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A new design of a 4-channel optical demultiplexer based on photonic crystal ring resonator using a modified Y-branch

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In this paper, we propose a new structure to design a 4-channel optical demultiplexer using a modified Y-branch structure with 4 hexagonal photonic crystal ring resonators. A new optical filter with a high transfer coefficient and quality factor has been introduced and designed in the present paper using a hexagonal photonic crystal ring resonator, which has then been used to design a 4-channel optical demultiplexer. The proposed demultiplexer has an average transfer coefficient of 95.5% and a high quality factor of 4164.6. It also has a channel spacing of 2.75 nm and a spectral width of 0.4 nm. The maximum and minimum crosstalk values of the channels are –10.5 and –36.5 dB, respectively. To study the photonic band structure, the plane wave expansion method has been used and the finite-difference time-domain method has also been used to analyze the optical behavior of the structure.

Keywords: photonic crystal, ring resonator, optical filter, optical demultiplexer, photonic band gap.

1. Introduction

Wavelength division multiplexing (WDM) is an approach to achieve the optimal use of the fiber capacity with the aim of increasing the number of communication channels [1]. It is done by combining certain wavelengths and transmitting them all over a single optical fiber and finally, the separation of the desired wavelengths is carried out through the use of optical demultiplexers [2].

In optical demultiplexers, several design parameters are important to exploit the full capacity of optical fibers. These parameters include, low channel spacing, high quality factor, high transfer coefficient and low crosstalk. There are different materials to use when designing optical demultiplexers. Amongst them, photonic crystals provide the best platform [3].

Photonic crystals (PhCs) [4–6] are nanostructures with alternating refractive index, which, have created an appropriate platform in designing and developing optical integrated circuits (PICs) [7]. The most important feature that reveals the practical significance of photonic crystals is the photonic band gap (PBG). The guided light can be controlled fully by this feature. To control the light in photonic crystals, the intra-structure defects can be used. By creating appropriate defects, different optical devices based on the photonic crystals can be developed, including optical demultiplexers [3, 8–10], optical switches [11], optical filters [12, 13], optical logic gates [14], and optical sensor [15, 16]. There are different mechanisms to design optical devices based on photonic crystals, such as resonant cavities, defect mode, ring resonator and coupled waveguides [11].

So far various optical demultiplexers based on photonic crystals have been presented using ring resonators, linear or point defects. For example, ROSTAMI *et al.* [17], designed a 4-channel optical demultiplexer using Y-shaped linear defect. ALIPOUR-BANAEI *et al.* [8], presented a 4-channel optical demultiplexer by X-shaped resonators. Using linear defects, GUPTA and JANYANI [18], presented an optical demultiplexer with a very low channel spacing and high quality factor. MEHDIZADEH *et al.* [9], designed a 4-channel optical demultiplexer with high transfer coefficient using quasi-shaped ring resonators. Using linear defects, ALIPOUR-BANAEI *et al.* [3], designed initially an optical filter and then, using this optical filter, they designed an 8-channel, a 16-channel and a 32-channel demultiplexers with low channel spacing. TALEBZADEH and SOROOSH [19], used ring resonators to improve the quality factor and the transfer coefficient and also to reduce the channel spacing. MEHDIZADEH and SOROOSH [20], designed an 8-channel demultiplexer with low crosstalk by the use of linear defects. Using eight ring resonators of square type, VENKATACHALAM *et al.* [21], designed an 8-channel optical demultiplexer. KANNAIYAN *et al.* [22], designed another 8-channel demultiplexer, this time using an octagonal ring resonator. TALEBZADEH *et al.* [23] proposed a structure based on photonic crystals to realize a demultiplexer. To obtain high quality factor, they used arc cavities. Today, most studies conducted on optical demultiplexers based on photonic crystals are focused on reducing the channel separation and improving the crosstalk. In recent years, ring resonators have received considerable attention due to their high transmission efficiency, high quality factor, low crosstalk and flexibility in selecting an appropriate wavelength [8].

In this paper, a 4-channel optical demultiplexer has been designed using a modified Y-branch structure and 4 hexagonal photonic crystal ring resonators. The proposed demultiplexer has appropriate bandwidth, high quality factor and transfer coefficient. The maximum and minimum values of the crosstalk are equal to –10.5 and –36.5 dB, respectively, and the channel spacing is 2.75 nm. The proposed demultiplexer has results better than those of other reported structures.

