Engineering the light propagating features through the two-dimensional coupled-cavity photonic crystal waveguides*

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This paper studies the propagating characteristics of the electromagnetic waves through the coupled-resonator optical waveguides based on the two-dimensional square-lattice photonic crystals by the finite-difference time-domain method. When the traditional circular rods adjacent to the centre of the cavities are replaced by the oval rods, the simulated results show that the waveguide mode region can be adjusted only by the alteration of the oval rods' obliquity. When the obliquity of the oval rods around one cavity is different from the obliquity of that around the adjacent cavities, the group velocities of the waveguide modes can be greatly reduced and the information of different frequencies can be shared and chosen at the same time by the waveguide branches with different structures. If the obliquities of the oval rods around two adjacent cavities are equal and they alternate between two values, the group velocities can be further reduced and a maximum value of $0.0008c$ (c is the light velocity in vacuum) can be acquired.

Keywords: photonic crystal, waveguide, group velocity, the finite-difference time-domain method

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1. Introduction

Photonic crystals (PCs) are currently the subject of intense investigation due to their remarkable properties brought by the existence of photonic band gaps over which the propagation of electromagnetic (EM) waves is prohibited.[1,2] This prominent characteristic enables us to control the propagation of the EM waves in the PCs. By introducing different kinds of defects into otherwise perfect PCs, resonant states (guiding modes) within the band gap can be created and various optical devices can be realized, such as optical waveguides,[3−5] channel drop filters,[6−8] strongly wavelength-dependent delay line,[9] and ultrafast optical switches.[10,11]

Coupled-resonator optical waveguides (CROWs) consist of coupled defects arranged at regular intervals in PCs and can propagate photons by hopping from one defect to its nearest neighbour because of interactions between the neighbouring evanescent cavity modes.[12−17] The EM waves are guided by the coupling of the tight-confined localized modes supported in the defects. Both the low group velocity and the large optical field amplitude can be achieved in a CROW, so it can be employed to enhance nonlinear optical processes significantly or to construct efficient optical delay lines for high-speed all optical signal processing. As the optical devices based on PC structure are compact and integrated, the related research has attracted much attention and it is now at the forefront of the optical communications research.

In this paper, we studied the propagating characteristics of the EM waves through the two-dimensional square-lattice PC CROWs. The simulated results show that the frequency region of the guiding modes can be controlled by changing the obliquity of the oval rods adjacent to the cavities. When the rotation angles of the oval rods around each cavity are set to be equal and the rotation angles of the oval rods around two adjacent cavities are different, the group velocity can be greatly reduced and high transmission efficiency of light is insured. The information of different frequencies can be shared and chosen at the same time by the optical waveguide branch based on different structures. If the obliquities of the oval rods around two adjacent cavities are equal and they alternate between two values, the group velocities can be further reduced and a maximum of that $0.0008c$

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can be acquired (where c is the velocity of light in vacuum).

2. Numerical calculation and discussion

The CROWs studied in this paper are based on the two-dimensional square-lattice PC consisting of dielectric cylinders immersed in air. The permittivity of the dielectric is 8.9, the radius of the cylinders is $r = 3.0$ mm and the length of the lattice constant is $a = 10.0$ mm. For such a perfect PC, a photonic band gap exists within the frequency region from 14.1 to 17.0 GHz. Based on the above PC, we constructed an oval-rod CROW structure, which is shown in Fig.1. The length of the ellipse's long axis is $0.367a$ and that of the ellipse's short axis is $0.245a$, so the area of each ellipse is equal to that of the circle. The ellipse's long axis is set along the PC's ΓX direction, meaning that the ellipse's long axis is placed along the direction of light propagation.

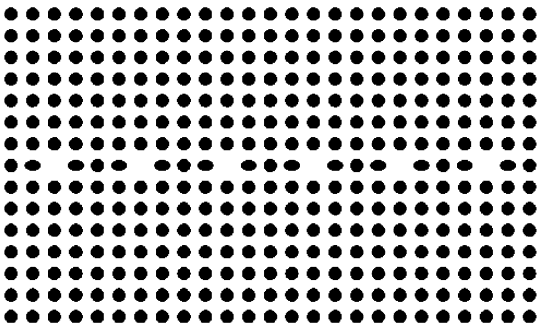


Fig. 1. Schematic geometry of the oval-rod photonic crystal waveguide.

