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Investigation of 2D-photonic crystal resonant cavity based WDM demultiplexer

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In this attempt, Two Dimensional Photonic Crystal (2DPC) Quasi Square Ring Resonator (QSRR) based four channel demultiplexer is proposed and designed for Wavelength Division Multiplexing systems. The performance parameters of the demultiplexer such as transmission efficiency, passband width, line spacing, Q factor and crosstalk are investigated. The proposed demultiplexer is composed of bus waveguide, drop waveguide and QSRR. In the proposed demultiplexer, the output ports are arranged separately in odd and even number, where an odd number of ports are located on the right side and even number of ports are located on the left side of the bus waveguide that are used to reduce the channel interference or crosstalk. Further, the refractive index of rods around the center rod is increased linearly one to another in order to improve the signal quality. The resonant wavelengths of the proposed demultiplexer are of 1521.1 nm, 1522.0 nm, 1523.2 nm and 1524.3 nm, respectively. The footprint of the device is of 180.96 μm^2. Then, a four channel point to point network is designed and the proposed four channel demultiplexer is implemented by replacing a conventional demultiplexer. Finally, functional parameters of the network, namely, BER, receiver sensitivity and Q factor are estimated by varying the link distance. This attempt could create new dimensions of research in the domain of photonic networks.

1. Introduction

Device miniaturization is one of the pioneering research areas in the optical community wherein Photonic Crystal (PC) technology supports extensively for miniaturization of the devices from 10 to 100 times. PC is composed of periodic dielectric material [1] which is classified into three types, namely, One Dimensional (1DPC), Two Dimensional (2DPC) and Three Dimensional (3DPC) models. These are differentiated by its structure such as periodic dielectric in a single direction for 1DPC, periodic dielectric in two directions and homogenous in third directions for 2DPC and periodic along three directions for 3DPC. In 2DPC, Plane Wave Expansion (PWE) computes complete Photonic Band Gap (PBG) [1,2] and its merits are easy fabrication, high aspect ratio, require lesser time and memory to simulate the device than 3DPC. Hence, 2DPC mostly considered for designing optical devices. The PBG in PC is an essential part to design a device which selects the operating wavelength of the device. The band gap of PC has similar behavior of electronic band gap in semiconductor devices. It control and manipulate the light beam in PC. The values of the structural parameters (lattice constant (a), radius of the rod (r) and refractive index (n)) are selected through gap map. Gap map [3] provides the information about the variation of TE/TM PBG for different structural parameters. From the PBG, the values are selected.

Typically, the 2DPC based optical devices are realized through square lattice and triangular lattice. The square lattice is structured periodically by arranging dielectric rods in air medium. Alternatively, the triangular lattice is developed by drilling periodic array of air holes in a dielectric medium. In triangular lattice, it is very difficult to make the air hole dimensions in uniform order which results propagation loss over square lattice. Further, The PC based devices are designed by introducing defects in the 2DPC structure. The defects are three types. They are point defects, line defects and surface defects. The point defect and line defect are employed in the structure which results light propagation inside the device. Point defects are employed to realize resonant cavity and linear or bus waveguide is generated by line defect. Both line defect and point defect are combined to design ring resonator. The resonant cavity and ring resonator are playing a major role to tune the resonant wavelength of the device. The defects are caused by changing the dimension of structural parameters and removing a single rod or many which results the defects inside the structure.

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The reported devices using 2DPCs such as filter [4–6], power splitters [7], polarization splitter [8], switches [9], waveguides and couplers [10] are made through the resonant cavity [11,12] and ring resonator [13–22]. In the literature, the point defect based resonant cavity [11,19], point and line defect based ring resonator are used in many shapes like circular, square [4], quasi square [13–18], rectangular, and elliptical [19] etc. Either resonant cavity or ring resonator is incorporated in square lattice or triangular lattice for designing 2DPC based devices. However, square lattice easy to make periodic arrangement of uniform dimensions of the rod. The triangular lattice has a very difficult task to make uniform dimension air holes which causes to generate radiation losses in the device [23]. Hence, the proposed device is considered to design in the square lattice. In this device, the refractive index is an important parameter to choose the channel wavelength and analyze the performance of Q factor and transmission efficiency. Then the proposed device is incorporated in WDM optical point to point network for analysing the performance, such as Bit Error Rate (BER), Receiver Sensitivity and Q factor.

The paper is continued as follows. The Section 2 enumerates structural design of demultiplexer. Section 3 describes device simulation and the results and Section 4 incorporates 2DPC demultiplexer and analyses the performance of four channel demultiplexer in a WDM system. Finally, Section 5 concludes the paper.

2. Design of 2DPC four channel demultiplexer

Fig. 1 represents the PBG structure of proposed demultiplexer. The structural parameters that are used in the structure are lattice constant (a), radius (r) and refractive index (n) of rods and its values are 580 nm, 120 nm and 3.2, respectively. The Plane Wave Expansion (PWE) method [24] gives PBG for the 2DPC structure before introducing defects and obtained two PBGs as shown in Fig. 1.

