

PHOTONIC CRYSTALS: SEMICONDUCTORS OF LIGHT

By Eli Yablonovitch

Nanostructured materials containing ordered arrays of holes could lead to an optoelectronics revolution, doing for light what silicon did for electrons

FIRST SUCCESSFUL PHOTONIC CRYSTAL was formed by drilling three intersecting arrays of holes into a block of a ceramic material. Each array is angled 35 degrees from vertical (into the page), producing a structure now called yablonovite. The pattern of six-millimeter-diameter holes blocks radio waves from 13 to 16 gigahertz.

IT WAS THE SECOND EXASPERATING PHONE CALL THAT I HAD RECEIVED.

Yet another group of theorists was saying that my discovery did not work. That was distressing. I had spent three long years trying and discarding countless designs to arrive at what I thought was success, but if the theorists were right, I had to go back to the lab and continue searching. And maybe what I was trying to create—

an artificial crystal structure that could manipulate beams of light in the same way that silicon and other semiconductors control electric currents—was not possible at all.

Electronic semiconductors, of course, are at the heart of all the computers and other devices that pervade the global economy. Semiconductors of light could lead the information and telecommunications

revolution still further by enabling higher-capacity optical fibers, nanoscopic lasers and photonic integrated circuits that might one day replace today's microchips.

Indeed, despite a rocky start in the late 1980s and much skepticism from the photonics research community early on, the field of photonic crystals has thrived. Around the world many researchers (including me) have founded companies that

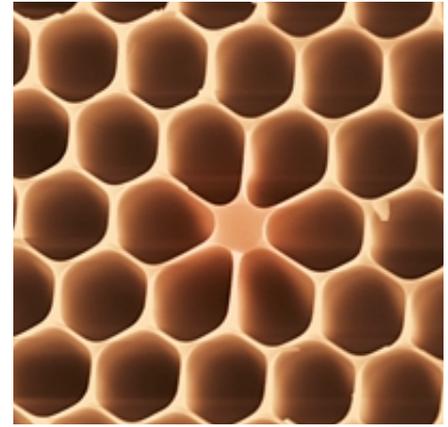
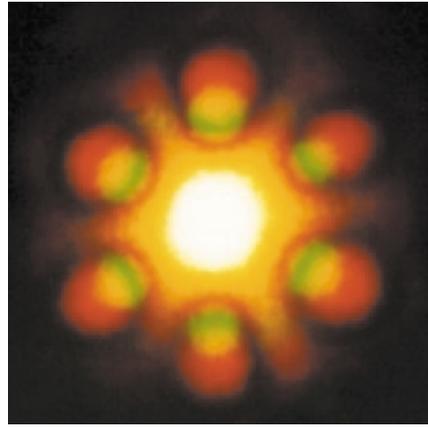
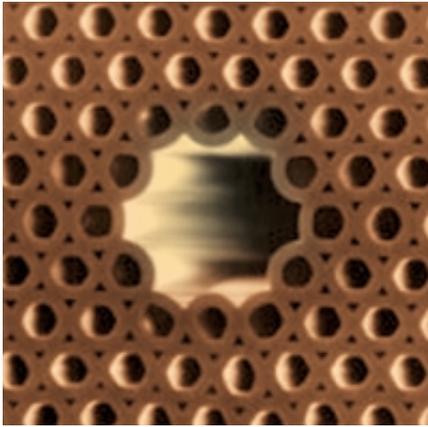
are developing commercial products. The key was proving the skeptics wrong by showing that it was possible to create for light the same kind of phenomenon seen in electronic semiconductors—namely, a so-called band gap.

The electronic band gap is a forbidden zone, a narrow range of energies that electrons cannot occupy. When the electrons in the semiconductor fill all the states available to them below the band gap, electric current cannot flow, because each electron has nowhere to go. Boosting an electron above the gap takes a lot of energy. If there are a few excess electrons, however, they automatically must sit above the gap, where they can easily roam through the wide open spaces of empty states. Similarly, a deficit of electrons opens up some positively charged “holes” below the gap, again providing a way for current to flow readily.

