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RESEARCH ARTICLE

Band gap properties of 2D square lattice photonic crystal composed of rectangular cells

Somaye SERAJMOHAMMADI (✉)[1], Hamed ALIPOUR-BANAEI[2]

1 Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Ahar, Iran
2 Department of Electronics, Tabriz Branch, Islamic Azad University, Tabriz, Iran

Abstract In this paper, the photonic band gap (PBG) properties of two dimensional (2D) square lattice photonic crystal structures composed of rectangular cells were studied. The effect of refractive index, rectangles length and the ratio of width to length of the rectangles on the PBG properties of the structure with different configurations was investigated. It is found that the density of gaps in both modes (transverse electric (TE) and transverse magnetic (TM)) is high for structure composed of rectangular dielectric rods in air, while the density of the gaps is very low for structure composed of rectangular air pores in dielectric material.

Keywords photonic crystal (PhC), band gap, refractive index

1 Introduction

Photonic crystals (PhCs) are good candidates for designing ultra-compact devices suitable for integrated photonic circuits. As far as we know, PhCs are regular arrays of dielectric layers with periodic refractive indices. According to the distribution periodicity of refractive index, these crystals are divided into three categories: 1) one-dimensional (1D), 2) two dimensional (2D) and 3) three-dimensional (3D) [1]. Optical filters [2–5], optical reflectors [6], optical switches [7], and optical demultiplexers [8–10] are some examples of all optical devices based on PhCs.

The most important characteristic of PhCs, by which designing the aforementioned devices become possible is their photonic band gap (PBG), PBG is a region, where the propagation of any electromagnetic wave is forbidden; in other word if a ray of light wave, whose wavelength is in the PBG of a PhC, reaches a surface of those devices, it would not be able to propagate inside PBG and will be reflected completely from the surface [11]. The key point of designing PhC based devices is that the operating wavelength should be in the PBG of the PhCs, so that the light would not dissipate inside the crystal.

There have been so many literatures about photonic band gap engineering. The earliest report about the band gap engineering was presented by Matthews et al. on band gap engineering and defect modes in PhCs with rotated hexagonal holes [12], in which the PBG structure of 2D PhC was created by a triangular lattice of rotated hexagonal holes, and the effects of reduced symmetry in the unit cell geometry on the PBG and the frequency of localized defect modes have been also studied. It was shown that the maximum PBG for the proposed structure was achieved for an intermediate rotation angle of holes. Then Kalra and Sinha studied the polarization dependent PBGs (transverse electric (TE) and transverse magnetic (TM)) in 2D PhC with square lattice, it was reported that PBG size was affected by both the ellipticity and the orientation of the elliptical rods [13]. Further, it was demonstrated that in a double hybrid rods structure of 2D PhC of a square lattice, in which a square dielectric rod was connected with slender rectangular dielectric veins in middle of each side of dielectric square rod, specific mode was sensitive to the length, dielectric constant and the shift position of the veins [14]. In another work, the band gap spectra of 2D anisotropic PhC with hexagonal lattice of rods covered by an interfacial layer (e.g. tellurium tubes) had been analyzed [15]. The PBG of hybrid 2D PhC had been also studied by Liu et al. This PBG was composed of 2D square lattice of hybrid rods in air with a square rod at the center of unit cell and additional circular rods with their outmost edges against the middle of each side of the lattice unit cell, it had a sizable complete PBG, adjustable by rotating the square rods and adding circular rods into lattice

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E-mail: s-seraj@iau-ahar.ac.ir

unit cell, so it was suitable for new microwave devices [16]. Most recently, the PBG properties of two new PhC structures have been studied. One is 2D PhC with rhombic lattice. It was shown that it provided more flexibility for designing PhC based devices [17]. The other one is 2D PhC of core-shell type dielectric nano-rod heterostructures. It was presented that PBG was strongly affected by the thickness and the dielectric constant of the interfacial layer. In this structure, the size of the PBG was considerably enhanced when the nano-rods were covered by a thin high refractive index material (GaAs) [18]. Lately, our group studied PBG properties of 2D PhC Thue-Morse structure, and found that in 2D Thue-Morse structures there have high density of PBG regions [19]. In previous works, PBG properties had been studied for different kinds of PhCs with different shapes and configurations. In this paper, we studied the PBG properties of a new structure composed of rectangle-shaped cells. The major characteristics of these structures are having very high density of PBGs and also having joint PBGs in dielectric rod structures composed of rectangle-shaped rods. Joint PBGs can be used for designing polarization independent optical devices based on 2D PhCs.