Typically, both TE and TM PBG may occur, however one of the band gap is an active role to develop devices based on the operating wavelength. The blue colour represents TE modes and red colour represents TM modes. The frequency range of wide TE band gap

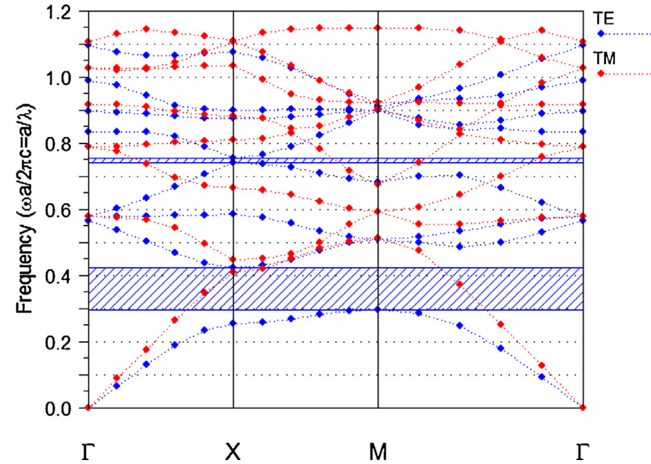

Fig. 1. Photonic Band gap structure of the proposed planar structure before introducing defects.

varies from 0.29651(a/λ) to 0.4186(a/λ) and narrow band gap from 0.74228(a/λ) to 0.75323 (a/λ). The wide PBG wavelength range 1385 nm to 1956 nm which is applicable for designing demultiplexer for WDM applications.

The structural design of proposed four channel demultiplexer is shown in Fig. 2. It has four Quasi Square Ring Resonators (QSRRs), L bend waveguide and bus waveguide. The bus waveguide separates an odd and even pair of QSRRs. Each QSRR consists of inner core which has five rods with the radius of 150 nm. The L shaped dropping waveguide is positioned at the side of QSRR and a small sized channel selector rod is located at the corner of each L bend dropping waveguide.

The sectional view of the single channel dropping section is shown Fig. 3. It has five important parts. They are described as follows.

i Quasi Square Ring Resonator (QSRR): A single line square shaped rods are removed and inserted a rod at the corner (both line and

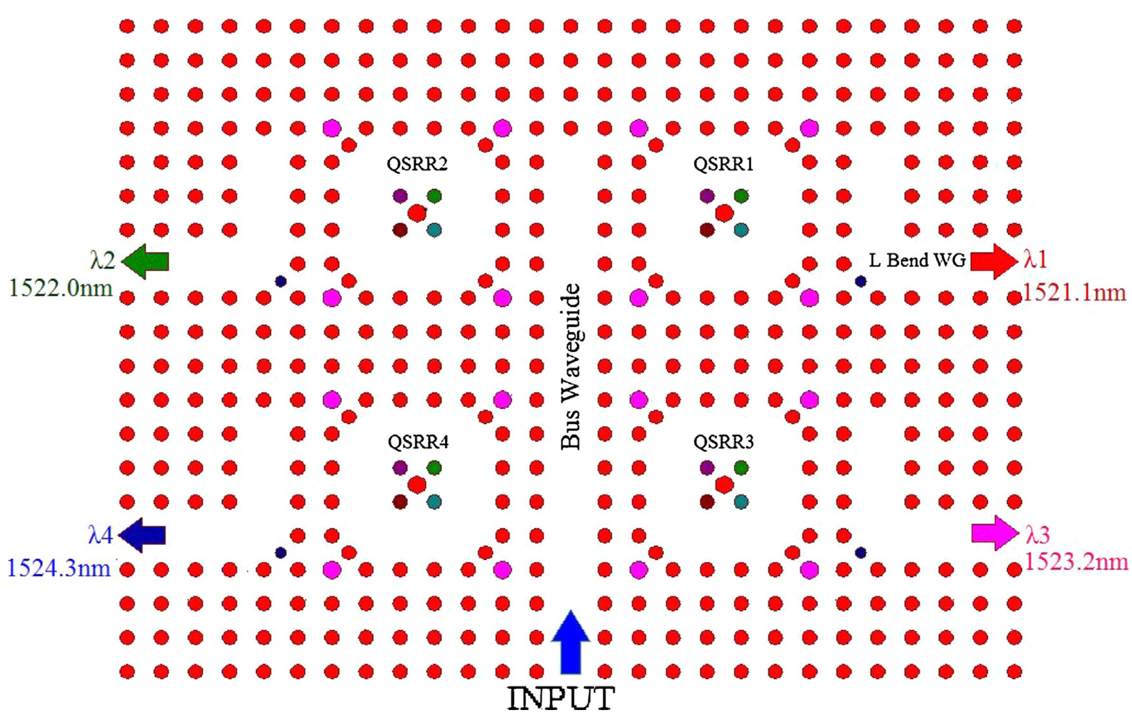

Fig. 2. Schematic representation of proposed QSRR four channel demultiplexer.

