TWO-DIMENSIONAL PHOTONIC CRYSTAL OPTICAL WAVEGUIDES AND THEIR APPLICATION TO OPTICAL DEVICES

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ABSTRACT

We analyze propagation characteristics of two-dimensional photonic crystal optical waveguides numerically. Here we evaluate two types of photonic crystal waveguides constructed by circular dielectric pillars in air and circular air-hole in dielectric material. First, we check the dispersion relation of the waveguides and confirm the performance of a single mode propagation in both types of photonic crystal waveguides. Next we calculate the transmission characteristics of an L-shaped bent waveguide with additional dielectric-pillars/air-holes at the corner region and show that reflected waves from the right-angle corner can be completely eliminated due to resonant tunneling.

INTRODUCTION

Great interest has been given to the photonic crystals [1, 2] because their photonic band gap have attracted considerable possibility. By using the strong confinement of the light by the photonic band gap, it is expected that waveguide devices whose size is the order of the wavelength of light can be realized [2]. In fact, several microscale photonic crystal optical waveguide devices have been proposed [3–7]. Moreover, it is important to design high density integrated optical devices to clarify fundamental properties of basic photonic crystal waveguides such as straight waveguide, right angle bend, directional coupler, and so on [5–7]. To design such devices, we need a highly accurate numerical analysis method for investigating behavior of electromagnetic waves in the photonic crystal waveguide because photonic crystal have complicated structure and media. One of the effective numerical analysis methods is the finite-difference time-domain (FD-TD) method based on the principles of multidimensional wave digital filters [5, 8, 9].

We numerically analyze the characteristics of two-dimensional photonic crystal optical waveguides. Here we evaluate two types of photonic crystal waveguides constructed by circular dielectric pillars in air and circular air-hole in dielectric material. First, we examine the eigen mode in the photonic crystal optical waveguides and calculate their propagation constants using the Prony's method which is used for determining spatial wavenumber [10]. As a result we can find that electromagnetic fields intensities in the waveguides oscillate in the period of lattice constant of photonic crystal. Next, we check the dispersion relation of the waveguides and confirm the performance of a single mode propagation in both types of photonic crystal waveguides. We also find that the performance of single mode propagation in air-hole type photonic crystal waveguides is different from that of the pillar type one. In air-hole type photonic crystal waveguides, the single mode propagation is attained in the cutoff frequencies of higher-order modes.

Finally, we design reflection-less L-shaped bent waveguide for pillar type one and air-hole type one. The L-shaped bent waveguide has additional dielectric-pillars/air-holes at the corner region which act as potential barriers making a resonant tunneling so that we can eliminate reflected waves from the right-angle corner. In fact we evaluate mode field profiles in the L-shaped bent waveguide by comparing those of input and output waveguide. In the input side of the waveguide we can find that there are no reflected waves and confirm the formation of eigenmode which is the same as in the straight waveguide. Moreover it is noted that transmission band widths can be controlled by changing parameters of additional pillars/air-holes. Using the L-shaped bent waveguide we can design compact size optical waveguide devices such as wavelength multi/demultiplexer [7, 11].

FORMULATION OF PROBLEMS AND NUMERICAL RESULTS

We consider a two-dimensional photonic crystal optical waveguide as shown in Fig. 1. In this paper, we evaluate two types of photonic crystal waveguides composed of circular dielectric pillars in air and circular air-hole in dielectric material on a squared array with lattice constant a. In both cases, the relative permittivity of the dielectric material is $\varepsilon_a = 11.56$. In order to obtain wide range of photonic band gap, we have chosen the radii of pillars and air-holes r_a as $r_a/a = 0.175$

and 0.475, respectively. The pillar type photonic crystal has photonic band gap for E polarized field (E_y, H_x, H_z) which extend from frequency $\omega a/2\pi c = 0.320$ to 0.462 where c is the speed of light in vacuum. The air-hole type has photonic band gap for E polarized field which extends from $\omega a/2\pi c = 0.245$ to 0.306.