The transmission spectrum of the TM-polarized EM waves through the above structure is calculated by the finite-difference time-domain method,[18,19] which is shown by the solid line in Fig. 2. It can be seen that a guiding mode band appears within the photonic band gap and it spans the frequencies 14.8 and 14.98 GHz. When the ellipses are rotated in the lattice and the angles from the light transmission direction (also the PC's ΓK direction) to the direction of the ellipse's long axis are 45° and 90°, the transmission spectra of the EM waves through the corresponding structures are shown by the dashed line and the dotted line in Fig. 2, respectively. From Fig. 2 it can be seen that the guiding modes move to the higher frequencies when the rotation angle of the ellipse is increased. So the frequency region of the guiding modes can be adjusted only by the alteration of the ellipses' rotation angle.

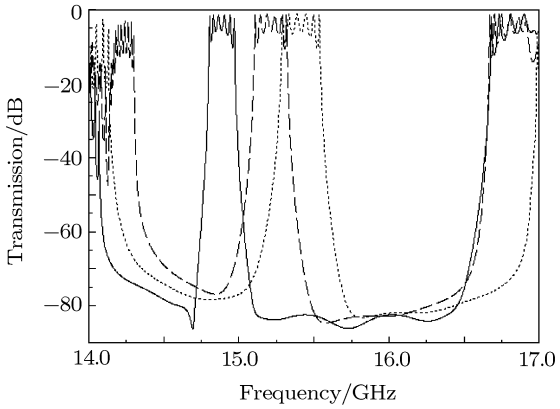


Fig. 2. Transmission spectra of the EM waves through the oval-rod CROWs.

Channel filters with different structures are utilized to select and acquire the wanted information of different frequencies. In some particular situations, we want to select the frequency within a certain region under the condition that the EM waves within another frequency region can propagate through the guides freely and even a small group velocity of the EM waves is needed. In the structure shown in Fig. 3, the rotation angle of the oval rods around one cavity is set to be 0° and the rotation angle of the oval rods around the adjacent cavity is 45°. The band structure of this CROW is shown by the hollow dots in Fig. 4(a), from which we can see that a guiding band spans the frequencies 14.858 and 14.892 GHz and another guiding band exists in the frequency region 15.200–15.232 GHz. The corresponding transmission spectrum of the EM waves through this structure is shown by the dotted line in Fig. 4(b), it can be seen that the guiding modes transmit through the structure with a high efficiency.

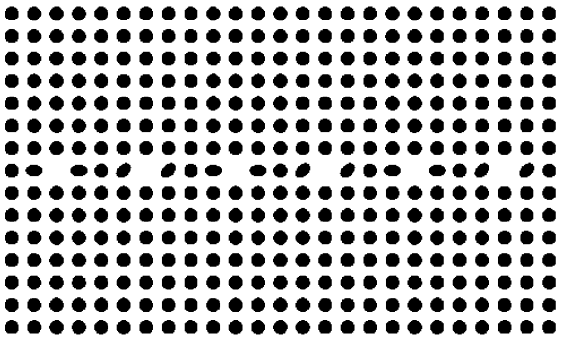


Fig. 3. Schematic geometry of the oval-dielectric photonic crystal coupled-cavity waveguide.

Keeping all the other parameters unchanged, we alter the obliquity of the ellipse around the cavities

from 45° to 90°, the corresponding calculated band structure is shown by the solid dots in Fig. 4(a). It can be seen that a guiding band spans the frequencies 14.862 and 14.894 GHz and another guiding band exists in the frequency region 15.367–15.395 GHz. Comparing the solid and hollow dots, we can clearly see that for a frequency region within 14.862 and 14.892 GHz, the EM waves can propagate through the above two structures. This phenomenon can also be clearly seen from Fig. 4(b), where the solid line is the transmission spectrum of the EM waves through the structure with the oval rod cavities whose rotation angles alternate between 0° and 90°.

