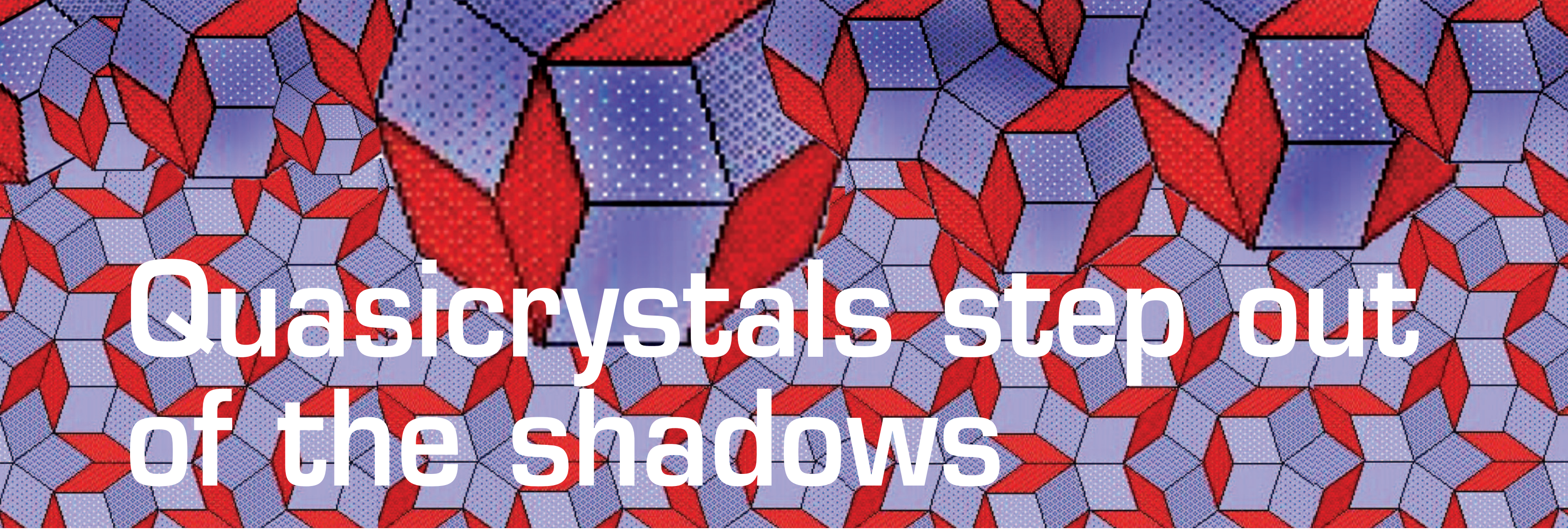

Quasicrystals step out of the shadows

Photonic quasicrystals, optical structures that are not strictly periodic but do show regular arrangements, are beginning to find applications beyond the laboratory. To understand them, one must first understand conventional photonic crystals. *Materials Today* investigates the foundations of quasicrystals and looks at where they might find use.

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A quasicrystal is a special type of crystal that presents multiple planes of rotational symmetry to an extent that was conventionally believed to break the rules of crystallography, having so-called 'forbidden' symmetries. One of the first to be identified was an alloy of Al and Mn that displays a diffraction pattern showing both five- and ten-fold symmetries. These materials, which are under intense scrutiny by physicists worldwide, are moving on from being just rule-bending (and light-bending) curiosities; they are starting to find applications in scientific research, communications, and security inspection systems.

Although the first academic papers on photonic crystals appeared 25 years ago, the recent surge in activity can be traced back to pioneering studies by Eli Yablonovitch, now at the University of California, Los Angeles[1].

Yablonovitch speculated that a band gap could be created for photons in the same way that a semiconductor possesses an electronic band gap. He proved this theory by showing that microwaves would not propagate in a photonic structure created by drilling a three-dimensional array of millimeter-sized air holes in a dielectric material[2]. By 2000, at the height of the telecoms boom, photonic band gap (PBG) materials had become hot property and the first start-ups were spun out of university research groups. These early innovators knew that photonic structures could confine light extremely tightly, allowing radiation to be guided and bent around sharp corners with virtually no energy loss. Such attributes make photonic crystals ideal for creating miniature optical circuits and highly efficient optical fibers that avoid the need for costly regenerators.

