A high quality factor photonic crystal channel-drop filter with a linear gradient microcavity*

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We design a channel-drop filter (CDF) with a linear gradient microcavity in a two-dimensional (2D) photonic crystal (PC). The model of three-port CDF with reflector is used to achieve high quality factor (Q-factor) and 100% channel-drop efficiency. The research indicates that adjusting the distance between reference plane and reflector can simultaneously influence the Q-factor due to coupling to a bus waveguide and the phase retardation occurring in the round trip between a microcavity and a reflector. The calculation results of 2D finite-difference time-domain (FDTD) method show that the designed filter can achieve the drop efficiency of 96.7% and ultra-high Q-factor with an ultra-small modal volume.

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In optical communication and photonic integration, the channel-drop filters (CDFs) are essential components, which are widely used in optical switches, modulators, beam splitters, multiplexers/demultiplexers and components in integrated optics circuits[1,2]. Based on photonic crystals (PCs), CDFs have some new features. On one hand, due to small size, compact structure and low loss of PC-CDF, many research groups[3-17] have designed two-dimensional (2D) PC to realize channel-drop functions. On the other hand, the multichannel filters can be easily accomplished by introducing multiple microcavities to this three-port CDF using side coupling[9,10].

In order to save bandwidth resources, the PC-CDF with high quality factor (Q-factor) needs to be designed. However, in general, there is a trade-off between the increase of the cavity Q-factor and the decrease of the coupling/dropping efficiency[11]. The even worse is that the maximum drop efficiency of PC-CDF is less than 50%, because when the photons are coupled into the resonant microcavity, a large proportion of the photons will flow back to the bus waveguide. Many researchers have made an effort to improve the drop efficiency by introducing a reflector. Kim et al[12] have achieved 100% drop efficiency in a three-port CDF with reflection feedback at the end of the bus waveguide, but they have no further study about how to obtain a high Q-factor. In order to realize high Q-factor performance, a high-order three-port CDF has been designed by using two synthesized coupled resonators as channel-drop microcavity and wavelength-selective reflection microcavity in a 2D-PC waveguide[14]. However, two microcavities with the same resonant frequency are needed in such a design, which is difficult to realize in the preparation process. A line-shaped defect with three missing air holes was designed by Noda et al[15], in which the Q-factor can reach 2 900. Recently, a three-port CDF with the linearly tapered lattice constants near the cavity center has been designed by Yu et al[16], which is used to achieve high Q-factor and small modal volume in a 2D-PC. These studies have laid a foundation for the design of filter with high Q-factor.

In this paper, a three-port CDF with an ultra-high Q-factor is presented based on 2D-PC microcavity, and two conditions needed for 100% drop efficiency are discussed. The microcavity's capability of capturing photons can be greatly improved by increasing the number of dielectric rods between microcavity and two waveguides, but the drop efficiency of PC-CDF can not be improved due to weak coupling. In this case, a linear gradient microcavity is constructed, so that the CDF can meet the conditions of achieving 100% drop efficiency and high Q-factor. The designed CDF has the potential to become an important component in all-optical communication and photonic integration in the future, especially in dense wavelength division multiplexing (DWDM) system in which multiplexing/demultiplexing can be easily realized.

Fig.1 shows the CDF structure based on a three-port system with reflection at the end of the bus waveguide. The microcavity possesses a mirror reflection symmetry structure with respect to the reference plane, and it supports only one single mode. The microcavity is used to realize the wavelength selection[12]. When the wave is

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only launched into the bus waveguide, it's verified that 100% drop efficiency can be achieved at[12]

$$Q_1/Q_2=2\,, \quad (1)$$

$$\varphi=2\pi m\,, \quad (2)$$

where Q_1 and Q_2 are the Q-factors related to the rates of decaying into the bus waveguide and the drop waveguide, respectively, and φ is the phase retardation which occurs after a round trip between reference plane and reflector.

