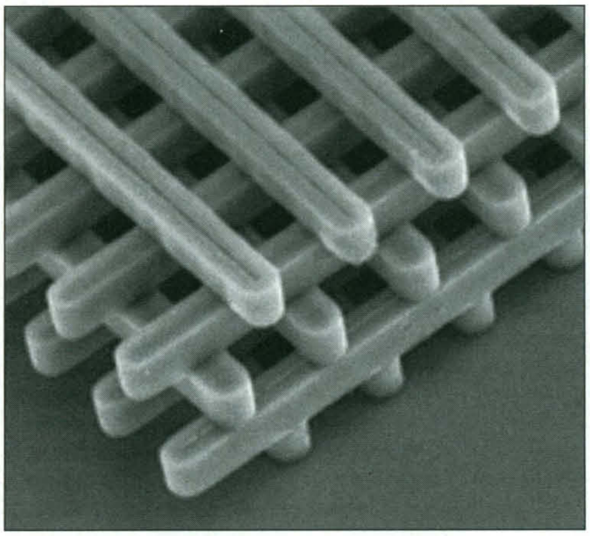
# Cages for Light Go From Concept to Reality

**Once a theorist's dream, intricate latticelike structures can serve as the optical equivalent of semiconductors, trapping and channeling light**

In 1987, when physicist Eli Yablonovitch published what is now recognized as the seminal paper that launched research into photonic crystals, he predicted it would be a blockbuster. The paper, in *Physical Review Letters*, described how specially designed materials, intricately structured to resemble microscopic honeycombs, could manipulate light—trapping, guiding, and filtering it much as semiconductors manipulate electrons. Such materials could be the key to ultrafast optical computing and communications. Yablonovitch, a professor at the University of California, Los Angeles, recalls that the day before publication, "I told my wife that people were going to read my article and say, 'Oh, that's so obvious; why didn't I think of it!' " But in fact, the paper was hardly noticed. "There were no citations to speak of in the first couple of years," he says. "I guess it wasn't obvious to anybody."

Work on photonic crystals may have been slow getting started, but the field has been making up for lost time. Yablonovitch says that since about 1993, by one rough count, the number of papers using the phrase "photonic bandgap" has been growing at the rate of 70% each year. At first the work was mostly theory and simulation. "If you went to the conferences 6 years ago, people were saying, 'Yeah, that's a great theory, but how are we going to actually make these devices?' " says John Pendry, a materials science theorist at Imperial College, London. Since then, experimentalists with the right know-how—expertise in thin films, silicon, and nanofabrication—have taken up the challenge.

The result, says John Joannopoulos, a theorist at the Massachusetts Institute of Technology (MIT), has been a recent series of firsts—the first three-dimensional (3D) photonic crystal that operates at optical wavelengths, the first waveguide that steers light waves around sharp corners, and the first photonic crystal laser. "All of these are breakthroughs that pave the way to be able to finally start putting things together and making real devices," Joannopoulos says. The end result, he adds, could be integrated photonic devices—the optical counterparts of integrated circuits—that might supplant electronic devices in communications and, eventually, in computers, multiplying their speed and efficiency.

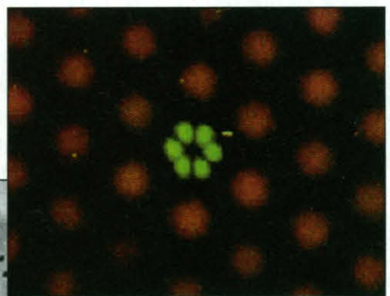


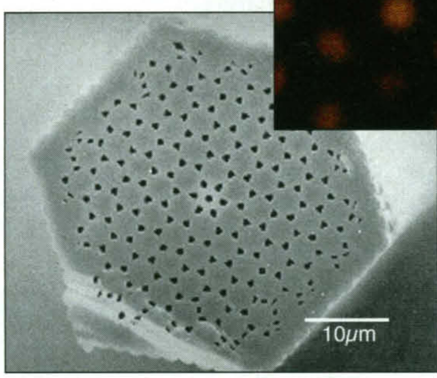
**Logjam for light.** A micrometer-scale silicon lattice, made at Sandia National Laboratories, is designed to exclude or trap certain wavelengths of light.

What Yablonovitch realized back in 1987 was that photons in properly constructed photonic crystals should obey many of the same principles as do electrons in semiconductors. Semiconductors have a crystalline structure that forbids electrons in an energy range known as the electronic bandgap from flowing through the material. Similarly, a lattice of materials with contrasting optical properties can trap light of a particular wavelength if the spacing of the lattice is right—about half the wavelength of the light. Light waves entering the lattice will reflect off the boundaries between materials, like ocean waves lapping against pilings, and cancel out incoming waves. As a result, the light in this optical bandgap won't be able to propagate, except where a defect disrupts the regular lattice, changing its properties the way dopant ions change the properties of a semiconductor.

