

A novel proposal for all optical demultiplexers based on photonic crystal

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In this paper, we used defective resonant cavity to design a 4-channel photonic crystal demultiplexer. We showed that by choosing appropriate values for the radius of defects located inside the resonant cavity, the desired wavelengths can be separated. The proposed platform is a hexagonal lattice of air pores created in dielectric material. The value of transmission efficiency for channels was obtained in 73% to 97% range. In addition, the maximum value of crosstalk and average quality factor for channels were calculated -27.6 dB and 5039 respectively.

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1. Introduction

Optical demultiplexers are one of the most crucial devices required in wavelength division multiplexing (WDM) systems. WDM technology has been proposed in order to make optimum use of the effective capacity of a multimode optical fiber. Optical demultiplexer can be used for separating the different optical channels received at the end of the optical fiber according to their central wavelengths.

One of the most promising candidates proposed for designing compact and high speed optical devices are photonic crystals (PhC). It has been shown that periodic modulation of refractive index of dielectric materials results in a photonic band gap (PBG) region [1-2], in which the propagation of optical waves is forbidden. Due to this issue, PhC can control the propagation of light inside compact waveguides. Optical filters [3-6], demultiplexers [7-10], sensors [11-13], switches [14-16], and logic gates [17-20] are some applications of optical devices designed based on PhC structures.

So far different mechanisms have been proposed for realizing PhC-based demultiplexers. Rostami et al [21] combined a T-branch waveguide with four resonant cavities and obtained a structure capable of separating four channels with channel spacing as low as 1 nm. The transmission efficiency of the channels in their structure was not flat such that the minimum and maximum transmission efficiencies were 49% and 79% respectively. A year later, their combined Y-branch waveguide with the four resonant cavities improved the transmission efficiency at the expense of channel spacing [22].

Rakhshani and Birjandi [23-25] using PhC ring resonators proposed three different optical demultiplexers. In all the proposed structures, they used similar ring resonators. In the first structure for achieving demultiplexing action they cascaded three channel drop filters with different refractive indices. In this structure the channel spacing was about 6.1 nm with bandwidth and

average transmission efficiency being 2.75 nm and 95%. Crosstalk and footprint were obtained -24.44 dB and 294.25 μm^2 respectively [23]. In another work they used one refractive index value for the overall structure but the resonant rings were different from each other in the radius of inner rods. In this structure channel spacing and bandwidth were 8 nm and 2.8 nm. Besides, Transmission efficiency, crosstalk and footprint were 90%, -20 dB and 317 μm^2 . The arrangement of the resonant rings in this structure was asymmetric [24]. They proposed a structure which was very similar to the previous one and the only difference was in the arrangement of the resonant rings, in which all the resonant rings being on one side of the input waveguide. For this structure channel spacing and bandwidth were 7.5 nm and 2.8 nm. The transmission efficiency and crosstalk were calculated 90% and -27.11 dB [25]. A Y-branch demultiplexer using Kagome lattice photonic crystal was proposed by Li et al [26]. This structure has transmission efficiency equal to 100%. A seven channel photonic crystal demultiplexer suitable for coarse wavelength division multiplexing (CWDM) has been proposed by Bouamami and Naoum [27]. In the resulted structure wavelength selection was realized by shifting the cutoff frequency of the fundamental photonic band gap mode in consecutive sections of the waveguide. The channel spacing is very large such that the first channel is at 1590 nm and the 7th channel is at 1400 nm. Another drawback of this structure is its very low transmission efficiency.

In this paper we proposed a novel defective resonant cavity structure for choosing the desired wavelength. The proposed cavity structure has very low bandwidth which results in a high quality factor. In the proposed cavity structure, by changing the defect size the resonant wavelength will change, so we have employed the cavity with different defect sizes to design a four channel optical demultiplexer. The most outstanding characteristics of the proposed structure are high quality factor and very low crosstalk values.

The rest of this paper organized as following: in section 2 we calculated the photonic band gap and presented the design procedure and then different parts of the demultiplexer have been introduced. Simulation and results have been discussed in section 3, and finally in section 4 we concluded from our work and simulations.

2. Demultiplexer design

In designing optical devices based on PhC structures, we should study the optical properties of these periodic structures. For this purpose the best solution is employing numerical methods. One of these popular numerical methods is plane wave expansion (PWE) [28] which is used for extracting the eigen-frequencies and PBG of the PhC structure. However, PWE cannot be used to study the propagation of optical waves inside PhC-based devices. Finite difference time domain (FDTD) method [29] has been proposed to study and analyze electromagnetic problems such as simulating the photonic crystal based devices.

