Appl Phys B (2009) 95: 341–344
DOI 10.1007/s00340-009-3398-y

Applied Physics B
Lasers and Optics

The directional emission sensitivity of photonic crystal waveguides to air hole removal

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Received: 17 October 2008 / Revised version: 19 January 2009 / Published online: 13 February 2009

Abstract To obtain highly directional light output from photonic crystal waveguides (PCWs), the emission characteristics of the narrow-width waveguide structures are investigated by tailoring the geometry of the exit sides. The local structural deformations in the form of air hole removal from the triangular-lattice photonic crystal (PC) show the effectiveness of the previously proposed approach that was implemented by us for another type of PC. The spatial broadening of the beam is greatly suppressed. With the modified waveguide exits, highly directional emissions with small side lobes are achieved. The frequency dependency of the directional emissions is evaluated. We show that the divergence angles of the beams depend linearly on the wavelength for a regular type of PCW but the modified PCW exits have local minima with respect to wavelength in terms of the divergence angle. The present work may prove to be helpful in the design of couplers and edge-emitting lasers and in the implementation of free-space optical communications.

PACS 42.70.Qs · 42.82.Et · 42.79.Ag

1 Introduction

The different aspects of photonic crystal waveguides (PCWs) have received great interest from researchers around the world because of the novel properties of the waveguide modes in the dispersion diagram [1]. PCWs are obtained by perturbing the purely periodic nature of the high refractive index contrast dielectric materials, which are known as photonic crystals (PCs). There have been great demands for engineering the profile of the emitted light from the PCW ends in order to have highly directional emissions [2–12]. This is mainly because of the fact that the proper control of the radiation pattern may produce highly directional propagation of light, which can reach the far-field region without suffering significantly from the spatial spreading. The beaming of light is crucial for many applications including the coupling phenomenon between waveguides of different widths, PCW edge-emitting lasers and free-space optical communications.

The different approaches targeting the beaming effect in PCWs were explained in a recent study [12]. In Ref. [12], we made contributions to the subject of beaming of light by proposing to utilize a tapered waveguide exit. The systematic analysis of the different configurations was carried out for square lattice dielectric rods in air background. In the end, highly directional emissions with certain waveguide configurations were revealed. The present study investigates the applicability of the previously proposed solution for another type of commonly used PC which is a two-dimensional triangular lattice structure composed of air holes in the dielectric background. In addition to the frequency dependency of the emission profile, the angular intensity distribution of the output beam with respect to the geometrical modifications is investigated. The necessities of implementing the previous idea proposed in Ref. [12] for another kind of PCW are due the differences between the two PC structures. The triangular-lattice PC provides a photonic band gap for the TE polarizations (electric field is in the plane), contrary to the previously examined PC that favors mainly TM band gaps. The nature of the waveguide modes between these two types of PC is also different. In the first one, the light is confined and guided in the high-index

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medium surrounded by the perforated holes. On the other hand, the waveguiding occurs in the air with the latter type of PCW. The confinement mechanism, however, for both types of PCW depends on the Bragg scattering due to the photonic band gap effect. As a result, by means of this work we wish to highlight the similarities and the differences of the radiation profiles of the beams emerging from the waveguide whose exit side is altered by omitting a certain number of unit cells. It is shown that the underlying mechanism producing the directional emission is the same albeit the different waveguide exit geometry. Moreover, we also show that the frequency dependency of the radiation profile of the beams shifts from a linear wavelength dependency for a regular PCW to a dependency with a local minimum for the altered PCW exit.

2 Photonic crystal waveguide structure

The structure under investigation is presented as an inset in Fig. 1. The air hole radius is $0.30a$, where a is the lattice constant and the background refractive index is 3.46. The waveguide is obtained by removing one row of holes along the ΓK direction. The width of the PCW is $\sqrt{3}a$. Although this PCW supports two types of modes (even and odd), one can excite only the even mode by appropriately selecting the profile of the input light. The photonic band gap calculated by the plane wave expansion method extends from $a/\lambda =$ 0.207 to 0.273. The operating frequency is taken to be at $a/\lambda = 0.25$, which is inside the band gap. The input source is a modulated Gaussian pulse.

