PHYSICS AND TECHNOLOGY FOREFRONTS

Photonic Crystals

By E. Yablonovitch

Photonic crystals are the *electromagnetic* analog of semiconductor crystals. They are artificial crystal structures that do for electromagnetic waves what semiconductor crystals do for electron waves. In today's world, electronic semiconductors are the basis for the micro-electronic, telecommunications, and computer industries. We are just now beginning to understand the exciting potential of their electromagnetic cousins for tomorrow's world.

The powerful analogy between photonic and semiconductor crystals has unleashed the collective scientific imagination of many creative physicists, engendering a profusion of synthetic electromagnetic crystal structures. These usually have an electromagnetic bandgap, a band of frequencies in which electromagnetic waves are forbidden. Various 2-dimensional and 3-dimensional photonic crystal structures have now been conceived for application in high capacity optical fibers, color pigments, and especially nano-photonic integrated circuits that might be included in standard microchips.

A Little History

In electronic semiconductor crystals, electron waves scatter off the layers or rows of atoms. Bumping into periodic row after periodic row of atoms, the backscattering is reinforced if the electron wavelength matches the spacing of successive layers. Venturing off in different directions, the electron waves meet other layers of atoms. No matter which direction they go, they just can't get through if their wavelengths roughly match the layer spacings. The result is the celebrated forbidden bandgap of electronic semiconductors like silicon.

While it took thousands of years of metallurgy and materials science to discover and bring to perfection electronic semiconductor crystals, photonic crystals are in principle more accessible. Since electromagnetic waves appear equally well at all wavelengths from giant radio waves to tiny gamma rays, artificial electromagnetic crystal structures can be made with any convenient row spacing and size.

Only human imagination limits the crystal design and structure—we are no longer restricted to real material crystals that grow in nature. Yet initially there was no assurance that any particular design would actually produce a forbidden photonic bandgap. Ultimately the search for the first electromagnetic bandgap crystal would take four years, and involve the participation of numerous experimentalists and theorists who had no idea in advance whether a true photonic bandgap could ever even exist.

The absence of early empirical success was compounded by the problems that faced theorists. Electromagnetic waves are vectors like electric fields. It therefore took time for theorists to retool their band structure computer programs to accept vector waves. Several groups that undertook this task, including M. Leung of Polytechnic University, and K.M. Ho, C.T. Chan and C.M. Soukoulis of Iowa State University, began to make valuable predictions. The Iowa State group discovered that the diamond structure would indeed produce a real bandgap. Diamond structure is a form of face-centered-cubic (fcc) in which two atoms, instead of one, are inscribed into each unit cell. The form of diamond structure that was most effective, giving the widest photonic bandgap, consisted of only the dielectric rods ("valence bonds") between the atoms, which were allowed to shrink simply to points.

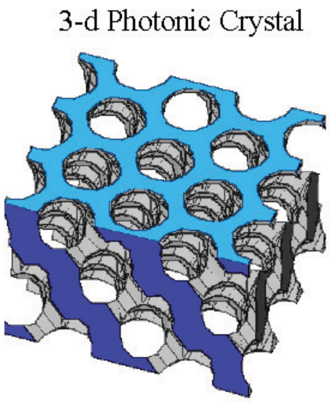

Figure 1: The first photonic crystal was formed by drilling three intersecting arrays of holes into a block of ceramic material. Each array is angled 35° into the plane, producing a structure now called Yablonovite. The pattern of 6mm-diameter holes blocks radio waves from 13 to 16 GHz.

There was also the question of whether the required refractive index might be unattainable in real materials, but the calculations showed that a refractive index of as little as 1.87 was enough in a diamond structure. As there are many optical materials available with refractive indices of up to 3.5, it seemed feasible that photonic bandgaps could be successfully made from real existing materials.

But theoretical searches for photonic bandgaps in fcc structures were at first elusive. Initially, only a pseudo-gap emerged between the 2nd and 3rd bands but eventually, at a little higher frequency, a bandgap emerged[2] between the 8th and 9th bands in fcc structures. Later, contrary to all expectations, H.S. Sozuer, J.W. Haus, and R. Inguva found that a bandgap, albeit a small one, could exist even in a simple cubic "scaffold" structure.

Some Real Life Photonic Crystals

Nature already makes photonic crystals, in the sparkling gem opal, and in the colors of butterfly wings. These have photonic band structures though not full photonic bandgaps. A complete bandgap seems to have eluded nature—it seems to require too much refractive index contrast. Nevertheless, an incomplete bandgap can still be very useful. Novel forms of synthetic opal can be self-assembled in titanium dioxide particles, the white pigment used in paint and to make printer paper white. Coherent scattering of light can give more whiteness for less titanium dioxide. One day we may find photonic crystals all around us on painted walls and in the stacks of documents that clutter our work desks!

While a perfect 3-dimensional structure is needed to block all waves in all directions, we have learned that 2-dimensional photonic crystals might be even more valuable. Two-dimensional photonic crystals come in many forms, since there is considerable freedom in handling the 3rd dimension. If the 3rd dimension is stretched out long and narrow, photonic crystals provide a new method for confining light in optical communications fibers, as first introduced by J. C. Knight, J. Broeng, T. A. Birks, and Philip St. J. Russell of Bath University. Normally light is trapped in optical fibers by total internal reflection in a high refractive index region at the core of the fiber. In contrast, bandgap confinement allows the core to have a lower refractive index, indeed to consist of an empty hole. These "holey" fibers allow new freedom in fiber design that can be valuable even when photonic bandgap confinement is absent. It is predicted that holey fibers may carry up to 100 times the information of conventional telecommunications fibers, potentially with such low losses that optical amplifiers and repeaters would be unnecessary.