2 Theoretical method

Currently, the best solution for studying the optical properties of periodic structures such as photonic crystals is numerical methods. Plane wave expansion (PWE) and finite difference time domain (FDTD) are the most popular numerical methods used for calculating the band structure and extracting the PBG of photonic crystals. PWE method calculates the eigenfrequencies and dispersion properties of PhCs, by numerically solving the Maxwell equations in frequency domain [20]. Proposing accurate results and high speed calculations are the most significant advantageous of PWE method. Therefore in this paper, we used BansSolve Simulation tool box of Rsoft Photonic CAD software for performing our simulations. This toolbox extracts the band diagrams and gap map diagrams of PhC structures based on PWE method.

3 Simulation results

3.1 Horizontal rectangular PhCs

The schematic diagram of a typical structure with horizontal rectangles is shown in Fig. 1. As shown in Fig. 1, the L and W are the length and width of the rectangles respectively, where $W = B*L$ (i.e., B is the width to length ratio), and a is the lattice constant of the structure. We studied the effect of different parameters on the PBG of structure with two different configurations: 1) PhC composed of horizontal rectangle dielectric rods, and 2) PhC composed of horizontal rectangle air pores in dielectric substrate.

3.1.1 Effect of refractive index

For studying the effect of refractive index on the PBG of the structure, we assumed other parameters (L, W, B and a) to be constant, then by changing the value of the refractive index we calculated the gap map diagrams of the structure for both configurations, which represents the variation of PBG region versus refractive index. Figure 2(a) shows the gap map diagram of a PhC structure composed of rectangular dielectric rods for different values of the refractive index (N), in which, red colored area is TE mode and blue colored area is TM mode. With increasing of the refractive index, the PBGs shift toward lower normalized frequencies. And for higher refractive index (values close to 4.0), we had obtained joint PBG region (green colored area) that is overlapping region of PBGs in both modes. Figure 2(b) shows the gap map diagram of a PhC structure composed of rectangular air pores in dielectric material for different values of the refractive index (N). We only had TE mode as refractive index values ranging from 3.4 to 4.0. With the increasing of the refractive index, the frequencies became lower. In both structures, the width of the PBG regions raised with the increasing of the refractive index. The PBG width of air pore structure was less than that of dielectric rod structure. Moreover, there was only one gap for every value of refractive index in air pore structure, while multiple gaps can be obtained for dielectric rod structure.

