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DESIGN OF TWO DIMENSIONAL PHOTONIC CRYSTAL RING RESONATOR BASED DEMULTIPLEXER

R. Masilamani[1] and S. Robinson[2]
Department of Electronics and Communication Engineering, Mount Zion College of Engineering and Technology, India
Email: [1]masila.1991@gmail.com, [2]mail2robinson@gmail.com

Abstract

In this paper, a Photonic Crystal Ring Resonator (PCRR) based demultiplexer is proposed and designed to drop four different channels. The proposed structure is consists of bus waveguide, dropping waveguide and butterfly shaped ring resonator. The demultiplexer performance parameters such as transmission efficiency, dropping efficiency, crosstalk, quality factor and resonant wavelength are investigated for each channel. Initially, the channel drop filter using proposed PCRR is carried out and its extended to drop four different channels by changing the refractive index of each channels that acts as demultiplexer. The designed structure can able to drop four different channels which are 1425 nm, 1445 nm, 1460 nm and 1475 nm. The Plane Wave Expansion (PWE) method is employed to get photonic band gap of the periodic and non-periodic structure. The 2D Finite Difference Time Domain (FDTD) method is utilized to calculate the normalized output spectra of the demultiplexer. The proposed butterfly shaped photonic crystal ring resonator is fulfilling the requirements of WDM systems hence it is highly suitable for WDM applications and Photonic Integrated Circuits.

Keywords:

Demultiplexer, FDTD Method, Photonic Band Gap, PWE Method, Ring Resonator

1. INTRODUCTION

In the growth of worldwide communications, Fiber Optic plays a vital role and it enables the use of Internet. In earliest technology, Researchers have designed the devices in the range of centimeter and millimeter. The most prominent and recent technology of designing the Demultiplexer (DEMUX) is using of Photonic Crystals in the range of nanometer. Typically Photonic Crystal (PC) [1-3] is a periodic structure that contain low and high dielectric constant that affect the propagation of electromagnetic waves (EM) inside the structure while propagating. Photonic crystals are classified into three types according to its periodicity in refractive index such as one dimensional photonic crystal (1DPC), two dimensional photonic crystal (2DPC), and three dimensional photonic crystals (3DPC) [2].

Two Dimensional Photonic Crystals (2DPC) are receiving much attention from the research and scientific community in designing the optical devices as they have attractive features including better confinement of light, efficient PBG calculation, effective control of spontaneous emission, relatively simple fabrication than 3DPCs and easy integration with other devices. In 2DPCs, the devices can be realized through square lattice or triangular lattice and the lattice may be in the form of dielectric rods in air host (rod type) or air holes in a dielectric region (hole type). Even though the triangular lattice offers wider band gap than square lattice, the square lattice PC based devices provides effective confinement of light, easy control of the propagation modes and the fabrication of this structure would be easier because of simple geometry. In addition, the rod type PCs have several advantages than holes type PCs such as low value for out of plane and propagation losses, easy fabrication, compatible with classical PICs, and effective single mode operation [1]-[3].

The Wavelengths that are allowed to travel are known as modes; the group of allowed modes called bands [4]. The group of disallowed bands of wavelength is called as Photonic Band Gaps (PBG) [5]-[8] and there is no mode propagation in band gap region. By introducing point and line defects inside the photonic crystal we can entirely broken the band gap region and to allow the electromagnetic waves. The components used in fiber optic communication systems are enormous, such as Add drop filter [9, 10], Amplifiers, Multiplexers [11], Demultiplexer [12]-[18], Switches, Isolators, etc. Generally, Photonic Crystal (PC) based optical devices have attracted great interest due to their compactness, speed of operation, long life and suitability for Photonic Integrated Circuits[19] (PIC). One of the most promising designs for DEMUX is ring resonator [20]-[26] which are received great attention in research community, as it offers high spectral selectivity, scalability, narrow channel spacing, efficient wavelength selection, and wide free spectral range.

