Investigation on Ultra-Compact 2DPC Coarse Wavelength Division Demultiplexer

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Abstract

A two dimensional Photonic Crystal (2DPC) based eight-channel wavelength division de-multiplexer is proposed and designed for Coarse Wavelength Division Multiplexing (CWDM) applications. The circular ring resonator, channel selector, circulator rod, L bend waveguide and linear bus waveguide are essential parts of the proposed system. The system's functional parameters such as Transmission efficiency, resonant wavelength, spectral width, channel spacing, Quality factor and crosstalk investigated this paper. The eight different wavelengths of channels are filtered out by altering the size of channel selector rod, setting the radius of the circle shaped cavity and relative refractive index of circulator rod. Initially the Photonic Band gap (PBG) is manipulated by applying Plane Wave Expansion (PWE) method of the 2DPC structure. The functional parameters are analysed by Finite Difference Time Domain (FDTD) method in periodic and non-periodic structure of the proposed system to arrive normalized transmission spectrum. The resonant wavelengths of designed eight paths of the device are varying from 1420nm to 1460nm with average spectral width and channel spacing are 5.8nm, 5.6nm respectively. The footprint of the device is 286.84μm2. Hence, this small device can be implemented for CWDM systems in Photonic Integrated Circuits (PIC).

Keywords: Two dimensional Photonic Crystal, Channel Selector Rod, Ring Resonator, Linear Bus Waveguide

Introduction

An ultra-small 2DPC structure in nanometre range utilized for designing Photo electronic devices. Typically, PC based devices are providing better performance of Optoelectronic communication system. A periodic and non-periodic dielectric PC structure have some attractive features such as long life, high speed of operation, compactness, better confinement to design miniaturised devices [1]. Generally, periodic variation of dielectric constant and distribution of refractive index in the medium of PC classified as one-dimensional PC (1DPC), two-dimensional PC (2DPC) and three-dimensional PC (3DPC). The structure of 2DPC classified as square lattice and triangular lattice. A periodic array of dielectric rods with low dielectric strength in air medium is called as Square lattice and the drilled air holes in dielectric slab is called as triangular lattice. Air holes depth and shape, which strongly affect the radiation losses. It is very difficult to attain unique dimension of drilled air holes in triangular lattice than the unique dimension of dielectric rods immersed in air medium of square lattice.

The 2DPC utilized for designing devices such as filters, sensors, switches, Polarizer, logic gates, power splitter, multiplexers, de-multiplexers etc. [2-23]. In most of the advanced communication systems, WDM technology is employed [23]. WDM technology is the powerful channel multiplexing and de-multiplexing with high efficiency. The 2DPC based WDM devices were made by introducing defects. Typically, point, line and surface defects are utilized for designing devices like bus waveguide, resonant cavity, ring resonator [2-4,6,8,9,11,14-16,17,19,21]. The ring resonators and resonant cavities are used in the form of circular, elliptical, square, quasi-square etc [2,4,17,21,23]. In the 2DPC based

devices. The size and shape of the resonant cavity is the effective tool in the device to tune the wavelength of the WDM device. The size and shape of the ring resonator employed in the device for enhancing signal performance the device.

Hence, the proposed CWDM device developed using 2DPC square lattice structure and square lattice offers low propagation loss than triangular lattice. Multiple channels with different wavelengths are transferring over a single fibre is called Wavelength Division Multiplexing (WDM). The methods of carrying information over the fibre classified as Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM). In CWDM, the channel spacing is less than or equal to 20nm and the DWDM, the channel spacing is lesser than or equal to 1.6nm.The channel spacing differs CWDM and DWDM.