Photonic crystals are materials patterned on the scale of the wavelength of light (some hundreds of nanometers). A periodic variation in dielectric constant gives rise to a PBG, which means that some wavelengths cannot travel through these materials (like the periodic potential in a semiconductor crystal gives an electronic band gap). Two-dimensional photonic crystals, for example, are typically regular arrangements of holes in triangular or square arrays spaced several hundred nanometers apart in a dielectric material. Such structures can have the limitation that different colors of light have different properties when propagating either along the lines of holes or diagonally across them. This is a problem for making materials that behave the same no matter which direction light is traveling through them.

In a photonic quasicrystal, the structure has a nonperiodic array of holes so that, while the average distance between the holes remains constant, they are able to have a higher degree of symmetry. This design means that instead of four (square) or six-fold (triangular) directionality, it is possible to achieve 12- or even 20-fold directionality. Thus, the materials appear to be much more isotropic as far as the light is concerned.

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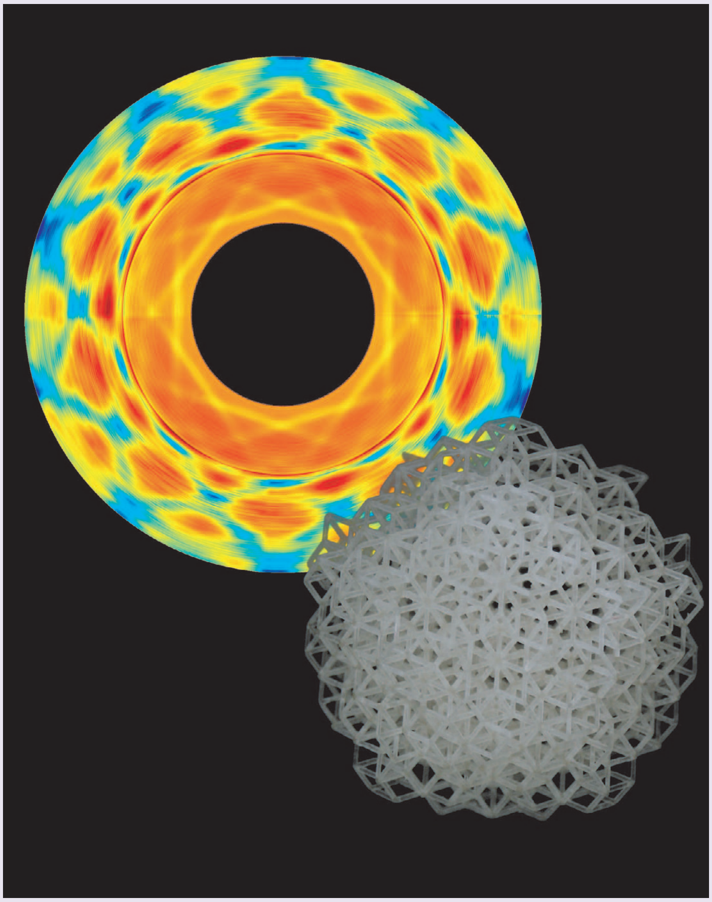
A quasicrystal pioneer

Paul J. Steinhardt is the Albert Einstein Professor in Science at Princeton University. Along with colleague Dov Levine at Technion - Israel Institute of Technology, he introduced the concept of quasicrystals as a new phase of solid matter with disallowed crystallographic symmetries. Steinhardt continues to make contributions to understanding the unique mathematical and physical properties of quasicrystals. Here, he describes some of his recent work[3] that has looked at icosahedral quasicrystals in particular.

What are the key achievements?

There are two real breakthroughs in this work[3]. Scientifically, we have made the first measurements of the photonic properties of a three-dimensional icosahedral quasicrystal – both its PBG structure and effective Brillouin zone. The quasicrystal itself is a physical structure synthesized from two or more different materials that are quasiperiodically distributed with an icosahedral symmetry that is impossible for ordinary crystals. The gap structure and Brillouin zone characterize the frequencies and directions for which incoming light is trapped by the structure.

