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.[1] 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.[2] Figure 1 shows an example of a 1D photonic crystal integrated in an optical channel waveguide.[3] 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[4] and John,[5] 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.[6] 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.[1] 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

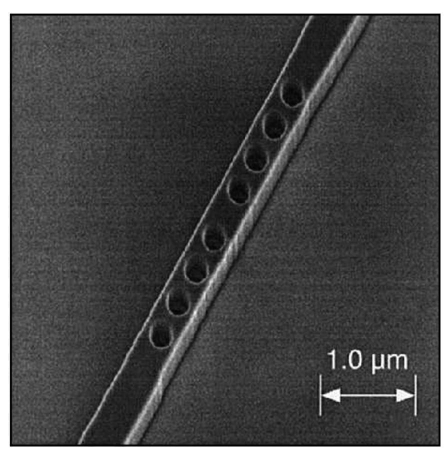

Figure 1. Scanning electron micrograph of a one-dimensional silicon photonic crystal integrated in an optical channel waveguide.

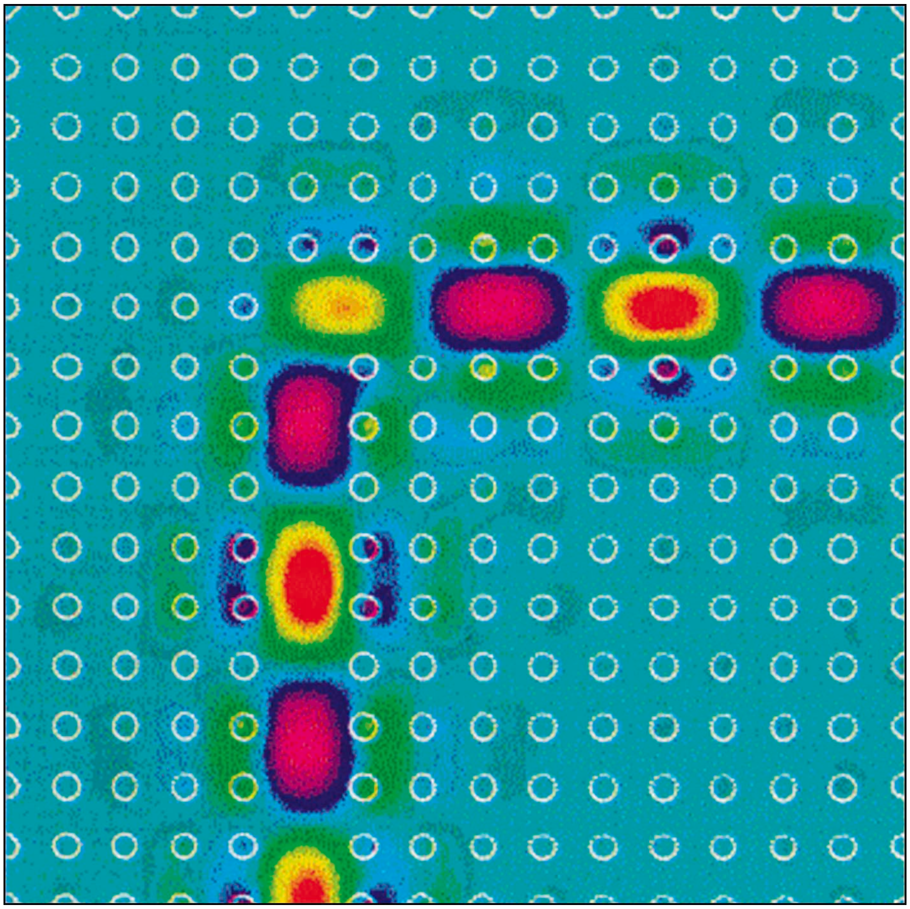

Figure 2. Simulation of the propagation of an optical mode traveling around a sharply bent waveguide in a (two-dimensional) 2D photonic crystal composed of a cubic array of dielectric cylinders. The calculation is performed for a refractive index n = 3.4, and the spacing between the centers of the cylinders is 0.35× the wavelength (e.g., at a wavelength of 1.55 μm, the spacing is 550 nm).

