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基于光子晶体单向传输波导的通道下路滤波器

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摘　要:基于光子晶体单向传输波导,设计了一种三端口和两种四端口结构的通道下路滤波器.为取得100%的通道下路效率,运用实时耦合模理论对这三种结构进行了分析.理论分析表明该通道下路滤波器比利用光子晶体普通介质波导设计的通道下路滤波器具有更简单的结构,降低了器件制作难度.用有限元方法对滤波器结构进行了数值仿真分析,仿真计算结果表明所设计的三种结构具有超过 90%的通道下路效率,与理论分析结果相符合.

关键词:集成光学;有限元方法;光子晶体;光子带隙;通道下路滤波;光子晶体单向波导;通道下路效率;耦合模理论

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Photonic Crystal Channel Drop Filter Based on One-way Waveguide

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Abstract: Based on photonic crystal one-way waveguide, one three-port system and two kinds of four-port systems were designed. According to coupled mode theory in time, it was confirmed that the channel drop filters on the basis of one-way waveguide have more simple structure than that with only general dielectric photonic crytal waveguides in order to achieve 100% channel drop efficiency, which is benefit to the solution to the fabrication difficulty of the devices. The simulation results calculated by the finite element method shows that the channel drop efficiencies are all over 90%, which does agree well with the theoretical analysis.

Key words: Optical communication; Integrated optics; Finite element method; Photonic crystals; Optical band gaps; Channel drop filter; Photonic crystal one-way waveguide; Channel drop efficiency; Coupled mode theory

OCIS Codes: 230.5298; 230.3810; 230.3120

0 Introduction

Photonic Crystal (PC) Channel Drop Filters (CDF) are attractive for their strong potential for large integration in Wavelength Division Multiplexing (WDM) communication network [1-16]. Recently, a 100 Gb/s WDM communication system using a PC four-channel drop filter has been proposed, the measured CDF device characteristics show good performances in terms of transmission and crosstalk. The PC CDF is obtained by using resonant coupling between PC micro-cavity modes and waveguide modes,

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and a lot of theoretical and experimental works with promising results have been proposed by some researchers, which confirms that the device have great potential to realize multi-channel WDM optical add-drop multiplexers[1-6]. In order to achieve 100% channel drop efficiency, the four-port PC CDF has been proposed by S. Fan *et al* [3], and its mechanisms are the standing-wave resonator supporting two degenerate modes between two parallel waveguides, but the structure bring a great challenge that such CDF structure has not been nanofabricated experimentally so far. Various researchers have also improved the channel drop efficiency of their three-port PC CDF by means of reflection feedback due to the additional structural designs, however, this leads to the same fabrication problems[3-6].

Recently, because Magneto-Optical Photonic Crystal (MO-PC) can support a so-called Chiral Edge State (CES) that exhibits a interesting one-way propagation characteristic and strong robustness against disorder and interface configuration, it has attracted a lot research interests, which is similar to the quantum hall effect for the semiconductor in a strong magnetic field[7-11]. On the basis of PC one-way waveguide, the coupling mechanisms between the waveguide modes and the micro-cavity modes has been essentially changed, and they are of fundamental importance in a PC integrated optical system, which can be utilized to build CDF, splitters, resonators, directional couplers, and other integrated optical devices. Although the four-port CDF based on PC one-way waveguide has been proposed and fabricated[7,9], the theoretical analysis on these structures has never been proposed thoroughly and the four-port CDF consisting of a general PC waveguide and a PC one-way waveguide has also never been presented. In this paper, the asymmetrical four-port CDF based on one-way waveguide has been proposed, and the three-port and four-port CDF are designed based on PC one-way waveguides about their individual advantages. The simulation results by using the Finite Element Method (FEM) agree well with the CMT results, and it is proved that this configuration is feasible.

1 Three-port CDF based on one-way waveguide

1.1 Theoretical model analysis

Fig. 1 shows the three-port CDF structure based on one-way waveguide, where both the micro-cavity and the waveguide support only one mode in the frequency range of interest. The point-defect micro-cavity possesses mirror reflection symmetry with respect to the reference plane, where is the center of the resonator. S_{+i} are described as the amplitudes of the incoming waves into the system and S_{-i} are the amplitudes for the outgoing waves ($i=1,2$). The time evolution of the cavity amplitude denoted by f can be written as[12]

