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Optimization transmission of photonic crystal coupled cavity and design of demultiplexer for wavelength division multiplexing application

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Abstract. A new method to optimize transmission of photonic crystal filter composed of coupled cavities is proposed. This method can improve transmission without changing 3 dB bandwidth and it is achieved by shifting the defect rods in two cavities centripetally to shorten the distance between energy distribution centers within two cavities. Finally, an ultra compact four-channel demultiplexer is demonstrated by using this optimization method, and this device satisfies the coarse wavelength division multiplexing standard of ITU-T G.694.2 with transmission 99% for each channel. [DOI: 10.1117/1.OE.51.8.084002]

Subject terms: demultiplexer; photonic crystal; coupled cavity.

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1 Introduction

Photonic crystal (PC) can control the light transmission flexibly, and the devices achieved by it possess many advantages of low energy loss, utralcompact size, etc. Therefore, PC is more suitable for applications in the field of integrated optics and optical networks, especially for designing the optical devices such as optical demultiplexers,[1–3] optical sensors[4,5] and optic buffers,[6,7] where an optical demultiplexer can separate different wavelengths of light and has been a key device in all-optical integrated communication networks.

PC coupled cavity waveguide (PCCCW)[8–12] has an attractive feature that the slope of guided mode in photonic band gap (PBG) is smaller than that of PC line defect waveguide (PCLDW),[8] namely the frequency range of light propagation in PCCCW is narrower than that of PCLDW, and therefore PCCCW is more suitable for designing filter[13–16] and demultiplexer[17–19] with narrow bandwidth.

In order to design a filter with narrow bandwidth, it's useful to increase the distance between neighboring cavities for PCCCW because the guided mode in PBG will become more flat and the frequency range that light can propagate will become small. However, narrowband is obtained at the cost of weak coupling between neighboring cavities, and the coupling intensity becomes very weak when distance between neighboring cavities increases especially when the distance is more than $3a$, where a is lattice constant.[12] Consequently, it is meaningful to not only improve the transmission of filter composed of PCCCW but also keep the narrow bandwidth unchanged.

In this paper, we propose one method that can improve the transmission of PCCCW with double cavities based on keeping the 3 dB bandwidth nearly unchanged at 3 nm. It is achieved by shifting the defect rods in two cavities centripetally and shortening the distance between energy distribution centers within two cavities, and therefore the coupling intensity is enhanced between two cavities and transmission is improved. And we find the optimum shifting distance is $0.6a$, where the normalized transmission is 99.5%. Finally, we apply this method to design a PC four-channel demultiplexer by integrating four channel PCCCWs, and the maximum normalized transmission can get 99% for each channel. The proposed demultiplexer satisfies the CWDM standard of ITU-T G. 694.2, and its channel spacing is 20 nm. Both plane wave expansion (PWE) and finite difference time domain (FDTD) methods are simulated by Bandsolve and Fullwave Simulator of Rsoft.

2 Optimization of Coupled Cavity

2.1 *Theory Analysis*

We consider a two-dimensional PC composed of triangular lattice Si rods in air background. The refractive index of the Si rods and the background-air is 3.48 and 1, respectively. The radius of Si rods of perfect PC is $r = 0.15a$, where a is equal to 626 nm. The dispersion curves of perfect PC are calculated by using PWE method. The band gap of the perfect PC exists in the frequency ranges of 0.32 to $0.52(a/\lambda)$ with transverse magnetic (TM) polarization (for which the incident electric field was parallel to the rods).

In this paper, we mainly study the PCCCW with double cavities and analyze the optimization method to improve the transmission of it. Then, we firstly analyze the properties of guided mode in PBG of PCCCW,[9] and the dispersion slope of guided mode can be written[9] as

$$S(\lambda) = -\frac{\lambda_0^2[(2\kappa\lambda)^2 - 4(\lambda_0 - \lambda)^2 - 3\kappa\lambda_0\lambda]}{2\pi c\Delta[(\kappa\lambda)^2 - (\lambda_0 - \lambda)^2]^{5/2}}, \tag{1}$$

where λ is the wavelength in vacuum, κ is the hopping parameter, Δ is the distance between neighboring cavities, λ_0 is the central wavelength and c is the light velocity in vacuum.

