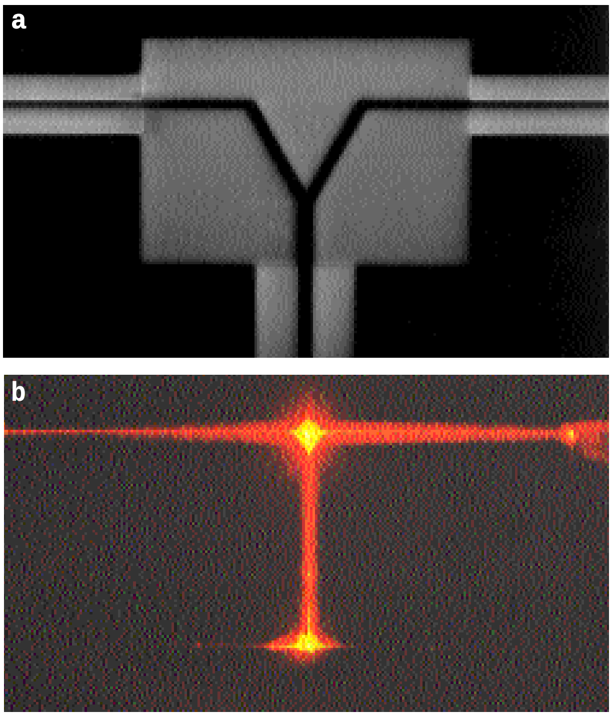
Seeing the Future in Photonic Crystals

by Jennifer Ouellette

After a decade of intensive research, photonic crystals are poised to reap their first commercial benefits. A handful of start-up companies will bring the technology to market, initially as waveguides (Figure 1a) and high-resolution spectral filters (Figure 3) in fiber-optic telecommunications. However, R&D now under way will give birth to photonic-crystal lasers, light-emitting diodes (LEDs), and photonic-crystal thin films to serve as anticounterfeit protection on credit cards. Ultimately, researchers hope to build diodes and transistors from this novel material that will one day enable the construction of an all-optical computer.

Can they control the flow of photons?

Photonic crystals usually consist of dielectric materials—that is, materials that serve as electrical insulators or in which an electromagnetic field can be propagated with low loss. Holes are arranged in a lattice-like structure in the dielectric and repeated identically and at regular intervals, a property known as "periodicity." If built precisely enough, the resulting crystal will have what is known as a photonic bandgap, a range of frequencies within which a specific wavelength of light is blocked. This phenomenon is similar to the silicon-crystal lattices used in the semiconductor industry.



Charlton and Parker

Figure 1. Light enters the rectangular photonic crystal beam splitter in which rows of holes have been removed to send the beam left and right (a). A red helium–neon laser glows as it enters the waveguide at the bottom and hits the photonic crystal at the top (b).

In addition, it is possible to create energy levels in the photonic bandgap by introducing defects. For example, changing the size of a few of the holes in a photonic crystal is "equivalent to breaking the perfect periodicity of the silicon-crystal lattice," says Greg Parker, a professor of photonics at Southampton University in England. Thus, although perfect crystals are valuable for fabricating dispersive elements such as superprisms and three-dimensional (3-D) mirrors, those with defects enable researchers to custom-design photonic crystals that allow precise control of the frequencies and directions of propagating electromagnetic waves. This feature makes them especially useful in optical telecommunications and as laser sources.

Much as the ability to control the flow of electrons in semiconductors led to the current explosion in information technology, photonic crystals promise similar control over photons and even greater control of material properties. "Given the impact that semiconductor materials have had on every sector of society, photonic crystals could play an even greater role in the 21st century, particularly in the optical communications industry," says Parker. Indeed, he believes that photonic materials could address many of the problems that currently limit the speed and capacity of optical communications networks.

Of course, such complicated structures are difficult to manufacture, even in the relatively controlled conditions of a laboratory. Researchers have become quite efficient at manufacturing one- and two-dimensional periodic structures, but constructing materials with 3-D periodicity is much more challenging. Photonic crystals with bandgaps in the microwave and radio frequencies are used in antennae that direct radiation away from the heads of cellular telephone users. Yet it has taken more than a decade to successfully fabricate materials with bandgaps in the near-infrared and visible frequencies.

"Ideally, we need to build a truly 3-D lattice structure to gain complete control of the light in all three dimensions," says Parker. "Fortunately, two-dimensional periodic lattices exhibit some of the useful properties of a truly 3-D photonic crystal and are far simpler to make. So they are a good compromise for many applications and are easily incorporated within planar waveguides, for example."

