



RESEARCH ARTICLE

DESIGN AND ANALYSIS OF PHOTONIC CRYSTAL RING RESONATOR BASED 2-CHANNEL DEMULTIPLEXER FOR CWDM APPLICATIONS.

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Abstract

In this paper, the design and performance of two dimensional (2-D) photonic crystal (PhC) coarse wavelength division (de)multiplexer is investigated using finite difference time domain (FDTD) method. The photonic band gap (PBG) is calculated by plane wave expansion (PWE) method. The proposed design provides two de-multiplexed central wavelengths one at 1551nm and another at 1591nm which belong to the most popular ITU-T G.694.2 CWDM grid wavelengths range in optical communication system. The calculated quality factors for the two wavelengths 1551nm and 1591nm are around 346 and 272 respectively. The de-multiplexer is designed by two dimensional photonic crystals having 40×35 dielectric rods of dielectric constant 3.49 suspended in the air background. This de-multiplexer may be used as a key component in optical integrated circuits and optical network applications. The device is ultra-compact with overall size of the wafer around $24 \mu\text{m} \times 21 \mu\text{m}$.

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Introduction:-

Photonic crystals (PhC) are composed of periodic dielectric nanostructures that affect the propagation of electromagnetic (EM) waves. These crystals are analogous to semiconductors, as they allow the control of photons as semiconductors do for the electrons. Based upon the variation of refractive index in one, two and three dimensions, these crystals are classified as one dimensional, two dimensional and three dimensional photonic crystals. The photonic crystals possesses photonic band gap (PBG) where the propagation of light is completely prohibited in certain frequency ranges [1]. In particular, we can design and construct photonic crystals with photonic band gap, preventing the light from propagation in certain directions with specified frequencies and allows propagation in anomalous and useful ways [1]. When point defect or line defect or both are introduced in these structures then the periodicity of the band gap is broken and the propagation of light can be localized at these defect regions. Researchers all around the world have reported many PhC based devices like multiplexers [2], de-multiplexers [3], add-drop filters [4], mach-zehnder interferometer [5], power splitters [6], band-pass filters [7], optical switches [8], optical interleavers [9] etc.

Optical de-multiplexer is the device to separate channels in the communication system and deliver them to appropriate user. Coarse wavelength division multiplexing (CWDM) and dense wavelength division multiplexing (DWDM) are the WDM technologies where CWDM is characterized by wider channel spacing.

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There are 18 central wavelengths as per the ITU-T G.694.2 CWDM grid, ranging from 1271nm to 1611nm with channel spacing of 20nm. Several designs of de-multiplexers have been reported so far. In 2013, S. Bouamami et al. [10] proposed a compact WDM de-multiplexer for seven channels in photonic crystal. They realized the filtering of wavelength channels by shifting the cutoff frequency of the fundamental photonic bandgap mode in consecutive sections of the waveguide. The shift is realized by modifying the size of the border holes. In 2013, a novel 4-channel de-multiplexer based on photonic crystal ring resonators was proposed by Hamed Alipour-Banaei et al. [11]. They introduced four scattering rods above and under the X-shaped ring resonators in the proposed structure for improving wavelength selectivity. They achieved minimum and maximum crosstalk of -23.7dB and -7.5dB respectively between channels. Hadi Ghorbanpour et al. [12] proposed 2-channel all optical de-multiplexer based on photonic crystal ring resonator, in the same year. In their design the output channels were respectively at 1590.8 and 1593.8 nm, correspondingly had the quality factors of 7954 and 3984, the cross talk values of -22 and -11dB separately. All these researchers used the FDTD based softwares for simulation and analysis. In our proposed design we have also utilized the FDTD method and we used OptiFDTD simulation software of Optiwave System Inc. for design, simulation and analysis using official license. The two CWDM wavelengths obtained from this de-multiplexer are 1551nm and 1591nm spaced 40nm apart. The proposed wavelength de-multiplexer is designed by using wavelength-selective filtering structures.