When the cavity spacing Δ increases, the coupling intensity between neighboring cavities will become weakened and

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the slope of guided mode in PBG will decrease.[12] In order to analyze the relationship between dispersion slop $S(\lambda)$ and bandwidth for PCCCW, we simulate LDW, CCW1 with $\Delta = 2a$ and CCW2 with $\Delta = 3a$, respectively, as shown in Fig. 1. The bandwidths we discuss in this paper are all 3 dB bandwidth and named $\Delta\lambda_{3\mathrm{dB}}$. Figure 1(a)–1(c) show the dispersion curves and Fig. 1(d)–1(f) shows the normalized transmission of LDW, CCW1 and CCW2, respectively. The transmission is simulated by FDTD method. From Fig. 1, we can see that dispersion slope $S(\lambda)$ decreases with increasing distance between neighboring cavities, while the bandwidth of transmission spectrum also becomes narrower. We can see that the bigger Δ is, the smaller $S(\lambda)$ is, and the narrower the bandwidth is.

We analyze the slope $S(\lambda)$ when $\lambda = \lambda_0$, and Eq. (1) can be written as

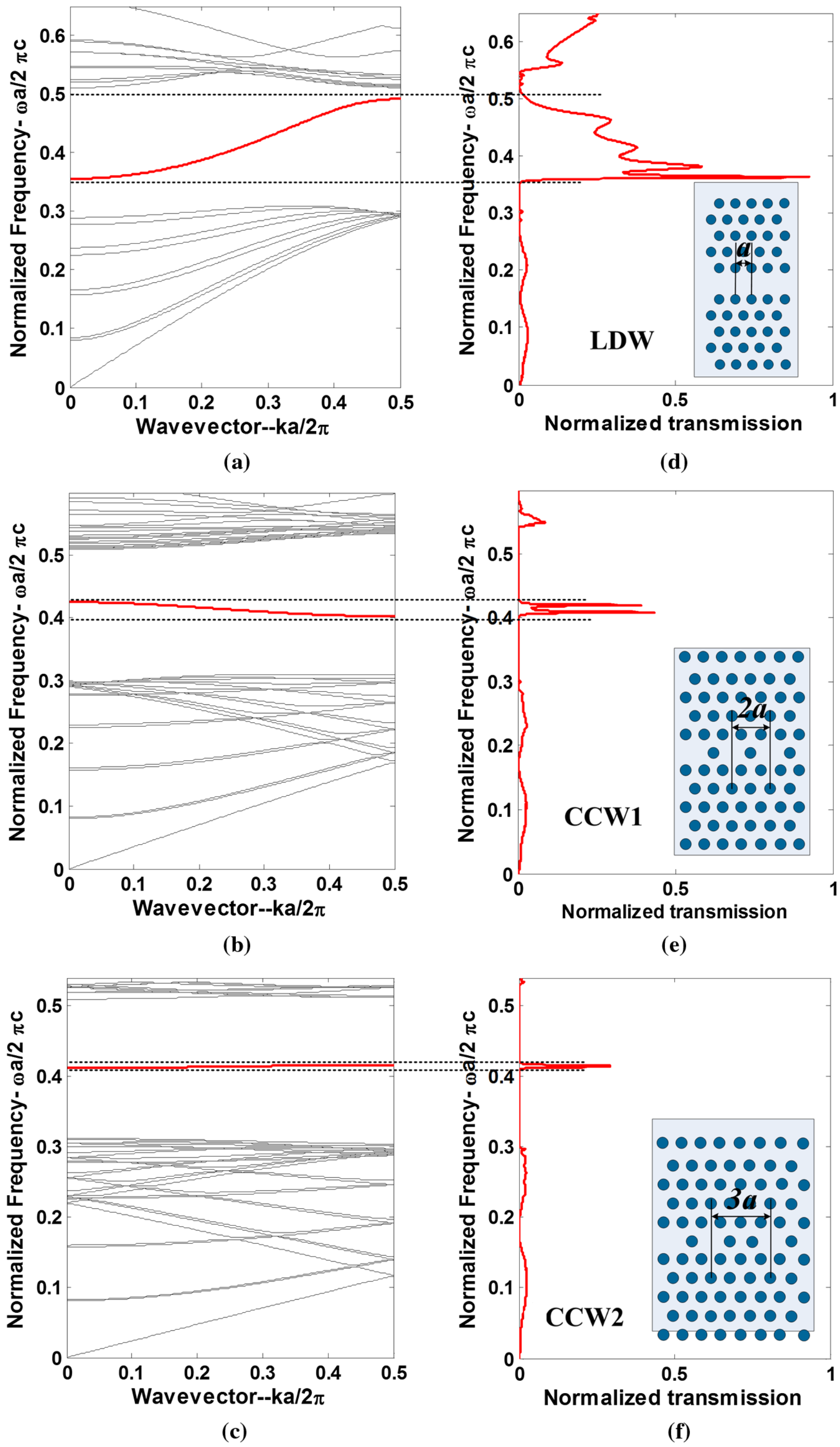

Fig. 1 (a)–(c) Dispersion curves of LDW, CCW1 and CCW2; (d)–(f) Normalized transmission of LDW, CCW1, and CCW2, and the corresponding waveguide structures are shown in insets, respectively.

$$S(\lambda_{0)} = -\frac{\lambda_0^2[(2\kappa\lambda_0)^2 - 4(\lambda_0 - \lambda_0)^2 - 3\kappa\lambda_0\lambda_0]}{2\pi c\Delta[(\kappa\lambda_0)^2 - (\lambda_0 - \lambda_0)^2]^{5/2}} = -\frac{1}{2\pi c\Delta\lambda_0\kappa^4}. \quad (2)$$

It can be seen that $S(\lambda_0)$ depends on the product of Δ, λ_0 and κ^4, and therefore we can keep $S(\lambda_0)$ and the 3 dB bandwidth unchanged by keeping this product and Δ unchanged, namely the product of λ_0 and κ^4 is unchanged. However, if we want to design a narrowband filter composed of coupled cavity, we should fix Δ at a bigger value, but transmission and bandwidth will decrease simultaneously while Δ increases, as shown in Fig. 1. It means that $S(\lambda_0)$ and κ both decrease when Δ increases. Therefore when we obtain the desired 3 dB bandwidth and fix Δ at certain value (especially bigger than $3a$), we must improve the transmission by enhancing the coupling intensity between neighboring cavities, namely κ must be enlarged. It can be said that we need to find a method which can enhance the coupling intensity between neighboring cavities while Δ is unchanged. Therefore, for a PCCCW with fixed Δ, we can improve its transmission by shortening the distance between energy distribution centers in two cavities without changing Δ. Here, the energy distribution center is a position where energy mainly concentrates. We define the distance between energy distribution centers in two neighboring cavities as L, and we can enlarge κ and improve the transmission by shortening L, and keep bandwidth nearly unchanged by keeping Δ and the product of Δ, λ_0 and κ^4 nearly unchanged.