A two-dimensional finite-difference time-domain (FDTD) method is employed to investigate the beam propagation throughout the computational domain [13]. The perfectly matched layer absorbing boundary condition surrounds the computational domain [14]. The coupling of the mode within the unmodified waveguide exit to the outside is first examined not only to have a reference case for comparison purposes but also to indicate the highly diffusive pattern of the out-propagating beam. The result is shown in Fig. 1. The waveguide length is taken to be long enough to make sure that it supports only the waveguide mode. A systematic search is carried out next to monitor the emission profiles of each case when a local deformation is introduced to the waveguide exit. The symmetric removal of air holes along the two sides of the waveguide exit causes the deformations. Three types of intensity profiles are mainly obtained as a result of these perturbations. We should point out that different intensity profiles arise due to the variations of the light interference. The first type of profile has two large side lobes with a relatively small central lobe. This profile is not the desired radiation pattern so it is discarded in the study. The second type has an intensity profile which is not much different than the radiation profile of a regular PCW that shows strongly the effect of the diffraction. Finally, in the third category lies the interference pattern of the beams which create highly directional emissions. Due to the goal of this study, the cases provided later in the paper are the ones that yield more directionality than the others.

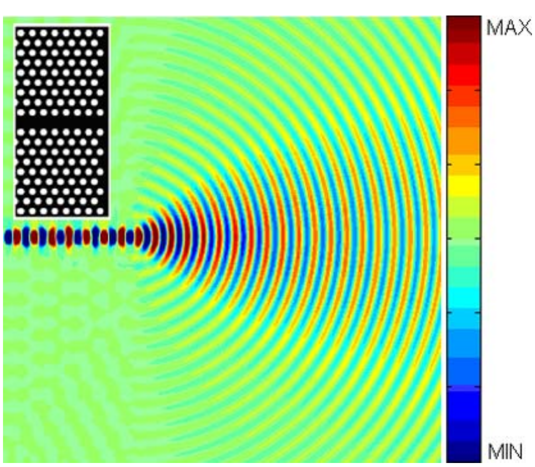

Fig. 1 The optical field distribution of the photonic crystal waveguide whose schematic representation is presented as an *inset*. There is no modification made to the exit of the waveguide

3 Numerical results and discussion

The numerous possibilities of the ways in which one may introduce the deformations in the structure directed us to focus our attention to a waveguide region such that only the two rows of air holes along both sides of the waveguide center line are considered for the perturbations. Figure 2a shows the steady-state magnetic field of one selected type of the local deformation. To be more specific and consistent with the notation used in our earlier work, we have $N_1 = 5$ and $N_2 = 1$ in Fig. 2a. That means that five holes in the first row and one hole in the second row are omitted. The magnified version of the exit is presented as an inset in Fig. 2a. One can see from the figure that the interference of the field creates highly directional emission. Even though the side lobes are small in amplitude compared to the central lobe, they receive some of the output power. The search for the structural deformations that yield the beaming of light gives us another case with $N_1 = 7$ and $N_2 = 4$. The field map plot of the beam in this case is shown in Fig. 2b. Similar to Fig. 2a, the emission is highly directional. However, in addition to the primary lobes, there are also secondary lobes all of which have a smaller angle with respect to the waveguide center line in Fig. 2b than in Fig. 2a. The quantitative comparisons of these two cases in terms of the divergence angle are

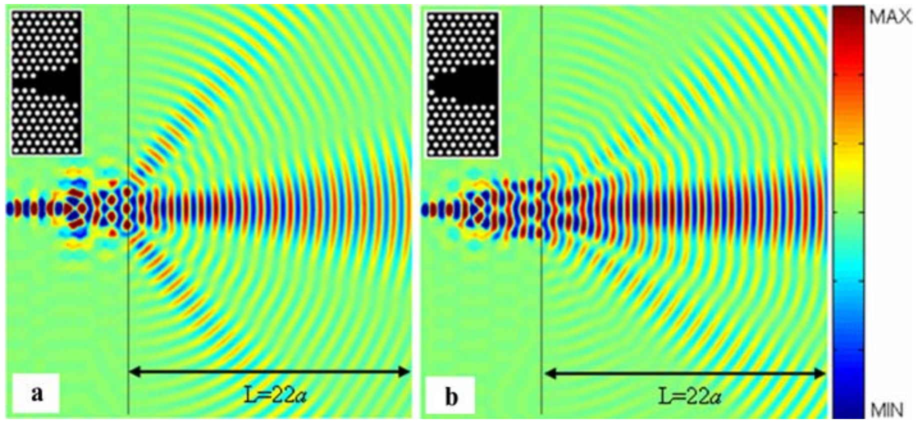

Fig. 2 The optical field distributions of the photonic crystal waveguide whose exit sides are altered. The *insets* show the modified structures. **a** Five holes from the *first row* and one hole from the *second row* are removed. **b** Seven holes from the *first row* and four holes from the *second row* are removed