Better waveguides

Miniature waveguides that can transmit light signals between different devices are critical to achieving integrated optical circuits, in which a single chip contains components such as multiple waveguides, switches, and modulators. To date, the difficulty of guiding light efficiently around tight bends has limited the development of such small-scale interconnects. In conventional fiber-optic waveguides, a tight curve results in an angle of incidence that is too large for total internal reflection to occur. Thus, light escapes at the corners, which weakens the signal. Photonic-crystal waveguides, however, can confine light in a narrow beam around tight corners.

"The basic idea is to carve a waveguide out of an otherwise perfect photonic crystal. Once we have a photonic crystal with a bandgap, we can introduce a defect to attempt to either trap or localize the light," says John Joannopoulos, a professor of physics at the Massachusetts Institute of Technology (MIT). "If we use a line defect, we can also guide light from one location to another." Joannopoulos is also a cofounder of Omniguide Communications (Cambridge, MA), a start-up venture based on the MIT photonic-crystal research.

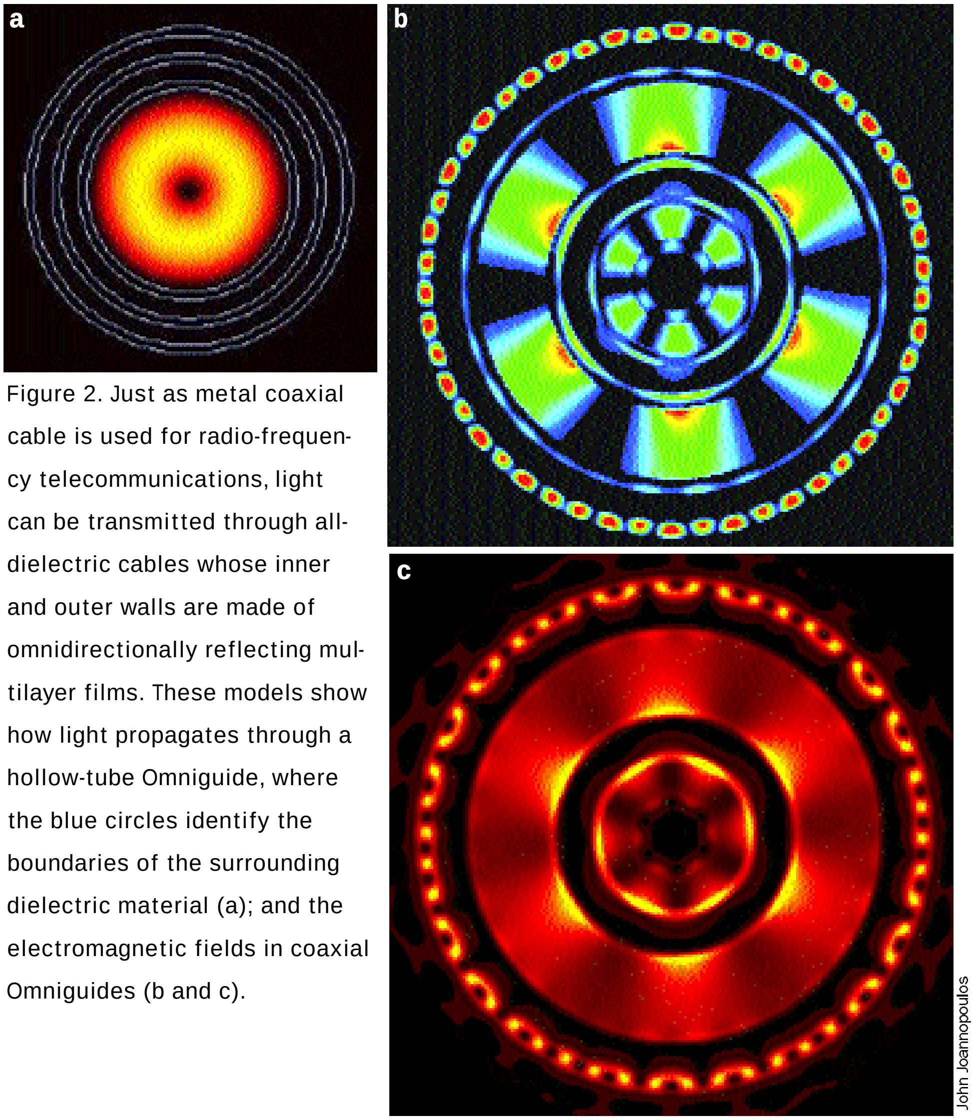


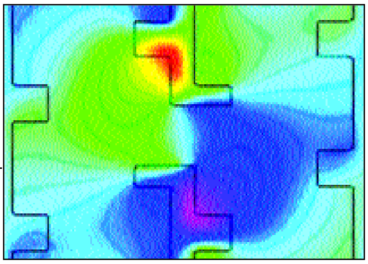
Figure 2. Just as metal coaxial cable is used for radio-frequency telecommunications, light can be transmitted through all-dielectric cables whose inner and outer walls are made of omnidirectionally reflecting multilayer films. These models show how light propagates through a hollow-tube Omniguide, where the blue circles identify the boundaries of the surrounding dielectric material (a); and the electromagnetic fields in coaxial Omniguides (b and c).

