Materials Science
Aspects of
Photonic Crystals
Albert Polman and Pierre Wiltzius,
Guest Editors

The electronics revolution of the past 50 years has its roots in two scientific and technological areas. On the one hand, there have been tremendous advancements in our understanding of the physics of metals, dielectrics, and semiconductors, leading to the development of devices such as the transistor. On the other hand, a variety of processing techniques such as thin-film growth and deposition, ion implantation, and photolithography have allowed the massive integration of electronic functionality within a very small area, leading to microprocessors and high-density memory, among other innovations.

Our ability to control photons is in many ways in its infancy, compared with how we can manipulate electrons. Passive devices such as optical fibers, waveguides, splitters, and multiplexers are well developed. But as soon as more complex functionality or integration is required, the optical solutions do not yet exist. For example, all-optical switches are still very rudimentary and bulky, and the size of an optical integrated circuit (IC) is most often in the millimeter or centimeter range rather than the submicrometer dimensions common in electronic technology.

Nevertheless, there is a clear need to develop new materials and concepts with increased optical functionality for a variety of applications. The global telecommunications market is on an extraordinarily steep growth curve, driven largely by the explosion of the Internet, which plays an increasingly pervasive role in our daily life. The demand for broadband communications networks is expected to grow for many years to come. New approaches for the manipulation of photons will have to be developed to realize the more advanced optical elements needed for networks in the coming decade. Photonic crystals may play an important role in this development.

A photonic crystal is a regularly structured material that exhibits strong interaction with light. The conceptually simplest example of such a material is a multilayer stack of alternating high- and low-dielectric-constant materials. Strong interaction with light occurs in such a material because of interference between the light beams that are reflected and refracted at all interfaces inside the material. The final optical response is determined by the coherent superposition of all of these optical waves. It has long been known that such multilayer stacks can be engineered to have, for example, nearly perfect reflection over a (narrow or broad) wavelength range, a so-called stop band. Thin-film deposition techniques have made such structures widely available. Well-known examples of such “one-dimensional” (1D) photonic crystals are dielectric mirrors, filters, fiber gratings, distributed-feedback structures, and vertical-cavity surface-emitting lasers. Research is also being focused on “omnidirectional” mirrors that reflect light over a well-defined wavelength range in all directions, again using an alternating array of thin films with appropriately chosen optical properties.

Figure 1 shows an example of a 1D photonic crystal integrated in an optical channel waveguide. In this structure, fully based on silicon, an array of holes was etched by using standard lithographic techniques. The size and spacing between the holes defines the wavelength-dependence of optical transmission through the waveguide. The importance of this structure lies in its extremely small size and mode volume, and the possibility of its integration on a planar (silicon) substrate.

While many of the 1D structures mentioned have a wealth of applications, the fundamental optical concept behind their operation is relatively simple. In recent years, there has been much activity aimed at expanding the simple concepts of layered, 1D photonic structures to higher dimensions. As first proposed by Yablonovitch and John, the optical properties of such materials can be described by an “optical band structure.” This concept has analogies to the well-known band structure of electronic materials in the sense that in materials with particular structures, it predicts the existence of an optical bandgap, that is, a range of optical frequencies that cannot propagate in the material. This concept is particularly intriguing in a 3D photonic crystal, as it implies that in a particular frequency band, spontaneous emission would be completely suppressed. Initial searches for a structure that would possess a full bandgap led to fcc crystalline structures, but they failed to yield positive results. Soukoulis et al. made the important discovery that diamond symmetry eliminated a degeneracy in the band diagram, thus opening up a bandgap in all crystal directions. In the past few years, great progress has been made to realize such structures experimentally.