The fundamental platform employed for designing the proposed structure is a 2D PhC with hexagonal lattice, which is composed of airpores created in dielectric background. The effective refractive index of dielectric material and the radius of airpores are $n=3.47$ and $r=0.43*a$, respectively, where a is the lattice constant of PhC and equal to 482 nm. The dispersion curve simulated and displayed in Fig. 1. We found four PBGs, two in TE mode (blue color areas) and two PBGs in TM mode (red color area). The first PBG in TM mode which is between $0.27 < a/\lambda < 0.45$ is wide enough for optical communication applications so we consider it as the dominant PBG. Considering $a=482$ nm the dominant PBG will be at $1071 \text{ nm} < \lambda < 1785 \text{ nm}$, that covers the range of optical communication applications.

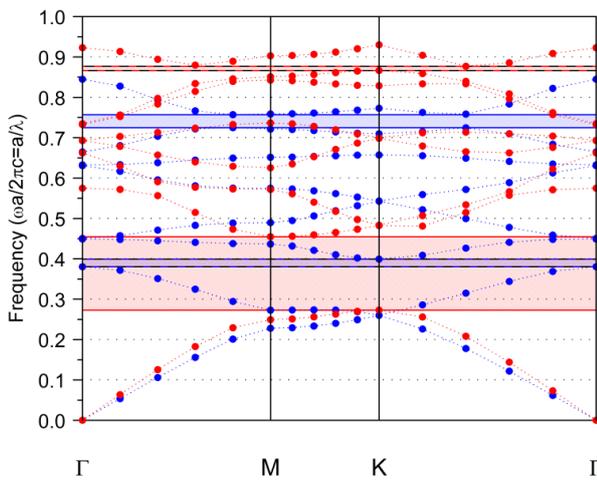


Fig. 1. The band structure diagram of the fundamental structure.

A schematic of the proposed device has shown in Fig. 2. The resonant cavity has been created by reducing the

radius of three adjacent rods into $R=98$ nm which are shown via blue color in Fig. 2. Another defect has been located at the beginning of the output waveguide whose radius is $R_0=103$ nm. The output defect is shown in black in Fig. 2. The output spectrum of the device is shown in Fig. 3. The proposed defective cavity has a resonant mode at $\lambda=1573$ nm and the transmission efficiency is about 80%. The bandwidth of the output spectrum is $\Delta\lambda=0.3$ nm so the quality factor will be $Q = \lambda / \Delta\lambda = 5243$.

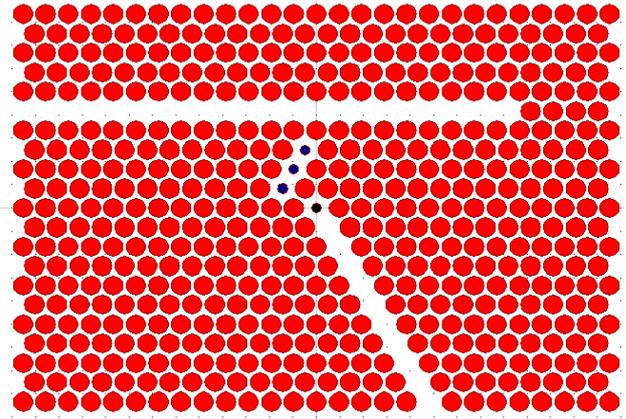


Fig. 2. Schematic of the proposed cavity.

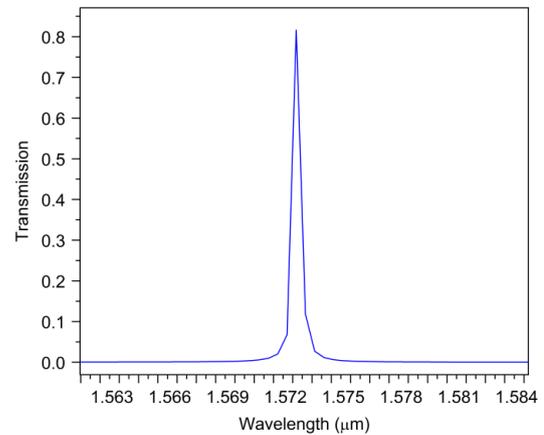


Fig. 3. The output spectrum of the proposed cavity.

