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Design of an Improved Optical Filter Based on Dual-Curved PCRR for WDM Systems

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Abstract: In this paper, an optical filter based on a two dimensional photonic crystal ring resonator (PCRR) with triangular lattice is designed and presented. For this purpose, the effects of positioning, arrangement and the number of the inner rods of the dual-curved PCRR on the performance characteristics of our optical filter such as the transmission coefficient and the quality factor have been fully investigated. Calculation results show that a transmission coefficient of 100% with a quality factor of 2400 at the operating wavelength of nearly 1576 nm can be achieved. The proposed optical filter comparatively performs better than the previously reported ones. In addition, this structure can be used for the design of optical multi-channel demultiplexer. To study the photonic band gap of our structure, the plane wave expansion (PWE) method has been used and the finite-difference time-domain (FDTD) method has also been employed to analyze the optical behavior of the proposed device.

Key words: Photonic crystal, Optical Filter, WDM, Photonic band gap, PWE, FDTD.

1. INTRODUCTION

Photonic crystals (PCs) are nanostructures with alternating refractive index which have created an appropriate platform in designing and developing optical integrated circuits (PICs) [1, 2]. The most important feature that reveals the practical significance of PCs is the photonic band gap (PBG) [3]. Band gap in PCs represents a forbidden energy range in which wave behaving photons cannot be transmitted through the structure. Therefore, by creating some defects, the light within the structure can be controlled.

By creating appropriate defects, different optical devices based on PCs can be developed, they include, optical filters [2], optical demultiplexers [4], optical switches [5], optical waveguides [6], optical logic gates [7], optical sensors [8], optical splitters [9], optical converters [10] and optical power dividers [11].

Amongst the various types of optical device mentioned above, optical filters are very much practical. Optical filters are used to selectively transmit or reject a wavelength or a range of wavelengths. Optical filters are used in wavelength division multiplexing (WDM) systems [2, 12].

To design an optical filter based on PCs, some defects are created in the structure of PC. Such defects are divided into several categories, such as point defects, linear defects and ring resonators.

In this paper, an optical filter is designed by a dual-curved photonic crystal ring resonator (PCRR). The proposed filter has a transmission coefficient of 100%, and a high quality factor of nearly 2400. The results of the proposed optical filter is comparatively better than those of other recently reported ones.

This paper is formed as follows. In Section 2, the design principle of a ring resonator based optical filter is presented. In Section 3, the photonic band gap of the structure prior to introducing defects and other structural parameters are described. Sections 4 and 5 focus on the proposed optical filter and the corresponding optical demultiplexer designed, and finally, the conclusions are presented in Section 6.

2. RING RESONATOR BASED OPTICAL FILTER

An optical ring resonator is positioned between two optical bus waveguides to provide an ideal basic structure for a ring resonator based optical filter. In this structure, a bus waveguide can couple to the ring resonator at its resonant frequency to trap the electromagnetic energy that is propagating in the waveguide and localize it in the ring resonator. In this optical filter, there are 2 ports; port 1 is the input terminal and port 2 is the transmission (output) terminal. In PC structures, two kinds of optical resonators can be designed: (1) line defect or point defect based resonators, i.e., one where changing the size or dielectric constant of each rod causes the consequent defect to behave as a resonator. And (2) ring resonators i.e., if we remove some rods in order to have a ring shape, we have a ring resonator. Compared to point-defect or line-defect PC cavities, PCRRs offer scalability in size, flexibility in mode design due to their multimode nature and adaptability in structure design because of numerous design parameters. The design parameters can be the radius of the scatters, coupling rods and the dielectric constant of the structure [13].

