Power splitter based photonic crystal ring resonator

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In this paper, we propose a new design of two dimensional photonic crystal ring resonator (2D-PCRR) based channel drop filter (CDF). Through the two-dimensional (2D) finite-difference time-domain (FDTD) method with perfectly matched layers (PMLs) absorbing boundary conditions in triangular lattice photonic crystal (PC) silicon rods, 100% backward dropping efficiency with the quality factor of more than 1385 can be achieved at the optical communication window while the resonant wavelength is 1550 nm. Moreover, the effects of changing the dielectric constant of silicon rods as well as radius of whole rods are discussed and conclusions are reached. Based on the proposed component, a splitting operation with equal backward drop efficiencies and a quality factor of 2040 across all channels can be obtained. The proposed device has appropriate performances and could be used in the future photonic applications.

1. Introduction

Photonic crystals (PCs) are optical materials in which a periodic modulation of the refractive index results in a photonic band gap (PBG). Possible miniaturisations of integrated optical components without radiation losses can be achieved by using PBG materials with a complete PBG. Many novel devices have been designed and fabricated based on PCs such as waveguides [1-3], resonant cavity with ultra-high Q [4, 5], optical switch [6, 7] and channel drop filters (CDFs) [8-11].

The CDFs have attracted a great deal of attention due to their potential applications in a wide variety of fields, such as photonic integrated circuits, telecommunications and quantum informatics. Fan et al. [12] analyzed a novel CDF based on 2D-PC with square lattice of dielectric rods embedded in air substrate. They showed that in order to achieve complete power transfer from one waveguide to another parallel waveguide, the single cavity must support two doubly degenerate modes with opposite symmetry. Using this process, a six channel filter in a 2D-PC was reported by Sharkawy et al. [13], in which the tunability of the dropping signal is obtained by means of a localized change in the geometrical or dielectric properties of the cavities. Noda et al. [14] presented 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 wavelength division multiplexing (DWDM) system [14]. Zhang et al. [15] presented a compact in-plane CDF using a single resonant cavity formed by altering the radius of air holes in the PC structure. They achieved a high forward dropping by modifying the upper boundary of the drop waveguide. Ren et al. [16] proposed a new CDF based on wavelength-selective reflection microcavity. Using coupled mode theory, they derived the conditions to achieve 100% drop efficiency. Takano et al. [17] demonstrated experimentally an in plane multi-CDF with high efficiency in a 2D-PC slab. They investigated a method to obtain multi-channel drop operation using the concept of heterostructure PCs.

Photonic crystal ring resonators (PCRRs) are also used in the design of CDFs [18]. It can offer scalability in size and flexibility in mode design. The first report of a photonic-crystal ring resonator (PCRR) was in a hexagonal waveguide ring laser cavity [19], where flexible mode design and efficient coupling were discussed. Later, the spectral characteristics of the waveguide-coupled rectangular ring resonators in PCs were investigated by Kumar et al. [20] where a large single quasi-rectangular ring was introduced as the frequency selective dropping elements. Recently, several types of CDF based on 2D PCRR have been proposed using quasi-square PCRR [18], square PCRR [18], dual square PCRR [18], dual curved PCRR [21], hexagonal PCRR [22], 45° PCRR [23], circular PCRR [24], X-shaped PCRR [25], modified X-shaped PCRR [26], elliptical- shaped PCRR [27], T-shaped PCRR [28] and H-shaped PCRR [29].

In this paper, a new design of 2D-PCRR based CDF is proposed and numerically demonstrated by using the 2D-FDTD method with perfectly matched layers (PMLs) absorbing boundary conditions in triangular lattice PC silicon rods. The present device provides the possibility of channel drop filter and could be used in the future photonic applications.