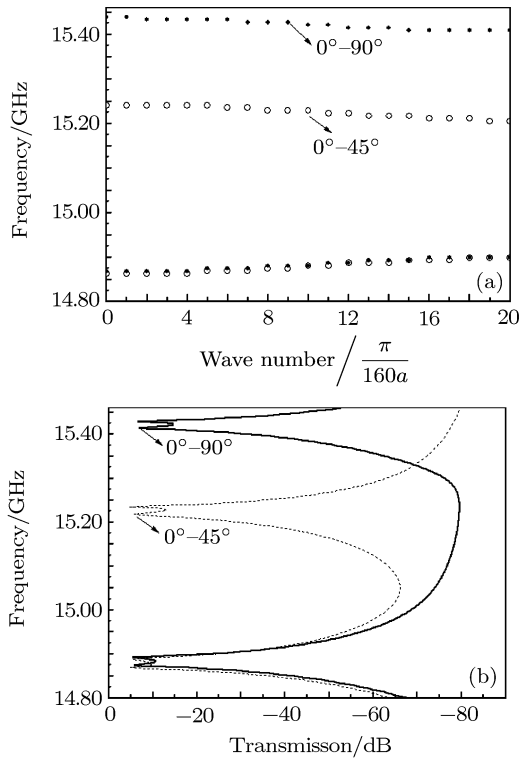


Fig. 4. Band structures (a) of the two CROWs and the corresponding transmission spectra (b).

Figure 5 shows the waveguide structure with one 1W-type input guide and two oval-rod output CROWs with different rotation angles. The intensity distribution of the EM waves through this guide structure with the frequencies 14.890, 15.235 and 15.430 GHz are shown in Figs. 6(a), 6(b) and 6(c), respectively. When the frequency of the incident EM wave is 14.890 GHz, the EM wave transmits through both CROWs with a high efficiency. It is also shown that most of the energy is localized around the centre of the cavities whose nearby ellipse is 0° rotation. From Fig. 6(b) it can be seen that the EM wave transmits only through one waveguide branch when the frequency becomes 15.227 GHz and the most of the energy is localized around the cavities which are enclosed by the oval rods with 45° rotation. The EM wave with the frequency 15.430 GHz transmits only through the other waveguide branch and the most of the energy is localized around the cavities whose nearby oval rods are 90° rotation, as can be seen in Fig. 6(c).

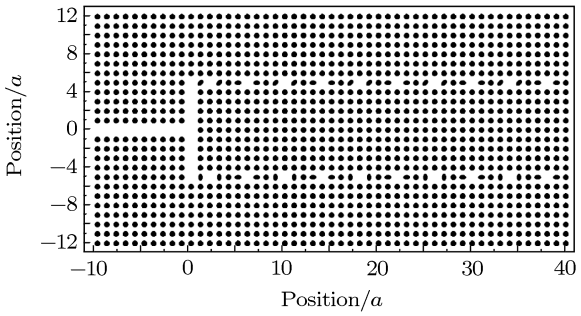


Fig. 5. Schematic geometry of the oval-dielectric photonic crystal branch waveguide.

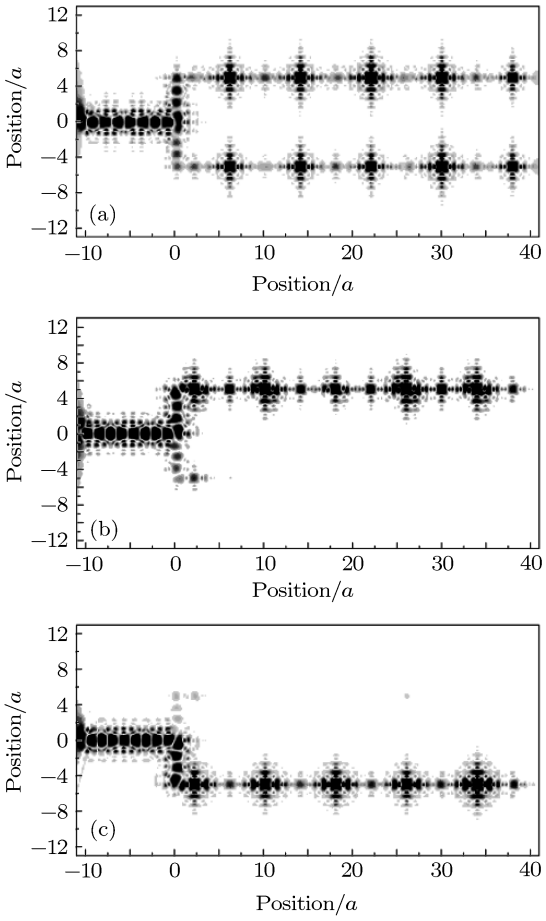


Fig. 6. Intensity distribution of EM waves through the structure with the following frequencies: (a) 14.890 GHz; (b) 15.235 GHz; (c) 15.430 GHz.