So far, different types of ring resonator for use in photonic crystal based optical filters have been designed, they include:

1. Circular PCRR,
2. Hexagonal PCRR,
3. Plus-shaped PCRR,
4. Flower-shaped PCRR
5. Quasi-shaped PCRR,

6. Egg-shaped PCRR,
7. H-shaped PCRR,
8. X-shaped PCRR,
9. Rectangular PCRR,
10. Dual-curved PCRR,
11. Square and quasi square-shaped PCRR,
12. Octagonal-shaped PCRR

3. PHOTONIC BAND GAP STRUCTURE

In this paper, plane wave expansion (PWE) method has been used to extract the photonic band gap of the proposed structure. First, to design the proposed optical filter, a 23*23 (The number of rods in x and z directions are 23 and 23, respectively) structure with a triangular lattice of dielectric rods immersed in air is used. The effective refractive index of dielectric rods is n_r= 3.9, the radius of the rods is R= 110 nm and the lattice constant is a= 610 nm [2, 4]. The band diagram of the structure with aforementioned values for refractive index, radius of the rods and the lattice constant is shown in Fig. 1. The structure has two photonic band gaps in TM mode and one in TE mode, amongst which only one of the PBGs of the TM mode can be used in the optical fiber telecommunication windows, since $0.262 \leq a/\lambda \leq 0.448$ which corresponds to $1361 \text{ nm} \leq \lambda \leq 2328$ nm. This wavelength range covers a wide spectrum of optical communication wavelengths, which is appropriate for designing optical filters.

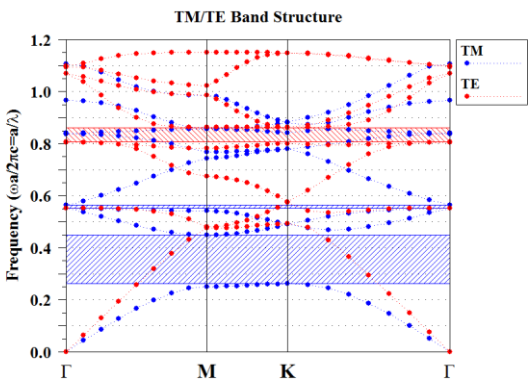

Fig. 1. The band gap of the proposed structure.

Beside band structure, we calculated the gap map diagrams of our structure. Gap map diagrams are shown in Fig. 2. Fig. 2a shows the variation of the PBG versus the delta (n_r - n_{air}) of the structure. As we can see, by increasing the delta of the dielectric rods the PBG shifts toward lower normalized frequencies, also by increasing the delta, the number of PBG regions increases too. In addition, as can be seen in Fig. 2b, the photonic band gap is shifted towards higher frequencies by increasing the lattice constant. Also by increasing the lattice constant, the number of PBG regions increases too. Moreover, it can be seen in Fig. 2c, that the photonic band gap is shifted towards lower frequencies by increasing the radius of the dielectric rods. Also by increasing the delta, the number of PBG regions increases as well.

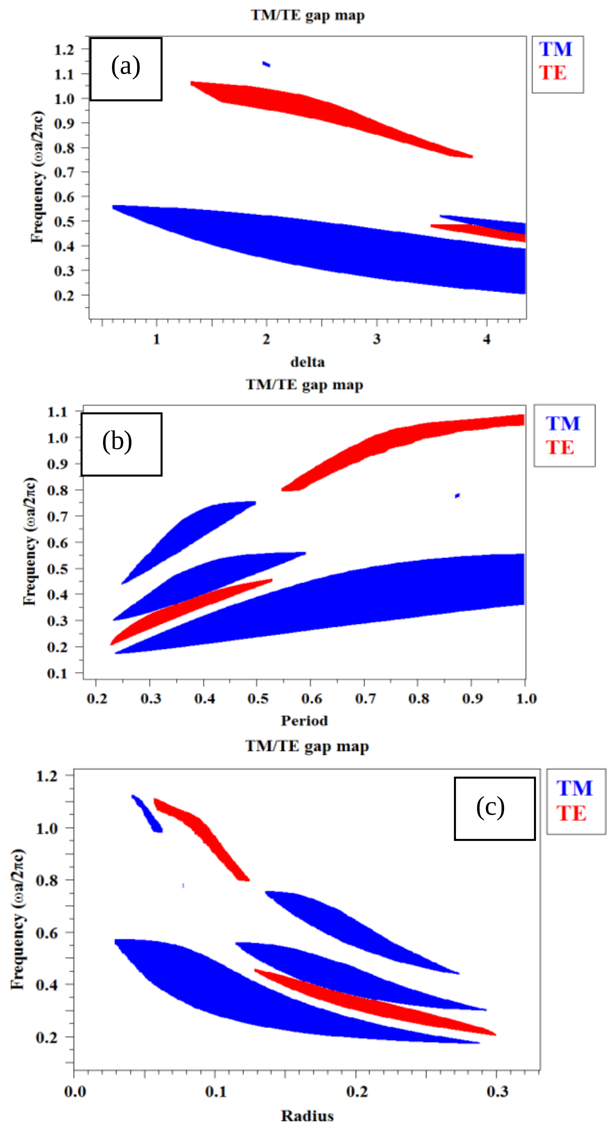

Fig. 2. Gap map diagrams: variation of PBG versus (a) delta, (b) lattice constant and (c) radius of dielectric rods

