Visible Progress Made in Three-Dimensional Photonic 'Crystals'

Researchers have made artificial structures that block light near visible wavelengths. Eventually, they hope to trap light within the structure or guide it along a prescribed path to make lasers, switches, waveguides and interconnects for photonic integrated circuits.

Spurred by the success of the semiconductor industry, researchers are trying to push circuit devices to higher speeds and greater functionality by using photons rather than electrons. At the heart of the semiconductor technology is the electronic bandgap, a range of energies within which electrons cannot propagate through a material. It turns out that certain material structures can have a photonic bandgap, a range of forbidden frequencies within which light cannot be transmitted. The electronic bandgap results from the periodic arrangement of atoms in the semiconductor; the photonic analog stems from a regular array of dielectric material, known as a photonic crystal.

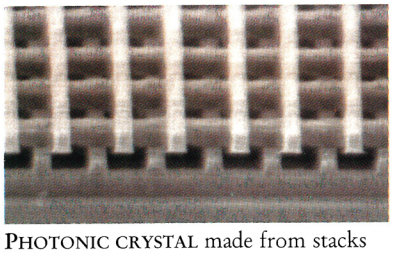
Photonic crystals don't occur naturally; somehow one must arrange dielectric matter in a periodic structure. That feat has been successfully accomplished to produce one-, two- and three-dimensional bandgaps for microwave and millimeter-wave radiation, and for shorter wavelengths in one- and two-dimensional structures. But the real push has been to get a three-dimensional photonic crystal with a bandgap around 1.5 μm—the wavelength now used for the transmission of telecommunications by optical fibers. After a quest of more than seven years, several research groups have now reported some success, most notably experimenters from Sandia National Laboratories,[1] who have produced a three-dimensional photonic crystal using a technique that lends itself to mass production.

Why does one want a photonic bandgap? It is a handle by which one can manipulate photons. For example, a disruption of the periodicity of the photonic crystal can create a state within the forbidden gap, giving rise to a localized electromagnetic wave that is trapped within the material. That trapping site can essentially be a tiny optical cavity—and perhaps the core of a single-mode light-emitting diode. A line of impurities in a photonic crystal can guide the forbidden frequency along a prescribed path and even around tight curves, with little leaking of the light into the surrounding crystal, where the full gap exists. Such engineering of the bandgap has already been demonstrated by many researchers on photonic crystals in one and two dimensions.[2]

Drilling holes and stacking logs

Photonic bandgaps were predicted in 1987 by Sajeev John (now at the University of Toronto) and Eli Yablonovitch (now at UCLA). (See the article by John in PHYSICS TODAY, May 1991, page 32.) To make a photonic bandgap material, one needs a large contrast in dielectric constants between the periodically arranged material (such as a semiconductor or a metal) and the surrounding medium (usually air). The lattice spacing in a photonic bandgap must be comparable to the wavelength one wants to block; the fraction of the volume occupied by the high-dielectric material must be relatively low; and the material should not be a strong absorber of the radiation.

Researchers have devised several different schemes for making such photonic crystals. Yablonovitch formulated a unique one in 1991 to vindicate his own predictions: Starting with a slab of dielectric material, he mechanically drilled many air channels in it.[3] The crisscrossing of the air channels drilled at different angles produced a crystal with the connectivity of a diamond-like structure, the most favorable geometry for photonic bandgaps.[4] The resulting structure had a full bandgap in the microwave region.