All the magic of semiconductors—the switching and logic functions—comes about from controlling the availability of electrons and holes above and below the band gap. The existence and properties of an electronic band gap depend crucially

Overview/*Photonic Crystals*

- The microelectronics and information revolution is based on the elaborate control of electric currents achieved with semiconductors such as silicon. That control depends on a phenomenon called the band gap: a range of energies in which electrons are blocked from traveling through the semiconductor.
- Scientists have produced materials with a photonic band gap—a range of wavelengths of light that is blocked by the material—by structuring the materials in carefully designed patterns at the nanoscopic-size scale. These photonic crystals function as “semiconductors for light” and promise innumerable technological applications.
- Many researchers greeted the idea of a photonic band gap with skepticism and disinterest when it was first proposed, but today photonic crystals are rapidly turning into big business. Photonic crystals have applications such as high-capacity optical fibers, color pigments and photonic integrated circuits that would manipulate light in addition to electric currents.



OPTICAL FIBERS can use the photonic band-gap principle to guide light. The cladding of several hundred silica capillary tubes forms an optical band-gap material that confines light to the central hole, which is about 15 microns in diameter (*left*). In the design at the right, in which the light is

confined to the two-micron solid core, the fiber is highly nonlinear, which can be useful for switching and shaping light pulses. In the center, a pattern of colors illustrates how the confinement property of a band-gap fiber varies for different wavelengths of light.

on the type of atoms in the material and their crystal structure—the spacing and shape of the lattice that they form. By substituting various other atoms (called dopants) into the lattice or its interstices, engineers can dictate the number of electrons or holes in the semiconductor and thereby tailor its properties.

In silicon and other semiconductors, adjacent atoms are separated by about a quarter of a nanometer. Photonic band-gap materials involve similar structures but at larger scales. A typical example would be a block of special glass drilled through with a closely spaced array of cylindrical holes, each with a diameter of 400 nanometers. These openings are analogous to the atoms in a semiconductor. In general, but not always, the spacing of the array must be reasonably close to the wavelength of the light or the electromagnetic waves to be controlled. Visible light has wavelengths ranging from about 400 to 700 nanometers; many cell phones use waves around 35 centimeters long.

Light entering the holey material will refract through and partially reflect off the myriad internal interfaces between air and glass. The complex pattern of overlapping beams will reinforce or cancel one another out according to the light's wavelength, its direction of travel through the crystal, the refractive index of the glass, and the size and arrangement of all the holes. Perfect cancellation in all directions for a narrow band of wave-

lengths is like the band gap for electrons in semiconductors: that band of light cannot propagate through the crystal. Modifying the band gap structure—for instance, by filling some holes—produces other effects, similar to what can be done by doping electronic semiconductors. Often a photonic crystal is made of an electronic semiconductor material, and so the crystal has both an electronic band gap and a photonic band gap.

500,000 Holes

THE QUEST for a photonic band gap originated quietly enough in 1987 with two independent proposals submitted for publication just two months apart: one by me and the other by Sajeew John, then at Princeton University. We had two very different goals in mind. I was at Bell Communications Research, the telephone research consortium in New Jersey, and I was seeking to make telecommunications lasers more efficient. Most of the electric current consumed to produce lasing was wasted as spontaneous light emission, and the photonic band gap could suppress that waste: atoms cannot spontaneously emit light when they are part of

a material that forbids light propagation.

John, in contrast, was pursuing a pure research goal. He proposed the photonic band gap to create what is known as light localization. The electronic analogue of this phenomenon, a quantum effect called electron localization, occurs in disordered materials such as amorphous semiconductors. The disorder traps, or localizes, electrons in fixed locations, obstructing current flow.

John and I had never met, but when we learned of each other's proposal, we were curious enough to arrange a get-acquainted lunch. We thought we were onto something, and we agreed to use the same terminology: "photonic band gap" and "photonic crystal." I returned to my lab rather overconfident. I thought that I might create the first working model within only a few months.

