Digest Journal of Nanomaterials and Biostructures Vol. 11, No. 4, October-December 2016, p. 1125-1134

TWO-DIMENSIONAL PHOTONIC CRYSTAL ASSISTED DWDM DEMULTIPLEXER WITH UNIFORM CHANNEL SPACING

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In this article, we have designed a four-channel Dense Wavelength Division Multiplexing demultiplexer through two-dimensional Photonic Crystal Square Resonant Cavity to fulfill the ITU-T G.694.1 DWDM systems. The DWDM demultiplexer consists of a Bus/Drop waveguide and Microscopic Square Resonant (MSR) cavity. The MSR cavity design has outer rods, inner rods and coupling rods. As the radius of the inner rods in MSR cavity changes, the cavity has the capability to drop different ITU-T G.6941 standard central wavelengths like 1556.5 nm, 1556.7 nm, 1556.9 nm, and 1557.1 nm with 0.2 nm / 25 GHz channel spacing. Since the simulation of various wavelengths help realization of the Q factor of 7785, uniform spectral Bandwidth of 0.2 nm, the transmission efficiency of 100%, the Crosstalk of -42 dB and the small footprint is about 395 μm^2.

(Received August 23, 2016; Accepted October 23, 2016)

Keywords: Photonic Crystals, Demultiplexer, Quality Factor, Spectral Bandwidth, Photonic Band Gap, Crosstalk, Wavelength Division Multiplexing, Finite Difference Time Domain.

1. Introduction

The optical fibers convey information through light, linking the two ends of fiber, which permit communication with a long distance at higher data rates than that present communication network. The Network is extremely costly while every consumer linked through a single fiber of obliges the existing million users due to the existence of millions of fiber and becoming problematical. The result for this problem lies in a single mode fiber concurrently for different customers.

The single mode optical fiber (SMF) use DWDM and WDM measures, used for convey a number of light with discrete wavelengths within the SMF .The transmit of numerous light wavelengths by SMF in the last part of the network uses a optical demultiplexer for dividing the unique resonant wavelengths for each consumer. They are two types of optical demultiplexer devices namely, Active demultiplexers and Passive demultiplexers. The Passive demultiplexer has Frequency Filters [1, 2], Prisms [3] and Diffraction Gratings [4]. On the other hand, the active demultiplexer has a arrangement of passive components and tunable detectors. The present technology limits low normalized optical transmission power, high crosstalk, low Quality factor, and footprint of centimeters, resulting in incapability to use in Photonic Integrated Circuits [PICs].

The PICs reduce the present technology drawback and foot print to micrometer demultiplexer devices. In PICs, Photonic crystals (PCs) decrease the device scale in micrometer/nanometer and the able to manage hundreds of channel in same scale. The PCs jointly with Photonic Band Gap (PBG) have control over the propagation of light [5, 6]. No light with unlike wavelengths can transmit through the PBG region.

The PBGs permit wavelength to transmit by producing defects in the periodic structure. In common, PCs defect created in two ways; point defects and line defects, the line defect is created with elimination or modify in structural-parameters (refractive index, lattice constant, radius of the rods)of the complete row of rods in the propose structure. The point defect is produced with the alteration in the structure parameters of the single rod or elimination of the rod. The designing of PC devices involve with the both the defects in the proposed structure. The PC is utilize for designing a demultiplexer [7] , Optical Switches [8], Beam Splitter [9] , Photonic Sensors [10] , Ring Resonators [11] and etc.

The WDM is classifying into Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM). The CWDM technology provide up to 8 wavelengths by 20 nm channel spacing, but the DWDM technology provide up to 512 wavelengths with 0.1 nm channel spacing. Present now, researchers viewing more towards the DWDM technology due to its unique features. Commonly, DWDM technology accomplish dynamic usage of bandwidth, less attenuation components of SMF; it uses numerous wavelengths as carriers and allow them for concurrent communication in the fiber all together [12], with ability to support up to 256 wavelengths with 0.2nm / 25 GHZ of spectral Bandwidth. The abovementioned features give the solution for troubles experienced by service provider such as high-speed capacity crisis, high flexibility, and long reach. The most important utility of the optical demultiplexer is to split the wavelength for coupling to the individual fibers.

