

Manipulating the flow of light with photonic crystals

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Structures with periodically varying indices of refraction allow light to be controlled for a variety of purposes. That's a trick Nature has used for 500 million years.

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Photonics is the science and technology of generating and controlling the flow of photons. It is persistently in the scientific limelight; one can read of it daily in the popular and technical science press, and it receives enormous levels of funding. Why all the fuss? Because photonics promises to underpin imminent technological revolutions in signal processing, communications, computing, astrophysics, biology, and even medicine.

Bragg diffraction

The photonic crystal is the working currency of photonics. It is a regular structure that offers propagating photons a periodic variation in refractive index. That periodicity can range in size from centimeters for some applications, down to tens of nanometers for others. Maxwell's equations coupled with the periodic boundary conditions imposed by the crystalline structure predict that the propagation of electromagnetic radiation through a photonic crystal will be inhibited if the periodicity has a length scale similar to the radiation's wavelength. And herein lies the technological allure: Intelligently engineered structural periodicity can inhibit the propagation of radiation within a material in one, two, or even all three dimensions. So say goodbye to electrically sent information, to subluminal data-processing speeds, and even to inefficient lighting. The age of technological photonics is dawning.

One fundamental way to understand the physics of photonics is by analogy with the energy bands in semiconductors. It is possible, however, simply to consider photonic crystals from the perspective of how light scatters from the various symmetry planes in the crystal. Strong reflections arise when certain wavelength bands of electromagnetic radiation coherently scatter by constructive interference from those planes. In 1913, William H. Bragg and his son William L. Bragg explained the diffraction pattern of x rays scattering from an atomic crystal by modeling the crystal as a set of discrete parallel planes separated by a constant distance. So the phenomenon is called Bragg diffraction. By scaling up by several magnitudes both the wavelength of the radiation and the size of the crystal, engineers enter the conventional optical photonic regime and can build crystals that produce strong colored reflections. Another way of interpreting the strong reflections in these photonic crystals is to say that Bragg diffraction simply prevents certain wavelength bands from propagating through the crystal in particular directions.

The exact nature of the reflected wavelength band de-

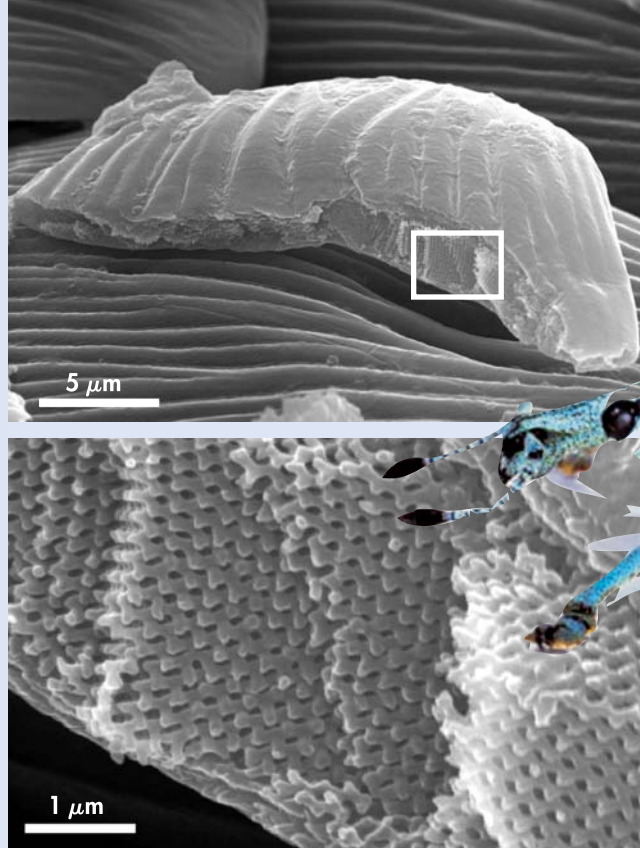
pends on three key variables. The design of the crystal is important since different directions through a crystal correspond to somewhat different periodic spacings. The difference in the refractive index of the constituent materials and the relative volumes they occupy are the other key variables, since they influence the nature of the standing (that is, nonpropagating) waves in the crystal. If the correct recipe of all three variables is chosen for a photonic crystal, then Bragg diffraction can occur in all three dimensions for the same wavelength band. In that case one has what is called a complete 3D photonic bandgap. That is, a particular band of electromagnetic radiation cannot propagate in any direction through the crystal.