Although "photonic" refers to light, the principle of the band gap applies equally well to electromagnetic waves of all wavelengths. Consequently, I could make trial crystal structures with any convenient row spacing and size and then test them with electromagnetic waves of the appropriate wavelength. Indeed, I began

THE AUTHOR

ELI YABLONOVITCH was an inventor of the photonic band-gap concept and made the first photonic band-gap crystal while at Bell Communications Research in New Jersey. In 1992 he moved to the electrical engineering department at the University of California, Los Angeles, where he leads the optoelectronics group. He is a founder of two companies in the burgeoning field of photonic crystals: Ethertronics and Luxtera. Before he became a faculty member, Yablonovitch had enough time to sail racing sloops.

COURTESY OF BLAZE PHOTONICS (*left and center*); CRYSTAL FIBRE A/S (*right*)

my quest for a photonic band-gap material in a machine shop, carving structures out of dielectric plates with a drill. Only human imagination limited the crystal design and structure. Therein lay a problem, however. Out of the innumerable choices available, which design would produce a photonic band gap?

In electronic semiconductor crystals, the band gap arises because electrons behave partly like a wave, and the waves scatter off the layers or rows of atoms. Part of the wave scatters back the way it came, and if the wavelength is about the same as the spacing of successive layers, all the backscattered waves add up coherently. Consequently, the electron's wave is reflected back completely, like light hitting a mirror. For a full band gap, this perfect reflection must occur over a range of wavelengths and for waves heading in any direction through the crystal.

physical intuition as calculations, my co-workers and I built structure after structure, searching for the right one. In the course of four years, my loyal machinist, John Gural, drilled more than 500,000 holes in dielectric (insulating) plates, admittedly assisted by a numerically controlled machine. It became unnerving as we produced failure after failure.

The Surprise of Diamond

WE EXPECTED the face-centered cubic (fcc) structure to be particularly favorable for making electromagnetic band gaps. You can build this structure by taking a checkerboard and placing a black cube on each white square and a white one on each black square. On the second layer, continue placing black cubes on white and vice versa, and so on up. The black cubes (and separately also the white ones) form an fcc lattice.

that of any existing transparent material.

Within weeks, however, the Iowa State group found that the diamond structure, the tetrahedral crystal geometry associated with the precious jewel, would produce a band gap. The form that gives the widest band gap consists of dielectric rods in the positions of the chemical bonds between carbon atoms, with the atoms shrunk to geometric points. Diamond itself is not a photonic band-gap material, as far as we know. Earlier in this piece I said that when we began our research, we knew we could not simply emulate the silicon crystal structure to produce a photonic band gap. How wrong we were: silicon's crystal structure is precisely that of diamond.

That the tetrahedral structure is the best for making a photonic band gap is startling and profound. Before the advent of photonic crystals, the diamond config-

Unlike lattices of atoms, **photonic crystals** have structural possibilities limited only by the human imagination. **Any shape** can be sculpted at the lattice sites.

For an electromagnetic band gap, I knew one could not simply emulate a silicon crystal. For light, the scattering is caused by changes of refractive index (for instance, between air and glass), and an interaction directly analogous to electrons and silicon atoms would require a material with an extraordinary refractive index.

Nor could one simply deduce a structure from theory: the band gap depends on how the waves interact with many hundreds of holes, a very complicated process. Theorists had developed computer models for doing the calculations for semiconductors, but these programs could not be used for photons. First, the equations of motion are different—Schrödinger's equation governs electrons, but Maxwell's equations describe the behavior of light. Second, with photons one cannot safely neglect polarization the way one can with electrons. Consequently, I had no way to determine whether a proposed structure would have a photonic band gap. And so, guided as much by

That structure still leaves an infinite variety of choices because you can substitute any other geometric shape for the black cubes, which alters how the light waves will be refracted and reflected. After two years, we arrived at something that seemed to work: an fcc structure in which each black cube was replaced by a spherical void in the material. I published this result, but I was mistaken.