Fig. 1 shows electric field intensities of air-hole type photonic crystal waveguides. The waveguide has cladding layers which are shifted mutually in the propagation direction as shown in the figure. The waveguide width and shift are $W/a = 0.75$ and $D/a = 0.7$, respectively and frequency of incident wave is $\omega a/2\pi c = 0.26$. We can see that electric field intensities oscillate in the propagation direction. Spatial profile of electric field intensity $|E_y|$ of the waveguide as a function of wavenumber in z direction k_z is shown in Fig. 2. Spatial wavenumber profile is calculated by the Prony's method [10]. From this figure we can see that there are two wavenumber of β_m and $(\beta_m - 2\pi/a)$. Then we can express the electric field in the photonic crystal waveguide $E_{ym}(x,z)$ as follow:

$$E_{ym}(x,z) = \psi_{1m}(x)e^{-j\beta_m z} + \psi_{2m}(x)e^{-j(\beta_m - 2\pi/a)z} = \left[\psi_{1m}(x) + \psi_{2m}(x)e^{j(2\pi/a)z}\right]e^{-j\beta_m z} \quad (1)$$

where $\psi_{1m}(x)$ and $\psi_{2m}(x)$ denote complex amplitude of transverse electric field profile whose wavenumber are β_m and $(\beta_m - 2\pi/a)$, respectively. It is noted that $\psi_{1m}(x)$ and $\psi_{2m}(x)$ are becoming real number when shift $D = 0$. From this expression we can find that electromagnetic fields in the photonic crystal waveguides propagate with a propagation constant β_m and their intensity oscillates in the period of lattice constant a as described in the brackets of (1).

Fig. 3 shows propagation constant of (a) pillar type and (b) air-hole type photonic crystal waveguides $\beta_m a/2\pi$ as a function of normalized frequency $\omega a/2\pi c$. The waveguide width and shift of pillar type and air-hole type are $W/a = 1.65, D = 0$ and $W/a = 0.75, D/a = 0.7$, respectively. From Fig. 3 we can see that fundamental and higher-order modes exist in the air-hole type photonic crystal waveguide while the pillar type one has only fundamental mode. In the air-hole type waveguide the light confinement can be done by photonic band gap and refractive index difference between waveguide layer and air-hole. Because of light confinement as the dielectric waveguide with a periodic boundary, two propagation modes become cut-off near the region $\beta_m a/2\pi = 0.5, 1.0, \ldots$ which correspond to the Bragg condition. Therefore the waveguide behaves a single mode one in the region whose frequency range is approximately from $0.25 (= \omega a/2\pi c)$ to 0.27.

Since we can confirm the single-mode propagation in both type photonic crystal waveguides, we design L-shaped bent waveguide with additional dielectric-pillars/air-holes in the corner region as shown in Fig. 4. In the corner region two additional dielectric-pillars/air-holes are placed whose radii and relative permittivity are r_{a2} and ε_{a2}, respectively. These additional dielectric-pillars/air-holes act as potential barriers making a resonant tunneling in a quantum wire [5, 7, 12]. Fig. 5 shows electric field intensity of an L-shaped bent waveguide for (a) pillar type and (b) air-hole type at the resonant frequency $\omega a/2\pi c = 0.389$ and 257, respectively. The radii and relative permittivity of additional pillars/air-hole are $r_{a2}/a = 0.175, \varepsilon_{a2} = 11.56$ for pillar type, and $r_{a2}/a = 0.35, \varepsilon_{a2} = 1.0$ for air-hole type, respectively. The waveguide width and shift of pillar type and air-hole type are $W/a = 1.65, D = 0$ and $W/a = 0.75, D/a = 0.7$, respectively. We can see that there are no reflected waves in the input side and electric fields concentrate at corner region due to resonant tunneling. More precisely, in the transmitted region the mode field profile shows the same transverse one as that of input region. In other words, there is no mode conversion and the eigenmode profile is kept even if the light propagates through right-angle bent waveguide. Fig. 6 shows optical power transmission characteristics versus radii of additional pillars/air-holes. By adding additional pillars/air-holes we can completely eliminate reflected waves from the right-angle corner at the resonant frequency for both type waveguides. We can see from these figures that for an increase of radii r_{a2} the resonant frequency shifts to a lower side and its quality factor increase. We can also find that transmission frequency ranges can be controlled by changing radii of additional pillars/air-holes. As an application we design compact size wavelength multi/demultiplexer using the L-shaped bent waveguide together with the several numbers of directional couplers and have confirmed that pillar type photonic crystal multi/demultiplexer can work as low-insertion-loss and high-extinction-ratio device [7, 11].