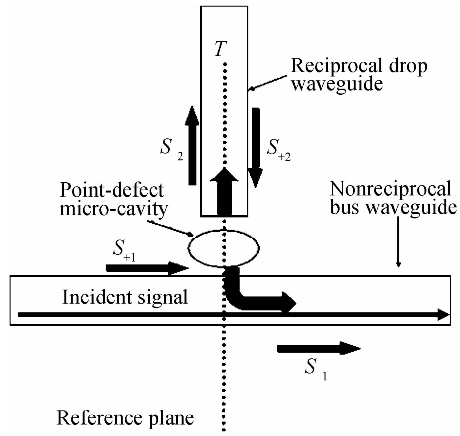

Fig. 1 The stretch of the three-port CDF based on one-way waveguide with only one general point-defect micro-cavity

$$\frac{df}{dt}=(j\omega_0-\frac{\omega_0}{Q_0}-\frac{\omega_0}{2Q_1}-\frac{\omega_0}{2Q_2})f+e^{j\theta_1}\sqrt{\frac{\omega_0}{Q_1}}S_{+1}+e^{j\theta_2}\sqrt{\frac{\omega_0}{Q_2}}S_{+2} \quad (1)$$

$$S_{-1}=S_{+1}-e^{-j\theta_1}\sqrt{\frac{\omega_0}{Q_1}}f \quad (2)$$

$$S_{-2}=-S_{+2}+e^{-j\theta_2}\sqrt{\frac{\omega_0}{Q_2}}f \quad (3)$$

where ω_0 is the resonant frequency of the point-defect micro-cavity, Q_o, Q_1 and Q_2 are the quality factors connected with the intrinsic loss of the micro-cavity, the rates of decay into the nonreciprocal bus waveguide and the drop waveguide, respectively, and θ_1, θ_2 are the phases of coupling coefficients between the micro-cavity and the nonreciprocal one-way bus waveguide or reciprocal drop waveguide, respectively. It is easily verified that the drop efficiency attains 100% from the Eqs. (1)~(3) at $Q_1/Q_2=1$.

1.2 Design of three-port CDF based on one-way waveguide

MO material Yttrium-Iron-Garnet (YIG) is used to design the PC one-way waveguide, which is built at the interface between a two-dimensional (2D) YIG MO PC and a general dielectric PC, as illustrated in Fig. 2 (a). The YIG PC is present at the lower layer, which is composed by a square lattice of YIG rods ($\varepsilon=15\varepsilon_0$) of radius 0.11$a$ in air (a is its lattice constant), while the upper one is the dielectric PC with a square lattice of alumina (A_l) rods ($\varepsilon=8.9\varepsilon_0$) in air, and its background radius is set to 0.27a, where the lattice constant of dielectric PC strong gyro-magnetic anisotropy is induced by an external direct current magnetic field applied in the out-of-plane ($\pm z$) direction, with the permeability tensor,

$$\boldsymbol{\mu}=\begin{bmatrix}\mu & \pm \mathrm{i}k & 0\\ \mp \mathrm{i}k & \mu & 0\\ 0 & 0 & \mu_0\end{bmatrix} \tag{4}$$

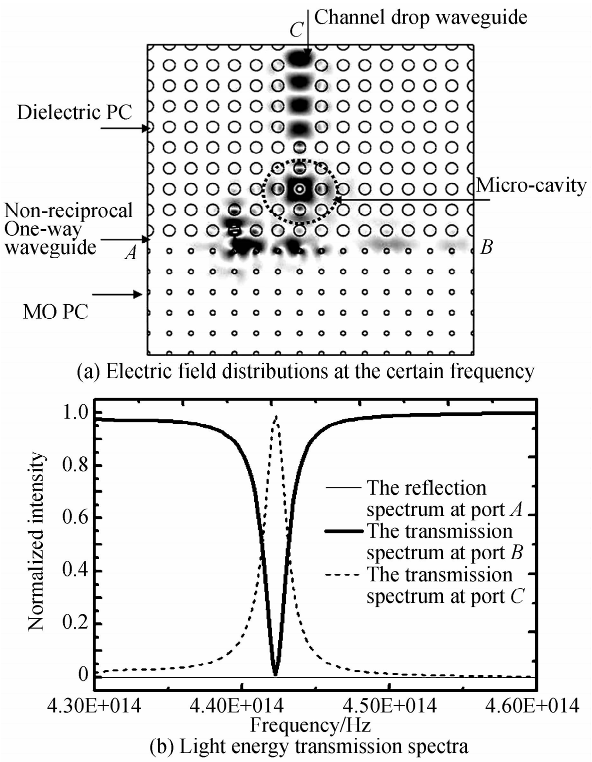

Fig. 2 The design of three-port CDF based on PC one-way waveguide

where $\mu = 14\mu_0$, $k = 12.4\mu_0$ as the external direct current magnetic field is equal to 1600G[8]. Subsequently, the CDF will be designed based on the one-way waveguide. As show in Fig. 2 (a), the channel drop waveguide is realized by removing a row of rods along the ΓM direction in the dielectric PC. The channel micro-cavity is obtained by increasing the radius, and the channel drop waveguide is connected with the non-reciprocal one-way waveguide by the channel drop micro-cavity.