2. Numerical results and analysis

The presented device mainly consist of 2D triangular lattice of silicon rods in an air background whose dielectric constant is $\mathcal{E} = 12$. The silicon has a radius of $0.2a$, where a is the lattice constant. The dispersion curves of the PC structure without and with defect are computed using the MIT Photonics-Bands (MPB) package [30]. It can be seen from Fig. 1 (a) that for the former case, the structure has two PBGs with gray color in the TM modes (transverse magnetic) and one with pink color in the TE modes (transverse electric). The first PBG is ranging from $0.444\ a/\lambda$ to $0.274\ a/\lambda$, the second PBG is from $0.593\ a/\lambda$ to $0.559\ a/\lambda$ whereas the last PBG is between $0.862\ a/\lambda$ to $0.821\ a/\lambda$. For the latter case, the so called W1 line defect waveguide in the PCs is formed by one missing row of silicon rods along the Γ–K direction as shown in Fig. 1(b). The waveguide supports a single-mode frequency (normalized) ranging from $0.442\ a/\lambda$ to $0.337\ a/\lambda$ below the light-line, where λ is the wavelength of light in free space.
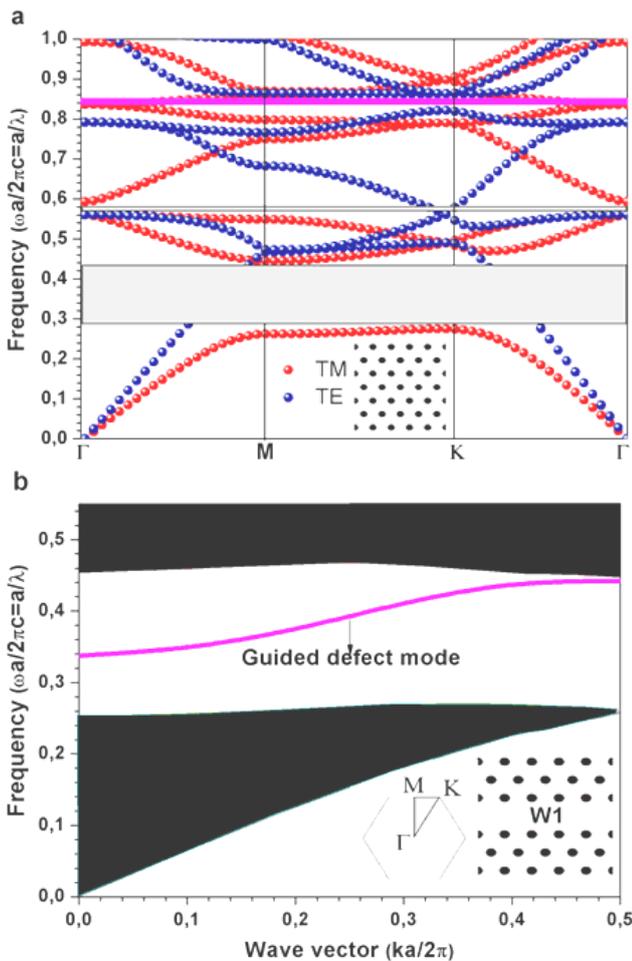
For the optical communication window, the lattice constant a is set as 644.97 nm. Thus the W1 PC waveguide is broadband in the wavelength range 1458 nm $< \lambda < 1912$ nm.