CONCLUSION

We have analyzed the propagation characteristics of two-dimensional optical waveguides constructed by pillar and air-hole type photonic crystal. First we have examined the eigen modes in the waveguides. As a result we can find that electromagnetic fields in the waveguides oscillate in the period of lattice constant of photonic crystal. We have checked the dispersion relation of the waveguide and confirm different performance of a single mode propagation in air-hole type photonic crystal waveguide from that of the pillar type one. Next, we have proposed an reflection-less L-shaped bent waveguide with additional pillars/air-holes in the corner region. Numerical results show that reflected waves from the right-angle corner can be completely eliminated by adding additional pillars/air-holes due to resonant tunneling and its transmission bandwidth can be controlled by changing parameters of additional pillars/air-holes. Using the L-shaped bent waveguide we can design compact size optical waveguide devices such as wavelength multi/demultiplexer [7, 11].

From these results, we can conclude that the photonic crystal optical waveguide is one of key waveguides for constructing high density integrated optical circuits.

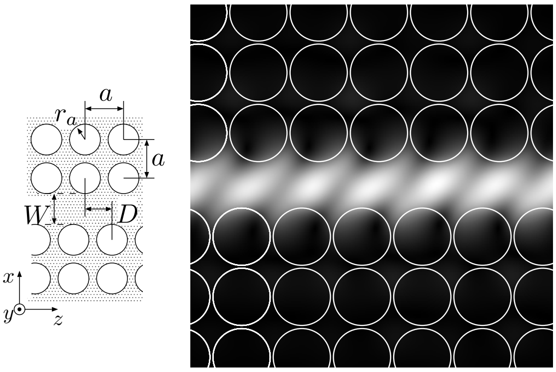

Fig. 1. Electric field intensity of air-hole type photonic crystal waveguide. ($\omega a/2\pi c = 0.26$, $W/a = 0.75$, and $D/a = 0.7$)

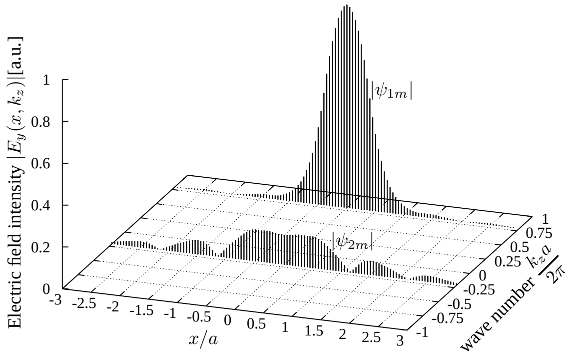

Fig. 2. Spatial profile of electric field intensity $|E_y|$ as a function of wavenumber $k_z a/2\pi$. ($\omega a/2\pi c = 0.26$, $W/a = 0.75$, and $D/a = 0.7$.)

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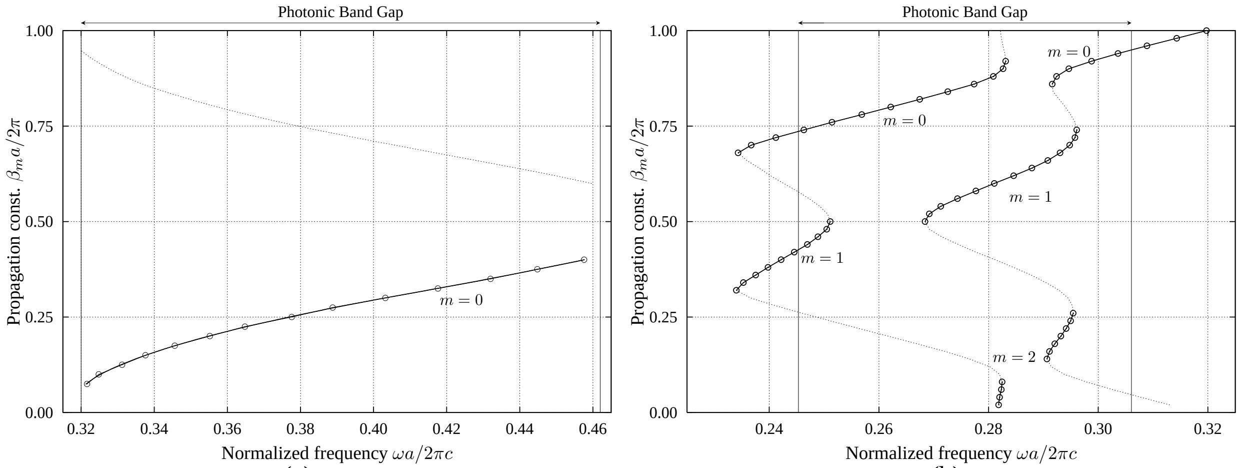