We can calculate the quality factors of the point-defect micro-cavity by means of the numerical simulation method. When the micro-cavity structure is adjusted, its quality factors are corresponding changed. So we can obtain the suitable quality factors of the micro-cavity by changing its structural parameters. As the lower magneto-optical crystal is not present in the Fig. 2 (a), the radius of small dielectric rod in the micro-cavity is $0.38a$. In this case, the incident wave is excited at the entrance to the port C in the channel drop waveguide, and we calculate the reflection spectrum of the structure at the incident port using the FEM. The numerical results show that the reflection coefficient is close to zero at resonance. By means of the coupled mode theory in time[12], at resonance, the reflection Rat the access port can be written as

$$R=\frac{\dfrac{1}{2Q_2'}-\dfrac{1}{2Q_1'}}{\dfrac{1}{2Q_1'}+\dfrac{1}{2Q_2'}} \tag{5}$$

From the Eg. (5), it is clear that $Q_1'/Q_2' \approx 1$ can be easily obtained at $|R|^2 \approx 0$, where Q_1' *and* Q_2' are denoted as the quality factors due to the rates of decay into the outer space of the crystal and channel drop waveguide, respectively. When the lower magneto-optical crystal exists for the structure in the Fig. 2 (a), the adjustments of quality factors are negligible. So $Q_1 = Q_1'$, $Q_2 \approx Q_2'$ can be gotten, the conditions of $Q_1/Q_2 = 1$ can be met.

The entire three-port CDF structure is calculated by the FEM. As shown in Fig. 2 (a), the light is launched at the port A, and the normalized power spectra of the device are shown in Fig. 2(b), where the spectra at port A, B and C are shown as the thin solid, thick solid, and short dashed curves, respectively. As the lattice constant is 375 nm, electric field distributions are shown in Fig. (a) At resonant frequency $f=442.28$ T Hz, and over 98% light energy is transferred via the three-port system.

2 Symmetrical four-port CDF based on one-way waveguide

2.1 Theoretical model analysis

Fig. 3 shows the symmetrical four-port CDF structure based on two parallel one-way waveguides and only one micro-cavity, where the micro-cavity is sandwiched into two parallel one-way waveguides. In the structure, two parallel non-reciprocal one-way waveguide have the same structure, and they are symmetrical about the micro-cavity. The amplitudes of the incoming waves into the system are denoted by S_{+i} and S_{+i}' are the amplitudes for the outgoing waves ($i=1, 2$). The time evolution of the cavity amplitude denoted by f can be expressed as[12]

$$\frac{\mathrm{d}f}{\mathrm{d}t}=(\mathrm{j}\omega_0-\frac{\omega_0}{Q_0}-\frac{\omega_0}{2Q_\mathrm{B}}-\frac{\omega_0}{2Q_\mathrm{D}})f+\mathrm{e}^{\mathrm{j}\theta_1}\sqrt{\frac{\omega_0}{Q_\mathrm{B}}}S_{+1}+\mathrm{e}^{\mathrm{j}\theta_2}\sqrt{\frac{\omega_0}{Q_\mathrm{D}}}S_{+2} \tag{6}$$

$$S_{+1}'=S_{+1}-\mathrm{e}^{-\mathrm{j}\theta_1}\sqrt{\frac{\omega_0}{Q_\mathrm{B}}}f \tag{7}$$

$$S_{+2}'=S_{+2}-\mathrm{e}^{-\mathrm{j}\theta_2}\sqrt{\frac{\omega_0}{Q_\mathrm{D}}}f \tag{8}$$

where ω_0 is the resonant frequency of the point-defect micro-cavity, Q_o is the quality factor due to intrinsic loss of the micro-cavity, Q_B and Q_D are the quality factors of the micro-cavity that are connected with the rates of decay into the bus nonreciprocal waveguide and the drop nonreciprocal waveguide, respectively. θ_1 and θ_2 are the phases of coupling coefficients between the micro-cavity and the bus nonreciprocal waveguide or drop nonreciprocal waveguide, respectively.

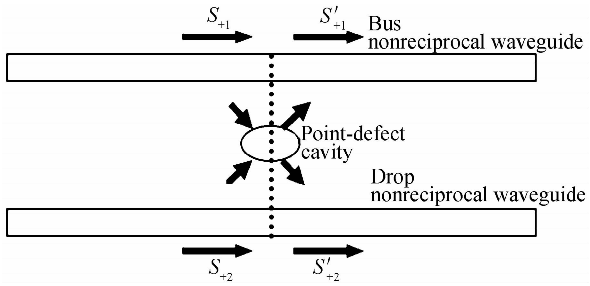

Fig. 3 The stretch of symmetrical four-port CDF based on two parallel one-way waveguides

According to the Eqs. (6)～(8), it is obvious that the drop efficiency achieves 100% at $Q_B/Q_D=1$. When the micro-cavity is symmetrical about two same PC one-way, the condition is satisfied, and 100% channel drop efficiency can be obtained. However, for the structure with asymmetrical structure based on two PC one-way waveguide, it is impossible to realize the desired channel drop efficiency because the condition of $Q_B/Q_D=1$ completely cannot be met.