2.2 *Optimization Method*

In order to illuminate the optimization principle more clearly, we only study the PCCCW with double cavities as shown in Fig. 2(a), where two cavities are both formed by reducing the radius of one defect rod in the center of cavity and marked as shadow. The distance between neighboring cavities is $\Delta = 4a$. The radius of defect rods in the center of two cavities is both $r_{\text{def}} = 0.05a$. The structures of two cavities in Fig. 2(a) are both symmetrical, and their energy distribution within cavity should be symmetrical. Then we study the impact of defect rods on the energy distribution and give three kinds of asymmetrical cavity structures formed by shifting defect rods along X-direction, $-X$-direction or both, as shown in Fig. 2(b)–2(d), respectively, where the shifting directions are all marked as red dashed arrows. Here, symmetry or asymmetry is about X-direction for each cavity. In Fig. 2(b), the defect rod in the first cavity is shifted along X-direction, while the defect rod in the second cavity is shifted along $-X$-direction, and the shifting distance is named d. In Fig. 2(c), the defect rod in the first cavity is shifted along $-X$-direction, while the defect rod in the second cavity is shifted along X-direction, and the shifting distance is named $d1$. In Fig. 2(d), two defect rods in two cavities are both shifted along X-direction, and the shifting distance is named D. We simulate the mode profiles to illustrate energy distributions within cavities as shown in Fig. 3, corresponding to the four cavity structures in Fig. 2 with shifting distance $d = d1 = D = 0.5a$, and the positions where the energy concentrates are marked as red dashed ellipse. It can be seen that energy distribution is symmetrical for symmetrical cavity structure shown in Fig. 3(a), and energy concentrates on the center defect rod and the rods around cavity. However, for asymmetrical cavity structure, energy concentrates mainly on the defect rod and the nearby rod, as shown in Fig. 3(b)–3(d). From Fig. 3(b), it can be seen that the distance L between energy distribution centers in two cavities is shorter than initial distance Δ between two cavity centers, namely $L < \Delta = 4a$. When Δ becomes shorter, and κ will become bigger,[12] therefore transmission should be improved. From Fig. 3(b), it can be seen that the distance L between energy distribution centers in two cavities is larger than initial distance Δ between two cavities, namely $L > \Delta = 4a$. When Δ becomes bigger, and κ becomes smaller, transmission should decrease.[12] From Fig. 3(c), it can be seen that the distance L between energy distribution centers in two cavities is equal to initial distance