The designed 2D-PCRR based CDF consists of two parallel W1 line defect waveguides and a single PCRR cavity sandwiched between them. The resonant cavity is formed by one missing row of silicon rods rotated 45° from the horizontal along the Γ–M direction. As shown in Fig. 2, the top waveguide is called as bus waveguide whereas the bottom waveguide is known as drop waveguide. The input channel is labelled as A whereas the transmission channel is defined as B. Ports C and D are denoted as forward drop and backward drop channels respectively. The footprint of the device is approximately 11.6µm × 10.9µm. The transmission characteristics of the CDF are calculated by using the open 2D FDTD method, with perfectly matched layers (PMLs) absorbing boundary conditions [31]. In the in-plane configuration, a practical device requires a full 3D analysis, which enormous calculations resources will be required. However, the 2D approach can gives an indication of the expected 3D behaviour. A TM Gaussian beam excitation covering the whole frequency range of interest, is launched at the input channel A. Power monitors were placed at each of the other three channels (B, C and D) to collect the transmitted spectral power density after Fourier-transformation. All of the transmitted spectral power densities were normalized to the incident light spectral power density from input channel A. The normalized transmission spectra at channels B, C and D are displayed in Fig. 3 as black, red and blue lines respectively.
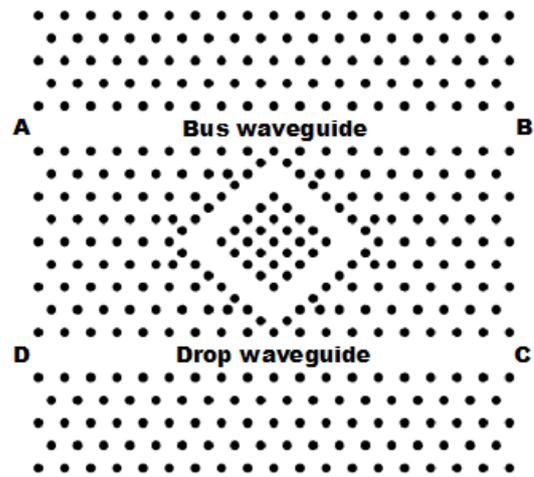

Fig. 1. Dispersion curves of the PC structure (a) without defect and (b) with defect

Fig. 2. Schematic diagram of the proposed 2D-PCRR based CDF
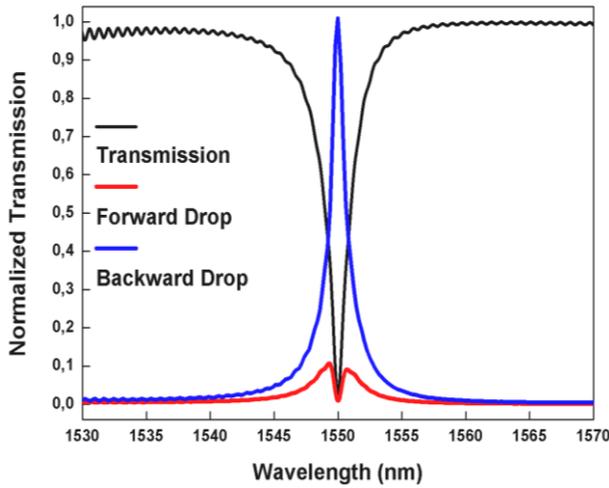
Fig. 3. Normalized transmission spectra of the 2D-PCRR based CDF at ports B, C and D respectively

Fig. 4. Electric field snapshots at (a) on-resonance (λ=1550 nm) and (b) off-resonance (λ=1570 nm)

As shown in Fig. 3, perfect channel drop operation from the input channel to the backward drop channel through the resonant ring is observed. At resonance, the propagating waveguide mode couples to the resonant modes of the PCRR cavity. Thus, all the power in the bus waveguide is extracted by using resonant tunnelling process and transferred into the drop waveguide. On the other words, the coupled mode in the PCRR ring cavity rotates in the clockwise direction with the propagating waveguide mode, which leads to the backward dropping. Note that the system can perform forward dropping operation by further tuning such as shifting, perturbing the radius and/or the refractive index of the rods. In this case, the propagating waveguide mode rotates in the counter-clockwise direction with the coupled mode in the PCRR ring cavity. 100% backward dropping efficiency with the quality factor of more than 1385 can be achieved at the optical communication window while the resonant wavelength is 1550 nm. By comparing our results with the earlier works in the literature [27- 29] the spectral selectivity and/or the quality factor of the proposed filter is higher.

