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Study on complete band gap of two-dimensional photonic crystal with quadrangular rods

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ABSTRACT

The plane wave expansion method (PWM) was employed to study the relation between the photonic band gap (PBG) of 2D triangular lattice photonic crystal (PC) and the shapes of rods and dielectric constant. It is shown that the PBG of PC with quadrangular rods is the widest one, compared with the other case with cross section shapes of triangular, circular and hexagon under the same filling ratio, and a peak value appears when the side length ratio of l_x/l_y is equal to 1.21 approximately to any filling ratio. In the aspect of the effects of dielectric constant, the PBG width does not increase monotonically with the increase permittivity ε_2 of the background material to certain permittivity ε_1 of the quadrangular rods, but has a peak value instead. However, the larger the permittivity ε_1 is, the narrower the band width is and the lower the central frequency is, and the dispersion $\Delta\varepsilon = \varepsilon_2 - \varepsilon_1$ is larger also.

1. Introduction

Many characteristics and applications of photonic crystals (PCs) [1,2] are based on its photonic band-gap (PBG) [3]. The PBG is thus the essential property of PC. In the last few years, a mass of theoretical and applied investigation of PCs was developed. Due to the existence of band-gaps, PCs are ideal material for developing optical devices with small mode volumes and high quality factors. Many different types of devices are needed in applications such as filters, lasers, waveguides, fibers [4–9] and other nonlinear optical devices. Among various types of PCs, the two-dimensional (2D) ones are of particular interest due to their comparative ease of fabrication, thanks to the planar fabrication techniques developed for the semiconductor industry. They are also much easier to integrate with current photonic devices. In addition, the triangular lattice [10] 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 [11] for some lattice parameters. In practice, the research of the periodic structure or medium of the PCs was reported extensively. The periodic structure consists of triangular lattice, square lattice [12], super-lattice structure above which is formed by columns, square or elliptical rods, etc. The dependence of PBG on different alterable factors is achieved. For example, the width of the PBG becomes wider with the increasing filling ratio and dielectric constant difference. However, the PBG width does not increase monotonically with the former. In this paper, we employ the plane-wave expansion method [13–15] to study the PBG of 2D photonic crystal with triangular lattice. Transmission spectra were obtained by theoretical calculations. The PBG width of PC with quadrangular rods structure is wider than the width of other PC with cross section shapes of triangular, circular or hexagon under the same filling ratio, and a peak value appears when the side length ratio of l_x/l_y is equal to 1.21 approximately to any filling ratio. Moreover, the case with filling ratio is 0.49 and l_x/l_y is 1.21 was calculated that the peak value $\Delta\omega$ is equal to $0.196\omega_e$ ($\omega_e = 2\pi c/\alpha$, α indicates lattice constant and c is speed of light in vacuum) and the maximal width is decrescent with the increasing of dielectric constant of quadrangular rods. These results suggest a new basis for designing PC devices.

2. The basic theories

The PWM has an obvious advantage that it is easier to reliably automate the identification of frequency bands and gaps and can display mode profiles with no additional efforts. The light spread can be described by Maxwell's equations in PCs. Considering the isotropic, non-loss and non-magnetic materials,

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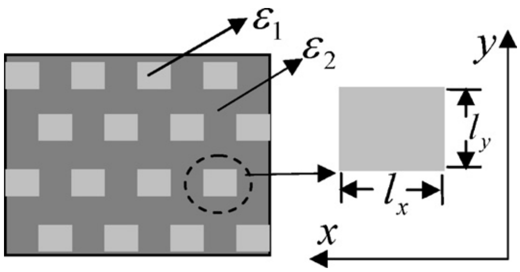

Fig. 1. Schematic diagram of 2D triangular lattice PC.

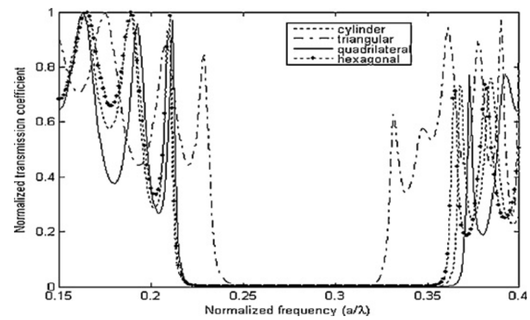

Fig. 2. Transmission spectrum with variation of section shape.

the time-dependent Maxwell's curl equations in PCs can be written as:

$$\nabla \times E(\vec{r}) = i\omega\mu_0 H(\vec{r}) \quad \nabla \times H(\vec{r}) = -i\omega\varepsilon_0\varepsilon(\vec{r})E(\vec{r}) \tag{1}$$

where $\vec{r} = (x, y)$ is the 2D position vector, $\varepsilon(\vec{r})$ is the position-dependent dielectric constant, ω is the eigen-angular frequency, and μ_0, ε_0 denote the permeability and permittivity of free space, respectively. With the assumption of the wave vector $\vec{k}$ in the x–y-plane, i.e., $\vec{k} = (kx, ky, 0)$, we will refer to as E parallel to the plane (H polarization). The wave equations for H polarizations reduce to:

$$\frac{\partial E_y(\vec{r})}{\partial x} - \frac{\partial E_x(\vec{r})}{\partial y} = i\omega\mu_0 H_z(\vec{r}), \quad \frac{\partial H_z(\vec{r})}{\partial x} = i\omega\frac{\varepsilon(\vec{r})E_y(\vec{r})}{c^2\mu_0}, \quad \frac{\partial H_z(\vec{r})}{\partial y} = -i\omega\frac{\varepsilon(\vec{r})E_x(\vec{r})}{c^2\mu_0} \tag{2}$$