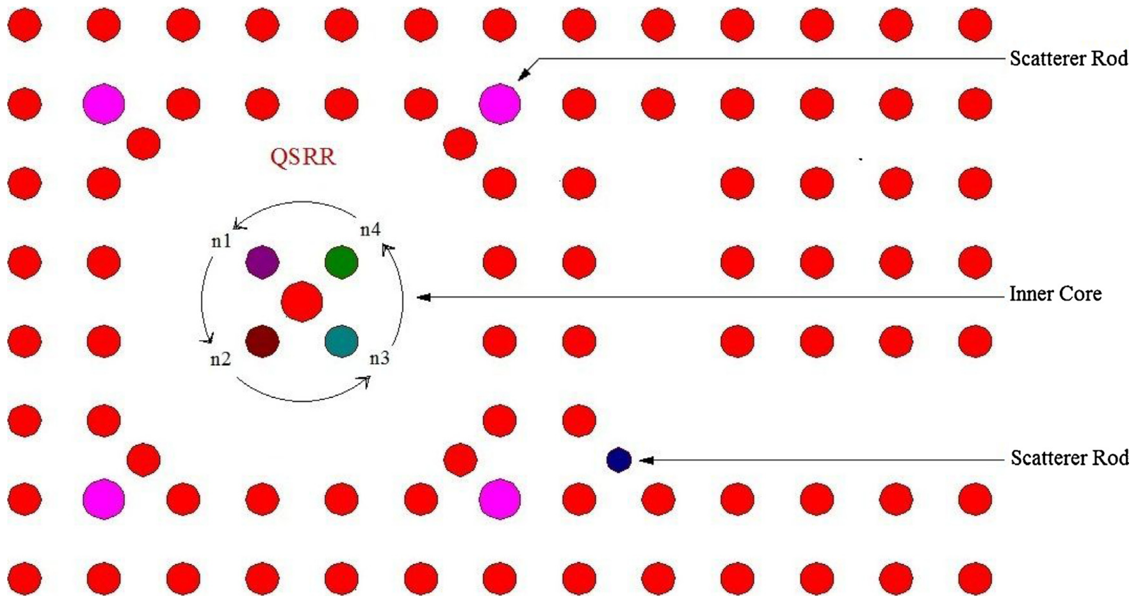

Fig. 3. Schematic view of Single QSRR.

point defects are introduced) of 2DPC structure to design QSRR. It is the path to circulate and strengthen the light signal.

ii Inner Core: It is acting as micro resonant cavity which is designed using five rods. The outer four rods are having unique refractive index for each channel. The refractive index of the four rods for each channel is shown in Fig. 4. The assigned refractive index values of four rods for channel 1 (λ1) = 3.10 (n1), 3.20 (n2), 3.30 (n3) and 3.40 (n4) are covering a single rod (150 nm) which is positioned at the centre. In similar way, for channel 2 (λ2) = 3.14, 3.24, 3.34 and 3.44, channel 3 (λ3) = 3.18, 3.28, 3.38, and 3.48, channel 4 (λ4) = 3.22, 3.32, 3.42, 3.52 respectively. This concept is newly introduced in the device to tune the resonant wavelength of the respective channel effectively.

iii Scatterer Rod: The 150 nm radius of scatterer rod is placed at the corner of QSRR and small sized rod radius 90 nm is incorporated in the corner L bend dropping waveguide. Both the rods are having intelligent behaviour to reduce the counter propagation loss inside of the structure.

iv L bend dropping waveguide: A single line of L shaped rods are removed from the 2DPC structure to have L bend dropping waveguide. The purpose of this waveguide is collecting signal from QSRR and send it to the output port.

v Bus waveguide: A line defect is introduced in the centre of bottom of general 2DPC square lattice structure that makes linear or bus waveguide. It is an important path to transmit light signal from source feed point to the other designed part of the proposed structure. The width of the bus waveguide is about 920 nm.

From Fig. 4, it clearly noticed that the refractive index of rods in the inner core (micro resonant cavity) of each QSRR is having unique value in increasing order of refractive index. It starts from 3.10 to 3.40 for channel 1 (λ1), 3.14 to 3.44 for channel 2 (λ2), 3.18 to 3.48 for channel 3 (λ3) and 3.22 to 3.52 for channel 4 (λ4). It is linearly mentioned that each QSRR near bus waveguide is having starting value of refractive index (n1) and increasing refractive index with 0.1 steps (n2-n4) in a clockwise direction of left side QSRRs of bus waveguide and counter clockwise in right side QSRRs of the bus waveguide. The refractive index of simultaneous rods in one QSRR differs with adjacent one is 0.04. Typically, the resonant wavelength is shifted to higher wavelength while increasing the value of refractive index due to an effective dielectric strength of the device. In this attempt, the resonant wavelength is shifted from increasing the refractive value of outer rods. Based on the refractive index change, the resonant wavelength will be shifted. The size of QSRR and unique refractive index of its micro resonant cavity of the proposed device are acting as filter to choose the channel wavelengths from λ1 to λ4 is 1521.1 nm to 1524.3 nm.

3. Simulation results and discussion

Finite Difference Time Domain (FDTD) is a numeric method which permits electromagnetic waves propagate through the photonic crystal devices with accurate behaviour. The accurate response will be arrived through 3DFDTD, however, the 3DFDTD simulation requires more time to perform the process as well as power and needs a more powerful computer.

In the proposed device, we used effective, unique refractive index for selecting the channels. Hence, the 2DFDTD [25] simulation is performed on the proposed structure in order to obtain the output response of the proposed demultiplexer. The perfectly matched layer is about 500 nm is incorporated in order to reduce the reflection of launching Gaussian light signal. The overall size of the structure is 180.96 μm^2 which is a periodic arrangement of 27 × 20 arrays of dielectric rods. The grid size in X and Y direction is a/16. The estimated time step (Δt) is chosen to be 0.016 and memory size is 18.3 MB. The stability could be considered in the simulation in order to satisfy the time steps (Δt) which can be calculated by

$$\Delta t \leq \frac{1}{c\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta z^2}}} \tag{1}$$

where 'c' is velocity of light and Δx, Δz be a spatial steps in X-Z directions.