The literature survey bring to reports from the 2D PC based demultiplexer for DWDM and CWDM system using ring resonators defect [13-16] (The shape of the ring resonator in created through introduction of point and line defects) and line defects [22]. In lieu of the fruitful benefits of ITU-T G.694.1 DWDM system, authors deem DWDM system here. The DWDM demultiplexer using 2D PC is finished with T-shape structure with line defects resonant cavity [17], P-shaped single resonant cavity with unlike rod radius to drop dissimilar wavelength [18], multi T-shaped structure with point/line defects [19-21], hetero structure resonant cavity [22] and X loop cavity [23]. The literature survey also identifies the design of demultiplexer via cavity of different shapes. However, the normalized Transmission Efficiency, Crosstalk, Q factor, Uniform Channel Spacing, Uniform Channel Bandwidth do not meet the standard ITU requirements. Hence, in this paper, a new MSR based DWDM demultiplexer is proposed. It has been designed in order to enhance the previously mentioned practical parameters.

In this article, a four-channel DWDM demultiplexer is proposed and designed .The demultiplexer designed using new MSR cavity modeled with inner rods, outer rods, coupling rods. The proposed MSR cavity can drop the desired wavelength by varying the inner rods and coupling rod, though keeping further parameters such as like refractive index, outer rod, lattice constant, non-defected rods are constant. The proposed model MSR cavity has been tailored with square size, which decreases the scattering losses, which, in turn, improve the coupling efficiency. Hence our proposed model places of interest with highlighted features like low crosstalk (> -40 dB), high transmission efficiency (> 98), high Q factor, small footprint, uniform channel spacing and uniform spectral Bandwidth These are not determined in the earlier works. The paper initiates with an analysis of two-cavity demultiplexer analysis and then developed into four-channel DWDM demultiplexer with ITU standard.

This paper has been organized as follows: Section 2, converse the PBG of the proposed structure before introducing the defects. Section 3, propose the two-cavity and four-cavity demultiplexer .The simulations results and discussion are stated in Section 4, Section5 concludes the paper

2. Photonic Crystal Geometry

The proposed DWDM demultiplexer makes use of 2-Dimensional square lattice PC for well parallel confinement of light. The demultiplexer is designed with 31×47 rods in X and Z direction for effective coupling of modes, Zinc Telluride *(ZnTe)* rod for the flexible properties of light confinement with existing photonic crystal. The radius of dielectric rod is $R=115\ nm$, lattice constant $a = 520\ nm$ and a refractive index of rods is 3.56 which is embedded in air.

The theoretical examination of 2DPC for Plane Wave Expansion method (PWE) and Finite Difference Time Domain method (FDTD) is studied. The PWE technique calculates the propagation of modes and the PBG of periodic and non-periodic structures. The propagation modes of electromagnetic waves in photonic crystal analysis satisfies Maxwell's equations [24, 25]

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

Where, $\varepsilon\left(r\right)$ represents the dielectric function, $'\omega'$ the angular frequency, $E(\mathrm{r})$ represents the electric field of periodic structure and 'c' is the speed of the light. Eq. (1) 2D determines the PC band structure. The FDTD method simulates the propagation of electromagnetic waves inside the PCs. [27].

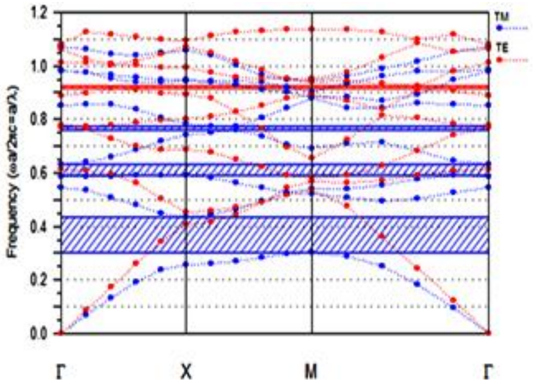

Fig.1.Band diagram for proposed structures before the inducing the defects.

