

Design and optimization of four channel Dense Wavelength Division Multiplexing demultiplexer using photonic crystals square resonant cavity

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A four-channel Dense Wavelength Division Multiplexing (DWDM) demultiplexer is proposed and designed using a two-dimensional photonic crystal square lattice in order to precisely confine the light in horizontal direction. The proposed demultiplexer comprises a T-shaped bus waveguide, four drop waveguides and four square resonant cavities. The T-shaped waveguide is designed with line defects, and wavelength selective filter is realized using square resonant cavity. The square resonant cavity designs with inner ring filter rods, outer ring rods, and resonant rods. The desired wavelength can be separate by adjusting the inner ring filter rod radius and resonant rod. The proposed PC based demultiplexer can drop four different wavelengths (1555 nm to 1558 nm) with 1 nm of uniform channel spacing, which is promptly suitable for DWDM applications. The channel bandwidth, transmission efficiency, crosstalk, and Q factor of the proposed device is about 0.2 nm, 99-100 %, - 40 dB and 7775-8000, respectively. The simulation is carried out with Two -Dimensional Finite Difference Time Domain (2D-FDTD) technique and Plane Wave Expansion (PWE) method with perfectly matched layers (PML) absorbing boundary conditions (ABC). The size of the proposed device is 447 μm^2 hence it could be implemented for Photonic Integrated Circuits (PICs).

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1. Introduction

The optical demultiplexer is one of the essential devices in the Wavelength Division Multiplexing (WDM) technology, which play a prominent role in enhancing the utilization of the resources such as spectral bandwidth in the optical range. The commercial demultiplexer has been obtained with various applications namely Fiber Bragg Gratings [1] and Arrayed Waveguide Gratings [2] and Prism Demultiplexer [3] etc., that have been developed in the range of centimeter to millimeter scale. However, in recent days, the design engineers have shown interest in the micrometer scale, with broad applications in the Photonic Integrated Circuits (PICs).

As an alternative, Photonic Crystals (PCs) have so far demonstrated their ability to control hundreds of channels in the micrometer size scales. For the past few decades, the utilization of PCs has risen from being a concealed technology to an important field of research. In the PCs, wavelengths of the lights are restricted to a maximum extent to travel inside the structure, due to the photonic band gap (PBG) [4, 5], where the wavelengths of the light are not entirely allowed to travel inside the structure. Hence, to allow a certain wavelength to propagate, it is highly essential to create defects in the periodic structure.

Generally, in PCs, the defects can be created in two ways, viz; line defects and point defects. The line defects are formed by removing/altering the structural parameters (such as lattice constant, refractive index, and radius of the rods) of the entire row of the rods in the designed structure. The introduction of the defects of both categories becomes imperative to enable the designing of PCs based devices. The PCs are also employed to design the wavelength demultiplexers [6], beam splitters [7], optical switches [8], and ring resonators [9], photonic sensors [10].

In recent years, researchers focus the DWDM device due to its unique features. The DWDM technology accomplishes dynamic usage of bandwidth and low attenuation components of single mode fibers, which uses multiple wavelengths as carriers and concedes them to transmit in the fiber simultaneously [11]. The DWDM consists of ITU-T G.694.1 standards with 0.1, 0.2, 0.4, 0.8 nm channels dispersing with 512 distinct wavelengths. Hence, these features enable the service providers to resolve the capacity crisis, attain high speed and high flexibility in transmission for long distance communication. The main function of the optical demultiplexer is to separate the wavelengths and couple to individual fibers. Among the two distinct demultiplexers,

the passive and the active, the design of the former has been done mostly either by the blocks of the prisms [12], or by the diffraction grating [13]. However, the active demultiplexers are generally designed with the combination of one of the above passive components and the tunable detectors [14]. Nevertheless, the existing demultiplexer has been reportedly having limitations such as low Q-factor, less normalized transmission power, high crosstalk, non-uniform channel spacing, non-uniform spectral bandwidth and centimeter size footprint while adapting in the PICs.