Technologically, these results mean that the icosahedral quasicrystal is the foremost candidate structure for making a complete PBG and hence to trap light. Consider a structure that completely reflects or diffracts a particular color of light independent of the incident direction. If the light were placed inside a material with that structure it could never get out. The search for such a structure with a gap forbidding the passage of light in all directions has fascinated physicists and engineers for the past two decades. Such photonic devices have many applications in research, computation, and communication.



Icosahedral photonic quasicrystal (white polymer structure) and a visualization of the Brillouin zone of a three-dimensional quasicrystal (the ring with yellow lines indicates nearly symmetrical zone boundaries). (Courtesy of Paul Steinhardt.)

Our discovery that there are few sizable PBGs in quasicrystals, that the positions of the gaps can be understood and controlled, and that the gap structure is almost spherically symmetric (much more so than competing crystalline structures), makes them the most desirable structures for photonics.

What are the implications of this work?

Our results point to a new direction for photonics – the use of quasicrystals of various symmetries for technological applications, as well as new directions in the study of quasicrystals – direct photonic measurements with computation as a method of exploring electronic properties.

What are the next steps?

Our research is already proceeding along three important directions. First, we are exploring the use of optical tweezers for constructing a miniature version of our photonic quasicrystals with band gaps at visible wavelengths. Working with David Grier at New York University, we have already assembled a sample with 250 spheres into a three-dimensional icosahedral quasicrystal structure. We plan to continue to pursue this and other fabrication methods, such as two-photon polymerization.

Second, we are investigating how to optimize the design of the photonic quasicrystal. Our first investigations have used structures composed of rods, but a combination of rods, spheres, and surfaces is probably optimal based on analogous studies of photonic crystals. We are developing a computational algorithm to find the optimal structural configuration for photonic applications.

Third, we are exploring different types of photonic, electronic, and acoustic applications of our quasicrystals.

Further information: www.physics.princeton.edu/~steinh/quasiphoton

Photonic crystals: the basics

"Introduce a crystal lattice pattern of tiny air holes into a dielectric material and you will see some interesting effects not readily explained by classical physics," says Jeremy Mills of Porisma, a marketing and strategy consultancy. "Photons within a particular wavelength range simply will not propagate through the otherwise transparent material. This effect, known as a PBG, is best understood by analogy with the physics of semiconductors, where the interaction of electrons with a crystal lattice produces allowed energy states and a prohibited band gap region."

To produce a PBG, the air holes in the dielectric medium need to be separated by a distance roughly equal to the photon wavelength divided by the refractive index of the dielectric. This implies that a hole spacing of about 450 nm is needed to achieve a band gap at 1550 nm (the typical optical communications wavelength) in Si. The width of the band gap depends on the contrast in refractive index between the two dielectric materials in the lattice (in this case Si and air), with a larger contrast yielding a wider band gap.

"As with semiconductors, introducing defects into a crystal lattice – in this case holes of different diameter – produces a band structure," adds Mills. "Thus a photonic crystal waveguide can be produced by omitting a row of holes. Extremely tight confinement within the waveguide region makes it possible to bend the light around sharp corners with low energy loss, enabling very small optical circuits."

Photonic crystal structures have been fabricated in one, two, and three dimensions. Most researchers' attention has focused on two-dimensional photonic structures, such as waveguides and planar circuits. One-dimensional versions, such as fiber Bragg gratings, are in widespread use, while three-dimensional photonic crystals include relatively recent stacked planar structures and self-assembled nanostructures.

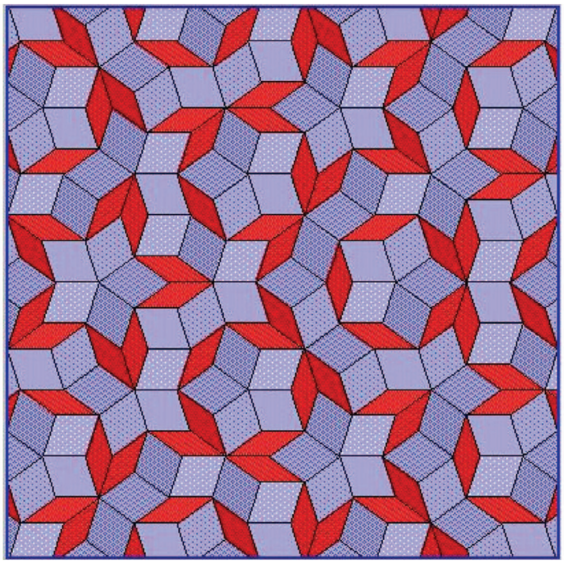


Fig. 1 Penrose tiling. Two shapes based on the golden ratio can be tiled to fill a two-dimensional space using a nonperiodic pattern. (Courtesy of Stuart Brand, Durham University, UK.)