The electric field snapshots in the time domain at on-resonance (λ=1550 nm) and off-resonance (λ=1570 nm) are shown in Figs. 4 (a) and (b) respectively.
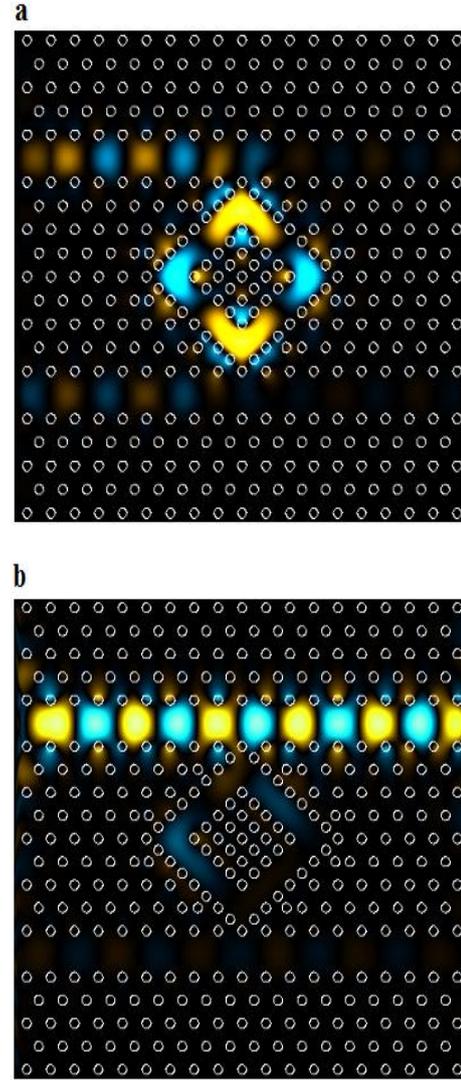
Based on the obtained results, parameters which affect the transmission responses of the proposed CDF can be investigated. Fig. 5 shows the normalized transmission spectra at port D for different dielectric constants of whole rods $\varepsilon = 11.5$, $\varepsilon = 11.75$, $\varepsilon = 12$, $\varepsilon = 12.25$ and $\varepsilon = 12.5$ respectively. As shown, the resonance wavelengths are tunable by means of a localized change in the dielectric constant of the rods. On the other hand, the maximum transfer efficiency shifts towards higher frequency as the dielectric constant of the rods increases. The drop efficiencies are close to 100% and the output wavelengths are 1533.63 nm, 1541.86 nm, 1550 nm, 1557.99 nm and 1566.07 nm respectively.
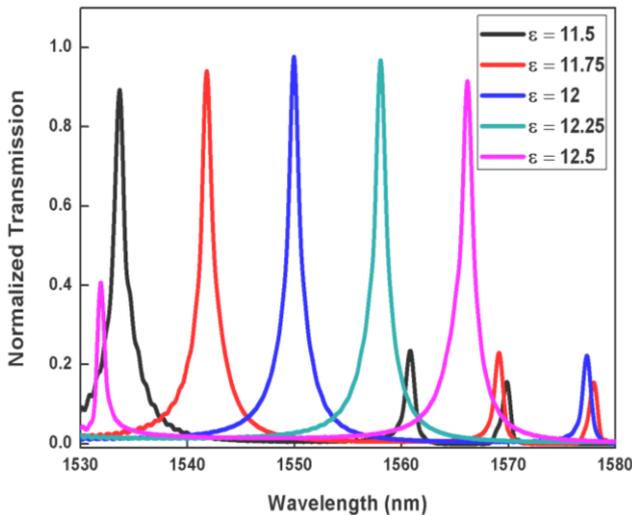
Fig. 5. Normalized transmission spectra for different dielectric constants of silicon rods ε = 11.5, ε = 11.75, ε = 12, ε = 12.25 and ε = 12.5 respectively

