A compact in-plane photonic crystal channel drop filter*

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This paper presents a novel in-plane photonic crystal channel drop filter. The device is composed of a resonant cavity sandwiched by two parallel waveguides. The cavity has two resonant modes with opposite symmetries. Tuning these two modes into degeneracy causes destructive interference in bus waveguide, which results in high forward drop efficiency at the resonant wavelength. From the result of numerical analysis by using two-dimensional finite-difference time-domain method, the channel drop filter has a drop efficiency of 96% and a Q value of over 3000, which can be used in dense wavelength division multiplexing systems.

Keywords: photonic band gap materials, integrated optics, optical waveguides, optical communications devices

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1. Introduction

Photonic crystals (PCs) are periodic dielectric structures. The propagation of light in these structures can be described by the photonic band structure. Light with frequencies in the photonic bandgap cannot be propagated in the PCs.[1,2] Therefore, the PCs can be used as perfect mirrors and inhibit spontaneous emission. An introduced defect might create a defect state in the bandgap. The PC structures with defects can be used as waveguides,[3−5] resonant cavity with high Q value,[6−10] delay lines,[11,12] optical switch,[13−15] and channel drop filters.[16−31] Furthermore, PC devices are compact, easy to be integrated. Thanks to these advantages, PC structures have potential application in integrated optics, laser and optical communication.

Wavelength division multiplexing (WDM) systems based on PC channel drop filters are very small in dimension and have a high efficiency. Since Fan *et al.* proposed a PC channel add-drop wavelength demultiplexer[16,17] composed of two identical resonant cavities sandwiched by two parallel waveguides which supports two resonant modes with opposite symmetries, PC channel drop filter has attracted extensive attention.[18−21] Noda *et al.*[22] raised another method to trap and drop photons into the vertical direction of the PC slab through the coupling of a single defect and a waveguide. They also proposed a method of tuning the resonant wavelength by changing the lattice constant of the PC structure in order to further construct a dense WDM (DWDM) system.[22] In principle, nearly 100% drop efficiency can be realized and then light can be collected in the normal direction of the PC slab. However, it is a real challenge to integrate this channel drop filter into a planar optical integrated circuit. Thus, various drop filters based on in-plane PC structures have been reported in literatures.[23−31] The fabrication of the channel drop filter composed of two identical cavities which support a resonant mode with two-fold degeneracy is quite complex. One way is to design a channel drop filter with only one cavity sandwiched by waveguides. In that case, introducing resonant mirrors[23,24] and utilizing the reflection of heterostructure interface[25] are put forward to enhance the drop efficiency. Ring resonators are also used in the design of PC channel drop filters.[26] Qiu presented a channel drop filter with only one cavity formed by altering the radius of air holes in the PC structure, which has two resonant modes with opposite symmetries.[29] This paper presents a novel microcavity supporting two resonant modes with opposite symmetries and a very compact in-plane PC channel drop filter is realized. The cavity

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is formed by adjusting the radius of holes and shifting the positions of the holes around a central hole. When these two modes in this single cavity are degenerate, a forward drop channel wavelength demultiplexer works. The drop efficiency is about 96% and the Q value is over 3000.

2. Cavity design and results

In a channel drop filter with two waveguides and a resonant cavity placed between waveguides, we consider the resonant cavity with not only a symmetrical plane perpendicular to the waveguides at $z = 0$, but also a symmetry plane parallel to the waveguides at $x = 0$, as shown in Fig. 1. Assuming that the cavity has two resonant modes which have opposite symmetries at these two symmetrical planes, we find that the system can perform different output direction as theoretically pointed out in Ref. [32] and verified by the results in Refs. [27]–[31]. We consider a situation different from that in Refs. [27]–[31] that these two modes are symmetric and asymmetric with respect to the plane $z = 0$, defined as even mode and odd mode. Meanwhile, both modes are asymmetric to the plane $x = 0$ (Figs. 1(b) and 1(c)). According to Ref. [32], when these two modes have the same resonant wavelength and become degenerate, this channel drop filter will result in high forward drop efficiency.