Demultiplexer is a device that is used to separates one signal into several stream of signal and it’s mostly used in telecommunication to carry the signal over the long distance, WDM applications [27] and cable television networks. There are several attempts are made to design and realize the demultiplexer for real time applications. The photonic crystal based demultiplexer is generally designed by using defects [12]-[18] and ring resonator [20]-[26]. The PCRR based demultiplexer is done by using square ring resonator [20-21], hexagonal ring resonator [22]-[23], quasi square ring resonator [24], diamond shaped ring resonator [25], X shaped ring resonator [26].The reported demultiplexers are larger in size which could not able to incorporate in photonic integrated circuits. Hence, in this paper, PCRR based demultiplexer and it characteristic are reported as photonic crystal is one of the right platform for device miniaturization. In this paper, four port demultiplexer using butterfly shaped Photonic Crystal Ring Resonator is proposed and designed whose corresponding parameters namely, transmission efficiency, dropping efficiency, quality factor and resonant wavelength are evaluated. Primarily, the channel drop filter is designed using proposed PCRR and it is extended for demultiplexer by having three different refractive index in a structure. The PWE [28] method is a popular method used to calculate the band gap of the structure which is used for calculating the PBG without introducing any defects. The normalized transmission spectra and resonance of the Demultiplexer is arrived by using FDTD [29] method.

The paper is arranged as follows: In section 2, the numerical analysis methods namely FDTD method and PWE method are discussed. The design of PCRR based demultiplexer and its PBG diagram is presented in section 3. The structural design and simulation results of proposed structure are discussed in section 4 and the extended version of the proposed structure is utilized for four port demultiplexers which are discussed in section 5 and section 6 concludes the paper.

2. NUMERICAL ANALYSIS

In order to analyze the dispersion behavior and the transmission spectra of PCs, PWE and FDTD methods are used. The PWE method is useful for analyzing the PC structures that can be expressed as a superposition of a set of plane waves. Although this method can obtain an accurate solution for the dispersion properties (propagation modes and band gap) of a PC structure, an alternative approach which has been widely adopted to calculate both transmission spectra and field distribution is based on numerical solutions of Maxwell's equation by using FDTD is used to calculate the spectrum of the power transmission. The Maxwell's Equations are useful for analyzing the propagation of electromagnetic waves in a Photonic crystal. It is assumed that the material is linear, isotropic, periodic with lattice vector and lossless; therefore, the Maxwell's equation has the following form [28]-[29].

$$\frac{\partial H}{\partial t} = \frac{1}{\mu}\nabla \times E \tag{1}$$

$$\frac{\partial E}{\partial t} = \frac{1}{\varepsilon}\nabla \times H \tag{2}$$

2.1 PWE METHOD

The band diagram calculations of electric field are carried out by solving Maxwell's equation which is

$$\nabla \times \left(\frac{1}{\varepsilon(r)}\nabla \times E(r)\right) = \frac{\omega^2}{c^2}E(r) \tag{3}$$

where 'c' is the speed of light, 'ω' is the angular frequency, $\varepsilon(r)$ is the dielectric constant (relative permittivity) and $E(r)$ is the electric field of the periodic function. The above equation describes the propagation of light in Photonic crystals and it is a consequence of the Bloch-Floquet theorem which signifies that the electromagnetic waves in the periodic media can propagate without scattering and their behavior governed by a periodic function modulated by a plane wave (the product of plane wave and periodic function with lattice period).Because of the periodic 2DPC, the dielectric constant, ε can be described as [28]

$$\varepsilon(r) = \varepsilon(r+R) \tag{4}$$

where R is the vector of the 2D lattice. Bolch-Floquet theorem provides the solutions for periodic Eigen problem that can take the form

$$H_k(r) = e^{ikr}u_k(r) \tag{5}$$

$$(ik+\nabla)\times\frac{1}{\varepsilon(r)}(ik+\nabla)\times u_k(r) = \frac{\omega(k)^2}{c^2}u_k(r) \tag{6}$$

where $u_k(r)$ is the periodic function of lattice that is

For a given Bloch vector k, the Eigen value Eq.(5) is discredited into a plane wave basis to yield an algebraic Eigen value problem. It is solved for the permissible frequencies ω of the modes, which in turn, are characterized by the Eigenvectors. By scanning k over the Brillouin zone, the band diagram is generated.

