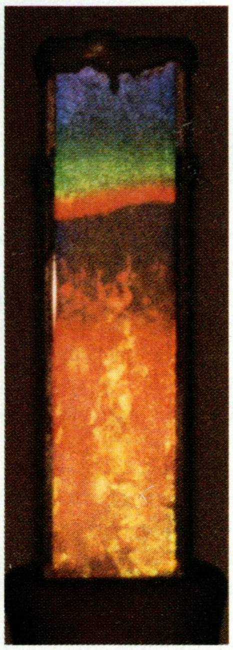
Designing Crystals That Say No to Photons

Crystals that forbid the emission or absorption of certain wavelengths of light could give photonic technologies a boost

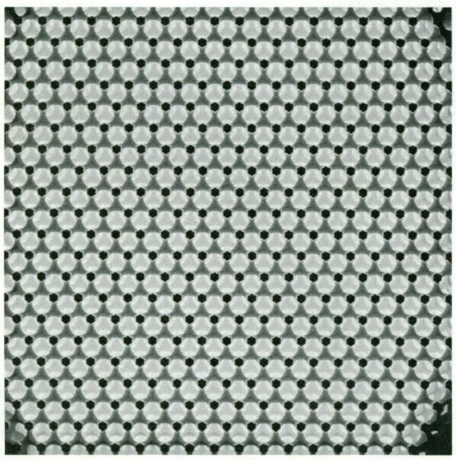
RESEARCHERS IN PHOTONICS—TECHNOLOGIES for communicating and computing with light—have long fantasized about having the exquisite control over photons that researchers in microelectronics are able to exercise over electrons. Their colleagues have it easy, thanks to semiconductors. Researchers can control electronic traffic across a semiconductor's "band gap," a kind of no-man's land for electrons, with, say, an electric field—an ability that has provided the basis for tiny solid state transistors and much of the electronics age. Now photonics researchers are taking steps to make their fantasies a little more real, by developing materials that may act like semiconductors for light.

At the American Physical Society (APS) meeting in Indianapolis this week, Eli Yablonovich of Bell Communications Research (Bellcore) and other researchers described artificial crystals that have a no-man's land for certain wavelengths of light and other electromagnetic radiation. Made of solids riddled with spaces like an intricate Swiss cheese or suspensions of fine plastic spheres, these "photonic crystals" include materials that could serve, for example, as microwave-antenna supports that would boost the antenna power by not absorbing broadcast energy, as conventional substrates do. Other photonic crystals discussed at the APS meeting could lead to new kinds of light-emitting diodes that would emit a very restricted band of wavelengths, like a laser, but consume only a fraction of the power needed for a laser. And there's more to come, says experimenter Robert D. Meade of the Massachusetts Institute of Technology: "Research is beginning to take off exponentially. In the last 2 or 3 months people have begun to understand what are the important characteristics of the structures."

LAWANDY *ET AL.*



YABLONOVICH *ET AL.*



How to block a photon. *Packing spheres* (right) *or drilling holes* (below) *are two strategies.*

In spite of their name, photonic crystals are unlikely to be mistaken for normal crystals. In familiar crystals such as diamond, the constituent atoms are spaced at intervals of a few angstroms, but the distances between the subunits of a photonic crystal are thousands of times longer or more—as long as the wavelengths of electromagnetic radiation that the materials are designed to control. Some of the structures scatter light that strikes their surface, much as milk or opals do. (Indeed, Nabil Lawandy of Brown University even mused in an interview that the opalescent beauty of the photonic crystals he and his coworkers are working with would make for a nice line of jewelry.) Other crystals with a smaller lattice spacing, which have yet to be made, presumably would look more like a mirror. But it is the crystals' interiors that intrigue their makers. There, according to the equations describing how electromagnetic waves travel in structured spaces, not all wavelengths get free passage.

Yablonovich touched off the search for photonic crystals 5 years ago when he set his sights on materials that could rein in the spontaneous emission of light and other radiation in solid-state lasers and other components of communications networks, a phenomenon that limits their performance. After many unsuccessful trials, hampered by an incomplete theoretical framework, Yablonovich's team achieved its first success by drilling intersecting sets of tiny holes into a commercially available dielectric (nonconducting) material, yielding a mostly empty Swiss-cheese structure. To the researchers' delight, the material refused to allow certain wavelengths of microwave radiation to pass through it in any direction whatever. Now, Bellcore researcher Axel Scherer is fabricating similar, though finer-scale, structures out of gallium arsenide. The resulting materials should have a similar effect on infrared radiation, which is used for optical communication, Yablonovich says.

Meanwhile, Lawandy and his colleagues are building photonic crystals from colloids—fine solid particles suspended in liquid. Lawandy's colloids consist of aqueous suspensions of minute polystyrene spheres, just 1000 angstroms or so across, which pack into "crystalline" arrays somewhat like stacks of tiny oranges. Unlike the solid Bellcore crystals, these colloidal versions have partial photonic band gaps that allow the forbidden wavelengths to propagate in certain directions. One possible advantage of colloids over solid-state photonic crystals, Lawandy argues, is the opportunity to tune the spacing between the crystals' polystyrene "atoms"—and hence the partial photonic band gap—simply by adding or subtracting water.

Lawandy and his colleagues are also varying the makeup of the colloidal crystals—an effort that could have a practical spinoff. One candidate material, titanium dioxide, is also a promising but inefficient catalyst for chemical jobs such as purifying drinking water by degrading halogenated hydrocarbons. That reaction requires an initial input of energy to activate the titanium dioxide particles, and chemists have been frustrated by the particles' readiness to reradiate the energy as light instead of channeling it into chemical work. Building a photonic band gap into the system to block the reradiation could well jack up its catalytic efficiency to practical levels, Lawandy suggests.

Yablonovich, Meade, and their colleagues are pursuing the analogy with semiconductors even further. In a joint effort, they have deliberately designed certain defects into photonic crystals. Rather like the foreign atoms with which semiconductors are doped to alter their electronic properties, the defects alter the photonic band gap. They open up tiny regions of it, enabling precise frequencies of radiation to slip through the material. "You can shape these dielectric structures to have the electromagnetic properties you want," Meade says. "They're the designer genes of electromagnetism."

■ IVAN AMATO