This paper is formed as follows. In Section 2, the photonic band gap of the structure prior to introducing defects and other structural parameter are described. Section 3 focuses on the optical filter and the corresponding optical demultiplexer designed. In Section 4, the simulation results are presented and discussed, and finally, the conclusions are presented in Section 5.

2. Photonic band gap structure

In the present paper, a plane wave expansion (PWE) method [24], has been used to extract the photonic band gap of the structure. To determine the parameters of the photonic crystal structure, the photonic band gap maps have been used. First, a 21 × 27 structure of dielectric rods immersed in air with triangular lattice is used. To determine the physical structural parameters of our proposed structure, one requires to calculate the gap map diagrams of the design. It should be mentioned that a band gap appropriate for optical telecommunication system is considered in the design. The photonic band gap is extracted using PWE calculations. Subsequently, in order to obtain the gap map diagrams, the band structure is calculated at various values of the photonic crystal parameters, namely, the refractive index, the rod radius and the lattice constant. In Fig. 1**a**, it can be seen that the photonic band gap is shifted towards lower frequencies by increasing the refractive index of the structure. In addition, as can be seen in Fig. 1**b**, the photonic band gap is shifted towards lower frequencies by increasing the *R*/*a* ratio,

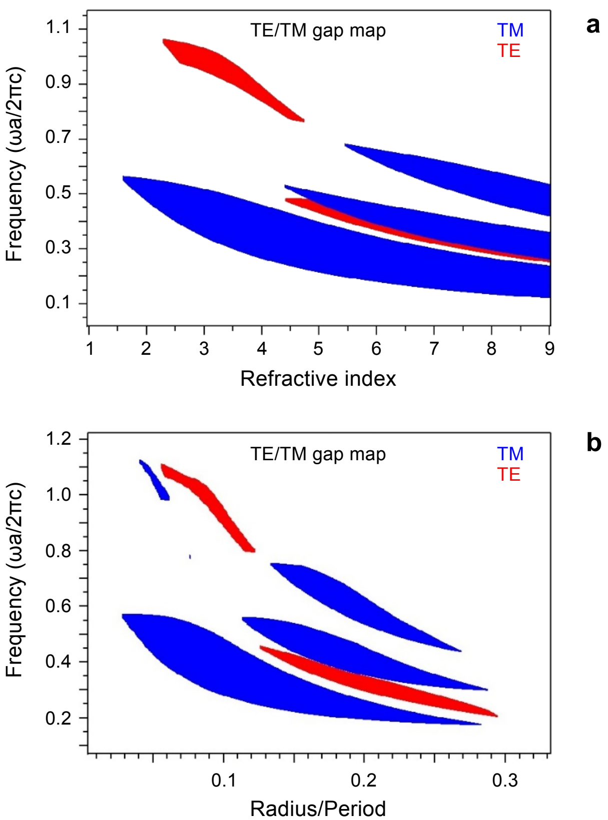

Fig. 1. Gap map diagrams: variation of PBG *versus* refractive index (**a**) and *R*/*a* ratio (**b**).

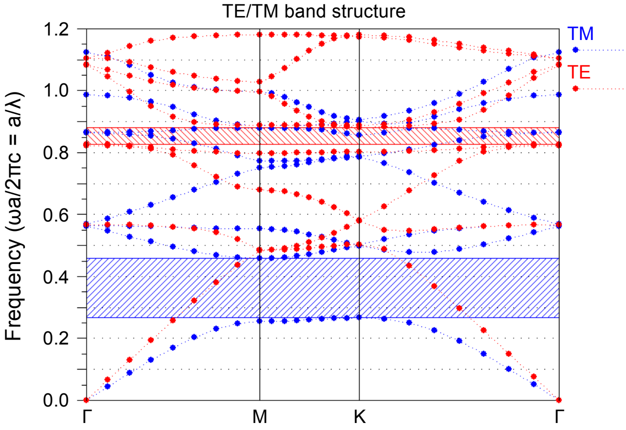

Fig. 2. The band structure of the fundamental structure.

(R is the radius of photonic crystal rods and a is the lattice constant of the structure). According to the photonic band gap maps in Fig. 1, we are able to determine the structural parameters. Hence, a refractive index n of 3.9, dielectric rods radius R of 106 nm and a lattice constant a of 603 nm are considered in the proposed structure.