2.2 FDTD METHOD

The FDTD method is useful for analyzing the transmission spectrum while performing the simulation. The equations are:

$$E_x\Big|_{i,j}^{n+1} = E_x\Big|_{i,j}^{n} + \frac{c\Delta t}{\varepsilon_0}\left[\frac{H_z\Big|_{i,j+1/2}^{n+1/2} - H_z\Big|_{i,j-1/2}^{n+1/2}}{\Delta_y}\right] \tag{7}$$

$$E_y\Big|_{i,j}^{n+1} = E_y\Big|_{i,j}^{n} - \frac{c\Delta t}{\varepsilon_0}\left[\frac{H_z\Big|_{i+1/2,j}^{n+1/2} - H_z\Big|_{i-1/2,j}^{n+1/2}}{\Delta_x}\right] \tag{8}$$

$$H_z\Big|_{i,j}^{n+1/2} = E_z\Big|_{i,j}^{n-1/2} + \frac{c\Delta t}{\mu_0}\left(\frac{E_x\Big|_{i,j+1/2}^{n} - E_x\Big|_{i,j-1/2}^{n}}{\Delta_y}\right) - \left(\frac{E_y\Big|_{i+1/2,j}^{n} - E_y\Big|_{i+1/2,j}^{n}}{\Delta_x}\right) \tag{9}$$

where the index 'n' denotes the discrete time step, indices 'i' and 'j' denote the discretized grid point in the X-Y plane. In order to produce an accurate simulation, the spatial grid must be small enough to resolve the smallest feature of the field to be simulated. To obtain a stable simulation, one must satisfies the following condition which relates the spatial and temporal step size [29].

$$\Delta t \le \frac{1}{c\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}}} \tag{10}$$

where 'c' is the speed of the light. A broadband Gaussian pulse is launched into input port. Then we placed a time monitor (detector) inside each waveguide channel to measure the time varying electric field. The time monitor is used to record the power flow along the Z direction as the function of time. The output power is calculated at each port by integrating the power over the cells of the output ports as shown in Eq.(9). Then stored data is Fourier transformed and integrated. Finally, the ratio is taken between obtained integrated results to incident spectra which results in transmission spectra versus wavelength. The output signal power is

$$P(t)=\frac{\mathrm{Re}\left[\int_A \left[E(t)\times H^{*}(t)\right]dA\right]}{\mathrm{Re}\left[\int_A \left[E(t_0)\times H^{*}(t_0)\right]dA\right]} \qquad (11)$$

where ‘E’ and ‘H’ are the electric and magnetic fields, and ‘A’ is the plane located within the domain of the time monitor. The length of the time monitor has no effect for a power as the integral is taken over the plane defined by the X` and Z` axis.

3. STRUCTURAL DESIGN

In the proposed structure of four channels Demultiplexer consists of square lattice with circular rods placed in a background of air. In square lattice, the number of rods in ‘X’ and ‘Z’ direction of 52 × 21. The distance between the two is 540nm which is termed as lattice constant and denoted by ‘a’. The si rods of the radius is 0.1μm .The band diagram of Photonic crystal structure at Δ = 2.4 shown in Fig.1 and corresponding Brillouin zone is obtained also shown in Fig.2. The Brillouin zone is the small repeating space in the periodic structure; hence the band diagram of single zone is equal to the whole zone .The band gap diagram shown in Fig.1, has PBG for transverse electric (TE) modes whose electric field is parallel to the rod axis .The PBG for the range from $0.3a/\lambda$ to $0.44a/\lambda$ whose corresponding wavelengths range from 1227nm to 1800nm, where ‘a’ is a lattice constant, ‘λ’ is a wavelength.

