Photonic Crystal Waveguide Based on 2-D Photonic Crystal With Absolute Photonic Band Gap

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***Abstract*—We propose an air-hole-type photonic crystal (PC) waveguide which can support both TE and TM waves. In order to realize such a waveguide, we employ a compound-type PC with absolute photonic bandgap and introduce a line defect with elliptical air holes. This PC waveguide realizes single-mode operation for both TE and TM waves. As an example of device application of this waveguide, a polarization splitter is demonstrated.**

***Index Terms*—Absolute photonic band gap (PBG), finite-element method (FEM), photonic crystal (PC) waveguide, polarization splitter.**

I. INTRODUCTION

EXTENSIVE investigations have been carried out in recent years on photonic crystals (PCs) with photonic band gaps (PBGs) in view of their potential ability in controlling light propagation. These PCs have many applications in optoelectronics, such as ultrasmall optical circuit devices, filters, switches, and lasers [1]. In general, two-dimensional (2-D) PCs, such as triangular and rectangular lattice, can give rise to PBGs for only either TE (H polarization) or TM (E polarization) waves within identical frequency region. Therefore, PC waveguides that have been reported so far support only either TE or TM PBG-effect bound modes. On the other hand, the ability to realize absolute PBGs, which forbid both TE and TM wave propagation, by reducing structural symmetry [2]–[8] has been reported. By using PCs which possess absolute PBGs, PC waveguides have the possibility that both TE and TM PBG-effect bound modes can be supported and it is expected that the applicability of PC devices will be further extended.

In this letter, we propose an air-hole-type PC waveguide which can support both TE and TM modes. In order to realize such a waveguide, we employ a compound-type PC of honeycomb and triangular lattices [2]. This choice is made since the resulting crystal can be easily realized by modifying the size of some of the air holes of the commonly fabricated triangular lattice. First, we optimize its structural parameters to get a large absolute PBG. Then, after investigating structures of a line defect to create PC waveguides, we introduce a defect which has elliptical air holes in the core region to realize single-mode operation for both TE and TM waves. It is also shown that a polarization splitter can be realized by utilizing the obtained PC waveguide.

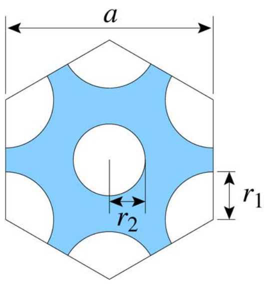

Fig. 1. Unit cell of proposed PC.

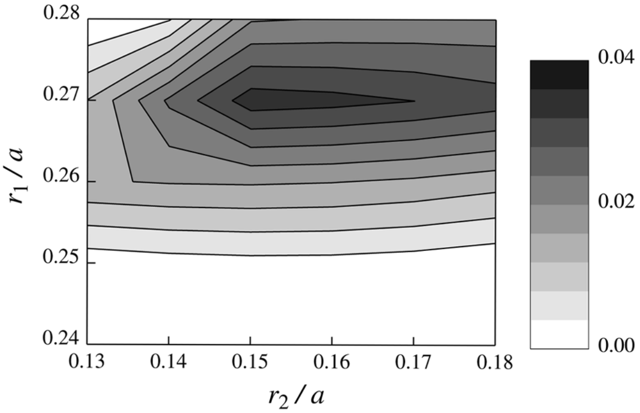

Fig. 2. Absolute PBG width as a function of r_1/a and r_2/a.

II. ABSOLUTE PBG

Some kinds of PC which possess absolute PBGs have been reported so far [2]–[8]. In this letter, we employ the air-hole-type PC, as shown in Fig. 1, and assume the background refractive index is 3.4. In this section, we determine the structural parameters of the PC in Fig. 1 to maximize absolute PBG bandwidth. Fig. 2 shows the normalized frequency bandwidth of absolute PBG related to the structural parameters, r_1 and r_2. The finite-element method (FEM) with periodic boundary condition was used to evaluate the band structure of the PC. We can see that the maximum bandwidth of absolute PBG is obtained when $r_1/a = 0.27$ and $r_2/a = 0.15$. Fig. 3 shows the dispersion relations of the PC with $r_1/a = 0.27$ and $r_2/a = 0.15$. We can see that the absolute PBG exists between $a/\lambda = 0.550$ and 0.584 with the above parameters.

