

A high quality complete coupling 4-channel demultiplexer based on photonic crystal ring resonators

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In this paper, we propose a compact structure to realize demultiplexing operation for Dense Wavelength Division Multiplexing communication systems using ring resonators in photonic crystal structure. The cross section of the structure is $790\mu\text{m}^2$ and desirable for integration based on popular planar technology. In order to improve power transmission coupling efficiency, we introduced phase matching condition between ring resonators and waveguides and the results showed 100% transmission efficiency. To obtain high quality factor we used interior layers of the rings as the mirrors and the quality factor as high as 4860 is achieved. The average pass bands of channels are near to 0.35nm and the channel spacing is approximately 2nm. The wavelengths of demultiplexer are 1307.7nm, 1309nm, 1311nm and 1313nm respectively. The crosstalk is between -20.5dB and -42dB and the mean value of the crosstalk is -28.66dB.

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1. Introduction

Photonic crystals (PCs) have attracted many attentions because of its unique features: photonic band gap (PBG) and strong photon confinement effects [1-2]. Also, the small sizes of devices which can be designed by PCs make it suitable for all optical integrated circuits which are needed in metropolitan networks. Reviewing recent reports in this field reveals the great tendency toward PCs which all are resulted because of its PBG properties [3]. PBG can be controlled by different parameters in the structure such as: lattice constant, dielectric constant of the used materials, radius of the rods and etc.

Various optical devices can be realized based on PBG of PCs such as optical switches [4-5], filters [6-7], splitters [8], demultiplexers [9], mirrors [10] and etc. optical demultiplexer is one of the vital components in optical networks. Several methods have been proposed by PCs to separate the channels from input signal such as line defect waveguides [11-12], coupled cavity waveguides [13], directional coupling [14], ring resonators [15-16] and etc.

A resonant cavity in T-shape PC structure which separate 4-channels from input signal has been proposed by Rostami et al [17]. They reported a demultiplexer structure which shows well channel spacing, well pass band and high quality factor. The mean crosstalk value which they reported is also good. But the power transmission coupling efficiency in their structure is very weak. Such that for some channels it is even lesser than 45% and as the outputs of channels are going to be detected by photodetectors, their structure is not suitable enough.

A type of heterostructure demultiplexer by PCs ring resonator is proposed by Rakhshani et al [18]. Their device can separate 3 different channels from the input light in the 1550nm window. The mean value of crosstalk they

reported is -24.44dB and they could achieve power coupling efficiency around 95%. To separate the channels, they utilized three ring resonators in which each one has a different dielectric constant. They used materials with $n_1=11.2$, $n_2=12$ and $n_3=12.4$ dielectric constants. The channels which they could drop were at $\lambda=1500$, 1510, 1516, 1522nm. The channel spacing which they achieved is around 6nm which prevent form optimized utilization of fiber capacitance and Although they used three different materials in their structure, the quality factor they reported is very low.

Another four channel demultiplexer based on PC ring resonators has been proposed by Alipour-Banaei et al [19]. Their proposed demultiplexer consists of four X-shaped resonators which can couple the input light to the output ports. In addition to the X-shape resonators, they used defects to obtain good performance. The quality factor they reported varies from 561 to 1954. Their structure suffers from the low power transmission efficiency in which their rings could couple just between 45% to 63% in the worst and best conditions. The crosstalk they reported in the minimum and maximum cases are -7.5 and -23.7dB respectively and are high values, so the crosstalking is another problem of their proposed structure. Also in the channels they have high quality factor, the magnitude of the output field drops a lot.

A compact WDM demultiplexer for seven channels in PCs is proposed by Boumami et al [20]. They suggest a T-branch WDM demultiplexer. The channel spacing they have reported is around 50nm which is not suitable at all. Also the transmission ratio they achieved is lower than 25% in some channels. The best power transmission coupling efficiency they reported is around 56% which is not suitable for detecting.

Rostami et al in another paper proposed a demultiplexer in a so called modified Y-branch structure

which is similar to their previous work [13]. In their new structure near to 1nm band width of each channel and 3.5nm of channel spacing are reported. The crosstalk in their proposed demultiplexer varies from -10.4947dB to -33.1855dB. Although this new demultiplexer could achieve better power transmission coupling efficiency, but still in some channels it's around 63%. The resulted quality factor is also lower compare to their previous work.