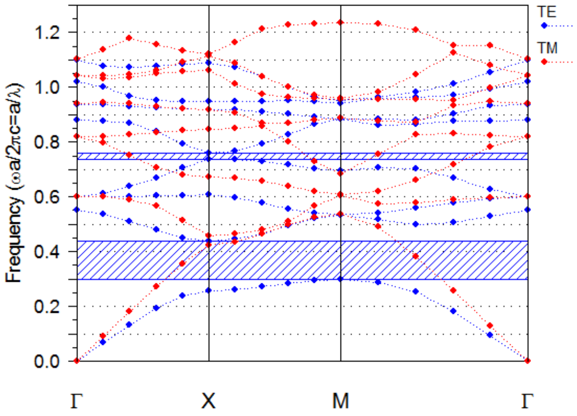


Fig.1. Band diagram of PC structure at Δ = 2.4

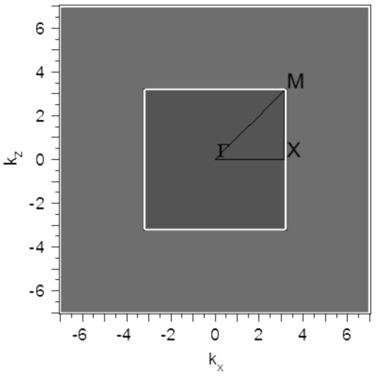
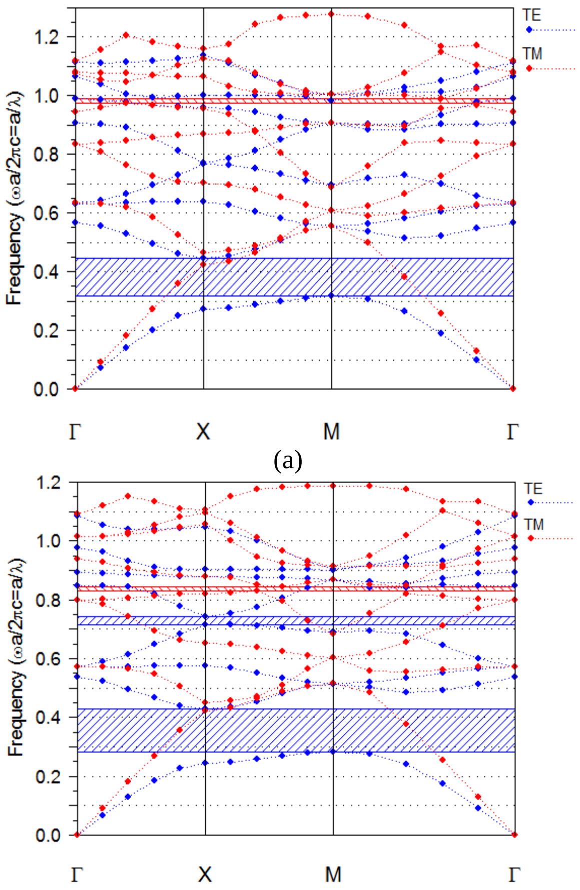


Fig.2. Brillouin zone and k path of 52 × 21 PC structure



(a)

(b)

Fig.3. Band diagram of PC structure at (a) Δ = 2.2 (b) Δ = 2.6

Table.1. Photonic bandgap, frequency range and wavelength range of proposed structure for different delta values

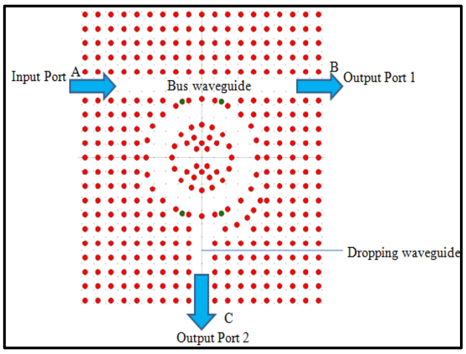
Refractive Index difference	**Photonic Band Gap**	**Frequency Range**	**Wavelength (nm)**
2.2	TE	0.45-0.32	1200nm-1687nm
	TM	0.991-0.975	544nm-553nm
2.4	TE	0.44-0.3	1227nm-1800nm
	TE	0.758-0.739	712nm-730nm
2.6	TE	0.43-0.28	1255nm-1928nm
	TE	0.743-0.715	726nm-755nm
	TM	0.84-0.83	642nm-650nm

When the defects (point and line) are created in the structure, the band gap is broken and to allow an electromagnetic waves inside the photonic Band gap region which is essential for complete signal transfer from the bus waveguide to drop wave guide through the ring resonator at resonant wavelength. The effect of PBG range when the delta value is 2.2 and 2.6 is shown in Fig.3(a) and Fig.3(b), respectively, whose corresponding normalized frequency and its wavelength range are listed in Table 1. From the table, it is noticed that completed PBG lies over the range between 1255nm-1687nm. Hence it’s considered for designing PCRR based Demultiplexer.