The Gaussian light signal is launched at the bottom end of the designed structure. The FFT is conducted on the field distribution in the device structure and its transmission spectra are determined by simulating 2DFDTD. The multiple channel wavelengths are circulated through the QSRR and dropped one channel of its respective L bend dropping waveguide. Fig. 5 represents selection of channel 3 (λ3) and its centre wavelength 1523.2 nm. Depending upon the refractive index is assigned in inner core rods respective channel

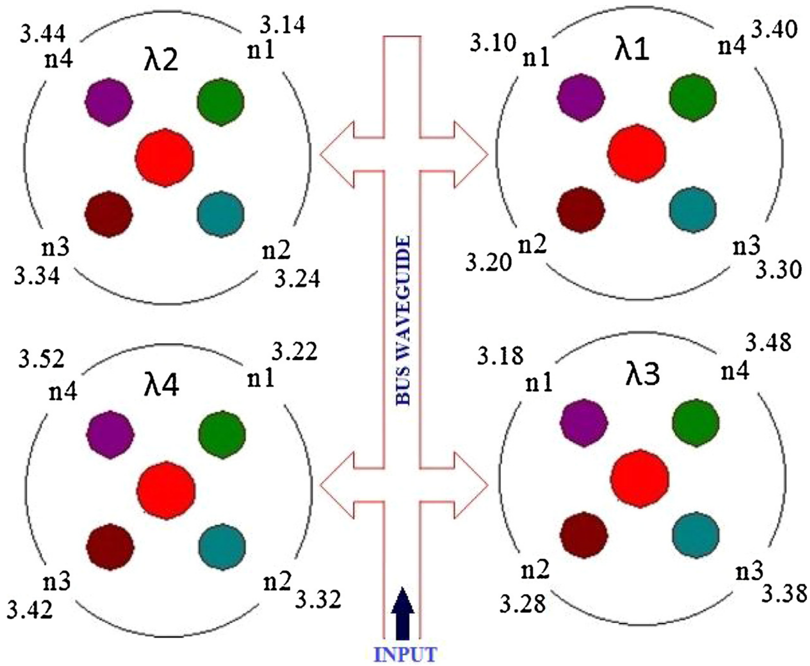

Fig. 4. Schematic view of Inner core of quasi square ring resonator.

Table 1
Resonant wavelength, passband width, channel spacing, transmission efficiency and Q factor of proposed four channel demultiplexer.

Channel (λ)	Resonant Wavelength (nm)	Passband Width (nm)	Channel Spacing (nm)	Transmission Efficiency (%)	Q Factor
λ1	1521.1	0.9	0.9	97	1690
λ2	1522.0	0.8	1.2	97	1902
λ3	1523.2	1.0	1.1	98	1523
λ4	1524.3	0.7	1.1	100	2178

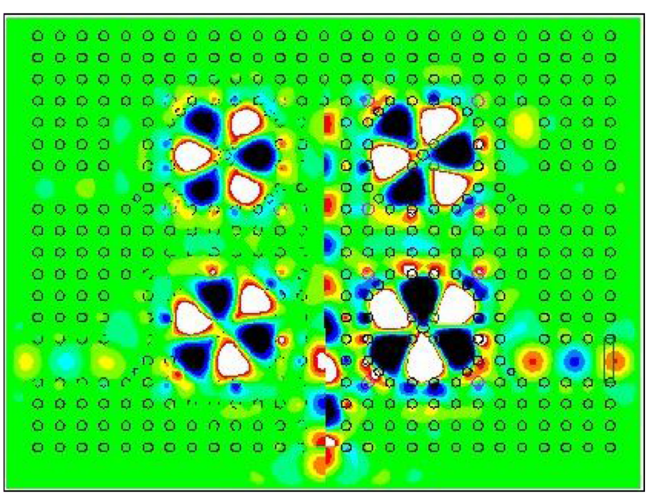

Fig. 5. Field distribution of proposed four channel demultiplexer for channel 3 (λ3) at 1523.2 nm.

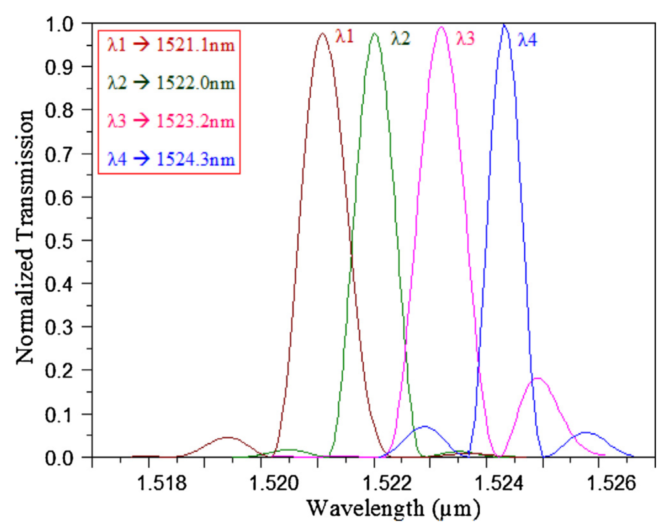

Fig. 6. Four channel output spectrum of proposed WDM demultiplexer.

circulates freely in the QSRR. Further, it is shown that maximum intensity of tuned signal is dropped at respective L bend waveguide.

