Light propagation properties of two-dimensional photonic crystal channel filters with elliptical micro-cavities*

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Light propagation through a channel filter based on two-dimensional photonic crystals with elliptical-rod defects is studied by the finite-difference time-domain method. Shape alteration of the defects from the usual circle to an ellipse offers a powerful approach to engineer the resonant frequency of channel filters. It is found that the resonant frequency can be flexibly adjusted by just changing the orientation angle of the elliptical defects. The sensitivity of the resonant wavelength to the alteration of the oval rods' shape is also studied. This kind of multi-channel filter is very suitable for systems requiring a large number of output channel filters.

Keywords: photonic crystal, defect, multi-channel filter, micro-cavity

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1. Introduction

Photonic crystal (PC) is an inhomogeneous periodic array of building blocks with a lattice constant comparable to the wavelength,[1,2] which is a promising platform to construct ultrasmall devices for future photonic integrated circuits. By introducing artificial defects, various PC devices can be realized, such as waveguides,[3−6] resonators,[7,8] and channel drop filters.[9−20] The channel drop filter is an important component of photonic integrated circuits and dense wavelength division multiplexing optical communication systems. To make full use of spectral bandwidth resources, channel spacing is becoming more and more dense, and a large number of spaced wavelength channels require a very small scale filter.[9]

Owing to their advantages of high precision and ease of fabrication, two-dimensional (2D) PC devices have attracted much interest as ultra-compact integrated photonic components, in which the channel filters are capable of extracting the light trapped in a point-defect cavity to another neighbouring waveguide. Noda *et al.* used a heterogeneous structure to confine photons in line cavities and formed a surface-emitting laser with an extremely high-quality factor in the vertical direction.[10] The resonant cavity traps photons at the resonant frequency from the waveguide through evanescent coupling and emits some of them in the vertical direction. Notomi *et al.* designed an ultra-small multi-channel drop filter based on a two-port resonant tunneling system in a 2D triangular-lattice photonic crystal. This filter does not require careful consideration of the interference process to achieve a high dropping efficiency.[11]

In our previous work, the influence of the irregular shape of air holes on the optical characteristics of channel-drop filters built in a 2D PC slab was studied both theoretically and experimentally.[12] We know that efficiency and flexibility are two important factors that need to be evaluated for an actual optical device. The traditional channel filters are based on circular micro-cavities, through which the resonant frequency is adjusted by changing the size of the circular defect. In this paper, we propose another method to flexibly engineer the frequency of the output light from the multi-channel filters by changing the shape of the scatterers from a traditional circle to an ellipse. The resonant frequency can be adjusted by altering the orientation angle of the ellipse and the frequency

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scope can be enlarged by increasing the ratio of the major axis to the minor axis of the ellipse. A ten-channel side-coupled drop filter is also proposed to select the resonant wavelength by changing the obliquity of the ellipse. Our theoretical result provides a feasible and flexible method for the design of efficient multi-channel filters.

2. Channel filters based on elliptical micro-cavities

We consider a 2D square-lattice PC consisting of dielectric cylinders immersed in air, whose relative permittivity is 8.9. The radius of the cylinders is $r = 260$ nm and the length of the lattice spacing is $a = 780$ nm. For such a PC, a photonic band gap exists from 1376.5 nm to 1659.6 nm. When one dielectric rod is removed from an otherwise-perfect PC, a defect mode resonant at 1554.8 nm is formed, whose electric intensity profile is shown in Fig. 1.

Based on the above structure, we construct one kind of channel filter by the connection of a W1-typed waveguide and a micro-cavity, which is formed by removing a dielectric rod from an otherwise-perfect PC and changing the shape of its two adjacent cylinders along the light transmission from a circle to an ellipse. The schematic geometry of this channel filter is shown in Fig. 2(a). The length of the ellipse's major axis is 513 nm and that of the ellipse's minor axis is 427 nm. So the area of each ellipse is equal to that of the circle. The length of the ellipse's major axis is 1.2 times that of the minor axis. The angle from the direction of the light transmission (also the PC's ΓX direction) to the direction of the ellipse's major axis is denoted by "θ" in Fig. 2(a).