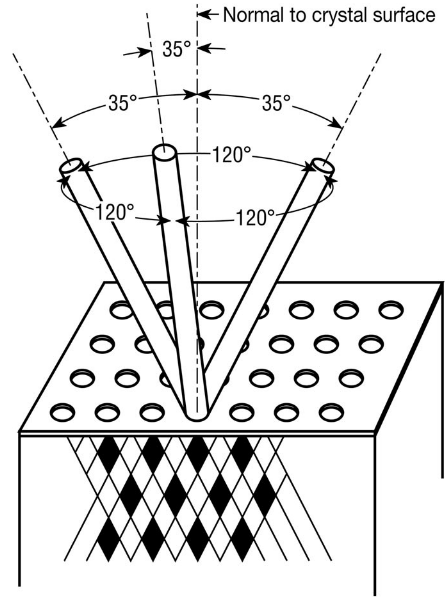

Figure 3. Schematic diagram of the construction of an fcc lattice. Three sets of holes are drilled on a 35° tilted axis into a slab of material. For microwave length scales, these holes can be drilled mechanically, whereas in the near-infrared, reactive ion etching has been used.

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[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 telecommunications[3] window (1.3 μm, 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.[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.[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_2, TiO_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-

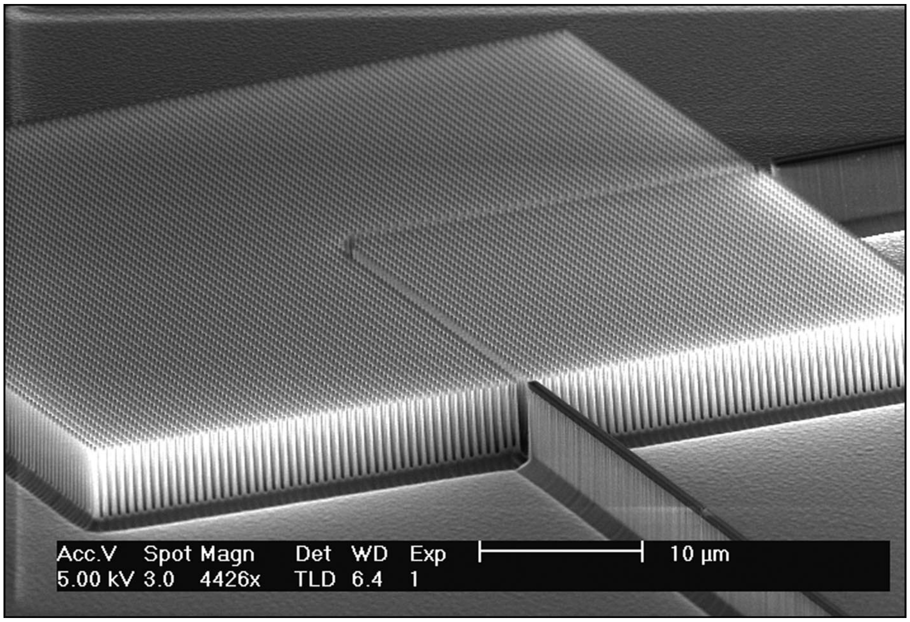

Figure 4. Scanning electron micrograph of a periodic array of silicon pillars fabricated using deep anisotropic etching. The silicon pillars are 205 nm in diameter and 5 μm tall. This structure possesses a bandgap of around 1.5 μm for transverse magnetic polarization. By removing an array of pillars, a waveguide bend may be fabricated. Input and output waveguides are integrated with the photonic crystal.

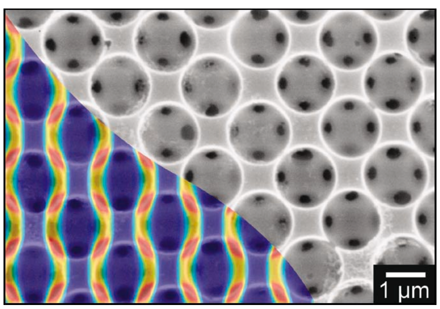

Figure 5. A scanning electron micrograph of a 3D photonic crystal. This structure was assembled by sedimentation of monodisperse colloidal silica on a template, thus forming an fcc structure. Subsequently, molten selenium, which has an index of refraction of 2.5 in the near-infrared and very low absorption, was imbibed into the interstitial space, and the silica was etched away to produce a high-dielectric-constant replica. (From Reference 9.)

Figure 6. 3D microstructures produced by two-photon polymerization.

resolution, compound-semiconductor processing technology.

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 photonic crystals is presented by Turberfield. Using holographic lithography, his group is able to build 3D structures in thick layers of photoresist. This technique is well suited for constructing crystals with submicrometer periodicity and a broad choice of crystal symmetries.

The contribution by Colvin covers approaches to building 3D microperiodic 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.