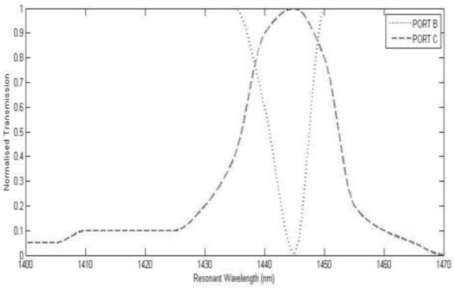
4. PHOTONIC CRYSTAL RING RESONATOR

In general, the resonators are located between two optical wave guides. The proposed structure consists of 21 × 19 square lattices with circular rod in Fig.4(a).The Butterfly shaped PCRR is designed inside the ring resonator by removing the inner rods. The butterfly shaped PCRR is formed by varying the position of inner rods and outer rods from their original position towards the center of the origin in both ‘X’ and ‘Z’ directions. To avoid the backward propagation, the scatter rods are placed at each corner of the four sides with half lattice constant .It enhances the coupling efficiency also. The port ‘A’ is a ‘input port’, while port ‘B’ is a ‘output port, while port ‘C’ is defined as ‘resonating output’.

At resonance, the wavelength is coupled into the ring resonator from the bus waveguide and exists through the output port ‘C’. The coupling and dropping efficiencies are detected by monitoring the power at ports ‘B’ and ‘C’, respectively. A Gaussian pulse is applied as input at port ‘A’ and the normalized transmission power spectrum is obtained at port ‘B’ and ‘C’. The simulation output is obtained using FDTD method. Fig.4(b) Shows that normalized transmission spectra of PCRR. The resonant wavelength of the proposed structure is obtained at 1445nm. The coupling efficiency and dropping efficiency of the proposed filter is about 100% which could be easily utilized for any applications.

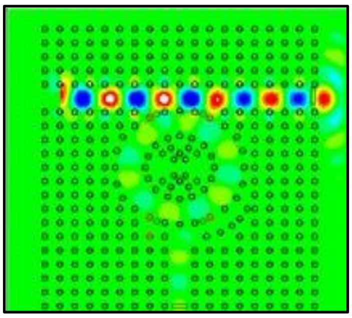


(a)

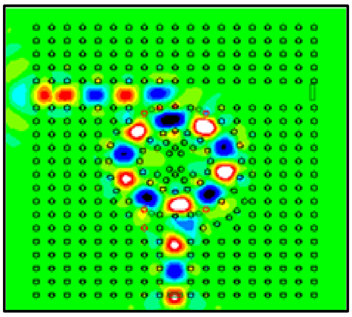


(b)

Fig.4. (a) Schematic structure and (b) normalized output spectra of Butterfly shaped Photonic crystal ring resonator



(a)



(b)

Fig.5. Electric field distribution of 2D butterfly shaped PCRR (a) at 1400 nm (OFF Resonance) (b)1445 nm (ON Resonance)

The Fig.5(a) represents the electric field pattern of butterfly shaped PCRR at ‘OFF’ resonance ie. 1400nm. At resonant wavelength λ = 1445nm the electric field at the bus waveguide is fully coupled into the ring and reached the output port 2 as shown in Fig.5(b). Further, it is also investigated that the resonant wavelength and other functional parameters of the filter will be shifted to longer wavelength while increasing the refractive index and vice versa. By utilizing the aforementioned principle the proposed structure is extended for demultiplexing applications which is discussed in the next section.

5. PHOTONIC CRYSTAL RING RESONATOR BASED DEMULTIPLEXER

The proposed structure is extended for demultiplexing application by increasing the total number of rods and by having three different refractive index in a structure. Typically, the resonant wavelength of the structure is altered by changing the lattice constant, radius of the rod and refractive index. While considering the lattice constant and radius of the rod, the resonant wavelength is shifted to longer wavelength when the parameter values are increased; however, the performance parameters are diminished. Hence, refractive index is considered to drop different channels as the loss is lower while dropping different wavelength using different refractive index. The refractive index of the rod is increased by enhancing the material density; hence the size of the rod and waveguide remains uniform.