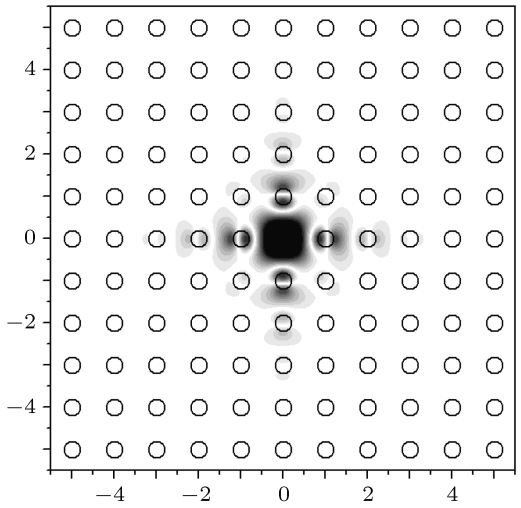


Fig. 1. Structure of the one-point defect and the electric intensity profile of the defect mode resonant at a wavelength of 1554.8 nm.

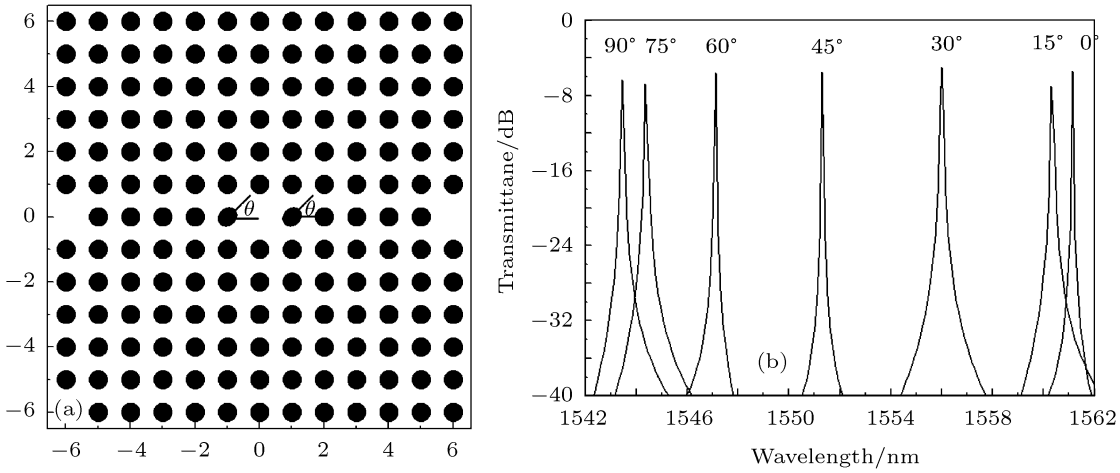


Fig. 2. Schematic geometry of the channel filter (a), the length of the major axis of the two ellipses adjacent to the central one-point defect is 513 nm and that of the minor axis is 427 nm. The corresponding transmittances for the structures with different orientation angles (b).

Figure 2(b) shows the corresponding transmittances of the incident light through the channel filters for different θ values calculated by the finite-different time-domain method.[21,22] In all calculations, the length of a lattice spacing is divided into 80 grids and through a long total calculation time of several million time intervals, a good calculation precision is ensured. When θ is equal to 0°, the ellipse's

major axis is placed along the direction of light propagation (also the PC's ΓX direction). It can be seen from Fig. 2(b) that the resonant peak is located at 1561.1 nm. Compared with the structure shown in Fig. 1(a), it can be seen that there is a wavelength variation of 6.2 nm when the circular rod is replaced by the elliptical rod. When the values of θ are changed as 15°, 30°, 45°, 60°, 75°, and 90°, the wavelengths at which the resonant peaks are located become 1560.3, 1556.0, 1551.3, 1547.1, 1544.3, and 1543.4 nm, respectively. The resonant frequency increases when the rotation angle of the oval rods becomes larger, and it is more sensitive to the alteration of θ when its value is around 45°. The resonant light transmits the corresponding structures with excellent efficiency.

Keeping the area of the ellipse constant, we change the length of the ellipse's major axis to 533 nm, so the ellipse's minor axis becomes 410 nm, as is shown in Fig. 3(a). The length of the ellipse's major axis is 1.3 times that of the minor axis. Figure 3(b) shows the calculated transmittances of the channel filters against different θ values. When θ is equal to 0°, the resonant peak is located at 1563.8 nm. Compared with the structure shown in Fig. 2(a), it can be seen that there is a wavelength variation of 2.7 nm with the change of the ellipse's shape. When the values of θ are changed as 15°, 30°, 45°, 60°, 75°, and 90°, the wavelengths at which the resonant peaks are located become 1561.9, 1555.6, 1548.1, 1542.0, 1538.0, and 1536.7 nm, respectively. The variation of the resonant wavelength with the alteration of the ellipse's rotation angle is similar to that of the structure shown in Fig. 2.

