SYMPOSIUM EP07

Tailored Disorder—Novel Materials for Advanced Optics and Photonics
November 26 - November 29, 2018

Symposium Organizers
Hui Cao, Yale University
Claudio Conti, University Sapienza
Sushil Mujumdar, Tata Institute of Fundamental Research
Cordt Zollfrank, Technische Universität München

* Invited Paper

SESSION EP07.01: Hyperuniformity
Session Chairs: Milivoj Belic and Cordt Zollfrank
Monday Afternoon, November 26, 2018
Hynes, Level 2, Room 205

1:30 PM *EP07.01.01
Tailored Disordered Hyperuniform Materials with Novel Properties Salvatore Torquato; Princeton Univ, Princeton, New Jersey, United States.

Hyperuniform states of matter include all perfect crystals, perfect quasicrystals, and some exotic disordered materials. Disordered hyperuniform materials can be regarded to be new states of amorphous matter in that they behave more like crystals or quasicrystals in the manner in which they suppress large-scale density fluctuations, and yet are also like liquids and glasses because they are statistically isotropic structures with no Bragg peaks. Thus, these special correlated disordered materials possess a "hidden order" that is not apparent on short length scales, which endows them with novel physical properties. I will describe procedures to design a variety of different disordered hyperuniform materials as well as their corresponding physical properties, including novel electromagnetic, photonic and transport characteristics.

2:00 PM EP07.01.02
A Black Forest of Silicon Nanowires—Striking Optical Properties Driven by Multiple Scattering of Light Barbara Fazio[1], Pietro Artoni[2], Cristiano D'Andrea[1], Stefano Pirotta[3], Maria Antonia Iatì[1], Maria José Lo Faro[2, 1], Salvatore Del Sorbo[3], Antonio A. Leonardi[4, 1], Giovanna Ruello[1], Rosalba Saija[5], Paolo Musumeci[4], Diederik Wiersma[6], Francesco Priolo[4], Matteo Galli[3] and Alessia Irrera[1]; [1]Istituto per i Processi Chimico Fisici, Consiglio Nazionale delle Ricerche, Messina, Italy; [2]IMM MATIS, Consiglio Nazionale delle Ricerche, Catania, Italy; [3]Dipartimento di Fisica, Università degli Studi di Pavia, Pavia, Italy; [4]Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, Catania, Italy; [5]Università di Messina, Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, Messina, Italy; [6]LENS, Università di Firenze, Firenze, Italy.

The optimization of novel textured nanomaterials, both ordered and disordered, plays a key role on the transport of the light towards striking optical performances based on light trapping and multiple scattering [1-2]. In this context, the production of a fractal arrangement of nanostructures represents the case of a material with a complex disorder and strong structural heterogeneities correlated at all length scales.Using Au layers at the percolation limit, that exhibit a fractal arrangement, as the catalyst of a metal-assisted wet etching process, a 2D random fractal array of vertically aligned silicon nanowires (NWs) has been obtained by means of an inexpensive, fast and maskless process compatible with Si technology [3,4]. We demonstrate as a morphological property such as *lacunarity*, defined as the measure of alternation of full and empty space, is the main actor in the light scattering phenomena for this material, since it is strongly related to the fluctuations of refractive index [5]. The occurrence of strong in plane multiple light scattering, resonant with the structure in a wide wavelength range, promotes a very high light-trapping efficiency across the entire visible and near infrared ranges. This strong scattering also leads to a greatly enhanced Raman signal, which is correlated at all length scales according to the spatial variations in refractive index. The forest of Si NWs so arranged, causing light to bounce around many times within the array, increases the likelihoodof light absorption.Since NWs obtained by this technique exhibit a room temperature PL [3,4], the direct consequence of the increased absorbance manifests in a very bright PL emission. Moreover, the random organization and the strong scattering performances allow for the observation of an unexpected and counterintuitive interference phenomenon in the inelastic scattering regime. We observe, in fact, thecoherent backscattering (CBS) effect, usually manifesting for elastically scattered radiation in random media, also for the generated Raman light [6]. The Raman CBS becomes, therefore, the first experimental signature in a macroscopic scale of the coherent nature of individual Raman scattering processes, typically occurring on the scale of the phonon coherence length and time. Our results are interpreted within a simple theoretical model of mixed Rayleigh-Raman random walks, for which reciprocity is assured by the symmetry of the Raman polarizability tensor and by the short dwell time of light inside the material, far below the phonon coherence time [6,7].
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[2] Brongersma, M.L., *et al*., *Nature Mater.*, Vol. 13, 451, 2014.
[3] Priolo, F. *et al*., *Nat. Nanotech.***9**, 19 (2014)
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[7] Skipetrov S.E. *Nat. Photon*. **11**, 144–146 (2017).

2:15 PM *EP07.01.03
Hyperuniform Disordered Photonic Networks—Band Gap Formation and Anderson Localization Frank Scheffold; University of Fribourg, 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 [1]. 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. Florescu et al. demonstrated that particular disordered materials can also display full photonic band gaps [2]. 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 [2]. Here we report on the fabrication and characterization of such photonic network structures in three dimensions and for optical wavelengths in the shortwave infrared [3]. 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 [4,5]. 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 [4].
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[2] M. Florescu, S. Torquato, P. J. Steinhardt, PNAS 106, 20658–20663 (2009); W. N. Man, et al. PNAS 110, 15886 (2013); S. F. Liew et al., Phys. Rev. A 84, 063818 (2011)
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[5] J. Haberko, L. S. Froufe-Pérez, and F. Scheffold, in preparation

2:45 PM BREAK

3:15 PM *EP07.01.04
Hyperuniformity and Local Self-Uniformity in Photonic Networks Marian Florescu[1, 2]; [1]Department of Physics, University of Surrey, Guildford, United Kingdom; [2]Advanced Technology Institute, University of Surrey, Guildford, United Kingdom.

The fundamental connection between geometrical and topological characteristics of structured photonic materials and advanced photonic functionalities is central to the design of novel photonic materials. Here, we introduce new metrics, hyperuniformity and local self-uniformity as measures of the structural order of photonic network structures. The hyperuniformity concept is built upon the properties of the structure in the reciprocal space, whereas local self-uniformity characterises the intimate connection between uniformity on local and global length scales. Hyperuniformity is associated with a constrained randomness such that density fluctuations on large scales behave more like those of ordered solids, crystals or quasicrystals, rather than those of conventional amorphous materials. On the other hand, local self-uniformity is a measure of a random network's internal structural similarity and can be used to rank networks on a continuous scale from crystalline, through glassy intermediate states, to chaotic configurations. Despite their distinct characteristics, both metrics provide novel design strategies for achieving advanced photonic functionalities in non-periodic materials.

We then explore the connection between the hyperuniformity and local self-uniformity and the photonic band gap formation and introduce a novel photonic-network architectures, the hyperuniform amorphous diamond network and the amorphous gyroid network or triamond. We demonstrate that all architectures displaying large photonic band gaps, be they periodic or disordered, are characterized by large values of the newly introduced disordered metrics. We then explore their distinct photonic properties: photonic band gaps, localisation and waveguiding, and photon transport. A comparison between their predicted properties and recent experimental results will also be provided. In the end, a series of applications of the new disordered photonic networks will be discussed including novel structuring for solar cell absorbers, wing-scale structuring in the butterfly Pseudolycaena marsyas and new designs for photonic integrated circuits and micro-opto-mechanical filters and modulators.

3:45 PM EP07.01.05
Optical Luneburg Lens with Hyperuniform Disordered Nanoparticles Yang Hao, Qiao Cheng and Haoyang Zhang; Queen Mary University of London, London, United Kingdom.

The design challenge of new functional composite materials consisting of multiphase materials has attracted an increasing interest in recent years [1-4]. In particular, understanding the role of distributions of ordered and disordered particles in a host media is scientifically and technologically important for designing novel materials and devices with superior spectral and angular properties. In this work, we propose to design optical Luneburg lens using hyperuniform disordered nano-composites. The desired electromagnetic properties are engineered by judiciously varying the volume fraction of the inclusion-to-host materials. Particularly, a different amount of low loss plasmonic nano-particles are applied in each layer in accordance with a generalised Maxwell-Garnett effective medium theory [1].

To accurately extract effective permittivity of a disordered composite material, a full-wave dipole-moment-based method [5], [6] is utilized for efficient numerical modelling of optical Luneburg lens. The point-dipole model coupled with the method of moments (MoM) allows us to model the proposed lens structure with up to 30,000 inclusions. Furthermore, we demonstrate that a Luneburg lens based on the proposed hyperuniform media has superior radiation properties in comparison with previously reported metamaterial designs and it may open up a new avenue in electromagnetic materials-by-design. Both measurement and simulation data will be presented at the conference.

References
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4:00 PM EP07.01.06
Fabrication of Nearly-Hyperuniform Substrates by Colloidal Structuring for Photonic Applications Peter M. Piechulla[1], Stefan Nanz[2], Alexander Sprafke[1], Aimi Abass[2], Carsten Rockstuhl[2] and Ralf B. Wehrspohn[1, 3]; [1]Martin Luther University Halle, Halle, Germany; [2]Institute for Theoretical Solid State Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany; [3]Fraunhofer Institute for Microstructure of Materials and Systems IMWS, Halle, Germany.

Textured scattering interfaces with a tailored optical response are a key ingredient to opto-electronic devices. In case of solar cells and large-area solid state lighting, costs and scalability are of utmost importance and forbid texturing techniques like conventional or e-beam lithography. Scalable techniques on the other hand, come with limited freedom of design: Random etching is specific for certain materials (e.g. silicon) and allows no control over periodicity, while other techniques (e.g. laser interference lithography) are only suitable for strictly periodic patterns. However, recent numerical works show that structures with a tailored degree of disorder outperform strictly periodic patterns due to their broadband response. In particular, so-called hyperuniform disordered structures have raised attention not only as a theoretical concept, but increasingly also on the application side.
Monodisperse colloidal particles tend to form well-ordered two-dimensional and three-dimensional structures and there are a number of both theoretical and experimental literature works on how this is exploited for use in opto-electronic devices. In contrast, the here presented structuring technique allows us to generate disordered structures. We obtain nearly-hyperuniform patterns of spherical nanoparticles deposited on an interface with controlled short-range correlations and low long-range density fluctuations. The interaction of particles and substrate is controlled by their respective surface charge: Negatively charged particles in a low solid content dispersion attach at random positions to a positively charged interface. Like-charge repulsion implies a characteristic separation and eventually limits the density of particles on the substrate. Consequently, the process is essentially self-limiting and leads to uniform structures. Varying the Debye screening length through ionic strength of the dispersion provides an effective lever to control the inter-particle spacing and thereby also the particle density.
The effects of particle size, polydispersity and ionic strength are included in a semi-phenomenological random sequential adsorption (RSA) model which enables the statistical prediction of the resulting particle patterns, adequately expressed by the structure factor S(q). Through S(q), the corresponding scattering response is tailored according to the requirements of a specific application, without the need of lengthy trial and error experiments. Angular resolved scattering measurements in comparison to the calculated response of predicted particle patterns will be presented. A future challenge remains in transferring such colloidal patterns to other materials to additionally tune the optical response of the individual scatterer (form factor).

4:15 PM EP07.01.07
Ewald Sphere Construction for Light Scattering in Disordered Media Lukas Maiwald[1], Slawa Lang[1], Dirk Jalas[1], Hagen Renner[1], Alexander Petrov[1, 2] and Manfred Eich[1, 3]; [1]Institute of Optical and Electronic Materials, Hamburg University of Technology, Hamburg, Germany; [2]ITMO University, St. Petersburg, Russian Federation; [3]Institute of Materials Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany.

We would like to present the Ewald sphere construction for the prediction of the scattering in disordered media with small refractive index contrast. The Ewald sphere construction is a geometrical tool that is based on the first-order approximation and often used in X-ray scattering. We review the first-order derivation, explain the geometrical construction and as an example show how the Ewald sphere construction can be used to explain structural color.
Non-iridescent (i.e. angle-independent) structural colors are widely found in nature, especially in the plumage of birds. Unlike regular pigment or dye-based colors, these colors are based on the selective scattering of light instead of selective absorption. The structures responsible for this scattering appear completely disordered but they exhibit a spherical shape in reciprocal space, indicating that they are actually short-range ordered.
We developed a model structure producing a spherical shell in reciprocal space. Using the Ewald sphere construction we were able to predict the scattering from a structured film. The results were checked by comparison to numerical simulations and show good agreement for light scattered in first order. The Ewald sphere construction also provides a vivid explanation for why there are many examples of structural colors in the short wavelength range while long-wavelength structural colors are barely found and have low color saturation. Finally, the results also indicate that the utilization of total internal reflection and thus frequency selective trapping of the scattered light can lead to a narrow reflection peak which may pave the way to long-wavelength structural colors.

Relevant Publications:
L. Maiwald et al., "*Ewald sphere construction for structural colors,*" Opt. Express **26**, 11352 (2018).
G. Shang et al., "*Photonic glass for high contrast structural color*," Sci. Rep. **8**, 7804 (2018).

4:30 PM EP07.01.08
Designing Nanophotonic Structures Using Deep Learning Sunae So[1] and Junsuk Rho[1, 2]; [1]Mechanical Engineering, Pohang University of Science and Technology, Pohang, Korea (the Republic of); [2]Chemical Engineering, Pohang University of Science and Technology, Pohang, Korea (the Republic of).

Designing structural components for desired properties has been a major challenge in the nanophotonics field. Recently, several data-driven design methods have provided novel systematic approaches[1-3], where deep neural networks are utilized to design metamaterials. However, all previous efforts have been limited to constraints where basic structures are predefined and the DNNs predict only structural parameters. Here, we report the first demonstration of designing metamaterials components that are not constrained to basic structure[4]. A deep neural network is used to learn the correlation between structural images and their corresponding reflection spectra. For given input reflection spectra, the network generates desirable designs in the form of images; this form allows suggestion of new structures that cannot be represented by structural parameters. Simulation results obtained from the generated designs agreed well with the input reflection spectrum. This method opens new avenues towards the development of nanophotonics by providing a fast and convenient approach to design complex nanophotonic structures that have desired optical properties.

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[4] S. So and J. Rho. Designing metamaterials using deep learning (in preparation).

4:45 PM EP07.01.09
Tuning Photonic Properties of Cellulose-Clay Nano Structures Ana C. Trindade[1], Susete Fernandes[2], Ville Liljestrom[1], Matthias Daab[3], Josef Breu[3], Maria H. Godinho[2] and Jon O. Fossum[1]; [1]Norwegian University of Science and Technology, Trondheim, Norway; [2]DCM and CENIMAT/I3N, FCT/UNL, Lisboa, Portugal; [3]University of Bayreuth, Bayreuth, Germany.

Solid films prepared from cellulose nano crystals (CNCs) present iridescence and selective reflection of left circularly polarized (LCP) light [1,2], while nano clay particles organize as lamellar structures in the solid state. It is well known that aqueous suspensions of sodium fluorohectorite (NaFh) clay biaxial platelets can form a nematic uniaxial liquid crystalline phase [3].
In this work we dissolved different quantities of cellulose nanorods in the clay nematic liquid crystalline suspensions (cellulose-NaFh nanocrystals (CNC/NaFh)) and we observed that the clay nematic structure undergoes a helical distortion by dissolving cellulose nanorods. Above a certain critical concentration the suspensions became iridescent with a left handed structure.
In order to preserve the photonic characteristics of the clay/nano rods suspensions solid films were prepared. We demonstrate that not only iridescent films can be produced but also their selective reflection of LCP light channel preserved.
The colors reflected by the films can vary from blue to red depending on the amount of CNCs added to the system.
This work demonstrates that the chirality-transfer, at the nano scale, induced by the CNCs on the clay nano platelets nematic phase translates into the photonic characteristics of solid films produced from aqueous CNCs/clay suspensions.
The precursor suspensions and the solid films were investigated by using different techniques as scanning electron microscopy (SEM), atomic force microscopy (AFM) and polarizing optical microscopy (POM).
This work opens new horizons to the design and control of nano-structured materials offering the possibility to produce material surfaces or coatings with engineered and targeted optical properties. Such structurally colored materials represent a viable alternative to toxic chemical pigment colorants: the optical response is independent of the chemical composition of the medium and can be tailored by controlling its interaction with light on the nano-scale.

SESSION EP07.02: Biological and Bioinspired Disordered Materials
Session Chairs: Francesco Riboli and Cordt Zollfrank
Tuesday Morning, November 27, 2018
Hynes, Level 2, Room 205

8:00 AM EP07.02.01
Bio-Inspired Highly Scattering Networks via Polymer Phase Separation Julia Syurik[1], Gianni Jacucci[2], Olimpia D. Onelli[2], Hendrik Hoelscher[1] and Silvia Vignolini[2]; [1]Karlsruhe Institute of Technology, Eggenstein Leopoldshafen, Germany; [2]University of Cambridge, Cambridge, United Kingdom.

Structural colors in nature are often the result of evolutionary-optimized complex nanoscale architectures. A well-known example of multiple scattering optimizations in a low refractive index medium is observed in the scales of *Cyphochilus* beetles. Here, the anisotropic chitin network inside the scales, which cover the insect's body out-performs practically all man-made low refractive index materials. The key to this optimization lies in the tuning of the filling fraction and in the anisotropic nature of the fibrillar structure in the scales.

