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Transmission Properties of 2D Photonic Crystals with Triangular Dielectric Rods

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Abstract: The transmission properties of two-dimensional photonic crystals with triangular dielectric rods were studied using the finite difference time domain (FDTD) method for different lattice structures, section areas, azimuth angles and incident angles. The results showed that the photonic band gap (PBG) width and the central frequency depends on the lattice structure and sectional areas. Azimuth angle of cylinder affects the PBG in some degree, however the widths of band gaps are the same when their effective incident section are equal, such as with the θ value of 0° or 60°. In addition, transmission characteristics have no changes with the variation of incident angle in range of low frequency (below $0.26a/\lambda$), but the transmission coefficient decreases dramatically with increasing frequency ($0.28a/\lambda \sim 0.37a/\lambda$), even new wider forbidden band is formed under certain conditions. This work will be of significance in fabricating PC devices.

Key words: two-dimensional photonic crystals; the finite difference time domain method; transmission characteristic; triangular dielectric rods
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1 Introduction

Photonic crystals (PCs) are artificially fabricated using periodic dielectric structure[1]. They may provide a possibility of forbidding light propagation within a frequency band. After twenty years development, the basic theories have become perfect. At present, the hottest themes are the discovery and application of PCs containing new materials or novel structure. In the aspect of material, PC is fabricated by using semi-conductive material, organic material, metallic material, activated dielectric material, *etc*. As to structure, quasi-periodic configurative non-crystal PCs are developed. Comparing with the one-dimensional (1D) or three-dimensional (3D) PCs, the two-dimensional (2D) PCs are currently favored because of their relatively easy fabrication and providing most of the functionality of 3D structures. Currently, the study of theory and application of 2D PC is the one of the hottest themes in the area of physics, material science, and photonic electronic science[2~6]. Many 2D PC structures have been proposed. PC devices have been realized with bulk, quantum well and quantum dot active regions. The width of forbidden band is relevant to many factors, such as lattice structure, relative permittivity, filling factor, *etc*. There are various methods on studying PC transmission characteristics, such as transfer matrix method (TMM)[7~9], FDTD method[10,11], multiple scattering method (Order-N)[12], the plane wave expansion (PWE) method[13], *etc*. Feng *et al*. used the PWE method to calculate the band structure of 2D PC with triangular lattice[14], but the transmission properties were not presented. In this

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paper, the transmission properties of the 2D PCs with triangular dielectric rods for different lattice structures, section areas, azimuth angles and incident angles were investigated. The transmission properties have no changes with the variation of the incident angle in the range of low frequency (below $0.26a/\lambda$). However, the transmission coefficient reduce with increasing incident angle, even the new forbidden band is formed in the high frequency band ($0.28a/\lambda \sim 0.37a/\lambda$). The calculated results expand the research of 2D PCs with the laser-like hetero-structure.

2 The Basic Theories

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

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

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

where $\varepsilon(\boldsymbol{r})$ is the position dependent permittivity and $\mu(\boldsymbol{r}) = \mu_0$ is permeability in vacuum. In a 2D case, the fields can be decoupled into two transversely polarized modes, *i. e.*, the TE mode and the TM mode. These equations can be described in space and time by a so called Yee-cell technique[15]. The following FDTD time stepping formulas are the spatial and time descriptions of Eqs. (1) and (2) on a discrete 2D mesh within the x-y coordinate system for the TE mode[16]

$$E_x^{n+1}(i,j) = E_x^n(i,j) + \frac{\Delta t}{\varepsilon(i,j)} \cdot \frac{H_z^{n+\frac{1}{2}}\left(i,j+\frac{1}{2}\right) - H_z^{n+\frac{1}{2}}\left(i,j-\frac{1}{2}\right)}{\Delta y} \tag{3}$$

$$E_y^{n+1}(i,j) = E_y^n(i,j) + \frac{\Delta t}{\varepsilon(i,j)} \cdot \frac{H_z^{n+\frac{1}{2}}\left(i+\frac{1}{2},j\right) - H_z^{n+\frac{1}{2}}\left(i-\frac{1}{2},j\right)}{\Delta x} \tag{4}$$

