PHYSICS

Photonic Crystal Made to Work At an Optical Wavelength

One of the great dreams of the telecommunications industry has been to use light, rather than electrons, to carry information. The reason: The speed of information communicated between and within computers would increase almost unimaginably. The industry has already taken the first step toward that goal in the form of fiber-optic cables that transmit information—telephone calls, for instance, or the frenetic buzz of the Internet—from one location to another. But a major bottleneck remains. Much of the work of getting information into and out of the fiber is still done with traditional electronics. Recent developments, however, could soon change that.

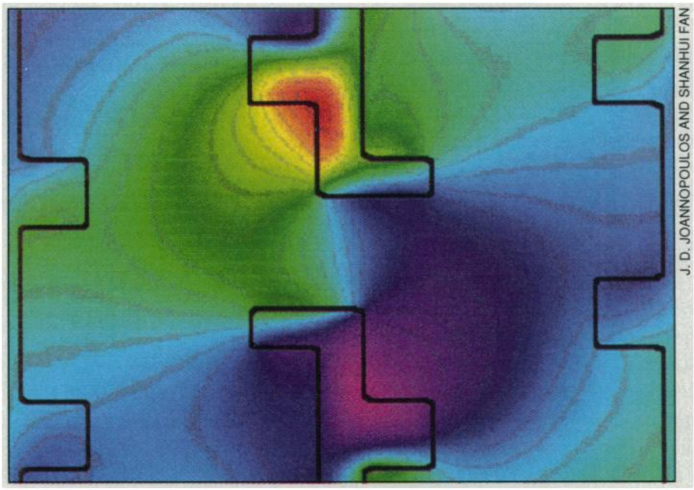
To bring about this "photonic revolution," researchers have to devise a key component: materials in which photons of light will behave the same way electrons do in semiconductors. The problem is that the features of these materials, known as photonic crystals, have to be several orders of magnitude smaller than those found in today's integrated circuits, and no one had been able to build such devices—until now, that is. Aided by x-ray lithography, a team of physicists and electrical engineers at the Massachusetts Institute of Technology (MIT) has created the first photonic crystal that works at an optical wavelength. The results were published in the 13 November issue of *Nature*.

The team, led by MIT physicist John Joannopoulos, accomplished this feat by using the lithography technique to drill a series of tiny holes in a silicon strip. By spacing the holes at critical distances, they were able to produce a "microcavity" half a micrometer across—just the size to trap light of the infrared wavelength used by the telecommunications industry in fiber optics. "For the first time, the opportunity exists to make structures that are significantly smaller than the wavelength of light," says physicist Axel Scherer of the California Institute of Technology in Pasadena.

That means, he says, that light can now be made to jump through the same kind of hoops as electrons do in integrated circuits. It can be forced, for example, to move through a crystal, even around bends, or only under certain conditions. And with that capability comes the possibility that researchers will be able to build lasers and light-emitting diodes (LEDs) small enough to pack onto integrated circuits, where they can be used to transmit and manipulate information.

For a decade, researchers have been trying to build photonic crystals that will do for light what semiconductors do for electrons. The beauty of a semiconductor is that the flow of electricity can be controlled because the semiconductor's crystalline structure forbids the passage of electrons in a well-defined energy range, known as the band gap. But by doping the semiconductor with another material—one that adds electrons, for instance—it can be made to conduct electricity as desired. It is this property that makes solid state transistors—and today's computers—possible.

To build a material with a band gap for light requires creating a photonic crystal, which has a unique periodic structure that will reflect and refract light of specific wavelengths. In the late 1980s, Eli Yablonovitch, a physicist at the University of California, Los Angeles, suggested that such a crystal could be made by creating regular arrays of materials with different dielectric properties and thus different abilities to bend light at their boundaries. "You make a three-dimensional dielectric structure that resembles a crystal," Yablonovitch says. As light waves try to propagate through the structure, they reflect off the interfaces between the different dielectrics and become out of phase to the point where they cancel completely. The result, depending on how the periodic interfaces are designed, can be either no back reflection at all, or total back reflection. What Yablonovitch was after, and what he eventually got, was a perfect three-dimensional mirror—a material that reflected light waves back no matter what direction they were moving.