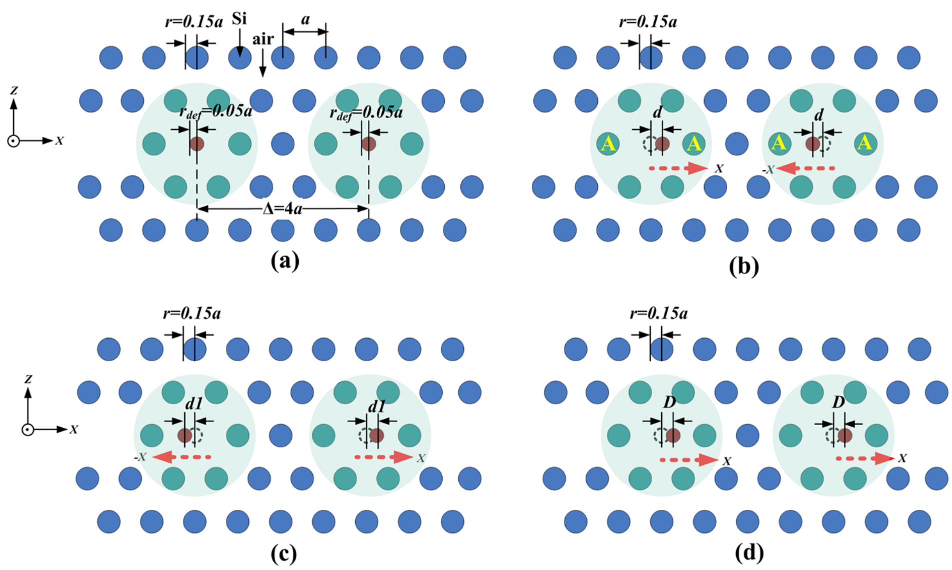

Fig. 2 (a) Schematic of PCCCW with double cavities, (b) Shifting of the defect rod in first and second cavity is along X-direction and $-X$-direction, respectively. (c) Shifting of the defect rod in first and second cavity is along $-X$-direction and X-direction, respectively. (d) Shifting of defect rods in two cavities are both along X-direction.

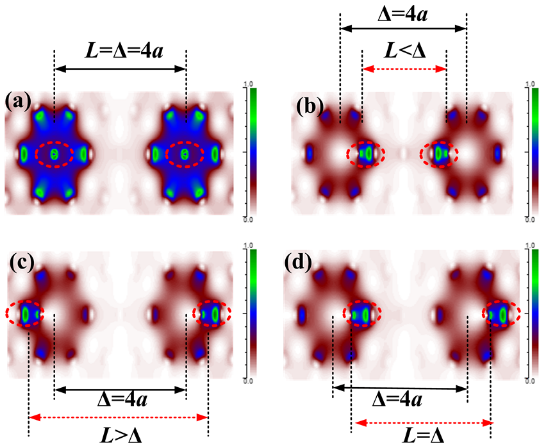

Fig. 3 Mode profiles in (a), (b), (c) and (d) corresponding to cavity structures in Fig. 2(a), , –2(d), respectively.

