Off-Plane Adjustment for Waveguide in Woodpile Structure

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(Received November 3, 2016; in final form February 22, 2017)

Waveguide is an essential building block of integrated optics. Using finite-difference time-domain method, waveguide in woodpile structure, which the dielectric constants for background media and dielectric rods are 1.0 and 9.0, is designed, analyzed, and simulated. Since, woodpile structure has periodical property in stacking direction, off-plane adjustment is considered. Our results show that the guide band can be also effectively adjusted by varying dielectric constant and lattice constant of layers located at the upper and lower of waveguide. For the single layer adjustment, the band width is from 0.41[c/a] to 0.44[c/a] when constant dielectric is 6.0. While it can be also from 0.43[c/a] to 0.46 [c/a] for the double layer adjustment.

DOI: 10.12693/APhysPolA.135.315

PACS/topics: woodpile structure, waveguide, finite-difference time-domain method

1. Introduction

Due to the potential application in optical integrated circuit, photonic crystals (PCs) [1, 2] have obtained much attention. This structure has a complete band gap and can realize the light localization when defect is introduced. Waveguide (WG) is an essential building block of integrated optics. Many optical devices, such as modulators [3], frequency dividers [4], filters [5–8], are formed by waveguide. Over the years, waveguide in two-dimensional (2D) PCs is designed and fabricated theoretically and experimentally [9–14]. For example, Meiks et al. [9] have demonstrated highly efficient transmission ($> 95\%$) of light around sharp corners in photonic band gap waveguides. Xing et al. [12] have improved the transmission bandwidth of 60° waveguide by displacements and enlargements of selected holes in bend regions. Xiao et al. [13] reduced the transmission loss by designing circular photonic crystals. Moghadam et al. [14] increased the bandwidth of a single mode WG by changing the radius of rods on both sides.

Compared with 2D PCs, three dimensional PCs are expected to serve as a good platform for ultra-compact novel optical devices. In recent years, there are a few reports about waveguide in three dimensional PCs [15–18]. For example, Kawashima et al. [16] investigated theoretically waveguide property formed by the introduction of dielectric line defects in woodpile structure. They have proved that the guide mode strongly depends on the volume, position and number of defects introduced. Kawashima et al. [17] have proved that the waveguides have an extremely large single-mode band width by introducing one acceptor-type and two donor-type line defects at the same time. Tang et al. [18] have reported designs of double-hetero junction optical waveguides in a three dimensional photonic crystal. Compact optical waveguide modes have been realized by modulating unit cells size. But there are few reports about optimization for waveguide in three-dimensional structure.

In this paper, based on finite-difference time-domain (FDTD) method developed by East FDTD, Dongjun Technology, Shanghai, China, we study the guide band adjustment of waveguide. Since, woodpile structure has also periodical property in stacking direction, off-plane design can be considered. The results show the guide band can be adjusted effectively by varying dielectric constant and lattice constant of layers located at the upper and lower of the waveguide.

The rest of the paper is organized as following. In Sect. 2, an x-type waveguide is designed and simulated. The single layer adjustment is also considered. In Sect. 3, the double-layer adjustment is analyzed. The influence of lattice constant is also considered in Sect. 4. Finally, we summarize the paper in Sect. 5.

2. The single layer adjustment for x-type waveguide

A woodpile-structure working in microwave wavelength is designed. In our design, many rods with square section are selected. The side length of rod is $0.3a$, where a is the center-to-center distance of the adjacent rods in the same layer. The dielectric constant for background media and rods are 1.0 and 9.0, respectively. The lattice constant is a. The transmission property for woodpile structure is simulated by FDTD method. The complete bandgap ranges from 0.38[c/a] to 0.47[c/a], where c is the velocity of light in vacuum. Our structure includes 20 layers along the stacking direction. The x-type waveguide formed by removing one rod is designed as shown in Fig. 1a. In order to display clearly, we only show three layers included of waveguide layer, substrate layer (marked with A) and coating layer (marked with B) as displayed in Fig. 1b. The waveguide is located at the 11th layer from the top of the sample, while substrate layer and coating layer are located at 12th and 10th layer, respectively. In our design, it is difference that both substrate layer and coating layer are also periodical along the waveguide direction.