Now, according to the above mentioned physical characteristics, the final band gap diagram is shown in Fig. 2. As can be noted from this figure, the structure has two photonic band gaps, one in TM and the other in TE mode, amongst which the photonic band gap in the TM mode is suitable. This is because, TM mode includes appropriate telecommunication channels. The value of the band gap mentioned in the TM mode is in the range of $0.275 \leq a/\lambda \leq 0.47$, which corresponds to wavelength in the range of $1340 \text{ nm} \leq \lambda \leq 2900 \text{ nm}$.

3. Design of optical filter and demultiplexer

In the present study, we have used a hexagonal photonic crystal ring resonator to design an optical filter for the selection of an appropriate wavelength. Two linear defects, one

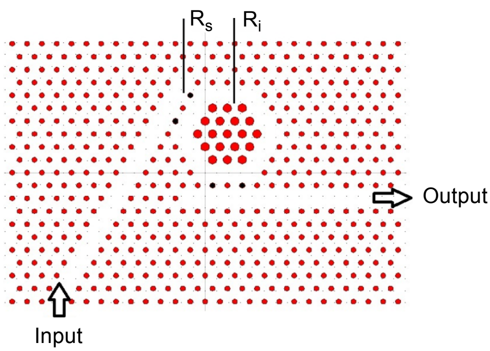

Fig. 3. The schematic diagram of the proposed filter.

in the input and the other in the output port along with a ring resonator to isolate the desired wavelength are used in the proposed optical filter. This is shown in Fig. 3. The ring resonator has an inner radius R_i of 180 nm and the radius of its scattering rods R_s is equal to 115 nm, which are used to prevent the scattering of light within the structure. Output spectrum of the structure is shown in Fig. 4. According to this figure, the structure has a transfer coefficient of 100% and the quality factor of 2446.

Next, the output spectrum of the proposed structure is explored by making changes to the radius of the inner rods of the ring resonator. According to Fig. 5, the output spectrum is shifted towards longer wavelengths with an increase in the radius of the inner rods of the resonator. Using this optical filter, we have proposed a new design for an appropriate optical demuliplexer.

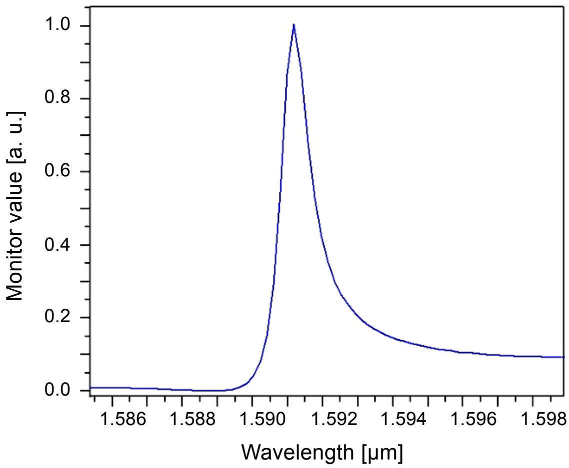

Fig. 4. The output spectrum of the proposed filter.

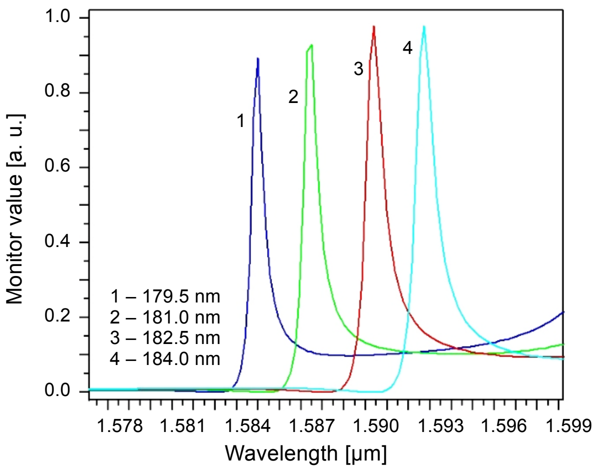

Fig. 5. The output spectra of the proposed filter for different values of R_1.

