Effect of scattering rods in the frequency response of photonic crystal demultiplexers

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Design and simulation of a novel structure for WDM communication demultiplexerhas been done. In this work, by using X-shaped ring resonators in a 2-D photonic crystal structure, the desired wavelengths for communication systems could be selected and simulations show that its important characteristics such as crosstalk, channel spacing and quality factor are appropriate for optical communication applications. Scattering rods that used in the rings play very important role in the central wavelength of the output channels in proposed demultiplexer. Minimum crosstalk value is -16 dB and maximum of it is -11 dB. In addition, the efficiency of the designed demultiplexer is enough for communication systems.

(Received November 24, 2014; accepted March 19, 2015)

Keywords: Scattering rods, Crosstalk, Photonic crystal, Demultiplexer, Ring resonator

1. Introduction

Since the proposal of Photonic Crystals (PhCs) in 1987 [1,2], so many researchers have devoted their works to these artificial structures [3-10]. Compactness, high speed of operation, better confinement of light in ultra-small spaces and long life period are their significant advantages over other structures used for designing optical devices [11]. The key feature of PhCs, which makes them suitable for designing all optical devices, is their Photonic Band Gap (PBG). By definition, PBG is a wavelength region in the band structure of PhCs in which the propagation of light waves inside these structures is strictly forbidden. In other words in this wavelength region PhCs behave like mirror for light waves [12]. Another excellent property of PhCs is their scalability [13]. In 2D PhCs by omitting a row of rods form the structure we can create a waveguide for guiding the light toward desired directions inside the crystal. However in order to minimize the power loss inside crystal we had to adjust the PBG of the structure such that our operating wavelength be in the PBG region of the crystal, otherwise light will scatter inside the crystal and will not follow the desired direction. This discussion shows the significant importance of PBG region in PhC based devices. Refractive index of dielectric material, the radius of rods and the lattice constant of the structure are crucial parameters influencing the PBG of 2D PhCs [14].

Photonic Crystal Ring Resonators (PhCRRs) are one of the useful and popular components for designing optical devices suitable for photonic integrated circuits. Add-Drop filters, optical switches, optical demultiplexers, optical bends and power splitters are some examples of optical devices realized based on PhCRRs. Kumar et al [15] investigated the implementation of waveguide coupled ring resonators in PhC, they found that ring dimensions and crystal parameters play an important role in resonance behavior of rig resonator. It has been shown that localization of the light in PhCRRs results in nonlinearity based on which one can design all optical switches [16]. By placing a low resonant ring at waveguide intersection, we can realize L-shaped bends and T-shaped power splitters. For T-shaped splitters the transmission window can be widened by changing the ring size [17]. Djavid et al [18] proposed a heterostrucutre wavelength division demultiplexer using PhCRRs, this demultiplexer separates four wavelength channels. Channel spacing in this structure was approximately 28 nm. They also proposed a T-shaped channel drop filter based on PhCRRs and investigated the effect of different parameters on switching wavelength. They found that dielectric constant of the inner rods and coupling rods is a suitable parameter for tuning the filter [19]. Multichannel-Drop filter using PhCRR is the most recent work done by Djavid and Abrishamian [20].

Recently two different structures have been proposed for designing optical channel-drop filters using PhCRRs, in which instead of conventional shapes for resonant ring the authors used an X-shaped structure as resonant ring [21, 22].

In this paper by applying some modifications in the X-shaped ring resonator based channel drop filter proposed by Mahmoud et al [22] we proposed and designed a 2-channel demultiplexer suitable for wavelength division multiplexing (WDM) applications. The average channel spacing in this structure is 4.4 nm. Crosstalk values are better than -11 dB and transmission efficiency is more than 76%. Compared with previous works this demultiplexer has better channel spacing than all 2 channel demultiplexers and some other works [18,23-28], crosstalk values of our work is better than some previously reported demultiplexers [18,26,29] another advantage of the proposed demultiplexer is its small footprint compared with other works [15-26,29-30].

The rest of this paper organized as follow: in section 2 we calculated the band structure and photonic band gap and also investigated the effect of fundamental parameters on the photonic band gap of the structure. In section 3 the design procedure and different parts of the demultiplexer has been introduced. Simulation and results have been discussed in section 4, and finally in section 5 we concluded from our work and simulations.