J. D. JOANNOPOULOS AND SHANHUI FAN

Locked in. This cross section of the transverse component of the magnetic field in a three-dimensional photonic crystal shows that light can be confined in a very small volume.

In Yablonovitch's early work, he took a simple approach to producing the periodicity. Guided by a theoretical model produced by a group led by physicist Costas Soukoulis at Iowa State University in Ames, he drilled a diamondlike pattern of holes into a piece of silicon. Because the holes were separated by centimeters, they interfered with light at centimeter wavelengths (microwaves) in such a way that light at these wavelengths bounced off the crystal, while light at other wavelengths passed through it.

But creating a band gap for light is only the first step. Like semiconductors, photonic crystals don't come alive as a useful technology until impurities or defects are added that can allow light of a particular wavelength to pass. If the periodicity of the crystal is broken by removing one of the air holes, for instance, light at that point no longer sees a perfect crystal in all directions, and a single forbidden frequency of light can exist in the neighborhood of the defect. The result is a microcavity that acts as a filter: It blocks a range of frequencies, but traps one frequency in that range temporarily and then passes that frequency forward out the other end.

This ability to trap light means, Joannopoulos says, that "you can do neat new things with light. You can confine it to very, very small dimensions and make it go wherever you want it to go." If the defect is pointlike, he explains, light trying to move away from the defect will see a perfect crystal, which pushes it back into the defect. And if the defect is a line, the photon will be forced to follow that line through the crystal. Even if it makes a perfect 90-degree turn, Joannopoulos says, "the light has to make that turn."

Since Yablonovitch's early work, researchers have perfected the models needed to predict the properties of photonic crystals with different kinds of defects. The catch has been that to interfere with light in any way, a device has to have features that are roughly half the wavelength of the light of interest—1.5 micrometers in the case of the infrared light used for telecommunications. Accurately creating features on that small a scale requires either x-ray or electron beam lithography, technologies that aren't widely available at university research labs.

Joannopoulos and his MIT colleagues, however, were fortunate enough to have a setup at team member Henry Smith's lab that they could use.

Still, it took the MIT researchers 3 years to fabricate and test the design they worked out for trapping infrared light. The design is what Joannopoulos calls a hybrid. Part of it is traditional technology—in particular the silicon waveguide, down which light will travel in a straight line—and part is entirely new: a series of periodic holes that create the photonic crystal and the necessary band gap.

Using x-ray lithography, Jim Foresi, who was then a graduate student at MIT, drilled a series of four air holes, spaced 0.22 micrometer apart, into the waveguide, followed by a gap of 0.42 micrometer, and then another series of four holes. The regularly spaced holes provide periodicity in one dimension along the waveguide, while the gap in the middle is the defect that creates the microcavity, allowing only light at a wavelength of 1.5 micrometers to pass. "You send in a pulse of light with a whole bunch of frequencies," says Joannopoulos. "When it hits that configuration of four plus four plus the defect, it can only go through if it has the frequency of that defect state." The MIT team then tested the device by sending in a pulse from a semiconductor laser and analyzing the light that made it through to the other end. The result, says team member Henry Ippen, was "surprisingly right on the money."

To take the next step in the photonic revolution, however, researchers must solve another problem—creating microcavities that actively emit light, rather than just allowing a single wavelength to pass through. Although virtually everyone in the field is trying to accomplish this, they are all reluctant to talk about their progress until they have a publication in the works. The idea, though, is to put a classical semiconductor laser or an LED in the middle of the microcavity, which requires making considerably more complex structures on the submicrometer distance scales of the MIT device. These would be designed to emit a wavelength of light identical to the wavelength the microcavity allows to exist. If such devices can be achieved, given the degree of miniaturization required, they would be perfect for generating the light that would be used to transmit information on integrated circuits that combined both electronics and photonics.