In similar way, the radius of silicon rods can be modified. Fig. 6 shows the normalized transmission spectra at port D for different radiuses of silicon rods r = 0.195a, r = 0.1975a, r = 0.2a, r = 0.2025a and r = 0.205a respectively (which a is the lattice constant). It can be seen that the maximum transfer efficiency increases as the radius of the rods increases. The drop efficiencies are 100% and the selected wavelengths are 1531.23 nm, 1540.45 nm, 1550 nm, 1559.43 nm and 1569.41 nm respectively. This way is advantageous because it reduce the complexity of the fabrication.
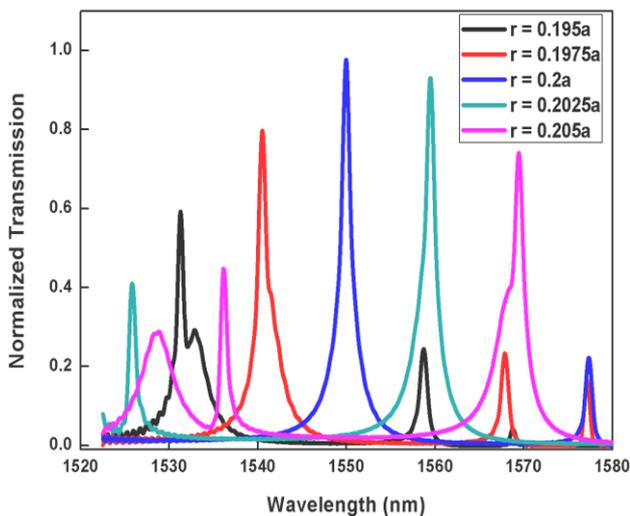

Fig. 6. Normalized transmission spectra for different radiuses of silicon rods r = 0.195, r = 0.1975, r = 0.2, r = 0.2025 and r = 0.205 respectively

Based on the result shown above, a splitting operation based on the proposed CDF is designed to perform complete power transfer from the input channel to the drop channels using the resonant tunneling process described previously. As depicted in Fig. 7, the designed 2D-PCRR

based splitter consists of three parallel W1 line defect waveguides and two parallel PCRRs cavity. The input channel is labelled as A whereas the backward drop channels are denoted as B and C respectively. The footprint of the device is approximately 11.6 µm × 16.7 µm. The normalized transmission spectra at channels B and C are displayed in Fig. 8 as black and red lines respectively.
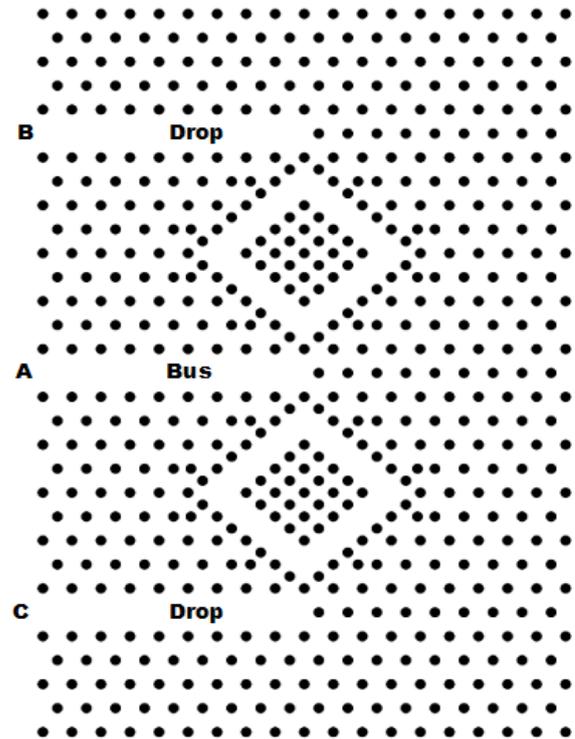

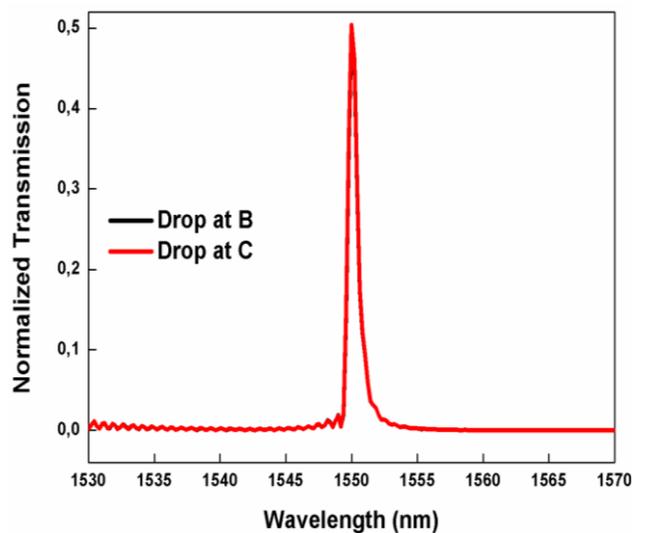*Fig. 7. Schematic diagram of the proposed 2D-PCRR based splitter*