Methodology

The PWE and FDTD simulation methods are the most powerful tool to provide accurate behaviour of PC structure. The PWE is utilizing for generating PBG and describing the modes in periodic and non-periodic dielectric structures [24,25]. However, it could not predict the extract backward reflections, field distribution and transmission spectra of the PC structure. Hence, FDTD method is solved the Maxwell's equations to analysis the transmission spectra of PC based Optical devices [26]. FDTD is simple, attractive, high accurate and efficient way to obtain transmission response. Typically, one-dimensional FDTD methods offers fast simulation with less accuracy and PWE evaluates incomplete Photonic Band Gap (PBG). Three-dimensional FDTD methods require more simulation time, large memory size and accurate behaviour of PCs and PWE provides complete PBG. Even though it affords accurate results, the same results can obtained using 2D FDTD simulates with less time and less memory space and fabrication is easier than 3DPC and two-dimensional PWE provides complete PBG. Hence, 2D FDTD method considered in the present work. The following FDTD solution that bounds the time steps to ensure the stability of the numerical method is

$$\Delta t \leq \frac{1}{c\sqrt{\dfrac{1}{\Delta x^2} + \dfrac{1}{\Delta z^2}}} \qquad (1)$$

Where Δt is the time step, c is velocity of light and Δx, Δz are space steps along x, z axes respectively. The propagation of light in a PC is z-direction.

The rest of the paper further organised as follows: The Section 3 describes the generation of PBG of the proposed PC structure. The Section 4 shows the structural design of the eight-channel CWDM de-multiplexer. In Section 5, the FDTD simulation results are discussed the functional parameters are summarised and concluded in Section 6 of the proposed device.

PBG Design

The 2DPWM computational technique generates the PBG in the 2DPC structure to identify the band of frequency, which utilized for designing a device. The structural parameters lattice constant (a), radius (a) and relative refractive index (Δ) are the active part of 2DPC square lattice to generate desired PBG.
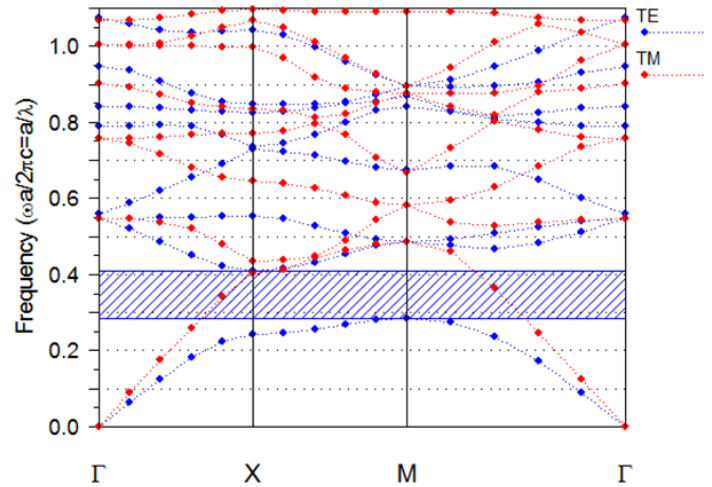

Figure 1: Schematic representation of PBG diagram of 2DPC structure

The radius of the dielectric rods are immersed in air is 100nm, spacing between the rods is lattice constant a=562nm and refractive index difference Δ=2.24. Before the introduction of defects, the PBG band diagram of the 2DPC structure shown in Figure 1. The band diagram consists of blue coloured transverse electric (TE) PBG and red coloured transverse magnetic (TM) PBG. PWM computes the PBG range is lies between 0.2846 to 0.4093 (a/λ) whose corresponding wavelength range is 1123nm to 1616nm which is calculated by f=a/λ= ωa/2πc.
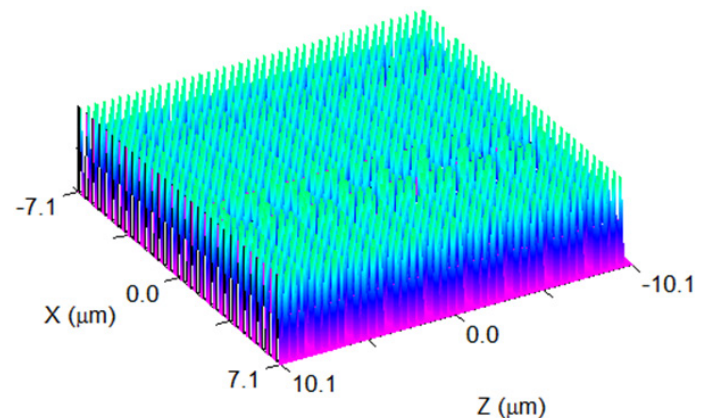

Figure 2: Schematic representation of 3D view of 2DPC structure

The Figure 2 shows 3D view of proposed 2DPC structure. The number of rods in X-Z direction is 31 and 44, respectively. The dimensional length of structure in X and Z direction is 14.2μm,

20.2µm respectively. Hence, footprint of the structure is about 286.84µm².

