Investigation of physical mechanisms in coupling photonic crystal waveguiding structures

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Abstract: We explain the fundamental physical mechanisms involved in coupling triangular lattice photonic crystal waveguides to conventional dielectric slab waveguides. We show that the two waveguides can be efficiently coupled outside the mode gap frequencies. We especially focus on the coupling of the two structures within the mode gap frequencies and show for the first time that the diffraction from the main photonic crystal structure plays an important role on the reflection of power back into the slab waveguide. The practical importance of this effect and possible strategies to modify it are also discussed.

OCIS codes: (050.0050) Diffraction and gratings; (250.5300) Photonic integrated circuits and (230.7370) Waveguides

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1. Introduction

Photonic crystals (PCs) [1,2] are novel optical structures with periodic variation of permittivity in space. Multiple scattering of electromagnetic waves from these periodic structures can result in the existence of a photonic bandgap (PBG), i.e., a range of frequency with no allowed electromagnetic modes. Ultrasmall optical devices such as cavities, waveguides, couplers, and lasers can be formed by adding defects to a perfect PC. Thus, PCs are attractive candidates for developing optical integrated circuits [3]. Photonic crystal waveguides (PCWs) [4,5] are essential parts of such integrated structures for providing low-loss large-bandwidth connectivity between different optical devices. The PCs that are suitable for planar integrated optics are in the form of a lattice of circular holes in a dielectric material such as Si or GaAs. A conventional PCW in such structures is formed by adding a line defect in the form of either a line of removed holes [6] or a linear chain of coupled cavities (i.e., a line of holes with modified radius) [7,8]. The former is more widely used in integrated optics applications and will be used throughout this paper.

Among all PCs, triangular lattice of air holes in a dielectric material is the most suitable structure for integrated optics applications due to its large PBG [9]. Conventional PCWs (formed by removing one row of holes) in these PC structures usually have two modes in the PBG [6]. Single mode PCWs were demonstrated by increasing the size of air holes in two rows of the structure next to the line defect [6]. Such single mode structures are necessary to avoid undesired signal distortion in PCWs. Furthermore, a new type of PCWs (named biperiodic PCWs) has been recently proposed to increase the low-loss guiding bandwidth and to reduce group velocity dispersion [10,11].

In addition to designing optimal single mode PCWs, efficient coupling of light into and out of these PCWs (and in general into all PC structures) is essential for designing practical PC integrated circuits. Using two tapered dielectric ridge waveguides that are coupled to PCWs in the input and output of the structure was proposed [12,13,14], and experimentally demonstrated [11,15]. It was shown that due to similarity between the mode patterns of a PCW and a slab (or ridge) waveguide with similar slab thickness, the two waveguides can be efficiently coupled over a large bandwidth [12]. The PCW used in the first demonstration of this idea had a reduced slab thickness to achieve single mode guiding [12], which makes it difficult to bend. More recent demonstrations of this coupling rely on conventional PCWs [14]. In this paper, we use the proposed single-mode PCWs discussed in Ref. [6].

In addition to coupling light into and out of PC structures, the study of coupling between a dielectric slab waveguide and a PCW is important for switching applications in which the incident light from a slab waveguide is either efficiently coupled into a PCW or efficiently reflected from it depending on the incident wavelength and/or the permittivity of the material inside the holes. Almost all previous reports on coupling slab waveguides and PCWs have focused only on transmission properties. However, for more novel applications like switching, reflection properties are as important.

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In this paper, we consider both transmission and reflection properties of the coupling between a slab waveguide and the single-mode PCW in the triangular lattice of air holes in Si. We explain all observed features based on fundamental physical mechanisms. The details of our simulations are summarized in Section 2. Transmission and reflection properties are summarized in Section 3. Major features of these coupled structures are explained in Section 4, and conclusions are made in Section 5.

