental realization and characterization of Hyperuniform Disordered Photonic Structures, we made further progresses in the a few directions. First, we extended our study into three-dimensional disordered systems. We verified the isotropic photonic bandgap in amorphous gyroid samples fabricated via three-dimensional ceramic printing and explored amorphous gyroid-like systems existing the nature, such as the wing-scale structures in the butterfly Pseudolycaena marsyas. More importantly, it is demonstrated that the local-self –uniformity (a measure of a random network's internal structural similarity) is critical for photonic bandgap formation in these amorphous gyroid structures. Second, we worked on functional-defect design and optimization for HUDS-based disordered photonic bandgap materials and demonstrated some of their potential advantages in making highly compact, flexible, and energy-efficient photonic devices. Most of these related works is designed for 1.55-mircon wavelength and a hollow HUDS based fiber is studied at the THz range. Last, other disordered photonic systems, including light-induced ones attribute to nonlinear response of the material and self-assembled HUD patterns are also investigated.



PHASE-SEPARATED DISORDERED NANOSTRUCTURES FOR ENERGY SAVING APPLICATIONS

Guillaume Gomard
Light Technology Institute, Karlsruhe Institute of Technology (KIT), Germany

Improving the efficiency of solar cells and organic light emitting diodes (OLEDs) can ameliorate our way of generating and utilizing electricity. To this end, light management solutions are essential to foster sunlight harvesting in photovoltaics, and to assist the extraction of trapped photons in the case of OLEDs, for instance in lightning applications. In both cases, the light scattering elements exploited should operate over a broad spectral and angular range, making correlated disordered nanostructures better suited than their periodic counterparts.

Taking the example of the black butterfly Pachliopta aristolochiae, it can be shown that the disordered nanoholes array decorating its wings strongly enhance sunlight absorption due to both an improved collection of the light, and to an efficient scattering scheme. Inspired by the black butterfly, we developed a synthetic route based on polymer blend lithography to fabricate disordered light scattering elements (nanoholes or nanopillars) with a tailored size and radial distribution function.

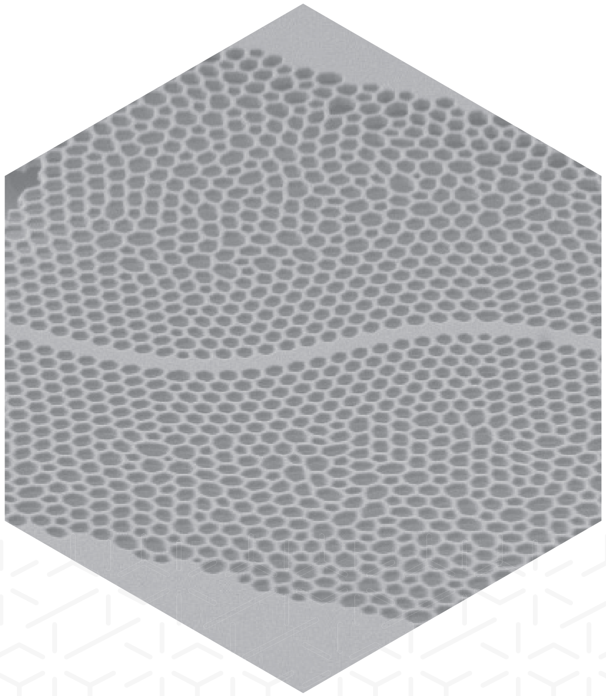
Upon implementation of these disordered light trapping structures in thin film solar cells, the resulting efficiency is increased by 65%rel compared to planar devices, and even overcomes the one obtained with randomly textured substrates, which are commonly used as a light trapping benchmark. The developed disordered light scattering nanostructures are also relevant for the inverse problem, i.e for outcoupling guided modes confined in the OLED thin film stack. Herein, we show that the efficiency is enhanced by 50%rel with respect to planar OLEDs and that color distortion effects are avoided.

The light scattering properties of these 2D planar, correlated disordered nanostructures can be accurately and time-efficiently evaluated by T-matrix simulations using the method of truncated Sommerfeld integrals. This point is illustrated by computing the light outcoupling by a large ensemble of disordered scatterers inserted within an OLED stack.