This complete inhibition of photon flow is all very well, but where is the usefulness or the application? The usefulness lies in the deliberate incorporation of, say, a path of defects from one region in a crystal to another region. Bragg diffraction is eliminated along the defect path, which allows previously excluded radiation to propagate freely along it. In that way, a nanoscale path may be designed and incorporated in a device to guide a light pulse or beam from one place to another—for instance, within an integrated circuit where the path is extremely short or along the center of a photonic-crystal fiber where the path is extremely long. This form of light guidance is not mediated by total internal reflection, as is the case with conventional optical fibers and effective-index crystal fibers, but by Bragg diffraction. In fibers, it offers several potential advantages, including lower loss across a broad range of wavelengths, higher power-handling capabilities, and the exploitation of nonlinear processes for specific desired effects.

The manufacture of photonic crystals is not straightforward, largely because of the nanoscale dimensions associated with optical photonic crystals and the incredible expense required to engineer highly precise samples. Only within the past decade or so has it been possible to fabricate useful 3D bandgap materials for optical wavelengths by using, for example, elaborate multiple-beam interferometry or electron-beam lithography. The fiber-drawing or extrusion-based procedures for manufacturing high-quality photonic-crystal fibers, which are 2D photonic-bandgap structures, have also become well established.

Photonic crystals in nature

Technological photonics development has existed for two decades, but a parallel world has exploited 50 million decades



The surfaces of many colored weevils are covered with circular scales whose intense angle-independent color originates from highly ordered, three-dimensional photonic structures. The scanning electron microscope images of a fractured weevil scale, shown at two resolutions, reveal the crystal structure. (Courtesy of Joseph Noyes and Peter Vukusic.)



different animal species, although they are more common in invertebrates. They create the structural color associated with, for example, the wing scales of some *Lepidoptera* (see the cover image), the colored body scales of weevils (see the figure), and the barbules of some bird feathers.

The photonic performance of natural samples, compared with synthetic ones, is restricted by the relatively small difference in the refractive indices of the two constituent media. Each biological species' photonic crystal comprises naturally grown materials; accordingly, the magnitude of the highest refractive index is limited. As a result, natural photonic systems cannot produce complete 3D photonic bandgaps. Consequently, the wavelength band whose propagation through the crystal is inhibited will change with the crystal's orientation. The inability to produce complete bandgaps influences the way nature seems to use its 3D photonic crystals. Instead of fabricating large-area systems from one single grain or domain of 3D structure, it tends to juxtapose small grains of identical structure in random orientations. Since each grain's orientation reflects a slightly different band of color, an overall averaged single color is created that is independent of observer perspective.

With only a few remarkable exceptions, the technical and the natural worlds use their photonic crystals for very different purposes. Nonetheless, the physics that underpins their applications is identical: The flow of electromagnetic radiation is controlled by Bragg scattering in specially fabricated and often multidimensional periodic structures. In the future, as the horizon of biotechnological capability broadens, the two photonic worlds may overlap. Imagine gene-coding a desirable photonic structure and then simply growing it. Now that would be something to make a fuss about.

Additional resources

- J. D. Joannopoulos, R. D. Meade, J. N. Winn, *Photonic Crystals: Molding the Flow of Light*, Princeton U. Press, Princeton, NJ (1995).
- S. G. Johnson, J. D. Joannopoulos, *Photonic Crystals: The Road from Theory to Practice*, Kluwer Academic Publishers, Boston (2002).

The online version of this Quick Study provides additional pedagogic material, photographs of natural photonic structures, and links to online resources.

of photonics development: This is the natural world. An enormous variety of photonics designs underpins the appearance of living systems; they manipulate light and color in one, two, or three dimensions for highly specific biological functions.

The structural color that evolved in some animals offers much more control over light than does pigmentary color and allows, in particular, for brighter reflections of the appropriate components of the UV and visible spectra. Additionally, if the periodicity in the structure is suitably designed, the reflection from structurally colored species may even be angle independent and linearly or circularly polarized. Many animal visual systems are sensitive to polarized light, so polarization is extremely useful as a signaling channel. While male *Morpho* butterflies, for example, famously use their brilliant colors to signal over long distances, often as much as a quarter of a mile, other insects, like some *Papilio* butterflies, and even some crustaceans, like shrimp, generate polarized light for signaling. Indeed, nature uses photonic crystals to control light not only for signaling but also for camouflage and even thermoregulation.

By far the most common type of photonic structures in living systems are forms of 1D periodic structure, generically referred to as multilayer reflectors. These are the simplest natural photonic crystals; they possess periodicity in only one dimension. Less frequently encountered are natural 2D and 3D photonic-crystal systems. In line with their higher dimensionality, they exhibit higher degrees of structural complexity. As with the 1D case, however, a periodic variation in the refractive index inhibits the propagation of specific wavelength bands. Those bands are then visible to an observer as bright reflections.

For the photonic engineer, 3D photonic crystals in nature are exceptionally fascinating systems. Gem opals are true natural 3D photonic crystals. They are, however, inanimate systems formed from precipitative settling processes. The 3D photonic structures in living systems that evolved for specific biological functions are much more interesting and morphologically diverse. Examples of these occur across a range of