2. Modeling methods

The literature survey deems that the inference of the two dimensional (2D) PC based demultiplexer for Coarse Wavelength Division Multiplexing (CWDM) and DWDM system is using line defects [15], ring resonators [15-18]. The DWDM demultiplexer using 2D PC is done by T-shape structure with the line defects resonant cavity [19], P-shaped single resonant cavity with different rod radius to drop different wavelength [20] and hence the multi T-shaped structure with line/point defects [21-23], heterostructure resonant cavity [24] and X-ring cavity [25]. From the literature survey, it is identified that the demultiplexer is designed using the different shape of the cavity. In the work presented here, a novel square ring resonant cavity based DWDM demultiplexer is developed and proposed as a research work to enhance the transmission efficiency, crosstalk, Q factor, uniform channel spacing with the constructive interference based proposed design. Therefore, the authors have considered prevailing benefits of DWDM and carried out the research work as per ITU-T G.694.1 standard with uniform channel bandwidth and channel spacing, whose results are presented here with the benefits at the end.

A new square shape resonant cavity has been modeled with outer ring rods, inner ring filter rods, and resonant rods. It can filter the desired wavelength by changing the radius of the inner ring filter rods and resonant rods; however, the other parameters such as outer ring rod, refractive index, non-defected rod radius, and lattice constant are kept constant. Hence, the proposed model of resonant cavity has been designed with a square size, which reduces the scattering losses and alternatively enhances the coupling efficiency. Therefore, the model is proposed to improve various features such as crosstalk, transmission efficiency, Q factor, etc. For this a Plane Wave Expansion (PWE) and Finite Difference Time Domain (FDTD) methods are employed for obtaining the PBG and normalized transmission spectra for the proposed structure. The paper initially covers the modeling of single cavity structure and then extended to four cavity structure. At the end, the results are analyzed and discussed.

3. Geometry of photonic crystal

The filter is the basic device for the demultiplexer, designed using the square lattice PC. The total amount of rods in 'X' and 'Z' direction is 33 and 47 respectively as shown in Fig.1. The lattice constant $a=520$ nm and the radius of non-defected rod $R=115$ nm. The refractive index of the dielectric TiO_2 rod is 3.71, which is embedded in air. The theoretical analysis of 2D PC is carried out by PWE method [26] and FDTD method [27-28]. The PBG of periodic and non-periodic structures and propagation modes are calculated using the PWE method primarily. The PWE Method realize with Maxwell's equations [28].

$$\nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times E(r) \right) = \frac{\omega^2}{c^2} E(r) \quad (1)$$

Where, $\varepsilon(r)$ is the dielectric function

ω is the angular frequency

$E(r)$ is the electric field of the periodic structure,

and 'c' is the speed of the light in free space.

The solution of Eq. (1) is represented in the form of band structure. The spatial detention of the photon in PC achieve through introduction of defects. The propagation of electromagnetic modes inside the PC structures is studied by FDTD method, which has been introduced by Yee in 1966 [27]. The FDTD is considered as the most powerful solution to Maxwell's equation, due to its simplicity. In this simulation FDTD mesh size and time step are $\Delta x=a/20$ and $\Delta t=\Delta x/16$, respectively. The 2D- FDTD method use to obtain the transmission spectrum of the proposed demultiplexer.

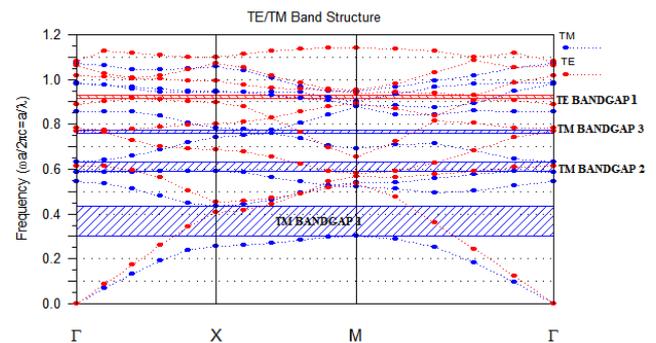


Fig. 1. Band gap diagram for 33*47 PC structures with hybrid mode (TE & TM)

The Fig.1, illustrate the band diagram for 33×47 PC structure with hybrid mode (TM & TE), it has three TM-PBG and one TE-PBG. Here, the first TM PBG lie in between the frequency in the range of $0.29771 < a/\lambda < 0.435$, the related wavelength lies between of 1195 nm – 1746.6 nm of the PBG. The TM PBG, which covers the wavelength range of the conventional (C -window) of the optical communication .All the simulation, has been carried out for TM mode where the electric field is at a 90-degree angle to the rod axis. The frequency and its resultant wavelength obtained are listed in Table 1.