Fig.1. Shows the band diagram with 31×47 PC square lattice structure before inducing the defects. It has three TM PBGs and a TE PBG in band gap diagram as shown in Fig.1. The type of PBG, Normalized frequency and its wavelength range is listed in Table 1.The table, shows first TM PBG wavelength between 1168 nm-1730 nm as meant for low loss communication, since the frequency lies in conventional window of optical communication, which is considered for our work. The entire simulation is carrying out with TM mode where the electric field is perpendicular to the rod axis. The proposed crystal band structure design uses a two/four cavity DWDM filter

Table 1. Photonic band gap, normalized frequency and its actual wavelength

S.NO	PBG	Normalized frequency (a/λ)	Wavelength (nm)
1	TM PBG	0.3-0.445	1168-1730
		0.588-0.6455	805-884
		0.768-0.778	668-677
2	TE PBG	0.923-0.934	556-563

3. PC Based Two/Four Channel Demultiplexer Design

The PC of two/four-channel DWDM demultiplexer for the proposed band gap structure. The Fig.2. shows the schematic structure of two-channel MSR cavity demultiplexer.

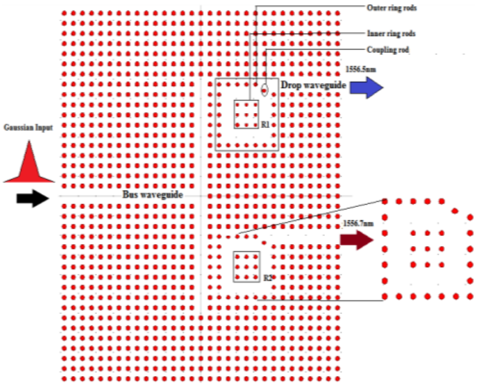

Fig. 2. Proposed MSR based DWDM demultiplexer

The proposed MSR cavity filter consists of outer rods, inner rods, coupling rods and square ring cavity. The square ring cavity is created with the line defects where line/point defects is used for designing a square shape of resonant cavity. In MSR cavity, inner rods positioned within the cavity, rods located external the cavity are outer rods. The coupling rod is positioned at the right turn of the square ring resonator for coupling the signal power from square resonant cavity to drop waveguide.

The T-shape bus waveguide utilizes two channels DWDM filter in the 2D PC crystal. The radius of inner, outer, and coupling rods for proposed demultiplexer is list in Table2.

Table 2. Rod Radius for Inner, Outer, and Coupling Rods

Central Wavelength for drop channel	Outer rod radius	Inner rod radius (Ri; i=1,2)	Coupling Rod radius
λ_1 -1556.5 nm	115 nm	78 nm	98 nm
λ_2 -1556.7 nm	115 nm	78.4 nm	98 nm

The radii of the inner ring rods optimized with 1200 simulations under different conditions, like characteristics of lattice constant, rod radius and refractive index. The Perfect Matched Layer Absorbing Boundary Conditions (PML ABC) is used for reducing the reflection of electromagnetic waves for all the frequencies and angle of incidence. It is originate through Maxwell's equations. The proposed 2D PC crystal utilizes PML ABC for optimizing the edge region without reflection of electromagnetic waves [28, 29].

In the PML ABC structure, absorption rate is higher, contrast to other boundary conditions show high reflections during simulations. The power monitor is placed at the end of the drop waveguide to enable obtaining a normalized transmission spectrum.

Fig.3. shows the normalized transmission output spectra for the two-channel DWDM demultiplexer. The central wavelength, transmission efficiency, and Q factor of the proposed design at are 1556.5nm, 1556.7 nm, 100% and 7782.5, 7783.5, respectively. The Quality factor calculated with Eq.2 [26]

$$Q=\frac{\lambda_r}{\Delta\lambda} \tag{2}$$

Where, λ_r is the central wavelength, $\Delta\lambda$ is the spectral Bandwidth or full width as half-maximum. The spectral Bandwidth is 0.2 nm obtained at the wavelength of 1556.5 nm, sufficient to drop a channel for ITU standard DWDM system. As the demultiplexing function itself utilizes a filter, two-channel demultiplexer/filter has been extended to four channels for dropping four distinct channels.

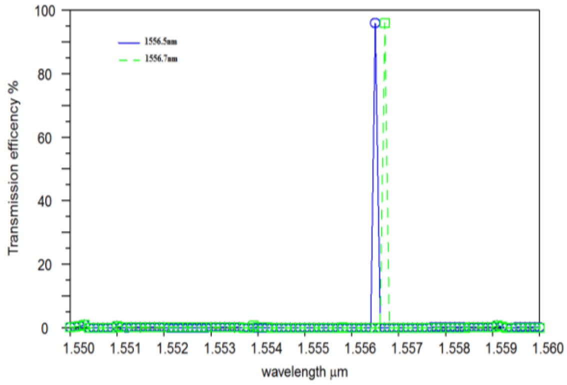

Fig.3. normalized transmission spectrum of the proposed MSR cavity for two channel.