LOCAL SELF-UNIFORM PHOTONIC NETWORKS

Marian Florescu
Advanced Technology Institute and Department of Physics, University of Surrey, UK

The interaction of a material with light is intimately related to its wavelength-scale structure. Simple connections between structure and optical response empower us with essential intuition to engineer complex optical functionalities. Here we develop local self-uniformity as a measure of a random network's internal structural similarity, ranking networks on a continuous scale from crystalline, through glassy intermediate states, to chaotic configurations. We demonstrate that complete photonic bandgap structures possess substantial local self-uniformity and validate its importance in gap formation through design of amorphous gyroid structures. Amorphous gyroid samples are fabricated via three-dimensional ceramic printing and the bandgaps experimentally verified. We explore also the wing-scale structuring in the butterfly Pseudolycaena marsyas and show that it possesses substantial amorphous gyroid character, demonstrating the subtle order achieved by evolutionary optimization and the possibility of an amorphous gyroid's self-assembly.



PHOTONIC NETWORKS RANDOM LASERS

Riccardo Sapienza
Department of Physics, Imperial College London, UK

When two light emitters in vacuum are more than a wavelength apart, their optical coupling is practically zero and no energy can be transferred between them. This limits progress in optical transistors and computing at the single photon level, and those optical technologies based on collective optical synchronization such as lasing.

I will show that a disordered nanophotonic network, composed of connected sub-wavelength waveguides, is an ideal scattering geometry to route photons, promote coupling between embedded emitters and enhance stimulated emission. I will discuss how the optical properties can be designed from its topological correlations, ranging from order to disorder, as measured by the degree of hyperuniformity. The network controls single-photon emitters, as indicated by momentum spectroscopy experiments, as well as (random) lasing action when many emitters are coupled.

Random lasing is especially interesting as it can be dynamically controlled via adaptive pumping of the network modes, and can form the basis of very sensitive sensors for living tissue integration.

FANO RESONANCE IN CORRELATED DISORDERED COLLOIDS

Alvaro Blanco
Institute of Materials Science of Madrid, Spain

Asymmetric resonances can occur in many different experiments belonging to different fields and the way we describe them is by using a special shape U. Fano found in 1935 analysing the Rydberg absorption lines in noble gases. These line-shapes are the result of two interacting resonances and the final asymmetry depends on the strength of that interaction. In photonics, they often appear in many systems like plasmons, photonic crystals or meta-surfaces, to name just a few. In this field, Important applications such as sensors, switchers or lasers are envisioned where, taking advantage of Fano line-shapes, their performance can be controlled and enhanced. However, in many situations identifying the different interacting resonances is not trivial and thus, the desirable control of their interaction turns impossible.

In this talk, I will give some examples, all of them performed in colloidal photonic crystals, where such interaction can be tuned by different means. I particular, I will discuss how by controlling the number of vacancies present in a self-assembled photonic crystal one can finely tuned disorder and through it, the optical response of the system. This response can be easily correlated using the Fano formula to the interaction between band gap and the continuous provided by Mie Scattering. Further and interestingly, Fano parameter q vanishes when the system crosses the percolation threshold for vacancies.

DISORDERED SOLAR ABSORBERS

Esther Alarcon Llado
3D Photovoltaics Group, AMOLF, Netherlands

Next generation solar cells are a new domain in the solar energy conversion in which the ratio efficiency-to-cost is significantly increased with respect to traditional bulk and thin film devices. Reducing the material usage is one simple approach to reduce costs. Even for Si-based solar cells, the second highest most impactful parameter on the final cost of the module is the silicon feedstock itself. However, due to the indirect nature of its bandgap, micrometer and nanometer thin Si becomes transparent to the NIR light, dramatically impacting the SC efficiency.

This talk focuses on how both local and homogeneous correlated photonic structures can be implemented on top of um-thin Si cells to boost their efficiency close to those of bulk. The physical mechanism relies on the photonic structure providing the in-plane momentum necessary to couple into the waveguided modes of the Si slab.

OPTICAL STRUCTURES WITH SP2 CARBON

Jose Anguita
Advanced Technology Institute, University of Surrey, UK

Graphitic forms of carbon are seldom used in optical components. However here we propose some examples where this material can be used, in in thin-film form, to provide optical functionality. This could address some of the limitations of current refracting lens, such as bulkiness and cost of manufacture. Replacing these is necessary to enable compactness, light-weight and miniaturization of optical technologies to come. We will show a collimating nanostructure in compact, flat-slab form that is able to produce a highly-collimated and wide-diameter beam. The structure uses nanomaterials ordered into nanoscale patterns to provide an absorption coefficient that is highly anisotropic.