Quasicrystal geometry

In crystalline materials, the positions of atoms are arranged in a periodic lattice of points, which repeats itself in space throughout the entire crystal. Quasicrystals represent a relatively new state of matter that was unexpected only a few years ago. Quasicrystals are intriguing because they feature a combination of some properties of conventional crystals and others of noncrystalline matter, such as glass.

A quasicrystal was first observed in an Al_6Mn alloy, which has a five-fold symmetry once thought to be impossible. Since then, quasicrystals have been found in a wide variety of other substances.

Quasicrystals fill space with five-fold symmetry based on the golden ratio or ϕ, where $\phi = ½ (1 + \sqrt{5})$. Penrose tiles allow a two-

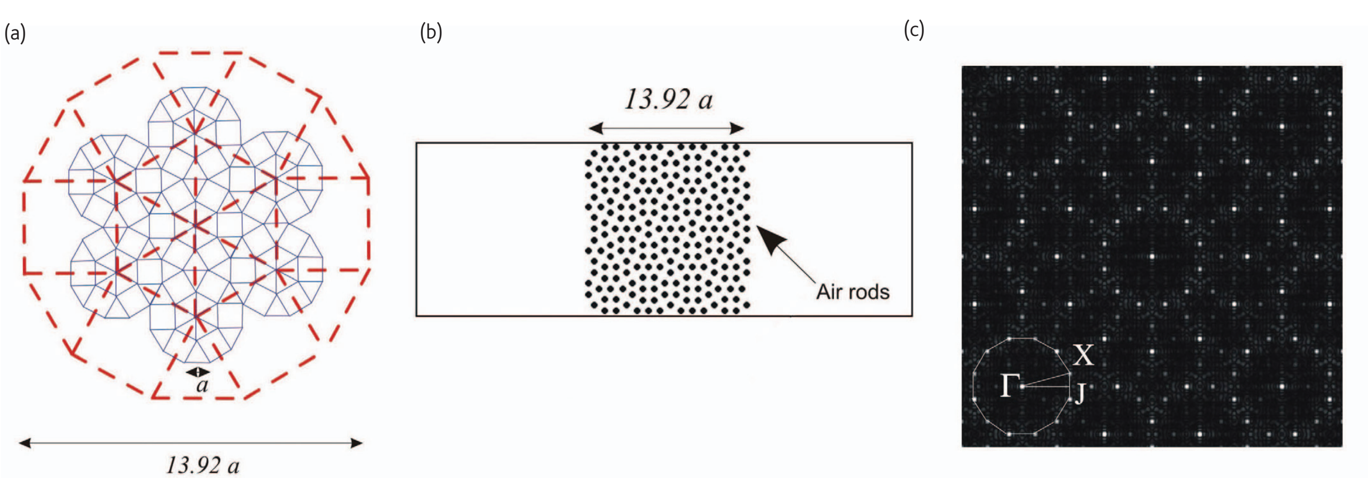


Fig. 2 (a) Quasicrystal pattern based on a square-triangular tiling. (b) Plan of air rods placed at quasicrystal vertices and etched though a planar waveguide. (c) Representation of the quasicrystal reciprocal lattice, showing 12-fold symmetry. The Brillouin zone (white dodecagon) corresponds to the supercell shown dashed in (a). (Reprinted with permission from[4]. © 2000 Nature Publishing Group.)