Inspired by these natural design principles, we fabricated highly scattering white networks solely constituted by polymethylmethacrylate (PMMA). The resulting porous films are flexible and show the shortest transport mean free path reported in the literature for low refractive index materials [1]. We demonstrated that the scattering strength of the network can be enhanced by varying the molecular weight of PMMA to achieve transport mean free paths (l_t) as low as 1 μm for an incident wavelength around 500 nm. Having such a short transport mean free path yields a reflectance of 75% for a 4 μm thick film. Due to their low refractive index (close to 1.5 over the whole visible range) and porosity, the produced free-standing films can be easily index-matched with water and other conventional solvents, providing a tunable response, which transitions from white to transparent upon wetting. This property, in addition with the high flexibility of the films, allows for various coating applications. We demonstrate that the scattering properties are maintained when the porous films are grinded into powders, opening their exploitation as white enhancers in paints, paper, and cosmetics.

[1] J. Syurik, G. Jacucci, O. D. Onelli, H. Hölscher, S. Vignolini, *Adv. Funct. Mater*., 1706901 (2018)

8:15 AM EP07.02.02
A Bio-Based Photoresist for Direct Laser Writing of Disordered Architectures Maximilian Rothammer[1], Marie-Christin Angermann[2], Georg von Freymann[2] and Cordt Zollfrank[1]; [1]Chair for Biogenic Polymers, Technische Universität München, Straubing, Germany; [2]TU Kaiserslautern, Kaiserslautern, Germany.

The polysaccharide cellulose is next to chitin the most abundant biopolymer on earth and is considered an almost inexhaustible source of raw material for the increasing demand for environmentally friendly and biocompatible products.[1] The presented research includes the functionalization of cellulose enabling photo-crosslinking to generate biopolymer-based hierarchical architectures. This chemical modification is a prerequisite for the fabrication of two- and three-dimensional structures by direct laser writing (DLW). In combination with the inherent self-assembly capability of certain cellulose derivatives, there is the opportunity to introduce tailored disordered substructures through infiltration of the DLW-written framework and thus fabricate hierarchical architectures entirely from polysaccharides. Additionally, disorder on the nano-scale is created by the surface roughness of the DLW-written structures, which is caused by curling of the uncrosslinked ends of the cellulose chains in the resist. In contrast to common lithography, which uses photoresists based on polymers sourced from mineral oil, our approach conserves resources through replacing those polymers by sustainable materials such as polysaccharides. Polysaccharide-based photoresists have not been presented so far. We synthesized a bio-based photoresist, where a photo-reactive cellulose-derivative is dissolved in acetone together with a photoinitiator. This novel photoresist is curable by two-photon absorption (780 nm) in a DLW system (Nanoscribe Photonic Professional GT). With this setup, two-dimensional architectures with a linewidth of less than 500 nm and a feature size of 750 nm are achieved. Our bio-based photoresist allows three-dimensional structuring of cellulose on the μm scale via DLW. Curing of our cellulose derivative is generally possible in liquid and solid state via two-photon absorption.[2] This expands the operational areas of this photoresist, because writing in solid resist allows for more complicated structures, which have to be written in several disconnected sections. Additionally, this cellulosic photoresist is curable via one-photon absorption with a UV-lamp (365 nm) in liquid as well as in dried state. Our resist opens up a new class of photo-curable polymers based on sustainable and renewable materials.

References
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[2] M. Rothammer, et al., 2018 (submitted)

8:30 AM EP07.02.03
Direct Laser Writing of Iteratively-Designed Biomimetic Photonic Structures Exhibiting Tailored Disorder Bianca C. Datta, Sunny K. Jolly and V. Michael Bove; Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Structural color phenomena exhibited by several organisms result from interference and diffraction of light incident upon multilayer nanostructures. The wings of the Morpho butterfly are a well-studied example of a biological system exhibiting structural coloration and a high degree of wide-angle iridescence due to a non-negligible degree of disorder in the photonic nanostructure. Recent work has demonstrated the fabrication of artificial, Morpho-inspired nanostructures that exhibit structural coloration effects via a variety of fabrication techniques; however, prior work has largely neglected the role of tailored disorder in generating iridescence in such bioinspired nanostructures.

Such complex biological systems require advanced fabrication techniques, and replication of nanoscale features of this complexity has been difficult. Existing methods include multi-step deposition, etching, and assembly processes. In comparison to existing fabrication methods for Morpho-inspired structures, such as interference lithography, colloidal self-assembly, sputtering, atomic layer deposition, or electron beam lithography, direct laser writing methods allow for flexible, three-dimensional, volumetric feature patterning on multiple length scales.

Here we present a comprehensive method for iterative inverse design of a biomimetic Morpho-inspired photonic structure exhibiting tailored disorder and a fabrication methodology based around direct femtosecond laser writing. Our design framework explicitly accounts for the important role of disorder in generating the iridescent effects seen in biological examples of structural coloration.

We evaluate optical properties such as spectral response, interference, diffraction, and reflectance of photonic structures fabricated using direct laser writing techniques such as two photon polymerization. We compare our model system and simulations to fabricated structures using optical microscopy, scanning electron microscopy, and angular spectrometry. This process provides a toolkit with which to examine and build other bio-inspired, tunable, and responsive photonic systems and expand the range of achievable structural colors.

The use of femtosecond laser direct writing allows for the rapid prototyping of complex, hierarchical micro- and nano-structures. When combined with the design and optimization process presented here, this method allows for the use of the Morpho structure as a baseline for iteration, both to incorporate tailored disorder, and to produce structures with extended functionality beyond existing systems. In doing so, we present a versatile approach to bio-inspired materials design and and provide a platform with applications ranging from light harvesting and steering, to chemical sensing, high performance displays, responsive products and architecture.

8:45 AM EP07.02.04
Bio-Inspired, Large Scale, Highly-Scattering Films for Nanoparticle-Alternative White Surfaces Julia Syurik[1], Radwanul Hasan Siddique[2, 1], Antje Dollmann[1], Marc Schneider[1], Siegbert Johnsen[1], Matthias Worgull[1], Gabriele Wiegand[1] and Hendrik Hoelscher[1]; [1]Karlsruhe Institute of Technology, Eggenstein Leopoldshafen, Germany; [2]California Institute of Technology, Pasadena, California, United States.

White is the most popular color for today's industrial products. Being the essential color for interiors, white pigments are widely found in plastics, inks, paints, cosmetics, and even food. In many of these products, their whiteness is achieved by incorporating titanium dioxide (TiO_2) particles, which, due to their high refractive index, effectively scatter incoming visible light. However, fabricating white polymeric films and bulk parts with TiO_2particles causes some issues ranging from possible environmental harm to suspected health issues. Consequently, particle-free alternatives are of particular interest.

Here, we present an approach to whiten thin polymer foils via saturation by supercritical carbon dioxide ($SC\text{-}CO_2$), which is an industrial process suitable for large-scale fabrication. We tailored the parameters for the fabrication of thin and white nano-foams made from PMMA because it is a common, often used polymer. The process parameters effectively control size, shape and wall thickness of the pores, which act as scattering elements. Although the refractive index of PMMA ($n = 1.49$) is comparable low the films are perfectly white even for thin film thicknesses in the µm-range [1]. In order to demonstrate the process-ability of our porous white films, we fabricated ultra-white micro-channels from them.

[1] J. Syurik, R. H. Siddique, A. Dollmann, G. Gomard, M. Schneider, M. Worgull, G. Wiegand, H. Hölscher, *Scientific Reports* **7,**46637 (2017)

9:00 AM *EP07.02.05
Brilliant Coloration from Tailored Photonic Disorder in Weevil Scales Michael H. Bartl[1, 2]; [1]Department of Chemistry, University of Utah, Salt Lake City, Utah, United States; [2]Center for Energy Efficient Electronics Science, University of California, Berkeley, Berkeley, California, United States.

The world of insects displays myriad hues of colors produced by elaborate nanoscale architectures built into wings and exoskeletons. Many of these architectures display intricate hierarchical organization with varying degrees of ordering. For example, using a combination of optical and electron microscopy tools, photonic band structure calculations, and color mixing analysis, we recently discovered that the origin of the brilliant near angle-independent coloration of the weevil *Eupholus chevrolati* stems from tailored disorder involving multi-level photonic interactions: from diamond-based photonic crystal domains to seemingly random arrays of colored micro-pixels. This pointillist color-mixing scheme is responsible for a bright and multi-hued appearance, without the metallic sheen typical of photonic crystal colors found in many other beetles.

9:30 AM EP07.02.06
Disordered Tumor Spheroid Deep Optical Neural Network Davide Pierangeli[2], Valentina Palmieri[1], Giulia Marcucci[2], Giordano Perini[1], Marco De Spirito[1], Massimiliano Papi[1] and Claudio Conti[2]; [1]Physics, Catholic University of SH, Rome, Italy; [2]Physics, Sapienza University, Rome, Italy.

Light can propagate inside random media by iterative optimization of the input electromagnetic field. This training and scattering is a form of photonic machine learning, which we apply here to the special case of tumor cells. Specifically, we consider glioblastoma tumor spheroids that appear as an assembly of multiple scattering cells for a light beam. We show that by embedding these samples in an optical setup and using a feedback, the tumor cells can act as a computing reservoir and realize different optical transformation on the input light beam. The tumor cells act indeed as a multi-layered neural network that, with time, grows and gives additional deep computational layers to perform accurate and sophisticated functions. Once trained, this unconventional hybrid combination of living matter and photonic hardware returns information on its growth dynamics. For this random optical machine, we have grown glioblastoma cells in 3D spheroid architectures that represent modern model platforms for studying complex cell-to-cell interactions, anticancer therapeutics uptake and diffusion in tumor bulk. We tracked glioblastoma spheroids spontaneous evolution and their subcellular transformations stimulated by hyperthermia or chemotherapies. We demonstrated that brain tumor cells can be trained to track cancer evolution and subcellular transformation induced by external stimuli. We demonstrate that a higher resolution is obtained with this deep optical neural network compared to confocal microscopy and standard optical imaging. This hybrid photonic/living system is a novel artificial disordered photonic computing machine for real-time study and unprecedented measurements of tumor dynamics.

9:45 AM BREAK

SESSION EP07.03: Biological and Bioinspired Disorder
Session Chairs: Francesco Riboli and Cordt Zollfrank
Tuesday Morning, November 27, 2018
Hynes, Level 2, Room 205

10:15 AM *EP07.03.01
Interplay of Order and Disorder in Biological Photonic Materials Ullrich Steiner; Adolphe Merkle Institute, Fribourg, Switzerland.

The generation of well defined band-gaps requires perfectly ordered transparent material, which is technologically demanding. Biological organisms, animals and plants, are however able to generate striking optical effects, with a much lower degree of order that, seemingly, should be highly detrimental to realise the colour brilliance arising from well ordered structures. On the other hand, optimised disorder is required for the multiple scattering of light that produces white, requiring a different type of structural control.

The first part of my presentation will focus on the interplay of order and disorder of grating-like topographical features found on many flower petals, the optical effects they generate and their role in insect recognition. The second part discusses biological strategies to generate whiteness employing a minimal amount of material, which is particularly important for flying insects.

10:45 AM EP07.03.02
The Cyphochilus Beetle as an Inspiration for Sustainable White Materials Gianni Jacucci[1], Olimpia D. Onelli[1], Julia Syurik[3], Matti Toivonen[2], Hendrik Hoelscher[3], Olli Ikkala[2] and Silvia Vignolini[1]; [1]University of Cambridge, Cambridge, United Kingdom; [2]Aalto University School of Science, Espoo, Finland; [3]Karlsruhe Institute of Technology–Institute for Applied Materials, Karlsruhe, Germany.

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. [1]

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).[2,3,4]

Herein, after quantifying the scattering efficiency of the chitin network *via* a coherent backscattering setup, [5]we show an experimental approach to produce bio-inspired, sustainable white materials. [6,7] 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. [6,7]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. [7]

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11:00 AM EP07.03.03
Structural Adaptations for UV-Protection in the Setae of the Desert Ant *Cataglyphis bombycina* Bertram Schwind[2], Xia Wu[2] and Helge O. Fabritius[1]; [1]Microstructure Physics and Alloy Design, Max-Planck-Institut für Eisenforschung GmbH, Düsseldorf, Germany; [2]Department of Chemistry, Paderborn University, Paderborn, Germany.

All living organisms exposed to sunlight have to face the potentially negative effects from the UV parts of the solar radiation spectrum. This is particularly true for desert organisms such as the ant *Cataglyphis bombycina* that forages during mid-day when temperature and insolation are highest to avoid predation [1]. These animals are covered with a dense layer of hair-like setae with triangular cross-sections that function as photonic structures. The geometry of the setae enables both shielding the body from sunlight by total internal reflection of visible light [2, 3] and radiative cooling in MIR [2]. The upper sides of the setae are covered with micro-ribs that were suggested to function as an antireflection coating to enhance the total internal reflection [2]. The dimensions and geometry of these micro-ribs suggest that they may also help *C. bombycina* to protect itself from harmful UV radiation. We simulated the hemispherical reflection of seta models with structural parameters derived from a thorough structural characterization in the UV and VIS ranges. The results show that the influence of micro-ribs on scattering of visible light is negligible. In the UV range, however, setae with micro-ribs scatter more UV light away from the ant than setae without micro-ribs in an angular range that coincides with the incidence angle of sunlight during the foraging hours of the ants, when the UV radiation is particularly strong. Therefore, we assume that the main optical function of the micro-ribs is to reduce the harmful UV radiation dose below a critical level for the animals. Comparison with the surface structures of other desert organisms such as cacti reveal the presence of similar micro-ribs, indicating that such surface patterns may be a global evolutionary strategy to cope with high UV-exposure.
Mimicking these surface patterns on synthetic materials and structures provides the opportunity to endow them with structural UV protection.

11:15 AM EP07.03.04
A Simple Model Mimicking the White Beetles Dominic Meiers[1], Marie-Christin Angermann[1] and Georg von Freymann[1, 2]; [1]Physics Department and State Research Center OPTIMAS, Technische Universität Kaiserslautern, Kaiserslautern, Germany; [2]Fraunhofer Institute for Industrial Mathematics

ITWM, Kaiserslautern, Germany.

We develop a model of the white beetle scales' structure, which reproduces the optical properties in the visible spectral range. The model is composed of small Bragg reflectors with tailored disorder in layer thickness and filling fraction.

The *Lepitiota Stigma* and *Cyphochilus* beetles show a brilliant whiteness achieved by light scattering within the inner disordered chitin network of their scales. Although the scales are only about 5 µm to 15 µm thin, they belong to the strongest scattering biological materials [1,2]. Wilts et al. performed finite-difference time-domain (FDTD) simulations with an exact model of the scales obtained by computer tomography measurements showing that the scales are evolutionary optimized for light scattering in biological tissue [3]. Former studies revealed the structural details and the transport properties of the scales [2], but a model of the underlying functional principle has been elusive to date. We present such a model exhibiting and explaining all optical properties of the scales' structure.
All previous studies show a layer-like structure in the normal propagation direction of light. Thus, we start with a distributed Bragg reflector (DBR). As thickness of the chitin layer we choose the mean value of the strut diameter distribution of the scales' inner network provided by [3]. The thickness of the air layer is chosen accordingly. In the next step we introduce disorder by varying the thickness of the chitin layers according to the strut diameter distribution. To achieve a similar filling fraction like the scales, we randomly leave out one-third of the chitin layers. Comparison with the cross section of the scales shown in [3] reveals that the scales' structure cannot be modeled with a single disordered DBR but with a composition of many different small disordered DBRs. FDTD simulations performed with this model and the white beetle model exhibit quantitative agreement for the reflectance in the visible spectral range. Furthermore, calculations of the coloration of the far-field and of the time-of-flight yield similar results for both structures.
We show a simple model based on a composition of DBRs with tailored disorder which mimics the optical behavior of the white beetle scales. The model shows that constructive interference and multiple scattering between the DBRs causes the angle independent brilliant whiteness. Our model allows for tuning the optical properties and is producible layer-by-layer.
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11:30 AM EP07.03.05
Broadband Light Management by the Setae Covering the Saharan Silver Ant *Cataglyphis Bombycina* Bertram Schwind[1], Helge O. Fabritius[2] and Xia Wu[1]; [1]Universität Paderborn, Paderborn, Germany; [2]Max-Planck-Institut für Eisenforschung GmbH, Düsseldorf, Germany.