A second example is the optical absorption of graphene. This is the thinnest carbon allotrope known. It exhibits unique electrical characteristics that arise from its linear dispersion. However, as much as graphene illuminates the roadmap, graphene itself remains mostly blind to light, as it is only able to absorb ~ 2.3% of the light that is incident on it. Here we have learned from nature (the eye of the moth) to develop technologies for enhancing absorption. For millennia, moths have developed unique abilities for light-absorption that enable them to see in the dark, as well as remain invisible to their predators at night. We have reproduced the nanostructures that moths have developed in their corneas and use these to nanotexture a few-layers of electronically de-coupled graphene. Our results are in agreement with those obtained by moths, where we observe strong absorption values across the mid-IR to the UV, up to 99%, which is remarkable for an absorber layer that is only 15nm thin.

HYPERUNIFORM DISORDERED SILICON PHOTONICS FOR NEXT GENERATION OF PHOTONIC INTEGRATED CIRCUITS

Milan M. Milosevic
Optoelectronics Research Centre, University of Southampton, Southampton, United Kingdom

Silicon photonics is a rapidly expanding field of research and development with an ever-increasing industrial uptake and a predicted market capitalisation approaching 2 Billion USD by 2023. A large majority of this market capitalisation is expected to be in the area of short reach interconnects for applications in information and data-communication sectors, as well as for sensing and healthcare.

In contrast to traditional bandgap materials such as photonic crystals that have been widely studied, a new class of aperiodic structures known as hyperuniform disordered solids (HUDS) has emerged. The distinct characteristics of HUDS is that they exhibit large, isotropic, and complete photonic bandgaps for all directions and polarisations. Despite the discovery of hyperuniformity being very recent, HUDS based devices are expected to enable a range of devices to be realised in high-index contrast material systems such as narrow waveguides with arbitrary curvature, splitters at arbitrary angles, polarisers, low power consumption silicon photonics modulators and novel active devices with increased fabrication tolerances. HUDS may open up an entirely new prospects for silicon photonics due to its promising characteristics for an increased device density per unit chip area, improved layout flexibility and temperature stability. However, it might also be suitable for a wide variety of applications, including optical sensing and environmental monitoring since many pollutant and toxic gases and liquids that we wish to detect or monitor exhibit bands of absorption lines in the infrared part of the spectrum. This paper reviews and discusses our recent results on HUDS based silicon photonic devices such as waveguides, resonant cavities and polarisers, and their suitability for optical integrated circuits. Results reveal a great potential of silicon-on-insulator HUDS photonic integrated circuits for usage in a host of applications at both near and mid-infrared wavelengths.

EXPERIMENTAL REALIZATION OF A 3D ISOTROPIC PHOTONIC BAND GAP IN THE MICROWAVE-REGIME

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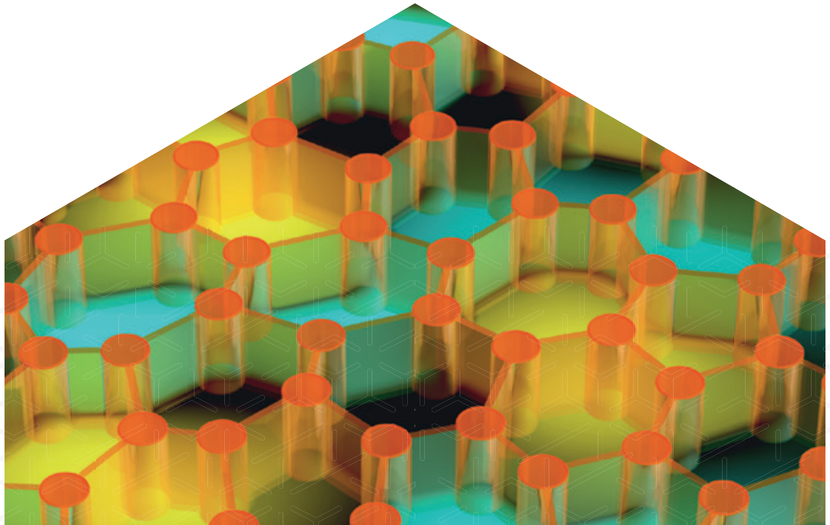
We compare microwave transmittance measurements of three different structures of 103 cm3 volume, manufactured with a 3D Laser sinter printer from a compound material consisting of 80% Al2O3-powder, 20% Polyamid12-powder and some carbon black. The refractive index of the compound is about n=2 in the microwave regime between 2-13GHz. The structures are a) a diamond structure, b) an amorphous structure constructed from 3D glass, and c) a hyperuniform structure designed for an isotropic photonic band gap (IPBG) by M. Florescu and P. Steinhardt.