The above simple equations can be easily reduced to a quadratic linear equation for $H_z(\vec{r})$ as follows:

$$\frac{\partial}{\partial x}\left[\frac{1}{\varepsilon(\vec{r})}\frac{\partial H_z(\vec{r})}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{1}{\varepsilon(\vec{r})}\frac{\partial H_z(\vec{r})}{\partial y}\right] + \frac{\omega^2}{c^2}H_z(\vec{r}) = 0 \tag{3}$$

To solve Eq. (3), we expand the fields $H_z(\vec{r})$ and dielectric function $\varepsilon^{-1}(r)$ in a series of plane waves for a given wave vector $\vec{k}$:

$$\frac{1}{\varepsilon(\vec{r})} = \sum_G K(\vec{G})\exp(i\vec{G}\cdot\vec{r}) \tag{4}$$

$$H_z(\vec{r}) = \sum_G H(\vec{k}+\vec{G})\exp(i(\vec{k}+\vec{G})\cdot\vec{r}) \tag{5}$$

where $K(\vec{G}) = 1/A\int_{\Omega}(1/\varepsilon(\vec{r}))\exp(-i\vec{G}\cdot\vec{r})\,d\vec{r}$, $\vec{G}$ is the reciprocal-lattice vector, and $H(\vec{k}+\vec{G})$ is expansion coefficient. When Eqs. (4) and (5) are substituted into Eq. (3), we can obtained the following eigen-value equation:

$$\sum_{G'}(\vec{k}+\vec{G})(\vec{k}+\vec{G}')K(\vec{G}-\vec{G}')H(\vec{k}+\vec{G}) = \frac{\omega^2}{c^2}H(\vec{k}+\vec{G}) \tag{6}$$

By solving the equation above, the PBG structure and the field distribution of each mode can be obtained.

3. Results and discussion

3.1. Theoretical model

For simplicity, we examine the 2D PC in which the dielectric structure is uniform in the z-direction and periodic in the x–y-plane. The proposed triangular lattice structure, shown in Fig. 1, consists of 16 rows air holes or dielectric rods in x direction and 16 columns in y direction. Here ε_1, ε_2 denote the permittivity of dielectric rods and background materials, respectively, and l_x, l_y indicate the side length of the dielectric rods. The direction of incident wave parallels with the y axis. In what follows of date

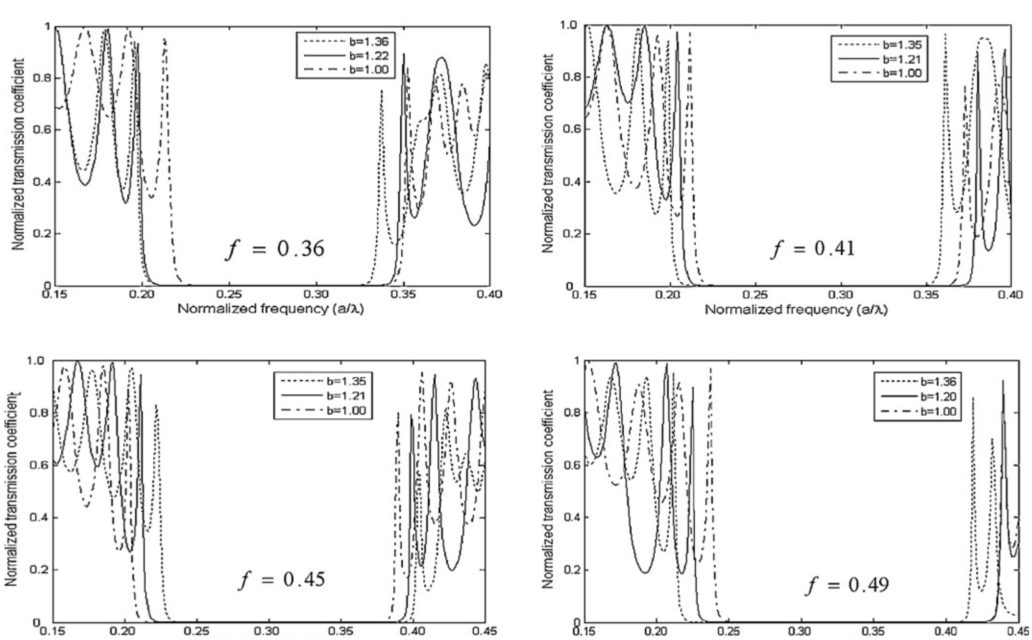

Fig. 3. Transmission spectra with variation of side length ratio.