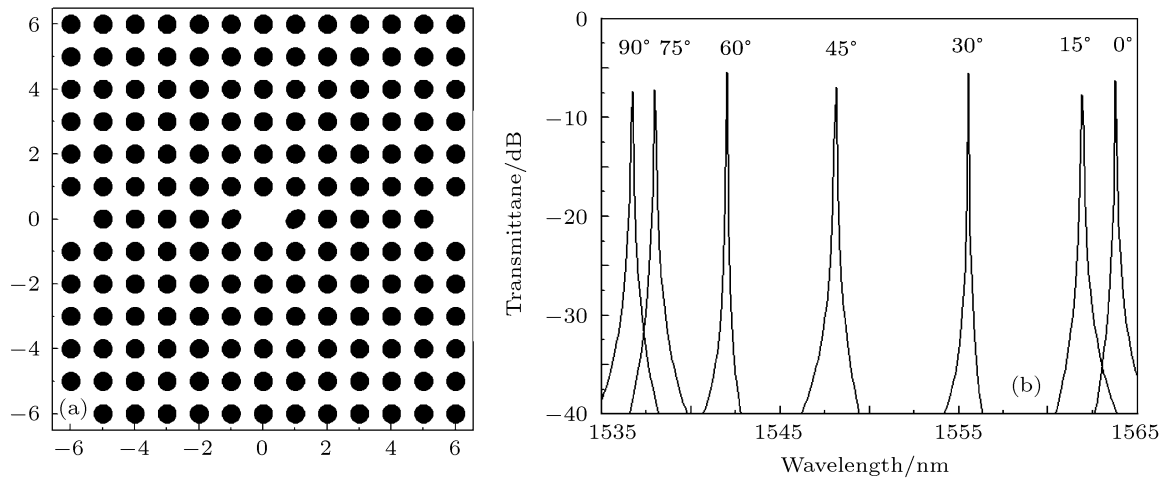


Fig. 3. Schematic geometry of the channel filter (a), the major axis of the two ellipses is 533 nm, and that of the minor axis is 410 nm. And the corresponding transmittances for the structures for different rotation angles (b).

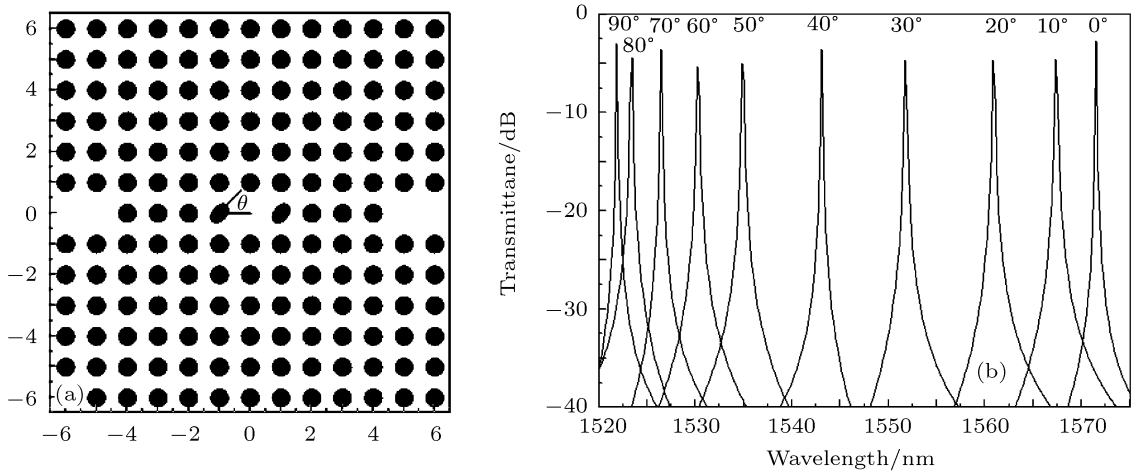


Fig. 4. Schematic geometry of the channel filter (a), the long axis of the two ellipses is 573 nm and that of the short axis is 382 nm. The corresponding transmittances for the structures for different orientation angles (b).