Now in order to investigate the effect of R variation on the optical behavior of the cavity assuming $R_0 = 103$ nm, we simulated the cavity for different values of R . The output spectra of the filter for different values of R are depicted in Fig. 4. According to Fig. 4, by choosing different values for R equal to 98 nm, 111 nm, and 114 nm, we can select different wavelengths equal to 1573 nm, 1561 nm, and 1549 nm respectively. These results show that by increasing R the selected wavelengths shift toward lower values. These results show that by choosing different values for R we can select different wavelengths at the output port of the proposed resonant cavity structure.

Our simulations show that the variation of R_0 has no effect on the resonant wavelength of the cavity and only will effect on the transmission efficiency of the resonant mode. The optimum value for R_0 obtained to be $R_0=96$ nm.

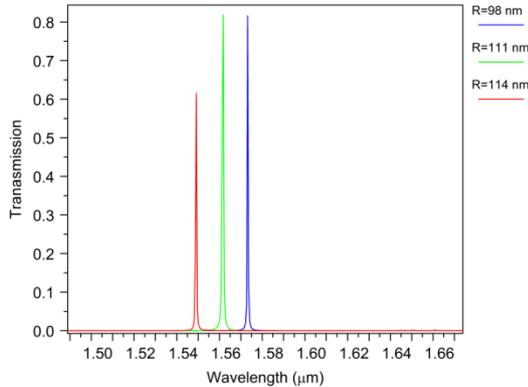


Fig. 4. Effect of R on the resonant mode of the cavity.

The overall structure consists of three main parts: (a) input waveguide, (b) resonant cavities and (c) output waveguides. For creating the input waveguide we removed 30 air pores in X direction. Then created four oblique output waveguide, for every output waveguide we removed 10 air pores and put a defect at the beginning of every output waveguide whose radius being $R_0=96$ nm. Finally, we located resonant cavities between the input waveguide and every output waveguides. In order to select four different wavelengths at the output ports these resonant cavities should be different from each other. It has been shown that the resonant wavelength of the proposed cavity depends on the radius of cavity central defects, R_i , which $i=1$ to 4 corresponding output ports. So the proposed values for R_i will be $R_1=95$ nm, $R_2=98$ nm, $R_3=111$ nm and $R_4=114$ nm. The final sketch of the proposed demultiplexer is shown in Fig. 5. The total footprint of the proposed structure will be $201.6 \mu\text{m}^2$.

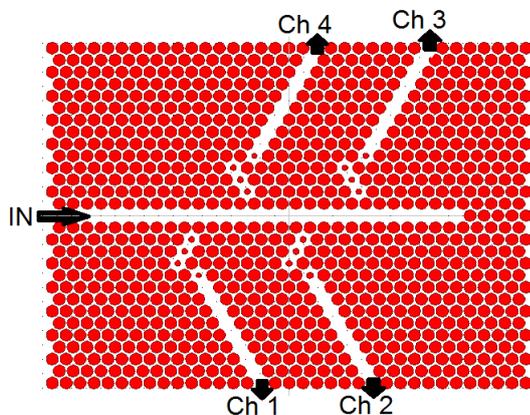


Fig. 5. The final sketch of the proposed demultiplexer.

3. Simulation and results

To simulate the proposed structure, we used full wave toolbox of R soft software which simulates the optical devices based on FDTD method. For accurate modeling of the demultiplexer we need 3D simulation, but it requires great amount of run time and very powerful computer. So we used effective index approximation method of PhCs for satisfying this requirement and with this approximation we reduce the 3D simulations to 2D simulations [30]. Grid sizes (Δx and Δz) in FDTD parameters are chosen to be $a/32$ which equals 15 nm. Due to stability considerations of the simulation the time step Δt should satisfy $\Delta t \leq 1/c \sqrt{(1/\Delta x)^2 + (1/\Delta z)^2}$, where c is the velocity of light in free space [29]. Following the mentioned rule for time step, $\Delta t=0.0098$ fs was chosen. The simulation is done during 20000 time steps, which requires 1281 min run time and 90 MB memory size for the proposed demultiplexer. The output spectrum of the device in linear and dB scales is depicted in Fig. 6 which shows that $\lambda_1=1580$ nm, $\lambda_2=1569$ nm, $\lambda_3=1558$ nm and $\lambda_4=1545$ nm are obtained for channels.