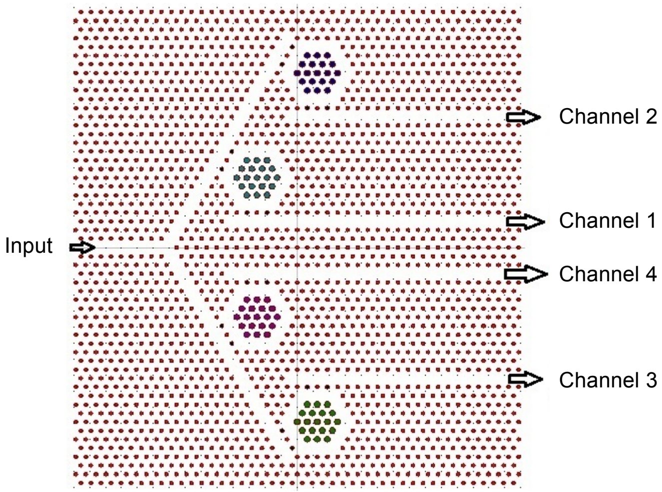

Fig. 6. The sketch of the proposed demultiplexer.

To design the proposed 4-channel optical demultiplexer, which is shown in Fig. 6, 4 hexagonal ring resonators with inner rods having radii of 178, 179.5, 181 and 182.5 nm for the first, second, third and fourth channels, respectively, are used.

4. Simulation results

The finite-difference time-domain (FDTD) [25] method has been used to carry out simulations and calculations. The main structure of the demultiplexer has 45 × 55 (the number of rods in x and z directions are 45 and 55, respectively) arrays of dielectric rods. As shown in Fig. 7, the proposed structure is able to isolate the wavelengths of 1581.5, 1584.75, 1587.25 and 1589.5 nm by the first, second, third and fourth channel, respectively. The exact values of the transfer coefficient, the quality factor and the spectral width of each channel are listed in Table 1. According to this table, the minimum and maximum values for the transfer coefficient are equal to 92% and 100%, respectively, and the minimum and maximum values for the quality factor are equal to 2890 and 5272.5, respectively. The average width of the spectrum is 0.4 nm and the

Table 1. Simulation results of the proposed demultiplexer.

	Central wavelength [nm]	Resonant rod [nm]	Spectral width [nm]	Quality factor	Transmission [%]
Channel 1	1581.75	178	0.3	5272.5	100
Channel 2	1584.75	179.5	0.35	4527.8	92
Channel 3	1587.25	181	0.4	3968.1	96
Channel 4	1589.5	182.5	0.55	2890	94

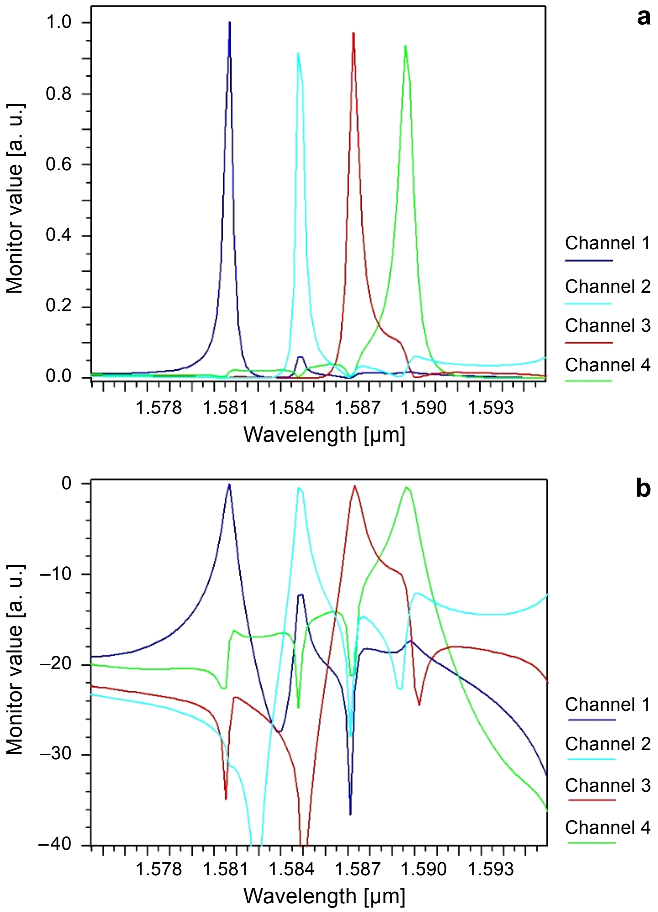

Fig. 7. The output spectra of the proposed demultiplexer. Linear (**a**) and dB (**b**) scale.

