Journal of Modern Science and Technology
Vol. 1. No. 1. May 2013 Issue. Pp.176-187

Nano Structure Based Power Splitter Design by Using 2D Photonic Crystals

Md. Masruf Khan

A nanostructure (80-100 μm^2) integrated power splitting devices two, three, four, six output with repectively (1x2), (1x3), (1x4) and (1x6) channel has been designed, simulated and optimized for Telecommunication purpose with T-Junction, Y-Junction, PC line defect waveguides integrated with Multimode interference block (PCLD-MMI) and multiple line defect PC waveguides (MLDPCW) configurations. The optical modeling of these proposed structures was investigated by finite difference time domain (FDTD) simulation. With optimization of the parameters (Hole Radius, R=0.128μm, Input Diameter, D=1.02 μm, Input wavelength, λ= 1.55 μm, Substrate Reflective Index, n_{sub}= Si (1.52), Photonic Crystal Material, n_{pcs}= InAs (3.45), and Rectangular crystal structure), 1x2 for Y-Junction (100%), 1x4 for T-Junction (92.8%) and 1x6 configuration for MLDPCW (81%) show maximum power transmission.

Field: Nano Technology Based Photonic Power Splitter Design for the Purpose of Tele-Communication Field.

1. Introduction

In the recent years, a lot of research has been focused on developing micro and nano photonic devices by using Photonic Crystals (PCs). Photonic Crystals (PCs) are artificial structure in which the periodic variation of dielectric constant is used to control the flow of light. PCs may be 1D, 2D & 3D crystal structure. Unlike electronic crystals (which are natural structure) that control the flow of electron by periodic variation of electron potential and follow Schrödinger equation, PCs follow Maxwell's equation [a].

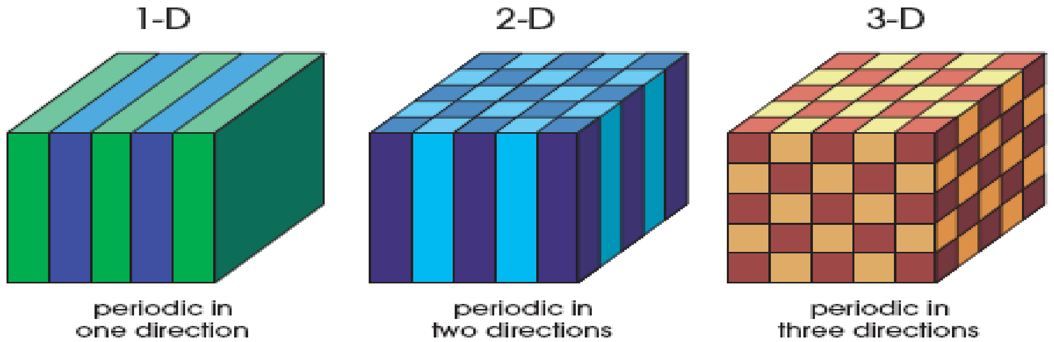
"Photonic Crystals (PCs)" are dielectric or metallo-dielectric structures with periodic spatial alternations of refractive index on the scale of the wavelength of light and power splitter is also called power divider, where one input source is converting into two or more output path/channel. Many optical devices have been proposed based on the photonic crystal. There are multiple ways by which equal amount of power of incoming signals can be divided into two, three and four output channels; for example using multiple coupled photonic crystal waveguides, directional coupling and cascaded multimode PC waveguides.

Department of Electronics and Electrical Engineering, University of Information Technology & Sciences, Dhaka, Bangladesh, Email: masrufsamgroup11@gmail.com

Now a day, from the idea of controlling light by means of Photonic Crystal (PC) has lead to many proposals and implementations for novel photonic integrated circuits including different types of optical power splitter or divider which is used in fiber optic networks. This is possible only for splitter splits input power from input port is equally divided into the output ports without any significant reflection and radiation loss. The traditional optical power splitter is Y- junction structure, having limitations on the reflection and large transmission loss due mode mismatch and bending. Those traditional limitations can be overcome by using an array of dielectric rods in air which is the basic concept of PCs.