DESIGN PARAMETERS:-

The proposed design of de-multiplexer in this paper provides two de-multiplexed wavelengths one at 1551nm and another one at 1591nm. Here, in this design the number of dielectric rods in z direction and in x directions are 40 and 35 respectively. These rods are surrounded by air host (refractive index=1). The refractive index of rods is 3.49 (Permittivity $\epsilon_r = 12.1801$). Thus there is high index contrast ratio between rods and air. The radius of dielectric rods is $r = 0.2 \cdot a \mu\text{m}$, where 'a' is lattice constant which is equal to 595nm. The wafer dimension is around $41a \mu\text{m} \times 36a \mu\text{m}$.

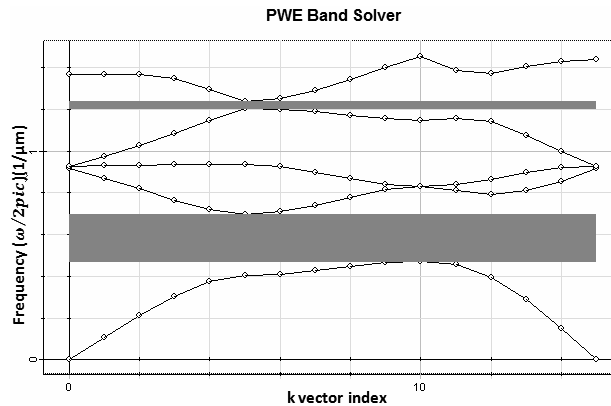


Figure 1:- Photonic band gap diagram of photonic crystal of square lattice with rods of dielectric constant 12.1801 surrounded by air for TE mode (without introducing any defect) obtained by PWE method. The shaded area shows the band gap.

The Photonic band gap (PBG) is calculated by PWE method [13-15]. PWE method uses an Eigen formulation of Maxwell's equation. Shangpine Guo et al. have summarized the plane wave method [15]. Accordingly, Maxwell's equations in a transparent, source free, time-invariant and non-permeable ($\mu = \mu_0$) space can be written as Helmholtz's equation:

$$\vec{\nabla} \times \frac{1}{\epsilon(r)} \vec{\nabla} \times \vec{H}(r) = \frac{\omega^2}{c^2} \vec{H}(r) \quad (1)$$

Where $\epsilon(r)$ the dielectric function, ω is the angular frequency and c is the speed of light in vacuum. This equation is sometimes referred as master equation. This equation represents a Hermitian Eigen problem. Using Bloch's theorem, in an infinite periodic photonic crystal, a mode in a periodic structure can be expanded as a sum of infinite number of plane waves:

$$\vec{H}(\vec{r}) = \sum_{\vec{G}, \lambda} h_{G, \lambda} \hat{e}_{\lambda} e^{i(\vec{k} + \vec{G}) \cdot \vec{r}} \quad (2)$$

Here, $\lambda=1, 2$, \vec{k} is the wave vector of the plane wave, \hat{e}_{λ} represents the two unit axis perpendicular to the propagation direction $\vec{k} + \vec{G}$. $(\hat{e}_1, \hat{e}_2, \vec{k} + \vec{G})$ are perpendicular to each other, \vec{G} is the reciprocal lattice vector. $h_{G, \lambda}$ is the coefficient of the H component along the axes \hat{e}_{λ} . The final Helmholtz's equation, transformed to an algebraic form [15, 16] is:

$$\sum_{\vec{G}'} |\vec{k} + \vec{G}'| |\vec{k} + \vec{G}| \varepsilon^{-1}(\vec{G} + \vec{G}') \begin{bmatrix} \hat{e}_2 \cdot \hat{e}_2 & -\hat{e}_2 \cdot \hat{e}_1 \\ -\hat{e}_1 \cdot \hat{e}_2 & \hat{e}_1 \cdot \hat{e}_1 \end{bmatrix} \begin{bmatrix} h_{1, G'} \\ h_{2, G'} \end{bmatrix} = \frac{\omega^2}{c^2} \begin{bmatrix} h_{1, G} \\ h_{2, G} \end{bmatrix} \quad (3)$$

Equation 3 is standard Eigenvalue problem and it can be solved using a standard Eigen-solver. The proposed de-multiplexer is based on two dimensional photonic crystals therefore equation 3 can be simplified accordingly.