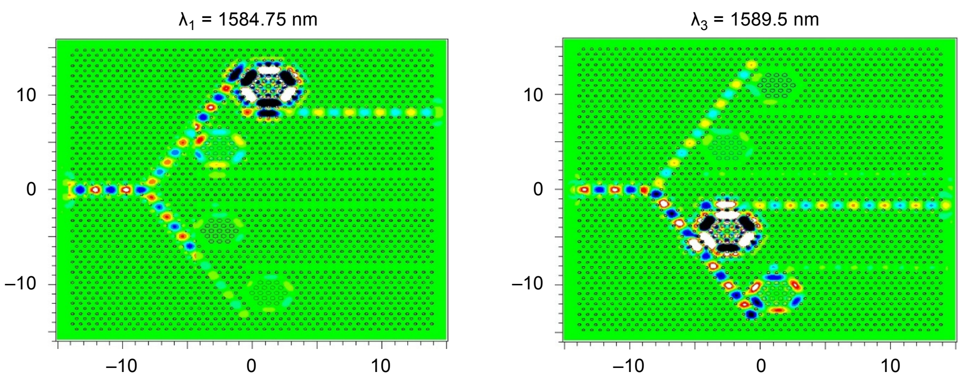

Fig. 8. The electric field distribution of the proposed demultiplexer.

Table 2. Crosstalk values of the proposed demultiplexer (dB).

	Channel 1	Channel 2	Channel 3	Channel 4
Channel 1	–	–12.5	–24	–18
Channel 2	–17.5	–	–20	–21.5
Channel 3	–27	–23.5	–	–10.5
Channel 4	–32	–36.5	–21	–

channel spacing is 2.75 nm. To better understand how the above mentioned wavelengths are isolated by the proposed demultiplexer, Fig. 8 is presented, according to which, light waves with wavelength of 1584.75 nm exit from channel 2 and with wavelength of 1589.5 nm exit from channel 4. The crosstalk values are presented in Table 2. It can be seen that the maximum and minimum values of crosstalk are equal to –10.5 and –36.5 dB, respectively.

To compare the proposed structure with other reported structures, including linear defects and ring resonators, Table 3 is presented. In this table, transfer coefficient, quality factor, channel spacing, spectral width and the crosstalk are compared.

According to the above table, our 4-channel demultiplexer has a high quality factor when compared to other reported structures, so it is much more suitable for DWDM systems. Our structure has also appropriate transfer coefficient, channel spacing and crosstalk values, while previously reported demultiplexers have some restrictions to all or some of the above mentioned parameters.

Table 3. Comparison of the proposed demultiplexer with the other reported ones.

	Proposed DMUX	[2]	[8]	[9]	[10]	[17]	[19]
Number of channels	4	4	4	4	4	4	4
Spectral width [nm]	0.4	0.475	1.7	1.35	0.425	1.05	0.3975
Channel spacing [nm]	2.75	3	3.03	3.2	2.06	3.5	2
Quality factor	4164.6	3409.7	1234.2	1224.7	4107.3	1496.7	3602
Transmission [%]	95.5	99.82	52.2	96.2	93.45	80.25	99.25
Maximum of crosstalk [dB]	–10.5	–19	–7.5	–17	–15.35	–10.49	–20.5
Minimum of crosstalk [dB]	–36.5	–40	–23.7	–38	–38.41	–33.18	–42
		[20]	[21]	[22]	[23]		
Number of channels		8	8	8	8		
Spectral width [nm]		0.675	1.8	0.787	1.48		
Channel spacing [nm]		2.1	4.2	1.7	1.75		
Quality factor		2391.8	825	1968.8	1200		
Transmission [%]		97.5	81	98	99		
Maximum of crosstalk [dB]		–11.2	–	–	–5		
Minimum of crosstalk [dB]		–40	–	–	–36.5		

5. Conclusions

In the present study, a new 4-channel optical demultiplexer based on hexagonal photonic crystal ring resonator is presented. This structure can be used in WDM systems. The photonic band gap maps have been used to determine the structural parameters. To separate the desired wavelengths, optical filters based on a ring resonator are used. The optical filter designed has indeed a very favorable transfer coefficient and quality factor. The average transfer coefficient and the quality factor are 95.5% and 4164, respectively. The bandwidth and the separation between the channels are 0.4 and 2.75 nm, respectively. In addition, in this structure, the maximum and minimum values of crosstalk are equal to –10.5 and –36.5 dB, respectively. As the proposed demultiplexer has both high transfer coefficient and quality factor and low crosstalk, hence it is a very good candidate for WDM systems.

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