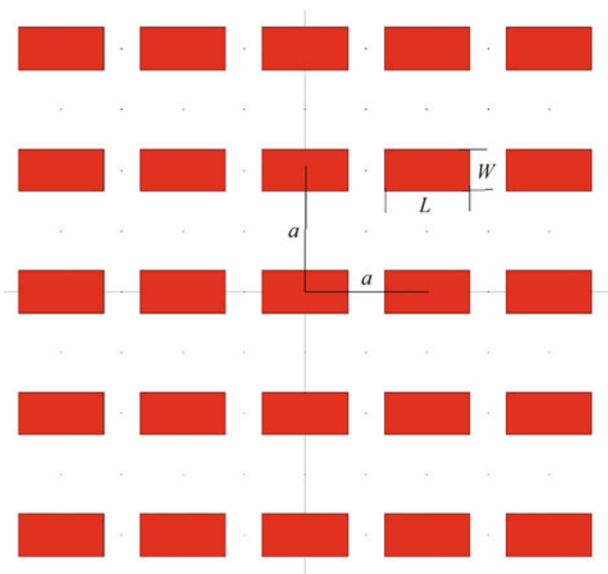

Fig. 1 Typical photonic crystal with horizontal rectangular cells

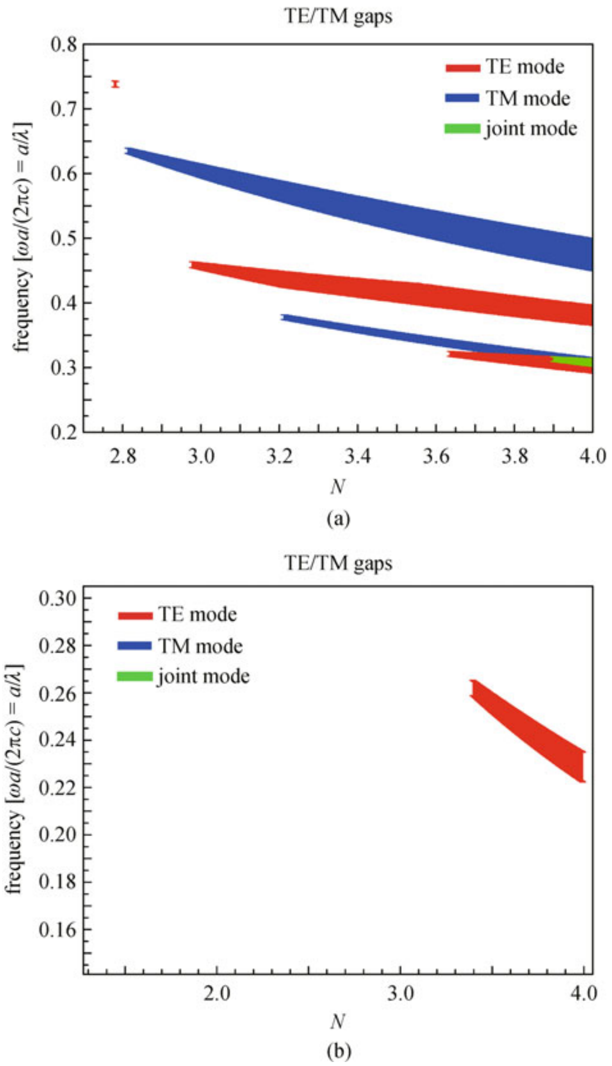

Fig. 2 Gap map of structure composed of horizontal (a) dielectric rods; (b) air pores versus refractive index (*N*)

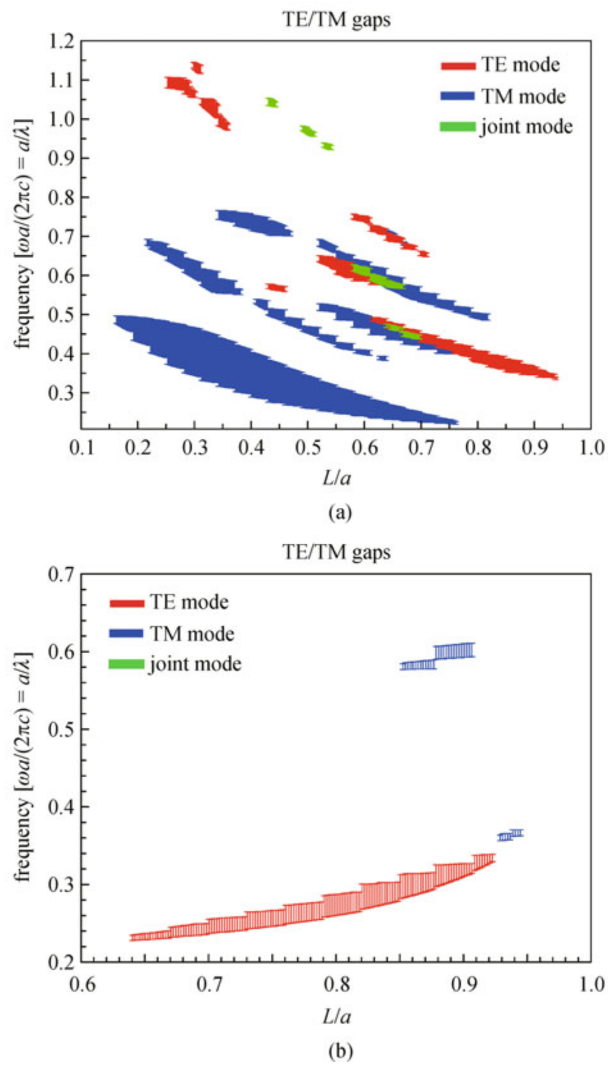

Fig. 3 Gap map of structure composed of horizontal (a) dielectric rods; (b) air pores versus *L*/*a* ratio