The proposed demultiplexer consists of 52 × 21 square lattices with circular rod in as shown in Fig.6. As the designated wavelength is dropped by having distinct refractive index, the refractive index of the structure is varied. The first PCRR is having the index difference of 2.2, the second one is having 2.4 and the third one is having 2.6. Four channels butterfly shaped Demultiplexer is designed inside the ring resonator by removing the inner rods. The top of the waveguide is called as bus waveguide and bottom of the wave guide is called as dropping waveguide. The bus and dropping waveguides are formed by introducing line defects whereas butterfly shaped Demultiplexer inside the ring resonator is formed by introducing point defects.

The butterfly shaped PCRR is formed by varying the position of inner rods and outer rods from their original position towards the center of the origin in both X and Z directions. To avoid the backward propagation, the scatter rods are placed at each corner of the four sides with half lattice constant .It enhances the coupling efficiency also. In the proposed structure consists of four output ports which are called as four channels Demultiplexer. The port 'A' is a 'input port', while port 'B' is a 'output port, while port 'C' ,'D' and 'E' are defined as 'resonating output'.

As the change in refractive index will change the resonant wavelength, the different resonant wavelength is dropped at its designated port. At resonance, the wavelength is coupled into the ring resonator from the bus waveguide and exists through any one of the output port 3, 4 and 5. The coupling and dropping efficiencies are detected by monitoring the power at ports 'B', 'C', 'D' and 'E' respectively.

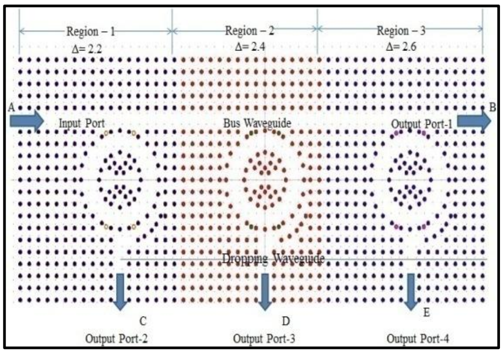


Fig.6. Schematic diagram of Photonic crystal ring resonator based Demultiplexer

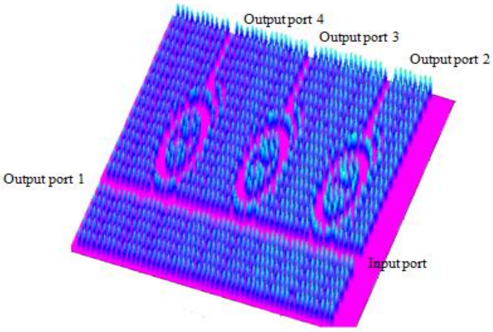


Fig.7. Schematic diagram of 3D view of Photonic crystal ring resonator based Demultiplexer

A Gaussian pulse is applied as input at port 'A'. The normalized transmission power spectrum is obtained at port 'B', 'C', 'D' and 'E' respectively. The simulation output is obtained using FDTD method. The input and output signal power is recorded through power monitor by placing them at port B, C, D and E. The normalized transmission is calculated through the following formula.

$$T(f) = \frac{1/2 \int \mathrm{real}\left(p(f)^{\mathrm{monitor}}\right) ds}{\text{Source Power}}$$

where, $T(f)$ is normalized transmission which is a function of frequency, $p(f)$ is a pointing vector and ds is the surface normal.

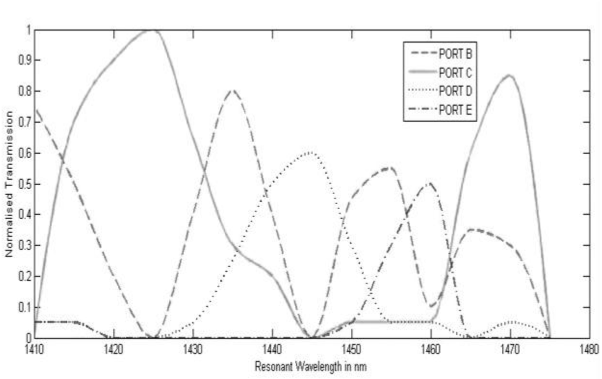
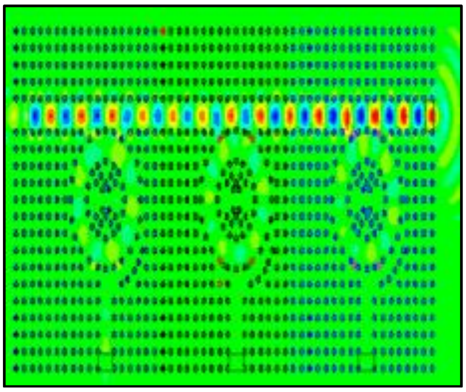