The essential function of the demultiplexer is to drop the desired wavelength for different channels. The demultiplexer extends to a four-channel port as of the two-channel port for dropping four preferred wavelengths. The schematic representation of four port demultiplexer is shown inFig.4**.**The demultiplexer comprise four resonant cavities, by each resonant cavity responsible for dropping the desired wavelengths. The desired wavelengths have been dropped with a reference coupling rod radius and different radii of inner rods for each channel as like a filter. Other parameters such as like outer rod, non-defected rods, lattice constant, and refractive index are constant.

The demultiplexer works with raising the inner rods radius that placed inside the MSR cavity. The dielectric strength of the rod enhance based on the radius of the inner rods. By enhancing, the dielectric strength causes to shift the resonance in higher central wavelength. For dropping the four different wavelength size of the inner rods are *Ri*=78 nm, 78.4 nm, 78.8 nm and 79.2 nm respectively. The designed demultiplexer selects the radii of the inner rods with 1200 optimized simulation under different conditions, like radius of rods, lattice constant, and refractive index.

Table 3 shows the in depth structure parameters for each distinct channel. The channels are optimized to drop the desired wavelength with high Q factor, transmission efficiency, uniform channel spacing, uniform spectral Bandwidth.

For separating the each ports in the demultiplexer, in ports 1 &2 and 3&4 ports split with 4 row of rods. The separation of rods add up between 2 & 3 ports increase more than four row of rods due to curve nature. The nature of the bend curve helps the photons to the desired coupling cavity, which fails when the separating rods are smaller in number. This entry of photons to the 2 and 3 port with a less number rods causes these deviation from the coupling concept theory.

Table 3. Radius of the Outer, Inner and Coupling rods of the proposed demultiplexer.

Channels	Radius of Outer Rods	Radius of Inner Rods (Ri,i=1.4)	Radius of Coupling Rods
λ_1 -1556.5 nm	115 nm	78 nm	98 nm
λ_2 -1556.7 nm	115 nm	78.4 nm	98 nm
λ_3 -1556.9 nm	115 nm	78 .8 nm	98 nm
λ_4 -1557.1 nm	115 nm	79.2 nm	98 nm

The results prove the four-channel DWDM demultiplexer using square ring resonant cavity. It is composed of a T shaped bus waveguide and four MSR cavities where each resonant cavity is responsible for dropping distinct channels. The counter propagation modes are reduced with introduction of the coupling rod at the precise corner of the MSR cavity, which reduces the back reflection, which in turn improve the constructive interference .The result, confirm that the designed demultiplexer with high transmission efficiency, high Q factor, uniform channel spacing, uniform spectral Bandwidth low crosstalk.

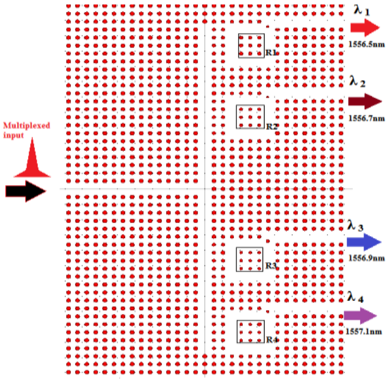

Fig. 4. Schematic structure of proposed four-port DWDM demultiplexer using MSR cavity

The 3D layout of proposed four-channel DWDM demultiplexer is shown in Fig.5.The footprint of the demultiplexer is 16.2 µm × 24.4 µm which is very tiny; Hence it could be easily adapt in PICs.

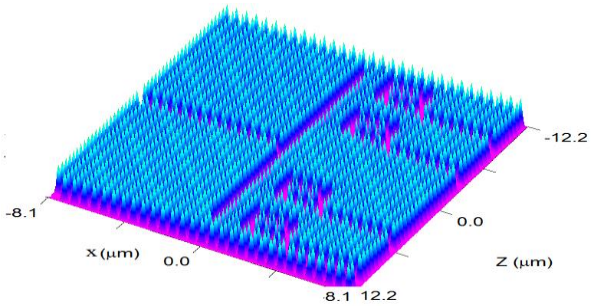

Fig.5.3D layout for proposed four-channel DWDM demultipler.

