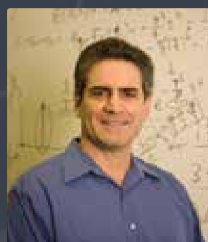
Advancing photonic functionalities

Professors Paul Steinhardt, Salvatore Torquato and Marian Florescu discuss hyperuniform materials use in the development of hyperuniform disordered solids, garnering better theoretical understanding of the physical properties of non-crystalline materials



To begin, could you outline your role within this project?

PS: I am a theoretical physicist in the Department of Physics and Department of Astrophysics, Princeton University, and Director of the Princeton Center for Theoretical Science. One of my longstanding interests is in the structure and properties of non-crystalline states of matter because their properties are still poorly understood and, hence, have the potential for exhibiting surprising features.

ST: I am a theoretician in the Department of Chemistry, Department of Physics, and Princeton Institute for the Science and Technology of Materials. My scientific research covers statistical mechanics, condensed matter, photonics and cancer modelling. Amorphous states of matter have always intrigued me; especially a new class called hyperuniform materials (HM).

MF: I am physicist in the Department of Physics and the Advanced Technology Institute, University of Surrey. My research interests lie in the fields of nanophotonics, quantum optics, and nanoelectronics. In particular, I focus on the identification of novel phenomena and functionalities in artificially structured photonic materials and in implementations of linear-optical quantum information processing in nanostructured materials.

What novel properties have you unearthed about photonic band gaps (PBG)? How will they have transferrable application?

PS, ST & MF: Motivated by work on disordered HM, we discovered a new class of photonic materials, known as hyperuniform disordered solids (HUDS). Disordered and isotropic – meaning they can be used in photonic integrated circuits and other applications without sensitive alignment of material, waveguides or cavities, and are much less sensitive to fabrication defects – they contradict conventional wisdom that PBG requires periodicity and anisotropy. Enabling freeform circuit design and a reduction in defects makes them the optimal material for virtually any photonic application. These discoveries have been enabled by the invention of a universal protocol for mapping point patterns into optimal designs.

We showed that it's possible to introduce waveguides in HUDS that can have arbitrary shape and trap light in cavities with select electromagnetic patterns. After discovering these novelties, both theoretically and numerically, we joined with experimental Professors Weining Man and Paul Chaikin to synthesise and test HUDS on the microwave- and infrared-scale.

Can you provide some insight into your research area?

PS: In 1984, Professor Dov Levine and I introduced the concept of quasicrystals, hypothetical solids with long-range quasiperiodic translational order and rotational symmetries that are forbidden for periodic solids. Independently, Professor Dan Shechtman and his collaborators found aluminium and manganese alloys that we identified as matching the predicted diffraction pattern for an icosahedral quasicrystal. In 2011, Shechtman won the Nobel Prize in Chemistry for his experimental discovery. I have since worked with various scientists to explore mathematical and elastic properties of quasicrystals. In 1998, I launched a systematic search for natural quasicrystals that culminated in the discovery 11 years later of quasicrystalline grains in a CV3 carbonaceous chondrite that formed 4.5 bn years ago, making quasicrystals one of the first solids to form in our solar system. I subsequently led a geological expedition to Kamchatka, where we successfully recovered additional samples and discovered other new mineral phases.

ST: Dr Frank Stillinger and I introduced the concept of Hyperuniform Matter, characterised by unusual suppression of density fluctuations, in 2003. Specifically, hyperuniform point (particle) configurations are categorised by vanishing infinite-wavelength density fluctuations and encompass all crystals, quasicrystals and special disordered many-particle systems. This provides a means to place an umbrella over both crystalline and special non-crystalline materials. HUDS can loosely be regarded as a state that is intermediate between perfect crystals and perfectly disordered materials. In 2008, we showed that stealthy HUDS can be created as disordered ground states and possess novel single-scattering properties, suggesting they may find applications in photonics.

MF: I have been involved in the early studies of quantum optical effects in photonic band gap materials, while working in the group of Professor Sajeev John, one of the inventors of the photonic crystal concept. My work on quantum optical effects in photonic crystals revealed coherent all-optical switching and transistor action in PGB materials. Subsequently, I developed the first general formalism for thermal emission in microstructured photonic systems, which provides a comprehensive understanding of Planck's radiation law modifications in these systems, rigorous design principles for spectral and angular-selective absorbers and highly efficient solar cell and thermophotovoltaic components.

Do you have plans to extend R&D?

PS, ST & MF: We have partnered with industry to create a start-up company, Etaphase Inc, that will develop our scientific discoveries into a range of products, including novel photonic integrated circuits for use in computer datacenters, sensors, improved photovoltaics and displays. With an eye to potential end uses, we hope to continue both basic science and applicationww and develop better theoretical understanding of PBG and other physical properties of HUDS. The path is full of challenges, but we do not foresee any showstoppers at this point.

