Photonics

The Vs and Qs of optical microcavities

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Periodic structures can be used to manipulate light. Such structures are called photonic bandgap materials, or photonic crystals¹, and promise to be as important to the progress of optical devices as semiconductors were to the development of electronic devices. Physicists didn't have a good 'box' for optical radiation (light with wavelengths in or near the visible region) before, because metals are not perfect reflectors at optical wavelengths. But photonic crystals can achieve very strong confinement of optical light. On page 143 of this issue², Foresi *et al.* of MIT report the most spatially localized photon mode ever, which was achieved using the photonic bandgap approach. The volume of their 'box' is $0.055 \mu\text{m}^3$, which is only five cubic half-wavelengths ($1.54\text{-}\mu\text{m}$ infrared light being shortened to $0.44 \mu\text{m}$ by the material's refractive index of 3.5). When the box is this small, the radiation properties of the material inside it are fundamentally altered³.

The work adds to the limited experimental evidence that photonic crystals do what they are supposed to do. The properties of these materials are thought to arise from multiple reflections at the periodically distributed interfaces, which add up to prevent light from propagating over a wide band of wavelengths. Although the transmission properties of photonic crystals have been measured before⁴, the mechanism had not been demonstrated so conclusively.

Introducing a cavity into the structure has made it possible to prove that reflection, rather than diffraction or other loss mechanisms, is responsible for the opaque spectral regions — an important distinction because it means that a cavity must have reflective walls to trap light. This method has also been used in larger cavities with two-dimensional photonic crystal boundaries⁵, which clearly demonstrate the simultaneous occurrence of low transmission and high reflection⁶.

The structure investigated by the MIT group⁷ is periodic in one dimension, consisting of a line of cylindrical holes etched through a ridge of silicon (Fig. 1a). The ridge is a waveguide, which confines light in two dimensions by total internal reflection at dielectric boundaries. In the third dimension (along the ridge) light is contained by the periodic structure. The first waveguide-based microcavity to have its spectral properties fully characterized⁸ was also a one-dimensional grating (Fig. 1b), which showed strong confinement but leaked into the substrate. By instead using a design where the

semiconductor material is placed on a glass substrate, the MIT researchers have created a structure with very low optical losses.

Foresi *et al.* created their cavity by introducing a single larger gap between holes in the middle of the line. This produces a very sharp transmission peak within the region of low transmission, where the cavity resonance occurs. So the device acts as an extremely narrow, wavelength-selective filter.

The ability of the cavity to confine radiation is described by the quality factor or 'Q', a measure of the sharpness of the transmission peak (the ratio of the width of the peak to its frequency). It is also the ratio of the optical power stored in the cavity to the cycle-average power radiated out of the cavity. Therefore the larger Q is, the longer radiation is trapped. Q and the volume V can be combined to create a figure of merit for microcavities, called the Purcell-number³ or the spontaneous emission enhancement factor. A high value of Q/V is desirable.

The MIT team have achieved this by making the volume tiny — $0.055 \mu\text{m}^3$ — which should give them a spontaneous emission enhancement factor of 34; that is, a radiating atom inside the cavity should generate light 34 times faster than it would

without the cavity, because of the resonant coupling. Brighter, more power-efficient devices could result. But, more importantly, devices such as laser diodes or light-emitting diodes could be modulated at a higher frequency, and so transmit more bits per second, increasing the capacity of optical communication systems.

This cannot be tested using the new structure, because it doesn't emit light, but the idea has been demonstrated with a pillar-type microcavity⁹ (Fig. 1c), for which the trapped mode of light had a Purcell-number of 4. Instead of having a tiny volume, this device uses quantum dots to provide a high-Q light source (J.-M. Gerard, personal communication). When the quantum dots were excited, they emitted light four times faster than they would have done without the cavity, as predicted.

To take full advantage of the high Purcell-number of their cavity, the MIT team will have to find a material with a Q that is comparable to the cavity Q. The problem is that although the cavity can increase the material's emission if the emission line and the resonance overlap, it can also suppress the emission if they don't. So if only a small part of the material's emission line overlaps with the cavity resonance (as happens when the Qs are very different), not much is gained. Finding such a high-Q material is not straightforward, considering that the material Q of standard light-emitting semiconductors is between 20 and 30, whereas the measured Q of the cavity is 265.

If the new structure is to develop into a commercial device for high-speed communications, Foresi *et al.* will also have to consider the other properties of their cavity, such as its luminescence and electrical conductivity. And they must find a way to inject current, as the glass substrate now used will not conduct. But it may be possible to combine an all-semiconductor approach with the MIT design to create a new source of light for ultra-fast communication systems. □

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Figure 1 Three traps for photons: a, the smallest optical microcavity yet built, formed by a larger gap in a periodic series of holes in a silicon waveguide²; b, an earlier, grating-like microcavity⁸; c, a cylindrical cavity, used to demonstrate the acceleration of optical emission⁹. (Not to scale.)

- Joannopoulos, J. D., Villeneuve, P. R. & Fan, S. *Nature* **386**, 143–149 (1997).
- Foresi, J. S. *et al.* *Nature* **390**, 143–145 (1997).
- Purcell, E. M. *Phys. Rev.* **69**, 681–681 (1946).
- Krauss, T. F., De La Rue, R. M. & Brand, S. *Nature* **383**, 699–702 (1996).
- Labilloy, D. *et al.* *Electron. Lett.* **33**, 1978–1979 (1997).
- Labilloy, D. *et al.* *Phys. Rev. Lett.* (in the press).
- Villeneuve, P. R. *et al.* in *Photonic Band Gap Materials* (ed. Soukoulis, C. M.) 411–426 (NATO ASI Series, Kluwer, Dordrecht, 1996).
- Krauss, T. F., Vögele, B., Stanley, C. R. & De La Rue, R. M. *IEEE Photonics Technol. Lett.* **9**, 176–178 (1997).
- Gerard, J.-M. *et al.* *Appl. Phys. Lett.* **69**, 449–451 (1996).