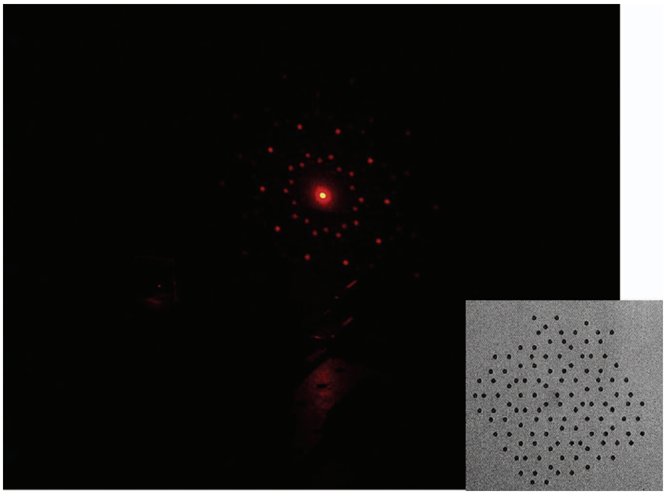


Fig. 3 Diffraction pattern showing five-fold rotational symmetry obtained from a SiO_2 substrate with holes drilled in an arrangement based on Penrose tiling. (Courtesy of Stuart Brand, Durham University, UK.)

dimensional area to be filled using two shapes based on ϕ in a nonrepeating, aperiodic pattern that has five-fold rotational symmetry (Fig. 1). Many scientists believed that filling a three-dimensional space in five-fold symmetry was impossible, but the answer was again found in ϕ. Where the solution in two dimensions required two shapes, it can be accomplished in three dimensions with just one. The shape has six sides, each one a diamond with diagonals that are in the ratio of ϕ.

Photonic quasicrystals

Jeremy J. Baumberg, director of the University of Southampton NanoForum and cofounder of photonic crystal company Mesophotonics is deeply involved in research into quasicrystals (Fig. 2)[4]. "Photonic crystals have a dielectric constant that varies periodically, making them interact with light in interesting ways," he says. "In analogy to electronic band diagrams for crystalline materials, one can think about photonic band structures in these materials," explains Baumberg. "Where there is a band gap, light cannot propagate through the material. In the same way that band gaps are used to control electronic transport in semiconductors, we hope that engineered photonic crystals can be used to control the routing and emission of light."

Quasicrystals have what Baumberg describes as 'a not-quite-periodic' structure. That is the building blocks don't quite follow a crystalline lattice. "It turns out that quasicrystals offer the possibility to achieve a PBG in three dimensions rather than just one or two," he says. "This capability could enable the trapping of light, and certainly close control of light transmission [see inset on Paul Steinhardt's work on page 45]. This interesting area brings together an exciting combination of fundamental materials science, optical theory, fabrication, and real applications."

Stuart Brand at Durham University, UK has worked on Penrose-tiled structures (Fig. 3), and is now concentrating on the terahertz frequency range for applications in materials research, medical imaging, and security. "Engineering colleagues are currently making two-dimensional structures composed of periodic arrays of semiconductor/metallic rods, but it is hoped that the work may extend to quasicrystal structures in due course," says Brand. "The structures are formed in Si by a lithographic process and then sputtered with metal. The end product consists of a 'forest' of metallic-like rods that functions in the same general way as a waveguide. We are also working with planar systems that are essentially patterned films."

Both standard photonic crystals and quasicrystals are known to exhibit pass and rejection bands of various widths, which suggests the possibility of tunable filter applications. "A useful development from this work would be the production of suitable filters in the terahertz frequency range," says Brand. "The particular range we are considering is 0-3 THz, centered around 1 THz, because that's the range accessible to our experimental colleagues." The work could eventually lead to structures of this type being used in the area of security applications, since clothing is transparent to terahertz radiation, allowing, say, airport scanners to identify potentially concealed weapons.

Quasicrystals, instead of being theoretical materials that exhibit mysterious 'forbidden' behavior with respect to their photonic band structures, are actually achievable and may offer new solutions in optical analysis. They seem likely to find applications in inspection and security systems, but that is only the beginning. It is quite possible that quasicrystals could open the door to a new branch of optics.

Some of the other unusual properties of quasicrystals include low electronic and thermal conductivity, low surface friction, and and a negative coefficient of resistivity. These properties suggest that quasicrystals could find other applications in wear-resistant coatings, hydrogen storage, catalysis, and microelectronics. mt

REFERENCES

1. Yablonovitch, E., *Phys. Rev. Lett.* (1987) **58**, 2059
2. Yablonovitch, E., and Gmitter, T. J., *Phys. Rev. Lett.* (1989) **63**, 1950
3. Man, W., *et al.*, *Nature* (2005) **436**, 993
4. Zoorob, M. E., *et al.*, *Nature* (2000) **404**, 740