3.1.2 Effect of rectangles length

For studying the effect of rectangle length on PBG of the structure, we calculated the gap map diagram of both structures for refractive index *N* and *B* values are equal to 3.46 and 0.7 respectively. Figure 3(a) shows the gap map diagram of a PhC structure composed of rectangular dielectric rods for different values of the *L*/*a* ratio. In Fig. 3(a), PBGs in both modes (TE (red colored area) mode and TM (blue colored area) mode) are presented. By increasing the *L*/*a* ratio, the normalized frequencies of PBGs move toward lower values, and for some values of the *L*/*a* joint PBG region (green colored area) can be observed. Figure 3(b) shows the gap map diagram of a PhC structure composed of rectangular air pores in dielectric material for different values of *L*/*a*. As shown in Fig. 3(b) *L*/*a* values of PBG ranged from 0.63 to 0.94, frequencies of PBG shift toward higher values, and the gaps in TE mode are dominant. The PBG width of air pore structure is less than that of dielectric rod structure. In dielectric rod structure, we have multiple gaps; but in air pore structure, mostly we have one gap for every value of *L*/*a*.

3.1.3 Effect of width to length ratio ($B = W/L$)

Figure 4 represents the gap map diagrams of both structures for $N = 3.46$, $L/a = 0.2$ and different values of *B* ($B = W/L$, where *W* and *L* are the width and length of rectangles respectively). According to Fig. 4(a), in dielectric rod structure we have a very high density of PBGs. PBGs in TM mode are dominant, however we have gaps in TM mode and joint gaps too. With increasing *B*, frequencies of PBG shift toward lower values. For $0.2 < B < 0.5$, gap width in TM mode is more than those

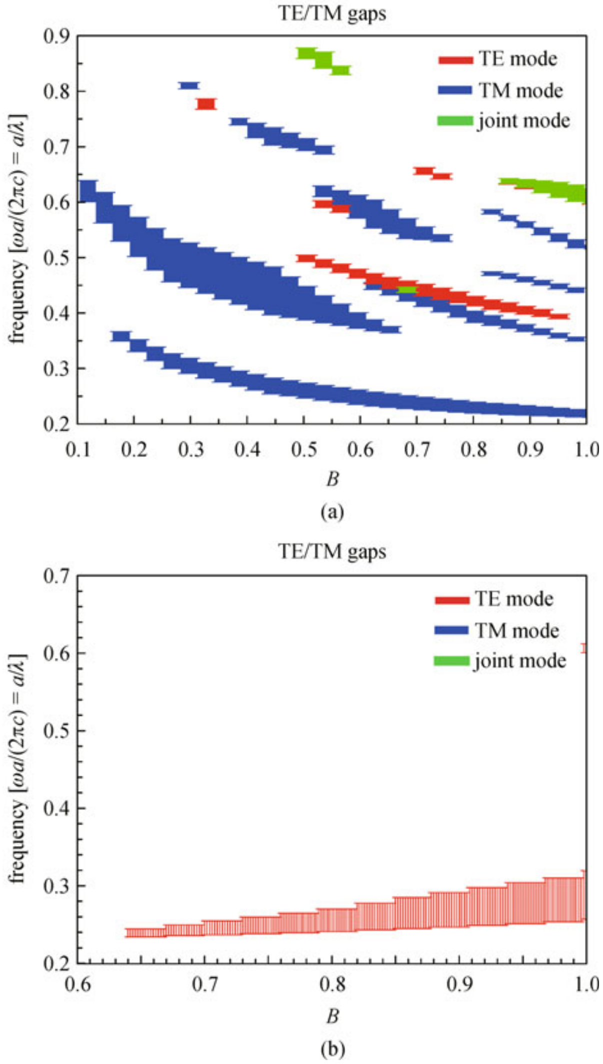

Fig. 4 Gap map of structure composed of horizontal (a) dielectric rods; (b) air pores versus width to length ratio (B)

of other values of B. According to Fig. 4(b), in air pore structure, PBGs are only in TE mode for $0.63 < B < 1.00$. By increasing B, frequencies of PBG shift toward higher values.