All of the above mentioned works show the high demand of the high performance demultiplexer which must have high quality factor, low pass band, good channel spacing, low crosstalk, high power transmission coupling efficiency and etc. In nowadays optical communication systems. In this paper we propose a special design with 2D PC ring resonators to achieve a four channel DWDM demultiplexer. In the proposed structure, the resonant cavity which is used shows near 0.3nm bandwidth. In addition to the ring resonators, suitable defects are designed in term of size of radii to improve quality factor and power transmission coupling efficiency and also separating wavelength channels. We used three layer ring resonators in which the inner layers have lower dielectric constants compare to the exterior layer, so the light can propagate more near to the surface and quality factor as high as 4860 can be obtained. For all the rings used in the structure the dielectric constants of exterior and interiors layers are $n=2.58$ and $n_1=2.3$ respectively. Then by changing the radii of the rods of the exterior ring (near 4nm to each other) the separation of channels is done.

In addition to the high quality factor and 100% power transmission coupling efficiency, the crosstalk in the structure is very low and all these properties make this demultiplexer suitable for all optical communications. The rest of the paper organized as follows: in section 2, the photonic band gap will be calculated and then the demultiplexer structure will be introduced. In section 3 the results will be investigated and compared with the last literatures and finally the conclusion from this work and simulation results will be done in section 4.

2. The proposed demultiplexer

The first step of designing an optical device by PCs is to investigate the PBG of proposed structure. The calculation of the PBG of demultiplexer is done by plane wave expansion (PWE) [21]. We employed Band Solve simulation tool to perform PWE calculations. The structure we used to design is a 67×26 cubic lattice of dielectric rods immersed in air. The effective refractive index of fundamental dielectric rods is $n=2.58$, the radius of rods is 162nm and the lattice constant is $a=676$ nm. The band structure diagram of the demultiplexer is shown in Fig. 1.

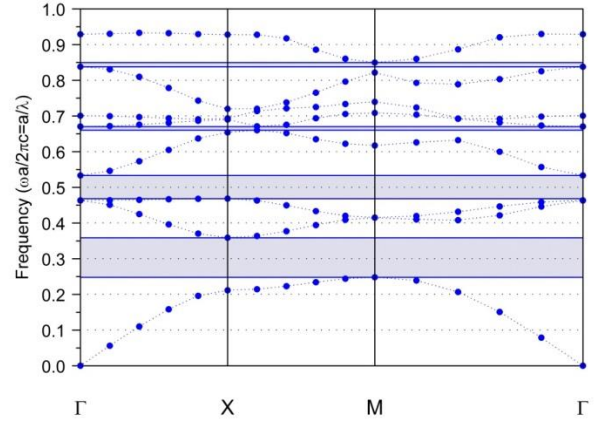


Fig. 1. The band structure diagram of fundamental structure.

As it can be seen from the figure1, there are four PBG regions in the structure which we designed the device to work in the second PBG region which has $0.4667 < a/\lambda < 0.5333$ and is equal to $1267\text{nm} < \lambda < 1448\text{nm}$. The results show that the proposed demultiplexer can work in the second communication window ($\lambda=1310\text{nm}$) and is suitable for all optical communications.

It can be seen from Fig. 2.a) that the structure consists of an input waveguide which is created by removing complete rods of a row and four output waveguides which are depicted as port A, B, C and D. In addition to these waveguides, there are four ring resonators which act as the couplers of the light. The macroscopic view of first two rings is shown in Fig. 2.b). Each of the ring resonators has three layers. In which the interior layers has the refractive indices lower than refractive index of the lattice ($n_1=2.3$) and is specified in the Fig. 2.b)

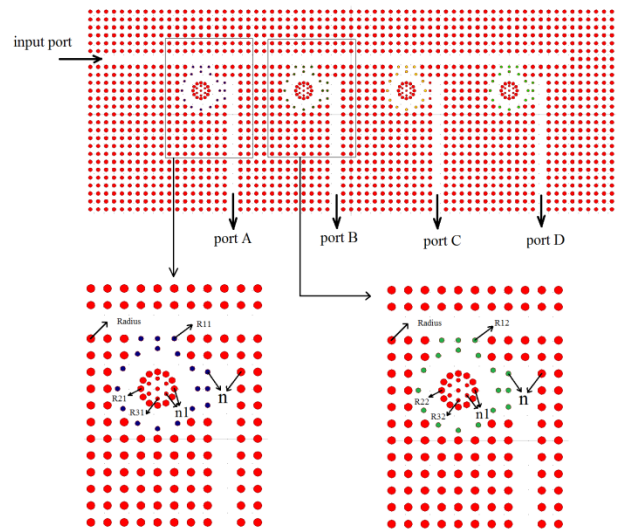


Fig. 2. (a) The schematic diagram of the proposed demultiplexer, (b) a macroscopic view of two first resonant rings.