The IPBG structure shows a band gap of about -30dB at 11.5 GHz. Due to scattering and absorption of the compound material, the transmittance stays below -10dB for frequencies above the gap-frequency. The amorphous reference sample drops below -15dB but does not show a gap, as expected and the diamond structure shows a gap of -20dB at 11.5 GHz. FDTD simulations for n=2 and without absorption revealed a much deeper gap for the diamond compared to the IPGB, thus the band gap or the IPBG structure seems to be more robust against absorption of the meta-material. This was confirmed by FDTD simulations including a finite adsorption.



POSTERS

LAMBERTIAN SCATTERING METASURFACES FOR PHOTOVOLTAICS

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We design reflective resonant metasurfaces that enable highly efficient wavefront shaping with arbitrary scattering pattern, based on the recently introduced metagrating concept. Using finite-sized arrays of suitably tailored optical antennas placed above a reflective ground plane, we create an omnidirectional Lambertian light scattering geometry that can find applications in colorful photovoltaics. Supercells of metagratings with close-to-unity efficiency can be combined in arrays to shape any desired wide-angle scattering pattern, creating a novel way to design light trapping geometries for photovoltaics.

We apply the metagrating concept to realize a Lambertian angular light scattering distribution. The surface is composed of supercells, each of which includes a small number of subcells formed by metagrating elements. In this configuration, each supercell is tuned to scatter light with a specific angular dependency and scattering efficiency. Together, the supercells form a metagrating that scatters an incident beam to a Lambertian scattering profile. Our initial Lambertian metasurface design is based on analytical antenna theory in which the far-field scattering pattern is calculated using magnetic dipoles as scattering elements. Experimentally, we implemented Si nanorods as resonant light scattering elements with a magnetic Mie resonance at λ=550nm, on top of a silver mirror with a glass spacing layer. The Lambertian behavior is measured optically in a well-defined spectral band, determined by the bandwidth of the Mie resonance, with an efficiency of more than 50%.

The resonant Lambertian metasurface design presented here enables the creation of artificial surfaces with a matt colored appearance. The new designs will enable many other applications where controlled beam steering in ultrathin optical devices is needed, specifically for light trapping in thin-film solar cells, and spectrum splitting in parallel and series-connected multi-junction architectures.

FROM ORDERED BRAGG REFLECTORS TOWARDS DISORDER AND HYPERUNIFORMITY IN 1D PHOTONIC CRYSTALS

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Most of the bright and vivid colours in nature originate from interference of light with nanostructured material. In many cases, the structure of the materials is not perfect and introducing disorder results in additional photonic reflects (strong reflection of one colour over a large angular range, metallic gleam, very bright colour). Our current research is focused on two questions: 1) How are the optical properties in influenced by disorder? 2) Can we replicate natural photonic structures with a controlled degree of disorder? We systematically investigated colour change of periodic 1D material with relation to (i) the numbers of layers, (ii) the various refractive index profiles and (iii) thickness in fabricated multilayers. We have deposited several layers of alternating porous materials, TiO_2 and SiO_2, respectively, each layer having different thickness and refractive index. We show that a reflector constructed of three repeating series of six layers, each having different refractive index and thickness, gives optical properties which are a result of disorder introduced into the reflectors structure. Although the disorder is not complete, small deviations in the reflector's structure have a large influence on its colour response. This signature is reminiscent of the optical response observed in living organisms whose structures are not perfectly aligned (e.g. in Morpho butteries). We started to investigate how hyperuniform distribution influences optical properties of periodic 1D material. Our preliminary simulations show interesting properties that we will discuss here.