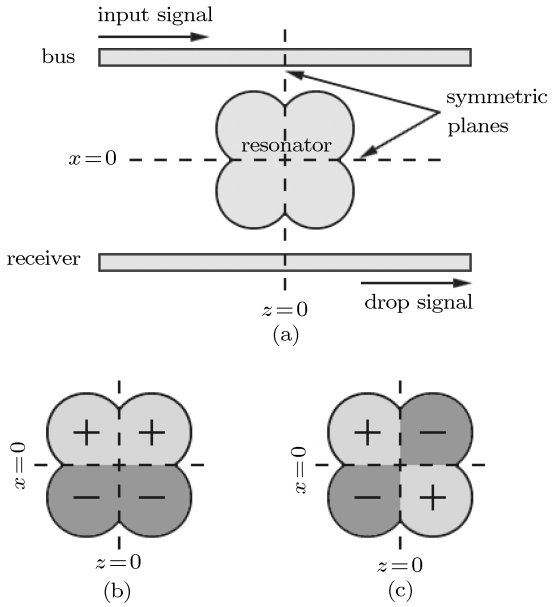


Fig. 1. (a) A four-port system consisting of a resonator with two symmetric planes perpendicular to two waveguides at $z = 0$ and parallel to the waveguides at $x = 0$, (b) the even mode symmetric to plane $z = 0$ and asymmetric to plane $x = 0$, (c) the odd mode asymmetric to plane $z = 0$ and asymmetric to plane $x = 0$.

A silicon-on-insulator wafer is used and the silicon layer is 220 nm. A triangular PC is formed on the silicon layer. In this paper, only TM waveguide modes (The magnetic field is along the axis of the holes) are considered. Because we use two-dimensional finite-difference time-domain (FDTD) simulation, we have to find the effective refractive index of the in-plane silicon layer. The effective refractive index of the silicon layer is 2.8148 at the wavelength of 1550 nm when the bottom cladding layer of silica is etched away.

Figure 2 shows the configuration of the resonant cavity in our device. The triangular PC structure has a lattice constant of $a = 450$ nm, and the radius of the periodical air holes in the PC slab is $r = 0.35a$. The waveguide on the right is the bus waveguide (port 1 and port 2), whereas the left waveguide is the drop waveguide (port 3 and port 4). The cavity is introduced between the waveguides. The radius of the air holes marked by O, A and B are r_O, r_A and r_B respectively. The positions of O hole and B holes are not adjusted, while A holes are moved from their original lattice points along the line OA to the new positions which make the distance between an A hole and the O hole be $r_{\rm d}$.

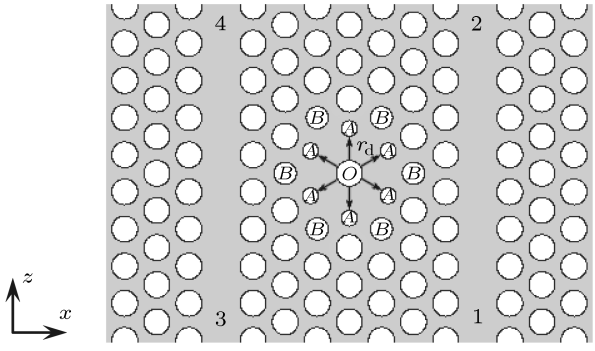


Fig. 2. The wavelength demultiplexer unit with a resonant cavity in the centre.

For the cavity with parameters set as $r_O = 0.35a$, $r_A = 0.23a$, $r_B = 0.30a$, $r_{\rm d} = 1.20a$, the normalized output power spectra at four ports simulated by FDTD method are shown in Fig. 3(a). It shows that there are drop signals in the receiver at 1535.5 nm and 1543.8 nm which implies that the cavity has two resonant modes. The magnetic intensity distributions of these two modes in the cavity are given by launching a continuous wave at 1535.5 nm and 1543.8 nm, as shown in Figs. 3(b) and 3(c) respectively. The mode in Fig. 3(b) is asymmetric to both plane $z = 0$ and plane $x = 0$, which should be an odd mode, while the mode in Fig. 3(c) is symmetric to plane $z = 0$ and

asymmetric to the plane $x = 0$, which should be an even mode.

These two modes meet the symmetrical conditions for a perfect channel drop filter mentioned previously. It means that if these two modes have the same resonant wavelength and become degenerate, it causes destructive interference in bus waveguide and results in high forward drop efficiency in drop waveguide, namely most of the signal energy at the resonant wavelength from port 1 can be dropped into port 4.

