Photonic Bandgap Based Designs for Nano-Photonic Integrated Circuits

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Photonic crystals are artificial crystal structures that do for electromagnetic waves what a semiconductor crystal does for electron waves. *Electronic* semiconductors are the basis for the micro-electronic, telecommunications, and computer industries, but photonic crystals are distinct, they are the *electromagnetic* analog of a semiconductor crystal.

Engineering design is sometimes inspired by Nature. The natural world is filled with crystals, periodic structures that interact with *electron waves*. Drawing on this analogy, photonic crystals are artificial periodic structures that are intended for *electromagnetic waves,* instead. This has now unleashed the collective scientific imagination of many creative engineers and scientists, engendering a profusion of synthetic electromagnetic crystal structures. In correspondence to semiconductor crystals, these usually have an electromagnetic bandgap, a band of frequencies in which electromagnetic waves are forbidden. A pictorial portfolio of various 2 and 3 dimensional photonic crystal structures is shown in Figures 1-4 (1). They have been conceived for various applications including high capacity optical fibers, color pigments, and especially nano-photonic integrated circuits that might become part of standard microchips.

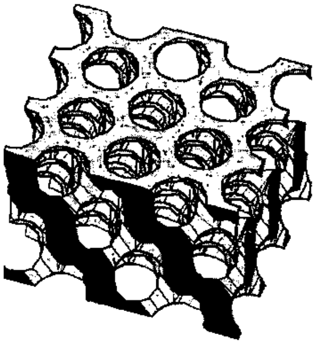
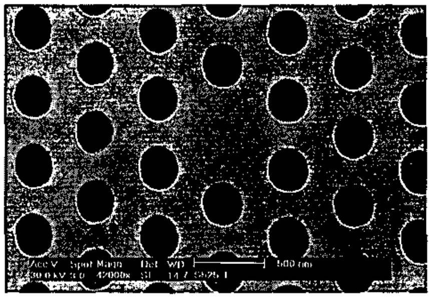


Fig. 1: 3-D photonic crystal.

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 cannot get through if their wavelengths roughly match the layer spacings. The result is the celebrated forbidden bandgap of electronic semiconductors, like Silicon.



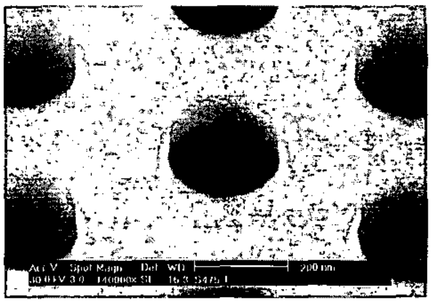


Fig. 2: 2D Photonic Crystal Defect Cavity: *InGaAs On Glass.*

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 would limit the crystal

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design and structure. We would not at all be restricted to real material crystals that grow in nature.

Therein lay the problem, there were so many choices available and there was no assurance that any particular design would actually produce a forbidden photonic bandgap. This triggered a search. For electromagnetic waves, nobody knew whether such a bandgap was even possible, or whether it would require a gigantic refractive index that did not even exist in nature. 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 empirical success was compounded by the puzzlingly slow acceptance of the photonic bandgap concept in the scientific world. At first, nobody seemed to know what to make of it. What seemed an utterly compelling proposal, left most scientists scratching the heads.

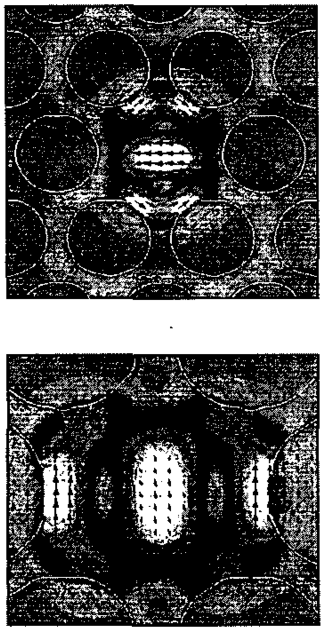

Fig. 3: Smallest Electromagnetic Cavity, Veff $\approx 2\times(\lambda/2n)^3$; Veff $\approx 0.005 \times \lambda^3$; High index contrast leads to miniaturization of the optical components.

But the theorists were having their problems too. They were accustomed to solving Schrodinger's equation for electrons in a semiconductor. To a good approximation, electron spin can be neglected, and the electron wave function can be regarded as a scalar. For electromagnetic waves, in contrast, the waves are vectors, like electric fields. It took some time for the theorists to retool their band structure computer programs to accept vector waves, and when they finally did, several groups, including M. Leung of Polytechnic Univ., and K.M. Ho et al of Iowa State University began to make valuable predictions. The Iowa State group would discover that diamond structure, the crystal structure geometry associated with the precious jewel, would indeed produce a real bandgap. Diamond structure is a form of face-centered-cubic in which two atoms, instead of one, are inscribed into each unit cell. (2) The form of diamond structure that is most effective, giving the widest bandgaps, consists of only the "valence bonds" dielectric rods between the atoms, the atoms being allowed to shrink simply to points.