Fig. 6 shows output spectra of proposed four channel WDM demultiplexer. From Fig. 5, it is noticed that the resonant wavelength of the proposed demultiplexer for channel 1 (λ1) wavelength is 1521.1 nm, channel 2 (λ2) is 1522.0 nm, channel 3 (λ3) is 1523.2 nm and channel 4 (λ4) is about 1524.3 nm. The channel spacing and passband width of the channel 1 (λ1) is 0.9 nm and channel 4 (λ4) is about 0.7 nm, 1.1 nm. Further, 97% of transmission efficiency, 1690 of Q factor is obtained from channel 1.

The functional parameters such as resonant wavelength, passband width, channel spacing, transmission efficiency and Q factor are listed in Table 1. The minimum passpand width (0.7 nm), maximum transmission power (100%) and high Q factor (2178) are obtained at channel 4 (λ4). The average channel spacing between the channels is 1.07 nm. The overall passband width is about 0.9 nm, transmission efficiency 98% and Q factor 1823.

Table 2 represents the crosstalk between the channels which is measured by the natural logarithm of the ratio of the cross power

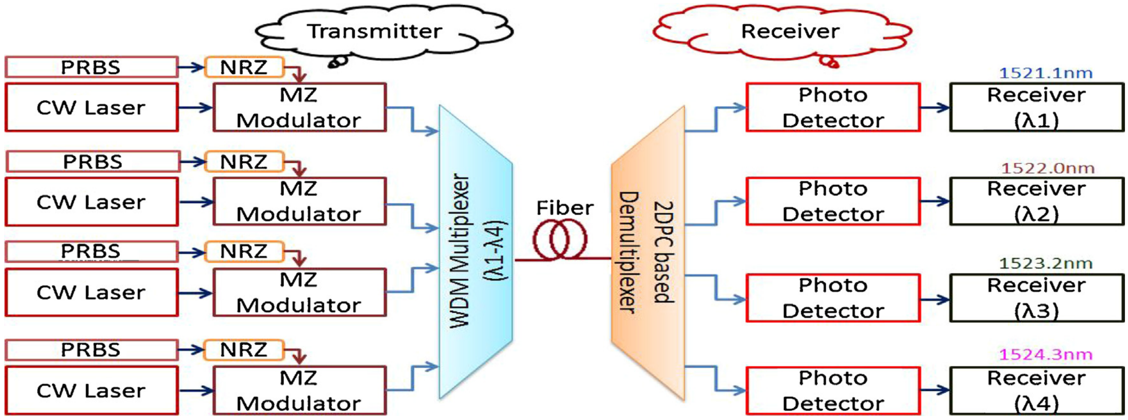

Fig. 7. Implementation of proposed four channel demultiplexer in the point to point communication WDM network.

Table 2
Crosstalk among the channels of proposed four channel demultiplexer.

Channels Crosstalk (dB)	λ1	λ2	λ3	λ4
λ1		−3.4	−26.8	
λ2	−3.4		−6.4	
λ3	−26.9	−6.5		−7.4
λ4			−7.3	

point between the channels to a maximum power of neighboring channel. The maximum and minimum crosstalk of the structure is −3.4 dB and −26.9 dB.

Table 3 represents the functional characteristics of proposed demultiplexer is compared with the existed one. Table 3 is noticed that the overall dimension, number of channels, passband width, channel spacing, transmission efficiency, Q factor and crosstalk of four channels proposed demultiplexer is better than reported one. The ref [11] shows the Q factor was very high, the transmission efficiency was poor and the size was also very high. From the ref [12], it is noticed that better pass band width and cross talk, however, overall size is 360 μm^2. The ref [13] reported low transmission efficiency, passband width and channel spacing are very high. In ref [14], low crosstalk, however, the overall area is 315 μm^2. The ref [18] reported very low passband width, transmission efficiency is about 95%, and however, channel spacing is 3 nm. From the above, the newly designed proposed demultiplexer is 180.96 μm^2 of size and 98% of transmission efficiency, which could be useful in photonic network communications.

4. Implementation of point to point communication WDM network

Fig. 7 shows the block diagram of WDM point to point communication network. Nowadays WDM technology is an emerging technology in the field of optical communication. It can be categorized as Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM). The DWDM has lesser channel spacing and more suitable for point to point high data rate/high speed applications. The DWDM also has less bandwidth utilization over CWDM technology. Hence, in this work, DWDM system is accounted. The modulated optical signals of the four channels are multiplexed by WDM multiplexer and it is transmitted over the optical fibre. The other end of the optical fibre is connected with 2DPC based demultiplexer. The 2DPC based demultiplexer separates the channels at specified wavelength and converted into electrical signal from the photo detector. Finally, the output is monitored by BER analyser and Optical power meter. The BER analyser compares the input and photo detector output, which provides BER and Q factor for the particular channel. The optical power meter measures receiving sensitivity (dBm) of the respective channel. The simulation parameters are listed in the following Table 4.

Table 4
Simulation parameters of four channel DWDM system.

Parameters	Values
Bit Rate	2.5 Gbps
Optical Source	CW laser
Fiber Length	50–90 km
Attenuation	0.2 dB/km
Insertion Loss	1.5 dB (Yuyang Zhuang et al. 2016)
Dispersion	17 ps/(nm × km)
Input Signal Power	5 mW
Modulation Format	NRZ
Photodetector	PIN Diode
Responsivity	1 A/W
Dark Current	10 nA
DWDM Channels (λ1, λ2, λ3, λ4)	1521.1 nm, 1522 nm, 1523.2 nm, 1524.3 nm

The proposed 2DPC based four channel demultiplexer is incorporated in the WDM point to point network which is shown in Fig. 8. The WDM channel wavelengths are acting as input sources of the WDM point to point network. The channels (1521.1 nm, 1522 nm,

Table 3
Comparison of proposed demultiplexer with existed one.