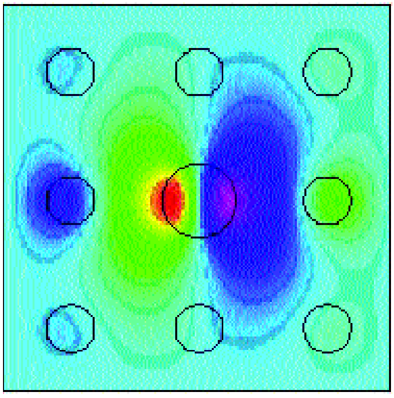
Another breakthrough technology is under development by Mesophotonics (Southampton, England), Parker's start-up venture to develop photonic-crystal components for dense-wavelength division multiplexing (DWDM) systems. The cornerstone of the venture is a planar-waveguide, photonic-crystal technology first devised by Parker and his colleagues at Southampton University. It functions as a small-scale optical "interconnect" capable of steering light around tight corners.

A key advantage of photonic-crystal waveguides is their size—about 100 × 100 µm square—compared with conventional arrayed waveguide gratings, which are roughly 4 cm long and 1 to 2 cm wide. "Two-dimensional photonic crystals will allow great miniaturization in the design of photonic integrated circuits, which will reduce the cost of future optical communications," says Eli Yablonovitch, a professor of electrical engineering at the University of California, Los Angeles, who helped pioneer the field.

Mesophotonics' technology is also compatible with standard silicon technology. In September, the company received $4 million in start-up funds, and progress has been so promising that Parker expects small-batch production of the devices to begin within three years, with a formal market introduction shortly thereafter.

Omniguide's technology stems from the research of Yoel Fink, a company co-founder, who in 1998 as an MIT graduate student fabricated a "perfect mirror" out of a photonic crystal. The device reflected light received from every angle, making it ideal for use as a cladding layer in optical fibers. Omniguide's cofounders took Fink's reflector and rolled it into a tube with a hollow core (Figure 2). The principle is simple: sending light through air rather than glass would increase the efficiency and capacity of optical telecommunication networks—because of less signal loss from dispersion—and reduce the need for signal boosting. However, to achieve the internal reflection necessary to confine light in the center of a conventional optical fiber, the cladding material must have a lower refractive index than the inner medium. Every known material has a higher refractive index than air. Photonic crystals provide a solution to the dispersion problem by acting as "light insulators" to trap light within the hollow core.



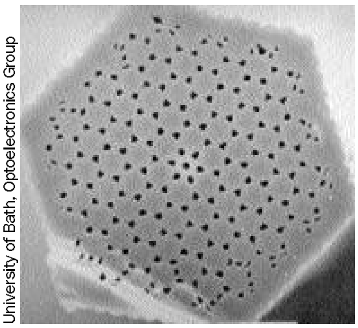


John Joannopoulos

Figure 3. By making point defects in a photonic crystal, light can be localized or trapped in the defect. Since the properties of defects can be finely tuned, such crystals make very sharp filters.

In theory, these hollow fibers reduce signal losses enough to eliminate the need for amplification. Also, the usable bandwidth will be substantially larger than that in existing optical fibers. Omniguide's filter can convey stronger signals with channels spaced closer together. Thus, more data can be contained within any given wavelength range—as much as 1,000 times more than in current optical fibers. Using a hollow fiber filled with air also eliminates the problem of intrinsic nonlinearities of the materials, which frequently impede performance. "When light travels through a material, it changes the refractive index and hence the properties of the system," says Joannopoulos. "The more power that is applied, the bigger the change, and that's why power levels are so limited in (conventional) fiber optics."

Blaze Photonics (Bath, England) seeks to develop recent research conducted at the University of Bath for the production of photonic-crystal glass fibers penetrated by an orderly array of holes (Figure 4). At the center of the optical fiber is an empty core through which light travels. Unlike Omniguide's simple structure, when cross-sectioned, the Blaze Photonics fiber resembles a honeycomb of air and silica, with holes that refuse entry to light of certain wavelengths. The hollow waveguide is created by drawing the glass fibers from a bundle of hollow capillary tubes packed into a hexagonal array. The bundle is then heated to soften the glass, and the array is pulled out into a fine fiber. The structure transmits a broad range of wavelengths with little dispersion.



University of Bath, Optoelectronics Group

Figure 4. Scanning electron micrograph of a photonic crystal fiber, 40 µm across, created by drawing the fiber from a bundle of hollow capillary tubes packed into a hexagonal array.