Finite difference time domain method has been utilized in this paper to observe the response of proposed de-multiplexer. The FDTD method was introduced by Yee in 1966 [17]. This method involves the discretization of Maxwell's electromagnetic equation in time and space [18]. In order to simulate the infinite structures in a finite computational domain, the Bloch boundary condition, which is defined by:

$$\vec{E}(\vec{R} + \vec{r}) = \vec{E}(\vec{r}) e^{i(\vec{k} \cdot \vec{R})} \quad \text{and,}$$

$$\vec{H}(\vec{R} + \vec{r}) = \vec{H}(\vec{r}) e^{i(\vec{k} \cdot \vec{R})}$$

Where, $i = \sqrt{-1}$, \vec{R} is the lattice vector of unit cell, \vec{r} is the position vector, and \vec{E}, \vec{H} are the electric and magnetic field component vectors characterized by \vec{k} wave vector in the reduced Brillouin zone, are applied to the computational boundary of the unit cell. A. Taflov et al. has given the standard FDTD algorithm [19] for this purpose.

Figure 1 shows photonic band gap of photonic crystal structure having dielectric constant 12.1801 without introducing any defects for TE mode which lie between $0.471161(1/\lambda) \sim 0.698333(1/\lambda)$ and $1.20221(1/\lambda) \sim 1.23593(1/\lambda)$. A minor photonic band gap is also obtained for TM mode. Therefore, all the simulation and analysis is done for the TE mode.

Defects in photonic crystals are introduced to guide or localize light. While photons with energies within the photonic band gap cannot propagate through the crystal, they can be confined to defect regions by creating the defects. This is a simple design with square lattice photonic crystal. Both point and line defects are created to achieve the de-multiplexing action.

As can be seen from the figure 2, there are two photonic crystal ring resonators PCRR1 and PCRR2. We utilized the filtering property of PCRRs in designing this de-multiplexer. There is one input waveguide and two output waveguide, one above the upper PCRR and other below the lower PCRR.

Observation points are placed at the ends of both the output waveguides to observe the response of this de-multiplexer. PCRR1 and PCRR2 has inner rod's radius $r_1 = 0.264a$ and $r_2 = 0.21a$ respectively as shown in figure 2. There are four scatterer rods at all the four corners of each PCRR as shown in this figure. The scatterer rods have radius $r_3 = 0.227a$. Scatterer rods are placed at $0.7a$ from their actual position, in both x and z directions. This is shown in figure 3. Wavelength 1551nm is obtained at output waveguide 1 and wavelength 1591nm is obtained at output waveguide 2.

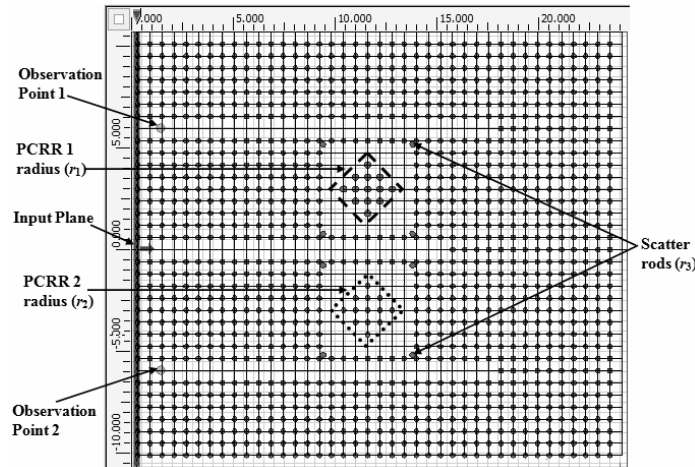


Figure 2:- The two-channel de-multiplexer based on 2-D photonic crystal structure.

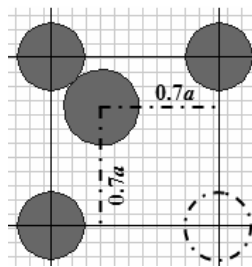


Figure 3:- Position of scatterer rods at all the four corners of PCRR.