Δ between two cavities, namely $L = \Delta = 4a$. Therefore κ has little change and transmission is nearly unchanged.

Next, we will analyze the impact of three shifting methods [shown as Fig. 2(b)–2(d)] on the transmission.

Firstly, we consider the shifting case shown as Fig. 2(b) and simulate the normalized transmission spectrums when shifting distance d is from 0 to $0.8a$ along the shifting direction shown as red dashed arrow, and the simulation results are shown in Fig. 4(a). We can see that the normalized transmission first increases until $d = 0.6a$, then it gradually decreases. It can be explained because when the defect rods are shifted along X-direction and $-X$-direction respectively, the distance-L between two energy distribution centers of two cavities becomes shorter than Δ, and κ will become bigger. According to Eq. (2), λ_0 will decrease when Δ and $S(\lambda_0)$ is both unchanged and κ increases. Therefore coupling intensity between two cavities become stronger and transmission will be improved. As shown in Fig. 4(a), when the shifting distance d is $0.6a$, the maximum normalized transmission can get 99.5% and $\Delta\lambda_{3\text{dB}}$ is nearly unchanged at 3 nm. Therefore this shifting method can improve the normalized transmission while keeping the $\Delta\lambda_{3\text{dB}}$ is narrow and unchanged. The coupled cavity structure with shifting

