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Citation: Applied Physics Letters 87, 111107 (2005); doi: 10.1063/1.2048823
View online: http://dx.doi.org/10.1063/1.2048823
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/87/11?ver=pdfcov
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Highly efficient wide-angle transmission into uniform rod-type photonic crystals

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(Received 4 April 2005; accepted 21 July 2005; published online 9 September 2005)

We report on very high coupling efficiencies into rod-type photonic crystal (PC) slabs with unmodified interfaces. Three-dimensional finite difference time domain simulations show that reflected powers of less than 1.5% can be achieved for incident angles from $0^\circ$ to more than $25^\circ$. We use this property to design a beam combiner exhibiting both high efficiency coupling and self-collimation. The results could be applied to the design of efficient superprisms and other dispersion-based PC devices. © 2005 American Institute of Physics. [DOI: 10.1063/1.2048823]

Planar photonic crystal (PC) devices are being proposed for a variety of optical applications, ranging from high-$Q$ cavities and nonlinear switches to superprisms and perfect lenses. Most of these applications are designed to exploit one of two unique PC properties. The first of these is the existence of photonic band gaps—frequencies at which light cannot propagate through the PC lattice in any direction. Here, we consider a second class of PC applications, namely those that use the unusual dispersion properties of propagating Bloch modes. Superprism effects, perfect lensing, negative refraction, and self-collimation effects all result from specific features in the PC bands. To use these effects in practical devices, it is essential that light can be coupled efficiently into and out of the PC structure. This is necessary not only to minimize insertion losses, but also to avoid unwanted reflections that can cause interference and cross talk between devices, an important consideration for compact integrated optical circuits.

Several techniques have been proposed to improve the coupling efficiency into uniform PC slabs, including the modification of the shape, size, or spacing of the first few layers of the PC, and the application of evanescent coupling from a waveguide above the slab. In the first case, Baba and Ohsaki calculated transmission efficiencies as high as 99.8% (0.01 dB) by elongating the first row of air holes in an air hole-type PC. However, the direction in which the holes are projected relative to the incident beam is critical, with a reported acceptance angle less than 3° for transmittance of better than 79% (~1 dB). In contrast, here we study transmission into rod-type PCs with high index cylinders, and show that it is possible to couple at least 98.5% (~0.065 dB) of the light at incident angles between $0^\circ$ and $25^\circ$ without modification to the interface. Combining this property with the unique dispersion properties of PCs will enable the design of efficient superprisms and other PC structures where light must be coupled into a uniform PC lattice with high index inclusions. As an example, we have designed a PC that exhibits highly efficient coupling and self-collimation effects and we show that this simple PC structure can be used as a collimating beam combiner.

Figure 1 shows the PC slab geometry considered here, where appropriate boundary conditions are used to simulate a semi-infinite cladding extending above and below the core slab, and in the $xz$ plane. This geometry is similar to that proposed in Ref. 4 with a cylinder radius $r=0.35d$ and slab height $h=3d$, where $d$ is the lattice period. Two- (2D) and three-dimensional (3D) finite difference time domain (FDTD) results are presented in addition to 2D Bloch mode matrix method (BMM) calculations. In the FDTD simulations, an elliptical Gaussian beam with full widths at half maximum of $w_x=5d$ and $w_y=2.5d$ is launched with transverse magnetic (TM) polarization (electric field along the $y$ axis) at an incident angle $\theta_i$ relative to the normal of the PC interface. The crystal is oriented such that the normal is parallel to the $\Gamma-M$ axis of the hexagonal Brillouin zone. The 2D calculations with rods of index $n_{cy}=3.4$ in a background of index $n_{b}=1.458$, are a good approximation to the 3D simulations, thus providing an efficient tool for optimizing parameters before launching computationally intensive 3D simulations.

Figure 2 shows the reflectance spectra for Gaussian beams with $\theta_i=0^\circ$ (solid curve) and $\theta_i=22.5^\circ$ (long dashed curve) at an incident angle $\theta_i$ relative to the normal of the PC interface. The crystal is oriented such that the normal is parallel to the $\Gamma-M$ axis of the hexagonal Brillouin zone. The 2D calculations with rods of index $n_{cy}=3.4$ in a background of index $n_{b}=1.458$, are a good approximation to the 3D simulations, thus providing an efficient tool for optimizing parameters before launching computationally intensive 3D simulations.

