PHOTONIC CRYSTALS

New designs to confine light

Although recent years have seen substantial improvements in the perfomance of photonic-crystal cavities, their design has been a rather hit and miss affair. By turning around the general approach to cavity design through the use of Bloch waves, an important avenue to the discovery of optimal cavity geometries could be opened.

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The management of resonance is common to many fields of science and technology including civil engineering, acoustics and photonics. The history of musical instrument development reveals that even simple resonant structures governed by linear physical equations can lead to rich and complex behaviour. Can photonics follow a similar path? Certainly the trend in the development of photonic devices is towards structures built at wavelength scales, as are musical instruments. But unlike the materials used for making such instruments, the small difference between the refractive index of the materials used to make photonic structures and devices and the surrounding air means that it is much more difficult to confine light than to confine sound. Consequently, many of the general rules learnt for controlling resonant phenomena in systems as diverse as bridges, organ pipes and microwave ovens are of little practical use to photonics practitioners. The absence of such design rules has meant that most of the improvements in the performance of wavelength-scale photonic cavities have occurred through a process of trial and error. Hoping to address this shortcoming, in a recent report in *Optics Express*[1], Englund and colleagues describe a theoretical design approach that reduces the guesswork needed to optimize the characteristics and performance of photonic-crystal cavities.

Photonic crystals offer the possibility to manipulate and use light in a similar way to that in which semiconducting crystals are used to manipulate and use electricity. In principle, the ideal photonic-crystal structure is three-dimensional, and exhibits a bandgap that forbids the propagation of light within a well-defined range of wavelength regardless of direction[2]. In practice, however, the degree of control needed to introduce useful features such as waveguides and optical cavities into periodic structures that are otherwise perfect in all three dimensions has proved difficult to attain.

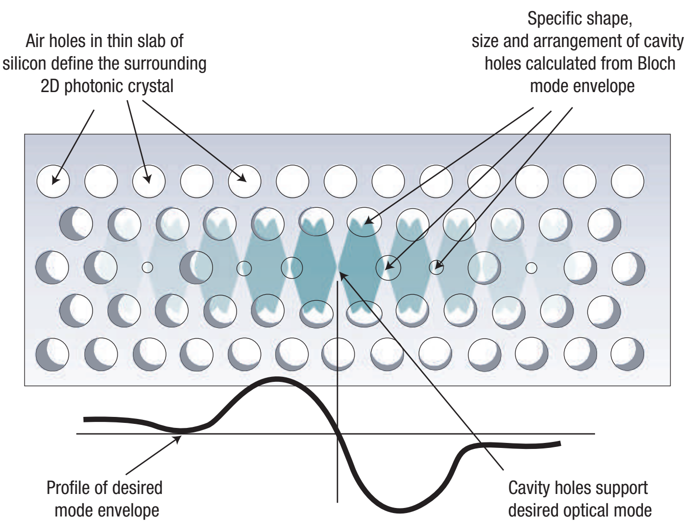

Figure 1 Designing a 2D photonic-crystal cavity with Bloch waves. The conventional approach to optimizing the performance of a photonic-crystal cavity is to begin with a predetermined initial geometry and to change the position, size and pattern of the air holes that make up the crystal until its light-confining characteristics improve. Turning this approach in its head, Englund *et al.*[1] start by defining a desired optical mode (represented by the grey shading) in terms of an optimal Bloch-wave distribution (see profile), which enables them to calculate the optimal cavity structure to support this mode.

Consequently, the focus of much research has turned to two-dimensional photonic crystals — most commonly consisting of a thin (200–300 nm) slab of optical material perforated with a periodic array of holes — which sacrifice a direction of periodicity in return for greater ease of construction (see Fig. 1).

From slow beginnings, the performance of optical cavities based on such structures has improved dramatically over the past few years, culminating in the realization of a structure with a very high cavity *Q*-factor (a measurement of a cavity's efficiency at confining light) of 600,000 earlier this year[3]. The usual approach to the design of such cavities has been to begin with a particular geometry that is known to confine light to some degree — such as a defect created by the absence of one or more adjacent holes in a photonic crystal — and then to vary the parameters such as the size and spacing of the surrounding holes, bit by bit, until the calculated optical mode of the cavity improves towards some desired optimal state. But although successful, this approach based on a parametric search does not provide much general insight into why the resulting cavities work as well as they do, nor does it guarantee that the structures found are globally optimal.

In contrast, Englund *et al.*[1] tackle the problem of cavity design from the opposite direction. Rather than starting from a predefined cavity geometry and calculating (and subsequently optimizing) the mode to fit the cavity, they begin with a desired cavity mode and calculate the cavity to produce the mode. The key lies in defining the target modes in terms of Bloch waves — wavefunctions more commonly used to describe charge carriers in semiconductors than packets of light. By finding an approximate analytical relation between a given distribution of Bloch waves and the cavity geometry that will support them, the authors reduce the problem to one of optimizing this distribution to produce the desired mode. Not only does this remove much of the guess work from cavity design, but enables the authors to derive entirely new cavity geometries supporting modes designed for low radiation losses. They predict theoretical Q-factors in excess of 4×10^6.

It is interesting to compare the results of this approach to those in closely related areas of photonics. A common trend in many areas of photonics is towards simplicity. For instance, the 'rugate' structures of state-of-the-art dielectric mirrors, which achieve reflectance values in excess of 99.99%, consist of nothing more complex than a multilayer sequence of two different thin-film materials of varying thickness. Yet it turns out that these structures perform poorly in attempts to incorporate them into 3D cavities built on the scale of a wavelength — Q factors of cylindrical micropillar cavities etched into such structures do not exceed ~20,000. What this and the more complex, better-performing 2D cavity geometries found by Englund *et al.* suggests is that simplicity is bad for high Q.

The use of Bloch waves in the context of photonic-crystal cavities is not new. Analysis of how the impedance and spatial patterns of Bloch waves are matched in reported high Q cavities has been offered as a sound explanation for their superlative performance (see refs 4,5 on mode matching and related phenomena in micropillars and photonic-crystal microcavities). And there is still a long way to go before the general utility of the particular approach presented by Englund *et al.* is more firmly established. But, at the very least, it opens a potential important source of inspiration for the design of new cavity structures beyond those described previously, and potentially provides an important step towards more complex photonic circuits, and the ultimate realization of the full potential of photonic crystals for manipulating light.

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