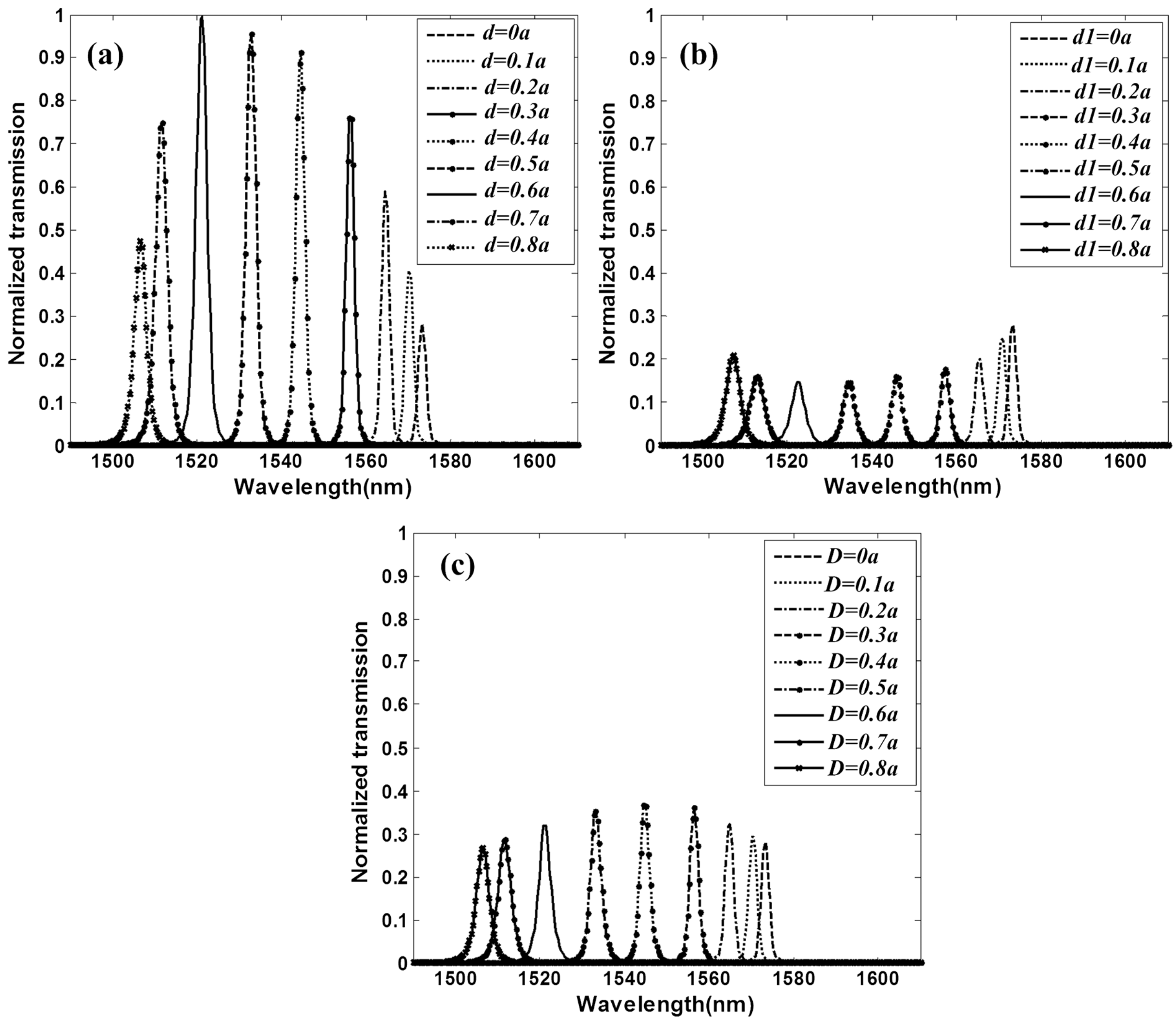

Fig. 4 (a) Normalized transmission versus shifting distances d for structure in Fig. 2(b). (b) Normalized transmission versus shifting distance $d1$ for structure in Fig. 2(c). (c) Normalized transmission versus shifting distance D for structure in Fig. 2(d).

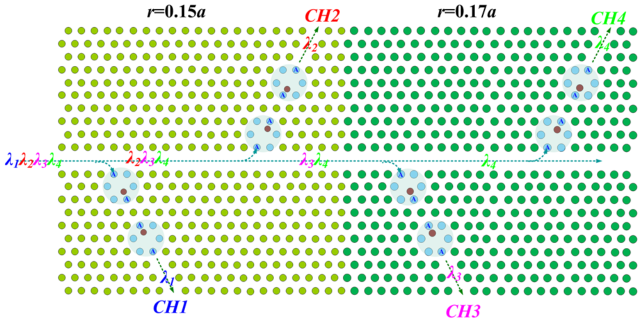

Fig. 5 Four-channel WDM demultiplexer.

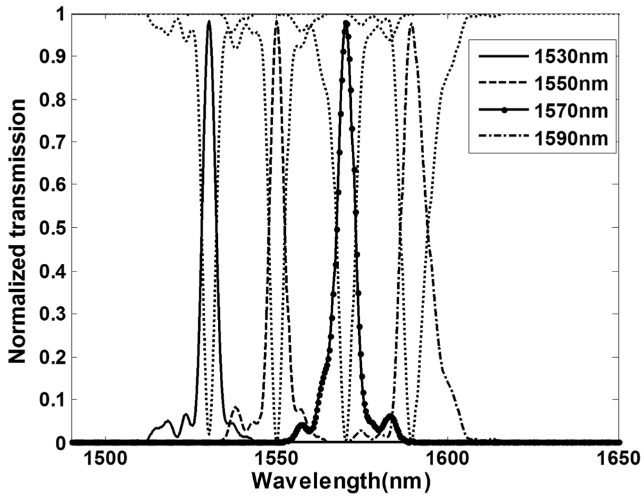

Fig. 6 Normalized transmission of four channels of CWDM demultiplexer.

distance $d = 0.6a$ is suitable for designing high-transmission and narrow bandwidth filter.

Secondly, we consider the shifting case shown as Fig. 2(c) and simulate the normalized transmission spectrums when shifting distance $d1$ is from 0 to $0.8a$ along the shifting direction shown as red dashed arrow, and the results are shown in Fig. 4(b). The simulation results illustrate the normalized transmission decreases when shifting distance $d1$ increases. That can be said, the distance, L, between two energy distribution centers of two cavities becomes larger than Δ, and κ will become smaller. Therefore coupling intensity between two cavities become weaker and transmission will decrease. And we can see that 3 dB bandwidth increases and λ_0 decreases when L increases. According to Eq. (2), $S(\lambda_0)$ will increase when λ_0 and κ are both decrease, and Δ is unchanged. This shifting method is not invalid to improve the transmission and it can increase the bandwidth.

