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FULL 2D PHOTONIC BAND GAPS IN SILICA/AIR STRUCTURES

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Abstract

Full 2D photonic band gaps are demonstrated for all polarisations in structures with refractive index contrasts as small as that of silica and air. They occur for light propagating out of the transverse plane, with a longitudinal component of wave vector. A new type of optical fibre based on these structures is proposed.

Introduction

A photonic crystal is a dielectric structure with a refractive index that varies periodically in space, with a period of the order of an optical wavelength. Such a material has a photonic stop band if light cannot propagate (in any state of polarisation) for certain values of frequency and direction; Bragg diffraction takes place. If the stop band persists for all directions at a given frequency, the light cannot propagate at all and the photonic crystal has a full photonic band gap (PBG)[1].

Much attention has been devoted to two dimensional (2D) photonic crystals invariant in the third dimension (the longitudinal, or z, direction). Typically, a regular array of rods of one index is buried in a material of another index[2,3]. When propagation is restricted to the transverse plane, 2D PBGs can appear for large enough index contrasts, though even the most favourable structure reported[2] requires an index ratio no less than 2.66.

There have been few studies of 2D photonic crystals that consider propagation out of the transverse plane[3]. We report that when β, the longitudinal component of wave vector, is fixed but non-zero, full 2D photonic band gaps for all states of polarisation can appear for much smaller index contrasts. In particular, we show the existence of band gaps for a structure comprising just air (index 1.00) and fused silica (index 1.45).

Results

The structure analysed consists of a hexagonal array of circular air rods in a background of fused silica, Fig. 1. An air filling fraction of 0.45, consistent with experimental techniques, is assumed (a larger value would have given wider gaps). The centre spacing of adjacent rods is denoted by Λ, and $k=\omega/c$ is the free space wave constant. For a given normalised frequency $k\Lambda$ and normalised propagation constant $\beta\Lambda$, the transverse wave-vectors for Bloch waves in the material are determined. If only complex values are found, this combination of ω and β is in a 2D PBG.

A real-space finite-element technique is used[4]. The unit cell is divided into a lattice of points, on which Maxwell's equations are discretised. The field in every layer of lattice points is related to that in the previous layer by transfer matrices, which can be concatenated to give the matrix for the entire unit cell. To retain accuracy, the transfer matrix method is only applied over groups of a few lattice layers; the fields in adjacent groups are related using a scattering matrix method.

The calculation gives Fig. 2, where the normalised frequencies of the band edges are plotted against the normalised propagation constant. The semi-infinite large-β "band gap" would be expected in any material; for instance, in a uniform medium of index n, no waves propagate for $\beta > kn$. However, additional finite gaps for lower β can also be seen. Some have β/k less than 1.0, the index of air, showing that the structure is not behaving simply as a uniform average-index material. For light with a free space wavelength of 1500 nm, the rod spacing required is about 2 μm.

Discussion

2D photonic band gaps for all polarisations can appear for much smaller index contrasts than have previously been reported, if β is sufficiently large. A new type of optical fibre, the PBG fibre, is possible. This consists of a periodic air/silica cladding surrounding a uniform core. The core can be solid silica or a hollow air region; indeed, any "defect" that breaks the periodicity of the rest of the structure. Any guided mode with β within a 2D PBG cannot fill the cladding and must be localised at the core. In other words, the light is confined to the core by Bragg reflection, in contrast to standard fibres that guide by total internal reflection.

Like standard fibres, PBG fibres would support cladding modes with β values outside the band gaps, as well as the core modes. Cladding modes fill the entire fibre, and so can be stripped off by a lossy high index coating. The core modes are given by a transverse resonance condition, and by adjusting the size of the core the fibre can be made single mode.

Applications arise from the fibre's unique properties. For example, the core effective index β/k of a standard silica fibre cannot be less than the cladding index, 1.45, if total internal reflection is to be maintained. However, Bragg reflection in a PBG fibre can be maintained for much smaller β/k while keeping the structure contiguous and substantially solid. The exposed evanescent field of a polished PBG fibre with an effective index around 1.33 would extend far into an aqueous medium. This could lead to sensitive water pollution and bio-sensors[5]; fibres with β/k close to 1.0 could give novel gas sensors. Other applications follow from the structure's complicated yet controllable polarisation properties.

Work is underway to make this fibre, by a multiple stack-and-draw process. Initial results show that a hexagonal array of air holes is maintained down to separations of 1.5 μm. Similar 2D photonic crystals have been made elsewhere for some time, by etching in glasses as well as semiconductors[6]. However, these techniques cannot give samples longer than a few millimetres in the z direction, whereas our fibre can in principle be kilometres long.