Table 1. Normalized frequency and wavelength of the proposed structure.

Photonic Band Gap	Normalized Frequency (a/λ)	Resultant Wavelength (nm)
TM PBG	0.29771-0.435	1195-1746.6
	0.59-0.627	829.3-881.3
	0.76-0.774	671-684
TE PBG	0.91-0.92	571-565

4. Simulation of single and multi channel demultiplexer

The single channel DWDM filter with square resonant cavity schematically represented in the Fig.2.

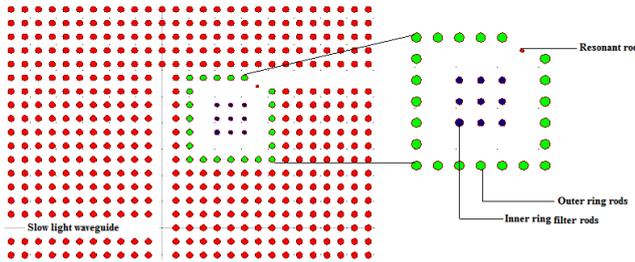


Fig. 2. Single filter based on square ring resonant cavity obtain with line/point defects in square shape

Inner ring filter rods, outer ring rods, resonant rods and waveguide are the inherent components in the square ring resonant cavity, being proposed in this research work. The resonant cavity create with introducing line defects; whereas, line/point defects are introduced to create a square shape of the resonant cavity. The dielectric rods are placed in 3 different layers to make a square ring resonant cavity. The rods along the periphery of the cavity are termed as outer ring rods. The rods, placed well inside the cavity are termed as inner ring filter. The rods positioned at the right corner, and enabling them to couple the output waveguide to the signal propagates from the square resonant cavity are known as resonant rods.

The L-shaped waveguide as the base structure, is being used to design the single channel filter, with the dimensions of the outer ring rods, inner ring filter rods and the resonant rods of resonant cavity being, 115 nm, 86 nm and 54 nm respectively in radius. The radius of the rod

optimized through experiment and error method. The radius of the outer ring rod has been fixed with 115 nm and remains same for all the four square resonant cavities except inner ring filter rod and resonant rods. The electromagnetic waves from the computing region are absorbed utilizing the FDTD method; with the perfectly matched layer (PML) absorbing boundary condition without any such reflection of the waves back into the interiors [27-28].The normalized output transmission is made possible with the help of a power monitor placed in the each drop waveguide at the end.

The Fig. 3 shows normalized optical power transmission spectrum of the proposed square ring resonant cavity for the single channel. The Q factor, normalized transmission efficiency and the central wavelength of the proposed filter is 7797, 100 % and 1557 nm respectively. The Q factor measures the losses in the cavity [29].

$$U(t) = U(0) \exp\left[\frac{-(\omega_0 t)}{Q}\right] \quad (2)$$

The Q-factor has been calculated by using [28].

$$Q = \frac{\lambda_r}{\Delta\lambda} \quad (3)$$

Where λ_r is the central wavelength, $\Delta\lambda$ is the channel bandwidth. For example, channel bandwidth of 0.2 nm obtained at 1557 nm is adequate to drop a channel for the DWDM. In this work the four distinct channels of filters with the demultiplexing capabilities are used, in place of a single channel filter.

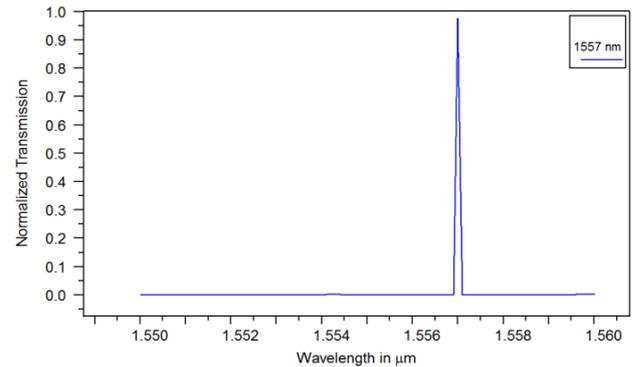


Fig. 3. The normalized optical power transmission spectrum of the proposed square rings resonant cavity for the single channel.

Fig. 4 schematically represents each square ring resonant cavity (C_1 , C_2 , C_3 , and C_4) of a four port demultiplexer, which are responsible for each channel. Here, the filter with distinct resonant rod whose radius separates the channels. The lattice constant, and refractive index are kept constant for non-defected rod radius in the

demultiplexer. The complete structural parameters for the individual channels are summarized in Table 2.