By now the theorists had started to catch up, and a few of them had retooled their band-structure computer programs to work with light. Several theory groups, including those led by K. Ming Leung of Polytechnic University and Kai Ming Ho of Iowa State University, began making those dreaded phone calls. My long-sought fcc structure had only a pseudo-gap: a forbidden "band" having zero width, meaning that just one exact wavelength of light was forbidden. After our years of effort, it appeared that nature might not permit a photonic band gap to exist at all. Perhaps it required a substance with a refractive index far beyond

uration was merely another mineral structure, arising out of a complex interplay of atoms, chemical bonds and energy minimization under suitable conditions of temperature and pressure. Its utility for forming a photonic band gap, which emerges entirely and solely from Maxwell's equations (the laws of electricity, magnetism and light), shows that the diamond configuration also has fundamental significance in relation to electromagnetism and the geometry of three-dimensional space.

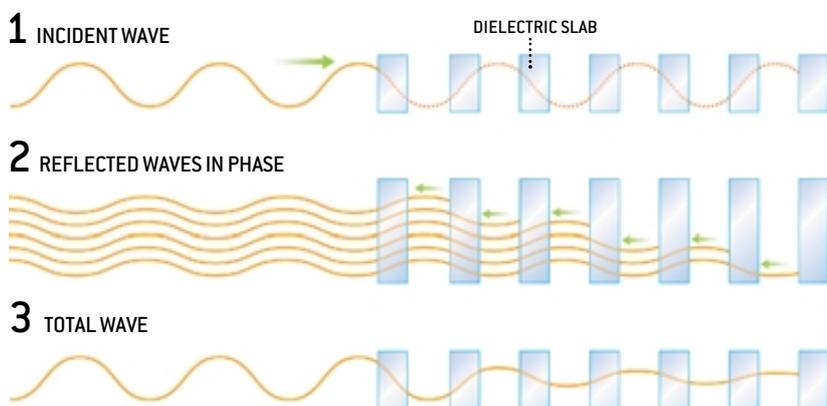
Diamond's tetrahedral structure takes on many different appearances according to what shape is placed in each lattice site and from which angle the crystal is viewed. The box on the opposite page includes two very dissimilar photonic crystals that are based on the diamond structure. My group made the first successful photonic band-gap crystal (this time for real) in 1991 using a variant of the diamond structure now called yablonovite. Nature is kind after all: a band gap occurs in the diamond structure for a refractive

MAKING BAND GAPS IN ALL DIMENSIONS

ONE DIMENSION

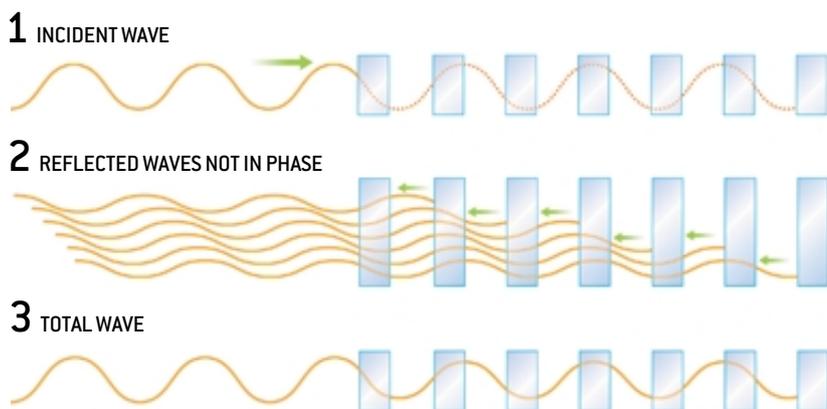
FOR WAVELENGTH IN BAND GAP

A wave incident on a band-gap material (1) partially reflects off each layer of the structure (2). The reflected waves are in phase and reinforce one another. They combine with the incident wave to produce a standing wave (3) that does not travel through the material.