3.2 Vertical rectangular PhCs

The schematic diagram of a typical structure with vertical rectangles is presented in Fig. 5. As specified in Fig. 5, the L and W are the length and width of the rectangles respectively, where $W = B*L$ (i.e., B is the width to length ratio), and a is the lattice constant of the structure. We studied the effect of different parameters on the PBG of structure with two different configurations: 1) PhC composed of horizontal rectangle dielectric rods, and 2) PhC composed of horizontal rectangle air pores in dielectric substrate. The results are presented and discussed in the following subsections.

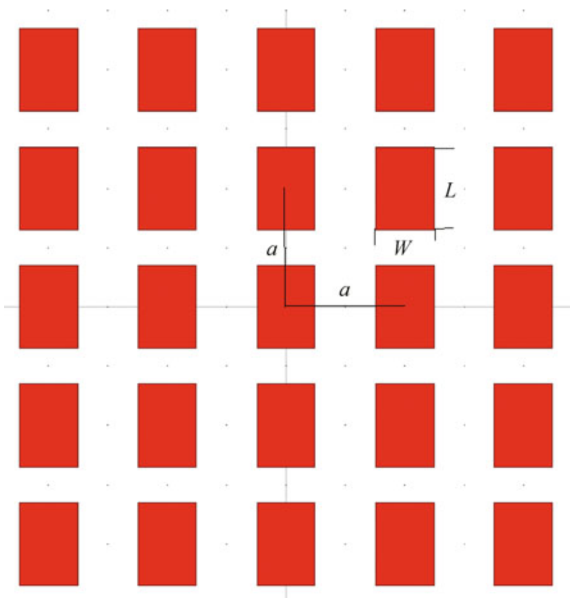

Fig. 5 Typical photonic crystal with vertical rectangular cells

3.2.1 Effect of refractive index

For studying the effect of refractive index on the PBG of the structure, we assumed the other parameters (L, W, B and a) to be constant, then by changing the value of the refractive index we calculated the gap map diagrams of the structure for both configurations, which represents the variation of PBG region versus refractive index. Figure 6(a) shows the gap map diagram of a PhC structure composed of rectangular dielectric rods for different values of the refractive index (N), in which, red colored area is TE mode and blue colored area is TM mode. Like the horizontal structure, with increasing the refractive index, the PBGs shift toward lower normalized frequencies, and for higher refractive index ($2.4 < N < 4.0$) we had joint PBG region (green colored area) that is overlapping region of PBGs in both mode. Figure 6(b) shows the gap map diagram of a PhC structure composed of rectangular air pores in dielectric material for different values of the refractive index. We only had in TE mode, which by increasing the refractive index the frequencies became lower. In both structures, the width of the PBG regions raised with increasing of the refractive index. The PBG width of air pore structure was less than that of dielectric rod structure. Moreover, there was only one gap for every value of refractive index in air pore structure, while multiple gaps can be obtained for dielectric rod structure.

3.2.2 Effect of rectangles length

For studying the effect of rectangle length on PBG of the structure, we calculated the gap map diagram of both