The geometry of the photonic structures formed by the scales or the layered exoskeleton of insects are adapted to the ecophysiological strains acting on the animals. One example for such adaptations are the setae of the desert ant *Cataglyphis bombycina,* which forages under extreme insolation and at very high temperatures during mid-day [1]. These setae have an elaborately shaped triangular cross section to shield the ant from sunlight by a combination of Mie scattering and total internal reflection of visible light [2, 3]. The layers formed by the setae increase the emissivity of the ant, which enhances the radiative cooling in MIR [2].
We are interested in the optical impact of the structural details of these setae on the cooling performance of the ant. We characterized the optical properties of the setae of *C. bombycina* over a broad spectral range from visible to MIR both experimentally and theoretically. Our data suggest that structural parameters such as the general size and the presence of a central canal are evolutionary adaptations to obtain an ideal compromise between the ability to scatter the solar radiation in the visible to NIR range and not to interfere with the body radiation in the MIR range.
The design rules we revealed have the potential to guide the creation of synthetic polymer fibres or surface microstructures which are able to mimic the silver ant's light management over a broad spectral range and can be scaled to dimensions suitable for adequate synthesis routes.
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11:45 AM EP07.03.06
Graphene Oxide Laser Patterning Controls Bone Tissue Regeneration Valentina Palmieri[1], Marta Barba[1], Lorena Di Pietro[1], Silvia Gentilini[2], Giordano Perini[1], Rosanna Larciprete[2], Wanda Lattanzi[1], Marco De Spirito[1], Claudio Conti[2] and Massimiliano Papi[1]; [1]Catholic University of SH, Rome, Italy; [2]ISC-CNR, Rome , Italy.

Graphene oxide (GO) and its reduced form (rGO) are capable of inducing mesenchymal stem cells differentiation and promote bone tissue formation with efficacy depending on reductive state of the material. Thus, modulation of the osteogenic process and of bone mineral density distribution is theoretically possible by controlling the GO oxidative state. In this study, we laser-printed GO surfaces to obtain both a local photo-thermal GO reduction and the formation of nano-wrinkles along precise patterns. In the first days of culture, cells migrated and accumulated on the reduced and wrinkled surface. When the local density of the stem cells on the reduced stripes was high, cells started to proliferate and occupy the also the GO. The designed surfaces morphology guided stem cell orientation and the reduction accelerated differentiation. This strategy can become a revolution in present and future trends of scaffolds design for regenerative medicine.

SESSION EP07.04: Mesoscopic Systems
Session Chairs: Michael Bartl and Martin Wegener
Tuesday Afternoon, November 27, 2018
Hynes, Level 2, Room 205

1:30 PM EP07.04.01
The Percolation Threshold Marks the Maximum Amount of Disorder Cefe Lopez; Consejo Superior de Investigaciones Científicas, Madrid, Spain.

Sparse defects in crystals can be assumed isolated and are well understood. Disordered scatterers forming photonic glasses,[1] present other kinds of features but are also fairly well understood. However, in the region where defects are neither few nor isolated, band theory or single scattering approaches offer little help.
By preparing photonic crystals with random missing scatterers we create crystals where disorder is embodied by vacancies in an otherwise perfect

lattice.[2] This is at variance with the usual positional or size disorder. We show that the amount of defects determines not only the intensity but also the nature of the light scattering. As the amount of defects varies, light scattering undergoes a transition whereby the usual signatures of photonic gaps (Bragg peak), appearing for very small amounts of defects, suffer line-shape changes (Bragg peak becoming a dip) that can be readily described in terms of Fano-like resonances. When the amount of vacancies reaches a value compatible with the site percolation threshold (20% for an fcc lattice) the Fano parameter *q* undergoes a sign change signalling the transition from a crystal to a mosaic of microcrystals through a state where scattering is maximum. Beyond that point, the system re-enters a state of low scattering revealed by a normal Bragg diffraction.
This highly controlled transition is a true example of disorder tailoring capable to tune the degree of disorder introduced and, in particular, to maximize its effect to the point of creating a minimum in reflectance where a maximum occurs for full order.

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1:45 PM EP07.04.02
Mesoscopic Behavior of Light Waves in Two-Dimensional Disordered Photonic Systems Francesco Riboli[1, 2] and Diederik Wiersma[2, 3]; [1]INO-CNR, Sesto Fiorentino, Italy; [2]LENS, Sesto Fiorentino, Italy; [3]INRIM, Torino, Italy.

The ability of disordered systems to diffuse and localize light waves depends on the dimensionality of the system and the "strength" of its structural disorder. While on one hand the possibility of light localization in three-dimensional systems is still an open and lively debated question, localized states have been already observed and well characterized for systems with lower dimensionalities. Two-dimensional disordered systems thus represent the perfect playground for testing theoretical models and investigate novel transport regimes and, more in general, mesoscopic effects of light waves that possibly go beyond the standard picture cast by the diffusion theory.
In this talk I will discuss some key aspects of the mesoscopic physics of light waves in two-dimensional disordered photonic systems. The local density of optical states (LDOS) is characterized by isolated resonances with finite spectral width and finite spatial extent [1]. The spectral features and the spatial profiles of the localized LDOS resonances can be tuned by changing the average strength of structural disorder, such as the density and size of the scattering centers or the structural correlation length of the disorder. Rarely we observe peculiar LDOS resonances resulting from the coherent mutual coupling between localized LDOS resonances whose coupling strength can be selectively modulated by locally engineering the structural disorder [2]. Finally, a statistical study of LDOS spectra is performed by means of correlation spectroscopy techniques and compared to the self-consistent theory of localization. We observe the expected universal renormalization of the Boltzmann diffusion coefficient D/D_B, but also non-universal contributions that are sensitive to subwavelength features of the material [3]. Potential applications of these class of systems in the field of renewable energies are discussed [4].

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2:00 PM *EP07.04.03
Light Trapping and Super Diffusion in Levy Glasses Francesco Utel[1, 2, 3], Lorenzo Pattelli[1, 2, 3], Diederik Wiersma[1, 2, 3] and Kevin Vynck[4]; [1]European Laboratory for Non-linear Spectroscopy, Turin, Italy; [2]Department of Physics, University of Florence, Turin, Italy; [3]National Metrology Laboratory INRIM, Turin, Italy; [4]Institut d'Optique, Université Bordeaux, Bordeaux, France.

For wave transport in disordered systems it is known that the dimensionality of the structure plays a crucial role. In particular, for dimensions equal to two or smaller, interference will give rise to localised modes for large enough system size.

In this contribution we show that this situation is actually only correct for the limiting case of homogeneous (Gaussian) disorder. We will discuss the general case of light transport in Levy glasses, which are materials in which a large inhomogeneity of the structure leads to super diffusion.

While one would expect super diffusion to counter balance localisation, we find the counter-intuive result of strong localisation in coexistence with extended modes.

2:30 PM EP07.04.04
Invariance of the Mean Path Length in Light-Scattering Media Romolo Savo[1], Romain Pierrat[2], Ulysse Najar[1], Rémi Carminati[2], Stefan Rotter[3] and Sylvain Gigan[1]; [1]Laboratoire Kastler Brossel, ENS-PSL Research University, CNRS, UPMC-Sorbonne Universités, Collège de France, Paris, France; [2]ESPCI Paris, PSL Research University, CNRS, Institut Langevin, Paris, France; [3]Institute for Theoretical Physics, Vienna University of Technology (TU Wien), Vienna, Austria.

Optical materials engineering lies on the assumption that the structure of a medium is inherently linked to its functional behavior. This is particularly true for light scattering properties, which depend very sensitively on whether a medium is homogeneous, structured or disordered. As opposite to this paradigm, a recent theoretical study pointed out that a very fundamental property of wave transport is extremely robust to the structure of the underlying medium [1]. This result was derived by generalizing an invariance property first found for random walks [2] to arbitrary wave scattering scenarios [2], such as for light in a disordered material. Specifically, it has been shown that, when all modes in a medium are equally excited, the mean path length $\langle s \rangle$ associated with wave scattering through a medium only depends on the mediums boundary geometry, but not on its internal micro-structure. Apart from limitation due to finite absoption the mean path length is found to be $\langle s \rangle = v_E \langle t \rangle = 4V/S$ for a three-dimensional geometry of volume V and surface S , where v_E is the energy velocity [1].
Here [3], we experimentally consider the case of a fully disordered medium, in which the crossover between systems with different degrees of disorder can be described by the transport mean free path l*. Applying the predicted invariance to this case would mean that any change of l* should leave the mean path length invariant. We investigate multiple scattering of light in colloidal suspensions of particles in water and tune the mean free path by varying the concentration and size of the particles. We develop a reverse version of diffusing-wave spectroscopy to measure the mean length of light trajectories through the temporal decorrelation of the optical speckle pattern. We unambiguously observe the invariance of the optical mean path length over almost two orders of magnitude of scattering strength - from a nearly transparent to a very opaque system.
The observed invariance sets rigid bounds for the optical path length enhancement in multiple scattering media and provides insights for the optimal design of light trapping and light storage devices. It crucially relies on the validity of the Equipartition Theorem and thus provides a stringent test of this fundamental principle in scattering media. We also emphasize that our results are not restricted to light propagation, but apply basically to all wave scattering problems.

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2:45 PM BREAK

3:15 PM EP07.04.05
Engineering Isotropic Light Scattering for Light Emission Control Sean Gorsky[1], Kidanemariam Kebede[1] and Luca Dal Negro[1, 2]; [1]Electrical and Computer Engineering, Boston University, Boston, Massachusetts, United States; [2]Materials Science and Engineering, Boston University, Boston, Massachusetts, United States.

Light extraction from high-index materials is an ongoing issue in modern LED technologies. Specifically, total internal reflection (TIR) significantly limits the amount of light that can be extracted from the high-index medium into free space. Photonic crystals coupled to emitting optical materials have been shown to enhance light extraction and control directionality by scattering TIR light into free space. In particular, the use of aperiodic and isotropic, disordered patterns such as the Golden Angle (GA) Vogel spiral has been shown to be particularly advantageous compared to traditional photonic crystals such as the hexagonal lattice as it enables the extraction of a wider domain of TIR waves across a broader angular range. However, in the case of the GA Vogel spiral, isotropic diffraction comes at the cost of weaker scattering strength which diminishes the overall light extraction capability. In order to solve this problem we introduce in this talk a new disordered, isotropic point pattern which features enhanced short range order, and therefore enhanced scattering when compared to the GA Vogel spiral. In particular, we demonstrate that the first radial correlation peak of this engineered structure is 2X that of the GA Vogel spiral, while maintaining an overall isotropic character . The new pattern is created using the collective coordinate control method which allows for direct engineering of the pattern’s structure factor. We pattern transparent substrates with reflective nano-pillars arranged in these new patterns and experimentally measure the structure factor by illuminating with a 405 nm laser and measuring the optical Fourier transform on a CCD camera. The surfaces were patterned using magnetron co-sputtering, electron beam lithography (EBL) and reactive ion etching (RIE) techniques. A variety of the patterns were fabricated with varying nano-pillar diameter and mean particle separations. Finally, we use a model based on the kinematic scattering to assess their potential as transparent surface patterns to increase light extraction of incoherent radiation and enhance directional emission from active, high-index materials.

3:30 PM EP07.04.06
Reflectivity of Finite 3D GaAs Photonic Band Gap Crystals Willem Vos[1], Takeyoshi Tajiri[2], Shun Takahashi[3], Cornelis A. Harteveld[1], Diana A. Grishina[1, 4], Satoshi Iwamoto[2] and Yasuhiko Arakawa[5]; [1]Complex Photonic Systems (COPS), University of Twente, Enschede, Netherlands; [2]Institute of Industrial Science, The University of Tokyo, Tokyo, Japan; [3]Kyoto Institute of Technology, Kyoto, Japan; [4]Thermo Fisher Scientific, Eindhoven, Netherlands; [5]Institute for Nano Quantum Information Electronics, The University of Tokyo, Tokyo, Japan.

While the large majority of theoretical studies of photonic crystals pertain to infinite and perfect structures [1], any experimental study or practical device obviously concerns finite nanostructures with unavoidable deviations from perfect periodicity [2]. The quintessential property of any photonic crystal - regardless of dimensionality and the presence or not of a 3D photonic band gap - is of course the appearance of a stop gap in the dispersion relations for wave propagation in the direction perpendicular to the spatial periodicity [1]. Such a gap corresponds in real and finite structures to a stop band that is observed as a peak in reflectivity experiments. A seminal study reported the evolution of the width of stop band with crystal thickness [3]. It was found that the width of the stop gap scales inversely with the thickness, as later confirmed elsewhere [4]. However, it is still unknown how finite-size effects affect the width of stop gaps in photonic crystals that interact so strongly with light that they reveal a 3D complete photonic band gap.

Therefore, we experimentally study reflectivity of 3D GaAs woodpile crystals with different number of layers N, made by advanced micro manipulation [5]. Plates with 2D arrays of parallel rods (445 nm period) of 134 nm width and 150 nm thickness are stacked one-by-one to form the 3D nanostructures. The rods are crossed between neighboring layers, and parallel and shifted by half a period in the secondary neighboring ones. The crystal thickness ranges from N=2 to N=8 layers. Optical spectra are measured with a tailor-made broadband micro-reflectivity setup with reflecting optics [6], and are interpreted with numerical results from FDTD simulations.

We observe that from N=2 to N=8 layers (4-fold increased thickness) the band width decreases only slightly from 4500 to 3500 1/cm (a 1.3-fold decrease). This behavior differs strongly from Bragg-like proportional one that is typical of weakly interacting photonic crystals [2,3].
We surmise that since the probed stop gap is part of complete 3D photonic band gap, the confinement is truly 3D. The confinement is then not only affected by the "thin" dimension perpendicular to the crystal slab, but also by stop gaps within the plane of the crystal structure where the crystal extent is much greater than the thickness.

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SESSION EP07.05: Nonlinearity I
Session Chairs: Claudio Conti and Willem Vos
Tuesday Afternoon, November 27, 2018
Hynes, Level 2, Room 205

3:45 PM *EP07.05.01

Managing Light in Media with Spatially Randomized Quadratic Nonlinearity Yan Sheng[2], Krzysztof Switkowski[1, 4], Jose Trull[3], Crina Cojocaru[3] and Wieslaw Krolikowski[1, 2]; [1]Texas A&M University at Qatar, Doha, Qatar; [2]Laser Physics Centre, The Australian National University, Canberra, Australian Capital Territory, Australia; [3] Physics Department, Universitat Politècnica de Catalunya, Terrassa, Spain; [4]Physics, Warsaw University of Technology, Warsaw, Poland.

Coherent optical phenomena are typically associated with the perfectly ordered medium since they relay on constructive or destructive contributions acquired during the light propagation in the bulk of the medium. However, it turns out that introducing disorder into otherwise ordered optical system can be, in fact, beneficial. It was demonstrated some time ago that the nonlinear optical process of frequency conversion is much more efficient when realized in a medium consisting of micron-size randomly oriented crystallites than the same process in a regular crystal of the same material, that does not satisfy the phase matching conditions [1]. In coherent wave interaction the transfer of energy between waves critically depends on their phase relation determined by the phase mismatch. As waves propagate the signal grows only if the contributions add constructively. By randomizing the nonlinear response, the contributions originated from different locations of the medium add incoherently. While the rate of the energy transfer is lower than in the coherent case, it is nevertheless monotonic.
In this presentation we review results of our theoretical and experimental works on frequency conversion in multi-domain ferroelectrics. In particular, we discuss the role of disorder of the ferroelectric domain distribution on the efficiency and transverse characteristics of the generated harmonics. This will include, for instance, the effect of long range randomness in regular periodic structures on the operating bandwidth of the frequency conversion [2] as well as the application of fully random domain patterns as a diagnostic tool for short laser pulse monitoring [3].

This work was supported by the Qatar National Research Fund (grant # NPRP8-246-1-060).

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4:15 PM EP07.05.02
Second Harmonic Generation in Disordered Nano-Oxides Assemblies Romolo Savo[1], Simeon Reichen[1], Flavia Timpu[1], Viola Vogler-Neuling[1], Marc Reig Escalé[1], Fabian Kaufmann[1], Michele Zanini[2], Lucio Isa[2] and Rachel Grange[1]; [1]Optical Nanomaterial Group, Institute for Quantum Electronics, Department of Physics, ETH Zürich, Zurich, Switzerland; [2]Laboratory for Interfaces, Soft Matter and Assembly, Department of Materials, ETH Zürich, Zurich, Switzerland.

The interplay between disorder and nonlinearity can provide original opportunities to overcome some of the most challenging limits in the development of future optical technologies. For instance, a standard frequency doubler based on a birefringent crystal can be hardly integrated on a chip due to tight phase-matching conditions and bulky structure with non-standard etching process. Differently a disordered χ^2 material would provide much more relaxed phase-matching condition and tremendous advantages in terms of fabrication, scalability and cost. Indeed, it has been shown that an effectively incoherent Second Harmonic Generation (SHG) is possible in transparent films of semiconductors and ferroelectrics that are disordered only in the spatial distribution of the second order susceptibility χ^2, with a large-acceptance angle and a broadband conversion [1-4].
Here we realize second-order disordered nonlinear structures by self-assembly of perovskite nanoparticles ($BaTiO_3$, $LiNbO_3$) [5] with different packing densities and geometries. Our structures show signatures of pure incoherent SHG with a nearly flat broadband conversion in the visible range ($400\ nm < \lambda/2 < 510\ nm$). Very interestingly our structures are also completely opaque, so that multiple light scattering (of both ω and 2ω) and SHG coexist, influencing each other in a way that is still under investigation. We additionally propose an application of our methods at the wavelength scale, where scattering plays a marginal role and self-assembly becomes a valuable tool to mimic bulk properties, with the advantage of a high control over the system size. We foresee that the complexity created by disorder, multiple scattering and functional Mie resonances of the scattering centers could generate unconventional mechanisms for nonlinear optical conversion and pave the way to the development of highly versatile disordered photonic devices.