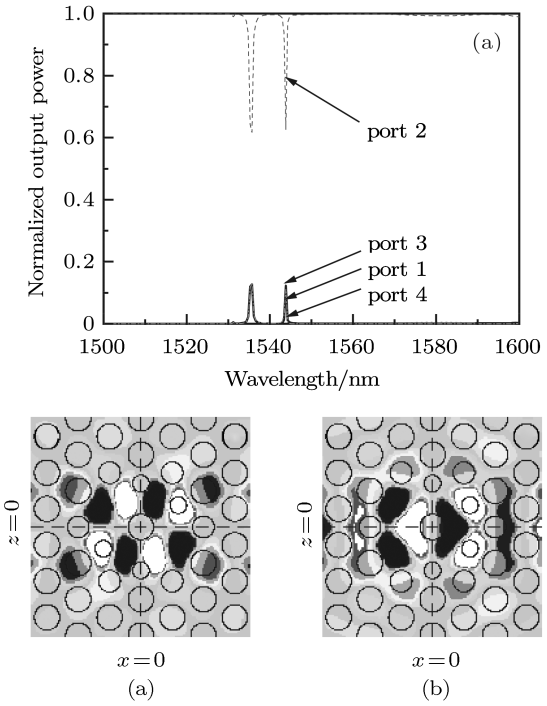


Fig. 3. (a) Normalized output power spectra at the four ports with the parameters of the cavity set as $r_O = 0.35a$, $r_A = 0.23a$, $r_B = 0.30a$, $r_{\rm d} = 1.20a$; (b) the magnetic intensity distribution of the odd mode at 1535.5 nm which is asymmetric to both plane $z = 0$ and plane $x = 0$; (c) the magnetic intensity distribution of the even mode at 1543.8 nm which is symmetric to plane $z = 0$ and asymmetric to plane $x = 0$.

To force the odd and even modes into degeneracy, fine adjustment of the cavity parameters is required. We made a series of optimizations, when the parameters are set as $r_O = 0.35a$, $r_A = 0.20a$, $r_B = 0.29a$, $r_{\rm d} = 1.21a$, the odd and even modes are degenerate. In this condition, the normalized output power spectra are shown in Fig. 4. The resonant wavelength of the cavity is 1567.1 nm, with very high drop efficiency of 99%. The bandwidth of the drop signal is about 0.5 nm and the Q value is over 3000.

From the output power spectra shown in Fig. 4, we can find that there is an unexpected mode at 1555.4 nm. Light at the wavelength of 1555.4 nm will be attenuated when it propagates in the bus waveguide. For an ideal wavelength demultiplexer, light with wavelength out of the resonant mode should transmit through the bus waveguide without attenuation. This unexpected mode will shorten the available transmission bandwidth of the bus waveguide and should be removed. After further tuning the parameters, we found that enlarging the radius of the air holes marked by C shown in Fig. 5 can move the unexpected mode towards short wavelength.

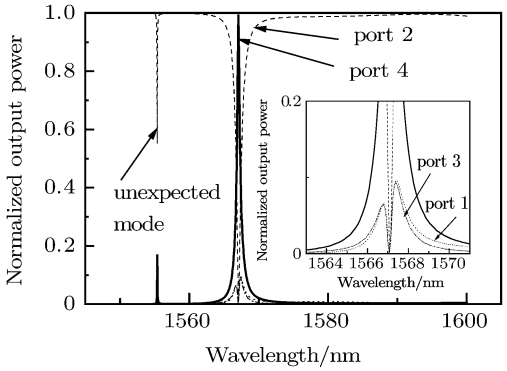


Fig. 4. Normalized output power spectra at the four ports when the parameters of the cavity are set as $r_O = 0.35a$, $r_A = 0.20a$, $r_B = 0.29a$, $r_{\rm d} = 1.21a$. Insert shows output power of port 1 and port 3.

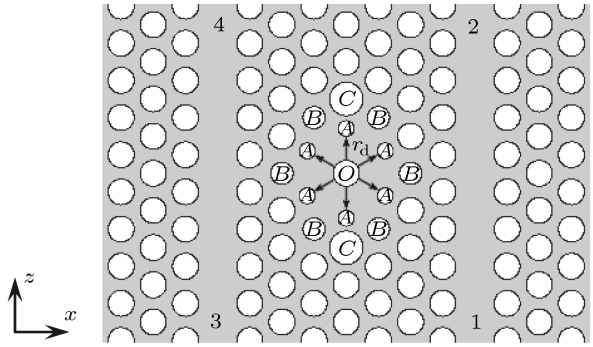


Fig. 5. Top view of the resonant cavity after enlarging the radius of the air holes marked by C.

After fine tuning, the optimized parameters of the cavity are $r_O = 0.35a$, $r_A = 0.21a$, $r_B = 0.30a$, $r_C = 0.46a$, and $r_{\rm d} = 1.21a$. From the normalized output power spectra shown in Fig. 6, we can find that the unexpected mode shifts to around 1510 nm and the system has much lower power loss at that wavelength. The transmission band edge of the waveguide at the long wavelength region is around 1600 nm. Thus, the ideal transmission bandwidth of the bus waveguide is about 90 nm which is very wide for the signals transmitting in telecommunication band around 1550 nm.