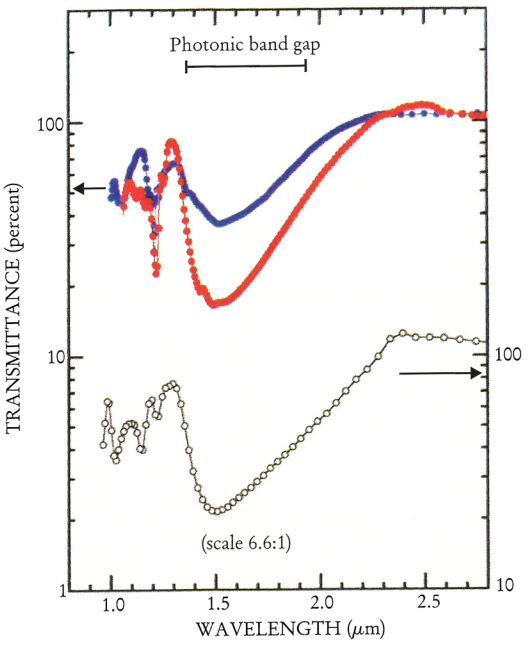
PHOTONIC CRYSTAL made from stacks of polysilicon rods by advanced silicon processing techniques. The sharp dielectric contrast between silicon and air scatters light as it traverses this structure. The resulting wave interference prevents light in a certain frequency range—known as the photonic bandgap—from getting through the crystal. (Electron micrograph courtesy of Sandia National Laboratories.)

A different means of fabricating a photonic crystal is to stack rods of dielectric material, much as one might arrange logs in a woodpile: Each successive layer is lined up at right angles to the layer underneath.[5] Actually, as pointed out in 1994 by a group at Iowa State University,[6] one has to make a slight modification to this stacking scheme to get a complete bandgap: offset the logs in every other row by half of the interlog spacing. The result is a face-centered tetragonal structure. The Iowa State group used this approach to make photonic crystals for microwaves and has even extended it into the millimeter region.[7]

Scaling these three-dimensional layered structures down to the micrometer scale has been challenging and, admits Costas Soukoulis of Iowa State, frustrating. Early last year, Shawn Lin of Sandia told us, he realized that there were very powerful silicon processing techniques—developed for producing both advanced microelectromechanical systems and integrated circuits—that could be used to create a stacked structure.

Lin, together with James Fleming, formulated a multistep process involving photopatterning, etching and plasma-enhanced deposition to fabricate the layered structure proposed by the Iowa State group. Each layer is a parallel row of polysilicon bars, whose widths and heights are a few tenths of a micrometer, spaced 0.65 μm apart (see the photograph at left). As each row is completed, Lin and Fleming fill the space between the polysilicon bars with silicon dioxide (which they later remove) to make a plane surface on which the next layer can be fabricated. Doing so, Lin feels, avoids propagating any imperfections from one layer into subsequent layers.

The figure on page 18 shows the transmittance measured at Sandia as a function of wavelength for samples with three and four layers. To show a true bandgap, one must demonstrate a deep dip in the transmittance not just in one but in all directions, with



PHOTONIC BANDGAP is signaled by a dip in the transmittance as a function of frequency of light traversing a sample. The top two curves show the transmittance through Sandia National Laboratories' silicon photonic crystals at optical wavelengths. Around 1.5 μm, the photonic bandgap for a structure with four layers (red) is several times deeper than that with three layers (blue). The bottom curve shows the similar bandgap measured on an infrared crystal; the frequency has been scaled accordingly by a factor of 6.6.

some overlap in wavelength between the dips measured in different directions. Lin and Fleming found a bandgap at angles up to 60° away from the normal to the symmetry direction. The transmittance (which is 100% for a completely transparent object) dips by about 85% for the four-layer structure: Lin told us that he and Fleming now have a sample with seven-layer structure, and that the light transmission in the region of 1.35–1.95 μm has an attenuation of 99% (or equivalently, 1% transmittance). By extrapolation, the Sandia experimenters estimate that a ten-layer structure might give 0.1% transmission, good enough to make a high-quality cavity, with a Q value of a few thousand.

Lin and Fleming have also measured the reflectance for the seven-layer sample and found it to be 99%, the same as the attenuation. In the absence of absorption, any light that doesn't bounce back from the surface must make it through the material. Thus, the match between reflectance and transmittance is further confirmation that the observed dip in transmission is indeed caused by a bandgap and not by absorption.

A key virtue of the Sandia team's fabrication method is that it lends itself to mass production, with accompanying low costs and high reliability. Lin told us that silicon processing techniques can typically handle 15 6-inch silicon wafers at one time; each wafer yields about one million devices. Each layer currently requires one week to fabricate. The technique also allows one to introduce impurities in a controlled manner, by adding or removing bars, thus facilitating the bandgap engineering.