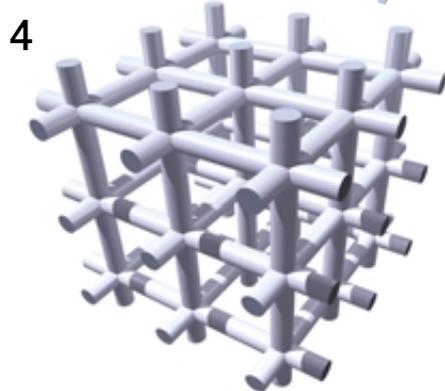
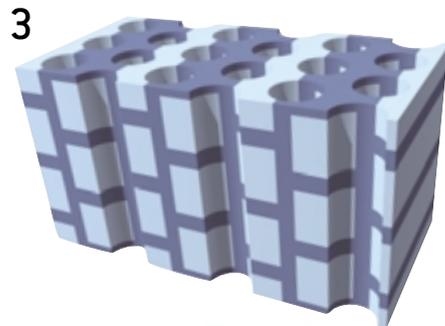
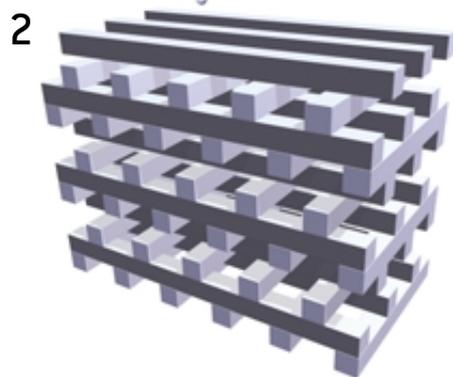
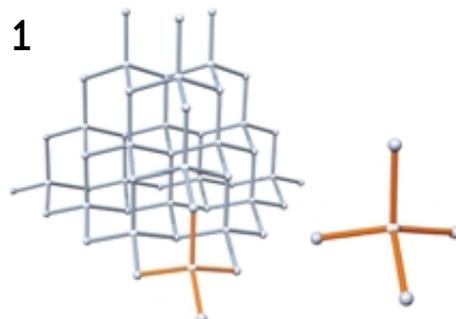
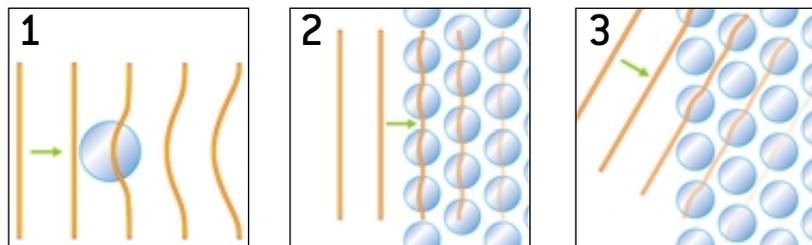
FOR WAVELENGTH NOT IN BAND GAP

At a wavelength outside the band gap (1), the reflected waves are out of phase and cancel one another (2). The light propagates through the material only slightly attenuated (3).



TWO DIMENSIONS

For a two-dimensional band gap, each unit cell of the structure (1) produces reflected waves (not shown) and refracted waves that must combine to cancel out the incoming wave (2) no matter what direction it is traveling (3). A full three-dimensional band-gap material works the same way but in all three dimensions.



THREE DIMENSIONS

Diamond's tetrahedral configuration (1) is the most effective geometry for making three-dimensional band-gap materials. This geometry occurs in disguised form in yablonovite (see pages 46 and 47), the "stack of logs" (2), and this design (3), which uses silicon dioxide channels (light) in silicon (dark). The scaffold structure (4) is a rare example that has a different underlying symmetry, but it has only a small band gap.

index as small as 1.87, and many optical materials are available with refractive indices as high as 3.6.

The diamond structure isn't the only structure having a photonic band gap. In 1992 theorist Joseph W. Haus, then at Rensselaer Polytechnic Institute, showed that we had discarded the fcc structures too quickly. Scientists had searched the fcc structures for band gaps only at wavelengths for which about half a wave fits

in the wings and in the hairs of a worm-like creature called the sea mouse. Each of these has a photonic band structure, though not a full band gap, in that light can still propagate in some directions. A complete band gap has eluded nature, perhaps because it requires too much refractive-index contrast.

