Very Low Fresnel Losses in Rod-Type Photonic Crystals

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Abstract

We show that two-dimensional rod-type photonic crystals can have very low Fresnel losses for a wide range of incident angles at a wavelength in the second band. We use this to design an efficient beam combiner.

Introduction—Photonic crystals (PCs), structures in which the refractive index is a periodic function of position, broadly have two types of applications. The first of these apply for wavelengths within a photonic bandgap where the PC is strongly reflecting. Applications of this type include PC-based waveguides, cavities and lasers, where the strong reflection leads to confinement of the light.[1] The second type of applications apply for wavelengths in one of the PC's bands. These applications rely on the unusual propagation behavior of light at these wavelengths, including a weak or strong dependence of the direction of the energy flow on wavelength and incident angle, leading to self-collimation[2,3] and to the superprism effect,[4] respectively. Any practical application of the second type requires efficient coupling of the light into and out of the PC; we refer to the reflection losses between the PC and free space as Fresnel losses. While any losses are undesirable, Fresnel losses also lead to stray light in the optical system. In this paper we demonstrate that the Fresnel losses in realistic rod-type PCs without surface modifications can be surprisingly small at incident angles up to approximately 30°. We explain this behaviour in terms of the scattering properties of the individual inclusions and apply it to the design of a beam collimator with low losses.

Because of the difficulty of fabricating three-dimensional PCs, structures in which the refractive index varies periodically in three dimensions, most papers in the literature deal with two-dimensional PCs. We do so here as well. There are two types of two-dimensional PC. The first, and most common of these, air-hole type PCs, consists of a thin-membrane in which a periodic array of holes has been fabricated. The second type, rod-type PCs, consist of a periodic array of high-index rods in air.

Strictly two-dimensional geometries—Fig.1 shows the reflection spectrum versus wavelength and incident angle of a rod-type PC. This is an idealized structure in which the rods have been taken to be infinitely long so that the geometry is strictly two-dimensional. The rods have a refractive index $n = 3$, and a radius $r/d = 0.34$, where d is the lattice constant of the square lattice, and the electric field is polarized along the rods. The background is air, with refractive index $n = 1$. Note the very high transmission when $d/\lambda \approx 0.34$ in the second band, which extends to incident angles exceeding 70°. Note also that another high-transmission frequency exists in the third band at $d/\lambda \approx 0.58$, but we do not discuss it here.

Our calculations[5] show that the wide-angle, high transmission is quite robust and that the associated wavelength depends weakly on the PC period or even on the lattice type. It also occurs in *gratings*, i.e., structures consisting of a one-dimensional array of rods. In contrast, it depends strongly on the properties of the rods (radius, refractive index). This implies that the high transmission is associated with the individual rods, rather than with a lattice property. This is illustrated in Fig.2, which shows three sets of information. The first of these is the normal incidence transmission (solid curve). The dashed curve shows the scattering cross section per unit length of the rod.[6] Note that it has a number of features, the strongest of which is close to the high-transmission frequency of $d/\lambda \approx 0.34$. Finally, the dashed-dotted curve shows the asymmetry parameter $g = \langle \cos\varphi \rangle$, where φ is the scattering angle of the incident radiation;[6] here $\varphi = 0$ corresponds to forward scattering, whereas $\varphi = \pi$ corresponds to backward scattering. Thus, if $g = 1$ $(g = -1)$ then all light is scattered strictly in the forward (backward) direction. Notice from Fig. 2 that the high-transmission wavelength also coincides with a strong peak in the asymmetry parameter, where essentially all light is scattered forward.

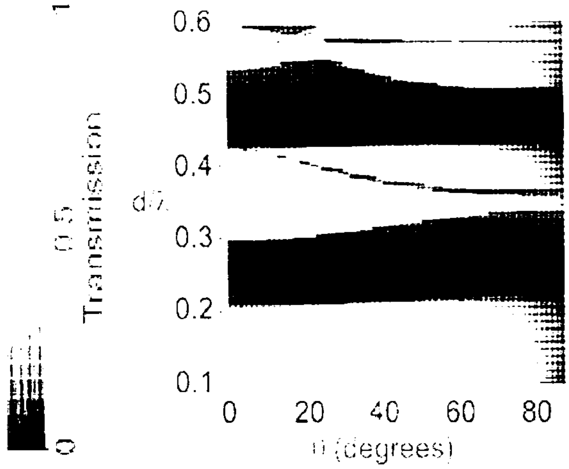

Fig. 1 Transmission versus dimensionless frequency d/λ, and the incident angle θ_i for the strictly two-dimensional geometry discussed in the text.

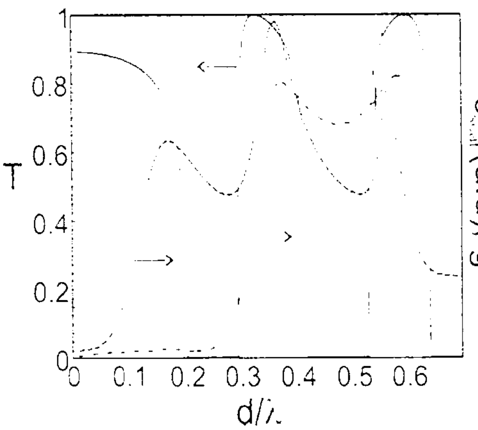

Fig. 2 Normal incidence transmission (solid curve), asymmetry parameter g (dashed-dotted), and scattering cross section (dashed), versus dimensionless frequency d/λ.