Unlocking the potential of HUDS

Physicists at Princeton University use novel computational tools and employ proven fabricating methods to discover the broader electronic and photonic applications of a new class of materials

PHOTONIC BANDGAP (PBG) materials are synthetically designed materials that block light for a finite band of energies and then transmit light with energies outside that band, similar to the way in which a semiconductor acts for electrons. The development of PBG materials is seen as increasingly vital in the replacement of electronics (electron transport) with photonics (light transport), which is necessary to realise the next generation of communications and computer devices, as well as improved sensors, LEDs, display devices and photovoltaics.

In order to control and manipulate light flow, specifically-designed defects can be introduced into PBG materials that make it possible to transmit or trap specific frequencies within. Because these frequencies are far from those above and below the band gap, their behaviour is not degraded by mixing with modes with similar frequencies, thus enabling the ultimate regulation of light flow. Through their invention of a new form of PBG materials with unique symmetries and statistical properties, scientists at Princeton University's Department of Physics have delivered ground-breaking work with numerous important applications.

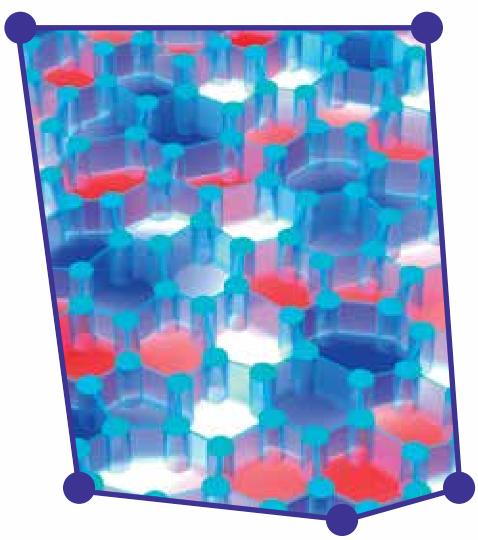


Figure 1. Electromagnetic Field Propagating through a hyperuniform disordered structure (semi-transparent region: dielectric hyperuniform structure, shades of blue/red, maxima and minima of the electric field).

The group has been developing two classes of novel non-crystalline designer materials, composed of photonic quasicrystals and hyperuniform disordered solids (HUDS), which act as a photonic semiconductor. Principal Investigator, Professor Paul Steinhardt, explains that their work has expanded the traditional view of PBG materials by showing that HUDS, whilst isotropic and with no translational order, have large and complete band gaps for both polarisations of light; a result which "contradicts the longstanding conventional wisdom that only crystalline materials have PBG". He adds: "As photonic crystals are inherently anisotropic (blocking different bands of light propagating in different directions) they impose delicate constraints on designing photonic circuits, and are also difficult to fabricate accurately".

Because HUDS are isotropic and thus inherently disordered, they are less sensitive to fabrication defects and are an optimal base material which, co-PI Dr Marian Florescu (now based at Surrey University) suggests: "Have broad physical implications beyond photonic materials. It may become possible, for instance, to produce different types of hyperuniform structures and, consequently, many distinct classes of novel electronic or phononic systems".

EXPLORING ELECTRONIC PROPERTIES

Steinhardt introduced, in 1984, along with his student Dov Levine, the concept of quasicrystals. These are solids with quasiperiodic translational order and rotational symmetry forbidden to crystals, such as fivefold symmetry in 2D and icosahedral symmetry in 3D. At that time, Steinhardt recognised that the question of being able to fully understand the electronic properties of quasicrystals had yet to be answered. In 2005, along with Professors Weining Man (San Fransisco State University) and Paul Chaikin (New York University), Steinhardt was presented with the opportunity to explore the band structure of a photonic quasicrystal that offered an easily synthesised and precisely testable solid. "The photonic quasicrystal network," he observed, "had a quasiperiodic pattern with icosahedral rotational symmetry. Photonic quasicrystals, we discovered, have a band gap that is more isotropic than in photonic crystals – a highly desirable property for many applications."

In an effort to find the optimal design of these quasicrystals, Steinhardt joined with theorists Professor Salvatore Torquato, an expert on hyperuniform materials and optimisation problems, and photonics expert Florescu. Their research led them to challenge the conventional view that periodicity or quasiperiodicity is required to have a complete PBG. In doing so they found that it is, in fact, possible to obtain large complete band gaps in a new form of material that is isotropic and disordered like glass but also 'hyperuniform' like crystal. The concept of hyperuniformity had been introduced and studied earlier by Torquato and his colleague Dr Frank Stillinger.

"HUDS," as Torquato expands, "have long-range density variations that are uniform like crystals, even though they are isotropic". They discovered that HUDS exhibit large, perfectly isotropic band gaps, even though they are not periodic or quasiperiodic. Since isotropy is enormously advantageous in many optical applications, this presented them with the opportunity to look at a new class of photonic solids with properties that are superior to photonic crystals and led to current experimentation on hyperuniform disordered PBG materials.

INNOVATION IN DESIGN

Initially a theoretical project, the work has now grown into a fully-fledged trial. Led by expert theorists Steinhardt, Torquato and Florescu, this collaborative effort into computer design and simulation of HUDS has been supported by a National Science Foundation (NSF) Early-concept Grant for Exploratory Research (EAGER). The research also benefits from the knowledge of Chaikin and Man who have been fabricating and testing the theorists' designs.