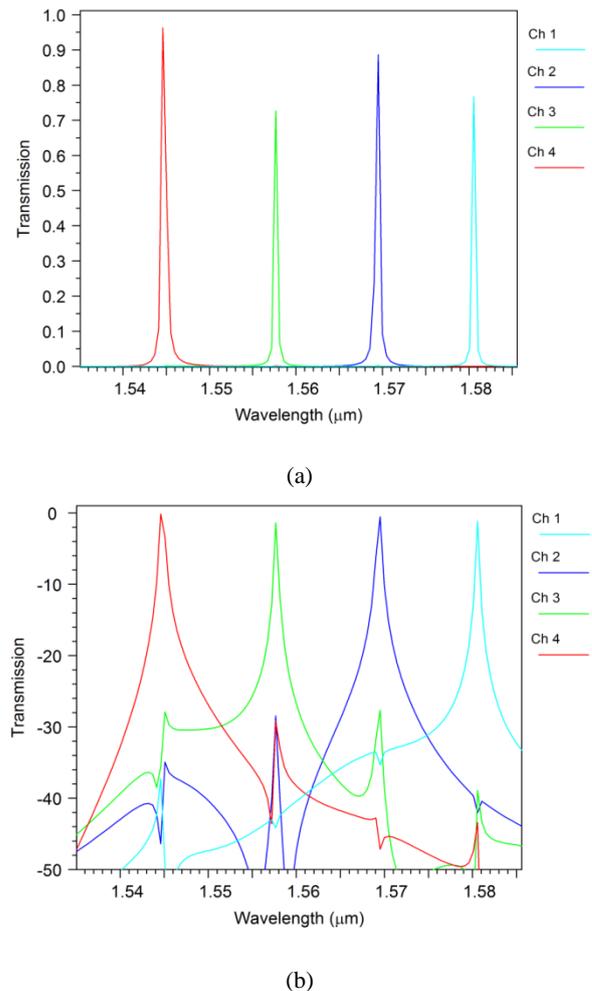


Fig. 6. The output spectrum of the demultiplexer in (a) Linear and (b) dB scales.

The transmission efficiency (T.E) for the proposed demultiplexer is between 73% and 97% and the average transmission efficiency is 84%, which is better than some previously proposed structures [7, 23-24, 27]. These relatively high transmission values guarantee low insertion loss for the structure. An important parameter in optical demultiplexers is the quality factor (QF) and defined as central wavelength of the channel to its bandwidth ($\Delta\lambda$). Consequently, one can see that the less bandwidth results in higher quality factor. In the proposed structure the bandwidth of first, second, third and fourth channels are 0.25, 0.35, 0.25 and 0.5 nm therefore the corresponding quality factors will be 6320, 4482, 6232 and 3090 respectively (see Table 1). Compared with previous works, the proposed structure has better quality factor values than the works reported in [7-8, 23-24, 27].

Table 1. Simulation results of the demultiplexer.

Channel	λ (nm)	$\Delta\lambda$ (nm)	QF	T.E(%)
1	1580	0.25	6320	77
2	1568	0.35	4482	89
3	1558	0.25	6232	73
4	1545	0.5	3090	97

Crosstalk is another crucial parameter in designing optical demultiplexers. The crosstalk values are listed in Table 2, in which they are named as X_{ij} , (i, j varies from 1 to 4) that means the effect of i -th channel in j -th channel. In Table 2, i and j indices are shown in column and row respectively. The crosstalk level for the structure varies from -10 dB to -33dB.

The comparison of the device with some recent works has given in Table 3. According to the results proposed in Table 3 and compared with previously reported works the proposed structure has better performance and has a good potential to be used in CWDM applications.

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

Channel	1	2	3	4
1	-	-34.9	-43.9	-40
2	-42	-	-31.4	-36
3	-39	-27.6	-	-28
4	-43.4	-46	-29	-

Table 3. Comparing obtained results with some previous works.

Works	Channel Spacing (nm)	QF	$\Delta\lambda$ (nm)	Worst case T.E(%)	Worst case Crosstalk (dB)
Ref [7]	3	< 1954	> 2.8	45	-7.5
Ref [8]	28	< 61	> 25	80	NA
Ref [22]	3	1296	1.2	63	-11
Ref [23]	15	NA	NA	24	NA
Ref [27]	6	460	2.75	92	-24
Ref [26]	3	561	2.8	50	-7.5
Our work	13	5031	0.5	73	-27.6

4. Conclusion

In this paper, we proposed a novel defective cavity structure based on 2D photonic crystal to perform wavelength selection task. It has been shown that by changing the radius of defects the resonant wavelength of the cavity will change. So we located 4 cavities with different defect sizes and proposed a four channel demultiplexer. The dominant characteristics of the proposed demultiplexer are very high quality factor values – the average quality factor is more than 5031- and very low crosstalk values, which is between -27dB and -46 dB.