III. PC WAVEGUIDE BASED ON 2-D PC WITH ABSOLUTE PBG

In order to realize PC waveguides which can support both TE and TM modes, we introduce a line defect into the PC with absolute PBG presented in Section II. First, we consider the line defect, as shown in Fig. 4(a). In this structure, two larger air

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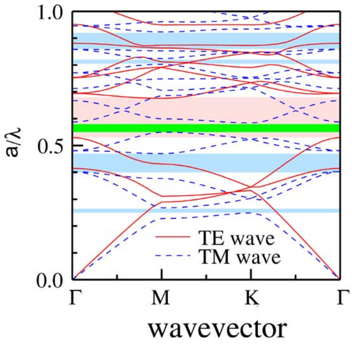
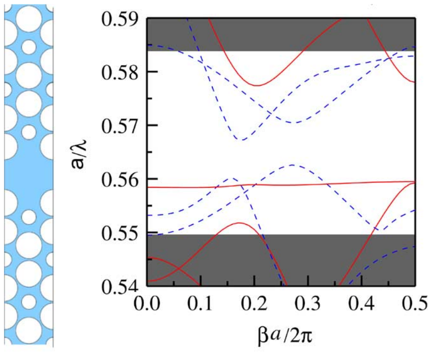
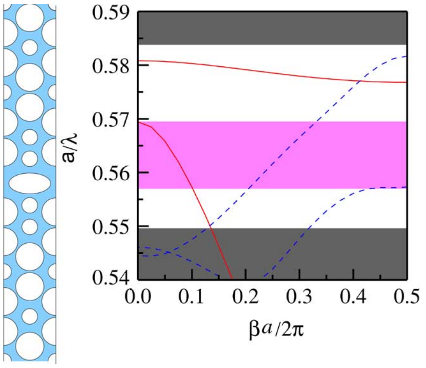


Fig. 3. Dispersion relations of proposed PC with $r_1/a = 0.27$ and $r_2/a = 0.15$. The solid lines and dashed lines show TE and TM waves, respectively.



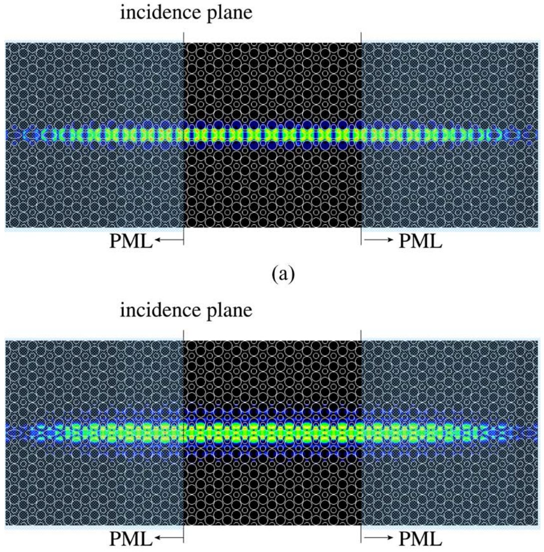
(a) (b)

Fig. 4. PC waveguide based on PC with absolute PBG. (a) Waveguide structure. (b) Dispersion relations. The solid lines and dashed lines show TE and TM mode, respectively.



(a) (b)

Fig. 5. PC waveguide with an elliptical air hole. (a) Waveguide structure. (b) Dispersion relations. The solid lines and dashed lines show TE and TM mode, respectively.



(a)

(b)

Fig. 6. Propagating fields in the PC waveguide with an elliptical air hole. (a) TE mode. (b) TM mode.

holes and one smaller air hole are removed. Fig. 4(b) shows the dispersion relations for both TE and TM modes. The dispersion relations are calculated by using FEM with periodic boundary condition [9]. In Fig. 4(b), some guided modes can be observed in the absolute PBG region. However, this waveguide structure results in multimode operation in the absolute PBG region. So, in order to realize a single-mode operation for both TE and TM modes within an identical frequency region, we consider the PC waveguide structure as shown in Fig. 5(a). In this structure, two smaller air holes and one elliptical air hole are added to the PC waveguide, as shown in Fig. 4(a). The radius of two small air holes is r_2 and these air holes are arranged to be on the same tangential line with the adjacent larger air holes. The major and minor axes of the elliptical air hole are $0.4a$ and $0.2a$, respectively. The large elliptical air hole is introduced for the aim of reducing the number of modes since the reduction of the average refractive index in the core region corresponds to the reduction of the effective waveguide width. Fig. 5(b) shows the dispersion relations of the PC waveguide, as shown in Fig. 5(a). In this waveguide structure, a single-mode operation for both TE and TM modes can be realized between $a/\lambda = 0.557$ and 0.569. Fig. 6 shows the propagating fields at $a/\lambda = 0.565$ for both TE and TM modes. These are calculated by FEM with perfectly matched layer (PML)[9]. The right and left shaded region denote PML region to absorb reflected and transmitted wave without any reflection. The PML condition is the same as that in [9]. A fundamental TE or TM mode with $a/\lambda = 0.565$ is input at incidence plane [9]. Each propagating mode is well confined in the core region and no radiated field is observed. In this calculation, the whole region in Fig. 6 is treated by FEM without using symmetry condition. The number of nodes is 159915 and the computational memory and time are 188 MB and 14.3 s with Pentium IV 3.2 GHz, respectively.

Fig. 7 shows the single-mode bandwidth for TE and TM modes as a function of major axis of an elliptical air hole. The ratio between major and minor axes is kept to be two. We observe that the single-mode bandwidth for both TE and TM modes has a maximum value near 0.42 a of the major axis of an elliptical air hole.