4. DESIGN OF OPTICAL FILTER

The finite-difference time-domain (FDTD) numerical method has been used to obtain the output spectrum of the structure designed. In this paper, we have used a dual-curved PCRR to design optical filter for selection of an appropriate wavelength. In the proposed optical filter as shown in Fig. 3, two waveguides using linear defects are made, one in the input and the other in the output port along with a ring resonator to isolate the desired wavelength. The ring resonator have an inner rods radius (Ri) of 180 nm and the radius of its scattering rods (Rs) is equal to 115 nm which are used to prevent the scattering of light within the structure [14]. According to this figure, the structure has 5 rows of inner rods with a total of 14 rods all together. A transmission coefficient of 100% and a quality factor of 2446 at the wavelength of 1576 nm are achieved. In order to further investigate the proposed filter structure, some changes in the positioning and the number of the inner rods of the ring resonator have been made. This is shown in Fig. 4. According to this figure, the structure has 4 rows of inner rods with a total of 16 rods all together. A transmission coefficient of 100% and a quality factor of 2320 at the wavelength of 1578 nm are achieved. In addition, parameters such as resonator type, transmission coefficient and quality factor of our design are compared with other designs in the literature as listed in Table 1. It can be seen that our filter performs better than the previously reported ones.

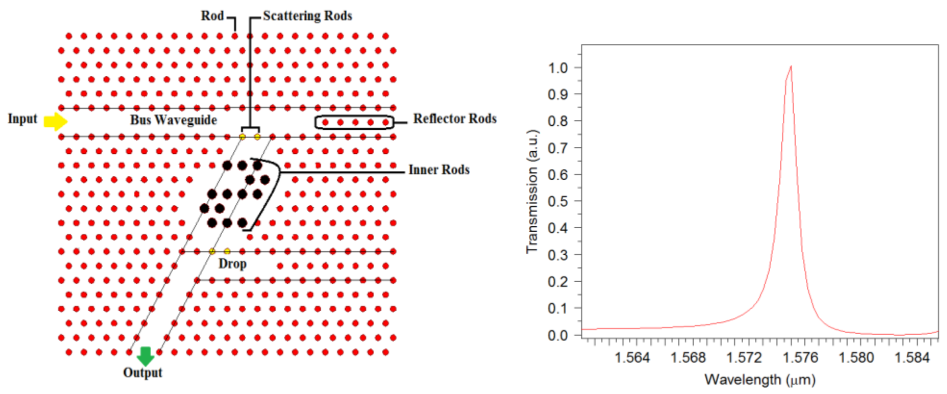

Fig. 3. The schematic diagram and output spectrum of the proposed filter.

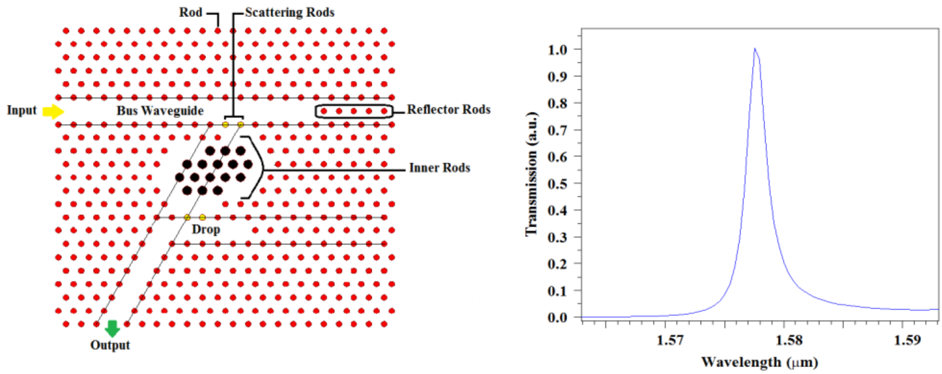

Fig. 4. The schematic diagram and output spectrum of the proposed filter by making changes to the way of arranging the inner rods of the PCRR.