With the right architecture and the right pattern of defects, photonic crystals should trap and channel photons much as semiconductor devices do electrons. And photonic crystals could reduce the scale and increase the efficiency of optical circuits by orders of magnitude by supplanting bulky lenses, mirrors, and optical fibers, just as semiconductors proved far tinier and more efficient than the vacuum tubes they replaced.

The challenge, however, has been in building regular lattices minute enough to snare light, a feat that, for infrared wavelengths, requires a lattice spacing of about 0.5 micrometer—1/100 the thickness of a human hair. Pioneers in the field proved the principle of photonic crystals by devising coarser lattices that could control longer wavelength radiation, such as microwaves, which have wavelengths of a centimeter or so. To work with light, says Pendry, photonic-crystal enthusiasts had to attract the interest of people familiar with "all sorts of really weird [fabrication techniques] you didn't know about because your field was optics."






**Light pipe.** Tiny holes running the length of this glass fiber made at the University of Bath create a photonic bandgap that traps light in the core of the fiber *(inset)*.

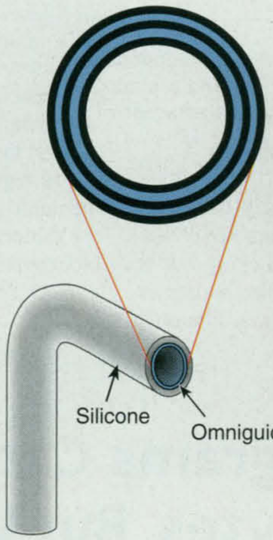
### Little Lincoln Logs

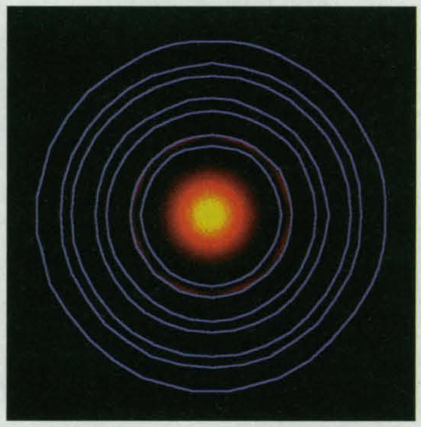
One such person is Shawn-Yu Lin, an applied physicist at Sandia National Laboratories in Albuquerque, New Mexico. A specialist in silicon fabrication techniques, Lin realized about 2 years ago, he says, that "you can utilize the very advanced silicon technology to make photonic crystals."

Working in collaboration with Joannopoulos and other theorists at MIT, his group first set out to prove that a photonic crystal could get electromagnetic waves to swerve around a 90-degree corner. They built a square array of 0.5-mm aluminum oxide columns spaced 1.27 mm apart, an arrange-

CREDITS: (TOP TO BOTTOM) SANDIA; UNIVERSITY OF BATH ment tuned to block millimeter waves, which lie between infrared and microwave radiation. By omitting a series of aluminum oxide columns, they created a channel that turned a 90-degree corner within the array—a defect through which millimeter waves confined by the rest of the lattice should propagate freely. As theory had predicted, the waves made the turn effortlessly, in a distance roughly equal to their wavelength—a feat no conventional optical fiber or waveguide could match (*Science*, 9 October 1998, p. 274).

Lin's group is now trying to duplicate the feat at visible and near-infrared wavelengths, which is where his silicon fabrication expertise comes in, because the structures required are 1/100th the size of the millimeter-wave array. What's more, whereas a 2D photonic crystal adequately confined the millimeter waves, Lin believes that it will take 3D crystals to control light.



**No way out.** A computer simulation *(right)* shows how light is confined in MIT's "omniguide" by concentric layers of polystyrene and tellurium, which create a photonic bandgap. The arrangement can guide light around tight corners *(left)*.

CREDIT: JOANNOPOULOS ET AL.

To craft this 3D structure, he and his colleagues build it up layer by layer. They first put down a thin film of silicon and then selectively etch it away to leave a row of what look like uniformly spaced squarish silicon logs. In a process called chemical-mechanical polishing, akin to fine-sanding woodwork, they smooth the logs to uniform dimensions. Then they convert a second silicon layer into logs and lay it down at right angles to the first. Stacking up five or six layers creates a honeycomb structure resembling a neat, intersecting stack of uniform Lincoln Logs.

So far, they have demonstrated that this 3D crystal can exclude some wavelengths of visible light. Now they are working to get the light to turn a corner. Building a lattice structured precisely enough to manipulate such short wavelengths has proven more challenging than the researchers originally expected. "But we are very close," Lin says. "We are a few months away from being able to bend [visible light]."

