Design of a Low-Loss Y-Splitter for Optical Telecommunication using a 2D Photonics Crystal

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ABSTRACT

In this study a wide bend, low loss (>2.0dB) Y-splitter has been designed for TE-polarized light. The structure consists of hexagonal lattice where circular Si-dielectric rods in air background have been organized. For optimal design of photonic band gap, inter-cell distance and cell radius have been varied to find the largest photonic band gap which should corresponds to the optical communication wavelength ranging from 1.3μm to 1.6μm. From the study, cell radius of 0.3μm and lattice constant of 0.98μm were the optimum values which provided the wavelength range of 1.34μm to 1.58 μm. Using this structure, waveguide properties have been studied varying the cell radius of the adjacent cell of the propagating path. With the optimized waveguide deign, a Y-splitter has been designed. Less than 2dB loss has been realized for wavelength ranging from 1.38μm to 1.56μm using the designed Y-splitter. And a minimum loss of 0.46 dB has been realized at wavelength 1.56μm. By using plane wave expansion (PWE) method band gap of the structure have been evaluated. Finite difference time domain (FDTD) method has also been used to compute the transmission power, electric field distribution and magnetic field distribution properties of the system.

General Terms

Photonic Crystal Waveguide, Power Splitter, Lattice Constant, Cell Radius.

Keywords

Plane Wave Expansion(PWE), Plane Wave Expansion Method(PWEM), Finite Difference Time Domain(FDTD), Photonic Carystals(PhCs), Photonic Band gap(PBG), Transverse Electric(TE), Transverse Magnetic(TM), Line Defect Waveguide(LDW).

1. INTRODUCTION

When an electromagnetic (EM) wave propagates in such a structure whose period is comparable to the wavelength of the wave, interesting phenomena occur. Among the most interesting is the possibility of forming a complete photonic band gap (CPBG). Most of the known structures with a CPBG are based on the face centered cubic (fcc) or diamond symmetry. Photonic crystals are a kind of nanostructures for light, the refractive index of which changes periodically. Photonic crystals are of great interest for optical information processing applications because these crystals provide a common platform to miniaturize a large number of optical components on chip down to single wavelength scale.[1-7]

Among the most basic optical components for integrated optics applications are linear waveguides, waveguide bends, and Y splitters.[8] In the past few years, there have been many reports on the design, fabrication, and testing of two-dimensional (2D) photonic crystal guides and bends.[9–12] Quantitative analysis of guiding and bending efficiency at 1.5-1.6 μm wavelengths has also been carried out.[10,11] It is demonstrated that a 2D photonic band gap (PBG) is effective in light guiding and bending in the 2D plane. It is also possible to minimize radiation loss along the third direction by use of a strong-index cladding design.[13–15] The same PBG guiding principle can also be applied to the design of a Y splitter with high efficiency. A PBG splitter can support large angle splitting (>60^0), is low loss, and also has a miniature size, <5 μm×5 μm. However, for a conventional waveguide branch (or Y splitter), the Y-splitting angle is restricted by radiation loss to a few (<10) degrees.[16, 17] In this paper we present the design of a 2D PhC waveguide based Y-splitter. To our knowledge, few works have been proposed and analyzed in this field.

The organization of this paper is as follows. In section 2 we discuss about the previous works and their findings and difficulties. In section 3 we explain in detail the design procedure for 2D PhC waveguide based Y-splitter, for both cases of silicon pillars in air background as well as perforated silicon slab, we also find out the appropriate pillar radius and lattice constant of the PhC structure which has the band gap in desirable range, necessary to design a Y-splitter. In section 4 we present the FDTD results obtained for the proposed Y-splitter realization, and finally in section 5 we present our concluding remarks.

