Adiabatic coupling between conventional dielectric waveguides and waveguides with discrete translational symmetry

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We study adiabatic transformation in optical waveguides with discrete translational symmetry. We calculate the reflection and transmission coefficient for a structure consisting of a slab waveguide that is adiabatically transformed into a photonic crystal waveguide and then back into a slab waveguide. The calculation yields high transmission over a wide frequency range of the photonic crystal waveguide band and indicates efficient coupling between the slab waveguide and the photonic crystal waveguide. Other applications of adiabatic mode transformation in photonic crystal waveguides and the coupled-resonator optical waveguides are also discussed.

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In quantum mechanics it is well known that, if the Hamiltonian of a system changes slowly, the eigenmode at any one moment is adiabatically transformed into a pure and different eigenmode at any later time.[1] Similarly in optoelectronics, if we slowly modify an optical waveguide with distance, the optical mode can be adiabatically changed into another pure mode with different spatial characteristics. By use of this property, many devices such as waveguide fiber couplers[2] and add–drop filters[3] have been constructed. The waveguides that are involved in those applications are all based on guiding as a result of total internal reflection. The unperturbed waveguides have continuous spatial translation symmetry along the mode propagation direction. As a consequence, one can easily achieve the condition of adiabaticity by slowly and continuously varying the waveguide parameters as the optical modes propagate.[4] However, there are other types of waveguide (for example, the waveguides constructed from photonic crystals[5,6]) that possess only discrete translational symmetry, for which the optical confinement is achieved by multiple Bragg reflections. In these types of geometry, the refractive index of the dielectric medium and the optical modes usually change significantly within a single unit cell. Therefore, for these structures it is not clear that we can achieve adiabatic mode transformation or, if we can, how slow the transformation should be to satisfy the adiabaticity condition. This problem is of significant practical interest and, until now, has been untreated.

As an example of adiabatic mode transformation in waveguides with discrete translational symmetry, we study a geometry shown in Fig. 1(a), where a slab waveguide is tapered and changed into a square-lattice photonic crystal waveguide and then back into a slab waveguide. Because of numerical discretization constraints, we choose the slab waveguide taper to be a simple angled cut, as illustrated in Fig. 1(a). For an arbitrary taper angle θ, the slab waveguide mode and the photonic crystal waveguide mode do not couple well to each other, because they have different spatial characteristics and dispersion relations. This mode mismatch will in general cause significant backreflection. However, for a small taper angle it is possible to achieve adiabatic mode coupling and obtain high transmission over a wide frequency range. Here we use a finite-difference time-domain method[7] to find the reflection and transmission coefficients. As shown in Fig. 1(a), we use a Huygens source[8] located at incident surface

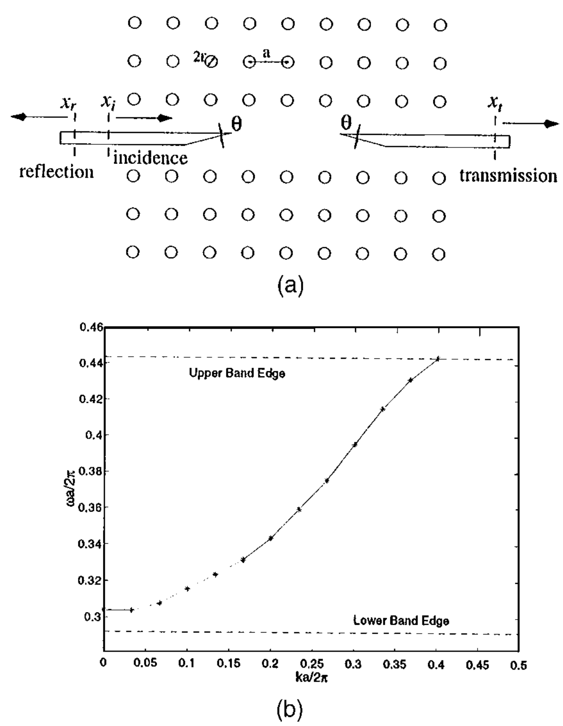

Fig. 1. (a) Schematic of the two-dimensional computational domain. A tapered slab semiconductor waveguide is connected with a square-lattice photonic crystal waveguide and back into a tapered slab waveguide. For small taper angle, adiabatic mode conversion can be achieved. (b) The dispersion relation of the single TM waveguide mode in a square-lattice photonic crystal waveguide formed by removal of one row of semiconductor rods.