presented next. We should note that a similar beaming effect was obtained in the square-lattice PC but with different structural changes, i.e. different N_1 and N_2 values [12].

We calculated the divergence angles of the three cases at full-width at half-maximum (FWHM). The reference case presented in Fig. 1 has a divergence angle of approximately $2\theta = 35°$. This value is reduced to $2\theta = 16°$ in Fig. 2a with the modifications made to the waveguide exit. Finally, the angle is lowered to approximately $2\theta = 11°$ in Fig. 2b. By comparing these numbers, one can deduce that the local deformations in the form of air hole removal induce highly directional emissions. One may question the possibility to further decrease the divergence angle by implementing additional parametric changes made to the PCW such as displacement of the hole locations or changing the radii of the holes. However, these options are kept outside of the scope of the present work.

The leading physical mechanism governing the beaming of light in the present study is due to the interference pattern created inside the enlarged region of the waveguide. A careful inspection of the field plot in Fig. 2 reveals that the tapered waveguide region sustains multimode interaction whose steady-state field resembles closely the pattern of the interference of a three-point source [7, 9]. As a result, highly directional emission with weak side lobes occurs. The role of the tapered waveguide is twofold. The foremost one is to provide a larger waveguide aperture; hence, the reduction in the diffraction. The second one is to obtain an interference pattern that imitates point-like sources. The combination of these two conditions has to be satisfied to obtain directional emission.

There are two subtle distinctions that need to be mentioned when a comparison is made between the present study and Ref. [12]. The first one is the initial conditions which are different for the two cases. The widths of the waveguides as well as the operating wavelengths are not the same. As a result, the spreading from the triangular-lattice PCW is less severe as compared with the square-lattice PCW. This can be concluded from the field plots in

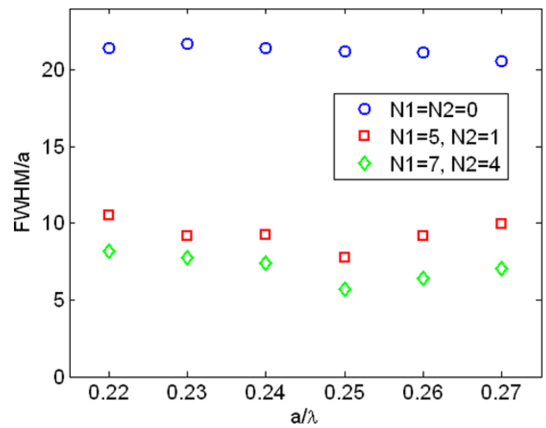

Fig. 3 The full-width at half-maximum (FWHM) values of the normalized amplitude of the magnetic field with respect to the normalized frequency for the three cases at a distance of $22a$ away from the end of the photonic crystal waveguide

Fig. 1 of both the present study and Ref. [12]. The second distinction occurs in terms of the performance improvement. The order of the improvement in the beam divergence angle reduction in the triangular-lattice PC is very close to the square-lattice PC albeit the different combination of the removed holes versus that of rods. This is expected because the physical mechanism which is responsible for the beaming of light in the two PCs is the same.

The search for the optimized local deformations that yield directional emissions was carried out for a central frequency of $a/\lambda = 0.25$. It is known, however, that the emission profiles show wavelength dependency. Therefore, we perform FDTD calculations of the PCW by spanning the frequency interval which corresponds to the waveguide modes of the PCW. The first case is for a regular PCW. The next two cases are for $(N_1 = 5, N_2 = 1)$ and $(N_1 = 7, N_2 = 4)$, respectively. The FWHM values at a distance of $22a$ away from the exit of the PCW are read by using the normalized magnetic field amplitude plot. The result is shown in Fig. 3. One can observe the following remarks from this plot. When we increase the frequency from 0.22 to 0.27 the regular PCW shows a linear wavelength dependency such that the divergence angle reduces with a decrease in wavelength, as expected. The other important observation occurs for the modified PCW exits. The reduction in FWHM reaches more than three times smaller values with the modified structure. Since the optimization was carried out at the normalized frequency of 0.25, we can see that the FWHM values have local minima for the two selected tapered waveguide exits. This tells us that when we change the frequency, the optimized structure may have different N_1 and N_2 combinations that produce a narrow divergence angle.