According to the dimensions of the periodicity, PCs are classified into one-dimensional (1D), i.e. where the dielectric variation is along one direction. Similarly two-dimensional (2D) and three-dimensional (3D) PC are defined when the dielectric constant varies along two and three direction respectively. Schematic samples of different types of PCs are shown in Figure 1.1 [a].

Figure 1.1: Schematic Depiction of three Types of Photonic Crystals (A) 1-D, (B) 2D (C) 3-D. The Different Colours Represent Materials with Different Dielectric Constants [A].



(a) (b) (c)

In this work,I have proposed different techniques of optical power splitting using (a) T-junction (b)Y-junction, (c) PC line defect waveguides integrated with multimode interference block (PCLD-MMI) (d) multiple line defect PC waveguides (MLDPCW) [b].

From my curiosity about the nano technology I have studied almost 16 month and I have also completed my thesis about it. Now a day, from the idea of controlling light by means of Photonic Crystal (PC) has led to many proposals and implementations for novel devices including different types of power splitters has generated wide interest in the communication field.

This is possible only for periodic variation of the refractive index causes photonic band gap and artificially introduced defects to divide the input power equally into the output channels without significant reflection or radiation losses with compact in size. The traditional limitation on power splitter based optical fiber on is on transmission loss can be minimized by the photons splitter as optimal one [b].

It has many advantages such as low loss, good uniformity, insensitive to operation wavelength, polarization, large bandwidth, simple fabrication technique, larger tolerance, minimized structure, temperature and other environmental factors.Researchers have theoretically investigated photonic crystal with an array of dielectric rods in air. Based on this concept the T-junction, Y-junction and MMI effects have already been extensively studied [d,e]. Unfortunately, the 'rod in air' approach does not provide sufficient vertical confinement and is difficult to implement for most practically useful device implementations in the optical regime. A slab waveguide structure consists of air holes etched into a dielectric medium such as silicon, GaAs/AlGaAs hetrostructure or a semiconductor membrane which remedies this problem and allows waveguides with tolerable losses [f,g]. This multimode leads to mode-mixing problem at intersection of the PCW which creates a mismatch between input and output fields and introduces large reflections at the interface.

In this paper, a matter of great significance that new power splitting techniques using 2-D and 2-D slab PC line defect waveguides are investigated. In order to achieve this, initially we investigated (a) T-junction structure for 1×2 and 1×4 applications. Then, (b) Y-junction with 1x2, 1x4, 1x6 structures are also invested. In this scheme, we have improved the power transmission and output spectrum in 1×2 application which is better than published result where as in 1×4 and 1x6 applications the power transmission and output spectrum is not good enough for practical application point of view. So, in order to improve the power transmission and output spectrum we have investigated two new designs where one is (c) PC line defect waveguides are integrated with a multimode interference (MMI) block and multiple line defect PC waveguides (MLPCW) for1x2,1×4,1x6 power splitting applications. In MLPCW scheme, we have investigated the three versions which are a combination of three, five and seven line defect waveguides.

These two structures are more compact than the previous design but relatively broad spectrum. Among those structures Y-junction based 1×2 power splitter was found great significance with 100% transmission and equally splitting. Optical modeling is used to demonstrate that the power is equally divided at each output channel with a relatively broad spectrum. Moreover, FDTD simulation method is used to overcome some of the difficulties of previous works (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.

2. Literature Review

During the last 20 years, photonic crystals have been the subject of intensive theoretical and experimental research owing to promising applications in micro- and optoelectronics (Sakoda 2004). With artificial periodic structure, photonic crystals (Phc) can generate band gaps that forbid light propagation at certain frequency ranges (Yablonovitch 1987; John 1987). Utilizing the photonic band gap effect, a lot of ultra small optical devices are implemented, including filters, modulators, and switches, and so on, which show much fascinating characteristics, and are envisioned as good candidates for integrated optics circuits and dense wavelength division multiplexing (DWDM) optical communication systems (Sharkawy *et al.*2001) [c].