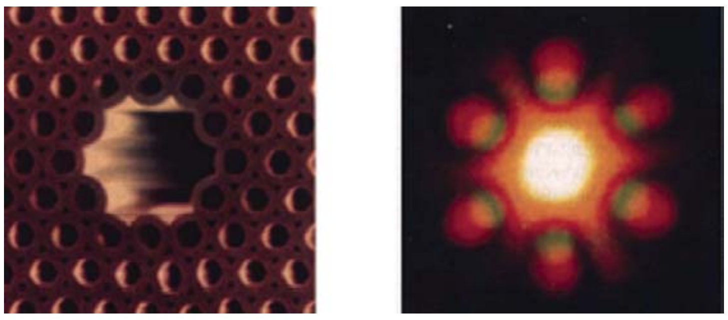

Figure 2: Left: the cladding of several hundred capillary tubes confines light to the central hole which is about 15 microns in diameter. Right: the pattern of colors shows that the optical confinement of a bandgap fiber depends strongly on wavelength.

Images courtesy of University of Bath, UK.

A photonic crystal is often most functional when an artificial defect is introduced, similar to doping in a conventional electronic semiconductor. Added dielectric material is equivalent to "donor" doping, and deleted dielectric material is equivalent to "acceptor" doping.

An example of this is the thin film 2-dimensional hexagonal-array photonic crystal. John Joannopoulos, Shanhui Fan and Pierre Villeneuve of MIT and E. F. Schubert of Boston University did some of the first calculations on thin-film 2-dimensional slab photonic crystals. Such thin films were not thought to be useful for trapping light, since they are completely open, top and bottom. Nonetheless, they are intriguing in that they could be easily patterned by standard integrated circuit production methods. When one of the holes is left plugged up, the result is a "donor" cavity, a local electromagnetic mode in a region with an otherwise forbidden bandgap.

Surprisingly, these 2-dimensional cavities can be very effective for trapping light, in spite of being open top and bottom. Indeed O. Painter, R.K. Lee, A. Scherer, A. Yariv, J.D. O'Brien, P.D. Dapkus, and I. Kim at Cal Tech and USC have recently fabricated the tiniest lasers ever from them. These 2-dimensional photonic crystal thin films can be readily patterned into optical circuits that would represent the ultimate limit of optoelectronic miniaturization. Many researchers believe that these types of photonic crystal integrated circuits stand ready to extend the integrated circuit revolution into the domain of high bandwidth optical signals, following the same miniaturization trajectory as conventional electronic integrated circuits.

From the ultimate miniaturization of tiny optical waves, we go to macroscopic radio waves. Can the concept of an electromagnetic bandgap be useful for radio waves? (Given their long wavelength they should be called "electromagnetic crystals" rather than "photonic crystals") For example a cellular telephone often uses radio waves that are 35cm long in free space. The corresponding electromagnetic crystal consisting of multiple periods would have to be even larger than that and not very practical for carrying around. Here the common electrical circuit of inductors and capacitors ("LC-circuit") rescues us. An LC-circuit can confine an electromagnetic wave to a small volume and arrays of LC circuits can behave as photonic crystals, controlling long electromagnetic waves, even though the whole array can be smaller than one free space wavelength.

This simple concept has led to a series of innovative new ideas in electromagnetics. For example, using arrays of LC-circuits, David Smith, Willie J. Padilla, D. C. Vier, S. C. Nemat-Nasser and Shelley Schultz of UCSD have created the first "left handed" materials, in which the group velocity and phase velocity are opposite!

Meanwhile, M.C.K. Wiltshire, J.B. Pendry, I.R. Young, D.J. Larkman, D.J. Gilderdale, and J.V. Hajnal of Imperial College have used LC electromagnetic bandgap arrays for manipulating the radio magnetic fields used in medical magnetic resonance imaging and D. Sievenpiper, Z. Lijun, R.F.J. Broas, N.G. Alexopolous, and E. Yablonovitch have used LC resonator arrays for controlling radio antennas.

It appears likely that these circuit concepts can be extended right back up to optical frequencies, where they emerge as so-called "plasmons", the optical frequency currents that can flow on metallic surfaces. Such ultra-miniature LC circuit arrays, smaller than an optical wavelength, may eventually represent the ultimate end point of photonic crystal miniaturization.

Eli Yablonovitch is professor of electrical engineering at the University of California, Los Angeles. He is a Fellow of the APS.

APS E-Board Passes Resolution on Perpetual Motion Machines

The APS Executive Board approved a resolution at its June 2002 meeting in Annapolis, MD, affirming the fraudulent nature of claims of perpetual motion machines.

The resolution was deemed necessary because of a recent increase in patent applications for such devices. Robert Park, APS Director of Public Information and author of the weekly electronic newsletter "What's New," reported that the US Patent Office has received several patent applications for perpetual motion machines during the first six months of this year alone. [Park's 2000 book, *Voodoo Science*, devoted considerable space to the phenomenon of such devices throughout history.] The text of the APS resolution follows.

> The Executive Board of the American Physical Society is concerned that in this period of unprecedented scientific advance, misguided or fraudulent claims of perpetual motion machines and other sources of unlimited free energy are proliferating. Such devices directly violate the most fundamental laws of nature, laws that have guided the scientific progress that is transforming our world.