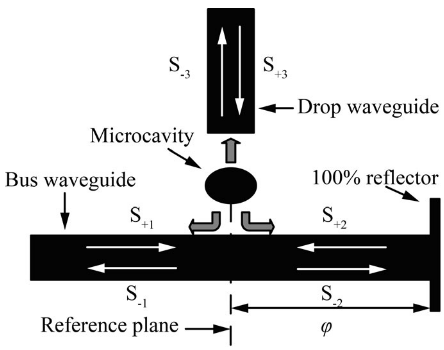


Fig.1 Schematic diagram of the three-port CDF with a 100% reflector

When there is no reflector, the drop efficiency $T(\omega)$ can be expressed as

$$T(\omega)=\left|\frac{\sqrt{\dfrac{1}{2Q_1Q_2}}}{\mathrm{j}(\dfrac{\omega}{\omega_0}-1)+\dfrac{1}{2Q_1}+\dfrac{1}{2Q_2}}\right|^2 . \quad (3)$$

It can be seen from Eq.(3) that the maximum drop efficiency is 50% when $Q_1/Q_2=1$, and the maximum drop efficiency is 44.4% when $Q_1/Q_2=2$. However, because Q_1 is affected by the reflector, the microcavity can not be designed in such a way, and the drop efficiency of filter without reflector becomes 44.4% ($Q_1/Q_2=2$) as claimed in Ref.[12].

Based on the theory above, we design a three-port CDF with reflector in a 2D-PC. The PC consists of square lattices of dielectric rods with high permittivity (ε=11.56) arranged periodically in air. The length of the lattice constant is described as a, and the radius of the rods is 0.2a. Owing to that in the perfect PC, only transverse magnetic (TM) mode (electric field direction is parallel to the rods) has a photonic bandgap (PBG), the calculations in this paper are based on TM mode. The structure of the three-port CDF with a 100% reflector in 2D-PC of square lattice composed of dielectric rods in air is shown in Fig.2(a). In the designed three-port CDF, a bus waveguide is constructed by removing one row of rods along the Γ-X direction, and a microcavity is formed by introducing a defect from the side of the bus waveguide. The other side of the microcavity is the drop waveguide, and only two rods exist between microcavity and two waveguides. As the end of the bus waveguide is blocked by rods, the 100% reflector is formed, and d is the distance that goes along with the bus waveguide between microcavity and reflector. The radius of rod in the center of microcavity is R=0.037 8a. Fig.2(b) shows the guide mode of the line defect waveguide is within the frequency range from 0.304c/a to 0.422c/a, and 0.371 2c/a represents the defect mode supported by the designed microcavity.

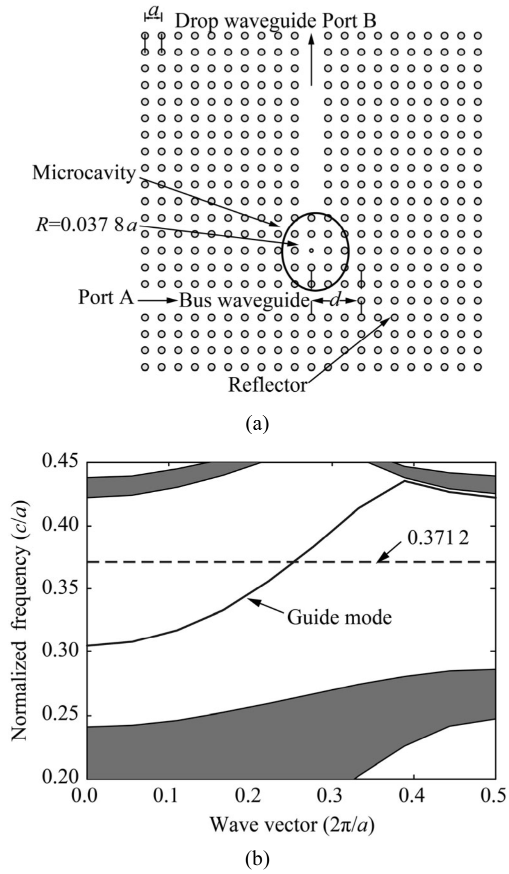


Fig.2 (a) The structure of the three-port CDF with only two rods existing between microcavity and two waveguides; (b) The guide mode of the line defect waveguide and the defect mode of the designed microcavity