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x_i to excite a temporal pulse of the fundamental slab waveguide mode propagating forward. Maxwell equations are solved, and the reflected power spectrum at surface x_r and the transmitted power spectrum at surface x_t are recorded. After normalizing the reflection and transmission power spectrum with respect to the incident optical power spectrum, we obtain the reflection and transmission coefficients at different frequencies in a single calculation. It should be noted that this is a two-dimensional calculation and the refractive index varies only in the plane. We consider only the modes whose electric fields are polarized perpendicularly to the plane (TM modes). The computational domain is terminated by the perfectly matched layer[9] boundary condition, which can efficiently absorb the electromagnetic radiation in a slab waveguide.

The photonic crystal in Fig. 1(a) is a square lattice of semiconductor rods with refractive index $n = 3.6$ (GaAs) and $r/a = 0.18$, where r is the radius of the semiconductor rods and a is the distance between the neighboring semiconductor rods. The refractive index of the tapered slab waveguide in Fig. 1(a) is also 3.6; the width of the slab waveguide d is $d/a = 0.33$. The rest of the dielectric medium is air. The parameter r/a is chosen such that the TM photonic bandgap is maximized. Our calculation shows that the photonic crystal in Fig. 1(a) supports a TM bandgap for $\omega a/2\pi$ from 0.292 to 0.443. By removing one row of semiconductor rods we form a waveguide that supports a single propagating TM mode. Its dispersion relation is shown in Fig. 1(b). The thickness of the slab waveguide is chosen such that, for the frequency range of interest in this Letter, the slab waveguide supports only a single propagating mode whose **E** field points out of the plane. In the calculations we consider three slab waveguide taper angles, $\theta = 90°$, $\theta = 18.4°$, and $\theta = 6.3°$. The transmission and the reflection coefficients for the three cases are shown in Fig. 2.

First, consider the case when $\theta = 90°$, where the slab waveguide has a flat end (nontapered case). We observe two transmission peaks and correspondingly two reflection dips, at $\omega a/2\pi = 0.323$ and $\omega a/2\pi = 0.381$. For this flat-end case the photonic crystal waveguide mode does not couple well to the slab waveguide and encounters significant modal reflection at the slab waveguide end. At frequencies resonant with the Fabry–Perot modes formed between the two flat slab waveguide ends, the transmission coefficient will be high as a result of the process of resonant tunneling. Another interesting feature of this case is the high reflection below $\omega a/2\pi = 0.31$, which results from the fact that, within this frequency range, either the photonic crystal waveguide does not support propagating modes or the waveguide mode has a low group velocity. A few reflection coefficients about $\omega a/2\pi = 0.305$ rise slightly above unit by 1% or 2%; the rise is likely caused by numerical error. A similar phenomenon has also been reported in the literature.[10] For the tapering angle of $\theta = 18.4°$, we still observe transmission peaks in Fig. 2, which can also be attributed to the localized modes between the tapered slab waveguide. However, the widths of the transmission peaks in this case are wider than those for $\theta = 90°$, because the tapered slab waveguide ends offer less mode confinement and lead to lower modal Q. The peak frequencies are also changed, because the effective mode volume is not exactly the same as for the nontapered case.