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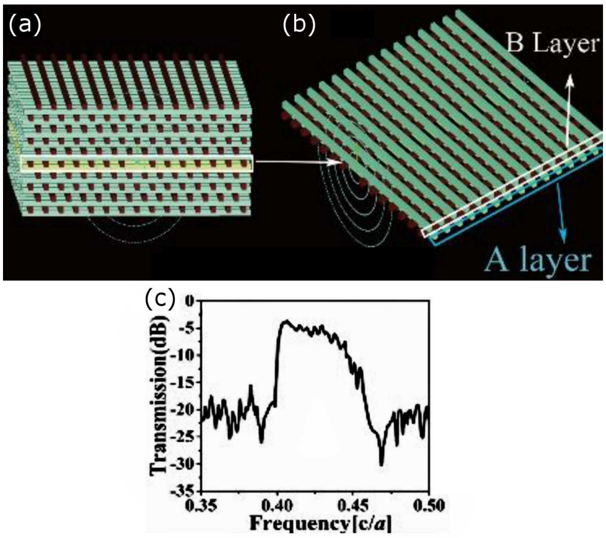

Fig. 1. (a) and (b) The x-type waveguide structure in woodpile. The dielectric constants for background media and dielectric rods are 1.0 and 9.0, respectively. The parameters for rods with square section are $0.3a \times 0.3a$. (c) The transmission spectrum for x-type waveguide. The guide band range is from $0.40[c/a]$ to $0.47[c/a]$.

In our simulation, the light source, which propagates along y positive direction, is placed at the distance $1.0a$ from the surface of the sample. The electric field is kept parallel to the stacking direction. The transmission spectrum is simulated and analyzed by FDTD method when all parameters are unchanged. The result is displayed in Fig. 1c with solid line. The result shows that the waveguide has a wide guide band. The range is from $0.40[c/a]$ to $0.47[c/a]$. The result shows that the waveguide has well propagation characteristics.

It is known that the adjustment for waveguide in two dimension PCs is only limited to an in-plane design. For example, the guide band can be effectively improved by adjusting the parameters of the rods or holes located on both sides of waveguide, such as changing the radius, adding certain rods or holes in bend location, shifting the location of rods or holes [19–23]. In woodpile structure, dielectric constant is also periodical along the stacking direction. Since, off-plane adjustment can be considered. In our design, because x-type waveguide has no bend location, we only consider the shifting of the guide band. From Fig. 1b, we can observe that there are two stacking layers in the upper and lower of x-type waveguide. One is a substrate layer (marked with A) located at the lower of waveguide, the other is coating layer (marked with B) located at the upper of waveguide. Dielectric constant has periodical constant along the waveguide direction. This is difference from the conventional dielectric waveguide. When we change the parameters of coating layer or substrate layer, we investigate whether the guide band can be adjusted effectively. In our research, there are many adjustment methods, such as a single layer or double-layer adjustment, dielectric constant changing, lattice constant varying, rectangle section rods introducing.

Firstly, the single layer adjustment is considered. It means that we change only A layer or B layer parameters. The simplest case of varying only dielectric constant is considered. In our design, the whole rod located at the A layer is changed. The transmission spectrum is simulated when dielectric constant has a tiny decreasing. The result of 8.5 is displayed in Fig. 2a with dot line. In order to compare, the result of 9.0 is also displayed with solid line. We can observe that the guide band remains basically unchanged. Only the low band edge has a tiny shifting. Next, we decrease further dielectric constant. The result for 6.0 is shown in Fig. 2b with dot line. The results show that guide band happens obvious shifting. The low band edge moves to the high frequency, while the high band edge moves along opposite direction. Since, the range of the guide band is narrow. At the same time, the transmissivity has a certain improvement. It is only from $0.41[c/a]$ to $0.44[c/a]$. The results prove sufficiently that the range of the guide band can be adjusted effectively by varying dielectric constant of substrate layer located at the lower of waveguide.

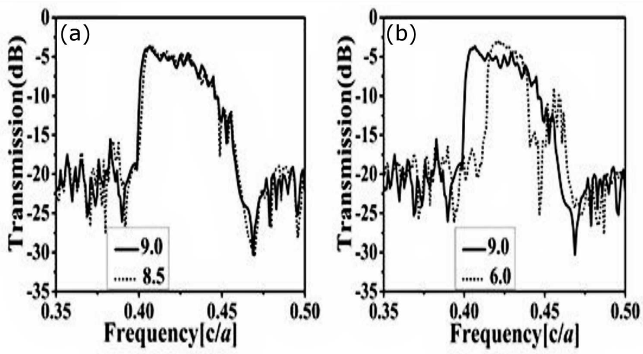

Fig. 2. The transmission spectra for dielectric constant of A-layer are 8.5 (a) and 6.0 (b), respectively.

In the above case, the adjustment is for the whole rod of substrate layer. In fact, we can vary only a part. The design is displayed in Fig. 3a. The width and dielectric constant of rods located in the red region is na and 6.0, where n is integer. When the width changes continuously, we investigate whether the guide band can be adjusted effectively.