2. Simulations

The main structure that we investigate in this paper is shown in Fig. 1. It consists of a dielectric slab waveguide coupled to a planar two-dimensional (2D) PCW. The thicknesses of the middle slabs of both waveguides are the same (represented by d in Fig. 1). The lattice constant of the photonic crystal is represented by a and the radius of the air holes is $r = 0.3a$ unless otherwise stated. The effective permittivity of the dielectric material used for the core of the slab waveguide and PCW is ε=7.9. Note that the dielectric material is Si with ε=11.4. However, in order to take the effect of the finite out-of-plane thickness of the planar structure (in the z-direction in Fig. 1) into account, we calculated the effective index of ε=7.9 using the method described in Ref. [16]. The polarization of the electromagnetic beams is TM (magnetic field normal to the plane of periodicity, i.e., in z direction in Fig. 1) throughout this paper due to the existence of a large PBG for this polarization. Also for having a single mode PCW we increased the radius of the air holes next to the guiding region from r=0.3a to r'=0.4a as described in Ref. [6]. To analyze transmission and reflection properties of this structure we used a computer code based on the two-dimensional finite difference time domain (2D-FDTD) method [17] and put perfectly matched layers (PML) [18] around the structures at all boundaries. In our calculations, the speed of light (c) is normalized to 1, and all spatial dimensions are in the units of FDTD calculation cells. To calculate the dispersion diagram of the guided modes of the PCW, we analyzed one period of the structure in the guiding direction and used enough layers of PC in the perpendicular direction as shown in Fig. 2(a). The dispersion diagram of the guided modes are then calculated using the order-N spectral technique [19] implemented using 2D-FDTD method with Bloch boundary condition in the guiding direction (i.e., x in Fig. 2(a)) and PML in the perpendicular direction (i.e., y direction in Fig. 2(a)). Further details of our simulations are described in Ref. [12].

To calculate the power transmission spectrum from the slab waveguide to the PCW, we used a pulsed Huygens source to excite the fundamental TM mode in the slab waveguide at x=x_0 in Fig. 1. We calculated the spectrum of the power transmitted through the PCW by taking the Fourier transform of the fields and then integrating the Poynting vector over a surface of 60 calculation cells centered at the middle of the PCW at x=x_1 in Fig. 1. The power transmission coefficient is then calculated as the ratio of the transmitted power to the incident power. Also for the calculation of reflection spectrum, we put another surface of calculation cells with the same size centered in the middle of the slab waveguide before the Huygens source at x=x_2 in Fig. 1. The power reflection coefficient is calculated as the ratio of the reflected power to the incident power.

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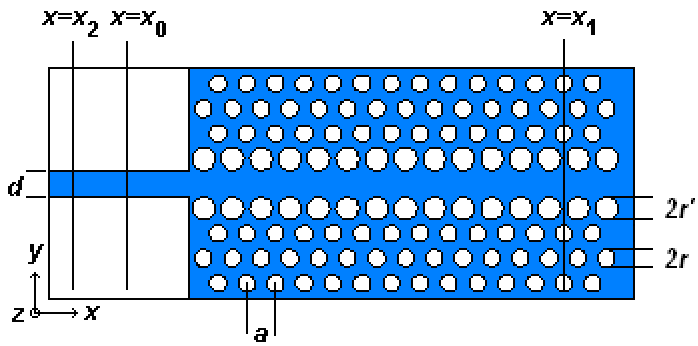

Fig. 1. Coupling of a slab waveguide to a triangular lattice PCW. The PCW is made by removing one row of air holes from a perfect PC. The thicknesses of both waveguides are the same and are equal to d=27 calculation cells. The PC lattice constant is a=24, and the radius of the air holes is r=0.3a. For designing single mode waveguide we increased the radii of the air holes next to the guiding region to r'=0.4a. The permittivity of dielectric used for the core of the slab waveguide and PCW is 7.9. Perfectly matched layers are used around the structure.

3. Theoretical results

Figure 2(a) shows one period of the PCW described in section 2. Magnetic field pattern of the fundamental even mode of this PCW at the normalized frequency a/λ=0.31 is also shown in Fig. 2(a). The dispersion diagram of the first two guided TM modes is shown in Fig. 2(b). It is clear from Fig. 2(b) that the odd mode is out of the PBG, thus, the PCW can be used for single–mode operation in the PBG. Note also that the fundamental even mode does not cover the entire PBG. The dispersion diagram of this mode is flattened in the middle of the PBG (around a/λ=0.295) due to the distributed Bragg reflection (DBR) in the guiding direction of the PCW [20].