Among various optical devices, a power splitter is one of the most indispensable components. Based on Phc, a power splitter with a *Y* –junction structure has been proposed (Fan *et al.* 2001; Ayre *et al.* 2005). Due to H. RENTAL. The de-mismatch of *Y* -junction and the bending losses of two output ports, however, the *Y* -junction and bending at output port have to be optimized to achieve fine transmittance, which brings difficulties to the device fabrication. The directional coupler in PhC is produced by nearly placing two parallel PhC line-defect waveguides, and the proximity between the two waveguides leads to a splitting of the guided mode of a single waveguide into two super-modes, which have odd and even symmetries with respect to a mirror plane located at the center of the waveguide (David *et al.* (2003)) [f].

A new power-splitting structure has already been proposed on the basis of such a directional coupling structure (Park *et al.* 2004), and it is formed by three parallel waveguides placed in close proximity, where the central waveguide is used as an input port. Although 47.6% transmittance per each output port is achieved, the bandwidth is narrow, which is accounted for from the operation mechanism of wavelength-selective directional coupling. Recently, a power splitter has been proposed by exciting and spatially splitting the odd mode of a PhC directional coupler formed by two coupled cavity waveguides (CCWs) (Martienez *et al.* 2003). In this paper, a power splitter is also proposed based on a similar operation mechanism, which consists of the input waveguide, coupling region and output region. In coupling region, the directional coupler is designed so that only one of the super-modes lies within the frequency ranges of interest. At the same time, in output region, the radius of air holes next to the guiding region is increased to realize the complete decoupling between two output waveguides. Using plane wave expansion (PWE) and two dimensional finite difference time domain (2D FDTD) computations, the structure is analyzed numerically, and it is demonstrated that over 45% transmission efficiency through each channel for frequencies within a wide frequency range is achieved [e].

The concept of photonic crystals, which was introduced in the 1980s, is essentially the photonic analogue of band electrons in solids. A dielectric structure whose refractive index is periodically modulated can exhibit a variety of novel optical properties due to its band nature. Photonic crystals were first realized in radio frequencies, and in the 1990s several groups had already started to fabricate photonic crystals in optical frequencies, which needed nanofabrication technologies.

3. Methodology

We have taken SiO_2 as a wafer material (reflective index 1.447) with dimension-length- 10µm and width- 10µm, Gaussian modulated continuous wave as an input signal with wavelength 1.55 µm. Both transverse and injection type of the input is Modal. The input signal used in the simulation expressed as:

$$E_y^{inc}(x, z_{inc}) = AT(t)\, F(x, z_{inc}) \sin(wt + \theta_i) \qquad (1)$$

Where, A is the field amplitude and F (x, z_{inc}) is the transverse field location at the incident field location z_{inc}. The initial offset θ_i is the phase difference between points in the incidence plane. This offset can be adjusted to define the direction of the incident field [1]. The planar PC structure is simulated on a silicon-on-insulator substrate with a Si slab of thickness t = 220nm separated from the Si substrate by 1μm silica layer. The holes are placed in a triangular lattice and have a diameter d = 0.588Λ, where 'Λ' is the lattice constant.

The propagation of light in the waveguides is simulated by 2D Finite-difference time-domain (FDTD) method using a standard simulator. FDTD is a time-domain numerical method used for modeling the propagation of electromagnetic waves in optical media, which is based on the discretization of Maxwell's equations in differential form in free space. Time domain methods have been found to be very accurate in simulating the propagation dynamics of signals in periodic dielectric media [h].We simulate for TE mode, actual Mesh used- 0.075μm (delta X) X 0.075μm (delta Z) with number of mesh cells 400 (X) and 650 (Z). For result finalization the simulation has been done for 4000 time steps. The Anisotropic Perfectly Matched Layer (APML) boundary condition is used. PC line defect waveguides (LDWs) integrated with MMI block for power splitting has potential to transmit power from the input to the output without any changes of the PC dielectric hole size. It has a large optical bandwidth as compared to existing power splitter. In proposing design there are no 120^0 junctions or 60^0 bends. As a consequence the single mode operation will not be suffered. The entire structure will be formed by triangular lattice of dielectric holes so the vertical confinement will be better as compared to the triangular lattice of dielectric rod structure. An account of having all these advantages the entire structure can be considered as a 2-D slab PC configuration. Therefore, the application of power splitter by using PCLDWs integrated with MMI is attractive.