Because only a single wavelength of light would be allowed to exist within the cavity, the efficiency of these "optoelectronic" devices would be much higher than today's strictly electronic devices, and they would need considerably less energy to run. Indeed, researchers predict they may someday make LEDs that will convert energy into light moving in a single direction with an efficiency of 90% compared to the 30% in present devices.

A microcavity laser would be what is known as a zero threshold laser. In traditional lasers, it takes time and energy to get to the point where the light is coherent and the laser is lasing. This would not be the case with a microcavity laser. "The very first photon that gets emitted goes straight into your laser beam," says MIT team member Pierre Villeneuve. With all other lasers, until that threshold is reached, "you're wasting energy."

Considering that LEDs are already ubiquitous, and someday photonic devices may be as densely packed on chips as present semiconductor devices, it becomes obvious why such savings in energy and heat loss make the photonic researchers believe they are onto something big. But they have some challenges to overcome first. One would be to devise ways of building photonic microcavities with technologies that are easier to come by than x-ray lithography. Villeneuve predicts, however, that that should be possible within a few years. If so, it should launch the photonic revolution out of the realm of fantasy.

Until then, however, Joannopoulos has one caveat. "We're still theorists," he says, "and so we have to learn how to play the game in the real world. It's fine to design something, but then someone has to make it and mass-produce and integrate what exists already. These are all difficult issues."

–Gary Taubes

BIOMEDICINE

Herpesvirus Linked to Multiple Sclerosis

A new study has yielded evidence linking a strain of herpesvirus to multiple sclerosis (MS). More than 70% of patients in the study with the most common form of MS showed signs of active infection with herpesvirus-6 (HHV-6). The finding, reported in the December issue of *Nature Medicine*, is not yet conclusive proof, however, and some researchers question whether the apparent association is a symptom rather than a possible cause of MS.

In multiple sclerosis, immune cells attack and inflame the myelin, fatlike sheaths surrounding neurons in the central nervous system. Symptoms can vary widely, but MS is generally characterized by muscle weakness and neurological impairments, and most patients see their condition wax and wane with new symptoms appearing or old ones becoming more severe, alternating with periods of remission. Eventually, however, it can lead to disability and paralysis. HHV-6—which infects young children, causing a condition called roseola marked by high fever and rashes—also inflames myelin. It is present in about 90% of the U.S. population and can become reactivated when the immune system is under stress from factors such as secondary infections or emotional strain. Virologist Steven Jacobson and his colleagues at the National Institute of Neurological Disorders and Stroke in Bethesda, Maryland, wondered whether there might be a link between HHV-6 infection and MS.

"Now, we think we're a little closer" to finding a viral link to multiple sclerosis.

—Steven Jacobson

The researchers looked for signatures of HHV-6 in the serum of 36 MS patients and 66 controls in a blind test. As expected, nearly all had long-term antibodies, known as IgGs, that react with HHV-6 antigens. But 73% of MS patients also had IgM, an early antibody response to HHV-6 antigens and a potential marker of active virus replication. Only 18% of the control group showed IgMs directed against HHV-6. DNA from the virus was also found in more than one-third of MS patients, but in none of the controls. Moreover, magnetic resonance imaging detected numerous lesions in the myelin in the brain of a recently deceased MS patient, and an autopsy revealed HHV-6 in the lesions, but not in the adjoining normal tissues.

Jacobson, who has been looking for a viral cause of MS for more than 20 years, says "Now, we think we're a little closer." But some other experts are not yet convinced. Patricia O'Looney, a biochemist with the National Multiple Sclerosis Society in New York City, points out that not all the MS patients showed indications of active HHV-6 infection. She also notes that "MS breaks down the blood-brain barrier," which "may allow the virus to migrate into the central nervous system." In that case, HHV-6 infection could simply be a symptom of MS.

Jacobson cautions that even if an association between HHV-6 and MS is strengthened with further studies, it will not lead directly to a treatment for MS because nothing is yet available that can kill the virus without aggravating the breakdown of the myelin sheath. But it could open up new avenues for research.

–Phil Berardelli

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