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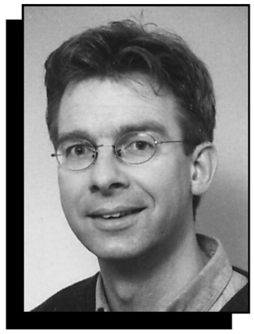

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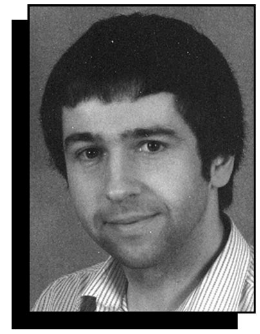

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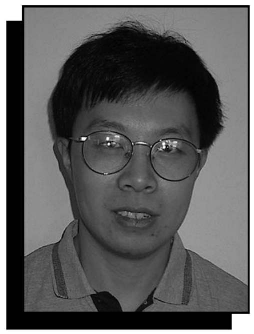


Edmond Chow

Vicki L. Colvin

James G. Fleming

Albert Polman, Guest Editor for this issue of *MRS Bulletin,* is a scientific group leader and head of the optoelectronic materials program at the FOM Institute for Atomic and Molecular Physics (AMOLF) in Amsterdam. His research interests include photonic-bandgap materials, rare-earth-doped photonic materials, colloidal photonic materials, semiconductor nanocrystals, and rare-earth-doped semiconductors, as well as the fundamentals of ion–solid interactions. In 1985, Polman received his master's degree in physics, and in 1989 he earned his PhD degree in materials science and engineering—both from the University of Utrecht. From 1989 to 1991, he was a postdoctoral researcher at AT&T Bell Laboratories. In 1991, he returned to AMOLF to start a new optoelectronic materials program. In 1996, he was appointed adjunct professor of materials science at Utrecht University.

Polman has coauthored some 150 papers on optoelectronic materials, participated in four conference proceedings, and is coinventor on three patents. He has served MRS as a symposium organizer and a Volume Organizer of *MRS Bulletin* and will co-chair the 2003 MRS Spring Meeting.

Polman can be reached by e-mail at polman@amolf.nl and via URL www.amolf.nl.

Pierre Wiltzius, Guest Editor for this issue of *MRS Bulletin,* is a director of semiconductor physics research at Bell Laboratories/Lucent Technologies. His research interests include soft condensed matter and complex fluids (e.g., polymers, colloids, liquid crystals, and their potential for photonic crystals). Wiltzius is also involved in plastic transistors on flexible substrates for various applications, including electronic paper. Some of the highlights in semiconductor physics research include wide-bandgap semiconductors, quantum cascade lasers, and molecular-scale electronics. He received the Diplomphysiker degree (1976) and the DSc.N. degree (1981) from the Swiss Federal Institute of Technology in Zurich. He was a postdoctoral fellow at the University of California—Santa Barbara between 1982 and 1984. Wiltzius then joined Lucent (formerly AT&T Bell Laboratories) in 1984 as a member of the technical staff. He is a Fellow of the American Physical Society and the American Association for the Advancement of Science and is currently a senior member of the IEEE.

Wiltzius can be reached by e-mail at wiltzius@lucent.com.

Tim A. Birks is a Senior Lecturer in the Department of Physics at the University of Bath, having previously worked in the Optoelectronics Research Center at the University of Southampton. Since 1994, Birks has pursued the development of photonic-crystal fiber and the understanding of its unusual optical properties. He has carried out experimental and theoretical research on single-mode fiber devices since 1986. Birks was awarded a BA degree in physics (1986) from Brasenose College, Oxford, and his PhD degree in electronics and computer engineering (1990) from the University of Limerick, Ireland. His work was recognized in 1995 by a Royal Society University Research Fellowship award.

Birks can be reached by e-mail at t.a.birks@bath.ac.uk.

Edmond Chow is currently a staff member at the Communication Optics Research Lab of Agilent Technologies Inc. His research interests focus on the design, fabrication, and characterization of nanophotonic devices.

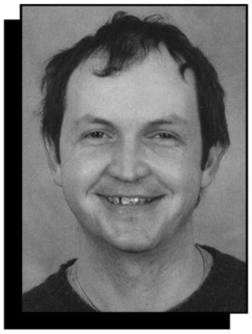
Chow received a BS degree from the Chinese University of Hong Kong in 1992. He received his MS and PhD degrees in physics from Indiana University in 1993 and 1997, respectively. He then worked with the single-electron transistor group at the Swedish Nanofabrication Lab as a postdoctoral researcher. From 1998 to 2000, he studied with the photonic-crystal group at Sandia National Laboratories.