The radius of the rods determine the optimized simulation under the different criteria, like lattice constant, characteristics of rods and refractive index to obtain a high normalized transmission efficiency, the Q factor, and the narrow channel bandwidth.

Table 2. Radius of the outer ring, inner ring filter, and resonant rods of the proposed demultiplexer

Channels	Radius of Outer Ring Rods	Radius of Inner Ring Filter Rods	Radius of Resonant Rods
λ_1 -1555 nm	115 nm	66 nm	100 nm
λ_2 -1556 nm	115 nm	76 nm	95 nm
λ_3 -1557 nm	115 nm	86 nm	54 nm
λ_4 -1558 nm	115 nm	96 nm	44 nm

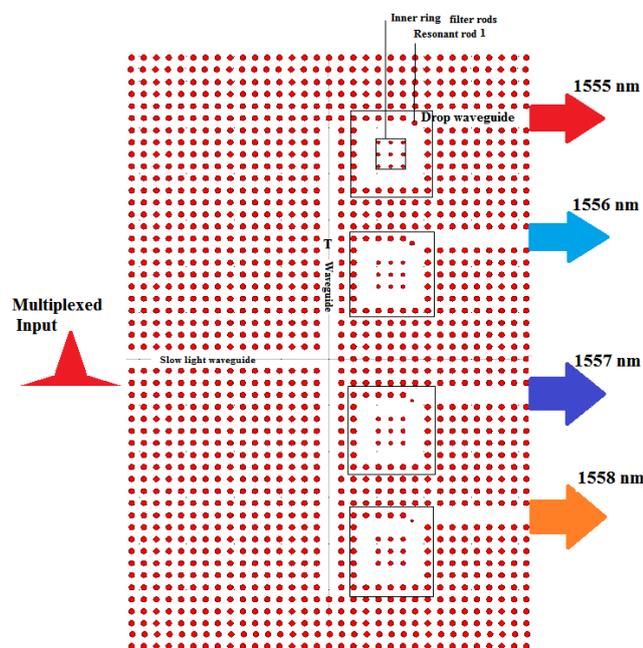


Fig. 4. Schematic view of final Four channel DWDM demultiplexer in a square lattice PC

The dropping of different channels from 1 through 4 is being made possible by each resonator, having a T-shaped waveguide and four square ring resonant cavities as shown in figure 4. The square ring resonant cavity is the combination of inner ring filter rod, outer ring rod, and resonant rod. The low resistance with specific wavelength occurs due to the entrapment of photons in the resonant cavity and helps the inner resonant rods to couple the distinct color wavelength to the output waveguide. The inner ring filter rods in resonant cavity cells helps to filter specific color wavelengths with adjusting the radius of inner rods. The radius of resonant rods is varied to adjust the power coupling through the drop waveguide for each channel. As soon as the radius of the inner filter ring rods

increase, the refractive index in rods increases which tends the central wavelength also shift with 1 nm channel spacing for distinct four resonant cavity. The lattice constants, the refractive index and the radius of rods under different conditions are taken to the optimized simulation, to enable the designed demultiplexer in selecting the appropriate radius of the inner ring filter and resonant rod. The demultiplexer has been designed with four ports to effectively drop the four desired wavelengths.

The square ring resonator with different inner filter ring rod radius has made the channel separation and resonant rod radius; however, the outer rods are remained same as other rods that are placed in the structure. The resonator carrying the resonant rods at the right corner suppresses the counter propagation modes; the coupling efficiency is enhanced with the resonant rods radius and reduces the back reflection loss. The proposed four channel demultiplexer in its three-dimensional view is shown in Fig. 5. As the dimension of the demultiplexer is in order of $17.2 \mu\text{m} \times 26 \mu\text{m}$, which is very tiny and hence it could be easily deployed in the PICs

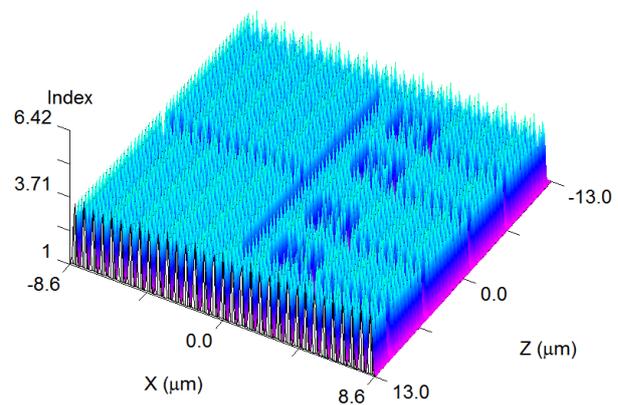


Fig. 5. 3D structure of four channel DWDM demultiplexer.