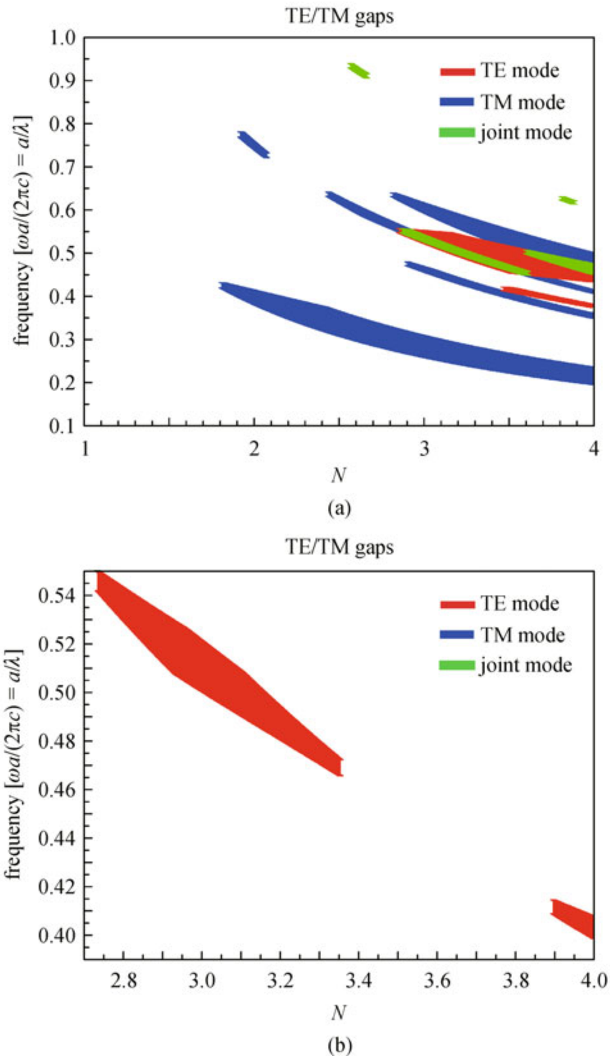

Fig. 6 Gap map of structure composed of vertical (a) dielectric rods; (b) air pores versus refractive index (*N*)

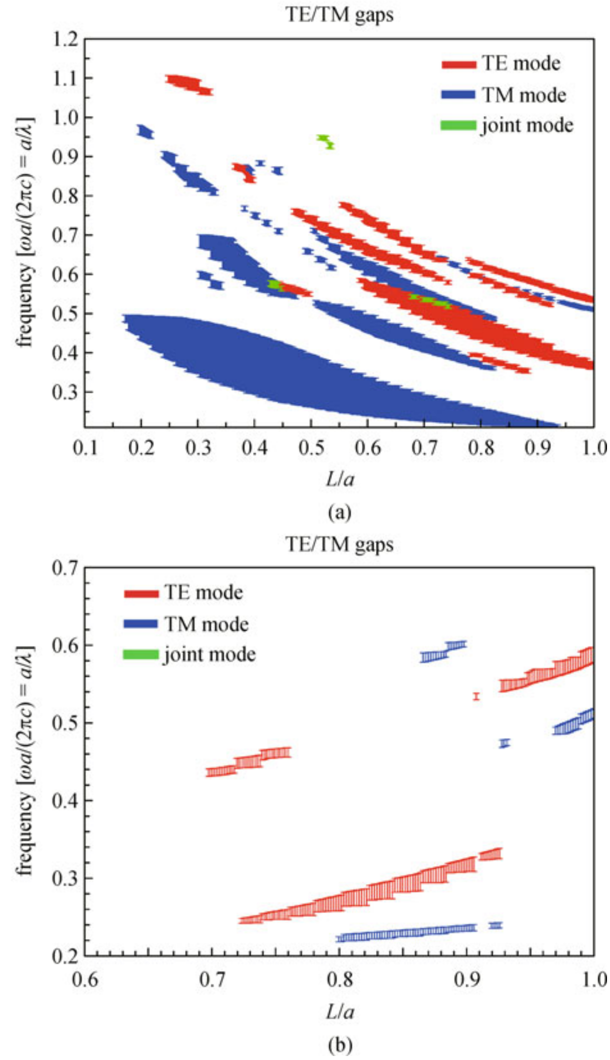

Fig. 7 Gap map of structure composed of vertical (a) dielectric rods; (b) air pores versus *L*/*a* ratio

structures for refractive index (*N*) and *B* values equal to 3.46 and 0.7, respectively. Figure 7(a) represents the gap map diagram of a PhC structure composed of vertical rectangular dielectric rods for different values of the *L*/*a* ratio. In which, red colored area is TE mode and blue colored area is TM mode. With increasing the *L*/*a* ratio, the PBGs shift toward lower normalized frequencies, and for some values of *L*/*a* we have joint PBG region (green colored area). Figure 7(b) shows the gap map diagram of a PhC structure composed of rectangular air pores in dielectric material for different values of the refractive index. As we see, we have PBG for *L*/*a* values ranged from 0.7 to 1.0, which by increasing the *L*/*a* shift toward higher frequencies and the gaps in TE mode are dominant. The PBG width of air pore structure is less than that of dielectric rod structure. The density of PBG region for dielectric rod structure is more than air pore structure.

