A novel polarization channel drop filter based on two-dimensional photonic crystals

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A novel polarization channel drop filter (PCDF) based on two-dimensional (2D) photonic crystals (PCs) is presented. It consists of two line defect waveguides and two point defect micro-cavities. In the line-defect waveguides, the transverse-electric (TE) and transverse-magnetic (TM) polarization lights are guided using photonic band-gap and total internal reflection effect, respectively. The light at the resonant frequency for TE polarization can be transferred from one waveguide to the other using the proposed system. Compared with the existing four-port PCDF based on PCs, the three-port structure can realize a multi-channel wavelength system of PCDF more easily and can be an essential device in future polarization wavelength division multiplexing (PWDM) systems.

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In the past two decades, photonic crystals (PCs) have attracted great interest due to their potential use in the area of ultra-compact devices for photonic integrated circuits (PICs)[1−3]. Many PC components, including waveguides, polarization devices, channel drop filters (CDFs), and so on, have been designed and fabricated based on PCs[4−11]. Among these components, the polarization beam splitter (PBS) and CDF are considered important for PICs and dense wavelength division multiplexing (DWDM) systems.

Recently, a PC polarization channel drop filter (PC-PCDF) has been proposed[9]. The PC-PCDF can be utilized as polarization channel dropping devices in future integrated PWDM. In the structure, the transverse-electric (TE) and transverse-magnetic (TM) polarization lights are guided by photonic band-gap (PBG) and total internal reflection (TIR) effect, respectively[5,12,13]. For the TE polarized light, the PCDF is used as a narrow bandwidth CDF via resonant systems, where two symmetrical micro-cavities with direct coupling are located in the central region between two parallel line-defect waveguides. The theoretical concepts of the four-port filter based on two-dimensional (2D) PCs have been studied thoroughly[6−9]. We likewise recently presented a three-port CDF with a wavelength-selective reflection micro-cavity[14−16]. In the three-port structure, two separate micro-cavities with different functions are used. One micro-cavity is used to realize wavelength-selective reflection feedback in the bus waveguide and consists of a point defect micro-cavity side-coupled to the bus waveguide. The other micro-cavity is used for a resonant tunneling-based channel drop operation composed of a point defect micro-cavity between the bus waveguide and channel drop waveguide. By adding several channel drop micro-cavities and wavelength-selective reflection feedback micro-cavities adjacent to the bus waveguide, the three-port CDF can realize a multi-channel wavelength system more easily than by using the four-port CDF[16].

In this letter, we design a compact three-port PCDF based on 2D PCs with hexangular lattice of air holes perforated in high refractive index materials. Our design not only combines the functions of PBS and CDF at the operating frequency but also avoids increasing system complexity. PC-PCDF is realized based on the three-port CDF. The TE polarization component of the special wavelength range can be dropped from the bus waveguide to the channel drop waveguide via the resonating system. In the two waveguides, the TE polarization is guided by the PBG effect, and the TM polarization is controlled by the TIR effect. For the CDF of the TE polarization, the phase condition is studied in detail at several operating frequencies to achieve high channel drop efficiency. The device can realize the multi-channel wavelength system of PCDF more easily than the previous four-port structure, and can be used in future integrated PWDM systems.

The first requirement of PCDF is that both TE and TM polarized lights must propagate with low loss in the device[9]. The 2D PCs have a hexagonal lattice of air holes in GaAs ($\varepsilon = 11.0224$). Generally, the PCs have a PBG only for the TE modes, making it difficult to obtain a complete PBG for both polarizations in PCs with air holes perforated in a high index dielectric slab. Although the complete PBG is realized in such PCs by increasing the radius of air holes sufficiently, the method leads to severe losses out of the plane.