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4:30 PM EP07.05.03
Nonlinear Transmission Matrices of Random Media Adam Fleming[1], Claudio Conti[2, 3] and Andrea Di Falco[1]; [1]University of St Andrews, St Andrews, United Kingdom; [2]Institute for Complex Systems, National Research Council (ISC-CNR), Rome, Italy; [3]Sapienza University, Rome, Italy.

The complex light matter interaction in disordered materials mediates many intriguing fundamental light transport phenomena, enabled by a large multitude of optical modes that can carry the information through random media and that can interact during propagation [1].

In recent years, the associated large number of degrees of freedom have been used in conjunction with wavefront shaping techniques, enabling breakthroughs such as diffraction limit beating focusing devices [2]. The ability to access a growing subset of the total individual channels has also enabled the acquisition of a transmission matrix (TM), which directly links input and output fields [3]. Again, this has allowed for the creation of remarkable optical devices such as fibre-based imaging and the simultaneous measurement of the spectral and polarimetric properties [4, 5].

Manipulation of the random media itself through nonlinear effects will allow the generation of even more powerful optical tools facilitated by additional degrees of control over the scattering system. For example, it is possible to use wavefront shaping and two photon fluorescence to focus ultrashort pulses in both space and time, providing enhancements over and above the experimental limits in linear wavefront shaping experiments [1,6].

Here, we characterize the TM in the nonlinear regime (NLTM), to describe the effect that nonlinear processes have on the long-range correlations of photon interference, and their various transmissive channels. To do so we use a series of pump-probe experiments to exploit the high optothermal nonlinearity of Silica Aerogel (SA), an ultra-porous material made of sparse silica aggregates. SA can host extremely high temperature spatial gradients,

which in turn mediates optothermal nonlinearities on the order of 10^{-12} m^2/W [7]. In addition to the measurement of the NLTM, we also demonstrate that the coupling to the transmission channels can be dynamically and reversibly tuned.

Just as the TM greatly enhanced the ability to manipulate light transport in the linear regime, we anticipate that providing access to the NLTM of a random medium will enable the creation of complex optical devices, whose characteristic behaviour can be modified directly and dynamically.

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4:45 PM EP07.05.04
Fermi-Pasta-Ulam-Tsingou Recurrence in Spatial Optical Dynamics Davide Pierangeli[1, 2, 3], Mariano Flammini[1], Lifu Zhang[3], Giulia Marcucci[1, 2], Aharon Agranat[4], Piotr Grinevich[5], Paolo Santini[1, 6], Claudio Conti[1, 2] and Eugenio DelRe[1, 2]; [1]Physics Department, University of Rome La Sapienza, Rome, Italy; [2]Institute for Complex Systems, ISC-CNR, Rome, Italy; [3]International Collaborative Laboratory of 2D Materials for Optoelectronic Science & Technology, College of Optoelectronic Engineering, Shenzhen University, Shenzhen, China; [4]4 Department of Applied Physics, Hebrew University of Jerusalem, Jerusalem, Israel; [5]Landau Institute for Theoretical Physics, Chernogolovka, Russian Federation; [6]INFN-Istituto Nazionale di Fisica Nucleare, Rome, Italy.

The reappearance of initial conditions in unstable and chaotic systems is one of the most controversial phenomena in nonlinear dynamics. Celebrated as the Fermi-Pasta-Ulam-Tsingou (FPUT) problem, the attempt to understand the formation of recurrences during the complex evolution towards equilibrium has deeply influenced the entire development of nonlinear science. Integrable models predict recurrence as exact solutions [1], but the difficulties involved in upholding integrability for a long dynamics has not allowed a quantitative experimental validation. Evidences of the recurrence of states have been reported from deep water waves [2] to optical fibers [3, 4]. However, investigations in Hamiltonian systems have so far been limited to one or two return cycles and the observation of the FPUT dynamics as predicted by exact solutions of an underlying integrable model remains an open challenge. Here, we report the observation of more than three Fermi-Pasta-Ulam-Tsingou recurrences in spatial nonlinear optics and provide evidence that the recurrent behavior is ruled by the exact solution of the Nonlinear Schrodinger Equation (NLSE).
Exploiting a three-waves interferometric setup to finely tune amplitude and phase of the single-mode input perturbation propagating in a pumped photorefractive medium, we reveal how the set of excited modes undergoes serveral growth and decay cycles, the signature of the FPUT dynamics. The modulationally unstable wave manifests the Akhmediev breathers profile and undergoes a recurrent behavior whose partial-period and phase-shift are determined by the initial excitation in remarkable agreement with the analytic NLSE theory. The observed recurrence gradually disappears as integrability is lost weakening the external pump, a finding that further corroborates integrability as the basis of the phenomenon. The deterministic properties of the recurrent behavior allows us to achieve one of the basic aspirations of nonlinear dynamics: the reconstruction, from the nonlinear stage of instability, of the exact initial condition of the system, ultimately proving that the complex evolution can be accurately predicted in experimental conditions. This results extends predictive approaches to unstable wave regimes and maps a strategy to achieve the control of localized large amplitude waves in environmental conditions. In general, our findings shed light on the foundations of the FPUT problem and represent a unique test for nonlinear wave theory, with broad implications in nonlinear optics, hydrodynamics, acoustics and beyond.

SESSION EP07.06: Poster Session: Tailored Disorder
Tuesday Afternoon, November 27, 2018
8:00 PM - 10:00 PM
Hynes, Level 1, Hall B

EP07.06.01
Optical Properties of Direct Versus Inverse 3D Chiral Photonic Crystals Shun Takahashi[1], Willem Vos[2], Takeyoshi Tajiri[3], Satoshi Iwamoto[3] and Yasuhiko Arakawa[3]; [1]Kyoto Institute of Technology, Kyoto, Japan; [2]University of Twente, Twente, Netherlands; [3]The University of Tokyo, Tokyo, Japan.

We study the optical properties of three-dimensional (3D) chiral photonic crystals by numerical methods. We compare direct structures whose fabrication has already been demonstrated by micro-manipulation techniques [1, 2], with complementary inverse structures that can readily be fabricated by reactive ion etching and advanced etch masks [3, 4]. Such a comparison builds on seminal work by Economou's team [5]. While tuning the photonic strength, we find that the band structures for these two classes of chiral nanostructures differ remarkably, even at constant average refractive index, causing distinctly different circular dichroism.
The unit cell of the direct crystal consists of 3 dielectric layers each with thickness h. The first layer is a 2D periodic array (period a) of square rods with width w. The 2nd layer has the same periodic rod pattern, rotated by 60 degrees in the in-plane direction. The 3rd layer is empty (in practice it will have distant thin spacers). The first layer of the inverse crystal is a 2D periodic array of square pores with the same parameters as the direct structure. The 2nd layer has the same pore array rotated by 60 degrees, and the 3rd layer is homogeneous. The thickness-to-period ratio of both crystals is h/a = 0.45. The refractive index of the backbone is chosen as n = 3.4 to represent semiconductors GaAs and Si that have been processed in real structures [1-4].
For a width-to-period ratio w/a = 0.75, the average refractive indices of both the direct and the inverse structures are equal, whence one might expect the same band structures and optical properties. To verify this hypothesis, we calculated photonic band structures by a plane wave expansion method for the lowest four bands in the Gamma-Z direction along the chiral axis. The direct structure has a gap between normalized frequencies fa/c = 0.147 and 0.192. The inverse structure has a gap between 0.129 and 0.186. The difference between the gaps shows that the naive hypothesis above is invalid.
Chiral structures have circularly polarized bands that induce different transmittance between orthogonal circular polarizations [1]: circular dichroism. We calculated transmittance of circularly polarized light through the two complementary structures by a finite-difference time domain method. The transmittance ratio between the orthogonal circular polarizations at fa/c = 0.190 is 1.07 and 0.11 for the direct and inverse structure, respectively. These results confirm the band structures.
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EP07.06.02
Dual-Moth-Eye Structure for Sample Collection in Mid-IR Spectroscopy Amirhossein Nateghi, Jieun Myung, Tae Yoon Jeon and Axel Scherer; California Institute of Technology, Pasadena, California, United States.

Mid-IR radiation covers light in the spectral region of 4000–400 cm^{-1} or 2-20 um which can be used to provide information on molecular structure as well as to gain insight into a molecule's local environment. Here, we present design and experimental demonstration of a sample collection and interrogation geometry that enables the spectroscopic measurement of materials in the mid-IR region. In this spectral region, silicon is relatively transparent, and a cuvette consisting of two silicon wafers bonded together can be made of this material. Such cuvettes however suffer from progressively higher reflectivity, resulting in low transmitted light. Although different anti-reflection methods can be used over small wavelength ranges, only few approaches work throughout the broad spectral regions needed for spectroscopy. Here we show a promising technique by micro-fabricating a geometric anti-reflection structure analogous to the moth-eye on silicon. This anti-reflection geometry can drastically reduce the reflectance from a silicon surface from ~30% to ~1% . We have built and characterized antireflection microstructures and have shown how our geometry can be used for sample collection on a surface of patterned silicon. Low reflectivity is measured by incorporating two moth-eye structures on both sides of a silicon wafer. This new method can be easily implemented to produce high transmission efficiencies through high-reflectivity materials over a large wavelength range and still obtain large surface areas both of which are necessary for spectroscopy.
The surface of the microfabricated moth-eye structure can collect sample within the crevices between the microfabricated pillars through surface tension. We can also geometrically filter materials on this surface by excluding particles, cells or other materials with sizes larger than the crevices formed between adjacent pillars, and thus the microfabricated anti-reflection geometry can function as a size-filter. If further coated with antibodies, aptamers or hybridization binding chemistries, this structure will be able to collect specific analytes from a complex solution for quantification and can be used not only to filter, but also to pre-concentrate materials for analysis. This is desirable when small concentrations of analytes are to be quantified from a complex solution, such as, for example, insulin in blood, urine, and sputum.

EP07.06.03
Tuning Light Scattering by Phase-Separated Nanostructures for Front- and Rear-Side Light Trapping in Photovoltaics Yidenekachew J. Donie[1, 2], Michael Smeets[3], Tsvetelina Merdzhanova[3], Vladimir Smirnov[3], Jan B. Preinfalk[1], Amos Egel[1, 2], Uli Lemmer[1, 2], Karsten Bittkau[3] and Guillaume Gomard[1, 2]; [1]Light Technology Institute, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany; [2]Institute for Microstructure Technology, KIT, Karlsruhe, Germany; [3]IEK5 – Photovoltaik, Forschungszentrum Jülich GmbH, Jülich, Germany.

If properly designed, disordered light scatterers can trap the collected photons in a photovoltaic (PV) active layer over an extended and targeted frequency range. This is particularly beneficial for enhancing the absorption in thin-film solar cells. Proof-of-concepts have been successfully performed by fabricating nanostructures with short-range structural correlation using a slow serial writing process (e-beam lithography), hence limiting the demonstration to small areas. This shortcoming can be circumvented by tailoring the morphology of self-assemblies which inherently incorporate structural disorder, and which can be more conveniently formed over large surfaces. Polymer blend lithography (PBL), relying on the lateral phase separation of a blend made of immiscible polymers, is a relevant patterning technique with that respect as it is can be carried out rapidly, cost-effectively and because it allows exploring a broad set of disordered configurations with tunable size distributions.

In the present communication, we first report on the development of self-assembled, high refractive index dielectric nanopillars (NP) which are introduced on the solar cell front side for improved light in-coupling and trapping. We show that they can be realized either by liquid-phase infiltration of titania nanoparticles into a disordered nanoholes array obtained by PBL, or via a lift-off process involving vacuum deposition and a similar PBL-based template. This route is exemplified by enhancing the absorption of a hydrogenated amorphous silicon (*a*-Si:H) absorber coupled to a rear side mirror, following the implementation of the disordered dielectric scatterers over few cm^2 onto the PV demonstrator.

We further demonstrate that the phase-separated nanostructures can also serve for realizing broadband light-trapping reflectors. To this end, a metallic layer is deposited atop a disordered NP array whose geometrical parameters are previously adjusted to achieve a light scattering coefficient (in air) exceeding 40% in the low absorbing region of the a-Si:H active layer. The low aspect ratio and smooth profile of the disordered NP enable a conformal deposition of the PV thin film stack atop, resulting in functional and reproducible devices. The latter exhibit a broadband absorption enhancement and a power-conversion efficiency increase of +65% relative to planar solar cells. The developed reflectors even overcome the light harvesting properties (Asahi-type) substrates based on random textures, thereby highlighting the advantage of controlling structural disorder for PV light management.

EP07.06.04
Random Laser Action in Disordered Electrospun Nanofibers Doped with Rhodamine B Dye Lucas F. Sciuti[1], Nathalia B. Tomazio[1], Luiza A. Marcante[2], Daniel S. Correa[2], Cleber Mendonca[1] and Leonardo de Boni[1]; [1]Institute of Physics of São Carlos, University of São Paulo, São Carlos, Brazil; [2]Nanotechnology National Laboratory for Agriculture, Embrapa Instrumentação, São Carlos, Brazil.

The scattering of light caused by disordered nanostructures enables the action of random laser. A random laser utilizes a disordered structure allowing multiple-scattering of light, embedded in an active media which amplifies it by stimulated emission. Random laser systems are of great interest due to their applications in speckle-free imaging, designing of photonic chips and also for identifying cancerous tissues. The search of different materials and architectures to provide the random laser mechanism is therefore highly important to support new applications.
In this work, polymeric nanofibers containing Rhodamine B (RhB) were fabricated by the electrospinning technique. The nanofibers were electrospun having average diameter of 500 nm. In order to investigate the random laser emission in these disordered thin layer nanofibers, a 532 nm pulsed laser was used as the pump beam. Samples were kept in a way that light emitted was collected perpendicularly to the pump beam. The light beam was focused by a 5 cm convergent lens, with the possibility of varying the sample position along the beam axis. The emitted light was captured by a set of convergent lenses and coupled to an optical fiber connected to a high resolution spectrometer. Nanofiber samples containing 2%, 5% and 10% RhB-doped were investigated. As it is expected for random laser, the output intensity as a function of the pump energy should present a threshold level and a decrease in the FWHM of the spectral emission. All three nanofibers samples studied presented a change in the slope for the output intensity as a function of the pump fluency. A narrowing of the emission band, showing a characteristic laser action, was also observed. It is important to say that the results related to the 2% RhB-doped sample, in which an incoherent-like random laser emission was measured. While for 5% and 10% RhB-doped samples, the random laser emission spectra showed a coherent-like random laser with the presence of several spikes. It is important to say that the spikes position does not change from shot to shot at a fixed pump energy, which could be related to the fact that the characteristic disorder of the electrospun nanofiber is static over time. Consequently, the cavities formed preserve the emission wavelength during time.
Changes in the RhB concentration show to play an important role in the spectral emission characteristics, presenting a red-shift with the increase of the concentration. Moreover, the spectral emission band width also increases with the concentration. One explanation for this effect is a possible reabsorption of the RhB due to some chromophores that are not excited, making possible the tuning of the laser wavelength emission. Furthermore, the transition from incoherent to coherent random laser when increasing the RhB concentration shows that the process of doping or the presence of the dye molecule tends to increase the disorder of the nanofibers.

EP07.06.05
Light-Path Engineering in Disordered Waveguiding Systems Paris Varytis[1], Wladislaw Hartmann[3, 4], Wolfram Pernice[3, 4] and Kurt Busch[1, 2]; [1]Max-Born-Institut, Berlin, Germany; [2]Institut für Physik, Humboldt-Universität zu Berlin, Berlin, Germany; [3]Institute of Physics, University of Münster, Münster, Germany; [4]CeNTech - Center for Nanotechnology, University of Münster, Münster, Germany.

Integrated nanophotonic circuits allow for realizing complex optical functionality in a compact and reproducible fashion through high-yield nanofabrication. Typically configured for single-mode operation in a single path, the optical propagation direction in such devices is determined by the waveguide layout which inherently requires smooth surfaces without scattering and restricts the device footprint to the limits of total internal reflection. By moving forward to multi-mode and multi-path designs in intentionally disordered waveguide structures, we will harness in-plane scattering effects to realize a new class of functional waveguiding devices. Through light-path engineering of free-standing dielectric membranes compact and broadband optical systems will be derived for operation in the classical and quantum regime. Our approach is based on multi-path interference, leading to the generation of wavelength dependent speckle patterns at the output of a tailored photonic nanostructure.

Random spectrometers represent prototypical examples for light-path engineered devices. Through exact numerical electrodynamic simulations (using a Discontinuous-Galerkin Time-Domain finite-element approach) in combination with multiple-scattering theory, we have demonstrated the feasibility of silicon-nitride-based high-resolution spectrometers in integrated optics layout for operation at near-IR and visible frequencies.