Table 1: Comparison between different parameters of the proposed optical filters with other ones.

Structure	Ring resonator type	Transmission (%)	Quality factor
Our structure (1)	Dual-curved	100	2446
Our structure (2)	Dual-curved	100	2320
[15]	H-shaped	100	221
[2]	Hexagonal	95	1290
[16]	Flower-shaped	100	205
[17]	X-shaped	100	100
[18]	Plus-shaped	99	1011
[19]	Circular	100	502
[20]	Quasi-shaped	90	387

5. DESIGN OF AN OPTICA DEMULTIPELEXER FOR WDM SYSTEMS

Between the two structures, the proposed optical filter (structure (1)) is a suitable device for designing a low loss and high quality factor demultiplexer. The output spectra of this structure for different values of Ri are shown in Fig. 5. According to this figure, by increasing Ri of the structure, the resonant wavelength is shifted towards longer wavelengths. Using this idea, we have proposed a new design for multi-channel demultiplexer based on PCRR.

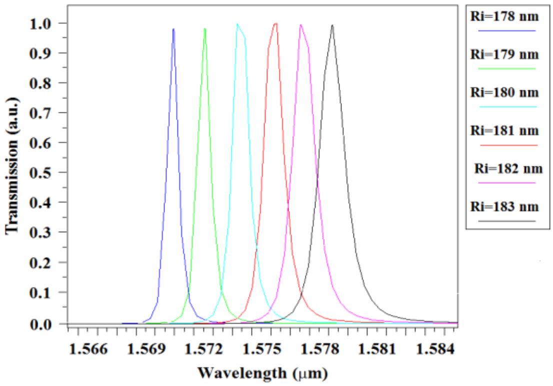

Fig. 5. The output spectra of the proposed filter for different values of Ri.

The proposed two-channel demultiplexer is shown in Fig. 6. The radii of the inner rods equal to Ri1= 180 nm and Ri2= 181.5 nm for the first and second channels, respectively. The main structure of the demultiplexer has 39*23 (The number of rods in *x* and *z* directions are 39 and 23, respectively) dielectric rods. As shown in Fig. 7, the proposed demultiplexer is able to isolate the wavelengths of 1574.6 nm and 1576. 5 nm by the first and second channel respectively. Furthermore, the transmission coefficient, the quality factor, and the spectral width of each channel is presented in Table 2. In order to better understand how the above mentioned wavelengths are isolated by the proposed demultiplexer, Fig. 8, is presented. In addition, the crosstalk values of each channel are presented in Table 3. In the proposed demultiplexer, the average channel spacing, quality factor and the transmission coefficient equal to 1.9 nm, 2296, and 98%, respectively.

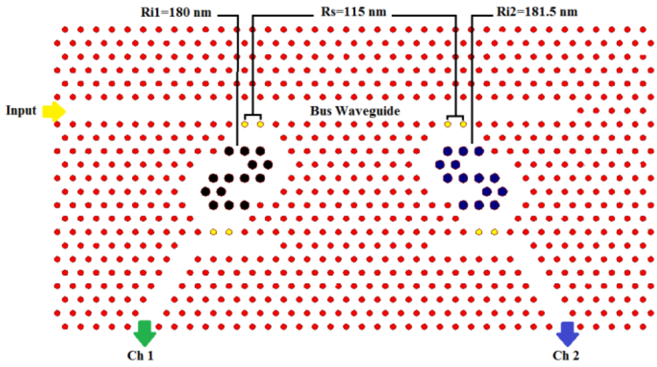

Fig. 6. Schematic diagram of the proposed optical demultiplexer.