Design of Ring Resonator Based De-multiplexer

In Figure 3A & 3B shows sectional view of a single channel path of an eight-channel CWDM de-multiplexer. Circular ring resonator, which is, clearly depicts the same kinds of rod in the structure. Figure 4 shows the device design, which consists of eight circular ring resonators, where all the eight ring resonators are, positioned serially one by one and right side of the linear bus waveguide. The right side of the circular ring resonators are having linear waveguide to drop the channel. This waveguide is known as dropping waveguide. The left side of the structure has seven T shaped waveguides for λ1 to λ7 and eighth path is having L bend waveguide.
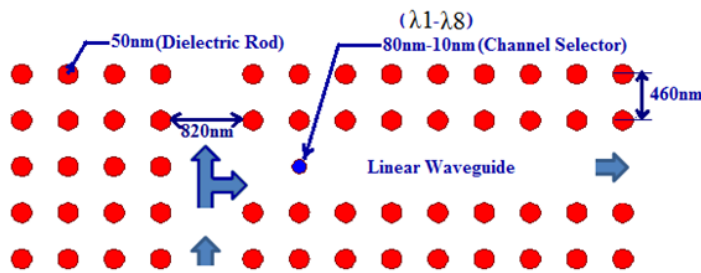

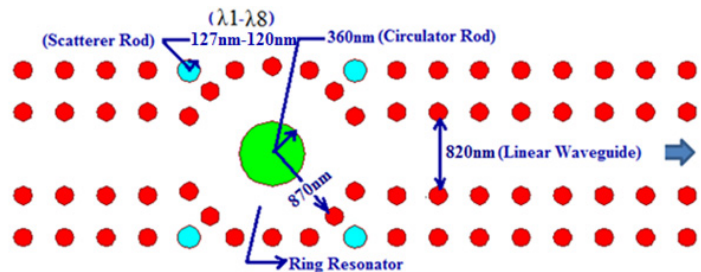**Figure 3A:** Sectional view of Linear Waveguide

Figure 3B: Sectional view of Circular Ring Resonator

The linear bus waveguide is formed by introducing line defects i.e. removing rods in a single column, which is used for passing the Gaussian light signal with better linearity. The width of linear waveguide is about 820nm. The width of the linear bus waveguide is calculated from the radius of the dielectric rod and lattice constant of a single periodic row or column of the proposed structure. The other important parts of the devices are circular ring resonator with centre rod, channel selector rod and scatterer rods.

