

## NONLINEAR OPTICS

## Controlling photons with light

A strongly nonlinear photonic crystal with a wavelength-tunable bandgap could provide the solution to realizing all-optical switches that are controlled by light.

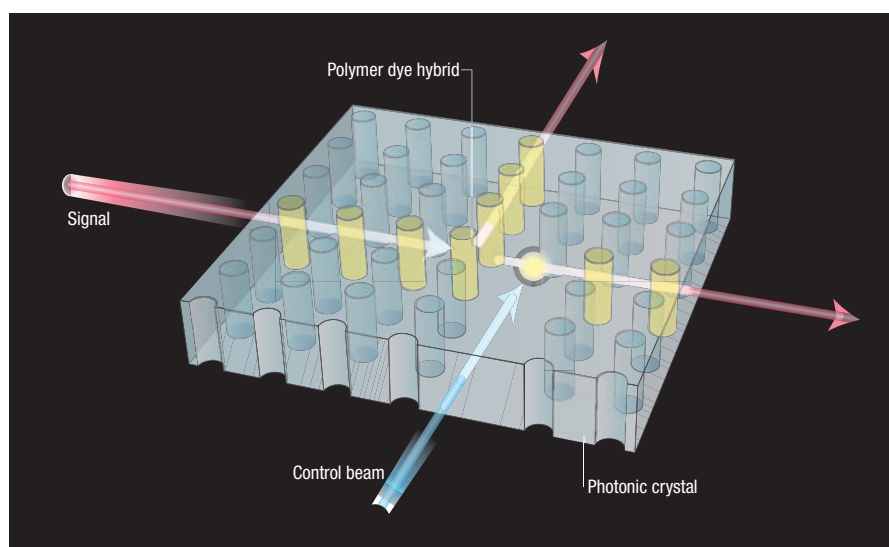
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**P**hotonic crystals are dielectric materials with a periodic structure that gives them fascinating optical properties. They can efficiently reflect wavelengths of light that are resonant with the crystal periodicity, which not only gives them a beautiful angular-dependent colour, but also provides them with the ability to trap light in specific frequency windows called photonic bandgaps<sup>1,2</sup>. Thanks to their capacity to confine light, photonic crystals can serve as the basis material for the development of photonic components capable of processing signals optically<sup>3</sup>. In practice, a photonic bandgap can be created, for instance, by drilling a periodic array of submicrometre-sized holes in a planar waveguide. This inhibits the propagation of light in the waveguide at frequencies within the bandgap. Leaving out or filling in a row of holes then creates a waveguide, and filling in, for instance, one specific hole creates a microresonator. To create photonic components that can process optical signals, like an optical switch or multiplexer, it is crucial to functionalize the material. That is, it should be possible to control the local optical response of the photonic crystal to an optical signal with a second optical control signal. This optical response should also be very fast to cope with high-bandwidth optical signals. On page xx of this issue<sup>4</sup>, Xiaoyong Hu and colleagues at Peking University report on an elegant approach to optical signal control by creating a strongly nonlinear photonic crystal. The nonlinearity in their material is capable of rapidly shifting the wavelength of the photonic bandgap when the control signal is present, thereby switching the transmission of the optical signal on and off. Previous attempts to achieve such nonlinearities required much higher intensities than could be realistically implemented in actual devices.

The trick that Hu *et al.* used to create this nonlinear effect is based on the careful



**Figure 1** A photonic crystal incorporating interplay between two molecules to create a strong nonlinear optical response and switch optical signals.

interplay between two molecules, namely a polymer and a laser dye (Fig. 1). Normally the nonlinear optical response of a material is relatively weak. The effect can be expressed as the change in the refractive index at a certain light intensity. In common photonic-crystal materials, this value is typically of the order of  $10^{-6}$  or less for laser intensities of the order of megawatts per square centimetre. This means that, to obtain an appreciable switching effect, the output of huge lasers would need to be focused on the device. This is not only impractical, but can often also destroy the material. To form an idea of the powers involved, similar intensities are used for laser welding and cutting metals. Ultrafast switching has been demonstrated in silicon-based photonic crystals using optical excitation of free charge carriers to achieve nonlinearity<sup>5,6</sup>, but the intensities required for switching remained high. Hu *et al.* have now managed to bring the required power down to the level available from a typical simple laser diode.

To obtain a nonlinear response, it is very advantageous to put molecules in an excited state, which creates a significant

change in the refractive index. However, absorption in the material should be avoided, as this attenuates and eventually destroys the optical signal. The dilemma is that for a molecule to be excited, it has to absorb energy in some way. The solution implemented by Hu *et al.* is to use one molecule to absorb the light and another one to create the nonlinear effect. The first molecule (laser dye in this case) absorbs the light from a control beam and then transfers its energy directly and efficiently to a polymer. The polymer then exhibits a nonlinear response in a very different wavelength window in which the absorption is negligible. This elegant trick of direct energy transfer has been studied on previous occasions<sup>7,8</sup>, but Hu *et al.* have now managed to do this with greater efficiency and have implemented it in a photonic crystal. The final result is simple, but amazingly effective.

These results open up the way to realizing optical control in structures based on photonic crystals and other polymer-based photonic devices. In addition to polymer structures, which are limited in terms of the contrast of the refractive index

that can be obtained, the concept could also be integrated with higher-contrast materials, such as silicon. Ideally the doped polymers would be incorporated locally in individual pores of a photonic crystal (see Fig. 1). Their function in this case would become twofold. On one hand the local change of the refractive index would create waveguide and resonator structures, and on the other hand, the nonlinearity of the doped polymer would allow the central wavelength of the resonators and waveguides to be tuned. A design in which a specific refractive index and nonlinear constant could be assigned to each individual pore could lead to the construction of devices, such as optical multiplexers and optical controlled-delay lines.

An issue that remains to be tackled is that of intrinsic disorder in the sample. Regular crystals, as used in electronics, are made from atoms or molecules that are naturally all the same size. This enables them to be extremely pure and ordered. Photonic crystals, on the other hand, are constructed from building blocks, such as pores in slab waveguides or microspheres

in the case of three-dimensional structures. These building blocks have size variations that are small but intrinsically present. Photonic crystals therefore suffer more from structural disorder than electronic ones.

Ironically, whereas disorder is now seen as a major bottleneck for the implementation of photonic-crystal technology, it was originally one of the inspirations to investigate such structures in the first place. The original motivation to realize and study photonic crystals was conceived within the context of confining light with disorder<sup>2</sup>. This effect, called localization, is caused by interference in disordered structures, which occurs both for electrons and light. Localization can trap waves that are multiply scattered, and the phenomenon is expected to be strongly enhanced inside a photonic-crystal structure<sup>3</sup>. Although the physics behind this complex phenomenon is not yet fully understood, it could provide an opportunity to solve the disorder bottleneck. The effect of a strong optical nonlinearity on localization would be fascinating from a fundamental point of view and could also be applied in

nonlinear components. The doped polymers created by Hu *et al.* would be ideal for creating the appropriate nonlinearities.

The field of photonic crystals is maturing, and the challenging applications originally envisioned related to optical data processing<sup>9</sup> might start to become a reality in the near future. The lesson we can learn from the development of the field is that promises of future applications can become a reality, but thorough fundamental research is nearly always required before such devices can be designed and developed.

#### References

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