2. Literature Review

Since, the implementation of photonic crystal by John and Yablonovitch in 1987 there have been increasing attention paid to develop the nanostructure in microscale device in various applications.[23, 24] PCs have the potential to provide ultracompact photonic component that will enable the miniaturization of optical circuits and promise to revolutionize integrated optics. These photonic components are based on the planar PC structure and operate in the PBG of the periodic dielectric structures which allow control of the light propagation on the wavelength scale. Photonic crystal waveguides (PCWs) are formed by line defects in PC. Thereby light is confined horizontally by an in-plane PBG and vertically by TIR. Because of the PBG effect in a PCW, light

can be routed around sharp corners with bending radii of the order of the wavelength. Due to the sharp bend higher-order modes are generated that affect the single mode operation in the PCW. [27]

Researchers have theoretically investigated photonic crystal with array of dielectric rods in air. Unfortunately, both the 'rod in air' and 'air hole in slab' approach do not provide sufficient vertical confinement and is difficult to implement for most practically useful device implementations in the optical regime. The most straightforward Y-splitter design consists of three single-defect ('W1') waveguides joined together at 120^0 which leads to strong reflections and narrow bandwidth operation. Due to strong reflection only 20% of the input power is transmitted at the output ports.[26] After that L.H.Frandsen et al. [24] proposed an alternate design which was based on a triple line defect waveguide. In their design the bandwidth and power transmission were improved by 25nm and 45% of input power by adding an additional hole at 120^0 junction and modified 60^0 bend. In this chapter, we investigated the PCW based Y-junction splitter through 2-D FDTD simulation method to overcome some of the above difficulties (i.e. mode mismatch, bandwidth and bending region transmission) and challenges. The structure can be applied to communication systems and also be integrated with other PC based devices.

3. Design Procedure

At first, we considered several photonic crystal structures of different material and find photonic band gap in acceptable range. Further this structure is used to design a Y-splitter. In this work, the results obtained from the simulation of two dimensional photonic structures made of silicon are presented for comparison. All the simulations have been performed with the Optiwave OptiFDTD 8.0 software, where 'PWE band solver' is used to calculate photonic band gap and "2D FDTD Simulation" is used to compute the different properties of the Y-splitter.

3.1 Find Photonic Band Gap

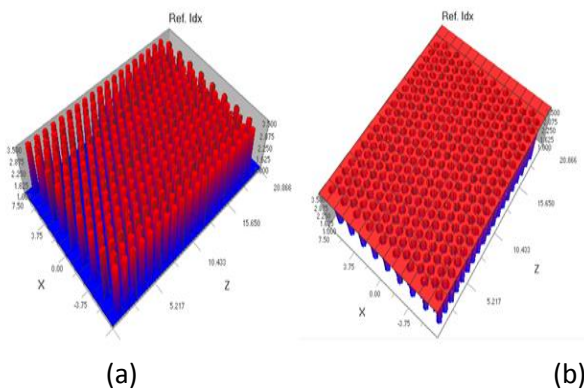
(a)   (b)

Fig 1:2D PhC slabs (a) Hexagonal lattice with circular Si dielectric pillar in air background (b) Perforated Si slab of hexagonal lattice with circular air hole.

We begin with 2D photonic crystal slab with a dimension $21\mu m \times 15\mu m$, where both silicon pillars in air background as well as perforated silicon slab are considered, as shown in Fig. 2(a) and 2(b). all the pillars and perforated air holes in the slab have radius 'r' called cell radius and they are separated by a distance 'a' called lattice constant. Using

PWE band solver we calculate the band gap in those structure. But, only Si pillar in air background shows band gap in acceptable range.
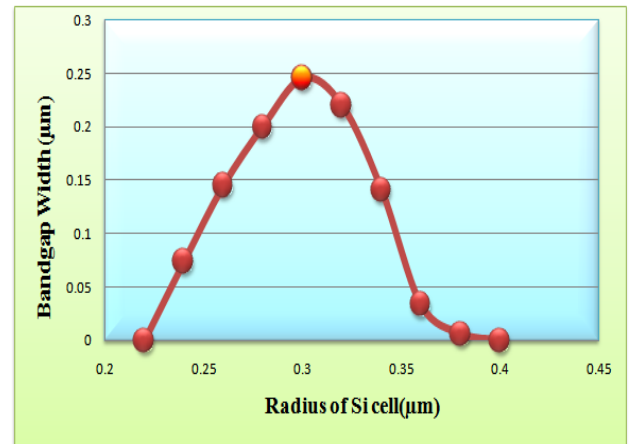