![FIG. 1. Geometry of the PC slab with core and cladding index $n_{slab}=1.460$ and $n_{clad}=1.458$. The upper cladding is lifted to show the interior structure. The triangular PC lattice is formed by cylinders of height $h=3d$, index $n_{cy}=3.4$, and radius $r=0.35d$, where $d$ is the lattice period.](Image)
The light transmitted into the crystal is coupled to the Bloch modes, and thus it is the dispersion properties of these modes that determine the propagation of the beam through the crystal. By choosing the PC parameters appropriately, superprism, perfect lensing, and self-collimation effects can be obtained. Self-collimation occurs when an incident beam couples into a Bloch mode where there is a point of inflection in the equifrequency curve. At this point, the small range of incident k vectors present in the beam all propagate in approximately the same direction within the crystal, and thus the beam is collimated. If the equifrequency curve is relatively flat, such that two beams with different incident angles are collimated in approximately the same direction, then the beams propagate together through the crystal. Quantitatively, collimation is measured by the parameter $p=(\partial \theta_{i}/\partial \theta_{r})_{\omega}$, where $\theta_{i}$ and $\theta_{r}$ are the angles of the incident beam and the beam in the photonic crystal, respectively. For good collimation, we require small $p$ values so that $\theta_{r}$ varies slowly with $\theta_{i}$. Recently it was shown that every band of every 2D photonic crystal has a contour along which $p=0$. In the example below, we have chosen to operate in the second band, where efficient coupling is possible for the reasons discussed above.

The generic nature of high efficiency coupling in rod-type PCs enables us to design a PC to simultaneously exhibit very low reflectance and self-collimation. Here, we have optimized the parameters for $\theta_{r}=22.5^\circ$, however the reflection remains low for angles less than this, as illustrated in Fig. 2. A single parameter optimization was performed by varying the cylinder radius in the slab design of Ref. 4, with a height of $h=3d$ to reduce the effect of the finite cylinder length. First, the 2D BMM method was used to calculate the reflectance as a function of frequency and cylinder radius for a plane wave incident on a semi-infinite PC at $\theta_{i}=22.5^\circ$. Next, 2D band surfaces were calculated for the second band with a range of radii using the software BANDSOLVE, from which the $p$ parameter was calculated over the Brillouin zone. Using a similar approach to Ref. 11, for each radius, we found the frequency at which the $\theta_{r}=22.5^\circ$ equi-incident angle and the $p=0$ curves intersect, thus obtaining a curve in radius-frequency space along which collimation occurs. Comparing this curve with the plane wave results shows that collimation of the incident beam and a reflectance of less than 1% occur for $r=0.35d$. The results in Fig. 2 show that the 2D reflectance calculations are a good approximation to the 3D simulations, thus providing an efficient tool for initial optimization calculations over a broad parameter space. The following results demonstrate that the 2D collimation calculations are also a good approximation to the 3D results.

In Fig. 3, we demonstrate a simple PC beam combiner exhibiting low reflection, wide angle coupling, and collimation that could be used to interact multiple beams for studying nonlinear effects in PCs. Two Gaussian beams with the parameters described previously are focussed onto the front

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**FIG. 2.** (Color online) 2D plane wave reflectance spectra (BMM method) for a semi-infinite PC and 3D FDTD reflectance spectra for a Gaussian beam of width $w_{x}=5d$ and $w_{y}=2.5d$ incident on 16 layers of cylinders. Results are shown for $\theta_{i}=0^\circ$ and $\theta_{i}=22.5^\circ$.

**FIG. 3.** 3D FDTD simulation showing the $|E_{y}|$ field component in the PC for two in-phase Gaussian beams launched with $\theta_{i}=\pm 22.5^\circ$. The solid curves show the input (left) and output (right) powers in the slab and the dashed curves show the Gaussian envelopes of the input and output beams.
face of a 16-layer PC at a scaled frequency of \( d/\lambda = 0.295 \), where the reflectance in Fig. 2 is 1.4\%. Interference of the beams results in the three-lobed pattern in Fig. 3, which is modulated by a Gaussian envelope of width \( 5 \cos(\theta)d \) as indicated by the dashed curve on the left. Inside the PC, the beams are collimated and propagate in approximately the same direction, emerging through the rear interface with a width of \( 5.8 \cos(\theta)d \). We have confirmed that this behavior is maintained for beams of any relative phase. Beyond the PC, the beams continue to propagate in their original directions. This structure could potentially be used for transferring more complex field modulations, such as images from one side of the crystal to the other. In contrast, if the two beams were coupled into a single finite waveguide, the conversion between waveguide and free space modes would destroy the original field profile without careful waveguide design.

Many applications could benefit from these design techniques and results, aside from the example presented here. For example, PC superprisms require light to be coupled efficiently through both interfaces while maintaining a good beam shape\(^9\) and there are proposals for optical chips based on self-collimated beams\(^12\), for which this work would clearly be of great benefit.

In conclusion, we have found that coupling into regular rod-type PCs can be significantly more efficient over a wide range of incident angles than for PCs with air holes, and this can be achieved without modifications to the interface. We have demonstrated that 2D simulations of this behavior can be used to optimize the parameters for realistic PC slab geometries, and that these properties are retained by the 3D structures. These results have been used to design an efficient PC self-collimating beam combiner that could be used for studying nonlinear interactions in PCs.

This work was produced with the assistance of the Australian Research Council under the ARC Centres of Excellence program.