Authors/Year	Lattice Structure	Dimension (μm^2)	Number of Channels	Passband Width (nm)	Channel Spacing (nm)	Transmission Efficiency (%)	Quality (Q) Factor	Crosstalk (dB)
Gupta, et.al., [11]	Square	484	4	0.2	0.8	Less than 7%	7800	***
Talebzadeh, et. al. [12]	Square	360	4	0.4	2	93	4107	−27.33
Djavid et al., [13]	Square	***	4	30	28	82	***	***
Rakhshani, et. al [14]	Square	315	4	***	***	90	***	−25
Alipour-Banaei, et. al [18]	Square	***	4	0.5	3	95	2600	−19
This Work	Square	180.96	4	0.9	1	98	1823	−3.4 to 26.9

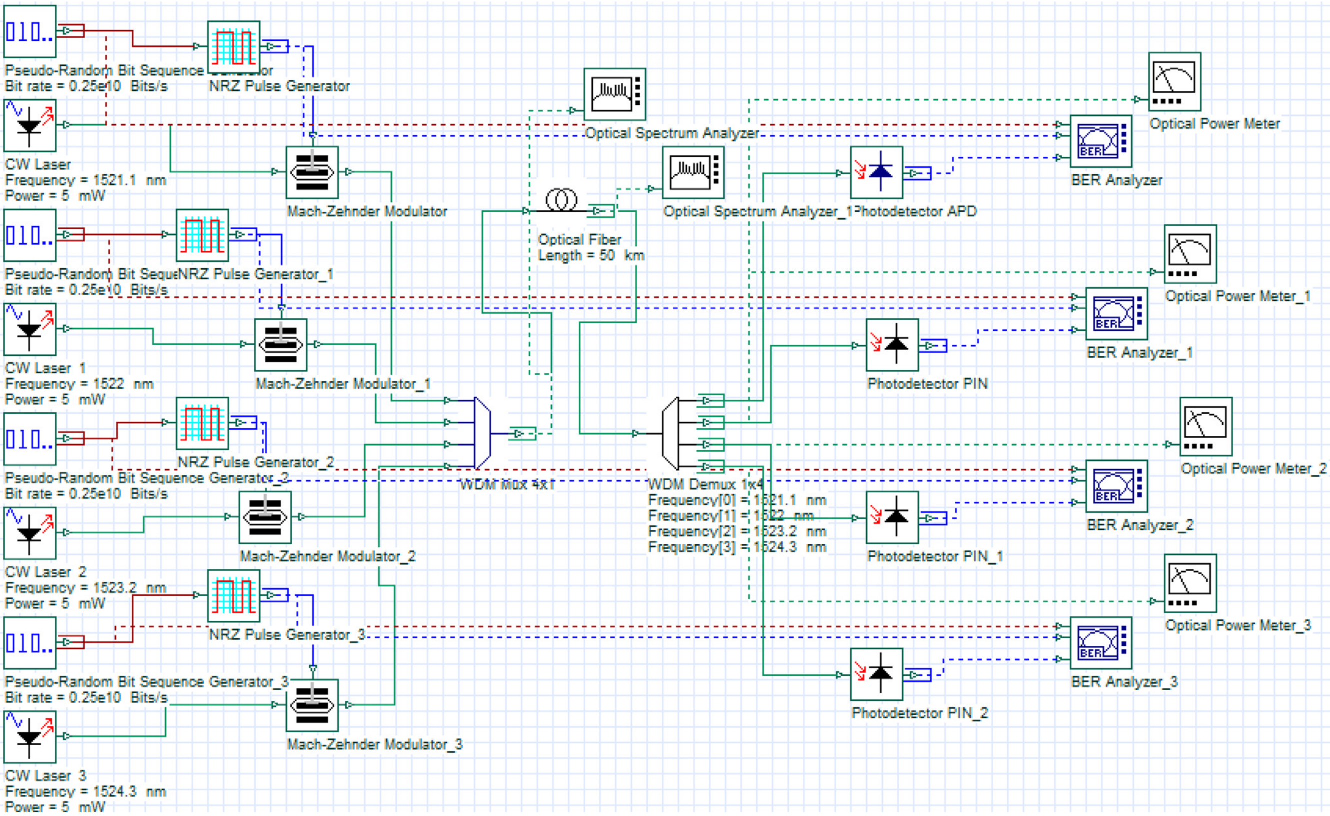

Fig. 8. Network of proposed four channel demultiplexer in the point to point DWDM network.