EP07.06.06
Cellulose-Based Photoresist for Curing Films with Disordered Microstructures by UV-Lithography Andrea Obendorfer, Maximilian Rothammer and Cordt Zollfrank; Biogenic Polymers, Technische Universität München, Straubing, Germany.

Cellulose is the most abundant biopolymer on earth and is considered an almost inexhaustible source of raw material for the increasing demand for environmentally friendly and biocompatible products.[1] The presented research includes the esterification of cellulose diacetate with methacrylic acid anhydride.[2] This reactive methacrylic side group is essential for a subsequent photopolymerization reaction during UV-lithography. We created a bio-based photoresist, where the above mentioned photo-reactive cellulose-derivative is dissolved in acetone together with a photoinitiator. Therefore, this photoresist can be subjected to surface patterning techniques (e.g. mold casting) to obtain surface structured films entirely made from polysaccharides via UV-curing. As a result, transparent patterned cellulosic films with distinct optical properties are accessible. The imprinted diffraction pattern consists of pillars in the micron range and evokes brilliant colors, which depend on the reflection angle of the incident light. Disordered areas can be generated through swelling and random self-agglomeration of several pillars, if the UV-cured film is moistened with an organic solvent. The resulting optical properties can be tuned by altering the dimensions of the pillars or their distances, which tailors the disordered cluster size and their arrangement. Additionally, there is still a high degree of freedom for the system within certain limits, since the cellulose-based pillars are subjected to a self-organization process. This example demonstrates the versatility of fabrication of tailor-made disordered materials from biogenic polymers. It is interesting to note that curing of this cellulose-based resist is possible in liquid and solid state via one-photon absorption. Our approach conserves resources through replacing polymers sourced from mineral oil by biopolymers such the polysaccharide cellulose.

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SESSION EP07.07: Application of Disorder
Session Chair: Sushil Mujumdar
Wednesday Morning, November 28, 2018
Hynes, Level 2, Room 205

8:00 AM *EP07.07.01
Tailoring Disorder via Coordinate Transformations of the Diffusion Equation of Light Martin Wegener; Karlsruhe Institute of Technology, Karlsruhe, Germany.

A large part of the field of linear optics & photonics aims at achieving specific functions of optical systems and devices by molding the flow of light. In ballistic optics in ordered systems, this task is routinely accomplished by tailoring spatial distributions of the refractive index (tensor). For diffuse optics in disordered systems, we tackle this task by designing and realizing tailored spatially graded, locally random disorder, i.e., by tailoring spatial distributions of the light diffusivity (tensor).

Here, we review our corresponding recent theoretical and experimental work. This includes core-shell invisibility cloaks [1-3] and architectures eliminating the shadow cast by opaque metal contacts on diffusively light-emitting devices [4,5]. We will also discuss limitations due to partially coherent light [6] and due to deviations from strictly diffusive behavior (unpublished).

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8:30 AM EP07.07.02
Bottom-Up Amorphous Nano-Optics—Short-Range-Ordered Nanoantenna Arrays for the Tunable Optics, Thermoplasmonics and Nanophotovoltaics Alexandre Dmitriev[2, 1]; [1]Materials Science & Engineering, Stanford University, Stanford, California, United States; [2]Department of Physics, University of Gothenburg, Gothenburg, Sweden.

Abstract: We show how using the bottom-up nanofabrication opens the possibilities to produce the amorphous arrays of optical nanoantennas that can be

used in a broadest scope of photonics applications. One example is of giving the dynamic tunability to the large-scale optical surfaces by introducing the magnetically-tunable optical elements to the optical nanoantennas. Another theme is adding such nanostructures to the thin-film photovoltaics and glass surfaces for the visible photons and thermal management. Finally, tunable nanoantenna-assisted photochemistry can also be realized.

We have a long history of developing the bottom-up nanopatterning methods for nanophotonics [1]. Further extension of those include a method for seamless transfer from a parent flat substrate of basically any lithographic top-down or bottom-up pattern onto essentially any kind of surface [2]. Another development is producing the highly conformal bottom-up nanopatterns with a short-range order [3].

With such portfolio of bottom-up nanofab methods, we tackle the development of nanometer-thin magnetically tunable optical surfaces [4], thermoplasmonics [5] and the ultra-thin crystalline solar cells structuring for their efficiency improvement [6].

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8:45 AM EP07.07.03
Femtosecond Laser Structuring of Metal Oxide Thin Films for Enhanced Optical Properties Danny Bialuschewski[1], Jan Hoppius[2], Evgeny Gurevich[2] and Sanjay Mathur[1]; [1]Institute of Inorganic Chemistry, Cologne, Germany; [2]Chair of Applied Laser Technologies, Bochum, Germany.

Disorder in materials, either chemical or structural, often result in new and unique properties, especially regarding different light interaction and interference of ordered and disordered structures. Here, ultra short femtosecond laser pulses are used to tailor specific properties in different metal and metal oxide materials. By optimizing parameters such as laser fluence, pulse duration or repetition rate, we can modify substrates on a physical or/and chemical level. In this work, we show that by inducing structural disorder in metals, for example by creating laser induced periodic surface structures (LIPSS), light harvesting properties like absorption, photoconversion and overall photoelectrochemical water splitting performance can be increased when compared to untreated substrates. This influence was investigated with and without additional top layers, regarding their spectroscopic (UV-VIS), microscopic (SEM), crystallographic (XRD and EBSD) and compositional (XPS) properties. Enhanced properties of periodic patterning was attributed to the increased specific surface area and light trapping compared to flat surfaces. Additionally, we used ultra fast laser pulses to form crystalline phases from amorphous metal oxides like iron or titanium oxide, prepared by plasma-enhanced chemical vapor deposition (PE-CVD).

9:00 AM EP07.07.04
Mie Glasses—Optically Disordered Materials for Optoelectronic Applications Jose Maria Miranda Muñoz, Gabriel Lozano and Hernán Míguez; Spanish Research Council, Seville, 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 TiO2 matrix in which crystalline TiO2 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 [1]. 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 [2].
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9:15 AM EP07.07.05
Humidity Sensitive Structural Colors from Randomly Distributed Titania Particles Syazwani Mohd Noor[1], Kyungnae Baek[1], Hansol Jang[1], Yi-Rong Pei[2], Al-Mahmnur Alam[1], Jin-Ho Choy[2] and Jerome Hyun[1]; [1]Chemistry and Nanoscience, Ewha Womans University, Seoul, Korea (the Republic of); [2]Center for Intelligent Nano-Bio Materials, Department of Chemistry and Nanoscience, Ewha Womans University, Seoul, Korea (the Republic of).

Popular approaches for generating structural color have been through spatially-controlled assemblies of uniformly-sized nanostructures. Contrary to this strategy, we have previously shown that structural color can also be created from randomly-distributed polydisperse anatase TiO_2 microspheres [1]. The display of color from such an arrangement is due to the fact that the noisy ‘white’ scattering spectra from individual particles can be weight-averaged according to the particle size distribution, yielding smooth variations in the overall scattering and extinction spectrum in the visible range. In this work, we show through the synthesis of amorphous, mesoporous titania microspheres, reversible modulation of the ensemble scattering properties between dry and humid conditions. In humid conditions, water vapour diffuses into the dense mesoporous sites within the particles, altering the overall refractive index. The color-based humidity sensitivity was found to depend on the porosity and particle size distribution. As the amorphous titania microspheres can be synthesized using cheap, scalable hydrothermal methods that provide control over the mesoporosity and particle distribution, our results provide intriguing and practical possibilities for imparting color-based humidity sensitivity to the widespread applications of titania microspheres such as antibacterial windows, catalysis, and photovoltaics.

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9:30 AM EP07.07.06
Bi-Phase Emulsion Droplets as Reconfigurable Optical Components Sara Nagelberg[1], Lauren Zarzar[2, 1], Lukas Zeininger[1], Amy Goodling[2], Timothy

M. Swager[1] and Mathias Kolle[1]; [1]Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; [2]The Pennsylvania State University, State College, Pennsylvania, United States.

Micro-scale optical elements play a key role in imaging and display technologies, biosensing, beam shaping, optical switching, wavefront analysis, and device miniaturization. Recently developed multi-phase micro-scale liquid droplets with tunable morphology show a variety of interesting optical properties. The droplets are formed from immicsible oils in an aqueous medium, and the morphology of the droplets can by dynamically adjusted by varying the interfacial tensions of the liquids. As refractive elements, the droplets can behave as micro-lenses with a variable focal length that can be adjusted continuously from positive (converging lens) to negative (diverging lens) focal lengths. When a fluorescent dye is dispersed within one of the droplets' phases, their emission profile is morphology-dependent, allowing the droplets to act as transducers in chemical and bacteria sensing systems. As reflective elements, certain morphologies of the droplets display structural color, which is also geometry dependent. A wide variety of stimuli, including altering the chemical environment, light, and heat, can be used to manipulate the shape and orientation of the droplets, and thus their optical properties.

9:45 AM BREAK

10:15 AM *EP07.07.07
Enhanced Light Backscattering by a Natural Random Nano-Texturing of the Back Metal Layer in Perovskite Solar Cells Jordi Martorell; ICFO - Institut de Ciències Fotòniques, Barcelona, Spain.

In a landmark paper by Yablonovitch it was established that a maximum light absorption in any absorber layer can be achieved by a random texturing of such layer's interfaces [1]. When such random surface texturing in solar cells is combined with a perfectly reflecting rear mirror, power conversion efficiencies close to the theoretical Shockley-Queisser limit may be possible even when the absorber layer thickness is very small. Unfortunately, introducing the slightest randomness in the majority of thin film solar cells may pose serious device fabrication issues.

In here, we consider the intrinsic random nanoscale texturing of the perovskite layer at its interface with the semiconductor charge transporting layer to achieve a broad angular light randomization is solar cells based on that material. By naturally transferring such perovskite random nano-texturing to the back semiconductor/Au interface, where the contrast in the imaginary part of the refractive index is very large, we demonstrate we can achieve an enhanced backscattering which reduces light escape leading to a very effective light absorption and bringing the power conversion efficiency of an already very good cell to about 20% [2]. The light trapping capacity of such surface roughness is compared to the one achieved by a half-cylinder lens array inducing an intermittent chaotic trajectory for the light rays. In that later case light absorption is enhanced by a partially ergodic light ray propagation [3].

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10:45 AM EP07.07.08
ZnO Nanoforest Optical PUFs Nafisa Noor[1], Venkata Manthina[1, 2], Sadid Muneer[1], Alexander Agrios[1], Ali Gokirmak[1] and Helena Silva[1]; [1]University of Connecticut, Storrs, Connecticut, United States; [2]Nanotech Biomachines, Inc., Milpitas, California, United States.

Physical Unclonable Functions (PUFs) are partly disordered physical systems used for identification in hardware security applications. The 'response' generated from a PUF depends on an externally applied 'challenge' and the unique and unclonable disorder present in the system. It should be difficult or impossible for an adversary to predict the response of a PUF and clone the exact disorder into another device [1]. Various types of PUFs have been implemented using electrical and optical systems [1], [2]. Optical PUFs are expected to be inexpensive and to enable strong security. Optical PUFs based on light scattering tokens using randomly placed sub-millimeter size (~500 μm) glass spheres have been reported earlier [3], [4]. Exploiting the variability in optical properties arising at micro- and nano-scales in different materials or structures can lead to new advances in the field of optical PUFs. ZnO can be a good choice of material for this purpose as it is a direct band gap material with numerous types of spontaneous and stimulated emissions [5] and it easily forms into random and intricate nanostructures.
For this study, dense ZnO nanoforests composed of nanorods of ~ 200-300 nm in diameter have been grown on SiO_2 and p+ polycrystalline silicon substrates using a chemical bath deposition (CBD) technique. A relatively diluted seed solution results in high density nanorods grown mostly in the upright direction with some vertical hollow spots in between neighboring nanorods. This nanorod arrangement works as a nano-porous thin film and produces Fabry-Pérot fringes under perpendicularly incident white light. Optical scattering measurements have been conducted using an optical fiber placed at ~45° angle and connected to a spectrum analyzer to collect and analyze the scattered light. The local variations in density, height, diameter, orientation angle, and hexagonal perfection of the ZnO nanorods give rise to unique and reproducible scattering spectra that vary significantly from one spot on the sample to another. Example observed scattering spectra, statistical analysis of large numbers of spectra and uses for optical PUFs will be presented.

Acknowledgments: This work was supported by the Air Force Office of Scientific Research (AFOSR) through award FA9550-14-1-0351Z.

References:

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11:00 AM EP07.07.09
High Brightness Laser Illumination using Macroscopic 3D Boron Nitride Architectures Fabian Schutt[1], Robert Roeder[2], Maximilian Zapf[2], Helge Krueger[1], Juergen Carstensen[1], Soeren Kaps[1], Yogendra K. Mishra[1], Carsten Ronning[2] and Rainer Adelung[1]; [1]Functional Nanomaterials, Kiel University, Kiel, Germany; [2]Institute of Solid State Physics, University of Jena, Jena, Germany.

Laser diodes (LDs) are regarded as the next generation of ultra-efficient light sources, being able to produce more photons at high power densities than conventional light emitting diodes.[1] Even though most state-of-the-art technologies are based on a blue LD pumping a white-light emitting phosphor, an all-laser wavelength mixing approach, e.g. a combination of three (RGB) or even four (RGBY) laser wavelengths would outperform the efficiency of any other known white-light source.[2] However, in illumination applications, laser-based lighting systems still suffer from their monochromatic, low-divergent, and coherent nature, which demands a new generation of extremely efficient and versatile optical diffusers based on disordered nanostructured

materials.[2] In the here presented study, we demonstrate a macroscopically expanded, three-dimensional (3D) laser light diffuser based on a highly porous (>99.99%) nanoarchitecture, composed of interconnected hollow hexagonal boron nitride (h-BN) microtubes, with a wall thickness below 25 nm. The 3D hollow h-BN microtubular framework structure is synthesized by a novel template approach, which is based on a highly porous ceramic network consisting of tetrapodal-shaped microparticles.[3] The synthesis results in a highly disordered[4] and non-absorbing photonic network with thinly spread but highly effective light scattering centers, based on a combination of feature sizes greater than, equal to, and well below the magnitude of the impinging wavelength, allowing for pure light diffusion. The network structure basically resembles an artificial solid fog, but with a defined hierarchical internal structure. This enables an isotropic 3D light distribution from energetic, highly directional, as well as coherent laser light, with speckle contrasts well below the human sensitivity limit. In combination with the excellent heat management of the 3D h-BN exceptionally high laser damage thresholds (~3 J/cm^2) above commercial diffuser materials can be reached. Such aero-materials enable a new generation of optical downstream components of tremendous efficiency for brightest illumination applications and open new fundamental research prospects in the field of disordered photonics.

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*Corresponding Author: fas@tf.uni-kiel.de

11:15 AM EP07.07.10
Towards Inkjet Printing of Phase-Separated Nanostructures for Light Extraction in Organic Light Emitting Diodes Yidenekachew J. Donie[1, 2], Stefan Schlisske[1, 3], Jan B. Preinfalk[1], Jocelyn Van Leeuwen[1], Amos Egel[1, 2], Jürgen Hüpkes[4], Karsten Bittkau[4], Gerardo Hernandez-Sosa[1, 3], Uli Lemmer[1, 2, 3] and Guillaume Gomard[1, 2]; [1]Light Technology Institute, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany; [2]Institute of Microstructure Technology, KIT, Karlsruhe, Germany; [3]InnovationLab, Heidelberg, Germany; [4]IEK 5-Photovoltaik, Forschungszentrum Jülich GmbH, Jülich, Germany.

With only around 20% of light emitted into the ambient, organic light emitting diodes (OLEDs) suffer from detrimental optical losses arising from light trapped as (wave) guided modes and as surface plasmon polaritons. An attractive method to improve light out-coupling is to exploit the volumetric light scattering properties of composite layers based on nanoparticles that are randomly distributed in a polymer matrix. These layers promote light extraction over a broad spectral range and do not induce color distortion, which is desirable, for instance, in large area lighting applications. Moreover, it was demonstrated that they can be processed by screen- or inkjet-printing [1], making them industrially relevant in terms of fabrication throughput, design flexibility and material yield. Besides these micrometer thick layers, more compact layouts consisting of 2D planar light scatterers can be integrated in the OLED thin film stack to allow a good spatial overlap of the guided modes with the light outcouplers. Herein, structural disorder within the scatterers array (described by diameter size and inter-distance distribution functions) can be additionally tailored to optimize the light outcoupling conditions.

In this communication, we show that the up-scalable polymer blend lithography technique is a versatile platform for fabricating such 2D planar, disordered light scatterers [2]. Using spin-coating as the deposition method for a blend of two immiscible polymers dissolved in a common low boiling point solvent and by tuning the polymer blend composition and the process parameters, we first generate phase-separated nanostructures initiated by solvent extraction. Their morphology and light scattering properties are varied, and their light extraction potential subsequently tested in bottom-emitting OLEDs. We report an efficiency enhancement of up to +50% relative to non-corrugated devices, as well as an improved angular and spectral stability. Following this proof-of-concept, our approach is then adapted to make it compatible with inkjet printing by using high boiling point solvents. We present a formulation which achieves the desired phase separation and a homogeneous printing over cm^2 pixels, and we finally introduce a route to further include a planarization layer that helps the integration of the OLED thin film stack atop the light extraction layer.