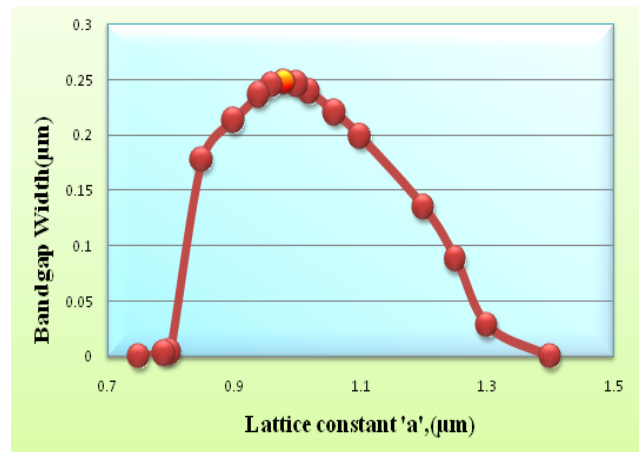**Fig 2: Graph for band gap width in different cell radius.**

Fig 3: Graph for band gap width in different lattice constant.

The band gap width is depends on the wafer and dielectric rod material, lattice constant and the cell radius. So, to achieve subsequent band width in desirable range, we vary the cell radius as well as the lattice constant of the structure. The graph of cell radius and lattice constant versus band gap width are shown in fig 2 and fig 3, where change in band width with respect to change in cell radius 'r' and lattice constant 'a' are plotted. From the above graph, the highest bandwidth is found for lattice constant **a**=980 nm with cell radius **r**=300nm.
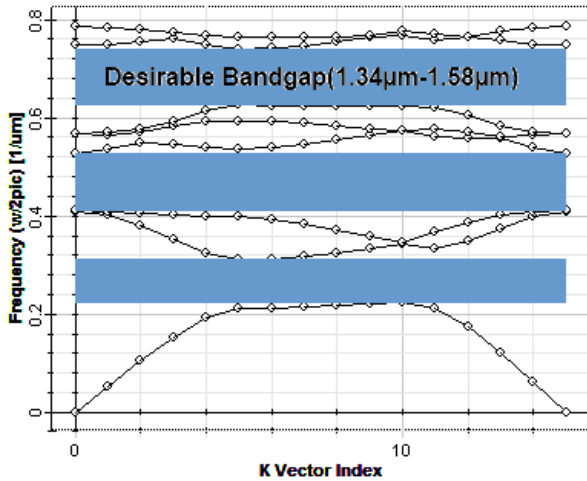
Fig 4: Hexagonal lattice with circular dielectric rods (Si rods) in air background with cell radius r=300nm and inter cell distance a=980nm band diagram of the structure.

After the above analysis, the desirable optical communication bandwidth (1.34μm-1.58μm) is founded for the structure organized by Si pillar in air background where the cell radius **r**=300nm and lattice constant **a**=980nm. Figure 4 shows the structure band diagram.
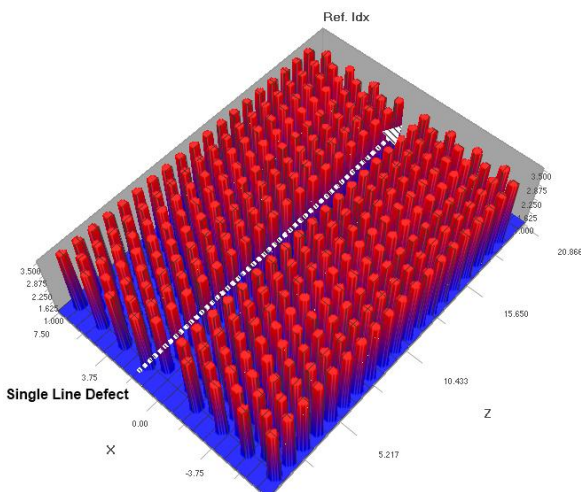
3.2 Photonic Crystal Waveguide