Lin's channels could one day be put to use steering light within integrated optical circuits. But other groups are applying photonic bandgap principles to steering light at larger scales, along optical fibers and waveguides. A group of materials scientists at MIT led by Edwin Thomas, who also works in collaboration with theorist Joannopoulos, last year reported the development of what they call an omnidirectional mirror, a structure that completely reflects light of particular wavelengths, no matter which direction it comes from or how it is polarized (*Science*, 27 November 1998, p. 1679). Their mirror is a stack of nine alternating micrometer-thick layers of polystyrene and tellurium. Infrared light approaching the surface from any angle sees a photonic bandgap, which excludes wavelengths of 10 to 15 micrometers and causes them to be reflected.

Other groups have claimed similar achievements, but Thomas and his colleagues are now looking at putting these mirrors to use in new ways. For example, graduate student Yoel Fink came up with the idea of rolling an omnidirectional mirror into a spaghetti-like flexible tube that would act as a waveguide. "If it doesn't matter what the angle [of the incident light] is, the mirror doesn't have to be flat," Thomas says. As the group describes in the November issue of the *IEEE Journal of Lightwave Technology*, the rolled mirror can steer infrared light from a carbon dioxide laser through a 90-degree bend with a 1-cm radius of curvature.

Thomas says they designed the "omniguide," as they call it, to handle carbon dioxide laser light because it is used in industry for welding, as well as for laser surgery, and no existing flexible waveguide can contain light of that wavelength at high powers. "On an assembly line, [a worker] is going to pick up this flexible cable and put the energy wherever he wants it," Thomas says. The group also thinks that, in smaller diameters, omniguides could carry light signals for communication.

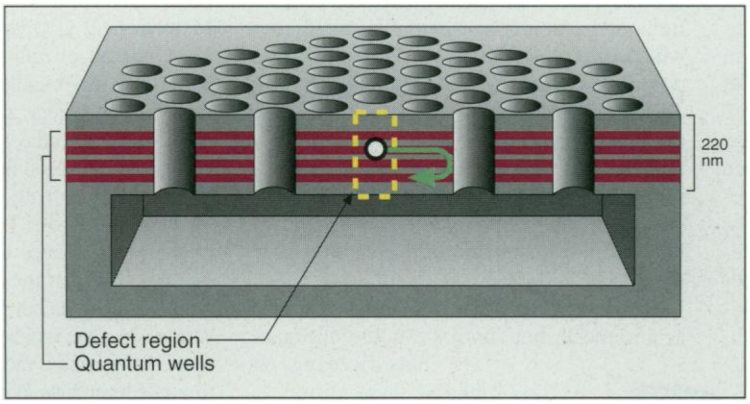
A different way to steer light with photonic crystals comes from a collaboration of the Optoelectronics Group at the University of Bath in the U.K.; the United Kingdom's Defence Evaluation and Research Agency in Malvern; and Corning Inc. in Corning, New York. Instead of rolling up a photonic crystal into a tube, they bundle hundreds of millimeter-thick hollow silica glass tubes together, but omit seven from the center, creating a hollow core. The stack is fused and drawn into a hexagonal fiber with a hollow core about 15 micrometers across. The arrangement and size of the holes creates a 2D photonic bandgap that traps light in the central core. Unlike the MIT waveguide, however, this bandgap only works when the incident light is nearly parallel to the fiber, which means it would not be able to guide light around sharp corners.

But it should be a champion at carrying high-intensity light. Group leader Philip Russell, a physicist at the University of Bath, explains that when ordinary fibers carry more than a few hundred watts, the light itself alters their optical properties, interfering with the flow of light. "The hollow-core fiber avoids those effects because the light is in the empty region," he says. "Potentially you might be able to guide incredibly high powers, maybe hundreds of kilowatts." Russell foresees industrial applications ranging from delivering ultrahigh-power laser light for machining applications, to transmitting ultraviolet light, which tends to get absorbed in conventional optical fibers. He also thinks laser beams channeled through the fibers could push cold atoms through the hollow core, like a stream of water driving a marble. "It would allow you to do nice types of lithography, building structures up atom by atom," he says.

**Light sources, light switches**

Besides steering light, photonic crystals can help generate it, as a group at the California Institute of Technology in Pasadena led by Axel Scherer has shown. Scherer had been working on vertical cavity lasers, tiny laser devices in which the light resonates between two reflective semiconductor layers, building up to high intensity. Vertical cavity lasers could serve as the light sources in integrated optical circuits, but they "are still relatively large," Scherer says. "What attracted me to photonic crystals was the prospect of confining light to even smaller volumes than what we could do with a vertical cavity." A single defect in a photonic crystal could trap and amplify light in a volume just a few wavelengths across.