The objective is to explore the properties of these solids for novel isotropic photonic devices, such as waveguides, splitters and wavelength-division multiplexers. There are some standard tools for fabricating photonic crystals which are just as effective when applied to fabricating photonic quasicrystals or HUDS. Methods include stereo-lithography, laser sintering, 'toothpaste' machines, direct laser writing and e-beam lithography, all of which begin with a theoretical design that is then converted to a variation of computer-

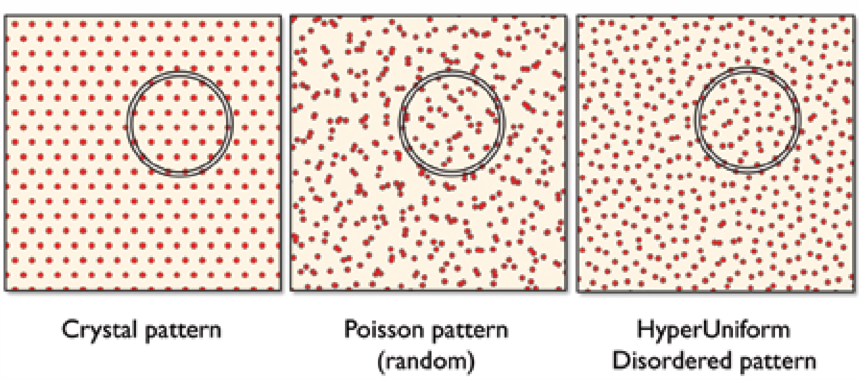
This research has important applications in optical communications, energy harvesting, non-linear optics and improved light sources

aided design. Steinhardt points out that the theoretical design is where innovation and invention play a key role: "Depending on the design, different energy bands are blocked in different directions. HUDS are optimal in that they are isotropic and, hence, have isotropic band gaps, giving them maximum flexibility in photonic circuit design". Florescu also notes: "Benefiting from a unified approach for generating near-optimal photonic solids, we are now ready to add an extra dimension to our planar HUDS, opening the door for fully 3D-integrated optical devices".

BROADER IMPACTS REALISED FROM RESEARCH

The group is focused on developing fundamentally novel devices and functionalities that can be garnered from HUDS. Firstly, the physicists have utilised finite difference time domain and band structure computer simulations to demonstrate that waveguide architectures of arbitrary shape can be constructed in hyperuniform disordered photonic solids – something that is not possible in photonic crystals – and show that optical cavities for trapping and manipulating light in a variety of modes can be designed and densely arranged into the structure. The collaborators have submitted two articles on HUDS that apply the ideas to novel waveguides and cavities and presented findings at a series of international conferences, including the 2012 American Physical Society meeting. Additionally, their research included a study that appeared in *Applied Physics Letters* in 2010 showing how band gap width and quality degrade due to random fabrication defects. This work has inspired the creation of a start-up company, Etaphase Inc, which aims to apply research advances to photonic integrated circuits, sensors, photovoltaics and displays.

NSF believes this work has the potential to significantly expand the development of a new material for next-generation concepts for advanced photonic devices. From Steinhardt's perspective, the efforts have important applications in "optical telecommunications, energy harvesting, non-linear optics and improved light sources".



In a hyperuniform distribution of points, the number of points within a circle varies according to where you the place the circle by an amount that depends on its circumference, as shown for the case of a crystal array of points (left); for a truly random distribution (middle), on its area; for HUDS (right), despite being disordered and isotropic like the random distribution, the variance depends on the circumference, the same result obtained for crystal.

INTELLIGENCE

EAGER: HYPERUNIFORM DISORDERED PHOTONIC BAND GAP MATERIALS

OBJECTIVES

To explore the properties of new photonic bandgap materials, called hyperuniform disordered solids, for novel isotropic photonic devices such as waveguides, cavities and splitters

KEY COLLABORATORS

Professor Paul Chaikin, New York University

Professor Weining Man, San Francisco State University

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PAUL J STEINHARDT is the Albert Einstein Professor in Science and Director of the Princeton Center for Theoretical Science at Princeton University. His research spans problems in particle physics, astrophysics, cosmology, geophysics and condensed matter physics, including the introduction and exploration of quasicrystal properties and HUDS.

SALVATORE TORQUATO is Professor of Chemistry at Princeton University. He is broadly interested in the fundamental microscopic understanding of the structure and bulk properties of condensed matter via statistical mechanics. His current work focuses on self-assembly theory, particle packings, hyperuniform materials, glasses, quasicrystals, optimisation of materials and cancer modeling.

MARIAN FLORESCU is Senior Lecturer at the University of Surrey. His research interests include nanophotonics, implementations of linear optical quantum computing and spintronics. His current activities are focused on non-crystallographic PBG materials, thermal radiation in photonic materials and quantum optics in structured photonic reservoirs.

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