Thirdly, we consider the shifting case shown as Fig. 2(d) and simulate the normalized transmission spectrums when shifting distance D is from 0 to $0.8a$ along the shifting direction shown as red dashed arrow, and the results are shown in Fig. 4(d). We can see that the normalized transmission becomes a little higher when the shifting distance D is larger, but the maximum value of normalized transmission is also below 40%. Therefore the transmission has no significant improvement. Based on the above-mentioned analyses, in this structure, the defect rod is shifted along same direction with same shifting distance and namely L is equal to Δ, and κ will have a little change. Therefore, transmission also has a little change.

3 Design of Demultiplexer

Finally, we design a four-channel demultiplexer based on above optimized filter structure shown in Fig. 2(b) with the shifting distance $d = 0.6a$, as shown in Fig. 5, the demultiplexer is achieved by integrating two kinds of PC. These two PCs have same lattice constant and component material but have different radius of rods. Filter channel CH1 and CH2 are created in PC with radius $r = 0.15a$, and filter channel CH3 and CH4 are created in PC with radius $r = 0.17a$ where a is 626 nm. The radius r_{def} of defect rods in two cavities for four channels is $0.05a$, $0.06a$, $0.06a$, and $0.06a$, respectively. In order to adjust the central wavelength of each filter channel to satisfy the CWDM standard of ITU-T G. 694.2 which states the channel spacing is 20 nm, we also modify the radius of rod-A [shown as Fig. 2(b)], and the radius of rod-A for four channels is $0.18a$, $0.18a$, $0.17a$, and $0.2a$, respectively. The simulation results for normalized transmission are shown in Fig. 6. The center wavelengths of

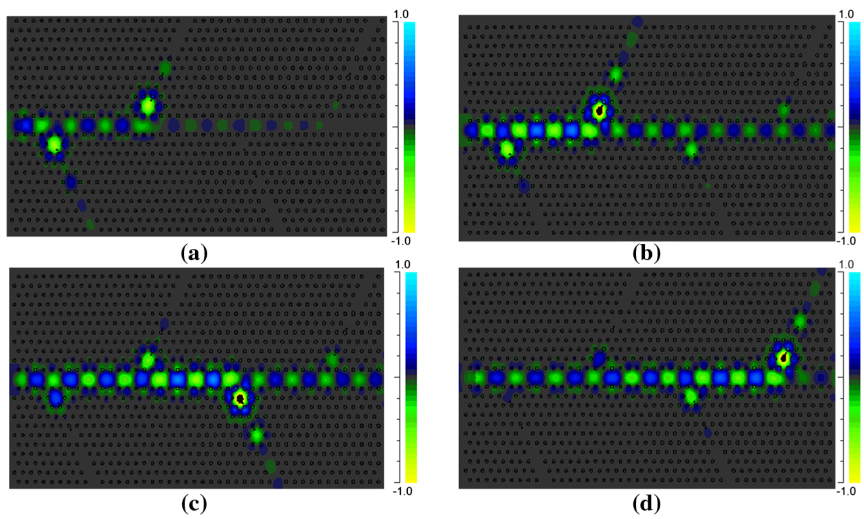

Fig. 7 Field distributions in (a), (b), (c) and (d) to show the performance of the proposed demultiplexer at 1530, 1550, 1570, and 1590 nm, respectively.

four channels are 1530, 1550, 1570, and 1590 nm, respectively. The 3 dB bandwidth of these four channels is all nearly 3 nm. In order to demonstrate the filter performance of this demultiplexer, we simulate the field distributions of this demultiplexer at 1530, 1550, 1570, and 1590 nm, as shown in Fig. 7(a)–7(d), respectively. Therefore the designed demultilexer is promising to apply for optical systems[20,21] to process optical signals.

4 Conclusion

In this paper, we propose an optimization method that can improve the transmission of PCCCW with double cavities. This method is only shifting the defect rods in two cavities centripetally, without changing the distance between neighboring cavities and the 3 dB bandwidth. The maximum normalized transmission can get 99.5%. And finally, we apply this method to design a four-channel demultiplexer according to CWDM standard of ITU-T G. 694.2 with channel spacing 20 nm and the normalized transmission of each channel of this demultiplexer all get 99%. This device has the potential to be key component in all optical integrated circuit.

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