Finally, we change the length of the ellipse's major axis to 573 nm and the ellipse's minor axis to 382 nm, as shown in Fig. 4(a). In this case, the length of the ellipse's major axis is 1.5 times that of the minor axis and the area of the ellipse is just the same as in the above two structures. Figure 3(b) shows the calculated transmittances of the channel filters for different θ values. When θ is equal to 0°, the resonant peak is located at 1569.0 nm. Compared with the structure shown in Fig. 2(a), it can be seen that there is an alteration of 7.9 nm with the change of the ellipse's shape. When the values of θ are changed as 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 90°, the wavelengths at which the resonant peaks are located become 1566.7, 1560.2, 1551.7, 1543.1, 1537.1, 1529.4, 1526.4, 1523.4, and 1521.9 nm, respectively. The variation of the resonant frequency with the alteration of the ellipse's rotation angle is also similar to the above structures. as shown in Figs. 2 and 3.

According to the above results, we construct a channel filter with two output frequencies, which is shown in Fig. 5. The rotation angle of the two ellipses in the upper branch channel is 20° and that in the lower branch is 30°. It can be seen from Fig. 6 that the incident light whose wavelength is 1560.2 nm transmits through the upper channel with a high efficiency, while the incident light of 1551.7 nm transmits through the lower channel efficiently.

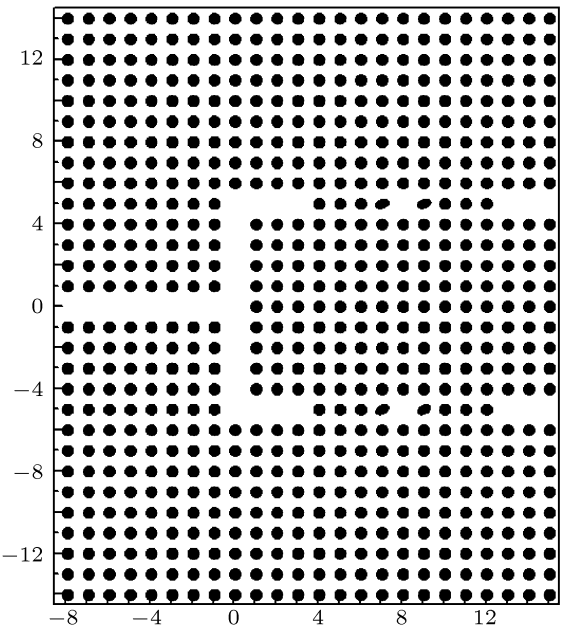


Fig. 5. Schematic geometry of the two-branch channel filter (a), the major axis of the two ellipses is 573 nm and that of the minor axis is 382 nm. The rotation angle of the ellipses in the upper branch is 20° and that in the lower branch is 30° (b).

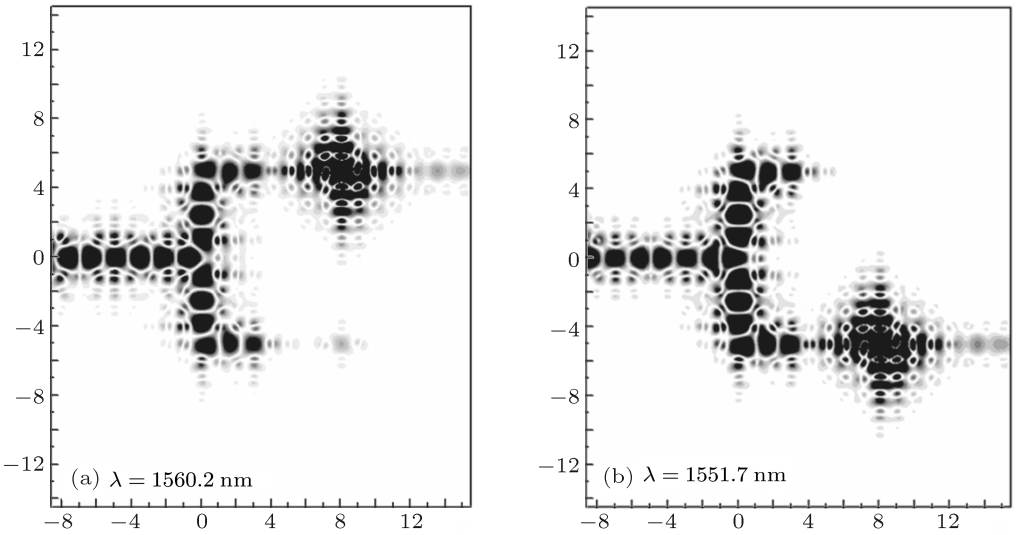


Fig. 6. Intensity profile of light transmission through the two-branch channel filter at different resonant wavelengths: (a) 1560.2 nm, (b) 1551.7 nm.