We firstly calculate the transmission spectrum when the width is $1a$. It means that n is equal to 1. The result is plotted in Fig. 3b. In order to compare, the results of 9.0 and 6.0 for the adjustment of the whole rod are also displayed with solid line and dash line, respectively. We can observe that there is obvious shifting at the high frequency region. The high frequency band edge is essentially in agreement with the whole rod case, while the low frequency band edge is coincidence with 9.0 case. The result indicates that the guide band can be also affected even if the changing is only a part of rod. Next, we increase continuously the width, which is equal to $2a$, the transmission property is also simulated and displayed in Fig. 3c. From the figure, we can observe that the low band edge shifts apparently and moves to-

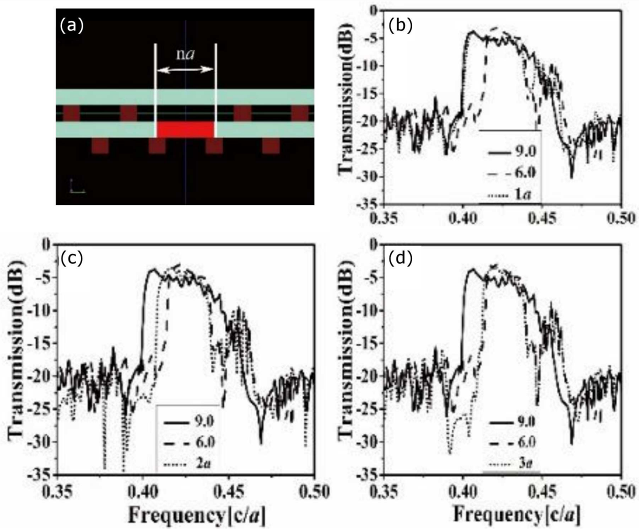

Fig. 3. (a) the structure for the single layer adjustment for a part of rods located at the A layer. The width in red region is na. Dielectric constant in red region is 6.0. The transmission spectra are plotted when the width is $1a$ (b), $2a$ (c), and $3a$ (d), respectively.

ward the high frequency. However, the high band edge remains unchanged. Last, the case of $3a$ width is also considered. The result is displayed in Fig. 3d. We can find that the range of guide band is essentially in agreement with the whole rod case. When we increase continuously the width, the guide band range remains unchanged. Compared with these results, we find that the high band edge position is determined when there is $1a$ width. But the low band edge position will move to high frequency with the increasing of the width of rod.

3. The double-layer adjustment for x-type waveguide

In the above simulation, we have observed that the guide band can be adjusted effectively whether the adjustment is for the whole rod or not. But we only consider the single layer adjustment. In fact, we could consider the double-layer adjustment. Namely, dielectric constant of A and B layers decrease simultaneously. Firstly, the varying for the whole rod is considered. The result for 8.5 is displayed in Fig. 4a with dot line. In order to compare, the result of 9.0 is also displayed with solid line. Compared Fig. 2a with Fig. 4a, we can find that there is obvious difference. The low band edge has a bigger shifting than that of single layer adjustment. Next, we decrease continuously dielectric constant. The result for 6.0 is shown in Fig. 4b with dot line. Compared Fig. 2b with Fig. 4b, we can observe that there is also obvious difference between the single layer and the double-layer adjustment. For the single layer adjustment, the low band edge and high band edge shifts along the opposite directions. Therefore, the width of guide band is reduced. However, for the double-layer adjustment,

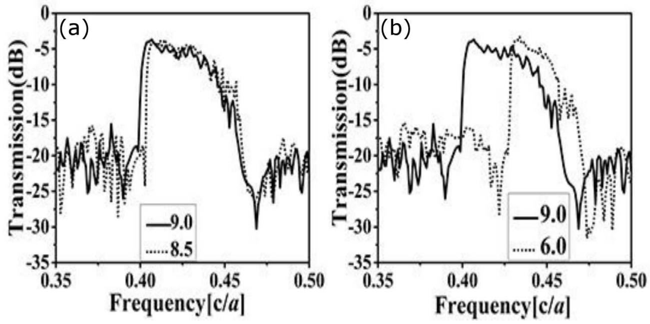

Fig. 4. The transmission spectra for the double-layer adjustment. Dielectric constant is 8.5 (a) and 6.0 (b), respectively.

both shift simultaneously along the high frequency direction. But the movement of the low band edge is bigger than that of the high band edge. So the range is from $0.43[c/a]$ to $0.46[c/a]$. All results illustrate that there is a difference principle between the single layer and the double-layer adjustment. For the single layer adjustment, the high and low band edges move along opposite directions. While they move along the same direction when the double-layer adjustment is considered.