Circular Ring Resonator

This is made by circular shaped resonator with centre rod. Each resonator contains one centre rod, which is named as circulator rod. The radius of the each ring resonator is about 870nm and radius of the centre rod is 360nm with relative refractive index is one. The circulator rod linearly circulates and boosts the light signal inside the resonator. The circular ring resonator is designed by introducing both line and point defects.
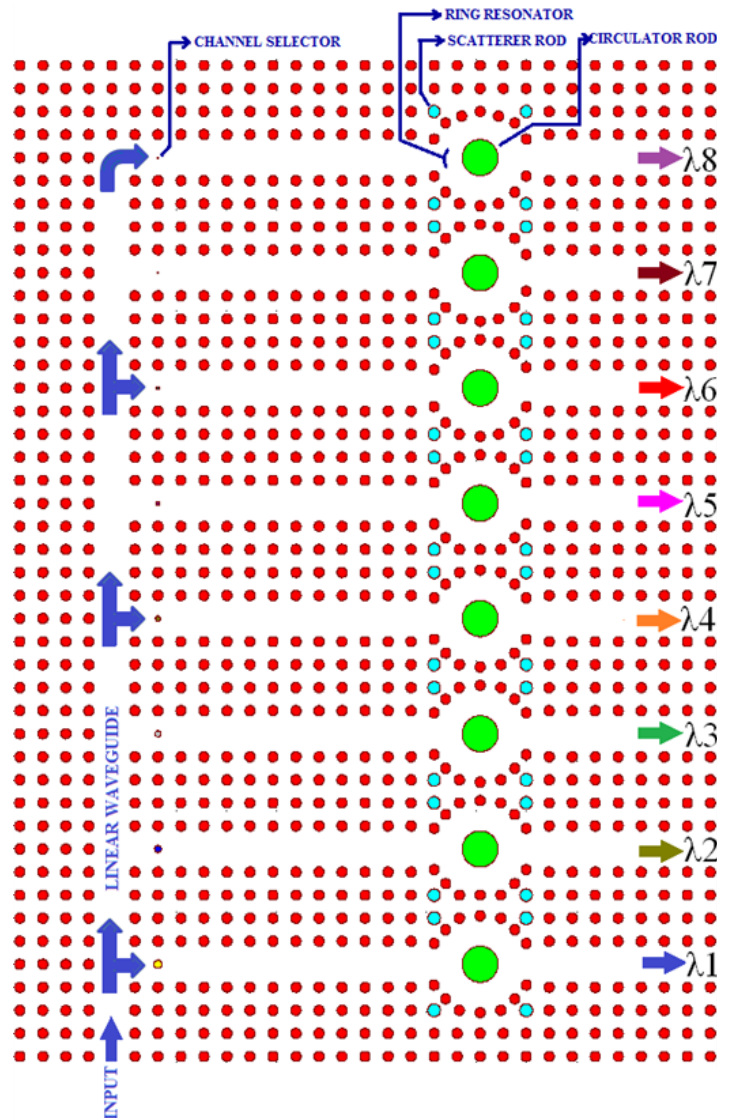

Figure 4: Schematic representation of proposed eight-channel de-multiplexer

Channel Selector Rod

The small sized channel selector rod placed at the starting end of the T shaped and L shaped bend waveguides. The radius of the rod is varying from 80nm to 10nm with decreased by the factor of 10nm for the channels λ1 to λ8. The channel selectivity and wavelength is based on the size of a rod is used in the device. The radius of this rod tunes the wavelength of the channel for the CWDM applications.

Scatterer Rod

The scatterer rod is incorporated at each corner of the circular ring resonator. Generally, the scattering rod is employed to reduce the counter propagations modes and back reflection of the incoming light signal inside the ring resonator. According to the channels λ1 to λ8, the radius of the rods is varying from 127nm to 120nm decreasing by the factor of 1nm. This process is enhancing the performance of the de-multiplexer.

Table 1: Channel selector rod radius, Scatterer rod radius and resonant wavelength of the proposed de-multiplexer

Channels	Channel Selector Rod Radius (nm)	Scatterer Rod Radius (nm)	Resonant Wavelength[λo] (nm)
λ1	80	127	1460.3
λ2	70	126	1450.1
λ3	60	125	1445.0
λ4	50	124	1440.0
λ5	40	123	1435.3
λ6	30	122	1430.2
λ7	20	121	1425.2
λ8	10	120	1420.3

Table 1 enumerates the resonant wavelength of the channels λ1 to λ8, which tuned by channel selector rods, and the scattered light rays, which are reducing by scatterer rods. According to the size of channel selector rod, circular ring resonator with effective refractive index of centre rod and scatterer rod positioned at the four corner each ring is the active role to select and drop the channels like 1460.3nm, 1450.3nm, 1445.0nm, 1440.0nm, 1435.3nm, 1430.2nm, 1425.2nm and 1420.3nm wavelengths (λ1-λ8) respectively.