Other applications

Corning, Inc., the top player in the $4.9 billion optical-fiber market, supported the original research at the University of Bath, although the groups have since parted ways. Corning's leadership remains skeptical that hollow fibers will improve sufficiently in performance to displace solid-core fibers because their leakage rates can be as much as 5,000 times higher than those of leading fibers already in the market. Corning's focus is on using cladding technology to counter dispersion in solid-core fibers, as well as for niche products such as switches, high-powered industrial lasers, and medical equipment.

Microcavities in photonic crystals fabricated from passive materials, such as silicon nitride and silicon oxynitride, can be used to create filters that transmit only a very narrow range of wavelengths, which would prove useful for selecting wavelength channels in a DWDM system. In fact, Parker maintains that arrays of these devices could one day be integrated onto a single chip to separate and sort light pulses of different wavelengths. At Caltech and Lucent Technologies' Bell Laboratories, researchers are building photonic crystals from photoemissive materials—such as III-V semiconductors and glasses doped with rare-earth atoms. They are using them to make narrow-linewidth lasers for possible integration with other components in an optical communications system.

Photonic crystals could also be used to create an LED that emits light at a specific wavelength and direction. Yablonovitch, however, points out that although photonic crystals can help increase the efficiency of LEDs more than 50%, "there are other ways of accomplishing the same goal."

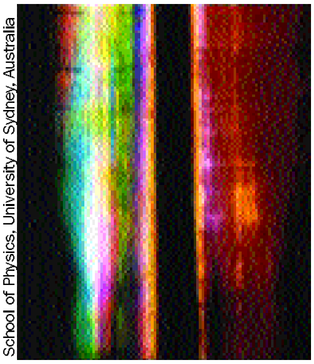
Innovations to further improve the usefulness of photonic crystals continue. Researchers at the University of Sydney in Australia have fabricated photonic-crystal fibers based on a polymer optical fiber. They say it is easier to manufacture than glass photonic-crystal fibers because only one polymer is involved and no dopants are required. Polymers also maintain their structure throughout the fiber better than glass fibers, whose internal structure occasionally collapses. Redfern Polymer Optics (Eveleigh, Australia) has already applied for patents on the new technology, which grew out of research at the Australian Photonics Cooperative Research Center (see The Industrial Physicist, April 1999, pp. 28–30). The company plans to manufacture prototype fiber components and short-haul transmission fibers and eventually to extend the technology to sensing, medical, and lighting applications.

Another University of Sydney team is looking to nature for additional insights into photonic-crystal structure by investigating a marine worm commonly known as the sea mouse. The worm is a predatory creature up to 8 in. long and 2 in. wide and covered with a pelt of iridescent, feltlike hairs whose structure is remarkably similar to that of photonic crystals, with similar optical effects (Figure 5). “Regarded either as a photonic crystal or a photonic-bandgap material, the sea mouse spines would be state of the art,” says Ross McPhedron, a professor of physics who heads the effort.

And, of course, researchers continue to develop and refine manufacturing techniques for the complex 3-D photonic crystals. In 1991, Yablonovitch, then with Bell Communications Research in New Jersey, and his colleagues produced the first 3-D periodic photonic crystal with a complete bandgap for the microwave regime. They achieved this by mechanically drilling holes into a slab of dielectric material covered with a mask consisting of a triangular array of tiny holes. Since then, many other researchers have succeeded in designing other 3-D photonic crystals, the smallest of which to date is designed for wavelengths of about 600 µm.

The ultimate goal for optoelectronic applications is to design and fabricate 3-D photonic crystals at an operating wavelength of 1.5 µm. “Research in the field has been advancing at high speeds since its beginning 10 years ago,” says Joannopoulos. “To maintain the same rate of progress, it will be necessary for experimentalists to overcome the challenges associated with the fabrication of small 3-D periodic structures with feature sizes of less than 1 µm. Only then will photonic crystals be able to fulfill our expectations.”

For Parker, the future of photonic crystals is unequivocally bright. He foresees highly efficient photonic-crystal lasers and extremely bright LEDs entering the marketplace within the next five years or so, along with Mesophotonics’ waveguides and the use of photonic crystals for high-resolution spectral filtering. Looking ahead 10 years, he believes that researchers will have demonstrated the first photonic-crystal diodes and transistors, and in about 25 years, he envisions the demonstration of a simple logic circuit and a prototype optical computer.



School of Physics, University of Sydney, Australia

Figure 5. The shiny spines of the sea mouse (*Aphrodita*) are made up of hexagonal cylinders stacked in layers to form a crystal-like structure, the first photonic crystal found in a living system.

Further reading

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Joannopoulos, J. D.; et al. Photonic Crystals: Putting a New Twist on Light. Nature 1997, 386, 143.

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