5. Results and Discussion

The Gaussian light signals launch in the input T shape bus waveguide with the power of 1mW and the output signal is collected at the output drop waveguide. The normalized transmission power of each port is obtained with keeping the power monitor at each port. In a simulation, the time step is very significant to get the accurate result to match with the real time environment. The change in grid sizes in the 'X' and 'Y' directions, are kept as $0.05a=26\text{nm}$, in order to achieve a high 'Q' factor. The condition to be satisfied by the step time as:

$$\Delta t \leq \frac{1}{c \sqrt{\frac{1}{\Delta X^2} + \frac{1}{\Delta Y^2}}} \quad (4)$$

Where Δt - is the step time, and c - is a speed of light in free space. The simulation is carried out using 2D - FDTD method [28], the width of PML and PML reflection for the

design is considered as $0.5 \mu\text{m}$, $1\text{e-}008$ respectively. To get the significant results for DWDM environment $X/20$ ($0.05a = 26 \text{ nm}$) FDTD grid size is being used in the simulation, with the memory of 38.4 MB & for 3600 minutes run time the filter has been simulated with 0.0001 nm increment to get high Q factor output.

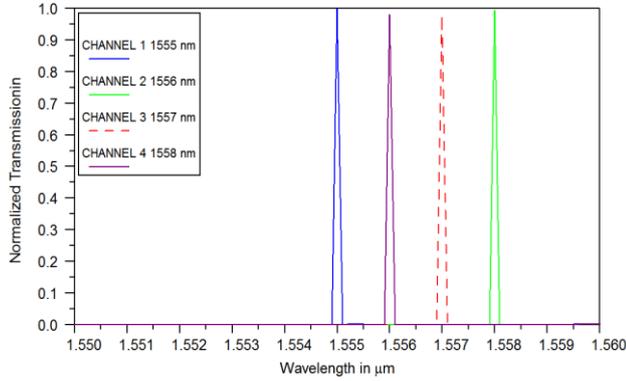


Fig .6 Normalized optical power transmission spectrum of a four channel DWDM demultiplexer.

The normalized optical power transmission spectrum of a four channel DWDM demultiplexer is shown in Fig.6. It is noticed that the channel spacing is 1 nm (1555 nm to 1558 nm), whose corresponding channel bandwidth is 0.2 nm . The output transmission efficiency and the Q factor are observed to be at about 100% and 7800 , respectively. The predominant parameters of the four channels PC based demultiplexer namely the central wavelength, the efficiency of the transmission power; the channel bandwidth and the Q factor are listed in Table 3. The reduced crosstalk defines the resolution, which is a measure of the performance of DWDM demultiplexer. The crosstalk among the channels is being calculated using the optical power transmission spectrum of a four channel DWDM demultiplexer in dB scale as shown in the Fig.7 in dB scale. The objectives and demanding task of any demultiplexer is to obtain a low crosstalk over the range of -27.74 dB to 40 dB . The Z_{uv} denotes the cross talk between the channels, which is much better than the reported demultiplexers in the literature. The crosstalk of the channel numbers are denoted by u and v . For example, Z_{32} gives the crosstalk at the channel 3 due to the channel 2. Subsequent crosstalks between the other channels are listed in Table 4.

Table 3. The summary of various parameter of a four channel PC based DWDM demultiplexer

Drop Channels	Central Wavelength(λ_r) (nm)	Transmission Efficiency	Channel bandwidth $\Delta \lambda_r$ (nm)	Q Factor
λ_1	1555	100 %	0.2 (1.5551-1.5549)	7775
λ_2	1556	99 %	0.2 (1.5561-1.5559)	7780
λ_3	1557	99 %	0.2 (1.5571-1.5569)	7785
λ_4	1558	99 %	0.2 (1.5581-1.5579)	7790

Table 4. Crosstalk values (Z_{uv}) of four channel PC based DWDM demultiplexer (dB).