Chow can be reached at Agilent Technologies, MS 26M-9B, 3500 Deer Creek Rd., Palo Alto, CA 94304, USA; and by e-mail at edmond_chow@agilent.com.

Vicki L. Colvin is an associate professor of chemistry at Rice University. Her research interests include template chemistry, photonic crystals, and the properties of liquids and glasses in nanoscale environments. She received her BS degree in chemistry and physics from Stanford University in 1988 and her PhD degree in chemistry from the University of California—Berkeley in 1994. Colvin became a member of the technical staff at Bell Laboratories in 1995 after postdoctoral training there and joined the faculty of Rice University in 1996. She was recently named an Alfred P. Sloan Fellow (2000) and a Camille Dreyfus Teacher-Scholar (2001).

Colvin can be reached at Rice University, Department of Chemistry, MS 60, Houston, TX 77005, USA; and by e-mail at colvin@ruf.rice.edu.

James G. Fleming has been with Sandia National Laboratories since 1988, where he is a distinguished member of the technical staff. He is actively involved in micromachining process development, chemical-vapor-deposition processes, complementary metal-oxide semiconductor process integration, and three-dimensional photonic lattice design and fabrication. Fleming received his undergraduate degree from the Johns Hopkins University in 1982 and his MS and PhD degrees



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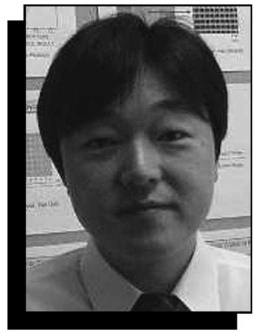

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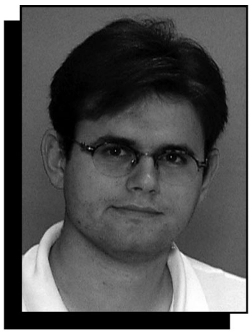

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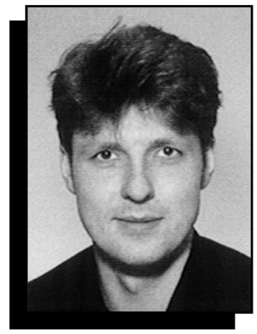

Ralf B. Wehrspohn

from Stanford University in materials science (1984) and engineering (1987), respectively. Fleming's thesis work concentrated on thermodynamics and kinetics studies of mercury cadmium telluride. During his graduate work, he was an Office of Naval Research Fellow, and following graduation, Fleming was awarded the Alexander von Humboldt Fellowship and worked at the Hahn-Meitner-Institut in Berlin from 1986 to 1988. His work in Berlin involved the development of FeS_2 and $CuInS_2$ for solar-energy conversion. Fleming is the author or co-author of over 100 publications and holds seven patents in the areas of field-emitter design, chemical vapor deposition, and MEMS processing. He is the recipient of two R&D 100 awards, an Industry Week 25 award, and a Lockheed Martin Nova Award.

Fleming can be reached by e-mail at fleminjg@sandia.gov.

Jonathan C. Knight is a professor in the Department of Physics at the University of Bath. His research interests encompass photonic-crystal fibers, scanning near-field microscopy, and microlasers.

He was awarded his PhD degree from the University of Cape Town, South Africa, and performed postdoctoral work at the Laboratory Kastler Brossel at the École Normale Supérieure, Paris, and at the Optoelectronics Research Center, University of Southampton.

Knight can be reached by e-mail at pysjck@bath.sc.uk.

Shawn-Yu Lin joined Sandia National Laboratories in 1994 as a member of the technical staff and currently leads an effort developing photonic-crystal devices for optical communication and display and energy applications. In 2000, Lin became an adjunct professor at the Georgia Institute of Technology and Iowa State University. Most recently, he leads the Department of Energy's multilaboratory effort in nanostructural photonics initiatives. He is interested primarily in nanophotonics, integrated optics, silicon-based photonics, and quantum electronic devices. Lin received his PhD degree from Princeton University in 1992 and joined the IBM T.J. Watson Research Center as a postdoctoral researcher the same year. At IBM, Lin worked on wave-function symmetry of high-temperature superconductors, as well as ultrafast photoconductive switches. Lin is the recipient of Lockheed Martin's NOVA award, the Technology of the Year award from Industry Week Magazine, and the R&D 100 award. Also, *Science Magazine* cited his work on photonic crystals as "one of the most important breakthroughs in 1999."

Lin can be reached by e-mail at slin@sandia.gov.