While 2D crystals seem less appealing because of their lack of optical control over the third dimension, they have the advantage of possible integration with planar optical-waveguide technology. In addition, external probes can be used to determine properties inside the crystal. The group led by Joannopoulos has proposed a large variety of 2D structures, many of which are now being studied experimentally. As an example, Figure 2 shows a simulation of the propagation of an optical mode traveling around a sharply bent waveguide in a 2D photonic crystal composed of a cubic array of dielectric...
cylinders. Note that this particular property of the photonic crystals is due to a carefully chosen defect, that is, a missing row and column of cylinders. Indeed, defects and disorder play an extremely important role in photonic-crystal research, as they enable the tailoring of particular properties for specific wavelengths.

The first experimental realizations of 3D photonic crystals were for wavelengths in the microwave region. Yablonovitch and collaborators\textsuperscript{7} invented an ingenious scheme of holes made in a dielectric using mechanical drilling (see Figure 3). This structure is probably the first 3D structure with a full bandgap in the microwave regime. Obviously, many applications of photonic crystals are in the visible wavelength range or the near-infrared telecom
communications\textsuperscript{3} window (1.3–1.5 μm), and submicrometer resolution in the fabrication technology is therefore required. This can be done by taking advantage of the latest techniques in submicrometer patterning, initially developed for the IC industry. As an example, Figure 4 shows a 2D photonic crystal composed of Si pillars with diameters as small as 205 nm made using high-resolution lithography.\textsuperscript{8} Alternative methods such as the self-assembly of colloids have led to important new photonic-crystal fabrication technology as well. A promising example is shown in Figure 5. A completely different approach to building 3D structures with micrometer-scale features was demonstrated by Marder and collaborators.\textsuperscript{10} Using two-photon polymerization of photoresists and advanced scanning tools, they built structures such as those in Figure 6.

Semiconductors such as Si and GaAs possess the high dielectric contrast and low absorption required for a full photonic bandgap in two or three dimensions. At the same time, photonic crystals made of dielectric materials with a lower refractive index, such as SiO\textsubscript{2}, TiO\textsubscript{2}, and polymers, while not having a full bandgap, can still have strong interaction with light and, therefore, interesting photonic properties. More recently, theory on photonic crystals partly composed of metals indicates a wealth of interesting phenomena in such materials, and the first experiments in this area are just appearing.

This issue of MRS Bulletin gives a snapshot of current developments and future trends in 2D and 3D photonic-crystal research and technology.

Optical fiber is the backbone of all-optical networks. Knight et al. review new concepts in microstructured optical fibers that have 2D patterns formed by drawing structured fiber preforms. In these fibers, light propagates in a core mostly composed of air, and several nonlinear properties are described.

The contribution by Noda covers the development of 2D and 3D photonic crystals at optical wavelengths made with III–V semiconducting materials. He discusses applications to ultrasmall optical ICs, including sharp bends in waveguides, lasers, and filters. He also presents a 3D photonic crystal with a full photonic bandgap in the near-infrared. The structures are made using state-of-the-art, high-
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Wehrspohn and Schilling describe electrochemical routes to building arrays of pores in silicon and aluminum oxide. These structures show photonic bandgaps in two dimensions. Optical characterization of these structures, including waveguides, is presented.

The article by Lin et al. reviews several examples of 3D photonic crystals with different symmetries that have been built using silicon VLSI (very large-scale integration) tools. A 3D photonic crystal with a full photonic bandgap in the near-infrared is discussed. They also show some of the basic building blocks for photonic structures such as waveguides and microcavities.

A radically different materials approach to building 3D microporous objects using colloidal self-assembly. These photonic crystals can be replicated using a variety of techniques, and optical and structural characterization are discussed.

The last article in this issue, by Vos and Polman, discusses recent advances in the control of the spontaneous emission of light in photonic crystals. The concept of local optical density of states is described, as well as experiments on the incorporation of optical probes inside photonic crystals.

We hope that this issue of MRS Bulletin will stimulate the materials research community and enable further progress toward achieving photonic crystals with desired properties, including full control of spontaneous emission, and applications in devices such as low-threshold lasers, low-loss waveguides, multiplexers, optical switching elements, and photonic integrated circuits with enhanced functionality.

References


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