The transmission spectrum of the designed CDF is calculated by using 2D finite-difference time-domain (FDTD) method with perfectly matched layers (PMLs) absorbing boundary conditions. Fig.3 shows the normalized intensity at port B and the Q-factor ratio of Q_1/Q_2, which are affected by the distance d between reference plane and reflector. With the increase of distance d, the phase condition of $\varphi=2\pi m$ is periodically met, and the Q-factor ratio of Q_1/Q_2 is in periodical oscillation. Fortunately, due to the insensitivity to the phase retardation and the Q-factor ratio of Q_1/Q_2[12], when the phase condition is met, and the ratio of Q_1/Q_2 close to 2 happens simultaneously, nearly 100% drop efficiency can be easily achieved. In addition, it can be intuitively seen in Fig.3 that the 100% drop efficiency will be presented periodically with the change of distance, and thus the highly efficient multi-channel-drop filters can be easily achieved. Owing to that there are only two rods between microcavity and two waveguides, as shown in Fig.2(a), the microcavity's capability of capturing photons is not strong, and the Q-factor is just 851.

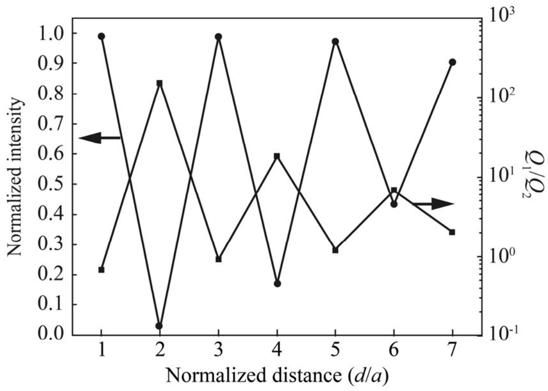


Fig.3 Normalized intensity at port B and Q-factor ratio as a function of distance *d* between reference plane and reflector

In order to achieve ultra-narrow-band filtering characteristic, the microcavity's capability of capturing photons can be improved by increasing the quantity of rods between microcavity and two waveguides. For that reason, one rod is added respectively between microcavity and two waveguides on the basis of the structure shown in Fig.2(a). However, it doesn't meet the requirement of achieving 100% drop efficiency by adding one rod directly. On the contrary, the coupling abilities between microcavity and two waveguides are both greatly weakened, and the drop efficiency of PC-CDF also declines. The influence on microcavity is determined by the surrounding rods' radii, positions, reflective indices, etc. The closer the rod to the center of the microcavity, the greater impact on the microcavity. Therefore, by changing the physical parameters of rods around the microcavity, the conditions needed for 100% drop efficiency are met, and the Q-factor of microcavity can be increased simultaneously. The structure of the designed PC-CDF is shown in Fig.4(a), in which the radii of rods between microcavity and two waveguides change linearly and reduce gradually from outside to inside. While other physical parameters remain the same, the radius of rod in the center of microcavity is R_1=0.062 3a, the radius of two adjacent rods is R_2=0.145a, the radius of two outermost rods near bus waveguide and drop waveguide is R_4=0.173a, and the radius of two rods in the secondary outer is R_3=0.165a. The mode supported by the microcavity above is still at the frequency of 0.371 2c/a as shown in Fig.4(b).

The normalized transmission spectrum of the designed CDF shown in Fig.4(a) is calculated by using 2D-FDTD method with PMLs absorbing boundary conditions. The drop efficiency of 96.3% is achieved in port B at the frequency of 0.371 2c/a with only a small amount of energy returning to port A. The microcavity's capability of capturing photons is greatly improved, and the Q-factor of microcavity reaches 2 905($\lambda/\Delta\lambda$).