The frequency range of $0.266<a/\lambda<0.295$ inside the PBG for which no guided mode exists is referred to as the mode gap [21] throughout this paper. While a guided mode with linear dispersion over a large bandwidth is desired for integrated optics applications, the existence (and especially the dynamic modification) of the mode gap is useful for switching applications. Also note that the magnetic field pattern of the fundamental TM even mode of the PCW is similar to that of the same mode in a slab waveguide with similar thickness. Thus, we expect to have good coupling between the two waveguides outside the mode gap.

To investigate the transmission and reflection properties of the coupling structure in Fig. 1, we placed a Huygens source at $x=x_0$=40 and calculated the power transmission and reflection coefficients at different frequencies (as described in section 2) at $x=x_1$=450 and $x=x_2$=20, respectively. The power transmission and reflection spectra are shown in Fig. 3(a). It is clear from Fig. 3(a) that the coupling between the two waveguides is very efficient outside the mode gap (or in the linear dispersion regime of the PCW). The small drop in the transmission around a/λ=0.343 is due to the excitation of the odd mode of the PCW caused by the small asymmetry in the FDTD-simulated structure. The width of this dip is equal to the frequency extent of the odd mode. Note that the odd mode for PCW studied in this paper exists at frequencies outside the PBG and thus, it is lossy. This efficient coupling is similar to what reported before for other types of PCWs and the result of similar properties of the fundamental guided modes of the two waveguides [12].

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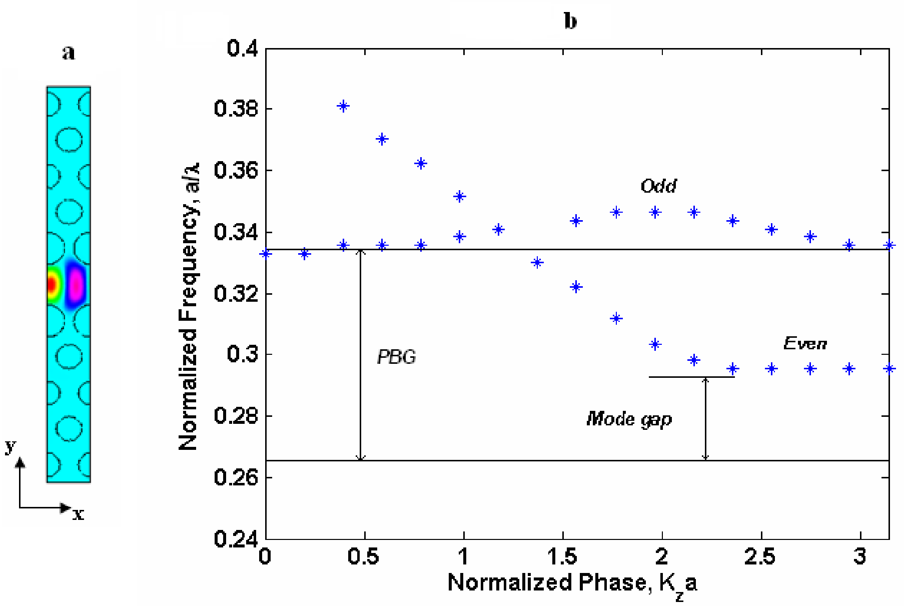

Fig. 2. (a) One period of the PCW with the magnetic field pattern of the fundamental even TM mode. (b) Dispersion diagram of the first two TM modes of the PCW in part (a). The odd mode exists outside the PBG and only the even mode remains inside the bandgap. The mode gap corresponds to the frequencies within the PBG with no allowed guided mode.