Fortunately, the PBG effect is not the only mechanism that can be used to guide the light in a PC waveguide[12]. Previous studies demonstrated theoretically and experimentally that the light can also be guided in a PC

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waveguide through the index contrast if the average index in the guiding region is higher than that in the surrounding area, and the guiding mechanism is similar to the TIR effect in the conventional dielectric slab waveguide[5]. The W1 line defect waveguide in the PCs is realized by removing a row of air holes along the ΓK direction in a hexagonal lattice PC that have PBG for TE light. The average index in the line defect region is higher than that in the surrounding region; thus, while the TE light is being guided by means of PBG effect, it should be possible to control the TM light through the above-mentioned TIR effect. The suitable structural parameters, including the relation between PC lattice constant and radius of the air holes, have been found to induce the W1 line defect waveguide in realizing high transmission efficiency for the TE and TM polarizations in the same frequency range. In this letter, a large air-filling factor is adopted in the PCs in order to yield a large TE PBG. The transmission efficiency of the line-defect waveguide in the PCs is calculated for both TE and TM lights. If low-loss transmission bands for the TM and TE lights are not achieved in such a way that they overlap in the frequency range, the air-filling factor would be decreased until the common low-loss transmission band is found. Certainly, the device performance should not close the TE PBG gradually with the reduction of the air-filling factor.

For 2D PCs with a hexagonal lattice of air holes in GaAs ($\varepsilon = 11.0224$), the radius of background air holes was chosen as $r = 0.33a$, where a represented the lattice constant. Figure 1 shows the dispersion curves of the W1 line defect PC waveguides for the TE polarization through the plane wave expansion (PWE) method; the inset shows the calculated supercell of the W1 PC waveguide. The waveguides demonstrated a single mode at a normalized frequency of $0.2658a/\lambda - 0.307a/\lambda$, where λ is the wavelength of light in free space. The transmission characteristics of the W1 PC waveguide were calculated in the case using the finite-difference time-domain (FDTD) method, with perfectly matched layers (PMLs) absorbing boundary conditions. The W1 PC waveguide can achieve over 95% transmission efficiency for both TE and TM polarizations in a frequency range of $0.302a/\lambda - 0.307a/\lambda$, where the W1 PC waveguide mode is single mode for TE polarization. As such, the W1 PC waveguide realized high transmission efficiency for the TE and TM polarizations in the same frequency range.

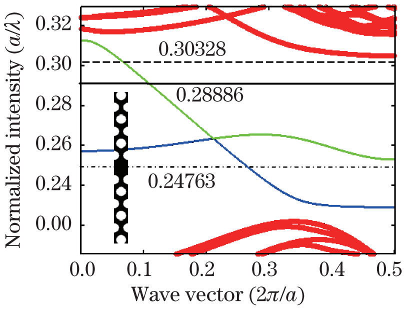

Fig. 1. Dispersion curves for the waveguide mode of the bus waveguide in PC with $r = 0.33a$. The operational frequency of the PC-PCDF is denoted by the dashed line ($0.30328a/\lambda$). The inset shows the supercell of the calculated W1 PC waveguide.

The second condition of PC-PCDFs is the combination of the functions of PBS and CDF[9]. Here, the CDF for the TE polarization was engineered in the PCs, and the device should have no effect on the propagation for TM polarized light totally. The CDF for the TE polarization was designed based on the aforementioned 2D PCs. The structure of the proposed CDF is described in Fig. 2. In the structure, two micro-cavities were obtained by increasing the radius of air holes and ensuring that each cavity can support one monopole mode. The radius of the central air holes in two micro-cavities was increased to $r_1 = 0.58a$, while the radius of the nearest six air holes surrounding the central one was increased to $r_2 = 0.4a$. The bus waveguide was created by removing one row of air holes in the ΓK direction. The channel drop waveguide connected with the channel drop micro-cavity was obtained by removing the air holes located along the orientation wherein the ΓK direction turned anti-clockwise by 60°.

According to the coupled mode theory in time, the conditions required to achieve 100% channel drop efficiency in the system are[14]

$$\omega_a = \omega_b, \tag{1}$$

$$Q_1/Q_2 = 2, \tag{2}$$

$$\varphi = 2\beta d = (2n+1)\pi, \tag{3}$$

where ω_a and ω_b are the resonant frequencies of channel drop micro-cavity and wavelength-selective reflection micro-cavity, respectively; Q_1 and Q_2 are the quality factors of the channel drop micro-cavity that are related to the rates of decay into bus and drop waveguides, respectively; β is the propagation constant of line defect waveguide at resonant frequency; d is the distance between the two cavities; n is an integer number.