The exterior layer of each ring which is shown by dark blue, dark green, yellow and light green for the output ports of A, B, C and D respectively have the effective refractive indices exactly such as the refractive index of the lattice ($n=2.58$) but have different radii. In fact by changing these radii which are shown in the Fig. 2.b) for first two rings by R12 and R21 we could change the resonant frequency in the rings and achieve the demultiplexer. The radii of these exterior rings differ near 4nm to each other and are $R_{11}\approx 92\text{nm}$, $R_{12}\approx 96\text{nm}$, $R_{13}\approx 100\text{nm}$ and $R_{14}\approx 104\text{nm}$.

To design the proposed demultiplexer, we emphasis on two concepts. First, where the coupling is happening ; i.e. the coupling between input waveguide and ring resonator and coupling between ring resonator and output port waveguides; the rods of rings and waveguides are choosed exactly equal to have better coupling. The results of the power transmission coupling efficiency verifies the validity of this assumption.

The second concept we paid attention to was the refractive indices of the rods in the interior rings (n_1 in the Fig. 2.b) which are choosed lower than the effective index of the lattice, so they will not let the light go to the center of the rings. Based on the classic whispering gallery mode theory and our last work [22-23], it is known that if the light propagate more near to the surface of a resonator, the higher quality factor can be achieved. By taking this into account, we could achieve quality factor as high as $Q=4862$ in the structure which again verifies the accuracy of this assumption.

3. Simulation results

This paper focuses on the design of a heterostructure demultiplexer which can show very high quality factor,

very low band pass, low channel spacing, complete coupling and very fine crosstalk. As it is shown in Fig. 3, the structure can separate 4 channels with central wavelengths equal to $\lambda_1=1307.7\text{nm}$, $\lambda_2=1309\text{nm}$, $\lambda_3=1311\text{nm}$ and $\lambda_4=1313\text{nm}$. It can be seen from Fig. 3 that except port A which shows 97% transmission efficiency, other ports show 100% transmission efficiency. One of the most important results which can be noticed is that the complete power transmission coupling efficiency is achieved and the quality factor is high too. As we mentioned earlier in the works which have been done to increase the transmission efficiency, the quality factor is lost. But in this demultiplexer both the complete coupling and also high quality factor are obtained. The complete details of the channels are given in the Table 1. The quality factor ($Q=\lambda/\Delta\lambda$) varies from 2179 to 4862.

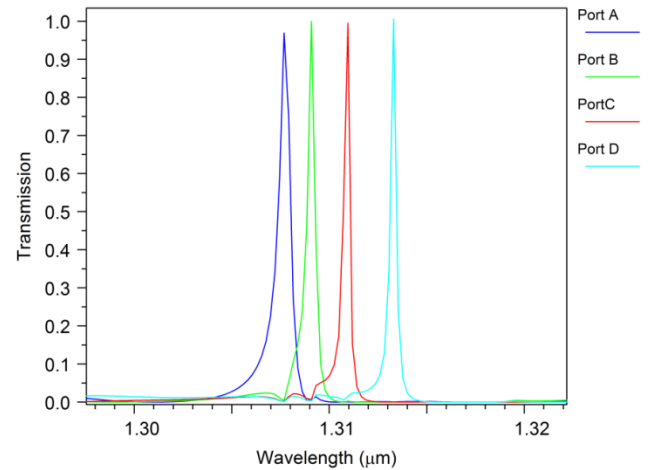


Fig. 3. Output spectra in ports A, B, C and D.

Table 1. The output characteristic of the demultiplexer.

channel	Central wavelength (nm)	Quality factor	Pass band (nm)	Transmission efficiency (%)
1	1307.7	2179	0.6	97
2	1309	3275	0.4	100
3	1311	4094	0.32	100
4	1313	4862	0.27	100

The distribution of optical wave inside the demultiplexer for 4 wavelengths $\lambda_1=1307.7\text{nm}$, $\lambda_2=1309\text{nm}$, $\lambda_3=1311\text{nm}$ and $\lambda_4=1313\text{nm}$ are shown in Fig. 4. Because all the wavelengths are located in the PBG region, they can't scatter in the structure and propagate in the waveguides. Fig. 4.a) demonstrates the first ring resonator can drop the incoming light at wavelength

$\lambda_1=1307.7\text{nm}$ to the Port A, while others cannot couple this frequency. The similar result can be watched in Figs. 4b, 4c and 4d, in which the rings can couple just their resonant frequency.