The Gaussian light signal with 1μW power launched into the linear waveguide. The field distribution of proposed de-multiplexer is attained by linear waveguides, T shape and L bend waveguides for the channel λ1 (1460.3nm) and channel λ8 (1420.3nm) is shown in Figure 5A and 5B, respectively. The following equations are analysing the electromagnetic field distribution inside the 2DPC devices.

$$Ex\Big|_{i,j}^{n+1} = Ex\Big|_{i,j}^{n} + \frac{c\Delta t}{\varepsilon o}\left[\frac{Hz\Big|_{i,j+1/2}^{n+1/2} - Hz\Big|_{i,j-1/2}^{n+1/2}}{\Delta y}\right] \tag{2}$$

$$Ey\Big|_{i,j}^{n+1} = Ey\Big|_{i,j}^{n} - \frac{c\Delta t}{\varepsilon o}\left[\frac{Hz\Big|_{i+1/2,j}^{n+1/2} - Hz\Big|_{i-1/2,j}^{n+1/2}}{\Delta x}\right] \tag{3}$$

$$Hz\Big|_{i,j}^{n+1/2} = Ez\Big|_{i,j}^{n-1/2} + \frac{c\Delta t}{\varepsilon o}\left[\left[\frac{\left[Ex\Big|_{i,j+1/2}^{n} - Ex\Big|_{i,j-1/2}^{n}\right]}{\Delta y}\right] - \left[\frac{\left[Ey\Big|_{i+1/2,j}^{n} - Ey\Big|_{i+1/2,j}^{n}\right]}{\Delta x}\right]\right] \tag{4}$$
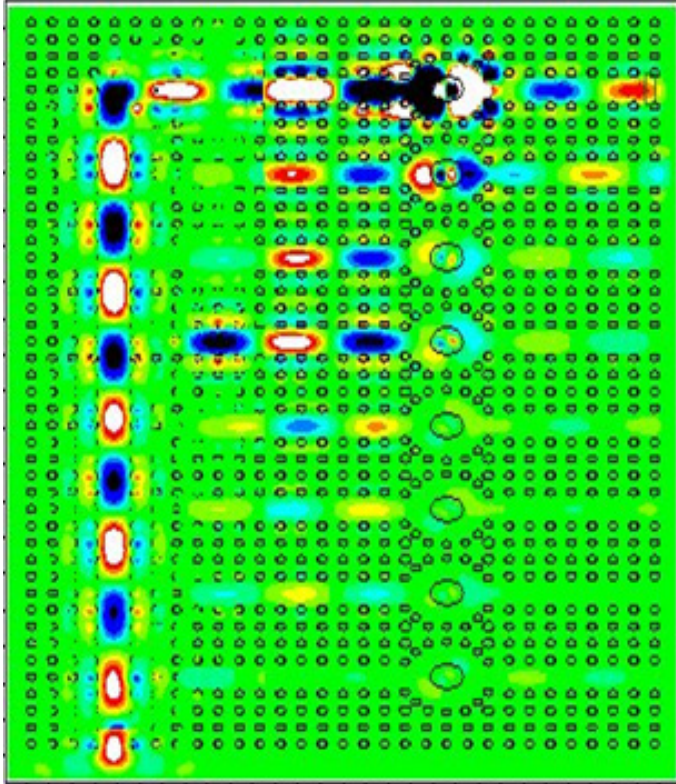
Figure 5A: Electric field distribution of proposed DE multiplexer (a) λ1=1460.3nm