Fig 5: Single line defect PhC waveguide

Waveguides are the important element of photonic integrated circuits (PIC). In this work, it is our core e lement to design a power Y-splitter. In a PhC, a simple LDW is created by removing a row of Si pillars along one of its main crystalline directions as shown in figure 5. Due to this defect optical signal can be carry between components in the integrated system.
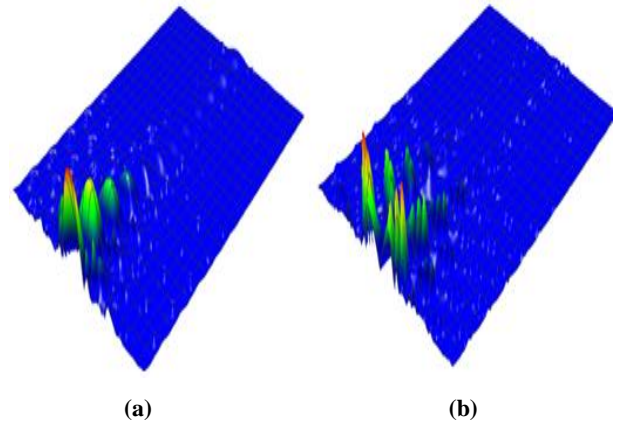

Fig 6: (a) Electric field distribution of the wave guide (b) Magnetic field distribution of the wave guide
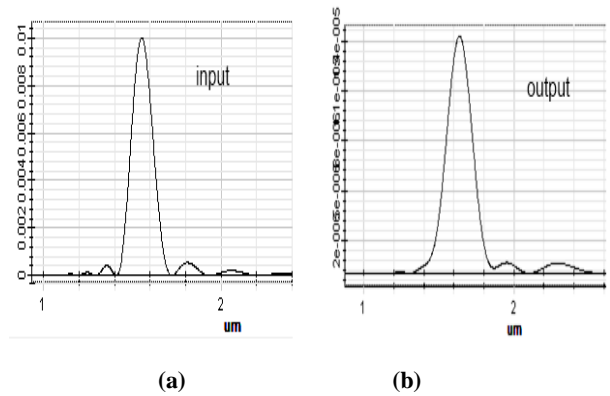

Fig 7: power curve for the waveguide (a) input power (b) output power

After analyzed with 2D FDTD simulation, the guiding properties such as the electric field and magnetic field distribution, radiation loss of the designed single line defect wave guide have been obtained and they are given in fig 6 and 7.

From the input and output power curve, we calculate the radiation loss, which is 19.031 dB that means the waveguide has low guiding properties and from the electric and magnetic field distribution we observe that the input signal spreads throughout the crystal structure and attenuated gradually. So we need to modify our design to improve the performance of the waveguide. Therefore we change the juxtapose cells radius in the two rows which are adjacent to signal guiding path and measure power. The graph for power loss (dB) for different adjacent cell radius is shown in fig 8.
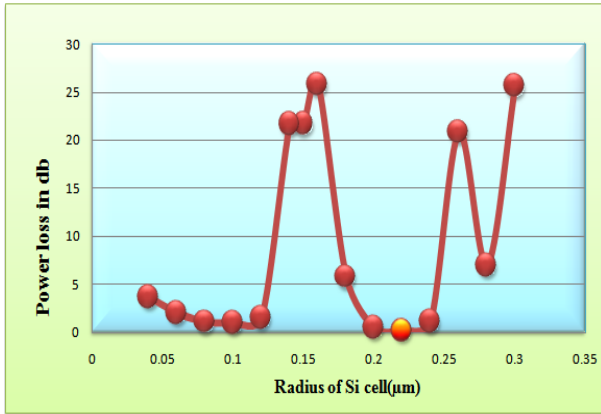
Fig 8: Graph for power loss for different adjacent cell radius.