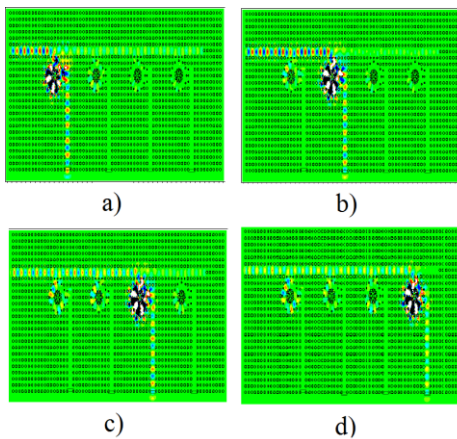


Fig. 4. The calculated field distribution inside the structure at four wavelengths (a) 1307.7nm, (b) 1309nm, (c) 1311nm and (d) 1313nm.

In the following of this paper, to calculate the crosstalks of channels and compare the proposed demultiplexer with other previous works, the output of the proposed device in dB scale is shown in Fig. 5.

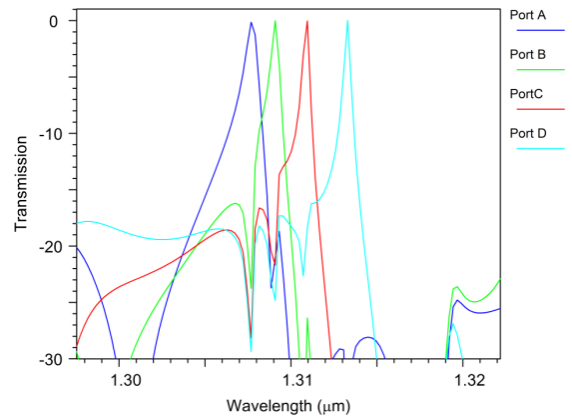


Fig. 5. Output spectrums in ports A, B, C and D in dB scale.

The comparison between our results and the recent works of demultiplexer is shown in Table 2.

Table 2. The comparison of our results with the other works.

Reference	Channel separation (nm)	Quality factor	Pass band (nm)	Transmission efficiency (%)
19	3	1234	1.7	50
17	1	3488	0.45	55
13	3.5	1497	1	80.25
18	6.1	842	2.75	95
This work	2	3600	0.3975	99.25

The crosstalk value between the channels is shown in more details in Table 3.

It can be seen from Table 3 that the minimum and maximum crosstalks are -20.5 and -42dB respectively which are very low. The mean value of crosstalks is -

28.66. A comparison between the mean value of crosstalks of other works and mean value of the crosstalks of our demultiplexer are shown in Table 4.

Table 3. The crosstalk value between the channels.

channels	1) $\lambda_1=1307.7\text{nm}$	2) $\lambda_2=1309\text{nm}$	3) $\lambda_3=1311\text{nm}$	4) $\lambda_4=1313\text{nm}$
1) $\lambda_1=1307.7\text{nm}$	-----	-23.5	-27.5	-29
2) $\lambda_2=1309\text{nm}$	-21	----	-22.5	-24
3) $\lambda_3=1311\text{nm}$	-31.5	-30	----	-20.5
4) $\lambda_4=1313\text{nm}$	-36.5	-42	-36	-----

Table 4. The comparison between the minimum, maximum and mean value of crosstalks of other works with the proposed demultiplexer.

Reference	Minimum of crosstalk	Maximum of crosstalk	Mean value of crosstalk
24	-2.8dB	-6.5dB	-5.1dB
19	-7.5dB	-23.7dB	-15.425dB
20	-10.49dB	-33.1855dB	-22.45dB
17	-14.2dB	-28.86dB	-21.1dB
This work	-20.5dB	-42dB	-28.66dB

One can see from the Table 4 that the crosstalk between the channels in the proposed demultiplexer is very lower compare to other works which makes it suitable for optical communication applications.

4. Conclusion

In this work, a 4-channel wavelength division demultiplexer in photonic crystal has been proposed. In the proposed structure, four ring resonators with different radii were suggested which could separate the wavelengths. The proposed structure showed very attractive properties which are excellent basis for demultiplexers. The output power efficiency of 100% was obtained in the proposed demultiplexer. Very low crosstalk, very high quality factor, very low bandwidth and low channel spacing are other significant properties which we could achieved. Four channels with channel spacing of 2nm, average bandwidth of 0.35nm and mean value crosstalk of -28.66dB had been obtained. The quality factor in port D of demultiplexer could reach to 4860 and the overall size of the demultiplexer is about $790\mu\text{m}^2$ which is practical for applications in photonic integrated circuits.

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