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

where the index n denotes the discrete time step, indices i and j denote the described 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 for a fixed total number of time steps the computational time is proportional to the number of discrete points in the computation domain. Special consideration should be given at the boundary of the finite computational domain, where the fields are updated using special boundary conditions as the information out of the domain is not available. Here, the perfectly matched layer (PML) method and periodic boundary condition (PBC) are used for the boundary treatment.

In calculation, the time increment Δt and the space intervals Δx and Δy need satisfy numerical stability conditions[17]

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

where, c is the speed of light in vacuum.

3 Calculation Results and Discussion

3.1 Theoretical Model

The 2D PCs consist of a triangular lattice with 16 rows air triangular rods etched through a dielectric material $\varepsilon = 10.5$ (InP/GaInAsP) laser-like hetero-structure with a lattice constant a. The rods are infinitely long in the z direction. The direction of incident wave parallels with the y-axis. The calculation model is shown in Fig. 1, in which only 8 rows are plotted for the convenience. A Gaussian pulse is incident perpendicularly toward the bottom surface. The transmission is calculated as the ratio of the output and input powers obtained by integration of the Poynting vector fluxes at the detector and the reference lines, respectively. The calculation is stopped after the Gaussian pulse has totally passed through the detector. All the results presented below are calculated with the same grid parameters.

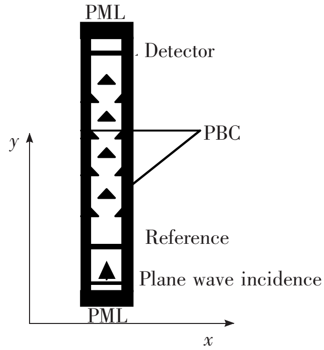

Fig. 1　Schematic of 2D triangular lattice PC

3.2　Transmission Properties with Different Lattices

The transmission coefficients of PC are calculated for triangular and square lattice, respectively. The side length of regular triangular air rod is $0.62a$. The calculated result is shown in Fig. 2. From the Fig. 2, the forbidden band of triangular lattice is wider than that of square lattice in the low frequency band; however, more forbidden bands appear in case of square lattice. So, the lattice significantly affects the transmission characteristic of 2D PC. The PC with square lattice is more suitable for fabricating multiple band stop filter than that with triangular lattice.

Fig. 2　Transmission spectra for the different lattices

3.3　Transmission Properties with the Variation of Rod Sectional Area

As for the transmission of the different sectional area of triangular rods, two different triangular rods with the side length of $0.52a$ and $0.62a$ are calculated, respectively, as shown in Fig. 3. The width of forbidden band is proportional to the size of the side length. The larger the side length is, the higher the central frequency is. This phenomenum is agree with the conclusion of other papers. So, the width of forbidden band can be adjusted by changing the value of the filling factor.

Fig. 3　Transmission spectra with the variation of sectional area

3.4　Transmission Properties with the Variation of Azimuth Angle

The transmission properties with the variation of azimuth angle are calculated. The rod is rotated θ degree along the anti-clockwise direction, where θ denotes azimuth angle as shown in Fig. 4. The transmission coefficients are calculated when θ is equal to $0°$ or $30°$, as shown in Fig. 4 (a). It is shown that the band width and central frequency are varied with the variation of azimuth angles. The results correspond

Fig. 4　Transmission spectra with the variation of azimuth angle well with the conclusion of other papers.

In addition, the transmission coefficient is calculated with the θ value of 60°, as shown in Fig. 4 (b). It is clearly shown that the forbidden band width and central frequency are the same with the θ value of 0°. However, the relationship between the band width and azimuth angle has not been revealed. To analysis the above results, the effective incident section which denotes a projected section in a plane that is perpendicular to the incident direction is introduced. The effective incident sections are the same when θ is equal to 0° or 60°. So, the transmission is determined by the effective incident sectional area when other factors are the same. The conclusion has not been reported by other papers.