2. Band Structure and PBG Calculation

The fundamental platform used for designing our proposed demultiplexer is a 27*31 hexagonal lattice of dielectric rods immersed in air. The effective refractive index of dielectric rods is $n_r=4$, the radius of the rods is r=121 nm and the lattice constant is a=615 nm. The first step in designing PhC based devices is calculating the band structure and obtaining the most suitable PBG with respect to our operational wavelength. Currently the best way for studying the band structure and obtaining the PBG of PhCs is numerical methods. One of these numerical methods is Plane Wave Expansion (PWE) [31]. Due to accuracy and time considerations in our work, we used Bandsolve simulation tool of Rsoft Photonic CAD software for extracting the band structure diagrams and PBG region of our structure, which performs the calculations based on PWE method. The band structure diagram of our structure with aforementioned values for refractive index, radius of rods and lattice constant is shown in Fig. 1.

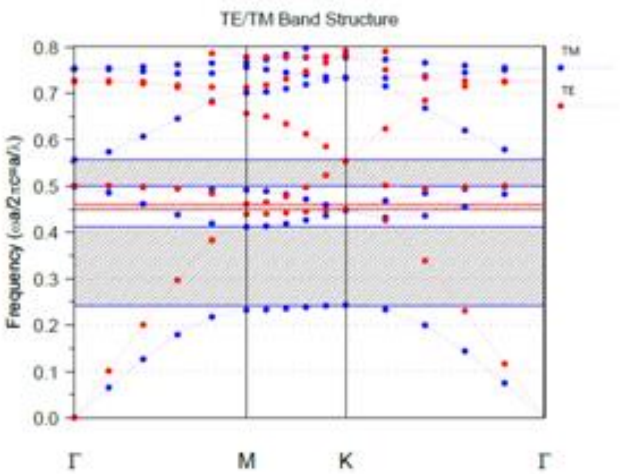


Fig. 1.Band structure and PBG regions

We observe that in TM mode we have two PBG regions in the band structure diagram and one PBG region in TE mode as follow:

PBG region in TM mode:

$$\begin{cases} 0.243 < a/\lambda < 0.411 \\ 0.500 < a/\lambda < 0.556 \end{cases}$$

And

PBG region in TE mode:

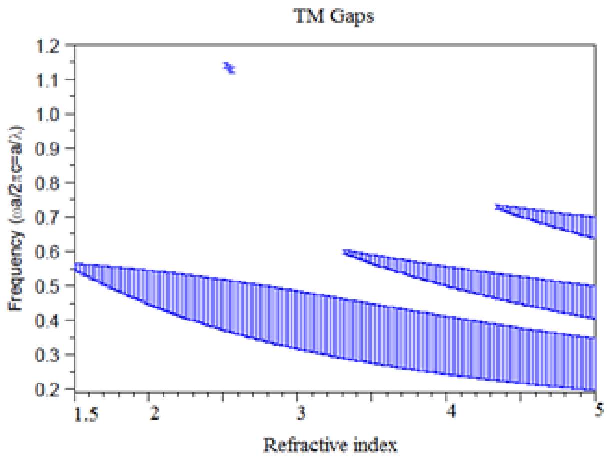
$$0.449 < a/\lambda < 0.460$$

Considering a=615 nm these regions are equal to:

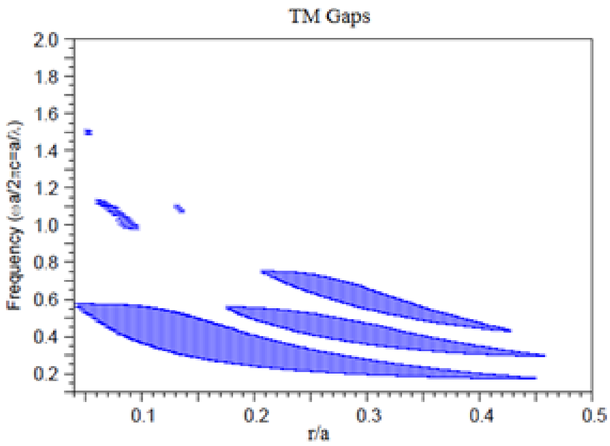
$$\begin{cases} 1496\ nm < \lambda < 2530\ nm \\ 1230\ nm < \lambda < 1106\ nm \end{cases} \text{for TM mode}$$

and $1336\ nm < \lambda < 1370\ nm$ for TE mode.