One drawback to a silicon photonic crystal is that silicon has an indirect bandgap, so that the rate of spontaneous emission is about ten thousand times lower than for a direct-bandgap III–V semiconductor, such as gallium arsenide. The III–V semiconductors are preferred for active elements such as light-emitting diodes and lasers. The low spontaneous emission rate is not an insurmountable problem for optical applications, Lin feels. He hopes to improve it by such measures as doping silicon with erbium atoms or doping the system with a dye, although the rate would still not match those achieved with III–V materials.

Another mass production scheme

At Kyoto University, Susumu Noda and Noritsugu Yamamoto have recently reported a bandgap material in the infrared, between 5 and 10 μm. They also fabricate the layered structure suggested by the Iowa State group, but they have developed a different approach to stacking semiconductor rods with micrometer dimensions.[8] First, they deposit a layer of gallium arsenide atop a substrate on a wafer and use electron beam lithography and reactive ion etching to form rows of gallium arsenide rods. Then they cleave the wafer in half and place one half, rotated by 90°, upside down on top of the other, much as one would make half a sandwich. The two layers are wafer fused by heating. Then the substrate of the top layer (the upper slice of bread in the sandwich) is etched away, leaving only the criss-crossed gallium arsenide rods. The procedure is repeated for each additional layer. Noda reports that his group can grow four layers (one unit cell) in five days.

By now, Noda and his colleagues have a sample with eight layers, corresponding to two unit cells. They report an attenuation of 99.9% in the wavelength range of 6 to 9 μm. As the direction of the incident light is rotated, Noda says, the bandgap persists, with attenuations of at least 99%.

Noda believes that the fabrication accuracy (less than 50 nm) and alignment are good enough to allow him and his colleagues to make structures with bandgaps around 1.5 μm. They are already moving in that direction, making structures of indium phosphide (InP), which lends itself to active devices at the wavelengths used for telecommunications. Like others working on photonic bandgaps, they hope to demonstrate the inhibition of spontaneous emission by embedding an InP/InGaAsP multiple quantum well as one layer within the stacked layers of an InP photonic crystal. Introducing disorder into the crystal should then produce single-mode optical emission.

Other short-wavelength bandgaps

Yablonovitch has continued to pursue his technique of drilling holes into a dielectric slab, but for optical wavelengths the drill must be a beam of ions and the appropriate material is gallium arsenide, with its direct bandgap. In this work, Yablonovitch has been joined by Axel Scherer of Caltech and other colleagues. They have used high-resolution electron beam lithography and anisotropic chemically assisted ion beam etching to produce smaller and smaller channels, as required to get a photonic crystal in the visible wavelengths. In 1996, the collaborators reported[9] a bandgap in the near-infrared, from 1.1 to 1.5 μm. The transmittance in this wavelength region fell by 80%, compared to the drop of 98% expected from theoretical calculations. Yablonovitch told us that his group has since improved the technique to give a 90% attenuation. He attributes the shortfall to imperfections in the fabrication technique. With their current method, the UCLA–Caltech group can produce crystals that are nearly two unit cells deep. But it's not easy for them to go much deeper.

A variant on the drilling method has been tried by the Iowa State group, together with colleagues from the Institute of Microtechnology in Mainz, the Foundation for Research and Technology Hellas in Crete, and the Max Planck Institute for Solid State Research in Stuttgart.[10] Because it is difficult to drill deep uniform holes in semiconductors, this collaboration drills

holes in a polymer and fills them with a high-dielectric material. They have used this approach to produce a structure with a bandgap at around 100 μm.

Yet a third variation in design was proposed in 1994 by John Joannopoulos and his group at MIT.[11] They envisioned a structure formed by stacking two solid materials—silicon and silicon dioxide—having a large ratio of dielectric constants, and then introducing vertical air channels for additional dielectric contrast. By now, Joannopoulos reports, his group has joined with that of Henry Smith, also of MIT, to build two layers of such a structure; they have calculated that these layers should reduce by 96% the incident light around 1.5 μm. At Sandia, Lin is building seven layers of a similar structure with a bandgap in the 7 μm region.