From the above the graph low power loss is observed for the adjacent cell having radius r=220nm. Using this analysis we modified our proposed wave guide. The modified structure layout and its transmission characteristics are shown in fig 9 and 10.
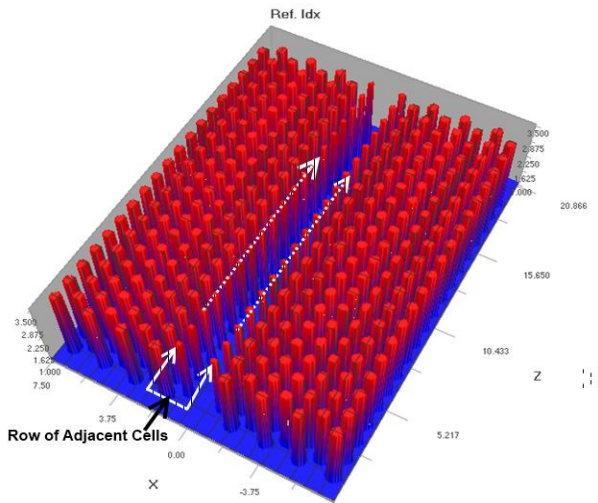

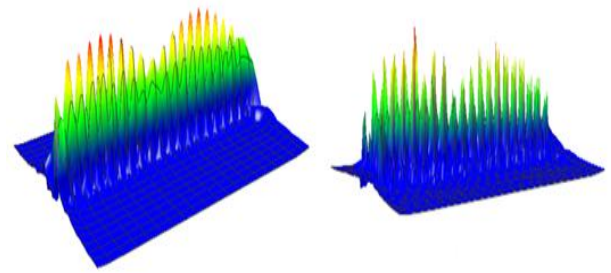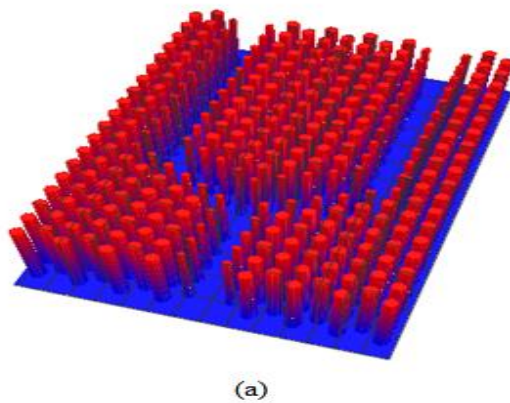**Fig 9: Layout and refractive index profile of the modified wave guide.**

Fig 10: Electric field and Magnetic field distribution of the wave guide.

From the power loss graph the power loss for the modified structure of the waveguide is 0.27 dB. That means the transmitted power loss is reduced by 98.58%. And the electric and magnetic field distribution of the signal is uniform throughout the guiding path and there is minimum attenuation of signal in the structure. This improved transmission which has been received by optimizing the cells radius of the adjacent rows of the structure is still lower than the existing design.[19] o we use this waveguide to make the Y-splitter with good guiding and bending

3.3 2D PhC Y-Splitter

The 2D PhCW based splitter is designed as a Y junction formed by the intersection of three PhCWs at 120°. To have the output channels of the Y splitter be parallel to the input channel, the two output channels have a 60° bend. Both the Y junction and the 60° bend represent sever discontinuities in the PhCWs and are potentially regions in which the single-mode operation might suffer from large transmission losses. Therefore the discontinuities in these regions were carefully designed. Figure 11 shows our ultimate layout of our proposed Y-splitter.

In summary, our planar PhC Y-junction based structure is defined by an array of Si pillars with refractive index of 3.47 (silicon) in air background, having dimension 21μm×15μm. The regular pillars are placed in a hexagonal lattice and have a radius r=300nm, where lattice constant a= 9800nm. Moreover, the cells radius of adjacent row of guiding path is r=220nm.The PC Y-junction base structure is formed by the intersection of three PCWs at 120^0. The output channels of Y splitter are parallel to the input channel and have a 60^0 bend and fifteen periods spaced from the Y junction.
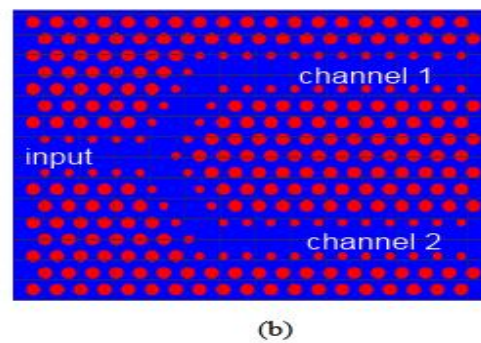

Fig 11: Layout and refractive index profile of the Y-splitter (a) Height plot (b) Curve plot.