2.2 Design of the symmetric four-port CDF based one-way waveguide

Symmetrical four-port CDF based one-way waveguide firstly is designed. As shown in Fig. 4, two parallel nonreciprocal waveguides modes are formed at the interface between Magneto-Optical (MO) PC and dielectric PC. Both the upper and lower parts are the MO PC, its parameters is same as that in the three-port CDF. External magnetic field is along the direction perpendicular to the plane, i. e., $+z$ or $-z$. In the middle part, the dielectric PC consists of a square lattice of alumina rods with dielectric constant $\varepsilon_2=10\varepsilon_0$ in air background, and its lattice direction with a 45° rotation to the YIG lattice is used to restrict the edge modes in nonreciprocal PC waveguides. In such dielectric PC, the lattice constant is $a_2=a/\sqrt{2}$, and the alumina rod radius is $r_2=0.106a$ (a is the lattice constant of MO). The point-defect micro-cavity

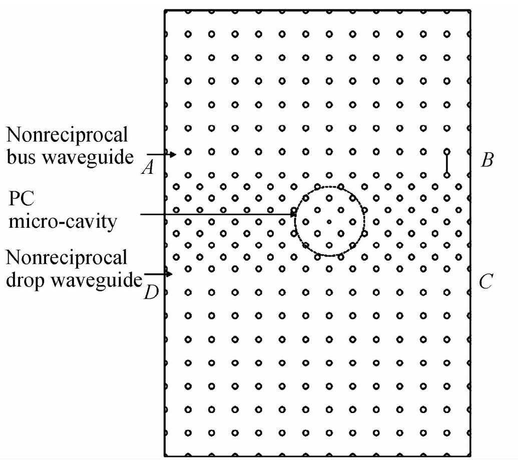

Fig. 4 The symmetrical four-port CDF based on PC one-way waveguide

is created by decreasing the radius of rod $r_2'=0.085a_2$ based on the dielectric PC. Because the micro-cavity structure is sandwiched symmetrically into two parallel nonreciprocal waveguides, the condition to achieve the desired channel drop efficiency is easily satisfied.

Fig. 5(a) depicts the normalized power spectra of the CDF calculated by the FEM, where the power reflection spectra at port A, and transmission spectra at B and C, are denoted as the dot dashed, short dashed, thick solid, and thin solid curves, respectively. Close to 100% power at resonant frequency $f=428.2$ THz

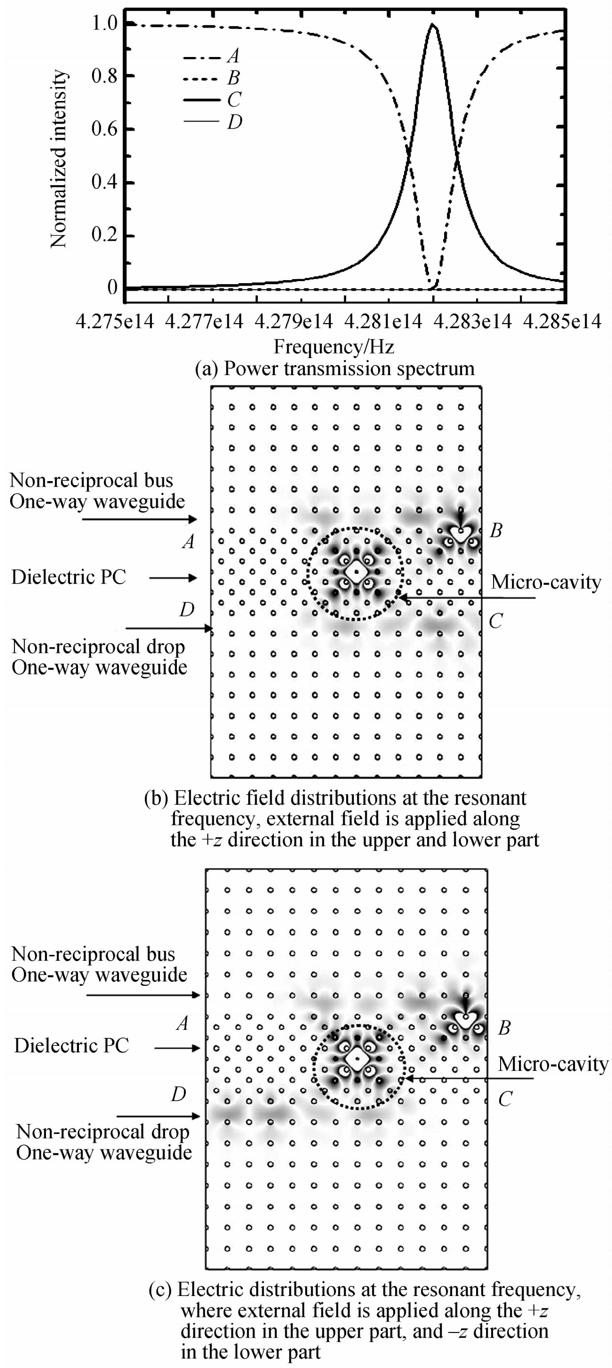

Fig. 5 The numerical results of the symmetrical four-port CDF based on PC one-way waveguide