A chemical approach

Micromachining is not the only way to get a periodic array of dielectric structure. Chemical methods hold promise as well, and a number of groups are pursuing this route. Researchers start with colloidal crystals, self-organized arrays of silica or latex spheres in solution. These are good building blocks because they have the periodicity required for photonic bandgaps and are far easier to produce, especially in large samples, than the microfabricated structures. But experimenters are working to overcome several challenges: the low index of refraction of the typical colloids, the face-centered cubic structure of colloidal crystals, which must be altered to give a larger bandgap; and the formation of domains, or discontinuities in the periodic structure.[12]

In one variant on the colloidal crystal approach, researchers have made inverse crystals, often called inverse opals. In recent work, for example, experimenters filled the void spaces around the colloidal particles with materials such as titanium oxide (which has a large index of refraction) and then removed the colloidal material. The result was an array of spherical spaces surrounded by a titanium oxide scaffolding.[13] **BARBARA GOSS LEVI**

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Combustion in Two Dimensions Yields Fingering Instability

In a two-dimensional geometry, burning paper develops a fingering instability. Is this phenomenon related to viscous fingering, dendritic growth and electrodeposition?

Many years ago, Elisha Moses stood high above a burning wheat field. "It burns essentially as a straight front. So long as the sky is open, there is no fingering. But if you could lower the sky, at some point the straight flame front would break into fingers."

That's how Moses described a recent experiment done at the Weizmann Institute of Science by Ory Zik, Zeev Olami and himself.[1] Instead of lowering the sky, they essentially did a two-dimensional combustion experiment involving paper and oxygen. Although combustion involves complicated chemical reactions and fluid dynamical processes, including the development of instabilities, by using a two-dimensional chamber that prevented convection, the team had a high degree of experimental control over the combustion and could study it in detail. A group from the National Institute of Standards and Technology and NASA's Lewis Research Center has also reported fingering—in their experiment involving smoldering on the Space Shuttle.[2]

Pattern formation in the interface between two phases—a solid and a fluid or two fluids—has been widely studied. One of the simplest problems of that kind is the Saffman–Taylor problem in which two fluids move in the narrow space between two plates. This geometry is called a Hele-Shaw cell, after the physicist who devised it 100 years ago. The so-called viscous fingering instability occurs in Hele-Shaw cells when a more viscous fluid is displaced by a less viscous fluid. Viscous fingering has served as a prototype of diffusion-controlled growth, helping to elucidate a variety of nonequilibrium phenomena such as dendritic growth, directional solidification and chemical electrodeposition.

Two-dimensional combustion

The Weizmann experimenters used a rectangular chamber, thin in the vertical direction, with a transparent top. Ordinary paper served as fuel, but they also tried other combustible materials, including cellulose dialysis bags and polyethylene sheets. They ignited the fuel electrically with an explosive-coated tungsten wire. The main experimental controls were the oxygen flow velocity, V_0 and the adjustable vertical gap between the two plates, h. The oxygen was supplied horizontally in a uniform flow opposite to the direction of the front propagation.

Measurements were made when the combustion was very slow—that is, the fuel was smoldering, a nonflaming mode in which the emitted gas doesn't glow. In this mode, the oxygen interacts with a solid fuel to produce char, gaseous products and the heat that keeps the process going.

As V_0 was decreased, the combustion front became sinusoidal, and then fingers formed. With some fuel materials, the team found melting and a glowing flame, but whether the particular fuel smoldered or flamed, fingering could be produced.

When V_0 was decreased below a critical value, the smooth front developed an irregular structure marking the onset of instability. (See the figure on page 21.) When the flow was decreased further, a cellular structure formed with a dominant wavelength. With a further reduction in flow, the peaks separated into fingers and as the flow was reduced still further, the finger tips split recurrently. (See the cover photograph.) If a finger was close to the oxygen source, it screened neighboring fingers from the oxygen, they stopped growing and the tips of the screening fingers split. The splitting was such that both the average finger width and the spacing between the fingers remained unchanged. With still further flow decrease, spacing