As shown in Fig. 3 with the circles, the regular PCW shows a linear wavelength dependency. The only discrepancy at the normalized frequency of 0.22 is due to the slow light nature of the waveguide mode at around that wavelength regime. The modified part of the waveguide end sustains a region where the waveguide mode creates the multimode interaction. When the wavelength changes, the interference of the light creates a different interference pattern. The reason to have minimum beam divergence at the normalized frequency of 0.25 as indicated in Fig. 3 with the squares and diamonds is mainly due to the procedure steps taken in the study. First, the operating frequency is fixed and then the structural modifications are introduced to search for the case where reduced beam spreading occurs. In order to have less divergence angle for the other frequencies a similar procedure has to be repeated.

One may wonder if some design rules can be drawn from the present study. The hole removal from the waveguide sides does not necessarily ensure the low divergence angle. Increasing the width of the waveguide at the exit side is a prior condition according to the relation $\theta \propto \lambda/\pi w$, where w is the width of the waveguide and θ is the divergence angle of the beam. However, not every way of obtaining tapered regions yields the highly directional emission. Since the feature size of the PC is on the order of the wavelength, one should check the field plot of the beam using FDTD calculations to make sure that the radiation pattern is directional.

4 Conclusions

To conclude, we have studied the emission patterns of the triangular-lattice PCW which is subject to deformations at the exit side in terms of the air hole removal. It was shown that by engineering the wavefront of the beams at the PCW exits one can reduce significantly the beam divergence angle. As a result, the radiated beam is confined in a narrow angle. By means of the presented procedure, different intensity patterns can be attained at the exit side of the PCW in which some of them produce highly directional and isotropic emissions. The main lobe residing at the waveguide center line carries the majority of the output power with beam divergence angle as small as 11°. The proposed solution may prove to be useful in the design of couplers and edge-emitting lasers and in the implementation of free-space communications.

References

1. J.D. Joannopoulos, R.D. Meade, J.N. Winn, *Photonic Crystals: Molding the Flow of Light* (Princeton University Press, Princeton, 1995)
2. P. Kramper, M. Agio, C.M. Soukoulis, A. Birner, F. Müller, R.B. Wehrspohn, U. Gösele, V. Sandoghar, Phys. Rev. Lett. **92**, 113903 (2004)
3. E. Moreno, F.J. García-Vidal, L. Martín-Moreno, Phys. Rev. B **69**, 121402 (2004)
4. S.K. Morrison, Y.S. Kivshar, Appl. Phys. Lett. **86**, 081110 (2005)
5. D. Tang, L. Chen, W. Ding, Appl. Phys. Lett. **89**, 131120 (2006)
6. I. Bulu, H. Caglayan, E. Ozbay, Opt. Lett. **30**, 3078 (2005)
7. Chii-Chang Chen, T. Pertsch, R. Iliev, F. Lederer, A. Tünnermann, Opt. Express **14**, 2423 (2006)
8. K. Guven, E. Ozbay, Opt. Express **15**, 14973 (2007)
9. Y. Zhang, Y. Zhang, B. Li, Opt. Express **15**, 9281 (2007)
10. E.H. Khoo, A.Q. Liu, T.H. Cheng, J. Li, D. Pinjala, Appl. Phys. Lett. **91**, 221105 (2007)
11. Z.H. Zhu, W.M. Ye, J.R. Ji, X.D. Yuan, C. Zen, Appl. Phys. B **86**, 327 (2007)
12. H. Kurt, IEEE Photon. Technol. Lett. **20**, 1682 (2008)
13. A. Taflove, *Computational Electromagnetics: The Finite-Difference Time-Domain Method* (Artech House, Norwood, 1995)
14. J.P. Berenger, J. Comput. Phys. **114**, 185 (1994)