Channels (Z_{uv})	λ_1	λ_2	λ_3	λ_4
λ_1	NA	-33.43	-39	-27.74
λ_2	-33.33	NA	-41	-34
λ_3	-39.79	-42.5	NA	-37.75
λ_4	-33.34	-33.52	-41.3	NA

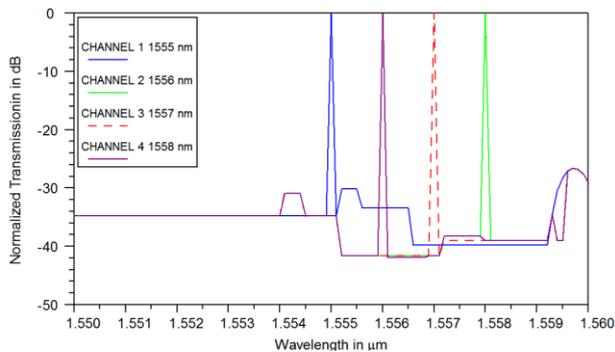


Fig. 7. Normalized optical power transmission spectrum of a four channel DWDM demultiplexer in dB scale.

The individuality of the four port DWDM demultiplexer has been evaluated and the performance parameters are summarized in Table 5. Prima face, the performance of the proposed square resonant cavity based demultiplexer is comparable to the reported results in the literature. Therefore, the functional parameters are deemed better than the others reported, as it has significantly enhanced with the smaller size of the foot print. Nonetheless, one of the salient features in proposed demultiplexer is uniform channel spacing and channel bandwidth for four drop wavelengths. Hence, the proposed demultiplexer can be implemented in the integrated optics.

Table 5. Comparing Square ring resonant cavity based DWDM demultiplexer is compared with variety of DWDM papers.

Authors, Year, Reference no.	No of Output Ports	Coupling Efficiency (%)		Q-Factor		Crosstalk (dB)		Foot Print (μm^2)	Channel Bandwidth (nm)	Channel Spacing
		Min	Max	Min	Max	Min	Max			
Rostami et al. 2009 [19]	4	42.5	86.5	3006	3912.5	-30.00	-14.2	536	0.4	1 nm U.C.S*
M.Djavid et al. 2012 [17]	3	82	91	NA	NA	NA	NA	NA	NA	NA
Mohammad Reza R et al. 2013 [24]	6	80	90	2000	2319	-34	-23	NA	2	3.0 N.U.C.S*
Hamed Alipoureta et al. 2013 [25]	4	45	63	561	1954	-23.70	-7.5	422.4	2.8	3.5 N.U.C.S*
Mohammed Ali M et al. 2013 [15]	3	80	96	390	891	-29	NA	317	3.8	8 nm N.U.C.S*
Abbasgholi et al. 2014 [22]	2	62.61	63.38	5264	7900	-24.59	-19.6	NA	0.3	0.8 nm U.C.S*
Nikhil Deep et al. 2014 [23]	4	40	80	7795	7807	NA	NA	NA	0.2	0.9 nm N.U.C.S
Farhad Mehdizadel et al. 2015 [21]	8	94	98	1723	3842	-40	-27.4	495	1	1.7 N.U.C.S
The work reports by the authors	4	99	100	7775	7790	-40	-27.7	447.2	0.2	1 nm U.C.S*

*U.C.S=Uniform channel spacing for dropped wavelengths

N.U.C.S= Non Uniform channel spacing for dropped wavelengths

6. Conclusion

A four channel demultiplexer comprises of a square resonant cavity based on the photonic crystal in a two-dimensional form has been designed, modeled for DWDM demultiplexer. The change in the inner ring filter rod radius positioned in the square ring resonant cavity, the required wavelengths are dropped and separated. The resonant rod, placed in the cavity, which is responsible for coupling higher transmission efficiency. The 2D FDTD method and Plane Wave Expansion Method simulated gives appreciable results. The spectral response of the proposed device has been obtained with the transmission efficiency close to 100 %, the crosstalk of -40 dB and with the Q-factor of 8000. Further, the uniform channel spacing and the channel band width between the channels are obtained as 1.0 nm and 0.2 nm respectively. The designed PC based demultiplexer, with the size in the order of $447\mu\text{m}^2$ deems fulfilling the requirements of the DWDM system and has been proposed to incorporate in the integrated optics.

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