4. Result and Analysis

From 2-D FDTD simulation time domain electromagnetic field is obtained. The Y-junction structure is simulated by a mode source located on the conventional waveguide which is attached with the Y-junction structure. This technique is very powerful and versatile and is useful for this type of waveguide [20, 21].
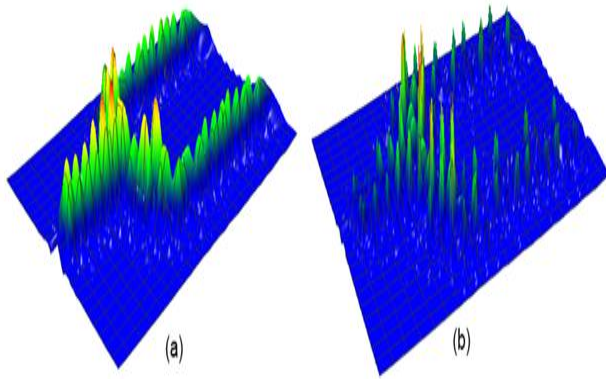

Fig 12: The field distribution of the Y-splitter (a) Electric field (b) Magnetic field.

The field distribution characteristics of the designed Y-splitter is uniform and not spread out that means the signal is not attenuated. Since the radiation loss or the power loss of the y-splitter is vary with the wavelength of the propagating wave within the band gap. So we calculate the power loss for different wavelength ranging from 13.4µm to 1.58µm by using '2D FDTD simulation'. The graph for power loss (dB) for different wavelength within the range is shown in fig 13 where the input power of the signal is 0.01w/m.
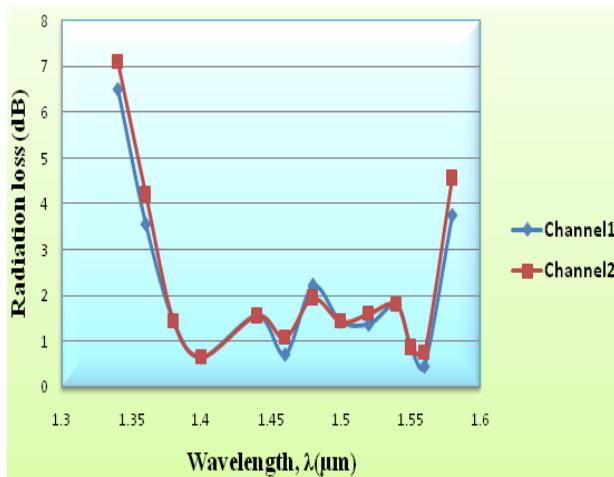

Fig 13: The radiation loss for different wavelength.

The transmission characteristics are shown in graph where wavelength versus radiation loss has been plotted. From the above graph the minimum loss 0.46dB is found at wavelength 1.56µm and the maximum loss 7.1dB is found at 1.34µm. And the power transmission characteristics in the two channels are approximately similar, that is our proposed Y-splitter has symmetrical power splitting ratio.

5. Conclusion

Our designed Y-junction based 1×2 power splitter formed in 2-D slab PC is analyzed primarily by using 2-D FDTD computational method. 120^0 junction and 60^0 bend are optimized for obtaining maximum power transmission in 1×2 Y-junction based power splitter. As a consequence, 94% of input power is transmitted with 240nm (1.34µm-1.58µm) broad spectrum. The combined splitting and bending loss is measured to be less than 2.0 dB at 1.34µm to 1.58µm. A noteworthy feature is the remarkable similarity of split signal power between the two output channels which is much better than the previous work. The length and width of the device is 21µm and width 15µm respectively. The length of the device is somewhat big but the output spectrum (240nm broad) and transmitted power is promising.

6. ACKNOWLEDGMENTS

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