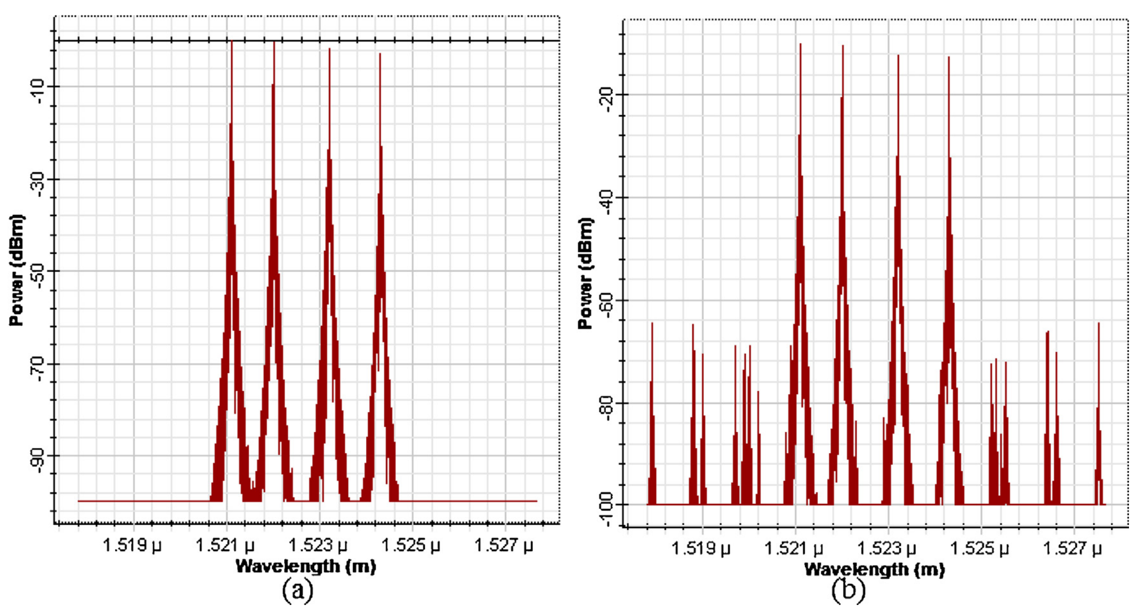

Fig. 9. Power spectrum output of WDM point to point Network (a) Multiplexed output before fibre and (b) Multiplexed output leaving from fibre.

1523.2 nm and 1524.3 nm) are assigned in a CW laser at 5 mw power is fed into the one input of the Mach-Zehnder modulator and other input from Pseudo Random Binary Sequence (PRBS) Generator's electrical signal at 2.5 Gbps is coded to the NRZ (Non Return Zero) modulation format, then it is converted into optical signals.

Fig. 9(a) and (b) shows the transmitted and received spectrum of the proposed point to point network. The input power is 0 dBm and the power obtained after the multiplexer is varies from −3 dBm to −5dBm. Similarly, the received power of selected channels varies from −12 dBm to −15dBm. The variation of transmitted power and receiver power is occurring due to the nature of wavelength. Further, there are some noise signal are also reported. As the input signal is travelling at a certain distance, the amount of power is getting minimized owing to the losses involves in the components available in the link.

The eye diagram of the proposed point to point network for each channel is shown in Fig. 10(a)–(d). The input data rate is 2.5Gbps. The eye diagram is obtained at 50Km. From Fig. 10(a)–(d), it is