It is known that the typical Y-junction structure has poor transmission without any structural tuning at the bends and input and output ports. In addition to that the performance of the Y-junction can be improved by tuning and displacing the holes at 120^0 junctions and also by bending the output ports but still difficulties exist which cannot be easily addressed for practical application. These difficulties arise from the mode-mismatch at 120^0 junctions and the bending loss from the output ports. It is conspicuous from a number of the researcher's work that Y-junction based power splitter itself identifies some problems in its own design. Here a unique design is proposed which will not be having any disturbances like 120^0junctions and bending loss. 2-D PC multiple line defect waveguides based power splitter is that proposed design which will be capable of addressing the issues of Y-junction based power splitter as mention before. PC multiple line defect waveguides power splitter minimizes the multimode problem occurred in the existing design. Therefore, this proposed scheme transmits more power as compared to the existing design. So, PC multiple line defect waveguides based power splitter should be investigated. The real motivation behind using PC waveguides over conventional dielectric waveguides for optical interconnects includes better routing capabilities with lower transmission, bending loss, coupling loss, reduced cross talk and larger design flexibility provided by the PC environment, monolithic integration with other on-chip photonic component like a PC based laser or photo-detector. A schematic representation of an optical signal distribution layer using PC based waveguides (Line defect waveguides) integrated with MMI block is shown in Figure 1. The architecture of output optical signal consists of four PC line defect waveguides (LDWs) which is integrated with MMI block. Optical signal is equally divided at the each output channel.

Figure 1(A): Layout Design of 1x2 T-Junction (A1), 1x4 T-Junction (A2), 1x2 Y-Junction(B1), 1x4y-Junction (B2), 1x2 PCLD-MMI (C1), 1x3 PCLDMMI (C2), 1x4pcld-MMI(C3), 1x6pcldmmi (C4), 1x2 MLDPCW (D1), 1x3 MLDPCW (D2), 1x4 MLDPCW (D3), 1x6 MLDPCW (D4).