Other, less simple, silica/air structures should give wider band gaps than those described above. It is worth noting that an array of parallel dielectric rods in air also possesses band gaps. For β/k well above 1, narrow pass bands (separated by wide gaps) correspond to the waveguide modes of the individual rods. However, such an array is not a rigid structure, and is in any case uninteresting as a fibre cladding.

Conclusion

It is possible to design a photonic crystal with full 2D photonic band gaps for all polarisations, using the modest refractive index contrast provided by air and fused silica. The band gaps appear for certain finite values of longitudinal wave constant, at a given optical frequency. This makes possible a new type of optical fibre that guides by Bragg reflection instead of total internal reflection.

Acknowledgement

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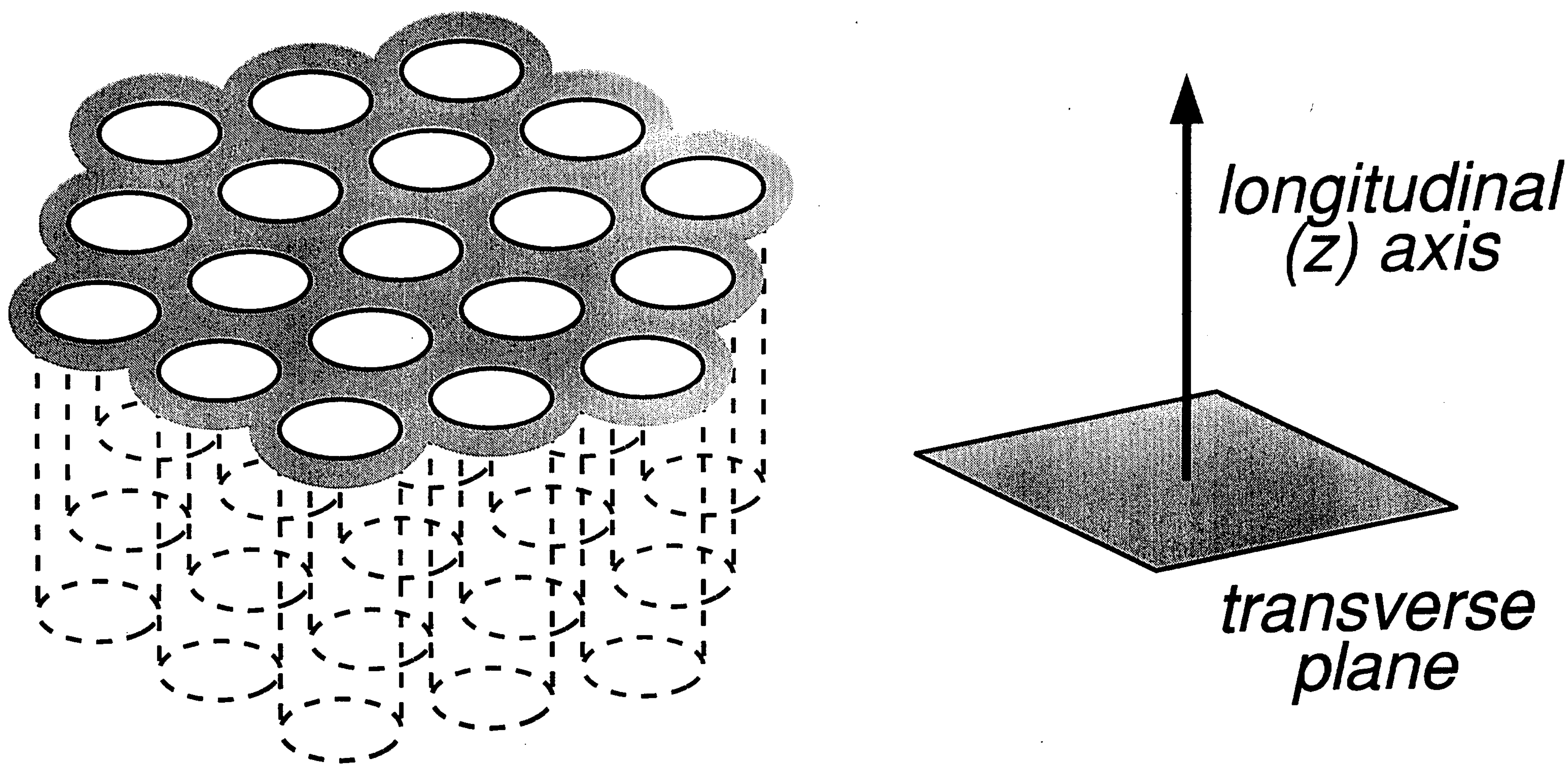
Figure captions