Despite extensive investigation of the efficient coupling between slab waveguides and PCWs outside the mode gap [21], the reflection properties of these structures (especially inside the mode gap) have not been investigated in detail. One might expect to get close to 100% reflection of power back into the slab waveguide in the mode gap since the PCW structure does not have any mode in the mode gap. However, the reflection spectrum in Fig. 3(a) shows a different behavior, i.e., only a small portion of the incident power is reflected back into the slab waveguide. This phenomenon is highly undesirable in switching applications resulting in a considerable loss of power.

To investigate the reason for the small reflection coefficient outside the mode gap, we calculated the field pattern in the structure (Fig. 1) when excited by a CW beam at a single normalized frequency (a/λ=0.28) inside the mode gap. The result is shown in Fig. 3(b). It is clear that the beam does not propagate in the PCW, and a large portion of the incident power is diffracted in the air above the dielectric slab and is absorbed by the PMLs. The fundamental physical reason for this behavior is discussed in section 4.

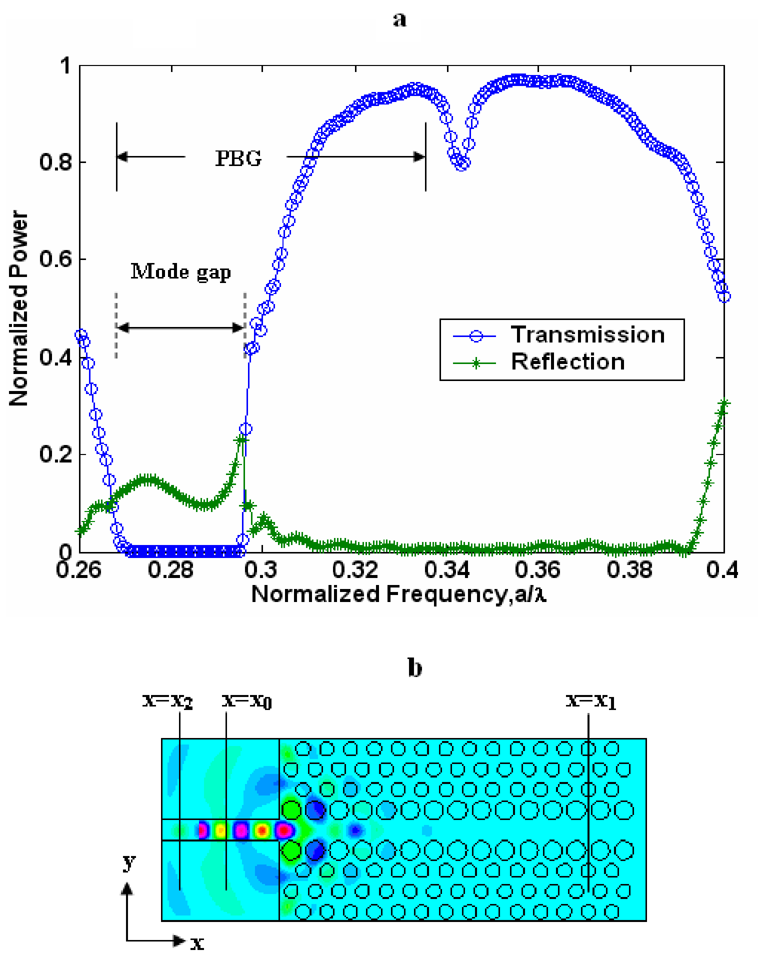

Fig. 3 (a) The transmission and reflection spectra of the power coupled from the slab waveguide to the PCW. A TM Huygens source is placed at $x=x_0=40$ and the transmitted and reflected powers at different frequencies are calculated at $x=x_1=450$ and $x=x_2=20$, respectively. Note that reflection coefficient within the mode gap is less than 100%. (b) The magnetic field profile at the normalized frequency $a/\lambda = 0.28$ inside the mode gap. The diffraction of power into the air above and below the dielectric slab is clear.