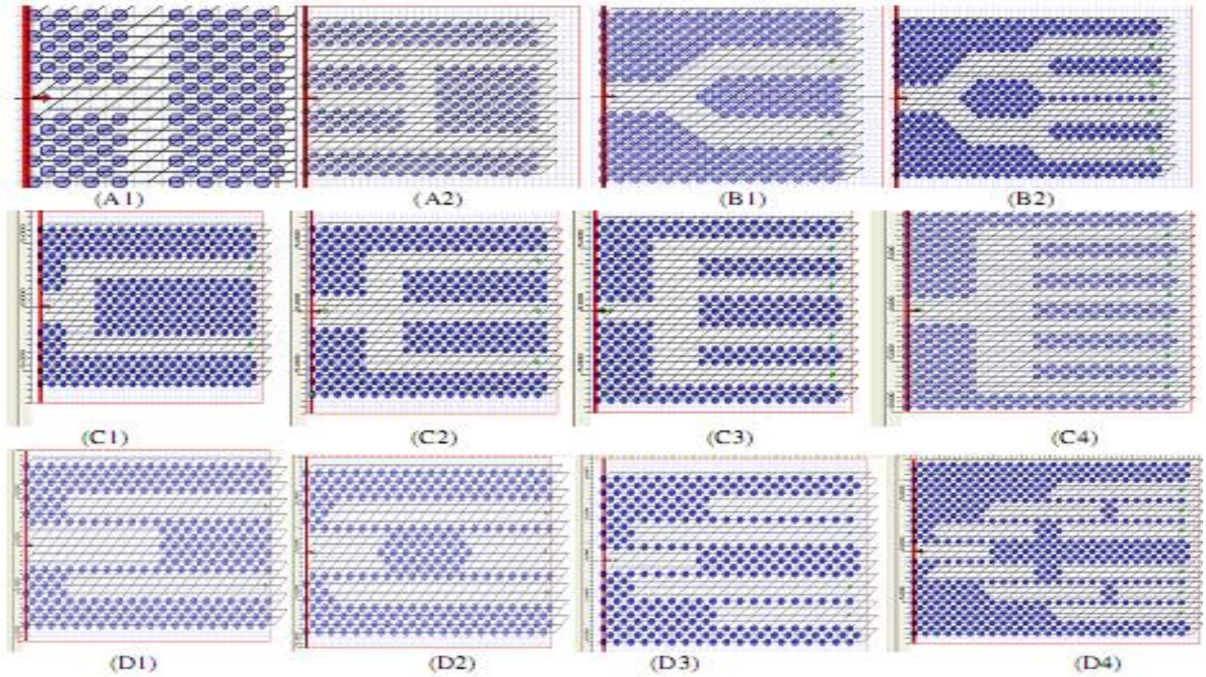


Figure 1(B): For1x2 T-Junction Air/Glass Rod Distribution by Refractive Index (P1), Simulation Start (P2), Simulation Complete (P3), Result Analyzer (P4), Output Curve Port 1(P5), Output Curve Port 2 (P6).

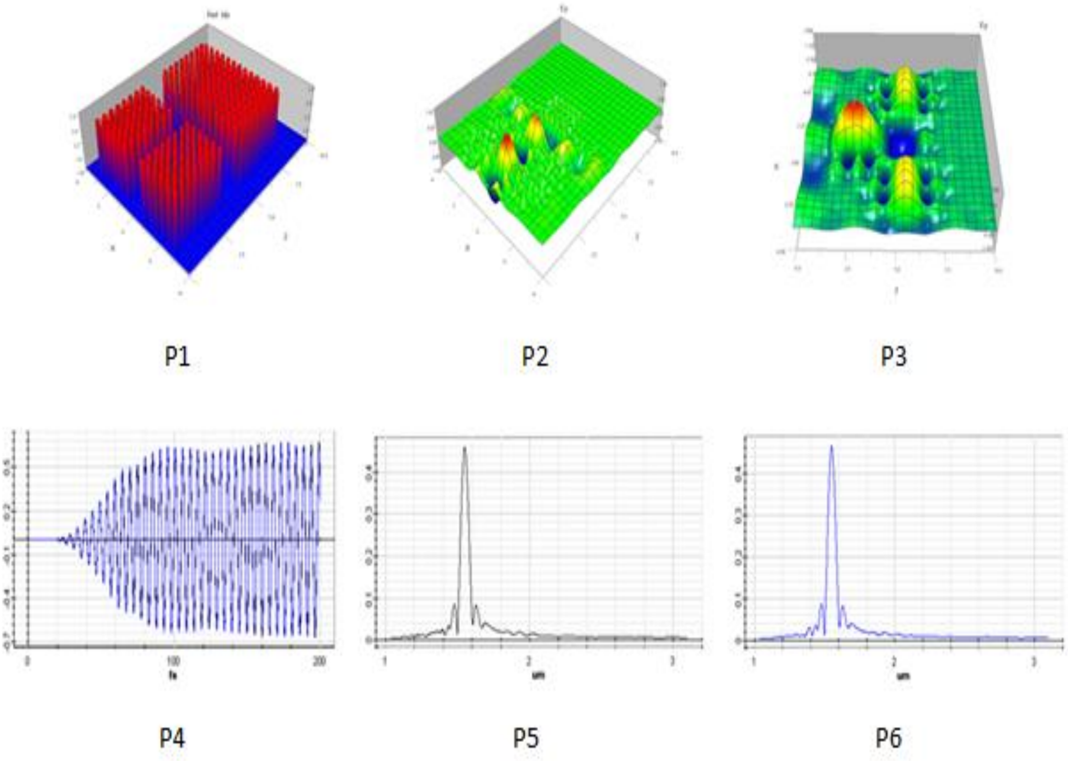
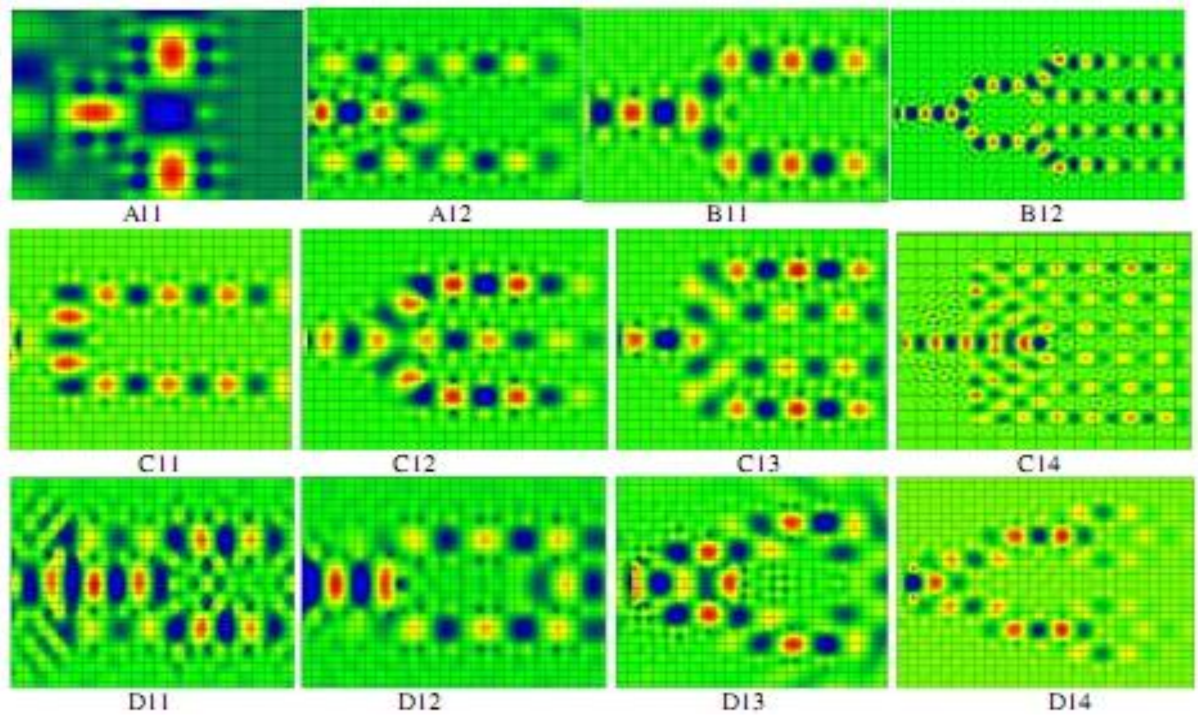