The case with $\theta = 6.3°$ is most interesting. For $\omega a/2\pi$ within the range 0.32–0.42, the transmission coefficient is consistently above 80%. Furthermore, we observe a broad transmission peak near $\omega a/2\pi = 0.323$, and for $\omega a/2\pi$ from 0.36 to 0.41 the transmission is quite flat and high. This result indicates that we can effectively transform the slab waveguide mode into a photonic crystal waveguide mode and vice versa. To illustrate this point directly, we show in Fig. 3 the **E** field distribution for $\theta = 6.3°$ at $\omega a/2\pi = 0.39$ and $\omega a/2\pi = 0.3$. In Fig. 3(a), where $\omega a/2\pi = 0.39$, we can clearly see the mode transformation from a slab waveguide to a photonic crystal waveguide. In Fig. 3(b), where $\omega a/2\pi = 0.3$, the **E** field decays in the region of photonic crystal waveguide, which is to be expected because no propagating mode is supported in the photonic crystal waveguide at that frequency, as shown in Fig. 1(b).

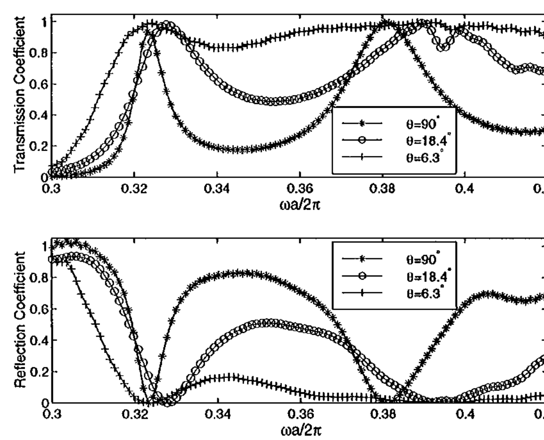

Fig. 2. Transmission and reflection spectra of the structure shown in Fig. 1(a). The parameter θ corresponds to the different taper angles shown in Fig. 1(a).

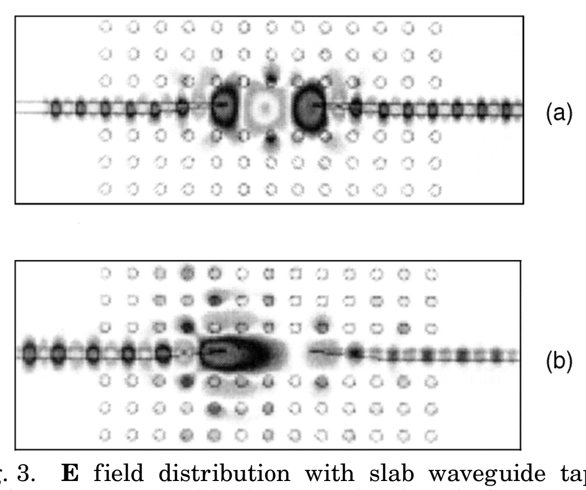

Fig. 3. **E** field distribution with slab waveguide taper angle $\theta = 6.3°$. In (a), the normalized mode frequency is $\omega a/2\pi = 0.39$; in (b), $\omega a/2\pi$ is 0.3.

It should be emphasized that the concept of adiabatic transformation in a waveguide with discrete translational symmetry is general. The square-lattice photonic crystal in Fig. 1 may be replaced by other types of photonic crystal, and adiabatic coupling can still be achieved. Thus adiabatic mode transformation offers a generic solution to the problem of efficiently coupling light into and out of a photonic crystal waveguide, which is essential for applications of photonic crystal waveguides in integrated optics. Using the same principle, we may taper a regular optical fiber and adiabatically couple it with a photonic crystal fiber.[11] The previous calculations indicate that such a coupler can have a high flat transmission over a wide frequency range. By slowly changing the lattice spacing it is also possible to convert one type of photonic crystal waveguide into a different one. For example, a square-lattice photonic crystal waveguide could be adiabatically converted into a triangular-lattice photonic crystal waveguide. Another possible application of adiabatic mode transformation is adiabatic coupling of a photonic crystal waveguide and a coupled-resonator optical waveguide[12,13] (CROW). The CROW has many interesting properties that may find applications in integrated optics and nonlinear optics. However, to realize those applications one must find a way to couple light efficiently into and out of a CROW. One method is to slowly change the photonic cell and adiabatically transform a photonic crystal waveguide into a CROW. All these possibilities are currently under investigation.

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