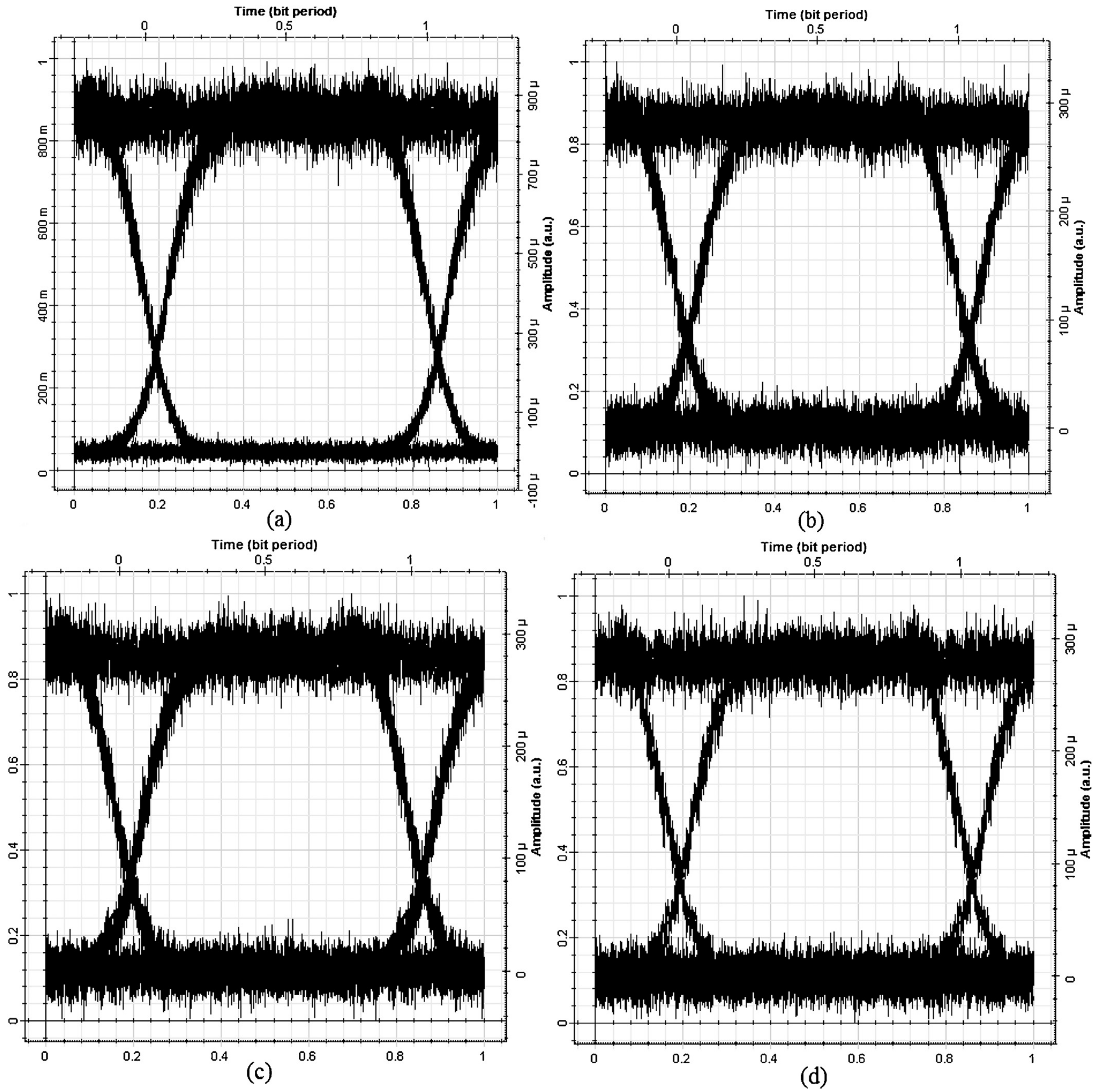

Fig. 10. Eye diagram of the proposed point to point network at (a) λ1 = 1521.1 nm, (b) λ2 = 1522 nm, (c) λ3 = 1523.2 nm and (d) λ4 = 1524.3 nm.

clearly observed that the eye opening is appeared clearly to get typical BER.

Fig. 11 depicts the impact of BER while varying the link distance. The BER is observed by accounting the insertion loss of 1.5 dB [26]. From the results, it is noticed that the maximum travelling distance of the network is about 85Km for all the channels. The maximum distance is estimated at the BER of 10^{-9}.

The minimum amount of received power required to get the desired BER (10^{-9}) is estimated for all the channels and it is shown in Fig. 12. The receiver sensitivity of the proposed network is about −16 dBm which is highly sufficient and suitable for WDM applications. The variation of link distance and receiver sensitivity for each is occurring due to the nature of wavelength.

5. Conclusion

In this paper, we have investigated 2DPC quasi square ring resonator based for four channel WDM demultiplexer. The proposed structure contains specialized unique refractive index based inner core which is involved in channel selection. The overall size of the structure is 180.96 μm^2. The resonant wavelength of the proposed four channel demultiplexer is varying from 1521.1 nm to 1524.3 nm with 1.1 nm spacing. The maximum transmission power and Q factor are about 100% and 2178, respectively. The optimum transmission power would be 100% and obtained high Q factor for channel 4. Further the 2DPC based demultiplexer is incorporated in the DWDM systems for analysing the performance of BER and

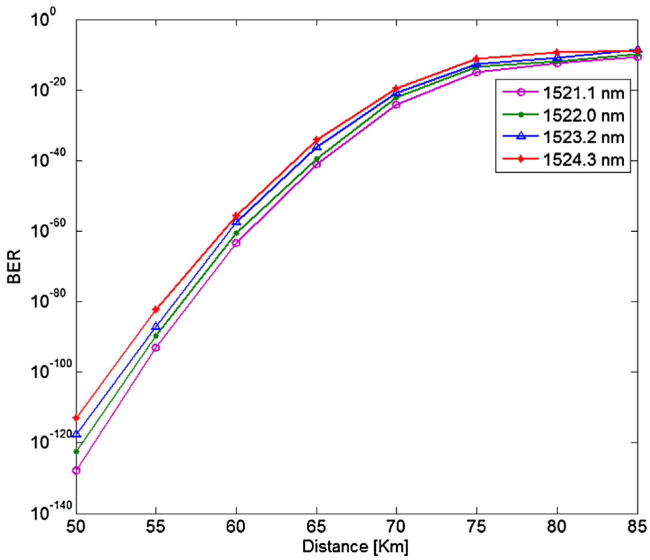

Fig. 11. Effect of BER verses distance of WDM point to point network.

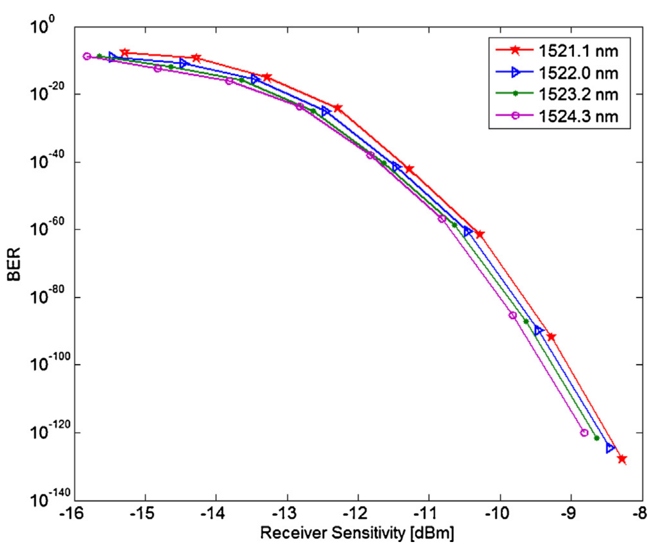

Fig. 12. Effect of BER verses Receiver Sensitivity of WDM point to point network.

receiver sensitivity for four channels. The maximum travelling distance and receiver sensitivity of the proposed network are 85Km and – 16dBm, respectively. This is applicable to develop photonic integrated circuits for real time applications.

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