(the lattice constant $a=375$ nm) is transferred from the nonreciprocal bus waveguide to drop waveguide through only one micro-cavity in the symmetrical four-port CDF structure. Fig. 5 (b) and (c) shows the electric distributions at the resonant frequency for the external magnetic field is applied along the $\pm z$ direction in the upper and lower part. As the light is launched at port B, with the external magnetic field being changed in the $-z$ direction from past $+z$ direction, the light energy is almost completely transferred to the port D from past port C. It is possible to obtain a novel PC switch by changing the direction of external magnetic field.

3 Asymmetrical four-port CDF based on one-way waveguide

3.1 Theoretical model analysis

Fig. 6 shows the asymmetrical four-port CDF structure consisting of a general PC waveguide , a PC

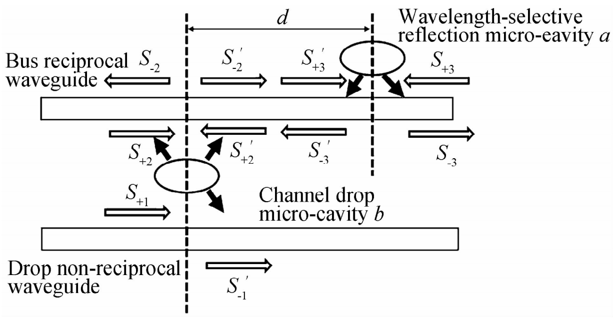

Fig. 6 The stretch of asymmetrical four-port CDF based on one-way waveguide

one-way waveguide, and two micro-cavities. In the structure, an additional wavelength-selective reflection micro-cavity is introduced in the bus reciprocal waveguide in order to improve the channel drop efficiency. The amplitudes of the incoming waves into the system are denoted by $S_{\pm i}$ or and $S'_{\pm i}$ are the amplitudes for the outgoing waves ($i=1, 2, 3$). By the same coupled mode theory, the time evolution of wavelength-selective reflection micro-cavity amplitude denoted by f_1 and channel drop micro-cavity amplitude denoted by f_2 can be written as

$$\frac{\mathrm{d}f_1}{\mathrm{d}t}=(\mathrm{j}\omega_{0a}-\frac{\omega_{0a}}{Q_{0a}}-\frac{\omega_{0a}}{2Q_3})f_1+\sqrt{\frac{\omega_{0a}}{2Q_3}}\mathrm{e}^{\mathrm{j}\theta_3}S_{+3}+\sqrt{\frac{\omega_{0a}}{2Q_3}}\mathrm{e}^{\mathrm{j}\theta_3}S'_{+3} \quad (9)$$

$$\frac{\mathrm{d}f_2}{\mathrm{d}t}=(\mathrm{j}\omega_{0b}-\frac{\omega_{0b}}{Q_{0b}}-\frac{\omega_{0b}}{2Q_2}-\frac{\omega_{0b}}{2Q_1})f_2+\sqrt{\frac{\omega_{0b}}{2Q_2}}\mathrm{e}^{\mathrm{j}\theta_2}S_{+2}+\sqrt{\frac{\omega_{0b}}{2Q_2}}\mathrm{e}^{\mathrm{j}\theta_2}S'_{+2}+\sqrt{\frac{\omega_{0b}}{Q_1}}\mathrm{e}^{\mathrm{j}\theta_1}S_{+1} \quad (10)$$

$$S_{-3}=S'_{+3}-\mathrm{e}^{-\mathrm{j}\theta_3}\sqrt{\frac{\omega_{0a}}{2Q_3}}f_1 \quad (11)$$

$$S'_{-3}=S_{+3}-\mathrm{e}^{-\mathrm{j}\theta_3}\sqrt{\frac{\omega_{0a}}{2Q_3}}f_1 \quad (12)$$

$$S_{-2}=S'_{+2}-\mathrm{e}^{-\mathrm{j}\theta_2}\sqrt{\frac{\omega_{0b}}{2Q_2}}f_2 \quad (13)$$

$$S'_{-2}=S_{+2}-\mathrm{e}^{-\mathrm{j}\theta_2}\sqrt{\frac{\omega_{0b}}{2Q_2}}f_2 \quad (14)$$