To satisfy the term (1), the radius of the air hole at the interface between the wavelength-selective reflection micro-cavity and the bus waveguide was adjusted to $r_3 = 0.329a$. The resonant frequencies of the wavelength-selective reflection micro-cavity and channel drop micro-cavity were calculated using the FDTD method. The calculated results show that they have equal normalized resonant frequency at $0.30328a/\lambda$. To meet the condition (2), the quality factor characteristics of the channel drop micro-cavity has to be studied solely. Only the wavelength-selective reflection micro-cavity is not present in the CDF structure; thus, channel drop efficiency was calculated using the FDTD method. When wave was

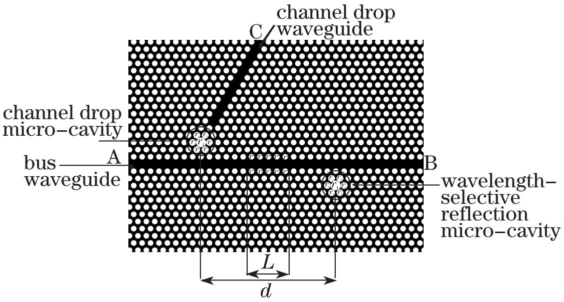

Fig. 2. Structure of the proposed PC-PCDF. $r = 0.33a$, $r_1 = 0.58a$, $r_2 = 0.4a$, $d = 16a$. In the bus waveguide section between the two micro-cavities, the waveguide propagation constant is changed to meet the phase term, $r' = 0.33a$. To satisfy the term (1), $r_3 = 0.329a$.

launched at input port A, the channel drop efficiency at port C was about 42% at resonance, and $Q_1/Q_2 \approx 2$ was easily obtained by means of the coupled mode theory in time. In our previous research[15], the phase condition (3) deviates vastly from the theoretical value when the CDF is designed in the PCs with a hexangular lattice. The reason for this is that the channel drop waveguide is not perpendicular to the bus waveguide, which directly leads to the phase shift compared with the theoretical value. In the previous study, we estimated that the phase shift value is dependent on the channel drop wavelength. In the example for the PCDF structure, the distance between the two cavities is $d = 16a$. The propagation constant is $\beta = 0.0656(2\pi/a)$ at the normalized frequency of $0.30328a/\lambda$ in Fig. 1, and thus the phase φ given by Eq. (3) is 4.1984π.

For the TE polarization, the CDF structure was calculated using the FDTD method. Figures 3(a) and (b) indicate that an incident TE polarization is transferred to port C efficiently at resonant frequency of $0.30328a/\lambda$, and TM polarization is transmitted to port B with low loss in the designed frequency range. More than 95% drop efficiency for TE polarization is obtained, and the quality factor Q is about 3046. The steady field pattern was achieved by launching a continuous-wave (CW) at the resonant frequency $0.30328a/\lambda$ at port A. Figures 3(c) and (d) show H_z and E_z field distributions at the resonant frequency for TM and TE polarizations, respectively. The calculated results confirm that the TM polarized light makes no difference as it propagates through the CDF. In the device, the combination of the functions of PBS and CDF was thus perfectly realized.

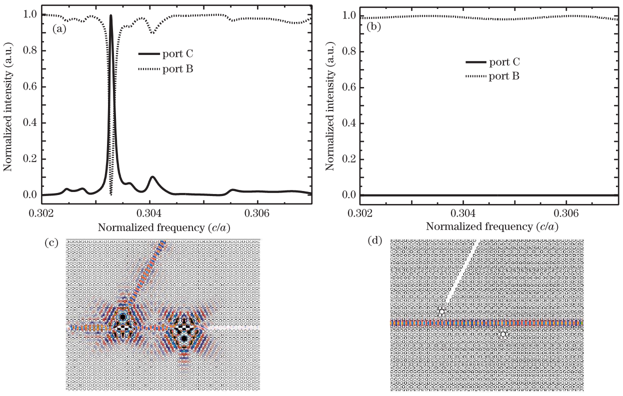

Fig. 3. Transmission intensity spectra for (a) TM and (b) TE calculated by the FDTD method; at the normalized frequency $f = 0.30328a/\lambda$, (c) H_z and (d) E_z field distributions are given.