Rather than trying to build a 3D photonic crystal, Scherer took a shortcut: creating a photonic bandgap that would prevent photons from traveling along a thin layer of light-emitting material, then relying on other optical effects, such as internal reflection, to trap the photons in the third direction and keep them from escaping. Working with colleagues at the University of Southern California in Los Angeles, Scherer's group created a slab of indium gallium arsenic phosphide. Like an elaborate club sandwich, the slab included four thin horizontal regions having slightly different electronic properties—so-called quantum wells, where photons would be generated. The group also pierced the slab with a pattern of vertical air holes, creating a 2D photonic crystal that would prevent light from traveling in the plane of the slab. But they omitted one hole to create a defect.




**Littlest laser.** Light emitted from thin layers called quantum wells cannot propagate through a thicker slab of optical material because it meets a photonic bandgap created by an array of holes. Trapped in a volume of just a fraction of a cubic micrometer, it builds up to laser intensity.

SOURCE: SCHERER *ET AL.*

When they pumped energy into the slab with another laser, photons emitted in the quantum wells were trapped at the site of the missing hole, confined horizontally by the 2D photonic crystal and vertically by the reflective air-film interface at the top and bottom of the slab. The result was the world's smallest laser, which trapped and amplified light within a volume of 0.03 cubic micrometer, two orders of magnitude smaller than in vertical cavity lasers. "This allows you to integrate [the structures] in large numbers," says Scherer.

Scherer envisions arrays of these light emitters fabricated within a single photonic crystal and interconnected by waveguides that would carry light signals from one cavity to another. Because the light wouldn't leave the photonic crystal, the scheme would avoid the diffraction losses that mount up when light is sent from one device to another, he says.

Such devices could form the heart of optical routers for communications networks and even serve as logic gates in optical computers—if researchers can develop one final element: a photonic-crystal switch that would control the flow of photons, as a transistor controls the flow of electrons. Scherer envisions two light sources (which could also be lasers) adjacent to one of his lasers. The lasing threshold would be set so that a stream of photons coming from just one of the light sources would not be enough to initiate lasing—the switch would be "off." But photons coming from both sources would trigger lasing, turning the switch "on" and sending an optical signal to the next device in the circuit. "That gives you the equivalent of a [logic] gate," Scherer says. "But this is very far away from where we are now."

Lin is also working on switching but is taking a different approach that harnesses both electrical and optical effects. Photonic crystals are designed to block a given wavelength or range of wavelengths. A defect in the crystal allows the forbidden wavelength to pass through. But an electric field can change the defect's electromagnetic properties, shifting the transmitted wavelength. The effect turns the defect into a shutter, opening or closing for a specific wavelength of light in response to an electric field.

And there's much more to come, as these tiny honeycombs inspire a buzz of experimental activity. Some groups are now coaxing photonic crystals to grow themselves, using polymers that naturally self-organize into complex structures while in solution. Others are making photonic crystals from colloids, natural or engineered particles suspended in a liquid that pack themselves into a regular lattice like marbles in a jar as the liquid is removed.

Yablonovitch's 1987 paper has proved a blockbuster after all. "It just took a lot longer to catch on than I expected," he says.

—DENNIS NORMILE

NEWS

# Holograms Can Store Terabytes, But Where?

**Finding the right material to store these optical inscriptions is the key to making this optical data storage technology work**

Five years ago, a group at Stanford University demonstrated a pioneering data storage system based on holograms, patterns written in a material by the play of lasers (*Science*, 5 August 1994, pp. 736 and 749). To the optimists, the prototype heralded full-fledged systems that might store hundreds of gigabytes of data—the contents of tens of hard drives—in a cubic centimeter of material, while also reading and writing the data almost instantly. New companies sprang up, and IBM, Lucent Technologies, and others stepped into the field. Some optimists predicted that such systems might hit the market within 2 or 3 years.

> **"Materials have always been the Achilles' heel of holographic storage."**
>
> **—Glenn Sincerbox**

After 5 years, the world is still waiting. The promise of holographic storage remains bright: By storing data in a three-dimensional (3D) volume of material rather than writing it on the surface of a disk, the scheme should achieve vastly greater storage densities than current magnetic and optical disk technology offer. And because it transfers data to and from the storage medium in entire pages rather than bit by bit, the scheme promises readout speeds of up to a gigabit per second. But holographic storage is still a method without an ideal medium.

"Materials have always been the Achilles' heel of holographic storage," says Glenn Sincerbox of the University of Arizona, Tucson. "We have always lacked one or two very important properties."

Most parts of the technology have made good progress since that early demonstration, by Stanford's Lambertus Hesselink and his colleagues. In 1995, Stanford, IBM's Almaden Research Center, and several universities and industries formed the Holographic Data Storage System (HDSS) consortium, with a 5-year budget of $32 million, half of it from the participants and half from the U.S. Defense Department's Advanced Research Projects Agency (DARPA). The consortium has