PHOTONIC CRYSTALS

Straightening out light

An approach for transmitting ever-more information across silicon chips is to use optics. The demonstration of super-collimated propagation over centimetre lengthscales therefore creates exciting opportunites for optical interconnects.

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Imagine driving on the crowded grid of roads on Manhattan Island in New York City. Imagine now the difference if all the cars could simply pass through one another. Electrical signals on the wiring grids on computer chips behave like conventional cars, they do not pass through one another without colliding. Light beams on the other hand slip through one another like ghosts. Could we therefore use that intriguing property of light to free the traffic jams in the wiring on the surface of silicon integrated circuits? On page 93 of this issue, Rakich *et al.* take an intriguing step towards that possibility[1]. Their light travels in photonic crystals, regular structures made by patterning a two-dimensional grid of tiny holes into a very thin sheet of silicon. Such photonic crystals show a wide range of interesting and surprising optical properties. Super-collimation is one such property that allows light beams to propagate without spreading out. Rakich *et al.* have shown that this super-collimation works over the centimetre lengthscale of a silicon integrated circuit, and that it tolerates minor variations inherent in such structures. In this approach, the light beams are like cars moving in straight lines from left to right or top to bottom, without danger of straying off the marked roads or traffic lanes.

When we pattern materials on the scale of an optical wavelength, we create structured meta-materials whose behaviour results more from the structure than the materials themselves. Such photonic structures have been known and used for decades, for example, in many dielectric interference filters, mirrors, and anti-reflection coatings in use today. Wave propagation in photonic structures has been understood for a long time, as their description is identical to the quantum mechanics of crystalline materials. In optical structures, it is relatively easy to observe a broad variety of wave-propagation effects; for example, various focusing, de-focusing and beam-steering phenomena have been shown[2] in one- and two-dimensional periodically patterned structures, known now as photonic crystals. A two-dimensional photonic crystal could consist of an array of air holes etched in a thin slab of silicon, as sketched in Fig. 1, with light propagating across the structure, from top to bottom in this case.

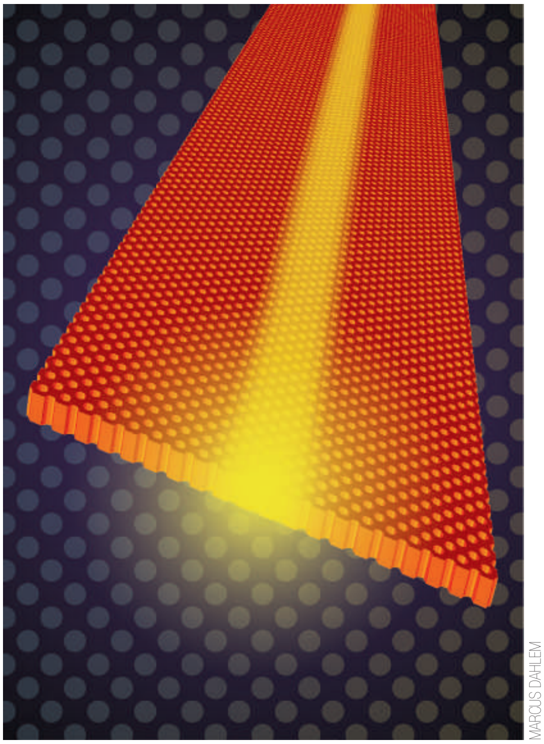

Figure 1 Sketch of a photonic crystal. An array of periodic holes is formed in a thin slab, with light entering on the top edge and exiting from the bottom.

Normally, in free space or some isotropic material such as glass, the propagation of light through the material is the same for all angles. A beam focused to a spot can always be thought of as consisting of a sum of wavefronts of different propagation angles, with tighter focused beams showing a larger angular