Similar to the single adjustment, we can only change a part of rod. The structure is plotted in Fig. 5a. The width and dielectric constant of rods located in the red region is na and 6.0, where n is integer. Firstly, the width we considered is $1a$. The result is displayed in Fig. 5b with dot line. In order to compare, the results of 9.0 and 6.0 for the whole rod are also displayed with solid line and dash line, respectively. We can observe that there is obvious shifting of guide band. The high band edge is essentially in agreement with the whole rod

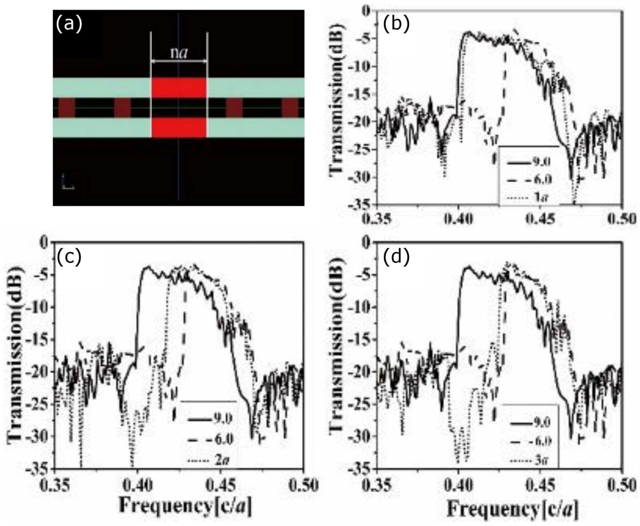

Fig. 5. (a) The structure for the double-layer adjustment for a part of rod. The width in red region is na. Dielectric constant in red region is 6.0. The transmission spectra are plotted when the width are $1a$ (b), $2a$ (c), and $3a$ (d), respectively.

case, while the low band edge has a tiny shifting against 9.0 case. Next, we increase continuously the width. The width we considered is $2a$. The transmission property is simulated and displayed in Fig. 5c. We can observe that the trend is similar with the Fig. 3c. The low band edge moves toward the high frequency, while the high band edge has no obvious shifting. Since, the guide mode range is getting narrower. The result for the $3a$ case is also displayed in Fig. 5d. Through these results, we can find that the principle is consistency. The low band edge is close to the result of the whole rod when the width increases $3a$. For $2a$ and $3a$ cases, the transmissivity has a certain improvement.

In conclusion, we know that there are differences between the single layer and the double-layer adjustment. For the single layer adjustment, the low band edge and high band edge move along the opposite direction. For the double-layer adjustment, the low band edge moves to high frequency, and the shifting for the high band edge is very tiny.

4. Lattice constant adjustment

For conventional dielectric waveguide, the coating layer and substrate layer are both dielectric materials. They have no periodicity. In our design, the coating layer and substrate layer are periodical along the propagation direction of waveguide. Since, the influence of lattice constant on the guide band is also considered. In this case, we only consider the double-layer adjustment. In our simulation, lattice constant we considered is $1.1a$ while the other parameters are unchanged. By FDTD method, the transmission spectrum is simulated and displayed in Fig. 6 with dot line. In order to compare, the result for $1.0a$ is also displayed with solid line. We can find that there is a clear difference. The high band edge shifts along the low frequency, while the low band edge has no shifting. The range of guide band is from $0.40[c/a]$ to $0.42[c/a]$. The transmissivity is near -1 dB at the frequency of $0.41[c/a]$. This result demonstrates adequately that the guide band is also affected by the periodic of coating and substrate layer.

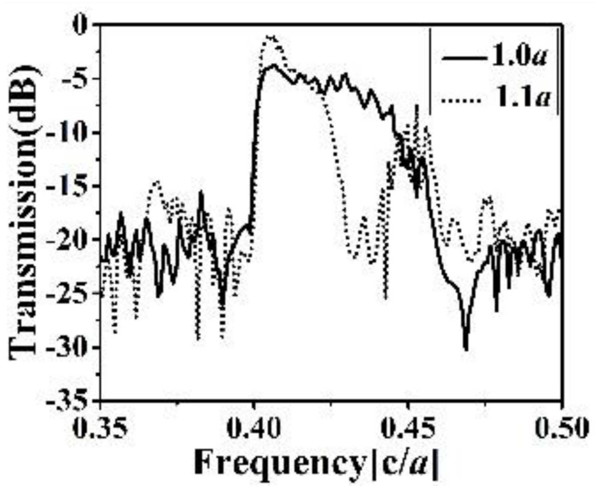

Fig. 6. The transmission spectra for the double-layer adjustment. Lattice constants are $1.0a$ (solid line) and $1.1a$ (dot line), respectively.

5. Conclusion

In conclusion, using FDTD method, we have investigated in detail the influence of dielectric constant on the guide band of x-type waveguide. The results show that there is a difference between the single layer and the double-layer adjustment. The periodicity of the coating layer and substrate layer is very important for the adjustment of the guide band.

Acknowledgments

Research was supported by SRF for ROCS, SEM and the long-term subsidy mechanism from the Ministry of Finance and the Ministry of Education of PRC. The National Natural Science Foundation of China with Grant No. 11374378 and the National Natural Science Foundation of China Grant No. 11104169, 11274207.

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