The results shows that just the first PBG in TM mode is suitable for WDM applications, so all the simulations will be done in TM mode. Beside band structure, we calculated the gap map diagrams of our structure. Gap map diagrams are shown in Fig. 2.



(a)



(b)

Fig. 2.Gap map diagrams:variation of PBG versus (a) refractive index and (b) r/a ratio

Fig. 2 (a) shows the variation of the PBG versus the refractive index of the dielectric rods. As we can see by increasing the refractive index of the dielectric rods the PBG shifts toward lower normalized frequencies also by increasing the refractive index the number of PBG regions increases too. Fig. 2 (b) shows the variation of the PBG versus the r/a ratio (where r and a are the radius of dielectric rods and lattice constant respectively). As we can see by increasing the r/a ratio the PBG shifts toward lower normalized frequencies also by increasing the r/a ratio the number of PBG regions increases too.

3. Demultiplexer Design

As we mentioned earlier our proposed demultiplexer is modified and generalized version of channel-drop filter proposed by Mahmoud et al [22]. The schematic diagram of our proposed demultiplexeris shown in figure 3. Our proposed structure consists of 3 main parts: i) one input waveguide in the center line of the structure, ii) two output waveguides in the upper and lower parts of the structure and iii) two resonant X-shaped rings located between the input waveguide and each output waveguide. In addition, in order to improve the wavelength selectivity we introduce four scattering rods above and under the X-shaped rings, which are highlighted with green color in schematic diagram of Fig. 3.

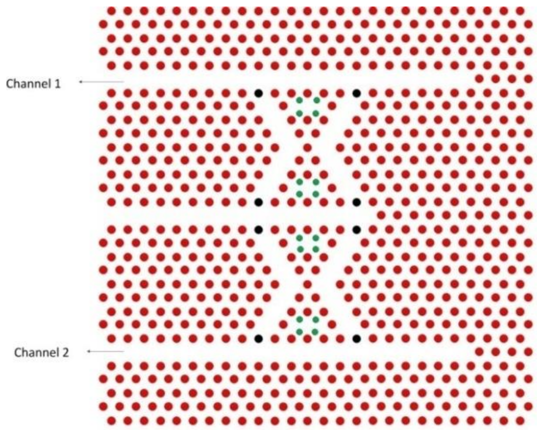
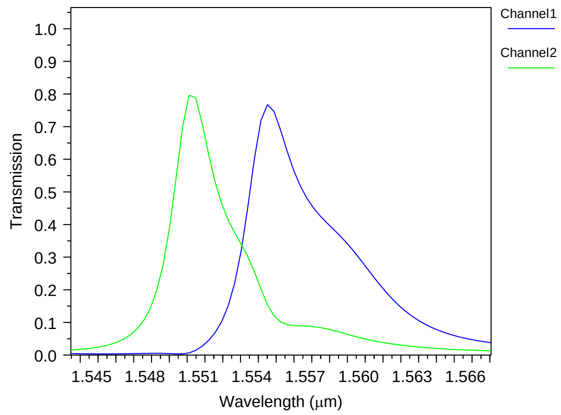


Fig. 3.Schematic diagram of our proposed demultiplexer

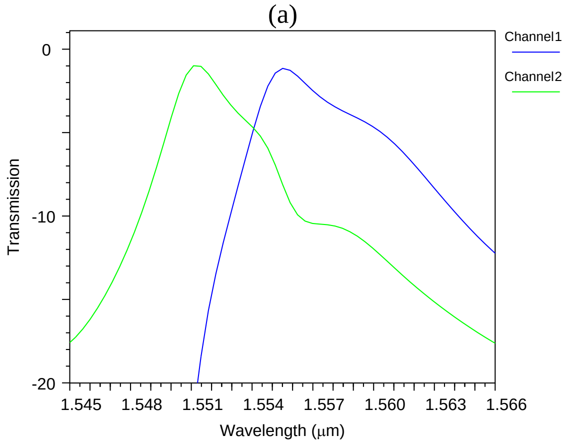
We call the radius of these scattering rods for channel 1 and 2, R_{S1} and R_{S2} respectively. Then in order to have better control over the wavelength selectivity of the rings we introduce another four defects in every X-shaped rings, these defects are highlighted with black color in the schematic diagram of figure 3. We call the radius of these defect rods for channel 1 and 2, R_{D1} and R_{D2} respectively. For having different output wavelengths in output channels we have to choose the values of R_{S1} and R_{D1} different from those of R_{S2} and R_{D2} respectively. Therefore, we chose the following values for these parameters: R_{S1}=90 nm, R_{S2}=117 nm, R_{D1}=100 nm and R_{D2}=117 nm. For improving the transmission efficiency of the demultiplexer we closed the end of the input waveguide, we also do the same for output waveguides. So the final sketch of the demultiplexer became like figure 3.