Fig.8. Optical transmission spectra of Butterfly shaped PCRR based Demultiplexer

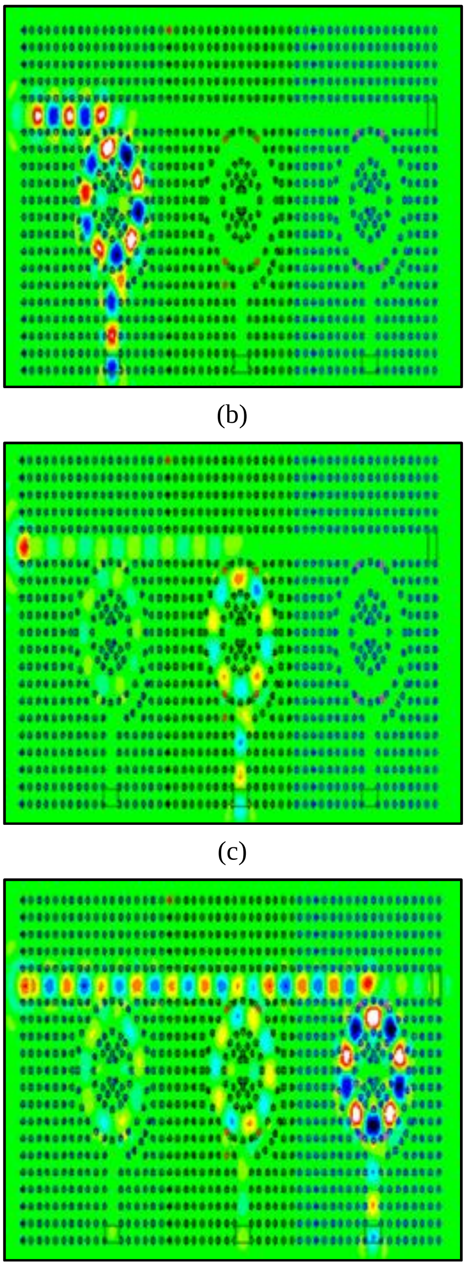
The Fig.8 shows that normalized transmission spectra of proposed four port demultiplexer. The resonant wavelength of channel I and channel II and Channel III are1425nm, 1445nm and 1460 nm, respectively and other functional parameters such as quality factor, transmission and dropping efficiencies are tabulated in Table.2.

Table.2. Transmission efficiency, dropping efficiency and Quality factor of butterfly shaped PCRR based Demultipexer

Resonant Wavelength (nm)	**Q-factor**	**Transmission Efficiency**	**Dropping Efficiency**
1425	71.25	100	100
1445	120.41	60	100
1460	365	50	90



(a)



(b)

(c)

(d)

Fig.9. Electric field Pattern of (a) at 1400nm (b) at 1425nm (c) at 1445nm (d) at 1460nm

The Fig.9(a) represent the electric field pattern of butterfly shaped Demultiplexer at OFF resonance at 1400nm and the electric field pattern at ON resonance for three different channels are shown in Fig.9(b), Fig.9(c) and Fig.9(d), respectively. At OFF resonance the input signal is directly reached output port without coupling the ring resonator, however, at ON resonance the input signal is coupled into the ring resonator and reached it respective output port.

6. CONCLUSION

Two dimensional photonic crystal ring resonator based filter is proposed and designed which is also extended for demultiplexing applications. The coupling efficiency, dropping efficiency and resonant wavelength of the designed filter is about 100%, 100% and 1445nm, respectively. The four port demultiplexer is designed using the proposed ring resonator where the designated output channel is dropped at its port. The size of the demulitplexer is very small (11.4µm × 30.4µm), Hence, such kinds of devices could be used for Photonic Integrated Circuits.

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