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Study on maximum band gap of two-dimensional photonic crystal with elliptical holes

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ABSTRACT

In this paper, the maximum photonic band gap (PBG) of two-dimensional (2D) photonic crystal (PC) with elliptical air holes was studied by the finite-difference time-domain (FDTD) method based on changing the ratio (semi-major axis length of elliptical hole to the filling ratio) and azimuth angle of elliptical holes, respectively. It is shown that the PBG exhibits a peak value when the ratio of semi-major axis length to the filling ratio is equal to 0.86 approximately by increasing the filling ratio, and central frequency and the low boundary frequency of PBG decrease linearly with the increasing of semi-major axis length. In the aspect of the influence of azimuth angle from 0 to 90°, the PBG presents a minimum value, and central frequency and the low boundary frequency of PBG become high non-linearly by the increasing of azimuth angle to any filling ratio.

1. Introduction

Two-dimensional (2D) photonic crystals (PCs) [1,2] have attracted global attention for their unique characteristics for manipulate light propagation and ease of fabrication, using mature semiconductor fabrication techniques. Many characteristics and applications of PCs are based on its PBG [3–5]. The PBG is thus the essential property of PCs. In the past two decades, a mass of theoretical and applied investigation of PCs was proposed. PCs are ideal material for developing useful optical devices such as mirrors, sensors, filters, delay lines, waveguides, and resonators [6–10]. As well known, the triangular lattice [11] is of a special interest since the structure can possess a large PBG for TE field polarization and can even possess a complete PBG for both TE and TM field polarization [12] for some lattice parameters. In practice, the width of the PBG becomes wider with the increasing filling ratio and dielectric constant difference, but this conclusion is not exactly, it is further revealed that the PBG width does not increase monotonically with changing of above factors.

In this paper, we further study the influence of the ratio of semi-major axis length to semi-minor axis length and azimuth angle of elliptical air holes on the PBG of 2D triangular lattice photonic crystal composed of elliptical air holes in background material with permittivity of $\varepsilon = 10.5$ using the finite-difference time-domain (FDTD) method [13–15]. We first investigate the influence of the semi-axis ratio on the PBG with different filling ratio, the transmission spectrum are presented by theoretical calculations. We then study the effects of the variation of azimuth angle of elliptical holes on the PBG. We also discuss the relation between central frequency and the low boundary frequency of the PBG and the semi-axis ratio and azimuth angle, respectively.

2. Theory and model description

In this paper, the non-loss and non-magnetic material was chosen. The time dependent Maxwell's equations in PCs can be written in the following form,

$$\frac{\partial \vec{E}}{\partial t} = \frac{1}{\varepsilon(\vec{r})} \cdot \nabla \times \vec{H} \tag{1}$$

$$\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu(\vec{r})} \cdot \nabla \times \vec{E} \tag{2}$$

where $\varepsilon(\vec{r})$ is the position dependent permittivity and $\mu(\vec{r}) = \mu_0$ is permeability in vacuum. In a 2D case, the fields can be decoupled into two transversely polarized modes, namely, the TE mode and the TM mode. These equations can be discretized in space and time by a so called Yee-cell technique [16]. The following FDTD time stepping formulas are the spatial and time discretizations of Eqs.

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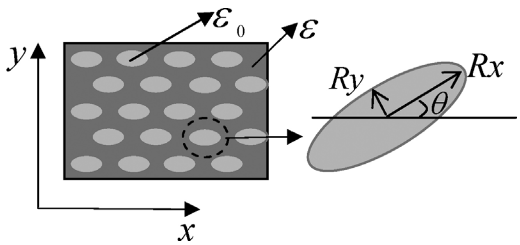

Fig. 1. Schematic diagram of 2D triangular lattice PC.

(1) and (2) on a discrete 2D mesh within the x–y coordinate system for the TE mode

$$E_x|_{i,j}^{n+1} = E_x|_{i,j}^{n} + \frac{\Delta t}{\varepsilon_{i,j}} \cdot \frac{H_z|_{i,j+1/2}^{n+1/2} - H_z|_{i,j-1/2}^{n+1/2}}{\Delta y} \tag{3}$$

$$E_y|_{i,j}^{n+1} = E_y|_{i,j}^{n} + \frac{\Delta t}{\varepsilon_{i,j}} \cdot \frac{H_z|_{i+1/2,j}^{n+1/2} - H_z|_{i-1/2,j}^{n+1/2}}{\Delta x} \tag{4}$$

$$H_z|_{i,j}^{n+1/2} = H_z|_{i,j}^{n-1/2} + \frac{\Delta t}{\mu_0} \cdot \left(\frac{H_z|_{i,j+1/2}^{n} - E_x|_{i,j-1/2}^{n}}{\Delta y} - \frac{E_y|_{i+1/2,j}^{n} - E_y|_{i-1/2,j}^{n}}{\Delta x} \right) \tag{5}$$

where n denotes the discrete time step, indices i and j denote the discretized grid point in the x–y plane, respectively. Δt is the time increment, and Δx and Δy are the intervals between two neighboring grid points along the x and y directions, respectively. One can easily see that the computational time is proportional to the number of discrete points in the computation domain for a fixed total number of time steps. In calculation, the time increment Δt and the space intervals Δx and Δy are satisfy numerical stability condition

$$\Delta t = \frac{0.95}{c} \left(\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} \right)^{-1/2} \tag{6}$$

where c is the speed of light in vacuum. In addition, to obtain the transmission of the PCW devices, one needs to calculate the average power flow, which is computed by spatially integrating the energy flux $S(\omega)$, i.e., the Poynting vector. The average power flux is defined by the following formula,

$$S_x(\omega) = \frac{1}{2} Re \left[E_y(\omega) \times H_z(\omega)^* \right] \tag{7}$$