4. Simulation and Results

The final step in designing PhC-based devices is calculating the propagation of light inside the structure and obtaining the transmission spectrum of the device. for simulating the proposed structure and obtaining the output spectrum of the demultiplexer we used Fullwave simulation tool of RSoft photonic CAD software, which employs Finite Difference Time Domain (FDTD) method [32-33] for simulation the PhC based devices. As we mentioned in section 2 the effective refractive index, the radius the dielectric rods and lattice constant of the demultiplexer are 4, 121 nm and 615 nm respectively, also the values of R_{S1}, R_{S2}, R_{D1}= and R_{D2} are 90 nm, 117nm 100nm and 117 nm respectively. For accurate modeling of the demultiplexer we need 3D simulation, but it requires great amount of run time and very powerful computer. Therefore, we used effective index approximation method of PhCs for satisfying this requirement and with this approximation we reduce the 3D simulations to 2D simulations [34]. The boundary condition used for our simulations chosen to be Perfectly Matched Layer (PML) with 500 nm width of PML surrounding our demultiplexer [34]. Grid sizes ($\Delta x$and Δz) in FDTD parameters are chosen to be a/16 which equals 38.4 nm. Due to stability considerations of the simulation the time step Δt should satisfy the$\Delta t \leq \frac{1}{c\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta z^2}}}$, where c is the velocity of light in free space [33]. Following the above-mentioned rule for time step, $\Delta t = 0.0248$was chosen. The simulation is done during 20000 time steps, which requires 104 min run time and 22 MB memory size for our proposed demultiplexer. Finally, the output spectrum of the demultiplexerhas been obtained and shown in Fig. 4. This demultiplexer can separate 2 channels with central wavelengths equal to $\lambda_1 = 1555.7\, nm$ and $\lambda_2 = 1551.3\, nm$.



(a)



(b)

Fig. 4.output spectrum of the demultiplexer (a) linear and (b) dB scale

The transmission efficiency of the first and second channel is 76% and 79% respectively. Another important parameter in demultiplexer is the quality factor ($Q = \lambda/\Delta\lambda$, where λ is the central wavelength and Δλ is the 3dB bandwidth of each channel), the quality factor of the proposed demultiplexer for channel 1 and 2 obtained as 331 and 443respectively. The major characteristics of the demultiplexerare shown in table 1.

Table 1 Simulation results of Demultiplexer.

Channel	λ_0 (nm)	Δλ	Q	Transmission
1	1555.7	4.5	331	76%
2	1551.3	3.5	433	79%

Also the crosstalk values are listed in table 2, in which crosstalk values are named as X_{ij}, (i,j =1 or 2) that shows the effect of j-th channel in i-th channel at central wavelength of i-th channel.

Table 2 Crosstalk values of Demultiplexer

X_{ij}	1	2
1	-	-16dB
2	-11dB	-

The average channel spacing in this structure is 4.4 nm. Compared with previous works this demultiplexer has better channel spacing than all 2 channel demultiplexers and some other works [23-29], crosstalk values of our work is better than some previously proposed demultiplexers [26,29-30] another advantage of our proposed demultiplexer is its small footprint compared with other works [25-26,30-31].

5. Conclusion

We have presented a novel two channel wavelength division demultiplexer based on photonic crystal ring resonators. X-shaped rings that involve scattering rods for tuning the desired wavelengths. Band structure of the proposed dedmultiplexer calculated and it is demonstrated that the structure is suitable for communication window. Also, the values of crosstalk verified this fact that the designed structure has minimum noise and the efficiency of the structure is acceptable.

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