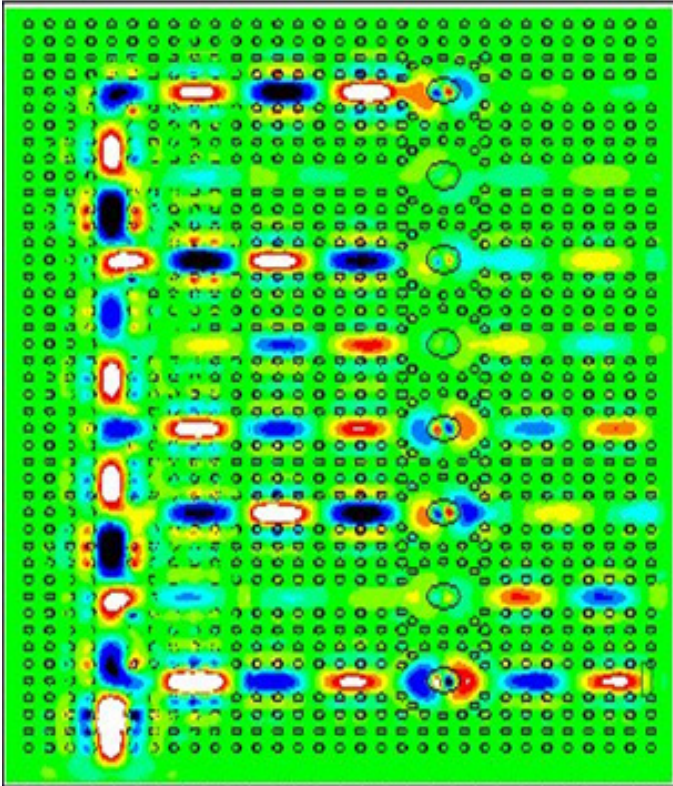**Figure 5B:** Electric field distribution of proposed DE multiplexer (b) λ8=1420.3nm

On resonance input signals are reached at λ1=1460.3nm with higher signal strength at port 1 and λ8=1420.3nm is reached at port 8. The off resonance signal is reflected to the source. However, the size of the structure is very small, the crosstalk among the channel little bit occurred in the proposed device.
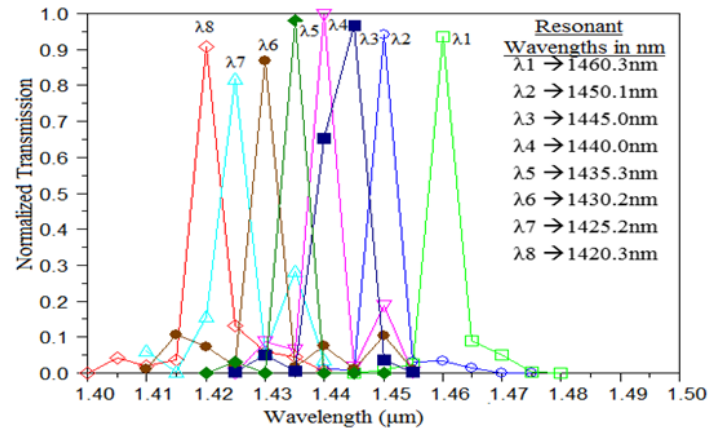
Simulation Results and Discussion

Figure 6: Output Spectrum of proposed eight-channel de-multiplexer

2DFDTD evaluates the spectral width (Δλ) of this proposed structure is around 5.8nm and channel spacing (λl) between the channels is about 5.6nm. The eight channel resonant wavelength (λ1-λ8) of proposed device shown in Figure 6. The channel spacing, spectral width and normalised transmission efficiency calculated from the output spectrum. The ratio of resonant wavelength ( ) and spectral width ( ) is the Full Width Half Maximum of the channels called Q factor. The quality factor calculated for the dropped channels of the structure is

$$Q = \frac{\lambda o}{\Delta \lambda} \qquad (5)$$

The Quality factor of channels λ1 to λ8 is 243, 254, 263, 277, 281, 161, 297 and 268. From the Table 2, observed that the functional characteristics such as the resonant wavelength, spectral width, channel spacing, transmission efficiency and Q factor of the proposed de-multiplexer are meeting the requirements of CWDM applications.