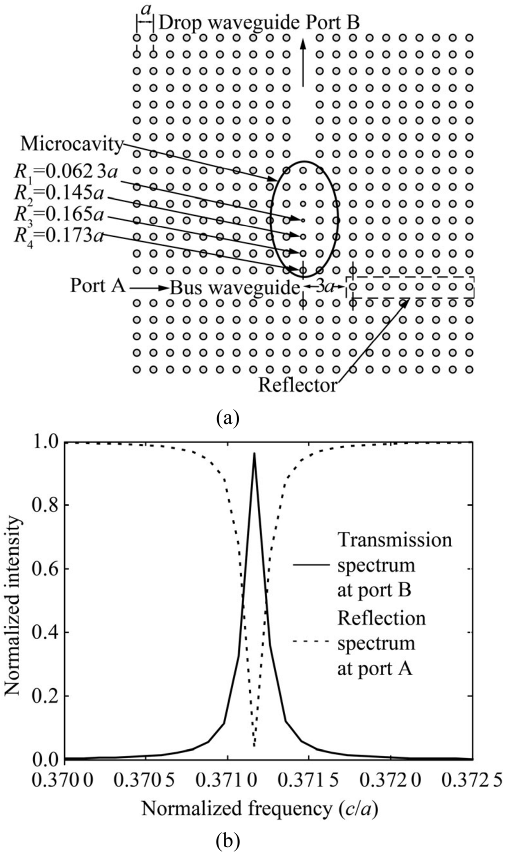
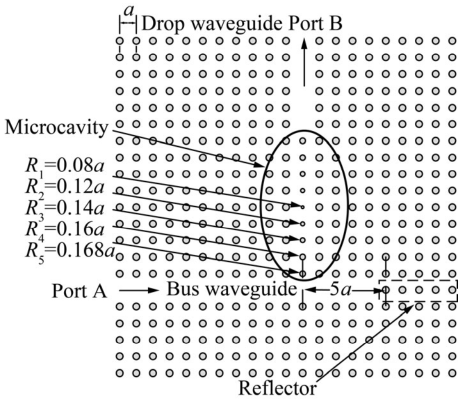


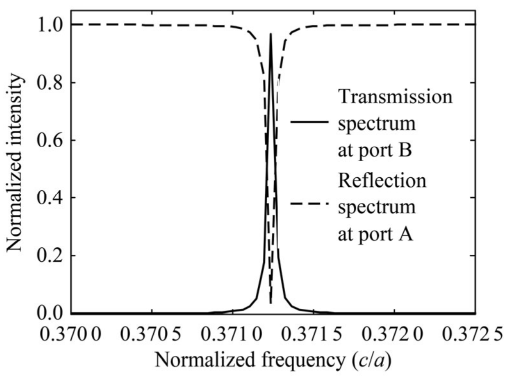
Fig.4 (a) The structure of three-port CDF with three rods existing between microcavity and two waveguides and the distance between reference plane and reflector of 3*a*; (b) Normalized transmission and reflection spectra of the designed filter calculated by using the 2D-FDTD method

Owing to that the distance between reference plane and reflector is 3a, the phase condition of $\varphi=2\pi m$ and $Q_1/Q_2=2$ can be met simultaneously, and thus 96.3% drop efficiency can be achieved in port A. In order to keep the characteristics of PBG and achieve an easier preparation process in PC, the distance between reference plane and reflector can merely be the integral multiple of lattice constant. Therefore, the phase condition of $\varphi=2\pi m$ and $Q_1/Q_2=2$ can not be always strictly met. In general, only the drop efficiency in the range from 96% to 99% can be achieved.