In the above CROW structures, the length of period along the waveguide direction is 80 mm. We increase the period length to 160 mm, for example, let

the obliquities of the oval around two adjacent cavities be equal and alternate them between the angles 0° and 45°, as is shown in Fig. 7(a).

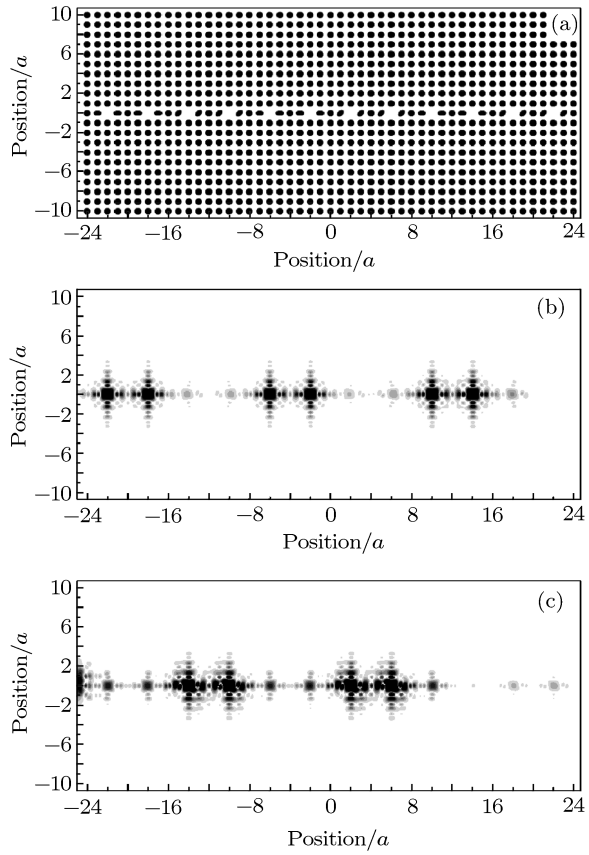


Fig. 7. Schematic geometry of the oval-rod CROW (a), the intensity distribution of EM waves through the structure with frequencies of (b) 14.84 GHz and (c) 15.165 GHz.

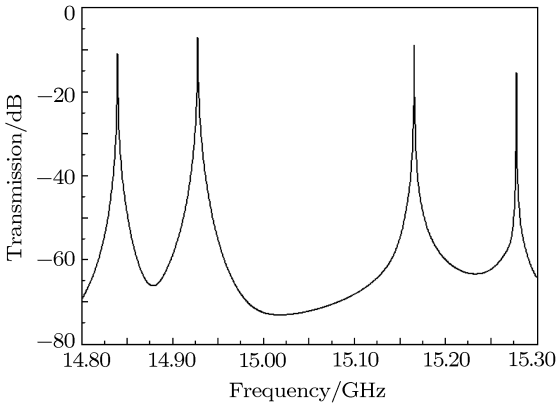


Fig. 8. Transmission spectrum of the EM waves through the oval-rod CROWs.

Figure 8 shows the corresponding calculated transmission spectrum, from which it can be seen that four sharp transmission peaks exist within the frequency region 14.8 GHz and 15.3 GHz. When the frequency of the incident EM wave is 14.840 GHz, from Fig. 7(b) we can see that the EM wave transmit through the structure with a high efficiency and most of the energy is localized at the centre of the cavities whose nearby ellipse is 0° rotation. Figure 7(c) shows that most of the energy is confined around the cavities which are enclosed by the oval rods with 45° rotation when the frequency becomes 15.165 GHz.

At last, we employ the tight-binding approximation to calculate the group velocities of the transmitting modes in different CROW structures. Keeping only the nearest-neighbour coupling the dispersion relationship for a CROW guide mode, we have

$$\omega(K) = \Omega\left[1 + \kappa\cos(KR)\right], \tag{1}$$

where Ω is the angular eigenfrequency of an isolated cavity, κ is the coupling strength between two nearest-neighbouring cavities, K is the wave number along the direction of the waveguide, R is the distance between them and ω is the angular frequency. Owing to the periodicity of the structure along the waveguide direction, the wave vector can be folded into the region $[0, \pi/R]$. Therefore, the width of the miniband of the waveguide mode is

$$\Delta\omega = 2\left|\kappa\right|\Omega. \tag{2}$$

From Eqs. (1) and (2), we can obtain

$$\left|\nu_g(K)\right| = \frac{\Delta\omega R}{2}\sin(KR). \tag{3}$$

The group velocities of the three waveguide modes in the CROWs shown in Figs. 1, 3 and 7(a) are displayed by the curves a, b and c in Fig. 9.