Table 2: Resonant Wavelength, Bandwidth, Transmission efficiency and Q Factor of eight-channel demultiplexer

Channels (λ)	Resonant Wave length (λo)nm	Spectral Width (Δλ)nm	Channel Spacing (λl)nm	Transmission (%)	Quality Factor (Q)
λ1	1460.3	6	10.2	93	243
λ2	1450.1	5.7	5.1	93	254
λ3	1445.0	5.5	5	96	263
λ4	1440.0	5.2	4.7	98	277
λ5	1435.3	5.1	5.1	97	281
λ6	1430.2	8.9	5	87	161
λ7	1425.2	4.8	4.9	82	297
λ8	1420.3	5.3	4.9	89	268

The crosstalk between the channels in Table 3 shown. The crosstalk of the proposed device is the important one to analysis the overall performance. Typically, the crosstalk should be minimum in the device. If crosstalk is minimum, the total channels occupying space will be more or spectral width will be reduced of each channel. In the proposed device, the crosstalk (-19.7dB) is less between the channels λ5 and λ7 and more crosstalk (-0.8dB) in between λ2 and λ5.

Table 3: Crosstalk between the Channels of proposed Eight Channel Demultiplexer

Xij[dB]	λ1	λ2	λ3	λ4	λ5	λ6	λ7	λ8
λ1	-	-2.1	-8.5	-12.0	-13.9	-13.8	-	-
λ2	-2.5	-	-2.9	-13.4	-6.3	-6.8	-	-
λ3	-8.6	-2.7	-	-3.2	-12.8	-	-	-
λ4	-11.7	-10.6	-2.7	-	-2.9	-4.0	-	-
λ5	-13.5	-0.8	-12.3	-2.9	-	-1.1	-19.7	-
λ6	-13.5	-1.3	-	-4.2	-1.3	-	-2.7	-
λ7	-	-	-	-	-19.7	-2.7	-	-12.7
λ8	-	-	-	-	-	-	-12.7	-

Table 4: Comparison of proposed demultiplexer with reported one

Author/ Year	PC Lattice Structure	Number of Channels	Footprint Size (μm²)	Wavelengths Used (nm)	Crosstalk (dB)	Transmission Efficiency (%)	Spectral-Width (Δλ)	Channel Spacing (nm)
Hadi Ghorbanpour et.al. 2013 [14].	Square	2	681.36	1590,1593	-22	90	0.3	3
Mohamed Ali Mansouri- et.al. 2013 [15].	Square	3	317	1507 - 1524	-29	90	2.8	8
Mohamma Reza Rakhshani,et.al. 2013 [16].	Square	3	294.25	1500 - 1522	-24.44	95	2.75	6.1
Nikhil Deep Gupta, et.al. 2014 [17].	Square	4	484	1500 - 1522	***	***	0.2	0.8
Talebzadeh et,al. 2016 [19].	Square	4	360	1550,1560	-27.33	93.45	0.4	2
Masoud Mohammadi et.al. 2019 [21].	Square	4	294.4	1528-1533	-46.68- -9.79	99	0.217	2.2
Talebzadeh et.al. 2017 [20].	Square	8	790	1542-1555	-18	99	1.5	1.75
Farhad Mehdizadeh, et,al. 2015 [18].	Square	8	495	1536 - 1551	-11 .2	96	0.7	19.5
Mohammadi, B, et.al. 2019 [22].	Square	8	675	1545-1571	-16- -40	98	1.3	3
Venkatachalam et.al. (2017) [23].	Square	8	434.16	1537-1545	-28.6- -2.3	98	0.7	0.7
This Work	**Square**	**8**	**286.84**	**1420-1460**	**-19.7- -0.8**	**92**	**5.8**	**5.6**

***→ Not discussed

From the above Table 4, it is noted that the proposed demultiplexer performs better than the reported one. Hence, this paper deals with CWDM application.

Conclusion

This paper is designed for the eight-channel demultiplexer for CWDM applications. 2DPC based circular ring resonator with effective refractive circulator centre rod is employed to enhance the signal performance of the proposed demultiplexer. A channel selector rod placed at the wave-splitting end of the linear waveguide is utilized for tuning the wavelength of the channel. According to the 2DFDTD analysis, the efficiency of normalized transmission spectra is 92% and the channel spacing and spectral width of the channel 5.8nm and 5.6 respectively. The overall bandwidth of occupying all eight channels is about 40 nm and size of the device is 286.84µm^2, which are very small to implement Photonic Integrated Circuits for the CWDM applications

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