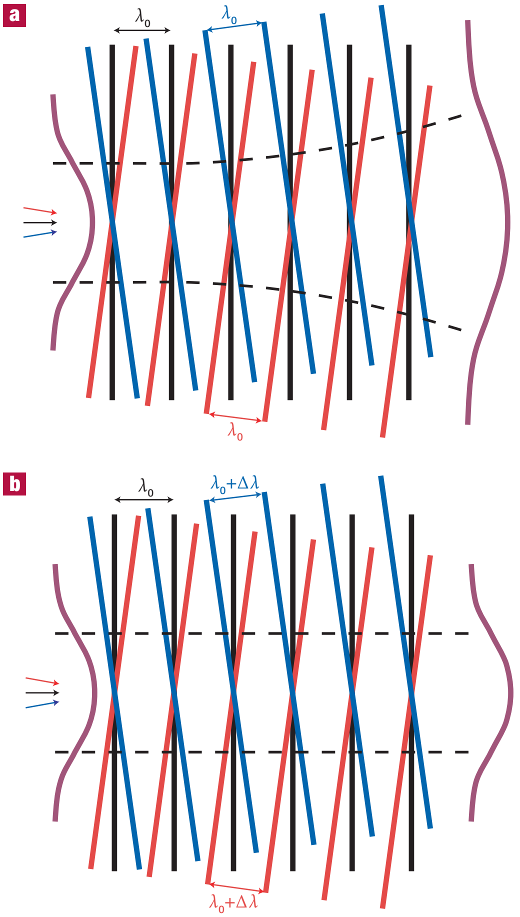

Figure 2 Propagation of a light beam of a given frequency. A beam can be considered as made up of a combination of plane-wave components at different angles. **a**, In a normal isotropic medium the wavefronts (the black, blue and red lines) of the different components progressively no longer cross at the centre, and the beam becomes bigger by diffraction. **b**, In a super-collimating photonic crystal the wavelength λ_0 of the beam inside the crystal increases slightly for angles deviating from the horizontal angle (the black wavefront) in such a way that the separation of the wavefronts along the horizontal axis remains the same, and the beam shape is unchanged with propagation.

range. Figure 2a depicts how wavefronts in a focused beam propagate through a material, exemplified by the behaviour of three characteristic plane-wave components having different angles. At the left, a focused beam enters the material, meaning that all plane waves making up the beam are lined up at one spot in the middle of the light beam. As the light beam propagates from left to right, however, the different maxima of the beam components no longer line up, and the light beam spreads out. This phenomenon is known as diffraction, and is unavoidable for light propagating in uniform, isotropic media, no matter how much we try to collimate the beam. If, however, we use a photonic crystal, diffraction can be compensated in such a way that plane-wave components propagating at different angles experience a slightly longer effective wavelength inside the material, and we can obtain the situation illustrated in Fig. 2b. Here, there is no change in the propagation of the wavefronts as we move from left to right, and the beam size does not change, hence resulting in a 'super-collimated' beam.

It is not hard to see that light incident at different angles on the edge of a photonic crystal will propagate in different ways; the structure obviously looks different if we look at it from different angles. As a result, under just the right conditions, it is possible to observe such super-collimation in a photonic crystal. In the work of Rakich *et al.* the distances over which this super-collimated propagation is observed, and the demonstration of tolerance to minor imperfections in the photonic crystal, are especially impressive.

With propagation lengths in the centimetre range, will this approach lead to optical interconnects on silicon chips? There is no doubt that there is a growing problem in sending signals over wire in electronics[3,4]. Physics tells us that optics could in principle solve such problems[4], allowing transmission of very high densities of information over long distances, and avoiding problems of signal reflections and cross-talk between wires, for example. In particular, the information density argument becomes most compelling at distances larger than the size of a chip[4,5]. On the other hand, on the chip it is easy to break long transmission lines into smaller segments separated by amplifiers, mitigating many problems[3]. Therefore, to be competitive an optical technology would need to deliver very large aggregate bandwidths across the chip (tens of terabits per second) to replace chip wiring layers in mainstream applications[3]. We would also need dense, high-speed, low-power optoelectronics to convert the electrical signals to optical ones. Integrating that optoelectronics with silicon (which only has weak optoelectronic effects) has been difficult, though recent developments are promising[6,7].

Although the realization of competitive on-chip interconnects still remains challenging, this demonstration by Rakich *et al.* opens up a new set of possibilities in a rapidly evolving field. It highlights yet another of the remarkable opportunities that photonic nanostructures and metamaterials are creating in optics. Just what we will do with this new generation of optics remains to be seen, but demonstrations like this show it will be exciting to find out.

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