(a) (b)

Fig. 3. Dispersion relation of photonic crystal waveguides. (a) pillar type ($W/a = 1.65, D = 0$) (b) air-hole type ($W/a = 0.75, D/a = 0.7$)

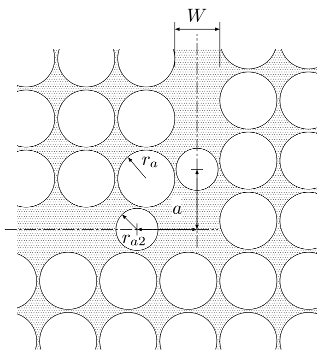
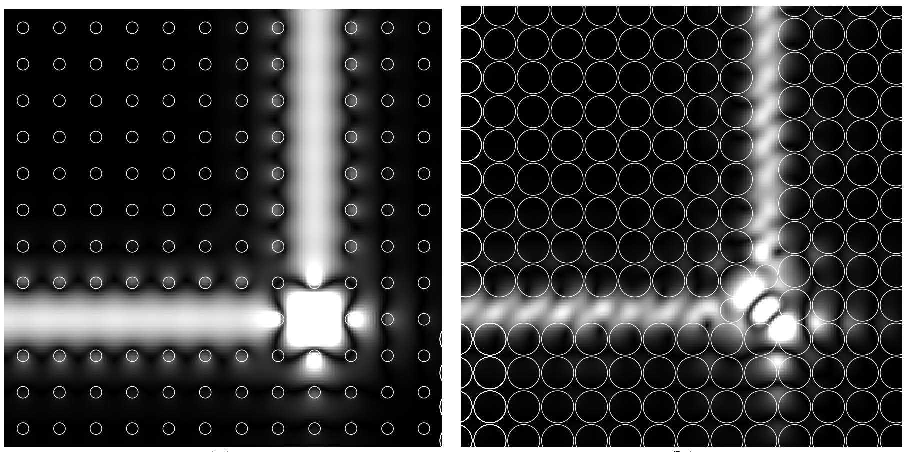
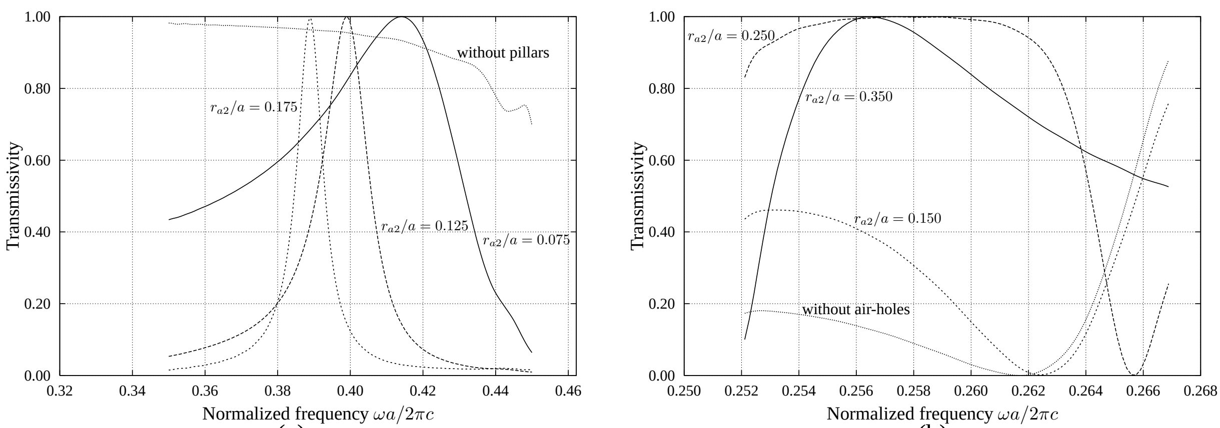


Fig. 4. Photonic crystal L-shaped bent waveguide with additional pillars/air-holes in the corner region.



(a) (b)

Fig. 5. Electric field intensity of L-shaped bent waveguide for (a) pillar type and (b) air-hole type at the resonant frequency $\omega a/2\pi c = 0.389$ and 0.257, respectively.



(a) (b)

Fig. 6. Optical power transmission characteristics of L-shaped bent waveguide when the radii of additional pillars/air-holes r_{a2} are changed. (a)pillar type (b)air-hole type