Figure 2: Simulation result of 1x2 T-Junction (A11), 1x4 T-Junction (A12), 1x2 Y-Junction (B11), 1x4 Y-Junction (B12), 1x2 PCLD-MMI (C11), 1x3 PCLD-MMI (C12), 1x4 PCLD-MMI (C13), 1x6 PCLD-MMI (C14), 1x2 MLDPCW (D11), 1x3 MLDPCW (D12), 1x4 MLDPCW (D13), 1x6 MLDPCW (D14).



4. Findings/ Discussion

We try to optimization of the parameters of the splitter. For the variation of the input port diameter (0.15-1.4 μm), optimize value found for 1.02 μm (keeping fixed the Lattice constant, Λ =0.435μm and Hole Radius, R= 0.128 μm). With optimize diameter (D =1.02 μm), the hole radius of the photonic crystal (R) are varied (0.1-0.15) to get the optimize value of hole radius, R = 0.128 μm (keeping fixed the Lattice constant, Λ = 0.435μm). Similarly, from the variation of the input wavelength, λ (1.5-1.6 μm) the optimize value found λ_1 =1.55 μm (TE Mode) and λ_2 =1.6μm (TM Mode). Moreover, we take Air (n=1), Glass /Si (n=1.52), GaAs (3.40), InAs(3.45), InGaAs(3.72) as a wafer and Photonic Crystal (PC) material and found Si as wafer and GaAs(3.40) as a optimize PC material. Similarly, with Rectangular, Hexagonal, Face-centered cubic (FCC) and Body-centered cubic (BCC), optimized structure is found in Rectangular Crystal. The decision of optimization is based maximum power transmission at the output ports.

We have investigated the transmission of the structures using 2D FDTD method with perfectly matched layer (PML) boundary condition. The output transmitted power of 1x2 T-Junction is monitored at two points on the 90^0 bend output waveguides; one at the output of channel 1 (CH1) and the other at the output of channel 2 (CH2) is indicated in Figure 1. The output spectrum indicates that a maximum of 46.4% of the input power through each channel and total 92.8% of input power is transmitted. Similarly, total 83% of input power is transmitted for 1x4 T-Junction. In this 1x2case, output ports are 90^0 bands to the inputs for single time but two times for 1x4 T-junctions and thus power reduces to 83% from 92.8%.