11:30 AM EP07.07.11
Long-Distance Transmission of Broadband near Infrared Light Guided by Semi-Disordered 2D Array of Metal Nanoparticles Hyounguk Kim[1], Seon Ju Yeo[1], Kinam Jung[2], Jeong Je Kim[1], Kwanil Lee[1], Il Ki Han[1] and S. Joon Kwon[1]; [1]Korea Institute of Science and Technology, Seoul, Korea (the Republic of); [2]Hannam University, Daejeon, Korea (the Republic of).

Near infrared (NIR) waveguide is a key component of planar photonic devices such as optical communication couplers, image sensors, and spectroscopy for chemical or biological molecules. Conventional NIR waveguides such as silicon-on-insulator (SOI) waveguides or channel/ridge-type metal micro-strips have been used for signal transmission. However, there are usually limitations in reducing either signal delay or signal loss in the optically integrated devices. In this study, a novel NIR waveguide composed of semi-disordered array of metal nanoparticles (sDAMNPs) on Si substrate was proposed, fabricated, and tested. The disordered metallic nanoparticles array is geometrically localized in the form of 1D metal strips, thus changing sDAMNPs to less lossy micro strip channel waveguides. From the measurements supported by various computational modellings, fabricated waveguides effectively operate at broadband NIR (1100-1700 nm). It does not support signal transmission ultra violet-visible spectrum due to strong signal absorption and localization effects inside the metal nanoparticles. Instead, it is capable of transmitting NIR over a distance longer than 100 mm (signal loss ~ 3.85 dB/100 μm for NIR in 1200-1600 nm), which is also sufficiently larger than the conventional surface plasmon polariton propagation distance at the metal-Si interface. Compared to the waveguide-free reference, the waveguide exhibited greatly improved signal transmission efficiency up to a factor of 7.42×10^4 at 1367 nm. It also exhibits a high sensitivity of deflection angle of 1.89 dB/0.01 rad, thus efficiently and straightly guiding the broadband NIR signal over long distance.

11:45 AM EP07.0712
Simultaneous Generation of Reflective Multi-Colour Using Broadband Absorber PilHoon Jung, Soo-Jung Kim, Seungho Baek, Sucheol Ju and Heon Lee; Korea Univ, Seoul, Korea (the Republic of).

Reflective multi-colour is expressed by Fabry–Perot (F–P) resonance cavities which is the interference effect in multilayer thin-films with metal–dielectric–metal. The F-P resonance is composed lossless core dielectric with partially reflective ultra-thin top metal layer and optically thick, highly reflective mirror. The absorption peak of multi-colour is tunable in the visible light range just by controlling the dielectric thickness.
In study, we fabricated the multi-absorber to realize various colours that top metal as silver (Ag) Nanocrystals (NC) solids, with dielectric layer as hydrogen silsesquioxane (HSQ) as a resist, and higly reflective mirror as thick Ag layer. As a novel material, Ag NCs solids possess optical and electrical features for electrical and plasmonic applications of comparable utility to evaporated silver, with the added advantage of enhanced stability against oxidation. Also, HSQ resist shows similar optical properties with SiO_2 and thus can be worked the dielectric layer for F–P cavities. In particular, we can adjust the residual layer of HSQ resist to obtain various colours using nanoimprint lithography (NIL). NIL has advantages over other techniques in that it forms various patterns such as nano-to-microscale structures on various substrates.
Consequently, we fabricated the various full-color optical micro-images (bear, flower, words, tiger) with 5μm square pixels on rigid substrate, non-planar

substrate, and flexible substrates.

SESSION EP07.08: Disorderd Photonic Materials
Session Chairs: Cornelia Denz and Frank Scheffold
Wednesday Afternoon, November 28, 2018
Hynes, Level 2, Room 205

1:30 PM *EP07.08.01
Shaping and Controlling the Flow of Light in Silicon Photonic Band Gap Crystals Willem Vos[1], Manashee Adhikary[1], Ravi Uppu[1], Diana A. Grishina[1, 3], Andreas S. Schulz[1], Cornelis A. Harteveld[1], D Devashish[1, 4], Shakeeb B. Hasan[1, 4], Alexandra Pacureanu[2], Peter Cloetens[2] and Ad Lagendijk[1]; [1]Complex Photonic Systems (COPS), University of Twente, Enschede, Netherlands; [2]European Synchrotron Radiation Facility (ESRF), Grenoble, France; [3]Thermo Fisher Scientific, Enschede, Netherlands; [4]ASML Netherlands B.V., Enschede, Netherlands.

In silicon nanophotonics one aims to exploit the complex transport and interactions of light in designer nanostructured silicon for advanced applications such as novel photonic interconnects, photovoltaics, sensing, and optoelectronics.
Recently, we have developed novel CMOS-compatible fabrication strategies to realize three-dimensional (3D) photonic band gap crystals with flexible architectures. Notably, we apply a single-step etch mask with ensured 3D alignment, followed by optimized deep reactive ion etching.

To investigate the performance of 3D nanostructures, it is vital to study in situ their internal structure non-destructively. Hence, we perform synchrotron X-ray holographic tomography on our 3D silicon photonic band gap crystals, without irreversible preparation steps that reveals exquisite spatial detail with as little as 20 nm resolution. We also perform X-ray fluorescence tomography to identify the positions of embedded quantum dot emitters.

As a basic optical technique, we employ micro-reflectivity. Good agreement is found of the measured stop bands and gaps in band structures obtained from plane-wave calculations, confirming that the targeted nanostructures are faithfully realized.

We address the unavoidable disorder in 3D nanostructures that is traditionally considered detrimental for applications. We harness the disorder to achieve enhanced control on light transport by applying advanced wavefront shaping methods to silicon 3D bandgap photonic crystals. To this end, we develop novel instrumentation to perform wavefront shaping in the near-infrared (0.95 – 1.65 micron) by employing a spectrally-filtered supercontinuum source. We measure an enhancement of more than >100x in the focus of the transmitted light across the accessible spectrum. In future, our hybrid approach of combined nanofabrication and wavefront engineering will enable fundamental light transport studies on mesoscopic correlations and even on 3D Anderson localization of light.

2:00 PM EP07.08.02
Yttria-Stabilized Zirconia Hollow Sphere Photonic Glasses for High-Temperature Stable Non-Iridescent Structural Coloration Yen Nguyen[1], Guoliang Shang[2], Alexander Petrov[2, 3], Manfred Eich[2, 4] and Gerold A. Schneider[1]; [1]Institute of Advanced Ceramics, Hamburg University of Technology, Hamburg, Germany; [2]Institute of Optical and Electronic Materials, Hamburg University of Technology, Hamburg, Germany; [3]ITMO University, St. Petersburg, Russian Federation; [4]Institute of Materials Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany.

Non-iridescent structural colors have a great potential to replace commercial pigments such as toxic metal oxides or organic pigments. Structural colors are generated by the refractive index distribution of the material and the observed colors result from light scattering by the structure of the material. Thus, structural colored materials show a high UV stability and can be tailored to high-temperature stability by using ceramics such as yttria-stabilized zirconia (YSZ). Non-iridescent structural colors can be generated by disordered arrangement of spheres, so-called photonic glasses (PhG). So far, PhGs for structural coloration reported in the literature are mainly based on polymer spheres with low color saturation. Theoretical predictions showed that high saturated structural coloration can be realized by a PhG from hollow spheres with YSZ shell.[1] We successfully fabricated a YSZ hollow sphere PhG which shows structural coloration with high saturation. The fabrication of these PhGs is divided into two steps: co-deposition of polystyrene (PS) spheres and YSZ nanoparticles by drop-casting and calcination to remove the PS template. Materials based on YSZ generating structural colors are suitable for high-temperature applications and with our easy and environmental-friendly fabrication method this material can be therefore a non-toxic substitute for color pigments in ceramic processing.
We studied the effect of the YSZ hollow sphere PhG structure parameters on the optical properties regarding the color impression and the effect of high-temperature treatment on the stability of the material's structure. The results show the possibility for tailoring the optical properties of the YSZ hollow sphere PhG and provide insights for developing other structural colors.

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2:15 PM EP07.08.03
Defect Strain Fields in Colloidal Crystals Bryan VanSaders[1], Julia Dshemuchadse[2] and Sharon C. Glotzer[1, 2, 3]; [1]Materials Science and Engineering, University of Michigan, Ann Arbor, Michigan, United States; [2]Chemical Engineering, University of Michigan, Ann Arbor, Michigan, United States; [3]Biointerfaces Institute, University of Michigan, Ann Arbor, Michigan, United States.

Functionality in photonic crystal devices is derived from defects (such as boundaries and other discontinuities). Naturally occurring crystalline defects display distinct mechanical fingerprints in the form of strain fields, which can be approximated as linear combinations of local motifs (strains) under the framework of linear elasticity theory. Often applied to atomic metals, we show that this approach to quantifying local disorder is a useful tool in colloidal systems as well. With greater understanding of the energetics of defect structures in colloidal materials it will become possible to consider colloidal *defect* assembly as a route to producing photonic devices. Our work explores the behavior of elastic moduli and strain fields around dislocation arrays within simulated colloidal crystals interacting through a family of repulsive potentials with varying steepness [1]. For steeper potentials, it is found that free energies of deformation are more dominated by entropy, tension-compression asymmetry near dislocation cores increases, and the strain range, within which the linear elastic approximation is applicable, shrinks. We show that pressure is a key parameter for expanding the window of linear elastic applicability for very steep potentials. Using these insights, we show under which conditions linear elasticity theory can be used as a predictive tool in exploring defect-defect interactions in colloidal crystals. We discuss how this understanding can be employed to design the self-assembly of defect microstructures.

[1] Bryan VanSaders, Julia Dshemuchadse, Sharon C. Glotzer, Physical Review Materials, in press (2018).

2:30 PM BREAK

3:30 PM EP07.08.04
High-Contrast Structural Color Based on Core-Shell Photonic Glass Guoliang Shang[1], Yen Nguyen[2], Kaline P. Furlan[2], Lukas Maiwald[1], Hagen Renner[1], Dirk Jalas[1], Maksym Dosta[3], Rolf Janßen[2], Stefan Heinrich[3], Gerold A. Schneider[2], Alexander Petrov[1, 4] and Manfred Eich[1, 5]; [1]Institute of Optical and Electronic Materials, Hamburg University of Technology, Hamburg, Germany; [2]Institute of Advanced Ceramics, Hamburg University of Technology, Hamburg, Germany; [3]Institute of Solids Process Engineering and Particle Technology, Hamburg University of Technology, Hamburg, Germany; [4]ITMO University, St. Petersburg, Russian Federation; [5]Institute of Materials Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany.

Photonic glasses are disordered assemblies of monodisperse (i.e. equally-sized) spherical particles. They are commonly used in research on non-iridescent (i.e. angle-independent) structural colors. However, no sufficient color saturation has been obtained so far as the reflectivity spectra of the realized structures show no sharp transitions.
Using first-order approximation the reflection spectrum of the structure can be related to the Fourier transform of its permittivity distribution. We show that by appropriately tailoring the individual particles in a photonic glass, its Fourier transform can be drastically changed. Using core-shell particles with a non-monotonous refractive index distribution from their center through their shell and into the background material the Fourier transform of the photonic glass can be shaped in such a way that a significant increase of the color saturation can be achieved. Our theoretical predictions were confirmed by numerical simulations.
Moreover, we experimentally realized a non-optimized photonic glass with full polystyrene spheres and an optimized photonic glass made from hollow zirconia spheres. Both structures were designed in such a way that they produce a similar reflection level and a transition at a similar wavelength. UV-vis spectroscopy measurements showed that the core-shell structure indeed produces a much sharper transition in its reflectivity.
To directly compare the resulting colors the measured reflection spectra were translated into a CIE xy chromaticity diagram. In such a diagram pure spectral colors lie on the outer arched curve while less saturated colors are positioned inside closer to the white point at the center. The optimized core-shell structure produces a point that is much closer to the outher arched curve which indicates that it causes a significantly higher color saturation.

Relevant Publications:
G. Shang et al., "*Photonic glass for high contrast structural color*," Sci. Rep. **8**, 7804 (2018).
L. Maiwald et al., "*Ewald sphere construction for structural colors,*" Opt. Express **26**, 11352 (2018).

3:45 PM EP07.08.05
3D Spatially-Resolved Optical Energy Density in Disordered Photonic Media Enhanced by Wavefront Shaping Oluwafemi S. Ojambati[1, 3], Peilong Hong[1, 2], Ad Lagendijk[1], Allard P. Mosk[1, 4] and Willem Vos[1]; [1]Complex Photonic Systems (COPS), University of Twente, Enschede, Netherlands; [2]Faculty of Science, Ningbo University, Ningbo, China; [3]NanoPhotonics Center, University of Cambridge, Cambridge, United Kingdom; [4]Debye Institute, University of Utrecht, Utrecht, Netherlands.

The interference of multiple scattered waves in complex disordered photonic media holds much fascinating physics such as coherent backscattering, Anderson localization, and mesoscopic correlations [1-4]. While a three-dimensional (3D) disordered photonic medium is from the outset opaque, such a medium sustains intriguing transport channels with near unity transmission that are eigenmodes of the transmission matrix. Remarkably, such open transmission channels are predicted to perfectly transmit a properly designed incident field, even if the medium is optically thick. It has recently been demonstrated that light is sent preferentially into a combination of open and highly transmitting channels by the spatial shaping of the incident wavefronts [5, 6]. These so-called "open channels" are currently under active scrutiny, and are pursued both for fundamental reasons and for applications in solid-state lighting, random lasers, solar cells, and biomedical optics.

Here, we study the 3D spatially-resolved distribution of the energy density of light in a 3D scattering medium upon the excitation of highly transmitting channels. The coupling into these channels is excited by spatially shaping the incident optical wavefront to a focus on the back surface [5]. To probe the local energy density, we excite isolated fluorescent nanospheres distributed inside the medium [7].
From the spatial fluorescent intensity pattern we obtain the 3D position of each nanosphere, while the total fluorescent intensity gauges the energy density.

Our 3D spatially-resolved measurements reveal that the differential fluorescent enhancement changes with depth, up to 26 times near the back surface of the medium, and the enhancement reveals a strong peak versus transverse position. We successfully interpret our results with a newly developed 3D model without adjustable parameters that considers the time-reversed diffusion starting from a point source at the back surface [8].

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[7) OS Ojambati *et al.*, NJP **18** (2016) 043032
[8) P Hong *et al.*, Optica (2018, in press)

4:00 PM EP07.08.06
Cavity Resonances in a Finite 3D Photonic Band Gap Crystal with Tailored Disorder D Devashish[1, 2, 3], Oluwafemi S. Ojambati[1, 4], Shakeeb B. Hasan[1, 3], Jaap van der Vegt[2] and Willem Vos[1]; [1]Complex Photonic Systems (COPS), University of Twente, Enschede, Netherlands; [2]Mathematics of Computational Science (MACS), University of Twente, Enschede, Netherlands; [3]ASML Netherlands B.V., Veldhoven, Netherlands; [4]Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom.

We study the transport and storage of light in a three-dimensional (3D) photonic band gap crystal doped by a single embedded resonant cavity by numerical methods. The crystal has finite support since it is surrounded by vacuum, as in experiments and devices, with a thickness of three unit cells. We employ the finite element method to model the diamond-like inverse woodpile crystal that consists of two orthogonal arrays of pores in a high-index dielectric similar to silicon. The point defect that functions as a resonant cavity is formed in the proximal region of two line defects, namely two selected orthogonal pores with a radius smaller than the ones in the bulk of the crystal. We present a field-field cross-correlation method to identify resonances in the finite crystal that has resonant states within the 3D photonic band gap of the infinite crystal. Out of five observed cavity resonances, one is s-polarized

and four are p-polarized for light incident in the X or Z directions. All cavity resonances are angle-independent, confirming the 3D confinement of light in the photonic band gap cavity. It is remarkable that quality factors up to Q = 1000 are found for such thin crystals, which is attributed to the relatively short Bragg length of inverse woodpile photonic crystals. As a result, the optical energy density is greatly enhanced at the cavity resonances, by up to 2400 times the incident energy density in vacuum or up to 1200 times the energy density of the equivalent effective medium. Fano resonances arise below the 3D photonic band gap due to interference between the discrete contribution of the fundamental cavity mode and the continuum of light scattered by the photonic crystal. Consequently, we find that an inverse woodpile photonic band gap cavity with a suitably adapted lattice parameter reveals a substantial absorption in the visible range, which is relevant for photovoltaic applications and optical sensing.

4:15 PM EP07.08.07
Finite-Size Scaling of the Density of States in Photonic Band Gap Crystals with Partial Disorder—Both Slow and Fast Shakeeb B. Hasan[1, 3], Allard P. Mosk[1, 2], Willem Vos[1] and Ad Lagendijk[1]; [1]Complex Photonic Systems (COPS), University of Twente, Enschede, Netherlands; [2]Debye Institute, University of Utrecht, Utrecht, Netherlands; [3]ASML Netherlands B.V., Veldhoven, Netherlands.