Nevertheless, an incomplete band gap can be very useful. For example, titanium dioxide particles smaller than a

core, which confines light by total internal reflection. Philip St. J. Russell of the University of Bath in England demonstrated in 1999 how to make photonic band-gap fibers. In one version, light travels along a central hole in the fiber, confined there by the two-dimensional band gap of the surrounding material. More optical power can be sent through such a central void than through glass, enabling greater information-carrying

Integrated circuits that combine conventional electronics and photonic crystals would represent the ultimate limit of optoelectronic miniaturization.

in one cell of the lattice (somewhat like the fundamental vibration of a guitar string). As we saw, only a pseudo-gap occurs at that frequency. Haus, however, also considered a higher frequency, for which a full wavelength fits in a cell (somewhat like the first harmonic of the guitar string), and proved that an fcc band gap would indeed emerge there. In addition, he discovered that even the simple cubic configuration known as the scaffold structure (for its similarity to scaffolding) could have a band gap, albeit a small one.

Butterflies and Microchips

WE HAVE NOW LEARNED that nature already makes photonic crystals in the sparkling gem opal, in a butterfly's col-

ored wings and in the hairs of a worm-like creature called the sea mouse. Each of these has a photonic band structure, though not a full band gap, in that light can still propagate in some directions. A complete band gap has eluded nature, perhaps because it requires too much refractive-index contrast. Nevertheless, an incomplete band gap can be very useful. For example, titanium dioxide particles smaller than a

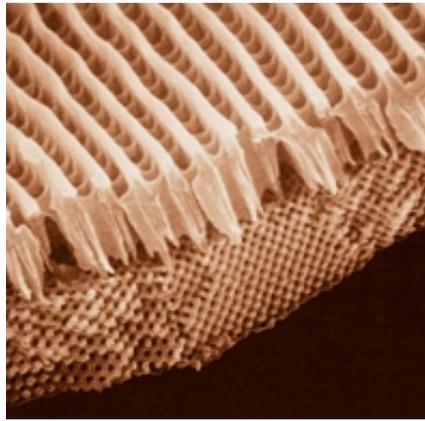
micron can be made to self-assemble in the opal structure. Titanium dioxide is the intensely white pigment used in paint and to make paper white. The coherent scattering of light that occurs from band-gap-structured titanium dioxide can impart more whiteness for less mass of titanium dioxide. One day photonic crystals may be all around us in the painted walls and in the stacks of paper cluttering our desks.

Another very useful type of incomplete band gap material is that of two-dimensional photonic crystals, which can block light from traveling within a plane. Such a structure can be stretched along the third dimension, forming a new kind of optical fiber. Conventional optical fibers have a high refractive index at their

capacity, perhaps 100 times that of conventional telecommunications fibers. Specialty fibers have advanced the most as commercial photonic band-gap products. Companies in Denmark and the U.K. have already distributed sample quantities and will soon begin volume production. Instead of stretching out a two-dimensional band-gap structure to make a fiber, one can go to the other extreme and make a two-dimensional thin-film photonic crystal, as was first calculated in 1997 by Shanhui Fan and John D. Joannopoulos, then both at the Massachusetts Institute of Technology. Thin-film photonic crystals can be easily patterned by standard methods used to produce integrated circuits. Introducing

APPLICATIONS FOR PHOTONIC CRYSTALS

DEVICE	DESCRIPTION	STATUS
OPTICAL FIBERS	2-D band-gap material stretched along the third dimension	Early versions already commercialized
NANOSCOPIC LASERS	World's tiniest optical cavities and tiniest lasers; formed in a thin-film 2-D band-gap material	Demonstrated in the lab
ULTRAWHITE PIGMENT	Incomplete 3-D band-gap material, usually patterned as opal structure	Demonstrated; low-cost manufacturing methods under development
RADIO-FREQUENCY ANTENNAS, REFLECTORS	Uses inductors and capacitors in place of ordinary dielectric materials	Demonstrated for magnetic resonance imaging and antennas
LIGHT-EMITTING DIODES	Photonic band-gap structure can extract light very efficiently (better than 50%)	Demonstrated, but must compete with other methods of achieving the same goal
PHOTONIC INTEGRATED CIRCUITS	2-D thin films can be patterned like conventional integrated circuits to make channel filters, modulators, couplers and so on	Under development