Fig. 8. Normalized transmission spectra of the 2D-PCRR based splitter at ports B and C respectively

As seen, equal backward drop efficiencies with equal quality factors across all channels can be obtained at 1550

nm. On the other words, the backward drop efficiencies at channels B and C are estimated to be 50% and the corresponding quality factors are about 2040.

The electric field snapshots in the time domain at on-resonance (λ=1550 nm) and off-resonance (λ=1570 nm) are shown in Figs. 9 (a) and (b) respectively.
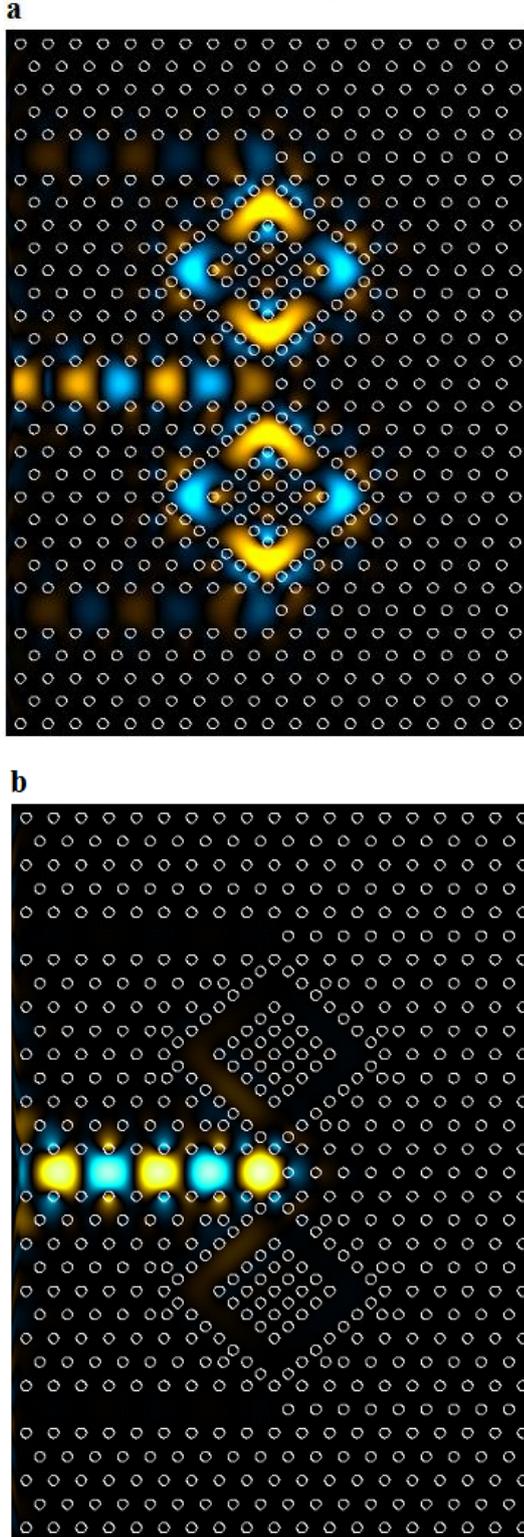
a

b

*Fig. 9. Electric field snapshots at (a) on-resonance
(λ=1550 nm) and (b) off-resonance (λ=1570 nm)*

3. Conclusions

In this paper, a new design of two dimensional photonic crystal ring resonator (2D-PCRR) based channel drop filter (CDF) was proposed and numerically demonstrated. 100% backward dropping efficiency with the quality factor of more than 1385 can be achieved at the optical communication window while the resonant wavelength is 1550 nm. Through the proposed component, a splitting operation with equal backward drop efficiencies and a quality factor of 2040 across all channels can be obtained. The proposed device has appropriate performances and could be used in the future photonic applications.

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