References

- [1] S. Sakoda 2001 (springer-Verlag Berlin).
- [2] Z. Wu, K. Xie, H. Yang, *Optik* **123**,534 (2012).
- [3] H. Alipour-Banaei, F. Mehdizadeh, *Optik* **124**, 2639 (2013).
- [4] M. Dajvid, M. S. Abrishamian, *Optik*, **123**,167 (2011).
- [5] F. Mehdizadeh, H. Alipour-Banaei, S. Serajmohammadi, *J. Opt.* **15**,075401 (2013) (7pp).
- [6] M. Y. Mahmoud, G. Bassou, A. Taalbi, Z. M. Chekroun, *Optics communications*, **285**, 368 (2012).
- [7] H. Alipour-Banaei, F. Mehdizadeh, S. Serajmohammadi, *Optik*, **124**, 5964 (2013).
- [8] M. Dajvid, F. Monifi, A. Ghaffari, M. S. Abrishamian, *Optics communications*, **281**, 4028 (2008).
- [9] S. M. Mousavizadeh, M. Soroosh, F. Mehdizadeh, *Optoelectron. Adv. Mater. – Rapid Comm.* **9**, 28 (2015).
- [10] M. H. M. Yusoff, H. A. Hassan, M. R. Hashim, M. K. Abd-Rahman, *Optics Communication* **284**, 1223 (2011).
- [11] A. K. Goyal, S. Pal, *Optik* **126**, 240 (2015).
- [12] P. Dhara, V. K. Singh, *Optical Fiber Technology* **21**, 154 (2015).
- [13] T. Ahmadi-Tame, B. M. Isfahani, N. Granpayeh, A. M. Javan, *Int. J. Electron. Commun (AEU)* **65**, 281 (2011).

- (2011).
- [14] Ahmed Sharkawy, Shouyuan Shi, Dennis W. Prather, *Opt. Express* **10**(20), 1048 (2002).
- [15] M. Danaie, H. Kaatuzian, *Photonics and Nanostructures – Fundamentals and Applications* **9**, 70 (2011).
- [16] W. Rao, Y. Song, M. Liu, C. Jin, *Optik* **121**, 1934 (2010).
- [17] Z. J. Li, Z. W. Chen, B. J. Li, *Opt. Express* **13**, 1033 (2005).
- [18] X. Zhang, Y. Wang, J. Sun, D. Liu, D. Huang, *Opt. Express* **12**, 361 (2004).
- [19] M. Danaei, H. Kaatuzian, *Opt Quant Electron* **44**, 27 (2012).
- [20] J. Wang, J. Sun, Q. Sun, *IEEE Photon. Technol. Lett.* **19**, 541 (2007).
- [21] A. Rostami, F. Nazari, H. AlipourBanaei, A. Bahrami, *Photonic and Nanostructures – Fundamentals and Applications* **8**, 14 (2010).
- [22] A. Rostami, H. Alipour Banei, F. Nazari, A. Bahrami, *Optik***122**, 1481 (2011).
- [23] M. R. Rakhshani, M. A. M. Birjandi, *Physica E*, **50**, 97 (2013).
- [24] M. R. Rakhshani, M. A. M. Birjandi, *J. Opt. Commun.* **35**, 9 (2014).
- [25] M. A. M. Birjandi, M. R. Rakhshani, *Optik* **124**, 5923 (2013).
- [26] L. Li, G. Q. Liu, H. D. Lu, *Optik* **124**, 2913 (2013).
- [27] S. Bouamami, R. Naoum, *Optik* **124**, S. Bouamami, R. Naoum, *Optik* **124**, 2373 (2013).
- [28] S. G. Johnson, J. D. Joannopoulos, *Opt. Express* **8**, 173 (2001).
- [29] S. D. Gedney, (Lexington KY: Morgan&Claypool) 2006.
- [30] M. Qiu, *Appl. Phys. Lett.* **81**, 1163 (2002).

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