ANALYSIS:-

A Gaussian modulated continuous wave signal is injected by vertical input plane at the input port and the output is observed by placing the observation points 1 and 2 at both the output ports. A 2-D 32 bit simulation is performed to observe the response of this de-multiplexer. The number of APML layers [20] is 10. For the FDTD, a simulation starts from a random initial condition to not exclude any possible modes and propagates for an adequate amount of time to give sufficient precision [21]. The Eigenmodes are then given by the peaks of the Fourier transform of the complex field components in the time domain recorded at various low-symmetry locations for a given propagation constant [21]. Here, the light propagates in the z direction. The structure is excited by TE polarization. The space steps in the x and z directions are Δx and Δz respectively. The time step for 2D structure is given by:

$$\Delta t \leq \frac{1}{c \sqrt{\left(\frac{1}{\Delta x^2}\right) + \left(\frac{1}{\Delta y^2}\right)}}$$

Where, c is the speed of light in vacuum. The simulation runs for 20,000 time steps. The output is obtained using frequency discrete Fourier transform (DFT) calculations of the field by finite difference time domain method. When two signals of wavelengths 1551nm and 1591nm are applied at the input of the device, the signal with wavelength 1551nm follows the upward path and signal with wavelength 1591nm follows the downward path. Thus the de-multiplexing action is realized.

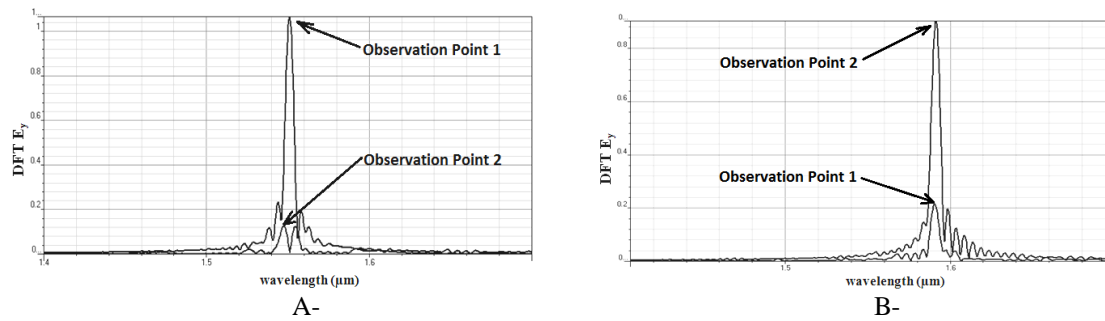


Figure 4(A) and figure 4(B):- shows the measurement (in the frequency DFT domain) for two wavelengths 1.551 μm and 1.591 μm at both the observation point 1 and 2.

The quality factor is given by $Q = \lambda_0 / \Delta\lambda_{FWHM}$. Here λ_0 is the center wavelength and $\Delta\lambda_{FWHM}$ is the full wavelength width at half maximum. This is the important parameter in wavelength division de-multiplexer. A high Q factor is always desirable. Several designs of photonic crystal devices with high quality factor are reported utilizing the micro-cavities [22] and nano-cavities [23]. Table I gives the quality factor of both the channels. The quality factor can be further increased by optimizing the various design parameters.

Table 1:- Quality Factor for both channels

Channel	λ_0 (nm)	$\Delta\lambda$ (nm)	Q
1	1551	4.48	346.20
2	1591	5.83	272.89

CONCLUSION:-

In this work, coarse wavelength division (de)multiplexer is proposed and investigated using finite difference time domain (FDTD) method. The photonic band gap (PBG) is calculated by plane wave expansion (PWE) method. Two de-multiplexed central wavelengths one at 1551nm and another at 1591nm are obtained which belong to the most popular ITU-T G.694.2 CWDM grid wavelengths range in optical communication system. The calculated quality factors for the two wavelengths 1551nm and 1591nm are around 346 and 272 respectively. The two wavelengths are 40 nm apart. The quality factor and output response of this de-multiplexer may be further optimized by varying the various design parameters. Compared with previous works, it has been found that this de-multiplexer has better channel spacing. This de-multiplexer may be used as a key component in optical integrated circuits and optical network applications. Another advantage is that this device is ultra-compact with overall size of the wafer around 504 μm².

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