4. Discussion

The PC structure has no propagating electromagnetic mode inside the mode gap. Thus, only the first few periods of the structure in the guiding direction (i.e., x in Fig. 3(b)) contribute to the reflection and/or diffraction of the incident beam. Since the defect line (or the PCW) has no guided mode in the mode gap, we expect that the PCW structure acts similarly to a perfect PC structure at these frequencies. To investigate this hypothesis, we studied the properties of a slab waveguide coupled to a perfect PC structure shown in Fig. 4. We placed a CW TM Huygens source with normalized frequency (a/λ=0.28) at $x=x_0=40$ and monitored the magnetic field everywhere above the slab waveguide (in the air region) for both the coupled PCW structure (Fig. 1) and the coupled PC structure (Fig. 4). We then calculated the 2D spatial Fourier transform of these fields to obtain their plane-wave spectra. The results for the PCW structure and the PC structure are shown in Fig. 5(a) and 5(b), respectively. The similarity between the plane-wave spectra of the diffracted beams of the two structures is clear from Fig. 5. Most importantly, the strongest diffracted component occurs at (k_x=0.0687, k_y=0.0192) for both structures. Note that similar results hold for the air region below the slab

#5104 - $15.00 US Received 24 August 2004; revised 20 September 2004; accepted 20 September 2004

waveguide due to the symmetry of the structure. The maximum diffraction components correspond to diffraction angles of ±15.9° with respect to the x-axis. Thus, the results shown in Fig. 5 confirm that the performance of the PCW structure in Fig. 1 inside the mode gap is primarily due to the PC structure and the line defect has a minor role. The diffraction from the periodic PC structure results in the low reflection of power back into the slab waveguide. In order to avoid this diffraction, the general properties of the PC structure at the boundary must be modified.

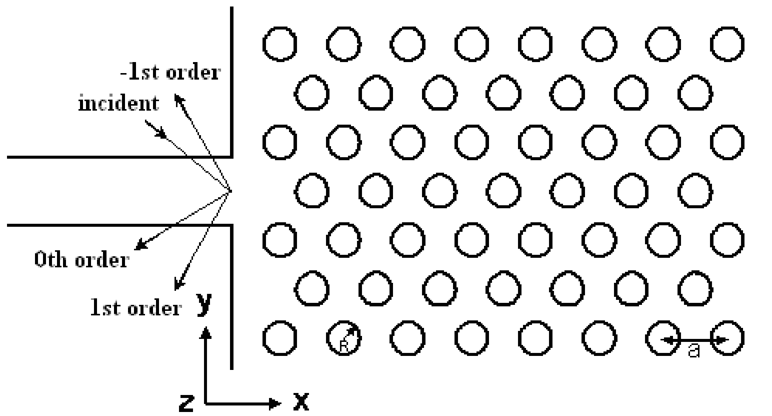

Fig. 4. A slab waveguide coupled to a perfect PC structure with r=0.3a (and a=24). Different diffracted orders are shown in the figure. Other properties of the structure are similar to those summarized in the captions of Fig. 1.

Since the PC structure in Fig. 4 is periodic, we can use an approximate technique based on grating diffraction to estimate its diffraction properties. In this approximation, the PC structure is considered as a 2D grating. The incident signal from the slab waveguide is expanded as a series of plane-wave components (using 2D spatial Fourier transformation) and the diffraction of each component is analyzed using coupled-wave theory [22]. The individual diffracted components are then added together to obtain the final diffracted beam. For the analysis of the diffracted beam, we assume the region on the left side of the boundary between the PC structure and the slab waveguide to be air. Furthermore, we approximate the incident field of the fundamental magnetic mode (TM_0) of the slab waveguide by the superposition of two plane waves with incident angles of ±48.8° with respect to x-axis as shown in Fig. 6(a). We calculated the incident angles by numerically solving the dispersion equation of the slab waveguide for the fundamental TM guided mode [23]. The variation of the relative strength of different diffraction orders with the incident angle is shown in Fig. 6(b).

