PHOTONICS

Light control at will

Sajeev John

Microchips that make use of light instead of electrons could outperform their electronic counterparts if light flow can be controlled at will. Photonic crystals are instrumental in achieving such a manoeuvre.

Photonic crystals are artificial materials made of periodically arranged insulating structures that are specially designed to aid the trapping and confinement of light within a very small area. These crystals offer the possibility of confining light on sub-wavelength scales in air, and provide a foundation for guiding light through circuit paths in a three-dimensional (3D) optical (as opposed to electronic) microchip without energy loss caused by light scattering. The crystals also enable unprecedented strong coupling effects between light and semiconductor nanocrystals, known as quantum dots. These effects provide a route to fast information processing and computing by optical means. However, such tantalizing opportunities require that photonic crystals be accurately synthesized and that light be efficiently manipulated both inside and at the surface of the crystal without loss. In this issue (page 367), Ishizaki and Noda[1] take an important step towards achieving these goals by demonstrating the control of light at the surface of a suitably constructed, gallium-arsenide-based, 3D photonic crystal.

The special, regularly repeating arrangement of insulating (dielectric) structures in photonic crystals gives them a special property: light waves with frequencies that fall within a range known as the photonic band gap (PBG) are prevented from propagating because of destructive wave-interference effects. This provides a clean slate on which to write optical circuit paths. Ishizaki and Noda's woodpile-type structure consists of layers of dielectric rods stacked together (see Fig. 1a on page 367). Although it exhibits a bulk 3D PBG — that is, frequencies within the PBG are blocked from flowing inside the material in all possible directions — there are frequencies (modes) within the otherwise forbidden gap in which light can leak from the crystal interior to the exterior surface, travel freely along the surface of the crystal and eventually escape into free space. In other words, the edges of the slate are not completely clean.

Modification

To control the leakage of light into unwanted surface modes, the authors[1] reapply the PBG concept to the surface itself. They modify the surface layer of the material by constructing a two-dimensional (2D) periodic structure to create a 2D PBG for the surface modes. The spectral overlap between the bulk 3D PBG and the 2D surface PBG then provides the desired frequency window in which no electromagnetic waves can propagate, either within the woodpile architecture or along its surface. With this completely clean slate, the last remaining escape pathways for light are removed and light within the 3D microchip can be controlled at will.

The experimental demonstration[1] of a simultaneous 3D PBG and 2D surface PBG has several implications. Ishizaki and Noda have used this to demonstrate a strongly localized state on the surface of their woodpile structure that persists for around 9,000 optical cycles before it releases its trapped light to free space. This light trap was engineered by introducing a defect — in the form of a local deviation from horizontal periodicity — on the surface of a thin 3D photonic crystal; that is, one with only two repeating units of vertical periodicity. If thicker 3D crystals were used, the lifetime would be expected to increase dramatically.

However, this is only one small indicator of the implications of the authors' successful integration of defects of different dimensionality within 3D PBG architectures. For example, circuits for light in an optical microchip are based on one-dimensional defects known as linear waveguides[2]. In optical communications and information processing, a crucial issue is the 'insertion loss' as light enters the in-chip waveguide from an external optical fibre. The efficiency of the coupling between the chip and the fibre is limited by light scattering into unwanted surface modes. Unlike their conventional equivalents, photonic-crystal fibres[3] — those carved out of otherwise-perfect 2D PBG crystals — would enable the efficient transfer of optical information from fibre to chip, provided that unwanted surface modes on the 3D chip are eliminated[4]. Ishizaki and Noda's results provide the required clean slate.

The 3D optical microchips of the future will require not only the bulk 3D PBG crystal to provide overall confinement of light within the chip, but also the integration of lower-dimensional defects and band-gap materials. This would completely control the flow of light and tailor its nonlinear interaction with the optical resonators embedded within the photonic crystal. One possible solution is to use PBG heterostructures, which involve sandwiching a layer of photonic crystal with a 2D PBG between two identical 3D PBG materials[5]. In their study[1], Ishizaki and Noda have, in effect, synthesized the open-faced version of the sandwich, a step towards constructing and demonstrating light flow within the fully 3D circuitry of a 3D optical microchip[5].

Optical computing in a photonic microchip requires that tiny pulses of laser light pass through the waveguide circuitry and that these pulses, in turn, control and switch the flow of other optical pulse streams. In free space, these pulse streams would simply pass through each other, transferring no information from one to the other. By coupling these optical pulses to 'artificial atoms' (quantum dots) embedded near or within a photonic-crystal waveguide, it should be possible to control light with light[6]. When the quantum dots are excited or de-excited by one pulse stream, they can coherently amplify or attenuate pulses in the second stream of optical information, enabling information processing.

Confinement

In conventional materials, high-power laser beams are needed to make this nonlinear process occur. However, with less than a milliwatt of laser power flowing through a 3D PBG waveguide, it is possible to deliver electric-field amplitudes in the range of 10,000–100,000 volts per centimetre as a result of the confinement of light modes on sub-wavelength scales by the 3D PBG material. This tight confinement and concentration of light prompts an otherwise unattainable response from quantum dots at modest levels of laser power. Whereas the 3D PBG is often associated with the inhibition of spontaneous emission of light from a quantum dot, suitably embedded planar and linear waveguides can be used to engineer spectral windows within the PBG in which the rate of spontaneous emission relative to that in free space is increased by several thousand.

This enhancement of the coupling of light to quantum dots, or more generally of the strength of light–matter interactions, will help novel quantum-electrodynamics phenomena — such as 'vacuum Rabi splitting' in single quantum dots[7] and large 'Mollow splitting' in a collection of quantum dots[6] — to emerge. The synthesis of high-quality 3D PBG materials and the control of their surface optical modes as demonstrated by Ishizaki and Noda is progress towards these and other far-reaching goals in both basic and applied science. ■

Sajeev John is in the Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada.
e-mail: john@physics.utoronto.ca

1. Ishizaki, K. & Noda, S. *Nature* **460,** 367–370 (2009).
2. Joannopoulos, J. D., Villeneuve, P. R. & Fan, S. *Nature* **386,** 143–149 (1997).
3. Knight, J. C., Broeng, J., Birks, T. A. & Russell, P. St J. *Science* **282,** 1476–1478 (1998).
4. Bauer, J. & John, S. *Phys. Rev. A* **77,** 013819 (2008).
5. Chutinan, A. & John, S. *Optics Express* **14,** 1266–1279 (2006).
6. Vujic, D. & John, S. *Phys. Rev. A* **76,** 063814 (2007).
7. Khitrova, G., Gibbs, H. M., Kira, M., Koch, S. W. & Scherer, A. *Nature Phys.* **2,** 81–90 (2006).