As an example of device application of the proposed PC waveguide, we consider a polarization splitting device. Fig. 8(a) shows the PC coupler and Fig. 8(b) shows the dispersion relations of even and odd modes of TE and TM supermodes. Fig. 9 shows the coupling length L_c of the PC coupler and coupling length ratio between TE and TM modes. Here, $L_{c,\mathrm{TE}}$

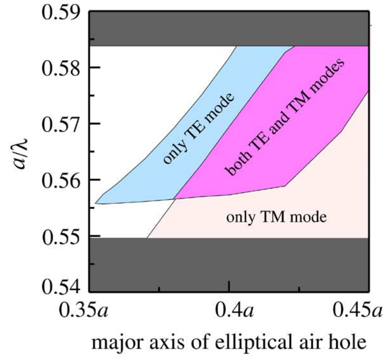
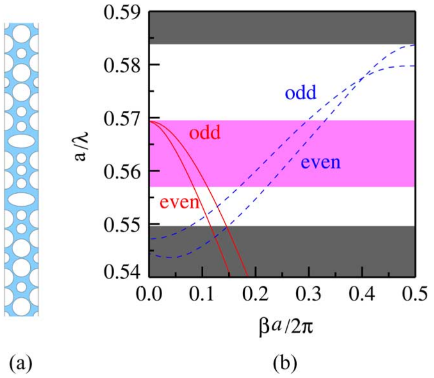


Fig. 7. Single-mode bandwidth for TE and TM modes.



(a) (b)

Fig. 8. PC coupler with elliptical air holes. (a) Waveguide structure. (b) Dispersion relation. The solid lines and dashed lines show TE and TM mode, respectively.

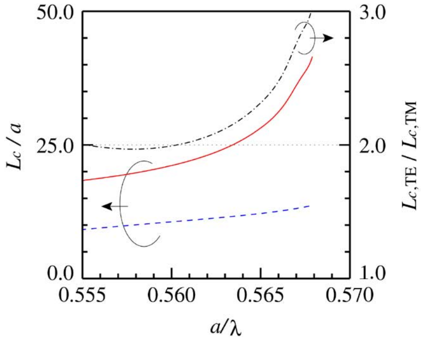
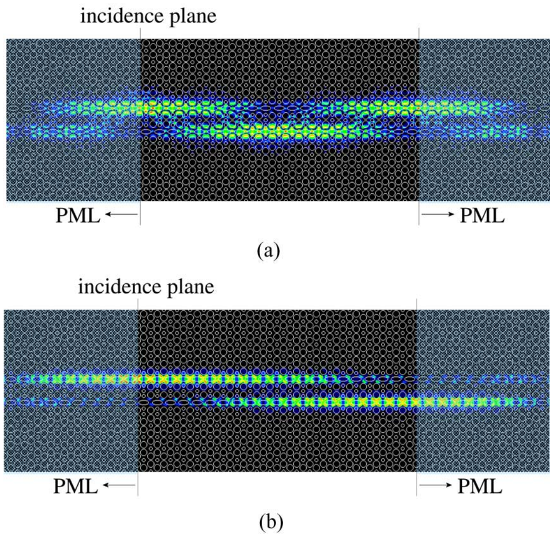


Fig. 9. Coupling length and coupling length ratio of the PC coupler with elliptical air holes. The solid lines and dashed lines show TE and TM mode, respectively.

and $L_{c,\mathrm{TM}}$ denote coupling length for TE and TM modes, respectively. In the case of $L_{c,\mathrm{TE}}/L_{c,\mathrm{TM}} = 2$, the PC coupler with device length $L_{c,\mathrm{TE}}$ can be used as a polarization splitter. Fig. 10 shows the propagating fields for TE and TM modes in the proposed PC coupler. A fundamental TE or TM mode with $a/\lambda = 0.560$ is input into the upper waveguide at incidence plane. We can see that TE and TM modes can be split using the PC coupler with length $L = 21a$. The PC waveguide has a large modal birefringence compared to refractive waveguide structures, so we can realize an ultrasmall polarization splitter [10]. In [10], the PC-based polarization splitter has been also proposed. However, in [10], the PBG effect is used for only TE mode and TM mode is confined by index-like effect. On the other hand, in our polarization splitter, both TE and TM modes are confined by PBG effect and sharp bends can be available for both TE and TM modes. The PC coupler proposed here exhibits perfect coupling with no radiation loss and the prospective bandwidth of 20-dB extinction ratio around 1550-nm wavelength is about 7 nm.



(a)

(b)

Fig. 10. Propagating fields in PC coupler with elliptical air holes. (a) TE mode. (b) TM mode.

IV. CONCLUSION

We presented the PC waveguide which can support TE and TM modes. By using a compound-type PC and introducing the elliptical air hole into the PC as a line defect, single-mode operation for both TE and TM modes was realized. The application of the proposed PC waveguide to the polarization splitter was also shown. Other device applications with this PC waveguide are now under consideration.

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