The discovery brought about by crystallography that a crystal consists of an infinite array of unit cells with periodic symmetry has led to the birth of modern condensed matter physics [1-3]. The quantum-mechanical description of electronic degrees of freedom of the solid state has led to the notion of the density of states (DOS), and to the characterization of semiconductors by a frequency range of a vanishing DOS, a band gap. An analogy can be drawn between electronic condensed matter and nanophotonic condensed matter phenomena, as the underlying mechanism for the formation of a band gap in both cases is wave interference.
The famous vanishing of the density of states (DOS) in a band gap, be it photonic or electronic, pertains to the infinite-crystal limit. In contrast, all experiments and device applications refer to finite crystals, which raises the question: Upon increasing the linear size L of a crystal, how fast does the DOS approach the infinite-crystal limit?
Therefore, we present a theory for finite crystals with the central feature that Bloch-modes become broadened due to the presence of the inevitable crystal boundaries. Our results demonstrate that the DOS for frequencies inside a band gap has a slow (1/L) scale dependence for crystals in one, two and three dimensions [4].
The results are independently verified by a new shell-model wherein the local density of states (LDOS) varies linearly from vacuum to the bulk value within one Bragg length. Consequently, we find that in finite-support photonic band gap crystals, almost all DOS contributions come from thin layers near the interfaces. Conversely, infinite-crystal inhibition in the bulk is approached very fast. Thus, applications that aim to control spontaneous emission can benefit from a strongly modified DOS when light sources are removed from the thin layer near the crystal's surface [4].

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SESSION EP07.09: Nonlinearity II
Session Chairs: Claudio Conti and Willem Vos
Thursday Morning, November 29, 2018
Hynes, Level 2, Room 205

8:00 AM EP07.09.01
Highly Nonlinear M-Cresol/Nylon Solution for Optical Shock Waves Giulia Marcucci[1, 2], Phillip Cala[3], Graham Siggins[3], Weining Man[3], Claudio Conti[1, 2] and Zhigang Chen[4, 3]; [1]Physics, Sapienza University, Rome, Italy; [2]Institute of Complex Systems, National Research Council, Rome, Italy; [3]Physics and Astronomy, San Francisco State University, San Francisco, California, United States; [4]TEDA Applied Physics Institute, Nankai University, Tianjin, China.

M-Cresol/Nylon is a chemical solution, which is made up of an organic solvent (m-cresol) and a synthetic polymeric solute (nylon). Recent experiments showed that this solution exhibits an isotropic giant self-defocusing nonlinearity, tunable by varying the nylon concentration. [1] When it is enlightened by a continuous-wave laser beam, light absorption induces heat gain, which reduces the refractive index: the material experiences a nonlinear thermo-optical effect, made nonlocal by the heat diffusion. Since the temperature changes with the beam intensity, this nonlinearity follows a nonlocal Kerr model, expressed by the nonlinear Schroedinger equation (NLSE). [2] In particular, V. Smith *et al.* measured the m-cresol/nylon nonlinear Kerr coefficient n_2 and found that, if for pure m-cresol it is -9x10^-8 cm^2/W, for a nylon mass concentration of 3.5% it is -1.6x10^-5 cm^2/W, a magnitude higher than most of the other thermal nonlinear materials reported in literature.
In optics, many phenomena are ruled by NLSE, such as soliton propagation and dispersive shock wave (DSW) generation. [1,2] We report experimental evidence of two-dimensional optical DSWs with an anisotropic zero-singularity. Fixing z as the longitudinal and x,y as the transverse directions, we start with a beam that has a Gaussian profile along y but a Gaussian first derivative along x, thus the intensity is null for x=0. This specific initial condition causes a new phenomenon, reported here for the first time: the shock develops undular bores on the beam external borders (as already known in literature [2]), but around the singularity it presents an abrupt intensity discontinuity. We theoretically analyze the wave breaking along all the propagation. By a hydrodynamic model, we study the beam before the shock point: the WKB approach and the characteristic method let us predict the wave breaking both in phase and in intensity. [2] In order to model the beam propagation beyond the shock point, we use mathematical tools of time asymmetric quantum mechanics and uncover the mechanism how such an abrupt intensity discontinuity is generated. [3] We numerically simulate these results and find remarkable agreement both with experiments and with theoretical predictions.
Our outcome not only confirms previous studies on the giant nonlinear response of m-cresol/nylon, but also discloses fundamental insights on propagation of DSWs with a singular initial intensity profile.

[1] V. Smith *et al.*, Opt. Mater. Express **4**, 1807 (2014)
[2] N. Ghofraniha *et al.*, Phys. Rev. Lett. **99**, 043903 (2007)
[3] G. Marcucci *et al.*, Phys. Rev. A **94**, 052136 (2016)

8:15 AM *EP07.09.02
Randomized Caustic Networks in Nonlinear Optical Media Alessandro Zannotti, Daniel Ehrmanntraut and Cornelia Denz; Institute of Applied Physics,

University of Muenster, Muenster, Germany.

Caustics represent natural optical phenomena concentrating the energy flow of light waves, being characterized by an abrupt intensity change. They may create complex light paths or ramified networks of light associated with ray optical singularities and extreme events. Although caustics are mostly known in optics, they are intrinsic to all waves and are strongly related to random phenomena. In nature, caustics in turbulent atmosphere cause starlight twinkle, fluctuations in the profile of an ocean floor generate random caustics that can focus the energy of tsunami waves, and the curved surface of shallow water may lead to dynamically changing caustic networks exhibiting extreme events. Since caustics can thus be observed on a broad range of different scales, and since they share many similarities to extreme waves such as rogue waves, being both characterized by high amplitudes at low probability, there is actually a huge interest to understand, model and control random focusing and extreme events in caustic networks.
While initial studies of rogue wave formation focused on the role of nonlinearities, recent experiments reported rogue waves in purely linear systems. This led to the hypothesis that such extreme events are originating from evolving random caustic networks or branched flows. Since they represent complex superpositions of fundamental caustic geometries like fold and cusp bifurcations which include extreme amplitudes and singularities of the intensity, the assumption can be verified in tailored disordered photonic media that allow linear as well as nonlinear light-matter interaction.
In our contribution, we discuss the formation of random optical caustic networks and their role in extreme wave formation by varying the strength of both, nonlinearity and scattering in a controlled randomized optical medium. On the one hand, we address they key question how caustic networks evolve when propagating through weakly scattering random media. For this purpose, we create paraxial light with random Gaussian wavefronts and control the formation of caustic networks by the correlation length of the Gaussian distribution and its amplitude, thus controlling the amount of caustic or speckle characteristics. While the intensity histograms of speckle patterns show an exponential decay, we find long-tail statistics for caustics as a criterion for rogue waves. On the other hand, we propagate caustic networks in strongly nonlinear refractive index media that parametrically enhance abrupt caustic intensity variations and thus increase the probability for extreme events. By optically inducing tailored randomization, two-dimensional refractive index potentials are created and probed by random Gaussian fields. With our approach, we provide novel insights into the general mechanisms of branched caustic flow formation in random linear to nonlinear media, thus merging the often separately treated aspects of random light and scattering media.

8:45 AM EP07.09.03
Replica Symmetry Breaking in Optical Wave Propagation Davide Pierangeli[1, 3, 2], Andrea Tavani[1], Fabrizio Di Mei[1], Aharon Agranat[4], Eugenio DelRe[1] and Claudio Conti[1, 3]; [1]Physics Department, University of Rome La Sapienza, Rome, Italy; [2]International Collaborative Laboratory of 2D Materials for Optoelectronic Science & Technology, College of Optoelectronic Engineering, Shenzhen University, Shenzhen, China; [3]Institute for Complex Systems-CNR, Rome, Italy; [4]Department of Applied Physics, Hebrew University of Jerusalem, Jerusalem, Israel.

Identical copies of a randomly interacting system can manifest completely different dynamics. This fundamental property, known as replica symmetry breaking (RSB), lies at the basis of spin-glass theory, which describes critical phenomena in disordered systems that range from condensed matter to social dynamics. The RSB scenario has been only recently observed in photonics in complex lasing systems [1,2], whereas the fact that a closed Hamiltonian system can exhibit glassy phases is an open fundamental question [3]. In general, RSB has been predicted for nonlinear waves [4], including Bose-Einstein condensates and optics, but it has never been observed. Here, we report the experimental observation of the breaking of replica symmetry in disordered nonlinear optical propagation [5].
We found that when mode interaction dominates light dynamics in a disordered photorefractive waveguide, replicated experimental realizations are found to have an anomalous overlap intensity distribution that signals a transition to an optical spin-glass phase. Specifically, a glassy state of light that emerges as nonlinear interaction overcomes a threshold and it is characterized by strong shot-to-shot variations of the speckle-like intensity distribution and the degree of spatial coherence. Surprisingly, these fluctuations are not randomly distributed but can be either completely correlated or anticorrelated. In close agreement with spin-glass theory, the Parisi overlap distribution between identical replicas incurs in a nontrivial change that indicates how the same realizations of the dynamics may give rise to different physical observables. Thus, RSB here indicates a global locking of several spatial modes so that completely anticorrelated states may emerge from equivalent conditions, the signature that different metastable states underlie dynamics. These findings are general and do not depend on the specific form of disorder and character of the nonlinearity. They can be extended to a large class of optical systems including nonlinear multimode fibers and multiple pulse filamentation. Our results demonstrate that wave propagation can manifest features typical of spin-glasses, thus providing a novel platform for testing fundamental physical theories for complex systems.
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9:00 AM EP07.09.04
Talbot Carpets by Rogue Waves Milivoj R. Belic; Texas A&M University at Qatar, Doha, Qatar.

Rogue waves are giant nonlinear waves that randomly appear and disappear in oceans and optics. Talbot carpets are periodic recurrent images of linear light and plasma waves. We demonstrate how to produce Talbot carpets by rogue waves. Such carpets can be used in nanoscale lithography.

9:15 AM *EP07.09.05
Coherently Engineered Disorder in Metal Oxide Semiconductors for Superior Solar-Assisted Hydrogen Production Sanjay Mathur[1], Danny Bialuschewski[1], Jan Hoppius[2] and Evgeny Gurevich[2]; [1]Institute of Inorganic Chemistry, Cologne, Germany; [2]Chair of Applied Laser Technologies, Bochum, Germany.

Disorder in materials often result in new and unique properties, like enhanced light absorption or electrical conductivity. Tailored chemical or structural disorder is of high technological interest for various applications especially in the energy harvesting/conversion sector. These controlled defect structures can consist of perturbed periodic patterns (correlated) or lacking of any long-range symmetry (random). Both have been reported to improve the spectral response of semiconductor films used in light harvesting application.
Available techniques to induce disorder in sample volume or surface range from mechanical processing to bombardment with high-energy particles like electrons, ions or neutrons. In order to precisely control the disordering process, ultra fast laser pulses can be used. While laser ablation or laser melting rely on long pulses of continuous wave lasers, ultra short pulses, usually below 100 femtoseconds, can be used for controlled structuring. The very beam duration with high peak intensity allow induction of surface defects at micro- and nano-scale by non-linear effects, shock wave propagation or heat-induced transport.
Engineered structural and chemical disorder is even capable of turning metal oxide semiconductor thin films into highly efficient solar absorbers. By laser-

assisted patterning, these substrates can be modulated in their structure and composition, which manifests in enhanced light-trapping and in-coupling, ultimately enhancing the photoelectrochemical water splitting performance.

9:45 AM BREAK

SESSION EP07.10: Random Lasing
Session Chairs: Sushil Mujumdar and Davide Pierangeli
Thursday Morning, November 29, 2018
Hynes, Level 2, Room 205

10:15 AM *EP07.10.01
Tailored Disorders in Photonic Crystals for Laser and Cavity QED Applications Satoshi Iwamoto[1], Yasutomo Ota[2], Kazuhiro Kuruma[1], Takeyoshi Tajiri[1], Shun Takahashi[2], Ryota Katsumi[1], Masahiro Kakuda[2], Katsuyuki Watanabe[2] and Yasuhiko Arakawa[2]; [1]Institute of Industrial Science, The University of Tokyo, Tokyo, Japan; [2]Institute for Nano Quantum Information Electronics, The University of Tokyo, Tokyo, Japan.

Tailored disorders in a photonic crystal (PhC), which is a periodic structure in refractive index with a wavelength-scale periodicity, function as optical cavities and waveguides. Particularly, PhC nanocavities with high Q factor and small mode volume are receiving much attention because they can be applicable not only to passive optical devices such as narrow band filters but also to active photonic components, lasers, modulators, nonlinear optical devices etc. The tight confinement of photons within a tiny volume also make PhC nanocavities a fascinating platform for the study of cavity quantum electrodynamics (cavity QED) using solid state quantum emitters like semiconductor quantum dots (QDs). In this talk, we will discuss our recent experimental progresses on nanocavity lasers and quantum-dot cavity QED utilizing photonic nanocavities formed in 1D, 2D and 3D PhCs.
Our long-lasting development of the fabrication technologies for high Q PhC nanocavities now makes possible the advanced studies on cavity QED phenomena in a 2D PhC nanocavity embedding InAs QDs. We will discuss the successful observation of the QD-based vacuum Rabi oscillations under carrier injection by means of time-resolved photoluminescence measurement. The time-domain investigations also enables the investigation of carrier dynamics which have not been detected by the spectral-domain measurements. We have been also developing the micromanipulation technique for 3D PhCs. In the method, 2D plates constructing the final 3D PhC are prepared using the conventional planar nanofabrication technique first. Then the plates are precisely stacked with micromanipulators in a SEM chamber. We will briefly introduce the method and will discuss a proof-of-concept demonstration of photonic integrate circuit, in which a nanocavity laser and waveguides were simultaneously integrated in a 3D PhC. The output of nanocavity laser was guided through the two orthogonally connected PhC waveguids and was observed from the output facet of the waveguide. Finally, if time allows, a new design approach of PhC nanocavity based on the photonic band topology will be discussed. A localized optical mode at the interface between two nanobeam PhCs with the same band structures but with different Zak phases were designed and fabricated. With optical gain of InAs QDs, we achieved the lasing oscillation utilizing the localized mode as an optical nanocavity.

10:45 AM EP07.10.02
Nanostars for Random Lasing Thomas A. Klar, Johannes Ziegler, Battulga Munkhbat and Calin Hrelescu; Institute of Applied Physics, Johannes Kepler Universität Linz, Linz, Austria.

Gold nanostars in dye doped media provide a double degree of randomness. First, the position of these strong scatterers is random within the active media, making them good candidates for scattering centers in random lasers, superior to spherical or rod shaped gold nanoparticles.[1] Second, the number, the size, and the directional distribution of the metallic tips are all random, hence making an ensemble of nanostars a broadband resonator.[2] In fact, it is possible for gold nanostars to provide feedback over almost a full octave of visible to near IR laser wavelengths.[3] Apart from organic dye molecules as active media, we also used colloidal semiconductor quantum dots in combination with gold nanostars and demonstrated random lasing, as well.[4]
A disadvantage, though, is the high absorption of gold nanoparticles due to Förster transfer and due to the large imaginary part of the dielectric function given by the single electron transition between the d- and the sp-band. Silver would be the much better plasmonic material, however, it is seldom used due to its chemical reactivity. We have found a way to circumvent this dilemma. Starting with gold nanostars, we overgrow them with silver, such that the resulting Ag@Au nanostars show substantially smaller lasing thresholds than pure gold nanostars.[5] Further, a 10 nm thin silica protection layer acts as a chemical passivation layer and simultaneously keeps the fluorophores away from the metallic surface. Within these 10 nm thick oxide layer, the quenching of the active material due to Förster transfer ceases, but the electric field is still enhanced at its surface. Finally, nanostars can also be used to improve the efficiency of organic light emitting diodes.[6]

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3. Ziegler, J.et al., Plasmonic nanostars as efficient broadband scatterers for random lasing. *ACS Photonics* **2016,** *3*, 919.
4. Gollner, C et al., Random Lasing with Systematic Threshold Behavior in Films of CdSe/CdS Core/Thick-Shell Colloidal Quantum Dots. *ACS Nano* **2015,** *9*, 9792.
5. Munkhbat, B.et al., Hybrid Multilayered Plasmonic Nanostars for Coherent Random Lasing. *Journal of Physical Chemistry C* **2016,** *120*, 23707.
6. Munkhbat, B.et al., Performance boost of organic light emitting diodes with plasmonic nanostars. *Adv. Opt. Mat.* **2016,** *4*, 772.

11:00 AM EP07.10.03
Designing and Writing Scattering Centres to Build a Ranom Dlaser Network Niccolo Caselli, Angel Mateos and Cefe Lopez; Consejo Superior de Investigaciones Científicas, Madrid, Spain.