3.2.3 Effect of width to length ratio ($B = W/L$)

Figure 8 shows the gap map diagrams of both structures for $N = 3.46$, $L/a = 0.2$ and different values of B ($B = W/L$, where W and L are the width and length of rectangles respectively). According to Fig. 8(a), in dielectric rod structure we have a very high density of PBGs. PBGs in TM mode are dominant, however we have gaps in TM mode and joint gaps too. By increasing *B*, the gaps shift toward lower frequencies. According to Fig. 8(b), in air pore structure, PBGs are only in TE mode for $0.6 < B < 1.0$. With increasing *B*, frequencies of PBG shift toward higher values and the width of the gaps increase.

4 Discussion

In this paper, we studied the PBG properties of 2D

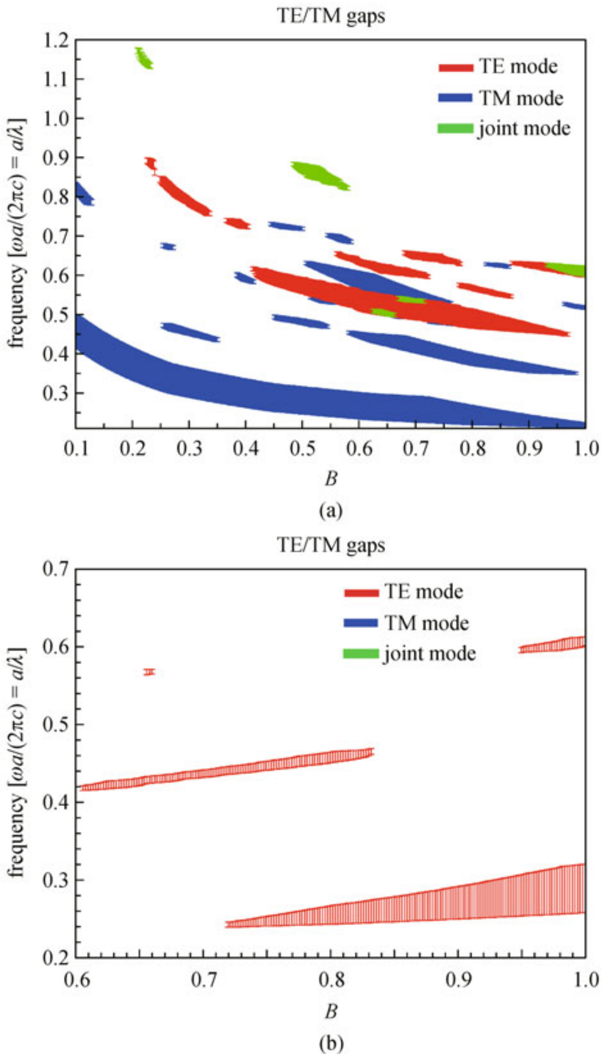

Fig. 8 Gap map of structure composed of vertical (a) dielectric rods; (b) air pores versus width to length ratio (B)

photonic crystal structure composed of rectangular cells, which has not been studied previously. We investigated the effect of different parameters on the PBG properties of rectangle cell PhCs with different configurations. For the structures composed of rectangle shaped air pores created in dielectric material, the density of PBGs are very low and PBGs are mostly in TE mode. But the most interesting structures are 2D PhCs composed of rectangle shaped dielectric rods immersed in air. Having very high density of PBGs in TE and TM modes also having joint PBGs are the most important characteristics of these structures compared with previously reported works [12 – 19]. The joint PBGs can be used for designing polarization independent optical devices.

5 Conclusions

In this paper, we studied the photonic band gap properties of 2D square lattice photonic crystal structures composed of rectangular cells in different configurations. For investigating the effect of different parameters such as refractive index, rectangle length to lattice constant ratio, and rectangle length to width ratio, in each part of our study we assumed two of the parameters to be constant, and for different values of the third parameter we obtained the gap map diagrams of the structures. According to the results by changing every one of these parameters, we can control the photonic band gap of the structure and obtain the suitable photonic band gap region according to our requirements.

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