3.5 Transmission Properties with the Variation of Incident Angle

Considering the periodical structure of PC and the symmetry of dielectric rod, the transmission with the variation of the incident angle and the fixed azimuth angle should be the same when azimuth angle is varied and incident angle is fixed. With the azimuth angle θ of 0°, the transmission coefficients are calculated with the variation of the incident angle β, as shown in Fig. 5. From the Fig. 5, it is clearly shown that in the low frequency band, the transmission spectra are the same; in the high frequency band, the width of three small forbidden bands are unvaried and the transmission ratio decrease with increasing the incident angle for non-perfectly forbidden band.

To validate the universality of the above results, the triangular air-rods is substituted for circular air-rods, the transmission properties are studied when β are equal to 0°, 30° or 60°, respectively, as shown in Fig. 6. The forbidden bands are all the same in the low frequency band (below $0.26a/\lambda$) The transmission coefficient reduce, with the increasing β in the band of $0.28a/\lambda$ to $0.37a/\lambda$, even the new forbidden band is formed when β is equal to 60°. The similar result is also obtained for the PC with rectangular air-rod. So, the width of forbidden band can change by adjusting the incident angle, which is easy to implement in fabrication using PCs with the laser-like hetero-structure. The similar result has not been reported.

Fig. 5 Transmission spectra with the variation of incident angle

Fig. 6 Transmission spectra of circular air-rods with the variation of incident angle

4 Conclusion

The transmission of 2D PC of triangular dielectric rods was studied using FDTD method. PBG is affected by changing the lattice structure. The width and central frequency location of the forbidden band can be adjusted in a certain range with the variation of azimuth angle of rod for the TE polarization wave. The simulated result showed that in the design of PBG of the triangular dielectric rod, the triangular lattice structure should be adopted and makes the cylinder section as large as possible. In addition, the PBG width and central frequency can be fine-tuned to fulfill design requirements by changing the cylinder azimuth angles. In particular, the transmission spectra are the same with the variation of the incident angle in the low frequency band (below $0.26a/\lambda$). However, in the high frequency band, the transmission ratio decreases with the increasing incident angle for non-perfectly forbidden band of $0.28a/\lambda$ to $0.37a/\lambda$, even the new wider forbidden band is formed. To our knowledge, there have been few reports that the band gap can be adjusted or the new band gap can be formed by changing the incident angle. This work will be of significance in future fabricating photonic crystal devices.

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二维三角柱光子晶体的传输特性

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摘要：利用时域有限差分方法对二维三角介质柱光子晶体的传输特性进行了研究，计算了不同晶格、同一晶格柱体截面面积不同、放置方位角不同、入射波入射方向不同时光子晶体的传输特性。结果表明：光子禁带的宽度与中心频率和晶格结构有很大关系，三角晶格更易形成平坦光子禁带，柱体截面面积大，则形成的禁带较宽，在其他因素相同的条件下柱体放置的方位角在一定范围内对光子禁带有重要影响；对不同入射方向时光子晶体的传输特性的研究结果表明，在低频范围内，入射角对禁带宽度和中心频率没有任何影响，在高频段，透射率随入射角变大而降低。研究结果为实验上制作三角柱光子晶体器件提供了重要的理论依据。

关　键　词：二维光子晶体；时域有限差分方法；传输特性；三角介质柱

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重要启示

本刊为方便广大作者的论文进行国际交流，并进一步加快我刊国际化进程，现向广大作者征集相关英语全文写作论文。对专家和编委审查合格的论文，我们将采取优先发表等优惠措施，欢迎广大作者踊跃投寄英语全文写作的学术论文。论文征集范围仍参见《发光学报》征稿简则。

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