Random lasers emerged as an alternative and accessible source of laser light. The noteworthy advantage relies on the low-cost and flexible fabrication approach, which is traditionally based on colloidal systems [1] or crystal powder [2,3]. Their omnidirectional emission with low spatial coherence makes them promising sources for imaging and lighting application [4]. However, control and stabilization of the emission in terms of number of the amplified modes and frequency, is an open challenge due to the absence of an optical cavity. As a matter of fact, even by employing the same fabrication design two different devices give rise to different modes.
Here, we implemented a direct laser-writing technique to engineer an optically active material (dye-doped biopolymer film) by creating circular holes that act as scattering centres for light. This approach is based on the generation of a single femtosecond-pulse that induces ablation of the polymer film on the micrometre-scale. The site-controlled fabrication allows to print holes of different dimension, depth and position inside the active medium. When a couple of identical scattering centres are drawn it is possible, by optically pumping the straight region that connect the two scatterers, to generate random laser

emission due to the feedback induced by the scatterers [5,6]. The spectral properties of these home-built random laser depends on the amount of disorder of the scatterers, that varies with their size and smoothness. Therefore, by tailoring the degree of disorder, that is by engineering and reproducing identical scattering centres, we achieved random lasers with a reproducible spectral emission. As a rule of thumb, in our devices larger and rougher holes give rise to a larger numbers of modes. The presented technique could open new ways to design and fabricate networks of random lasers where the nodes are represented by the holes acting as scattering centres and the connections are the straight line pumped regions of the active medium.

References:
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11:15 AM EP07.10.04
Investigation of Random Lasing Contributions to Lasing-Spasers Jill Tracey[1] and Deirdre O'Carroll[1, 2]; [1]Chemistry and Chemical Biology, Rutgers, The State University of New Jersey, Piscataway, New Jersey, United States; [2]Materials Science and Engineering, Rutgers, The State University of New Jersey, Piscataway, New Jersey, United States.

Lasing-spasers are physically-small metal/dielectric nanoparticle structures that emit light via stimulated emission of radiation due to amplification of surface plasmons. There have been relatively few experimental demonstrations to date, all of which have relied on ensembles of randomly arranged nanoparticles to exhibit spasing. This has lead to the possibility that it is not just solely the effects of stimulated emission of radiation by amplification of surface plasmons leading to the observed phenomenon. Potentially, a combination of effects from the amplification of surface plasmons, and the random arrangement of nanoparticles, or local interactions between nanoparticles leads to stimulated emission. It is truly necessary to analyze the effects of a single particle and small clusters of particles in order to fully determine if random lasing is contributing to or even obscuring lasing-spaser emission.
The goal of this research project is to fabricate functioning spasers utilizing silver nanoparticles and conjugated polymer gain media. Samples are fabricated by sequential deposition of the following layers on a glass substrate: poly(acrylic acid), silver nanoparticles (60 nm diameter), poly(9,9-di-n-octylfluorenyl-2,7-diyl) (PFO), followed by an optical epoxy encapsulant, and, finally, another glass slide. The thickness of the PFO gain layer is controlled to be less than 70 nm to inhibit photonic waveguide modes. The sample configuration is analyzed in two ways. First, stimulated emission from a dense, random arrangement of nanoparticles coated with a thin-film of the gain medium (PFO) is analyzed, to observe the effects of ensemble measurements, and potentially the effects of random lasing, if they do indeed contribute. From initial measurements, stimulated emission has been observed in samples with polymer thicknesses ranging between 30 nm to 70 nm, and was not observed in polymer films of the same thickness when nanoparticles were not present. However, as these were ensemble measurements, it is possible that the observed stimulated emission is from a combination of surface plasmon amplification, as well as nanoparticle interactions. The second approach is to use a less dense nanoparticle arrangement, in order to be able to probe single nanoparticles coated with the gain medium. This approach will allow us to determine if spasing is possible from a single nanoparticle, as well as to determine the effect that the random arrangement of particles contributes to the ensemble measurement results. Scanning electron microscopy is utilized to quantify the nanoparticle arrangement. Photoluminescence spectroscopy is used to determine if stimulated emission is occurring in both configurations, with the addition of an optical microscope for the single particle studies, in order to ensure that only one particle is probed at a time.

11:30 AM EP07.10.05
Random Lasing in Disordered Photonic Networks Dhruv Saxena[1], Michele Gaio[1], Alexis Arnaudon[1], Jacopo Bertolotti[3], Sophia Yaliraki[1], Mauricio Barahona[1], Dario Pisignano[2, 4], Andrea Camposeo[2] and Riccardo Sapienza[1]; [1]Imperial College London, London, United Kingdom; [2]Istituto Nanoscienze-CNR, Pisa, Italy; [3]University of Exeter, Exeter, United Kingdom; [4]Universita del Salento, Lecce, Italy.

Photonic networks, where light flows in a mesh of interconnected sub-wavelength waveguides, have attracted much attention due to their potential applications in quantum optics and integrated photonics. Here we report on a laser based on a disordered planar photonic network [1]. The network is composed of interconnected polymer nanofibers that are doped with a laser dye (Rhodamine-6G). We demonstrate lasing from the network, over a wide range of frequencies corresponding to many network modes, and show that the lasing modes can be designed via the network connectivity and topology.

The complexity of the photonic network lasers brings the opportunity to control the lasing action by selectively illuminating a very small subset of the network links. This surprising result is predicted by a graph description of Maxwell's equations, which is used to model the network laser. Our graph approach enables efficient modelling of large networks, which is not possible using conventional numerical methods of solving Maxwell's equations. Moreover, it facilitates design of the network topology for lasing and identification of the most important edges in the network that are necessary for sustaining a particular mode.

Following this strategy, we experimentally demonstrate control over the lasing modes and single-frequency operation. The controlled network laser is a compact laser source, CMOS compatible, capable of switching the lasing output, which could become an important component for future optical computing and processing.

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11:45 AM EP07.10.06
Nonlocal Random Laser and Replica Symmetry Breaking Loredana Maria Massaro[2], Silvia Gentilini[1], Cristina Colosi[3], Ilenia Viola[4], Claudio Conti[2, 1] and Neda Ghofraniha[1]; [1]Consiglio Nazionale delle Ricerche, Istituto dei Sistemi Complessi, Rome, Italy; [2]Dipartimento di Fisica, Università La Sapienza, Rome, Italy; [3]Istituto Italiano di Tecnologia, Rome, Italy; [4]Consiglio Nazionale delle Ricerche, Istituto Nanotec, Rome, Italy.

We propose a novel type of random lasers (RL) with disordered structure designed by using 3D bioprinting. Bioprinting uses a computer-controlled printing device to accurately deposit cells and biomaterials into precise architectures creating organized multicellular tissue structures [1]. In our sample we use a blend of alginate mixed with TiO2, which acts as structural template maintaining the printed multi-layer constructs without collapsing. After fabrication the printed structures are stored in a liquid medium and depending on the time spent in it they will present different final dimension. Rhodamine-B in diethylene glycol (RHB) is added as gain medium. The final result is a dyed sample with waffle-like structure made by crossing 30-100 micron thick stripes of TiO2-alginate-RHB and square empty holes.

Two different RLs with different dimension and microstructure are explored. The first one is dried and with a more compact structure inside the stripes, the second one is kept wet and with lower porosity.

We use a RL set-up previously reported [2] to examine the emission and two diverse behaviors are observed.
i) The dry sample shows incoherent RL emission with the well known large narrowing spectral peak typical of other TiO2 based RLs, but with an intriguing NONLOCAL behavior: strong RL emission far from the pumping point is observed both inside the stripes (with material) and more interestingly outside in the empty holes. This can be ascribed to a wave guiding mechanism not yet reported in similar disordered materials and is a clear demonstration of the propagation of RL radiation.

ii) The wet sample presents coherent RL emission with several sub-nanometric peaks as an indication of many longitudinal modes. Strong shot to shot spectral fluctuations are observed: each time the laser is on a different composition of the many peaks is given ranging from the only fluorescence band to few very sharp narrow peaks.
We use the Replica Symmetry Breaking (RSB) analysis recently introduced [3] to quantify such fluctuations. Differently, in the present work we explore by this method the statistical mechanics of coherent RL with many resonances.
We observe evident RSB of whole the spectra as well as of the single peaks as the demonstration of strong mode interaction and we define their different laser thresholds by investigating the distribution of the intensity overlaps. In this wet sample we do not observed the wave guiding mechanism present in the dry one.

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[2] Biomimetic Random Lasers with Tunable Spatial and Temporal Coherence
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SESSION EP07.11: Disorderd Plasmonics
Session Chairs: Satoshi Iwamoto and Massimiliano Papi
Thursday Afternoon, November 29, 2018
Hynes, Level 2, Room 205

1:30 PM *EP07.11.01
Engineering Aperiodic Electromagnetic Media for Photonics, Plasmonics and Metamaterials Device Applications Luca Dal Negro; Boston University, Boston, Massachusetts, United States.

The ability to manipulate light-matter interactions using complex, aperiodic electromagnetic media is at the heart of current nanoplasmonics and metamaterials technologies. Efficient approaches for multiscale electromagnetic field enhancement, concentration and manipulation of fields with designed spatial-frequency spectra in complex media enable the control of propagating and non-propagating electromagnetic modes in optical nanostructures with broadband/multi-band enhanced responses. Besides its fundamental interest, photonic-plasmonic interactions in complex aperiodic environments are also of great importance for a number of device applications such as multi-band nano-antennas, ultrafast optical switchers, nanoscale energy concentrators, laser nano-cavities, and optical biochemical sensors. In this talk, I will discuss our work on the design and engineering of wave localization, scattering and transport phenomena in novel aperiodic nanostructures and metamaterials with controllable structural correlation properties for novel Si-compatible, on-chip devices applications. Finally, I will introduce our current work on the design and of novel dielectric nanostructures and metamaterials with anomalous scattering properties driven by the Epsilon Near Zero (ENZ) response of Si-compatible novel materials.

2:00 PM EP07.11.02
Plasmonic Properties of Ordered Arrays of Metallic Nanostructures Fabricated by Nanosphere Lithography and MeV Ion Implantation Cecilia Salinas[1], Jose Miguel Zarate[1], Erick Flores-Romero[1, 2], Erika Rodriguez-Sevila[1, 2] and Juan-Carlos Cheang-Wong[1]; [1]Universidad Nacional Autonoma de Mexico, Ciudad de Mexico, Mexico; [2]Catedrático CONACyT, Ciudad de Mexico, Mexico.

In nanoscale electronic, photonic and plasmonic devices, feature dimensions shrink towards a critical limit, and new experimental approaches have to be explored in lithographic patterning to create ordered arrays of metallic nanostructures with useful optical properties. In this work, spherical submicrometer-sized colloidal silica particles were prepared by sol-gel and deposited onto silica glass plates by means of a spin coater system. By combining MeV ion implantation (Au, Ag ions) and nanosphere lithography, this silica particle monolayer acts as a mask to create regular arrays of metallic nanoscale features embedded in the silica plate. By this way, after removal of the silica particles and an adequate thermal annealing of the as-implanted samples, the formation of metallic nanostructures was confirmed by the presence of the corresponding surface plasmon resonance (SPR) in the optical absorption spectra. In order to modify the shape of such quasi-spherical nanoparticles embedded in the silica matrix, some of the samples were irradiated at room temperature with 8 MeV Si ions, leading to the formation of elongated metallic nanoparticles, achieving then the tuning of the SPR and the nonlinear optical properties. The size and shape of the arrays of silica particles and the embedded metallic nanoparticles were studied by scanning and transmission electron microscopy, respectively. The long range order of both the self-assembled monolayer of silica particles and the metallic nanoparticle arrays were characterized by a Fast Fourier Transform study. The plasmonic properties of the metallic nanostructures were characterized by optical absorption measurements as a function of the Si ion irradiation experimental parameters.

2:15 PM EP07.11.03
Light-Induced Disorder-to-Order Transition in Dissipative Colloidal Silver Nanoparticles Fan Nan, Fei Han and Zijie Yan; Clarkson University, Potsdam, New York, United States.

Upon laser illumination, electrodynamic interactions can arise among plasmonic silver nanoparticles in solution, leading to local energy minima on the potential energy surface. The silver nanoparticles will self-assemble into ordered structures if the potential wells are deep enough to maintain the structural stability under thermal fluctuations, otherwise they tend to be disordered. Here we report a dissipative colloidal system where ordered chains involving nanoparticle oligomers (such as dimers and linear trimers) transiently arise among largely disordered silver nanoparticles illuminated by a laser beam. The transition is driven by anisotropic electrodynamic interactions coupled with electrostatic interactions, and provides new opportunities to discover new dissipative structures and build novel mesoscale structures.

2:30 PM BREAK

3:00 PM EP07.11.04
Anderson Localization of Hybrid Plasmons in Terahertz Plasmonic Materials Sushil Mujumdar[1], Ajay Nahata[2] and M. Balasubrahmaniyam[1]; [1]Tata Institute of Fundamental Research, Mumbai, India; [2]Department of Electrical and Computer Engineering, The University of Utah, Salt Lake City, Utah, United States.

Disorder-induced Anderson localization of waves has been demonstrated in optical, acoustic, and matter wave domains, but lacks substantial research in the plasmonic domain due to the inherent losses. Towards a more calibrated study of plasmonic localization and dissipation, appropriate plasmonic materials need to be employed. Given that metallic losses are lower at lower frequencies, terahertz waves are promising candidates in the study of loss and localization. Our recent experiments provided evidence of Anderson localizationat terahertz frequencies in a linear array of subwavelength through-holes drilled in a thin stainless steel sheet. However, the limited spectral resolution prevented access to individual localized modes and their loss. The current work reports our theoretical analysis of Anderson localization in this system from the vantage point of the dispersion characteristics of the structure. The subwavelength holes act as resonators and confine resonant fields in the air in the holes. The steel surface supports a plasmon polariton that possesses a linear dispersion at terahertz frequencies. The Kondo-hybridisation of the cavity resonance and the polariton realizes hybrid plasmons that constitute the localized quasiparticles in this system.

We further elucidate critical differences between the localization of hybrid plasmons and that of photons occurring in conventional dielectric systems. The anti-crossing of the dispersion profiles of the resonator and the polariton opens a hybridisation gap that is centered on the resonant frequency of the resonator. The resultant upper transmission band is highly radiative, but the lower band is bound to the interface and supports surface transport, and is conducive to Anderson localization. The profile of the density of states (DoS) exhibits diverging DoS at the edges of the gap. Disorder is introduced into the structure by randomizing the positions of the holes. This shifts the band-edge states into the hybridization gap, and induces their localization as evidenced by the newly-developed exponential tails. We quantify the localization length separately from the loss-length, and find that the latter is at least an order of magnitude larger. Further, we find that the maximally-shifted gap modes cannot arbitrarily transit deep into the gap, even at strongest disorder. They exhibit a propensity to remain pinned to a frequency which depends on the resonance frequency of the subwavelength cavity. As a consequence, the hybridization gap never closes even at strongest disorder, and the midgap DoS remains zero. Such a situation is in stark constrast to conventional dielectric systems, where the DoS closes through the formation of a Lifshitz tail.

In conclusion, we have analyzed Anderson localization of hybrid plasmons, which exhibits hitherto-unstudied characteristics of localization. This study emphasizes the need and potential of novel hybrid plasmonic materials in studies of fundamental phenomena.

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Fourier-Space Spectroscopy of Disordered Plasmonic Metasurfaces Florian Sterl, Thomas Weiss, Steffen Both and Harald Giessen; 4th Physics Institute and Research Center SCoPE, University of Stuttgart, Stuttgart, Germany.

The optical properties of plasmonic nanoparticle ensembles are not only determined by the particle shape and size, but also depend on the arrangement of the nanoantennas. The angle-dependent transmission/reflection characteristics of a rectangular nanoparticle array are strongly influenced by lattice diffraction effects, while these effects are absent in a completely randomized ensemble. By introducing short- or long-range disorder into a nanoparticle lattice, one can furthermore strongly influence the optical properties.
We present both computational and experimental approaches to gain a better understanding of the impact of disorder on the bidirectional reflectance distribution function (BRDF) of complex plasmonic metasurfaces. We treat the nanoantennas as dipoles, and we simulate the electric field based on dipole-dipole coupling. We can then extract the wavelength-resolved far-field response [1] and convert it into RGB colors, to construct the optical appearance. Similarly, we can extract the wavelength-resolved Fourier space image, providing the angle-resolved far-field response. Varying the incident angle provides the full wavelength-resolved BRDF.
To compare the simulations to experimental data, we develop a designated back focal plane microspectroscopy setup, based on a modified 4-f setup [2]. This allows us to record the real- as well as Fourier-space images generated by nanoparticle ensembles at spot sizes down to 50 µm. The resulting image can either be projected onto an RGB CCD camera, or onto the entrance slit of an imaging spectrometer. In this way, the full wavelength- and angle-resolved far-field response can be recorded. By furthermore varying the incident angle, we can record the full BRDF of such microscopic metasurfaces.
In the case of 'frozen-phonon disorder', each element is displaced from its initial lattice position by a random amount in a random direction [3]. We can go from a fully ordered to a fully disordered arrangement in several steps by increasing the range of the displacement. We also consider correlated disorder, where the displacement of any element affects the surrounding elements with a certain correlation length and function. We aim to derive a correlation of these results with the two-point correlation function resulting from the spatial arrangement. Thus, we will be able to extract disorder kind and strength from our measurements, and, in turn, design the visible appearance of a metasurface by tailored disorder.

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