In our 2D case and for a detector line, the power flow $P(\omega)$ can be computed by integrating $S(\omega)$ along the detector line, the formula is written as following,

$$P = \int S_x(\omega)\, d\omega \tag{8}$$

The transmission spectra are then obtained by the ratio between the transmitted power and the incident power.

$$T(\omega) = \frac{\sum P_{ex}}{\sum P_{in}} \tag{9}$$

In the simulation, the proposed 2D triangular lattice PC structure which is uniform in the z-direction and periodic in the x–y-plane is shown in Fig. 1. Here ε_0, ε denote the permittivity of air holes and background materials, and Rx, Ry indicate the semi-major axis length and semi-minor axis length, respectively. The direction of incident wave parallels with the y axis. To possess the universality, in what follows of date processing, normalized frequency (a/λ) and transmission coefficient were carried out in x-axis and y-axis, respectively. In order to provide the optimal results, the H polarized wave which can present the wider PBG structure compared with E polarized wave was preferred. Special consideration should be given at the boundary of the finite computational domain, where the fields are updated using special boundary conditions as information out of the domain is not available. Here, the perfectly matched layer (PML) method is used for the boundary treatment.

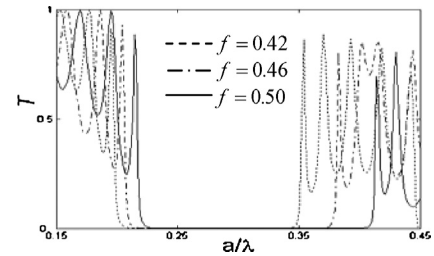

Fig. 2. Transmission spectrum with different filling ratio.

3. Results and discussion

Large numbers of references reported that the PBG width is lie on many different alterable factors such as filling ratio, dielectric rod cross-section. At the beginning, the transmission properties of PC with different filling ratio while the semi-major axis Rx is equal to $0.45a$ are considered. The result is shown in Fig. 2. It is obvious that the PBG width becomes wider by the increasing of filling ratio named as f from 0.42 to 0.50 and the central frequency becomes higher. The conclusion coincides with that other paper reported, especially, the low frequency boundary of PBG becomes higher a little while the high boundary shifts higher position fast. Thus, the changing of central frequency is not dependent on the shift of the whole PBG but the expansion of it.

The filling ratio is fixed, changing the valve of semi-major axis (Rx) and semi-minor axis (Ry). The case of the filling ratio $f = 0.42$, 0.46, 0.50 is considered and the corresponding transmission characteristics are obtained as shown in Fig. 3. The results reveal that the width of the PBG does not change wider with the increasing of the value of Rx all the while, but has a peak to each f. To transmission spectrum of case with $f = 0.42$, the width of PBG with $Rx = 0.39a$ is wider than that of $Rx = 0.35a$ or $0.43a$. Similarly, the PBG width when Rx is equal to $0.41a$ is wider than that of $Rx = 0.36a$ or $0.45a$ to the filling ratio $f = 0.46$, and for the filling ratio f is equal to 0.50, the PBG width of $Rx = 0.43a$ is widest comparing with the width of $Rx = 0.39a$ and $0.47a$. In a word, the PBG width does not widen monotonously by the increasing of Rx. We then pay our attention to the relation between the peak value of the PBG width and the semi-major axis Rx, and further discuss the condition when the peak value appeared to obtain the universal conclusion.

After a large number of cases under the different value of Rx calculated, we find that the above relation has no universality, that is, for different value of f, the values of Rx are different from each other when the peak of PBG width appears. Here, we introduce a variable r which indicates a ratio with Rx/f, the surprising phenomenon comes into being, the peak value may appears when r is equal to 0.86 approximately with the changing of f from 0.44 to 0.52. Where, the value of r is focused over the range from 0.6 to 1.2. The detailed transmission spectra are depicted in Fig. 4(a). The central frequency becomes higher by the increasing of the f to certain value of Rx, as accord with the results of Fig. 2 presented. But to fixed f, the central frequency becomes lower linearly by the increasing of Rx, as shown in Fig. 4(b). It is further revealed that the changing of the central frequency is independence of the width of PBG. Fig. 4(c) depicts the relation between low boundary frequency of PBG and semi-major axis Rx. It indicates that the low boundary frequency decreases rapidly by the increasing of Rx and the difference of the value of low boundary frequency when Rx is equal to $0.35a$ and $0.50a$ becomes less and less by the decreasing of f. So, we can say that the reduction of central frequency is induced mostly