NATURAL PHOTONIC BAND GAPS occur in some butterfly wings (*left*) and in opals (*right*). In both cases, the band gap is incomplete—it is not effective in every direction—but it produces iridescent colors. A micrograph of a

fractured iridescent green butterfly scale (*center*) shows the submicron-size face-centered cubic structure inside. Opals consist of submicron-size silica spheres arranged in a face-centered cubic [close-packed] structure.

defects to a band-gap structure is comparable to doping in an electronic semiconductor and opens up a vast range of functions. One example of a dopant is the central hole in photonic crystal optical fibers. Similarly, plugging one of the holes in a thin-film crystal produces a critical element of lasers, namely a small “cavity” that can hold a local electromagnetic mode—imagine a little standing wave of light trapped between mirrors. Recently Axel Scherer’s group at the California Institute of Technology used these tiniest of optical cavities to make lasers just 0.03 cubic micron in volume, the smallest ever.

Patterning photonic crystal thin films into optical circuits would represent the ultimate limit of optoelectronic miniaturization. Many researchers believe that integrated circuits that combine conventional electronics and photonics stand ready to extend the integrated-circuit revolution into the domain of high-bandwidth optical signals. This field of band-gap device development will probably draw the most attention in the next few years, but commercial products are still two to three years away.

You might not expect electromagnetic band-gap crystals to be of much use for radio waves, because excessively large crystals would seem to be required. Cellular telephones, for example, may use radio waves that are 35 centimeters long in free space or in air. A crystal with many holes or rods of that size and spac-

ing would hardly be portable. We are rescued by the common LC circuit of electronics, which combines an inductor (a coil; “L”) and a capacitor (parallel plates; “C”). Such a circuit can, in effect, cram an electromagnetic wave into a small volume. An array of LC circuits can behave as a photonic crystal and control electromagnetic waves that have free-space wavelengths much larger than the array.

Backward Light

SHELDON SCHULTZ and David R. Smith, both at the University of California at San Diego, used arrays of LC circuits to create “left-handed” materials, which have a negative refractive index at microwave frequencies. In these materials, electromagnetic waves travel backward: when the wave crests are moving from left to right, the energy of the wave is actually traveling from right to left!

John B. Pendry of Imperial College in England has used LC electromagnetic band-gap arrays for manipulating the radio-frequency magnetic fields used in medical magnetic resonance imaging. Collab-

orations of researchers from industry, the military and academia (including my group) are studying how LC resonator arrays can also be used for controlling radio waves. Possible advantages of such arrays include making GPS antennas more precise by suppressing signal reflections from Earth and increasing cell-phone handset efficiency by reducing the electromagnetic coupling to the user’s head.

It appears likely that these LC circuit concepts can be extended back down to optical wavelengths. These devices would use plasmons, which are currents oscillating at optical frequencies on metallic surfaces. Such tiny LC circuit arrays, smaller than an optical wavelength, may represent the ultimate end point of photonic crystal miniaturization.

Sometimes venturers need to be overconfident, or they would never set off on their quests and persevere to the finish. When I pause to consider the extent of activity in this field today, I am very glad that a decade ago I took those distressing phone calls as an appeal for further research and problem solving. SA

MORE TO EXPLORE

Photonic Crystals: Molding the Flow of Light. John D. Joannopoulos, Robert D. Meade and Joshua N. Winn. Princeton University Press, 1995.

Optical Properties of Photonic Crystals. Kazuaki Sakoda. Springer Series in *Optical Sciences*, Vol. 80. Springer Verlag, May 2001.

A thorough photonic and sonic band-gap bibliography is available at <http://home.earthlink.net/~jpdowling/pbgbib.html>

Yurii A. Vlasov’s Ultimate Collection of Photonic Band Gap Research Links is at www.pbglink.com

Two companies producing photonic crystal fibers are Crystal Fibre A/S (www.crystal-fibre.com) and Blaze Photonics (www.blazephotonics.com).