We further increase the distance to make the number of rods between microcavity and two waveguides become 4. The coupling ability between microcavity and waveguides is further weakened at this time. Similarly, the two conditions can be met to achieve 100% drop efficiency by changing the physical parameters of rods around microcavity. The designed structure is shown in Fig.5(a), in which the distance between reference plane and reflector is 5*a*. Likewise, the radii of rods between microcavity and two waveguides change linearly and reduce gradually from outside to inside. While other physical parameters remain the same, the radius of rod in the center of microcavity is R_1=0.08*a*, the radius of two adjacent rods is R_2=0.12*a*, the radius of another two outer rods is R_3=0.14*a*, the radius of two outermost rods near bus waveguide and drop waveguide is R_5=0.168*a*, and the radius of two rods in secondary outer is R_4=0.16*a*. The mode supported by the microcavity above is still at the frequency of 0.371 2*c*/*a* as shown in Fig.5(b).



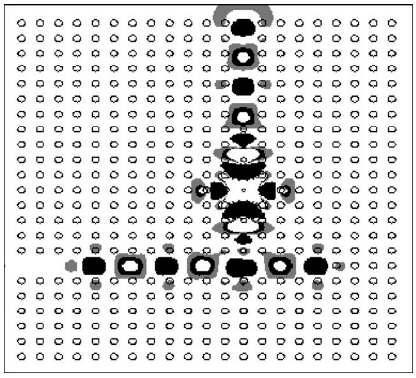
(a)



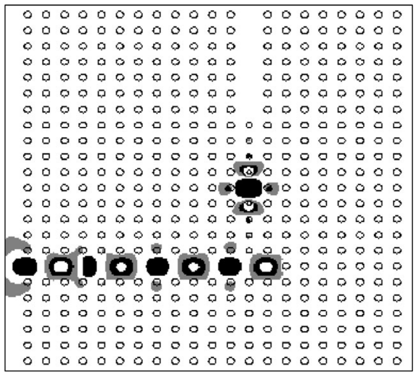
(b)

Fig.5 (a) The structure of three-port CDF with four rods existing between microcavity and two waveguides and the distance between reference plane and reflector of 5*a*; (b) Normalized transmission and reflection spectra of the designed filter calculated by using the 2D-FDTD method

The normalized transmission spectrum of the designed CDF shown in Fig.5(a) is calculated by using 2D-FDTD method with PMLs absorbing boundary conditions. THE simulation result in Fig.5(b) shows that 96.7% drop efficiency of port B is achieved at the frequency of 0.371 2*c*/*a*. If the length of lattice constant is 575.4 nm, the resonant wavelength of microcavity will be at the third communication window (1 550 nm), and the Q-factor will reach 6 570($\lambda/\Delta\lambda$) with an ultra-small model volume value of 0.030 72$(\lambda/n)^3$. Fig.6(a) shows steady state wave propagation at resonant frequency (f=0.371 2*c*/*a*) of the CDF. Fig.6(b) shows that if the distance between reference plane and reflector is 2*a*, the resonant mode of the microcavity will be excited. However, the two conditions of 100% drop efficiency couldn't be met, so the energy will return to the bus waveguide.



(a) *d*=5*a*



(b) *d*=2*a*

Fig.6 The steady state wave propagations at the resonant frequency (*f*=0.371 2*c*/*a*) of the designed CDFs with the distances between reference plane and reflector of (a) *d*=5*a* and (b) *d*=2*a*

In conclusion, the model of three-port PC-CDF with reflector is used to achieve high Q-factor and 100% drop efficiency. The performance of the designed CDF is calculated by using 2D-FDTD method. The simulation results show that the phase condition of $\varphi=2\pi m$ and Q-factor ratio of $Q_1/Q_2=2$ can be easily achieved simultaneously. Based on the theoretical model, a linear gradient microcavity is constructed in a 2D-PC. The results show that the designed filter can achieve the drop efficiency of 96.7% and a high Q-factor value of 6 570($\lambda/\Delta\lambda$) with an ultra-small modal volume of 0.030 72$(\lambda/n)^3$. Additionally, this kind of microcavity is a flexible structure that the quantity of rods between microcavity and two waveguides can be further increased, and the higher Q-factor can be achieved by adjusting the physical parameters of the surrounding rods. The designed filter provides a valuable reference for designing multiplexer in DWDM.

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