#5104 - $15.00 US Received 24 August 2004; revised 20 September 2004; accepted 20 September 2004

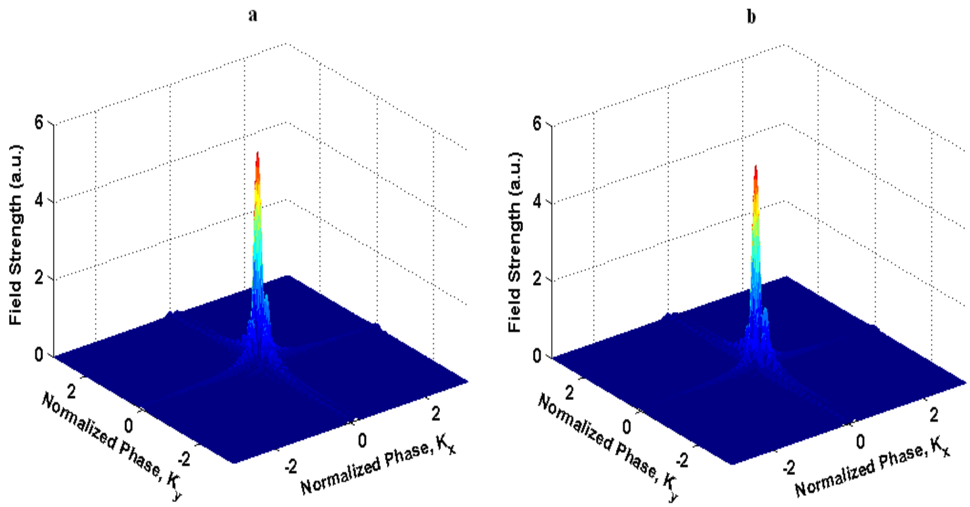

Fig. 5. The 2D spatial Fourier transform of the magnetic field above the slab waveguide for the case of a slab waveguide coupled to: (a) a PCW as shown in Fig. 1 and (b) a perfect PC structure with r=0.3a every where and no defect as shown in Fig. 4. All properties of the structures in (a) and (b) are the same as those in the caption of Fig. 1 and Fig. 4, respectively.

Figure 6(b) shows that for the approximate incident field from the slab waveguide (incident angle ±48.8°) most of the energy is diffracted into the first diffraction orders. Further we calculated the diffracted angle for these orders to be θ=±16.5° with respect to the x-axis. Considering the approximation involved in this calculation, the resulting diffracted angles agree with the angle calculated using FDTD simulations (i.e., θ=±15.9°). Figure 6 reconfirms that the diffraction from the PC structure plays a major role in coupling a slab waveguide to a PCW at frequencies inside the mode gap. This diffraction can reduce the reflection of power back into the slab waveguide at such frequencies making the design of optical switches based on the modification of the mode gap difficult.

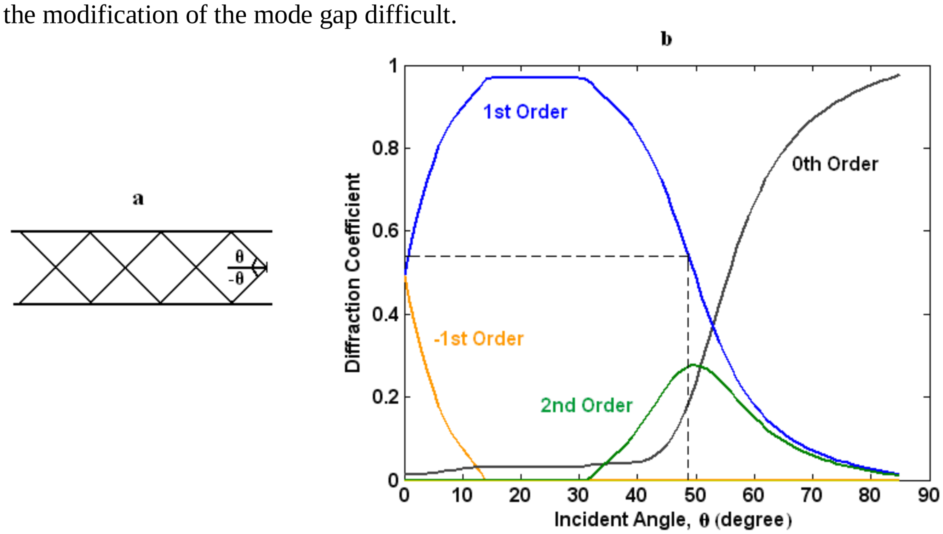

Fig. 6. (a) The slab waveguide with TM_0 mode as a superposition of two plane waves with incident angles of θ=±48.8°. (b)The variation of the approximate relative strength of different diffraction orders with the incident angle for the structure in Fig. 4 calculated using the grating theory with approximations described in the text. The dashed line corresponds to the incident angle of 48.8°