$$S'_{+3}=S'_{-2}\mathrm{e}^{-\mathrm{j}\beta d} \quad (15)$$

$$S'_{+2}=S'_{-3}\mathrm{e}^{-\mathrm{j}\beta d} \quad (16)$$

$$S'_{-1}=S_{+1}-\mathrm{e}^{-\mathrm{j}\theta_1}\sqrt{\frac{\omega_{0b}}{Q_1}}f_2 \quad (17)$$

where ω_{0a} and ω_{0b} is the resonant frequency of the wavelength-selective reflection micro-cavity and channel drop micro-cavity, respectively, Q_{0a} and Q_{0b} is the quality factor of two micro-cavities due to intrinsic loss of two micro-cavities, Q_1 and Q_2 are the quality factors of the channel micro-cavity that are connected with the rates of decay into the drop nonreciprocal waveguide and the bus reciprocal waveguide, respectively, Q_3 is the quality factors of the reflection micro-cavity that are related to the rate of decay into the bus reciprocal waveguide, θ_1, θ_2 are the phases of coupling coefficients between the channel drop micro-cavity and the bus nonreciprocal waveguide or drop nonreciprocal waveguide, respectively, θ_3 is the phase of coupling coefficient between the reflection micro-cavity and bus reciprocal waveguide, and d is the distance between the wavelength-selective reflection micro-cavity and the channel drop micro-cavity.

If $Q_{0a}\gg Q_3$, $Q_{0b}\gg Q_1$ and $\omega_{0a}=\omega_{0b}=\omega_0$, according to Eqs. (9) to (17), for the asymmetrical four-port CDF, the channel drop efficiency η can be expressed as

$$\eta=\frac{4(Q_1/Q_2)(1-\cos(2\beta d))}{(Q_1/Q_2)^2+2(Q_1/Q_2)(1-\cos(2\beta d)+2(1-\cos(2\beta d))} \quad (18)$$

From the Eq. (18), it is verified that the drop efficiency attains 100% at $Q_1/Q_2=2$ and $2\beta d=(2n+1)\pi$, where β is the propagation constant at resonant frequency, and n is the integer. This means that almost complete power transfer can ocuur from the reciprocal bus waveguide to the non-reciprocal drop waveguide via the asymmetrical four-port CDF.

3.1 Design of the asymmetric four-port CDF based One-way waveguide

A feasible MO material PCs in micro-wave regime is chosen to construct one-way waveguides. They are designed using MO material Yttrium-Iron-Garnet (YIG). The one-way waveguide is formed by an interface between a two-dimensional YIG PC and a regular 2D PC. The upper layer is the regular PC consisting of a square lattice of alumina (A_l) rods ($\varepsilon=8.9\varepsilon_0$) of radius 0.27$a$ in air, where a is the lattice constant, while the lower layer is the YIG PC consisting of a square lattice of YIG rods ($\varepsilon=15\varepsilon_0$) of radius 0.11 a in air. An external dc magnetic field applied in the out-of-plane ($+z$) direction induces strong gyro-magnetic anisotropy in YIG, with a form of a second-rank permeability tensor[1]. The bus reciprocal waveguide is produced by removing one row of rods in the dielectric PC, where it is parallel to the drop non-reciprocal waveguide at the interface between two layers PCs. Fig. 7 (a) and (b) shows the diagram of bands of one-way drop waveguide and reciprocal bus waveguide, respectively. The dashed line shows the normalized frequency position at $f=0.5535(c/a)$. The reciprocal waveguide modes in the A_1 PC are calculated by using Plane-Wave expansion Method (PWM). The one-way guiding mode at the interface between the two PCs is calculated by the FEM, but the numerical calculations are carried out on a super-cell, which consists of five A_1 rods and five YIG rods in one column. It is clearly seen that the one-way waveguide mode is an asymmetric dispersion relation with only a positive group velocity.