Brian J. Mangan is presently working for Blazephotonics, a start-up company located on the University of Bath campus and established to explore the commercial possibilities of photonic-crystal fibers. He was recently awarded his PhD degree from the University of Bath on the fabrication and properties of photonic-crystal fibers. He played a key role in setting up the fiber fabrication facilities at Bath and developed many of the techniques, now used routinely, used to make new types of photonic-crystal fibers. His work at the University of Bath led to the Rank Foundation awarding him a prize for his PhD thesis.

Mangan can be reached by e-mail at b.j.mangan@bath.ac.uk.

Susumu Noda joined Kyoto University in 1988 and is currently a professor in the Department of Electronic Science and Engineering. Since 2000, he has served as the research director of CREST (Core Research for Evolutional Science and Technology) at the Japan Science and Technology Corporation. His research interests focus on quantum optoelectronics, including photonic crystals and quantum nanostructures. Noda received BS, MS, and PhD degrees in electronics from Kyoto University in 1982, 1984, and 1991, respectively. From 1984 to 1988, he was with the Mitsubishi Electric Corporation and was engaged in the research of multi-quantum-well distributed-feedback lasers. Noda is a member of IEEE, IEICE (Institute of Electronics, Information, and Communication Engineers), and JSAP (Japan Society of Applied Physics). He has received the Ando Incentive Prize (1991), the Marubun Incentive Prize (1991), and the IBM Japan Science Award (2000).

Noda can be reached by e-mail at snoda@kuee.kyoto-u.ac.jp.

Philip St. J. Russell is head of the Optoelectronics Group at the University of Bath. Prior to this position, he headed a research group in the Optoelectronics Research Center at the University of Southampton, and he has also worked at Oxford University, the IBM T.J. Watson Research Center, the University of Hamburg—Harburg, and the University of Nice. Russell has 23 years of experience with just under 300 publications on light-propagation in waveguides and periodic structures. He has worked on photonic crystals and optical fibers for over two decades, proposing the original idea of photonic-crystal fibers in 1992. In 2000, he won the Fraunhofer Award from the Optical Society of America.

Russell can be reached by e-mail at p.s.j.russell@bath.ac.uk.

Jörg Schilling is a PhD candidate at the Max Planck Institute of Microstructure Physics in Halle, Germany. He fabricates and investigates two- and three-dimensional photonic crystals based on macroporous silicon. His research interests include photonic crystals and x-ray reflectivity of thin films. Schilling studied physics at Martin Luther University Halle–Wittenberg and at the Heriot-Watt University in Edinburgh, Scotland. In 1999, he received his diploma degree in physics from the Martin Luther University.

Schilling can be reached by e-mail at schill@mpi-halle.de.

Andrew J. Turberfield is a Reader in physics at Oxford University. He read Natural Sciences at Cambridge University, then studied for a D.Phil. degree at Oxford University. His research interests are in photonic-crystal fabrication, the optical spectroscopy of electron correlation phenomena in low-dimensional electron systems, and bionanotechnology, in particular, DNA nanostructures.

Turberfield can be reached by e-mail at a.turberfield@physics.oxford.ac.uk.

Willem L. Vos is a Universitair Docent (a tenured faculty member) in the Van der Waals–Zeeman Institute of the University of Amsterdam. His interests include ordered and disordered photonic materials, and the physics of conventional and soft condensed matter. Vos obtained his doctoraal (MSc) degree at the University of Amsterdam (1987) and his PhD degree cum laude at Amsterdam (1991) for studies of phase transitions at high pressures. After a postdoctoral Carnegie Fellowship at the Geophysical Laboratory, Carnegie Institution of Washington (1991–1994), he joined the University of Amsterdam.

Vos can be reached by e-mail at wvos@science.uva.nl and via URL www.thephotonicbandgaps.com.

Ralf B. Wehrspohn is responsible for activities relating to photonic crystals and porous materials at the Max Planck Institute of Microstructure Physics in Halle, Germany. His research interests include photonic crystals, thin-film technology, silicon electrochemistry, and ordered pore growth. He received his diploma degree in physics from the University of Oldenburg in 1995. He then carried out his PhD degree at the École Polytechnique in Palaiseau, France, on thin-film technology and electrochemistry. In 1998, Wehrspohn joined Philips Research Laboratories in Redhill, U.K., to work on thin-film transistors for active-matrix liquid-crystal displays (AMLCDs). Since the end of 1999, he has been working at the Max Planck Institute of Microstructure Physics.

Wehrspohn can be reached by e-mail at wehrspoh@mpi-halle.de. □

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