4. Results and Discussion

The proposed four-channel DWDM demultiplexer utilizes the gaussian pulse source as the input. The pulse source at the input port of the waveguide is in nanometer wavelength, which demultiplexes with resonant cavity to measure the power at each corresponding output port. The simulation perform using FDTD with PML ABC, the width of PML and PML reflection for the design are considered as 500 nm and 10^{-8} respectively. The FDTD grid size in the simulation is maintained at X/20(0.05a=26 nm) to get significant results for the DWDM environment. Maintenance of precise time step during the simulation is significant for getting accurate results. The time step obeys the following condition in the filter

$$\Delta t \leq \frac{1}{c\sqrt{\frac{1}{\Delta X^2}+\frac{1}{\Delta Y^2}}} \tag{3}$$

In Eq. (3), Δt represents the step time, and c represents the speed of light in free space. The filter simulates with increment of 0.0001nm for a 3600 min run time for memory structure of 41.8MB to get high Q factor output.

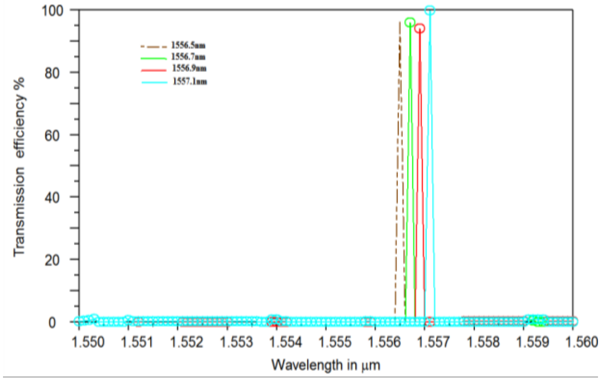

Fig.6.normalized transmission output spectra of four-channel DWDM demultiplexer.

The output transmission spectrum of the proposed four-channel DWDM demultiplexer has been given in Figure.6. The drop wavelengths in this figure attain ITU-T G.694.1 DWDM systems**.** The central wavelengths of the DWDM system is observed at 1556.5 nm, 1556.7 nm, 1556.9 nm, and 1557.1 nm that lie between Conventional band (C-band) of optical window. The C band window is commonly preferred to the consumer due to lossless communications. The simulation shows 100% transmission efficiency, 0.2 nm spectral bandwidth, uniform channel spacing, and Q factor is almost equal to 7790. The results attains the requirements of ITU-T G.694.1 DWDM systems. The central wavelength, spectral bandwidth, transmission efficiency, and Q factor of the proposed demultiplexer is listed in Table 4.

Table 4 Values of Central wavelength and Transmission efficiency, Spectral Bandwidth and Q factor of four channel PC based demultiplexer

Channels	Central Wavelength λ_r (nm)	Transmission Efficiency	Spectral Bandwidth $\Delta\lambda_r$ (nm)	Q Factor
λ_1	1556.5	95 %	0.2 (1.5566-1.5564)	7782.5
λ_2	1556.7	96 %	0.2 (1.5568-1.5566)	7783.5
λ_3	1556.9	94 %	0.2 (1.5570-1.5568)	7784.5
λ_4	1557.1	100 %	0.2 (1.5572-1.5570)	7785.5

The principal challenge in designing demultiplexer is to attain less cross talk. The demultiplexer design is paying attention on improvement of crosstalk with constructive interference design MSR cavity. The transmission spectral response of demultiplexer in dB scale is in Fig.7, and intended for calculation of crosstalk among the neighbour channels (Z_{ij}).Fig.7, shows variant of the crosstalk of the drop channels over the values from -30.25 dB to -42.0 dB, which produces a small crosstalk, evaluate with previous works.

The crosstalk among channels is Z_{ij}, where *i* and *j* indicate the channel numbers. For example P_{23} give the crosstalk among channel 2 and channel 3. The crosstalk between the four channels is list in Table 5.