Figure 1 is the first successful photonic crystal ever to be made, culminating the four-year search, and verifying the reality of the photonic bandgap concept. Now there was indeed an answer to the question of whether the required refractive index might be unattainable in real materials. With diamond structure a refractive index as little as n=1.87 was enough, and there are many optical materials available with index up to n=3.5, justifying that photonic bandgaps could be made successfully out of real existing materials. It is remarkable that diamond structure emerges whole and fully formed from Maxwell's equations.

Until now, the precious stone real diamond would emerge very indirectly from Schrodinger's equation, the other fundamental equation of physics. First you had to insert the atomic number 6 of carbon, and then add the Coulomb attraction to the nucleus, and then finally you had to avoid making graphite, and if you were lucky you would make diamond structure. But now we know diamond structure is not merely another mineral structure that you dig from the earth, it is fundamentally a 3-dimensional geometry of space that is implicit in Maxwell's equations.

It seemed that Diamond structure was in; but simple face-centered cubic (fcc) structures were out. This restriction didn't last long. Scientists had only searched the fcc structures for the most obvious bandgap, the one between the second and third bands that turned out to be merely a pseudo-gap. Later it was shown that if we had looked at a little higher frequency, between the eighth and ninth bands, an fcc bandgap would indeed emerge.

Later, it was even shown, contrary to all expectations, that even simple cubic structure in the form of a "scaffold" could have a bandgap, albeit a small one.

We have now learned that Nature already makes photonic crystals, in the sparkling gem opal, and in the colors of butterfly wings. These have photonic band structure, though not a full photonic bandgap. A complete bandgap has 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 self-assemble as titanium dioxide particles, TiO_2, the white pigment that is used in paint and that makes printer paper white. The coherent scattering of light can give more whiteness for less mass of TiO_2. One day we may find photonic crystals all around us in the painted walls, and in the stacks of documents that clutter our work desks.

A perfect 3-dimensional structure is needed to block all waves in all directions, but we were to learn that 2-dimensional photonic crystals could be even more valuable. Two-dimensional photonic crystals come in many forms, since there is considerable freedom in handling the third dimension. If the third dimension is stretched out long and narrow, photonic crystals form a new principle for confining light in optical communications fibers, as first introduced by Philip St. J. Russel of Bath University (4). Normally light is trapped in optical fibers by total internal reflection in a high refractive index region at the core of the fiber. Contrarily, bandgap confinement allows the core to have a lower refractive index, indeed to consist of an empty hole. The void on center can carry greater optical power levels than solid glass itself, and as we need more channels, more wavelengths, and more bits, more power will be needed. It is expected that holey fibers will be able to carry one hundred times the information of conventional telecommunications fibers. Holey fibers allow new freedom in fiber design that can be valuable even when full photonic bandgap confinement is absent.

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. Joannopoulos and Fan did some of the first calculations on thin-film 2-d slab photonic crystals (3). 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-d cavities can be very effective for trapping light, in spite of being open top and bottom. Q-factor, the number of optical periods before the light leaks away, measures light confinement. Q-factors up to 10^5 are projected. Indeed these are the smallest electromagnetic cavities ever made, and recently Prof. Axel Scherer's group at Caltech has fabricated them into the tiniest lasers ever made (6).

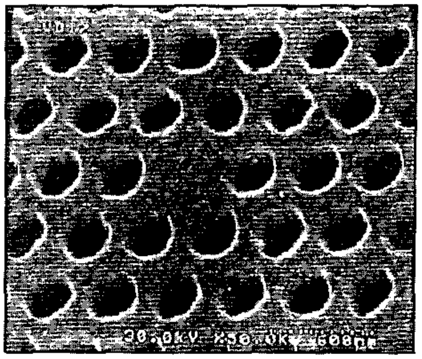

Fig. 4: Membrane microresonator in InGaAsP

These 2-d photonic crystal thin films can be readily patterned into optical circuits that would represent the ultimate limit of opto-electronic 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: not very practical for carrying around. Here we are rescued by the LC inductor/capacitor circuit of common electricity. An LC circuit can confine an electromagnetic wave to a small volume. 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 has led to a series of innovative new ideas in electromagnetics. For example, using arrays of LC circuits, Shelley Schultz and David Smith of UCSD have created the first "left handed" materials, in which electromagnetic waves seem to propagate backwards (7).

Prof. John Pendry of Imperial College has used LC electromagnetic bandgap arrays for manipulating the radio magnetic fields used in medical magnetic resonance imaging (5). LC resonator arrays can also be used for controlling radio antennas. Such an LC circuit array distributed on a metal surface is sometimes called a high-impedance ground plane.

Indeed 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 represent the ultimate end point of photonic crystal miniaturization.

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