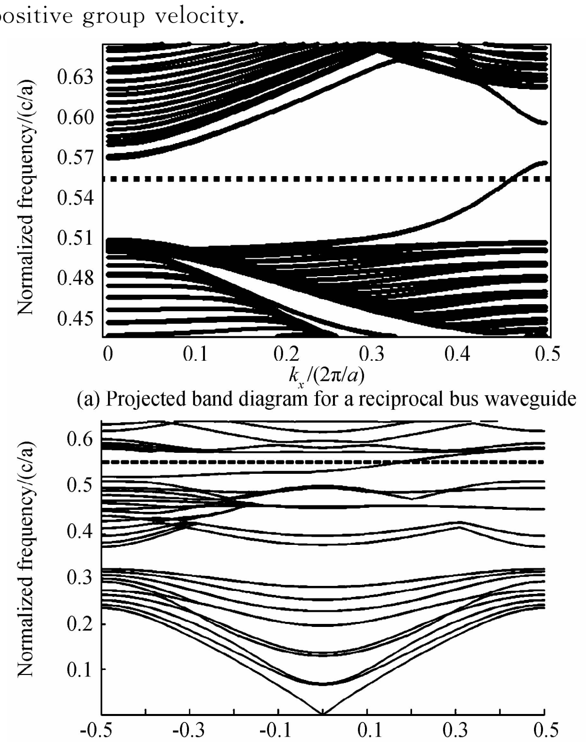

Fig. 7 The dispersion relations for the reciprocal and non-reciprocal waveguide

In Fig. 8 (a), the channel drop micro-cavity and wavelength-selective reflection micro-cavity are obtained by increasing the rods to 0.38 a (a is the lattice constant of MO PC). To ensure that each cavity can support one monopole mode with the same resonant frequency, the radius of the rod at the border between the reflection micro-cavity and bus reciprocal waveguide is reduced to 0.23a.

When the wavelength-selective reflection cavity is not present in Fig. 8 (a), the light wave is launched at the entrance to port A, and the channel drop efficiency at port C can be calculated. Then, we can calculate the result of $Q_1/Q_2\approx 2$ according to the coupled mode theory in time, where Q_1 and Q_2 are the corresponding quality factors of the channel drop cavity, respectively.

In the asymmetrical four-port CDF, the distance between the two cavities d is set to 11a. By means of the dispersion relations of reciprocal bus waveguide in Fig. 8 (a), β is 0.475($2\pi/a$) at the normalized resonant frequency $f=0.5535(c/a)$, where c is the light velocity in free space. So the phase condition of 2 βd is

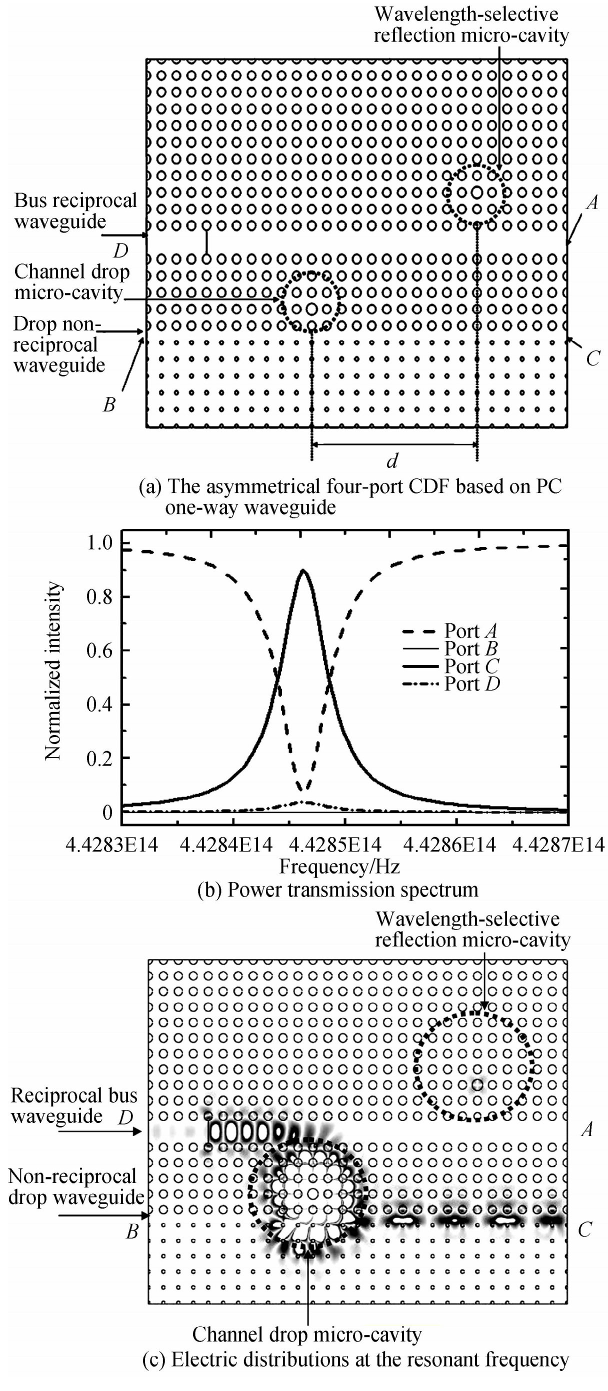

Fig. 8 The design of asymmetrical four-port CDF based on PC one-way waveguide and its simulation results

equal to 20.9π, which is close to odd multiple of π.