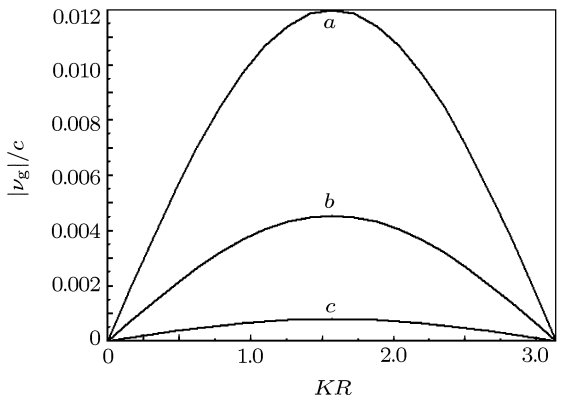


Fig. 9. Group velocities of EM waves through the oval-rod CROWs.

It is shown that the maximum of the group velocities of the guiding modes in the structure shown in Fig. 2 is about $0.012c$, while the corresponding value is $0.0045c$ in the CROW structure shown in Fig. 3. The maximum of the group velocities is reduced to be about $0.0008c$ in the CROW structure as shown

in Fig. 7(a). Comparing with the intensity distributions of the corresponding frequencies, we can see clearly that the distance between two adjacent localized modes increases when the rotation angles of the oval rod around the cavities are changed alternately and the corresponding group velocity can be greatly reduced.

3. Conclusions

The transmission characteristics of the EM waves through the oval-rod CROWs are studied. The guiding mode region can be controlled by the rotation of the oval rods around the cavities. When the rotating angles of the oval rods around two adjacent cavities are different, the group velocity can be greatly reduced and high efficiency of light transmission is insured. And the information of different frequencies can be shared and chosen by the PC waveguide branch based on the above structures. The above PC structures studied in this paper work for the frequencies within microwave region. It offers a feasible way to minimize the PC structure and finds similar results within the infrared and visible light region.

References

[1] Yablonovitch E 1987 *Phys. Rev. Lett.* **58** 2059
[2] John S 1987 *Phys. Rev. Lett.* **58** 2486
[3] Tokushima M and Yamada H 2002 *IEEE J. Quantum Electron* **38** 753
[4] Kong W J, Yun M J, Wang M and Shan F K 2009 *Acta Opt. Sin.* **29** 818 (in Chinese)
[5] Han S Z, Tian J, Ren C, Xu X S, Li Z Y, Cheng B Y and Zhang D Z 2005 *Chin. Phys. Lett.* **22** 1934
[6] Fan S, Villeneuve P R, Joannopoulos J D and Haus H A 1998 *Phys. Rev. Lett.* **80** 960
[7] Zhang Z Y and Qiu M 2006 *J. Opt. Soc. Am.* B **23** 104
[8] Takano S, Song B S, Asano T and Noda S 2006 *Opt. Express* **14** 3491
[9] Bayindir M and Ozbay E 2002 *Opt. Express* **10** 1279
[10] Villeneuve P R, Abrams D S, Fan S and Joannopoulos J D 1996 *Opt. Lett.* **21** 2017
[11] Hu X Y, Liu Y H, Tie J, Cheng B Y and Zhang D Z 2005 *Appl. Phys. Lett.* **86** 121102
[12] Olivier S, Smith C, Rattier M, Benisty H, Weisbuch C, Krauss T, Houdre R and Oesterle U 2001 *Opt. Lett.* **26** 1019
[13] Yariv A, Xu Y, Lee R K and Scherer A 1999 *Opt. Lett.* **24** 711
[14] Wang Y Q, Liu J, Zhang B, Feng S and Li Z Y 2006 *Phys. Rev.* B **73** 155107
[15] Shen H J, Tian H P and Ji Y F 2010 *Acta Phys. Sin.* **59** 2820 (in Chinese)
[16] Du X Y, Zheng W H, Ren G, Wang K, Xing M X and Chen L H 2008 *Acta Phys. Sin.* **57** 571 (in Chinese)
[17] Ye W M, Luo Z,Yuan X D and Zeng C 2010 *Chin. Phys.* B **19** 054215
[18] Yee K S 1966 *IEEE Trans Antenna Propag* **14** 302
[19] Berenger J P 1996 *J. Comput. Phys.* **127** 363