For the TE polarization, phase condition (3) is discussed at other operating frequencies to create a strong design for the CDF. Our previous study[15] indicated that the phase value in Eq. (3) was not easily satisfied at each frequency within the PBG due to the discrete structure of PCs, where the distance d between two micro-cavities must be the integral multiple of the lattice constant. The phase condition can be satisfied by changing the propagation constant of the bus waveguide section between the two micro-cavities; thus, Eq. (3) can be rewritten as

$$\varphi = 2\beta(d - L) + 2\beta' L, \tag{4}$$

where β' is the propagation constant of the modified bus waveguide, and L is its length. At the operating normalized frequencies of $0.24763a/\lambda$ and $0.28886a/\lambda$, the CDFs were built for TE polarization and the term (3) was discussed. At the normalized frequency of $0.28886a/\lambda$, the radii of the central air holes in two micro-cavities and the nearest six air holes surrounding the central one were $r_1 = 0.563a$ and $r_2 = 0.4a$, respectively. To meet condition (1), the radius of the air hole at the interface between the wavelength-selective reflection micro-cavity and bus waveguide was adjusted to $r_3 = 0.327a$. The distance d between two micro-cavities was $16a$. Condition (2) was still satisfied by the characteristics of the channel drop micro-cavity. To satisfy condition (3), the border air holes in the bus waveguide section were adjusted to $r' = 0.313a$ to tailor the propagation constant of the waveguide section, where the length of the section $L = 5a$. Thus, $\beta = 0.11665(2\pi/a)$ and $\beta' = 0.11(2\pi/a)$ were easily obtained from the corresponding dispersion curves of the waveguides at $f = 0.28886a/\lambda$. From Eq. (3), we can obtain the phase $\varphi = 7.3326\pi$. At $f = 0.24763a/\lambda$, the corresponding parameters are $d = 18a$, $r' = 0.322a$, $L = 7a$, $\beta = 0.2727(2\pi/a)$, and $\beta' = 0.26875(2\pi/a)$. Here, only the radius of the central air holes in two micro-cavities was increased to $r_1 = 0.58a$, while that for the nearest six air holes surrounding the central one was not changed ($r_2 = 0.33a$). To meet Eq. (1), the radius of the air hole at the interface between the channel drop micro-cavity and the channel drop waveguide was reduced to $r_3 = 0.329a$. Condition (2) was satisfied spontaneously by the structure of the channel drop micro-cavity. Thus, the phase $\varphi = 19.5238\pi$ is given by Eq. (3).

In the three examples given, the phase shifts compared with the theoretical value are -0.8016π, 0.3326π, and 0.5238π, respectively, as shown in Table 1. The phase shift value changes from $-\pi$ to π with the increase in frequency. This is because the channel drop waveguide is located at the orientation wherein the ΓK direction turns anti-clockwise by 60°, which is not perpendicular to the bus waveguide. Hence, it is not symmetric to the central plane of channel drop micro-cavity, which directly leads to the phase shift compared with the theoretical value. The calculated results confirm that phase shift value is dependent on the channel drop wavelength.

In conclusion, we have presented the novel design of a compact PC-PCDF based on the 2D hexangular lattice of air holes in GaAs. It combines the functions of CDF and PBS into one device. The size of PC-PCDF is about $26a$, which is smaller than other similar devices. The proposed device is an unsymmetrical three-port structure that can be fabricated more easily than the existing four-port symmetrical structure. It can be used as polarization channel drop filter or polarization channel switch if two beams are incident simultaneously into port A. The transmission efficiency is more than 95%, and the Q value of the whole PCDF is about 3046 for the TE polarization. To realize CDF with high drop efficiency, the phase term is discussed at several operating frequencies. The fact that the phase shift value is dependent on the operating frequency is confirmed.

Table 1. Parameters and Calculated Phases for Different Normalized Frequencies

Normalized Frequency	Distance Between Two Micro-Cavities	Length of Adjusted Bus Waveguide	Calculated Phase
$0.24763(a/\lambda)$	$18a$	$7a$	$(2\times9+1)\pi + 0.5238\pi$
$0.28886(a/\lambda)$	$16a$	$5a$	$(2\times3+1)\pi + 0.3326\pi$
$0.30328(a/\lambda)$	$16a$	0	$(2\times2+1)\pi-0.8016\pi$

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