Based on the above results, we construct a ten-channel PC filter, which is displayed in Fig. 7. The ten micro-cavities are located on the two sides of the central linear W1-typed waveguide. The elliptical rods in the ten channels have the same major and minor axes, but their orientation angles are different. The input light signal propagates along the central waveguide and each cavity is coupled with another W1 waveguide serving as the output channel. The distances between two adjacent channels are $9a$ (a=lattice spacing), which is far enough to avoid the interaction of the output signals. The electric field

distributions of the light propagation with different wavelenths through the above ten-channel filter are shown in Fig. 8. When the incident wavelength is 1569.0 nm, the light energy resonant with the oval-rod defect whose rotation angle is $\theta = 0°$. The light beam transmits the adjacent cavity when the wavelength becomes 1566.7 nm and the orientation angle of the ellipse is 10°, as can be seen in Fig. 8(b). It can be seen that the light beam transmits the microcavity with a rotation angle of 80° when the wavelength becomes 1523.4 nm. When the incident frequency is changed to 1521.9 nm, an excellent-quality resonance between the W1 waveguide and the oval-rod cavity with a rotation angle of 90° is observed.

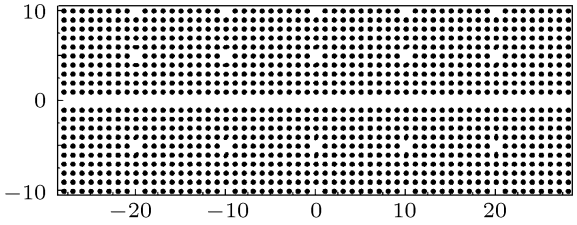


Fig. 7. Structure of a ten-channel-drop filter composed of a W1 waveguide and ten oval-rod defect resonators with different rotation angles.

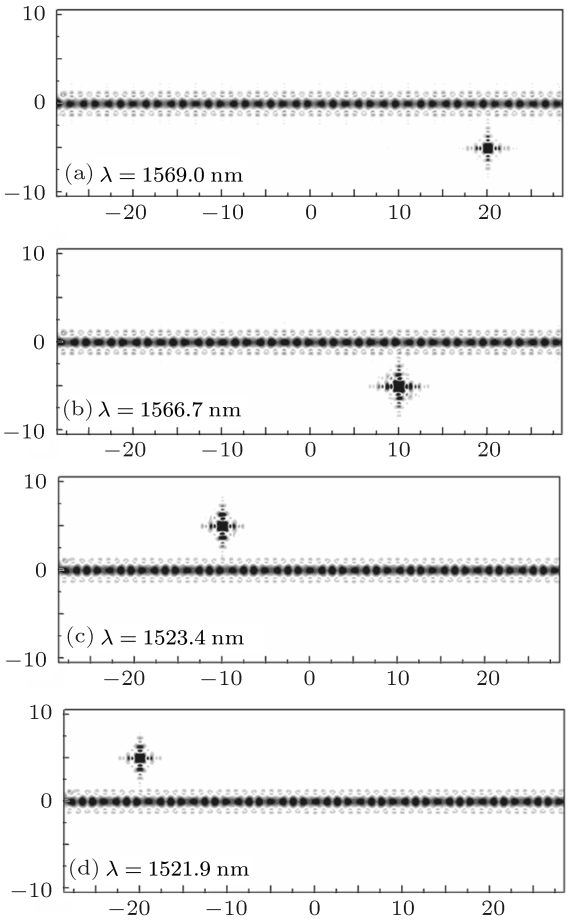


Fig. 8. Electric intensity profile in the ten-port resonant tunneling filter at different resonant wavelengths: (a) 1569.0 nm, (b) 1566.7 nm, (c) 1523.4 nm, and (d) 1521.9 nm.

3. Conclusions

The light propagation properties of oval-rod channel filters are systematically studied. It is found that the shape alteration of the defects from the usual circle to ellipse offers a powerful approach to engineer the resonant wavelength of channel filters. The resonant wavelength can be flexibly adjusted by just changing the orientation angle of the elliptical defects. The working wavelength region can be altered by changing the length of the axis of the ellipse. Our results provide a feasible suggestion for the design of resonant tunneling filters in future optical integrated circuits.

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