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Perspectives

APPLIED PHYSICS:

How to Be Truly Photonic

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Photonic crystals are three-dimensional (3D) dielectric structures with a forbidden gap for electromagnetic waves, analogous (1) to the electronic band gap in semiconductors that lies at the heart of silicon technology. A photonic band gap allows light to be trapped in the tiniest volumes and optoelectronic devices, which interface optical and electronic components, to reach their ultimate limit of miniaturization.

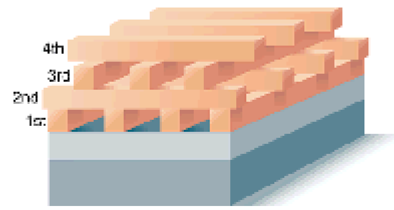
The dream of photonic integrated circuits--microchips for light--remains yet to be fulfilled, and many believe that tiny photonic crystal devices will hold the key. The Internet is demanding more and more communications capacity that will require vast numbers of such optical components. As reported on page 604, Noda *et al*. (2) now bring these devices one step closer to reality by creating a photonic crystal with unprecedented performance.

The first photonic crystals were reported about 10 years ago (3, 4), but they were hardly photonic at all. They were large structures and had gaps at microwave frequencies and centimeter wavelengths. Since then, the race has been on to shrink the structures down to optical wavelengths. This has not been an easy task, not least because photonic crystals are intricate 3D objects that must be created with nanometer precision.

Among the variety of optical materials, only those with a refractive index greater than roughly 2.0 are capable of supporting a photonic band gap. For fully functional optoelectronics, the classic III-V semiconductors, such as GaAs, will ultimately be preferred, because they combine both optical and electronic function. Although there has been considerable progress with other substances, such as TiO_2 and silicon, the III-V semiconductors remain the preeminent materials of choice.

The ideal structure for photonic band gaps must recreate, at the optical wavelength scale, the beautiful valence bond structure of diamond crystals at the atomic scale. Diamondlike connectivity or geometry in photonic crystals has provided the widest photonic band gaps observed to date even for relatively low refractive index contrast. Other crystal structures are easier to make. For example, face-centered cubic (fcc) crystals will self-assemble from microspheres in many types of colloidal solutions. But these fcc crystals have a relatively feeble gap that requires a refractive index greater than 2.8. These materials are likely to have other optical applications but are unlikely to provide full optoelectronic function, wherein electricity directly creates light.

Strategies for meeting the exacting set of requirements for a 3D, diamondlike nanostructure, with a III-V material base, for photonic crystals have long been sought. There have been some mildly successful efforts in the past (5, 6). A figure of merit has emerged to measure their success, with the rejection of optical intensity within the forbidden band gap becoming the accepted gauge. For a photonic band gap to be interesting, a rejection factor of 10 is deemed rather inadequate. Optical rejection should be much higher, at least 100 and up to 10,000 or more according to need.



The excellent report by Noda *et al.* (2) represents a watershed in photonic crystal research. The authors demonstrate unprecedented optical rejection >10,000 in a GaAs photonic band gap structure. All of the key requirements for photonic crystal-based optoelectronics are demonstrated in this work.

Their strategy, pursued for several years, has been marked by clear vision with few compromises. The particular diamondlike structure that Noda *et al.* fabricate is sometimes called the stack-of-logs structure, or the layer-by-layer structure introduced by the Iowa State group (7). (Actually, all 3D photonic crystal structures can be built up layer by layer.) The stack-of-logs structure (see the figure) represents the cubic <100> face of a diamond crystal. Its main advantage is that each face has a rectilinear appearance, easily programmed into electron-beam-writing lithography equipment. When the layers are precisely stacked above one another, the 3D structure emerges as diamondlike, with a strong photonic band gap.

Stacking assembly of photonic crystals. Just eight layers make a respectable photonic crystal. With the strategy of Noda *et al.* (2), this requires only three stacking and alignment steps.

CREDIT: FROM (3).

The stacking of successive layers can be accomplished by wafer fusion, where temperature and pressure allow two semiconductor crystal layers to merge. Here, Noda *et al.* have realized an excellent strategy. To make a full crystal requires many layers, each step necessitating exacting alignment, allowing errors to creep in. The authors noticed, however, that after stacking the first two layers, they could then work with both to stack four at a time, thus reducing the number of fabrication steps. Eight layers already make a respectable photonic crystal but require only three stacking and alignment steps (2).

This fabrication strategy has been fully vindicated by the excellent results presented in this issue. The internal waveguides demonstrated in the 3D crystal structure of Noda *et al.* may be the precursor of photonic integrated circuits. Soon we can expect to see tiny electromagnetic cavities, fully isolated from their surroundings in all three dimensions, that will exhibit unusual quantum effects.

Nevertheless, there are competing approaches. It has been noted that full 3D confinement, although meritorious, is not always essential. Excellent results have emerged recently in thin film semiconductor slabs perforated by a hexagonal array of holes, which form two-dimensional (2D) photonic crystals (8). These structures are much easier to make than 3D structures, while providing adequate index guiding in the third dimension. Recently, nanocavity lasers were demonstrated in such 2D photonic crystals (9). It appears that the race for technological supremacy will continue.

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