THE CYPHOCHILUS BEETLE AS AN INSPIRATION FOR SUSTAINABLE WHITE MATERIALS

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Whiteness arises when light interacts with disordered media, where different wavelengths are scattered with comparable intensity. Such appearance is the result of light undergoing multiple scattering events before exiting the object, i.e. when the object is optically thick. The optical thickness of a material is determined by the ratio between its physical thickness and the transport mean free path, namely the distance that light travels before losing information about its starting propagation direction. Commonly, the transport mean free path in low-refractive index white materials is about tens of micrometres long. Therefore, opacity is achieved for relatively large thicknesses (in the millimetres range) to allow a high enough number of scattering events.

Nature provides an invaluable source of inspiration for the study and the manufacturing of thin opaque white materials. The Cyphochilus white beetle achieves a high total reflectance (≈ 75% over the whole visible range) with a few micron thick, lightweight, anisotropic network of chitin fibres (n_c≈1.55).

Herein, after quantifying the scattering efficiency of the chitin network via a coherent backscattering setup, we show an experimental approach to produce bio-inspired, sustainable white materials. In particular, we demonstrate that tuning the morphology of a network of polymer fibres strongly affects its optical properties: from transparent, to bright white materials. Notably, our bio-inspired materials achieve high scattering efficiency whilst being only a few micrometres thick (up to 75% reflectance while only 4 µm thick). Our study illustrates the potential of using biopolymers as building blocks to produce next-generation sustainable and biocompatible highly scattering materials. In addition, we show that it is possible to manipulate the light transport regime, moving from standard to anomalous diffusion, when a long-tailed distribution of the fibres size is introduced.

PHOTONIC INTEGRATED CIRCUIT AND HOLLOW CORE WAVEGUIDE APPLICATION STUDIES FOR HYPERUNIFORM DISORDERED STRUCTURES

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Hyperuniform disordered structures (HUDS) were designed, fabricated, and tested for engineering the flow of light in silicon-on-insulator and in hollow core waveguides.

Fabrication in the silicon-on-insulator materials system leveraged the fabrication tools and techniques developed in support of the silicon CMOS electronics industry: electron beam lithography, reactive ion etching, and optical lithography.

Hollow-core waveguides were 3d printed in plastic and tested at National Physical Laboratory.

COMBINING 1D AND 2D WAVEGUIDING PROPERTIES FOR ULTRATHIN TANDEM SOLAR CELLS

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As an effective way to surpass the Shockley-Queisser efficiency limit multijunction solar cells have been designed and developed for many years now. Silicon, in particular, is very appealing as the low bandgap material in a tandem design given its technological readiness. On the other hand, III-V materials are shown to be best at light and carrier management. The implementation of both material families together is possible for vertically standing III-V nanowires on Si thanks to their intrinsic strain relaxation properties. The nanowire array offers unique optical features that enable new PV designs and lower material consumption.

In this work, we study light-matter interactions in GaAs-based nanowire arrays on ultrathin silicon (1-2um) film with the dual goal of obtaining large absorption in the array and to improving light trapping in the bottom thin film cell. By performing FDTD simulations we show that the coupling of the incident light to the HE11 waveguiding mode of the wires results into absorption efficiencies above 100% per nanowire. Moreover, by optimizing the nanowire array parameters the transmitted light's momentum is shown to be manipulated to match the momentum of the waveguiding modes of the slab for the wavelengths close to the bandgap of silicon –where the absorption coefficient is very low-. Overall, by proper nanostructuring of GaAs and Si, less materials is used without compromising efficiency and reducing the cost, size and weight of the solar cell. By combining these 1D and 2D waveguiding properties we calculate a conversion efficiency for the um-thin Si-based tandem cell much larger than that for bulk without anti-reflection (AR) coatings and close to that with AR (33 vs 25 and 41%, respectively.)

HYPERUNIFORM DISORDERED STRUCTURES FOR ENHANCED LIGHT ABSORPTION IN THIN FILMS

Richard Spalding
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Hyperuniform disordered structures (HUDS) can be employed in the design of a solar cell as a means of enhancing light absorption in frequency window 400 – 1050nm; we investigate the physical mechanisms to which this enhancement is attributed. HUDS are found to exhibit medium/high broadband absorption, owing largely to their rich diffraction pattern and isotropy. The performances of these structures are compared against highly optimised photonic crystals. We find that homogenised structures provide an improved absorption efficiency. From the structures investigated, spinodal-like structures (density waves) achieve the best performance with an integrated absorption of 84% of light incident on a 1µm thick Si membrane; a result that surpasses the optimised periodic design by 5.2%. This study identifies the major mechanisms at play for absorption, diffraction within the Si membrane and coupling to the waveguide modes of the slab.