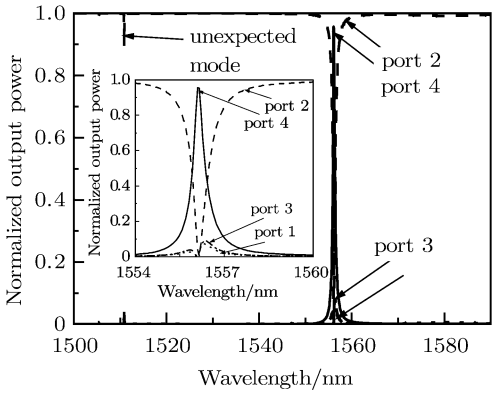


Fig. 6. Normalized output power spectra at the four ports when the parameters of the cavity are set as $r_O = 0.35a$, $r_A = 0.21a$, $r_B = 0.30a$, $r_C = 0.46a$ and $r_{\rm d} = 1.21a$. Insert shows the resonant peaks and dips.

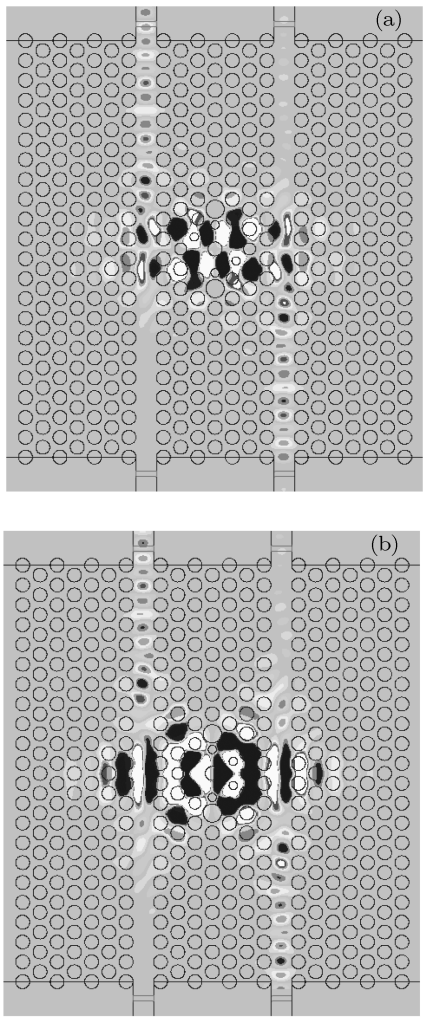


Fig. 7. Magnetic field distribution in steady state when continuous wave at resonant wavelength propagates through the structure shown in Fig. 5. (a) Odd mode and (b) even mode are degenerated in the bus waveguide and the signal is dropped from port 1 to port 4.

The resonant wavelength in this case is 1556.1 nm and the drop efficiency is about 96%. Figures 7(a) and 7(b) show the magnetic field distribution of odd mode and even mode at resonant wavelength. The two modes are degenerate in the bus waveguide and the signal is dropped from port 1 to port 4. The bandwidth of the signal is below 0.5 nm and the Q value is over 3000. This dropping bandwidth is narrow enough for the DWDM system. From Figs. 3(b) and 3(c), it is clear that most of the energy of the modes in the cavity is concentrated in the location without air holes, namely the high refractive index area. So the attenuation in the vertical direction will be very low because of high confinement. However, light with a wavelength near to the resonant wavelength has a transmitting proportion of about 8% at port 3 and reflection of 8% at port 1. It implies that 16% of the incident energy at these wavelengths will be lost after transmitting through the bus, which goes against shortening the available wavelength spacing of the device. This problem exists in most of the reported systems with single cavity,[26−28,30] but the cavity structure in Ref. [29] performs very low backward drop proportion near the resonant wavelength.

3. Conclusion

This paper presents a novel resonant cavity for a channel drop filter based on the triangular in-plane PC structure. The cavity is formed by adjusting the diameter of holes around the central hole and shifting the position of holes, which can support a symmetrical mode and an asymmetrical mode. Through forcing these two resonant modes in a single cavity into degeneracy, a channel drop filter system with very high drop efficiency and high Q value is achieved. In the optimized results, the drop efficiency is about 96%, and the Q value is over 3000. The available band for application is from 1510 nm to 1600 nm, namely a bandwidth of about 90 nm. It meets the requirements of DWDM systems for 1550 nm telecommunication band. As a PC device, it still inevitably has a high precision requirement. We hope it can be realized with the improvement of fabrication techniques.

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