Table 5.Crosstalk values (Zij) of proposed four-channel DWDM demultiplexer (dB)

Channels(Zij)	λ_1	λ_2	λ_3	λ_4
λ_1	-	-32.17	-33.43	-41.0
λ_2	-30.25	-	-33.10	-38.8
λ_3	-33.0	-33.43	-	-33.33
λ_4	-42.0	-39.11	-33.04	-

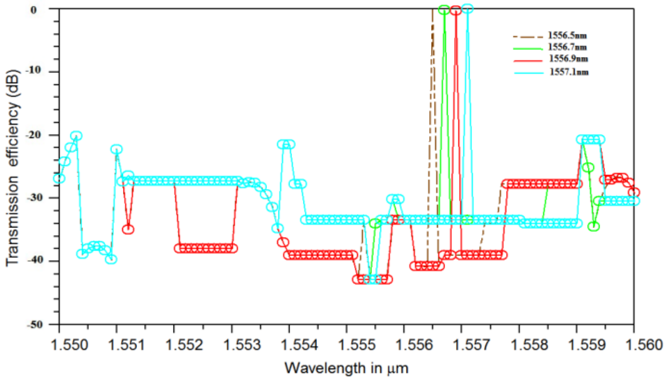

Fig.7. normalized transmission Spectral output for four channel DWDM demultiplexer in dB scale.

The structural parameters of the proposed four channels DWDM demultiplexer is assessed with the reported DWDM demultiplexers, which are displayed in Table 6 .The Table 6, confirm the work of the proposed MSR cavity as better to that of the existing DWDM systems. The simulation of distinct ITU standard wavelengths, which helps achievement of functional parameters such as Q factor of 8000, uniform spectral bandwidth of 0.2 nm, uniform channel spacing 0.2 nm , transmission efficiency of 95% - 98% , crosstalk of -42 dB and the foot print size is about 395 µm^2. The results shows the non uniform spectral bandwidth and channel spacing found in existing work is replaced to the uniform spectral bandwidth and channel spacing for the dropping ITU standard wavelengths The functional parameters are extensively enhanced with smaller footprint ,and hence the proposed DWDM demultiplexer can be adapted in the Photonic Integrated Circuits.

Table 6. The proposed MSR cavity based DWDM demultiplexer is compared with the reported DWDM demultiplexer

Authors/Year	No of Output Ports	Coupling Efficiency (%)		Q Factor		Crosstalk(dB)		Foot Print (µm)^2	Spectral Bandwidth (nm)
		Min	Max	Min	Max	Min	Max		
Rostami et al. [17]/2009	4	42.5	86.5	3006	3912.5	-30.00	-14.2	536	0.4 N.U.SL
M.Djavid et al.[15]/2012	3	82	91	NA	NA	NA	NA	NA	NA
Mohammad reza rakhnshani [22]/2013	6	80	90	2000	2319	-34	-23	NA	2 N.U.SL
Hamed Alipoureta et.al [23]/2013	4	45	63	561	1954	-23.70	-7.5	422.4	2.8 N.U.SL
Mohammed ali Mansouri et al.[13]/2013	3	80	96	390	891	-29	NA	317	3.8 N.U.SL
Abbasgholi et al.[20][2014]	2	62.61	63.38	5264	7900	-24.59	-19.6	NA	0.2 N.U.SL
Nikhil Deep et al.[21]/2014	4	40	60	7795	7807	NA	NA	NA	0.2 U.SL
Farhad Mehdizadel [29]/2015	8	94	98	1723	3842	-40	-11.2	495	1 N.U.SL
This work	4	95	100	7782.5	7785.5	-42.0	-30.25	395	0.2 U.SL

U.SL: Uniform spectral Bandwidth
N.U.SL: Non-uniform spectral Bandwidth

5. Conclusions

The proposed four-channel DWDM demultiplexer with two-dimensional Photonic Crystal MSR cavity fulfills the ITU-T recommendation of G.694.1 DWDM systems. The innovation in the proposed DWDM system is the dropping the desired wavelength by increasing the radius of the inner rods, and which is located in the MSR cavity. The transmission spectral response of the designed DWDM carries out about 98% of the transmission efficiency, -42dB crosstalk with the Q factor of 7790. Further, the uniform channel spacing, and spectral Bandwidth between the channels are 25 GHz and 0.2 nm, respectively. The proposed PC based DWDM demultiplexer is excellent in fulfilling the requirements of ITU-T G.694.1 DWDM system and size is very small about 395 µm^2, it could be incorporate for integrated optics. From the results, the reported DWDM system with non-uniform spectral bandwidth for drop wavelengths replace to the uniform spectral bandwidth. The crosstalk of the proposed DWDM demultiplexer with about -42 dB deemed better than the previous works presented in the literature.

Acknowledgements

The author Balaji would like acknowledge Dr.N.R.Shanker, Manager, Research and Development, Chase Technologies, Chennai for his support at different times.

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