1. A 2D photonic crystal comprising an array of rods in a background material with a different refractive index.

2. The full 2D band gaps (shaded) of the silica/air structure described in the text.


longitudinal
(z) axis
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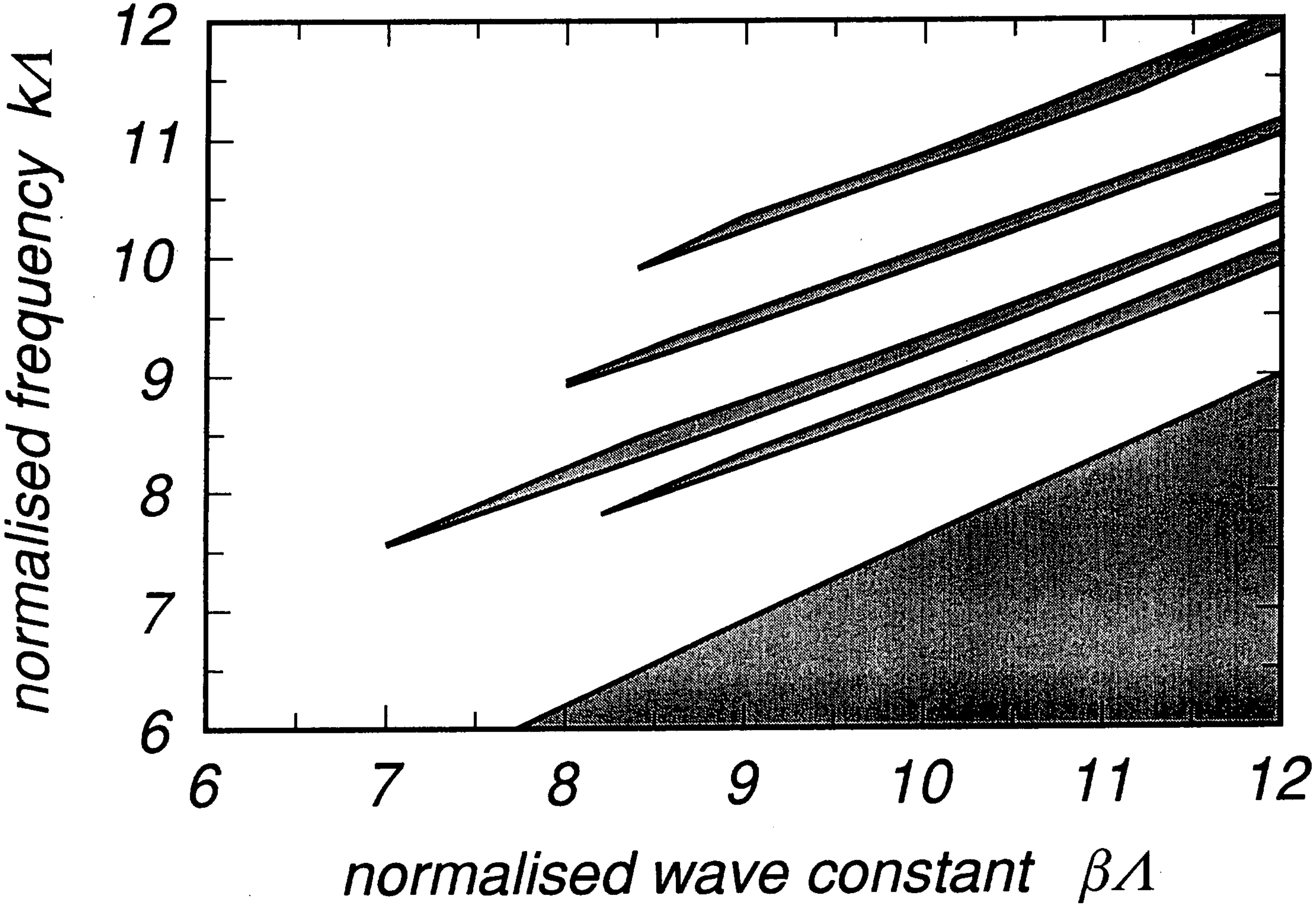
normalised frequency kΛ
12
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normalised wave constant βΛ