The transmission spectra of the four-port asymmetrical CDF based on only one one-way waveguide is calculated by using the FEM, as shown in Fig. 8 (b). Fig. 8 (c) shows the electric distributions at the resonant frequency $f = 442.846$ THz, and it is clear that the channel drop efficiency is close to 90% because the back reflection spectrum at port D is rather strong for the reciprocal bus waveguide due to the functional effect of wavelength-selective reflection micro-cavity. Compared with the four CDF based on general PC waveguide using the reflection mirror in Ref. [13], there is no wavelength-selective reflection micro-cavity present in the channel drop waveguide because the special coupling mechanism between the channel drop micro-cavity and the PC channel drop one-way waveguide. Two wavelength-selective reflection micro-cavities and one channel drop micro-cavity are required for the four-port CDF in Ref. [13], while the asymmetrical four-port CDF only needs two micro-cavities to get a high channel drop efficiency. For such CDF, the structural simplicity benefits to the solution of fabrication difficulties.

4 Conclusions

In this paper, one-way waveguide is used to realize the PC three-port CDF and four-port CDF with symmetric and asymmetric structures. Three-port CDF system based on one-way waveguide is more easily used to design multi-channel drop functions than the corresponding four-port systems on the basis of one-way waveguide. Symmetric four-port system can be utilized as the switch by adjusting the direction of external magnetic field, and asymmetric four-port CDF can realize the high efficient coupling between the parallel reciprocal and non-reciprocal waveguides. Compared with the CDFs based on the general PC CDF, it is possible for such CDF systems with simpler structures to reduce fabrication difficulties of the devices.

References

[1] NGUYE T, GAY M, LENGLE K, *et al*. 100-Gb/s wavelength division demultiplexing using a photonic crystal four-channel drop filter [J]. *IEEE Photonics Technology Letters*, 2013, **25**(2):813-816.

[2] OLMOS J, TOKUSHIMA M, KITAYAMA K. Photonic add-drop filter based on integrated photonic crystal structure[J]. *IEEE Journal of Selected Topics in Quantum Electronics*, 2010, **16**(5): 332-337.

[3] FAN S, VILLENEUVE R, JOANNOPOULOS J, *et al*. Channel drop tunneling through localized states[J]. *Physical Review Letter*, 1998, **80**(2):960-963.

[4] QIU M, JASKORZYNSKA B. Design of a channel drop filter in a two-dimensional triangular photonic crystal[J]. *Appied Physics Letters*, 2003, **83**(6):1074-1076.

[5] SONG B, NODA S, ASNAO T. Photonic devices based on in-plane hetero photonic crystals[J]. *Science*, 2003, **300**(1): 1537.

[6] REN Hong-liang, JIANG Chun, HU Wei-sheng, *et al*. Photonic crystal channel drop filter with a wavelength-selective reflection micro-cavity[J]. *Optics Express*, 2006: **14**(3): 2446-2459.

[7] YU Z, VERONI G, WANG Z , *et al*. One-way electromagnetic waveguide formed at the interface between a plasmonic metal under static magnetic field and a photonic crystal[J]. *Physical Review Letters*, 2008: **100**(2): 023902-023905.

[8] WANG Z , CHONG Y , JOANNOPOULOS J , *et al*. Reflection-free one-way edge modes in a gyromagnetic photonic crystal[J]. *Physical Review Letters*, 2008, **100**(8): 013905-013908.

[9] FU Jin-xin, LIAN Jin, LIU Rong-juan, *et al*. Unidirectional channel-drop filter by one-way gyromagnetic photonic crystal waveguides[J]. *Appied Physics Letters*, 2011, **98**(5): 211104-1-4.

[10] LIU Ke-xin, SHEN Lin-fang, ZHENG Xiao-dong, *et al*. Interaction between two one-way waveguides [J]. *IEEE Journal of Quantum Electronics*, 2012, **285**(6):1059-1064.

[11] REN Hong-liang, QIN Ya-li, WEN Hao, *et al*. Photonic crystal three-port channel drop filter based on one-way waveguide[J]. *IEEE Photonics Technology Letters*, 2012, **24**(3): 332-334.

[12] MANOLAYOU C, KHAN M, FAN S, *et al*. Coupling of modes analysis of resonant channel add-drop filters[J]. *IEEE Journal of Quantum Electronics*, 1999, **35**(9):1322-1331.

[13] ZHANG Z, QIU M. Coupled mode analysis of in-plane channel drop filters with resonant mirrors[J]. *Journal of the Optical Society of America B*, 2006, **13**(8):149-154.

[14] LI Jian-ming. A novel mode of single-negative media photonic crystal with anisotropic defect[J]. *Acta Photonica Sinica*, 2013, **42**(8):615-618.

[15] LI Lei, LIU Gui-qiang, CHEN Yuan-hao, *et al*. Photonic crystal three-wavelength power splitter based on directional coupling[J]. *Acta Photonica Sinica*, 2013, **42**(8):167-170.

[16] TANG Fa-lin, LIU Gui-qiang, LI Lei, *et al*. Three channels wavelength division multiplexing of two-dimensional triangular lattice photonic crystals [J]. *Acta Photonica Sinica*, 2013, **41**(12):1470-1473.