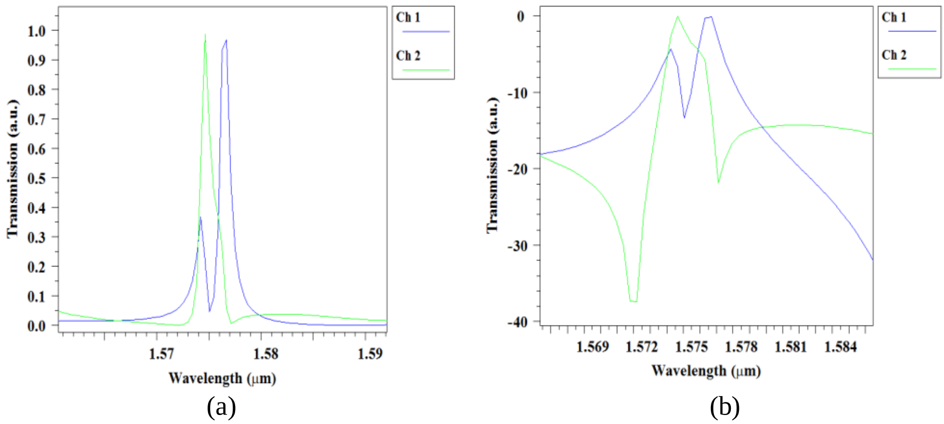

Fig. 7. Output spectra of the proposed demultiplexer, (a) Linear and (b) dB scales.

Table 2: Simulation results of the proposed demultiplexer.

Channel	Wavelength (nm)	spectral width (nm)	Transmission (%)	Quality factor
Channel 1	1574.6	0.6	99	2623
Channel 2	1576.5	0.8	97	1970

Table 3: Crosstalk values of the proposed demultiplexer (dB).

Channel	Channel 1	Channel 2
Channel 1	-	- 8 dB
Channel 2	- 15 dB	-

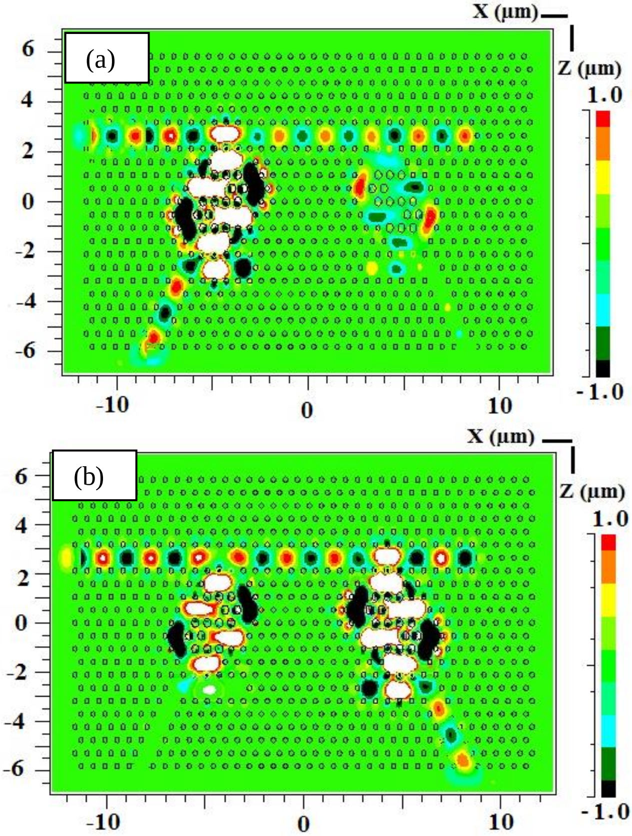

Fig. 8. Distribution of the optical power at (a) λ = 1574.6 nm and (b) λ = 1576.5 nm.

According to the results, our optical demultiplexer has a high quality factor, high transmission coefficient and low channel spacing, so it is comparatively much more suitable for WDM systems. We intend to use this design procedure for designing 4 and 8-channel optical dimultiplexers based on this type of ring resonator in the near future.

6. CONCLUSION

In this paper, two kinds of optical filters based on 2D photonic crystal with triangular lattice and dual curved PCRR are designed and presented. The effects of positioning, arrangement and the number of the inner rods of the dual curved PCRR on the performance characteristics of our optical filters are fully investigated. A transmission coefficient of 100% with a quality factor of nearly 2400, at the wavelength of nearly 1576 nm are achieved and the quality factor is comparatively improved. As a result, the proposed multi-channel demultiplexer, due to having a high quality factor is suitable for WDM systems.

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