LASING ACTION IN HYPERUNIFORM DISORDERED STRUCTURES

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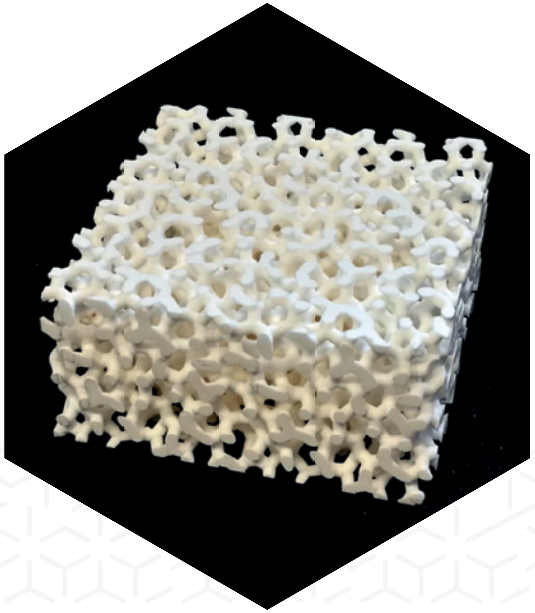
Lasing in hyperuniform disordered structures presents characteristics of both photonic-crystal lasers, such as a very low pumping threshold, band-edge emission and fast switching speeds, as well as of random lasers, such as isotropic light emission and unique emission spectrum defined by specific localised modes or by broader diffusive modes.

Here we present preliminary simulations of lasing action exploring different type of lasing mechanisms (band-edge, defect-mode and random lasing) that occur in hyperuniform structures. In contrast to photonic crystals, the photonic modes at band gap edge may become spatially localized, strongly affecting the lasing process. We focus our study on two types of samples characterized by low-index contrast and high-index contrast. We find that even in the low-refractive index contrast samples, collective interference induced by the positional uniformity in the structures enhances the confinement of light and provides sufficient optical feedback for lasing action. For samples with strong index of refraction contrast, the band edge modes tightly confined in the plane of hyperuniformity and the lasing occurs in the out of plane directions. The nature of the band edge modes is controlled by the structural uniformity of the structures and the optimal lasing frequency can then be tuned by the hyperuniformity order parameter.



HIGH-Q PHOTONIC CRYSTAL CAVITIES IN ALL-SEMICONDUCTOR PHOTONIC CRYSTAL HETEROSTRUCTURES

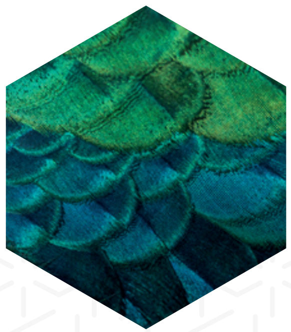
Cristopher Kemp
Advanced Technology Institute and
Department of Physics, University of Surrey, UK

Photonic crystal cavities enable the realization of high Q-factor and low mode-volume resonators, with typical architectures consisting of a thin suspended periodically patterned layer to maximize confinement of light by strong index guiding. We investigate a heterostructure-based approach comprising a high refractive index core and lower refractive index cladding layers. While confinement typically decreases with decreasing index contrast between the core and cladding layers, we show that, counterintuitively, due to the confinement provided by the photonic band structure in the cladding layers, it becomes possible to achieve Q factors >104 with only a small refractive index contrast. This opens up opportunities for implementing high-Q factor cavities in conventional semiconductor heterostructures, with direct applications to the design of electrically pumped nanocavity lasers using conventional fabrication approaches.

HYPERUNIFORM STRUCTURAL COLOUR

Sandro Mignuzzi
Imperial College London, UK

We present structural colours from nanostructure dielectric surfaces fabricated by direct laser writing. The colours originate from the interplay of single particle scattering and hyperuniform arrangements, as such they have azimuthal symmetry at difference with periodic patterns and show iridescence only in the polar angular direction.



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