We have found that for high transmission into the PC to occur, two conditions need to be satisfied simultaneously. The first of these is the occurrence of peaks in both the scattering cross section and the asymmetry parameter of the individual rods. The second is that $\lambda > d/2$; this means that if the light was incident on a grating of period *d*, the type of grating that comprises the PC, then there is only a single propagating diffracted order (the specular or undiffracted order) for *any* incident angle.

Low-loss beam combiner—One of the most compelling applications of photonic crystals for in-band frequencies is that of beam collimation.[2,3] In this case the diffraction of a beam propagating in a PC is significantly reduced so that a narrow beam can propagate without significantly widening. This property is quantified by the parameter $p = \partial\theta_{in} / \partial\theta_{out} |_{\omega}$, introduced by Baba *et al.*[4] Here θ_{in} is the incident angle and θ_{out} is the propagation angle of the energy flow in the PC. When $p=0$ then for a range of incident angles, the direction of energy propagation in the PC is constant, thus leading to reduced diffraction. Some of us recently proved that *every* photonic band of a two-dimensional PC has curves on which $p=0$.[7] We now combine this property with that of high-transmission discussed earlier, as in the structure shown in Fig. 3. It consists of a two-dimensional hexagonal array of rods with refractive index $n=3.4$ and height $h=3d$, in a uniform medium with refractive index $n=1.46$, sandwiched between two uniform media with refractive index $n=1.458$.[8] The planar waveguide geometry provides vertical confinement due to total internal reflection at the wavelength of operation.

Incident on this structure are two Gaussian beams propagating in the horizontal plane at angles of $\theta_i = \pm 22.5°$ to the ΓM-direction. These beams each have vertical widths of 2.5*d*, and a horizontal width of 5*d*. This is indicated schematically in Fig 4, which also shows the field strength in the incident plane on the left-hand side by the solid curve. The field envelope indicated by the dashed curve exhibits the Gaussian shape. The associated outgoing field, calculated using a three-dimensional Finite Difference Time Domain (FDTD) calculation, is shown on the right-hand side of Fig 4. Note that it has a similar width and field strength to the incident beam in spite of the propagation through the photonic crystal, confirming the absence of Fresnel losses and the suppression of diffraction. Using calculations not shown here the reflection losses were confirmed to be less than 1%. The central part of Fig. 4 shows the field inside the PC—note that the self-collimation effect is so strong that, even with the substantial incident angles, in the PC the field propagates in the ΓM-direction. The field distribution in the PC also does not depend on the propagation distance, confirming the absence of diffraction. Since the beams overlap strongly in the PC, they would interact very strongly if at least one of the PC constituents has an optical nonlinearity. Nonetheless, the beams are easily launched into the structure because their incident angles differ by 45°.

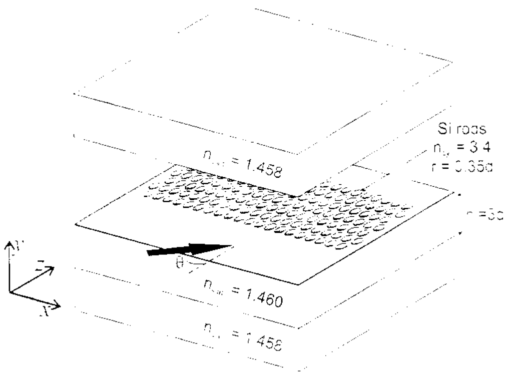

Fig. 3 Rod-type PC that we consider. The rods are embedded in a planar waveguide to provide vertical confinement.

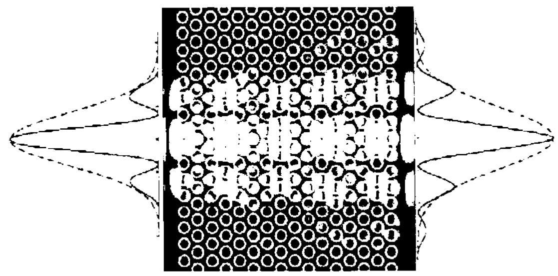

Fig. 4 Result of a full 3-dimensional simulation of the structure in Fig. 3. Shown on the left and right are incident and exiting Gaussian beams.

Discussion and Conclusion— The high-transmission property discussed here does not seem to occur for air-hole type PCs. This can be understood from the conditions for low-loss transmission. As already mentioned, the condition for this to occur is the coincidence of the strong rod resonance shown in Fig. 2, and absence of non-specular orders in the diffraction off the gratings that constitute the PC. In air-hole type PCs, these conditions can simply not be simultaneously satisfied. Indeed, to achieve low Fresnel losses in air-hole type PC significant interface modification is required,[9-10] by which high transmission at only a limited range of incident angles can be achieved.

We have shown that two-dimensional rod-type PCs can exhibit very high transmission in the second band. This property is strongest in strictly two-dimensional calculations, in which the rods have infinite length. However, even for the short rods considered here, high transmission (>99%) is obtained for incident angles up to 30°. This allowed us to design a structure in which narrow Gaussian beams are incident at a relative angle of 45°, while still overlapping completely in the PC.

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