#5104 - $15.00 US Received 24 August 2004; revised 20 September 2004; accepted 20 September 2004

One idea to increase the reflection inside the mode gap for the coupling structure in Fig. 1 is to reduce the diffraction strength by modifying the PC structure at the boundary. While the actual optimization of the structure is out of the scope of this paper, we consider an example in which the center of the holes in the PC structure at the boundary are modified by adding a random shift of $\pm 0.2a$ with uniform probability distribution. The structure is shown in Fig. 7(a) and the variations of the normalized transmitted and reflected power with normalized frequency are shown in Fig. 7(b). It is clear that by changing the properties of only one column of the holes at the boundary, we can increase the reflection coefficient in the mode gap considerably. Note that the spatial Fourier transform of the permittivity in the column of holes next to the boundary has still a strong component at a spatial frequency of $2\pi/a$. Thus, the effect of diffraction still exists. Also, note that the modification of the PC structure at the interface modifies the coupling strength to the odd mode (by changing the symmetry). This explains the change in the strength of the transmission dip around $a/\lambda=0.34$ in Fig. 7(b) compared to this in Fig. 3(a). A full optimization of the structure can be performed by considering both diffraction and coupling effects and finding the optimal PC structure at the interface. Using grating-based solution by modifying the periodicity of the PC structure at the boundary might also be considered.

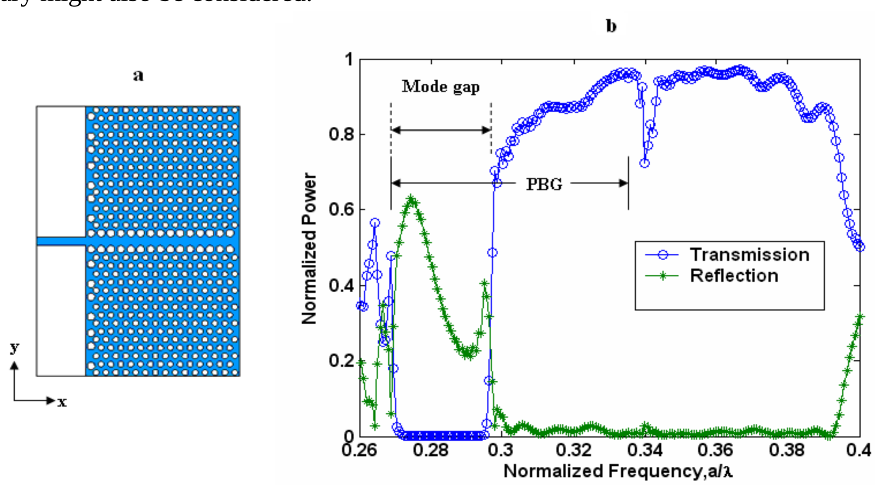

Fig. 7. (a) A slab waveguide coupled to a PCW with uniform perturbation of $\pm 0.2a$ in the center of air holes in the y direction next to the interface. (b) The transmission and reflection spectra of the power coupled from slab waveguide to this perturbed structure with $x=x_0=40$, $x=x_1=450$, and $x=x_2=20$.

5. Conclusion

We presented here the main physical effects that affect the coupling of electromagnetic waves from a slab waveguide to a single-mode photonic crystal waveguide. We showed that the two waveguides can be efficiently coupled in the frequencies outside the mode gap (where the PCW has guided modes). Within the mode gap frequencies, power transmission is low, and the incident power from the slab waveguide is partially reflected back to the waveguide and partially diffracted into the air (or cladding of the slab waveguide) by the periodic PC structure. The diffraction effect results in power loss in switching applications of PCWs and can be reduced (and eventually eliminated) by proper design of the PC structure at the interface.

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