The improved structure of T-junction is Y-junction in which total 100% and 86% are transmitted for 1x2 and 1x4 Y-junctions splitter due to lower bends (60^0) of output ports. The structure of this Y-junction is formed by the intersection of three PCW at 120^0. The output channels have an additional 60^0 bend which is parallel to the input channel as shown in figure 1. Due to 120^0 junction and 60^0 bend; single mode operation might suffer which can cause the reflection and large transmission loss. To overcome these difficulties the junction and bend must becarefully designed. The better transmission can be achieved by the modified Y branch structure in which The 60^0 bends are modified by displacing or removing one or more holes and changing their shapes in the bend.

The PC-based Y-junction power splitter has problems with mode mismatch and bending loss which excites the higher order modes. So in order to obtain an acceptable output transmission, the bending region needs to be carefully optimized which adds difficulties in design and fabrication. To minimize mode mismatch and bending loss, many researchers have investigated theoretically on array of dielectric rods in air.

To avoid some of the above difficulties and challenges, in this work we have investigated a novel idea for a 1×4 power splitting technique which is a 2D photonic crystal triangular lattice of dielectric air holes line defect waveguides integrated with an MMI block. Moreover, the proposed power splitter structure overcomes the mode matching phenomena, poor transmittance of Y-junction structure and the limited bandwidth and is easier to fabricate as compared to a Y-junction structure and MMI effect dielectric rod structure. The structure can be applied to optical communication systems and also be integrated with other PC-based devices.

Figure 3: Power Transmission (Mw, Y-Axis) Vs Wavelength (Mm, X-Axis) for 1x2 Photonic Splitter.

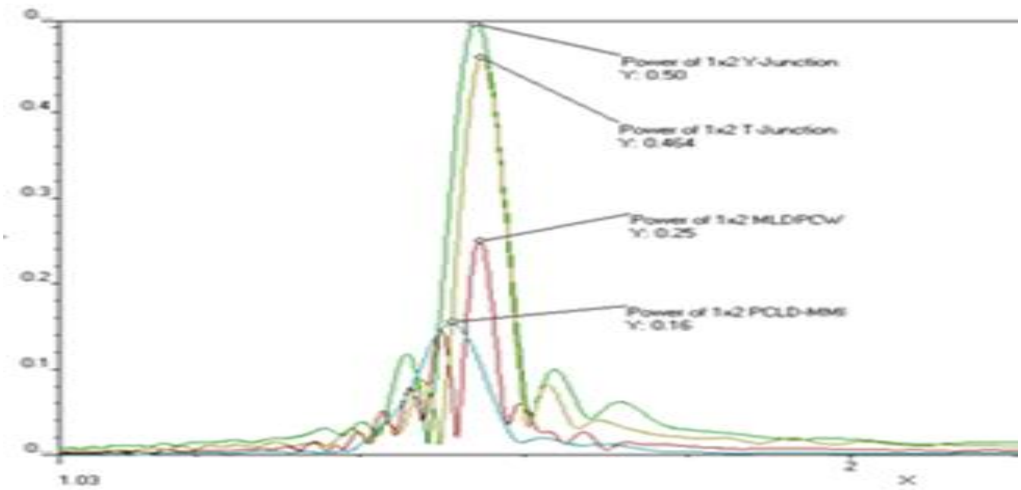


Table1: Comparison of Different 1x2 Power Splitters

Parameter	T-Junction Splitter	Y-Junction Splitter	PCLD-MMI Splitter	MLDPCW Splitter
Configuration	Holes with Rectangular lattice	Same	Same	Same
Parameters: Air fill faction = Air Hole Diameter (d) / Lattice constant (Λ) or d/Λ	0.588	Same	Same	Same
Max. Power Transmission at Each Output Ports (%)	61	58	39	53
Equal Splitting	Yes	Yes	Yes	Yes
Device Size (Length x Width)	10 μm x 9 μm	10 μm x 9 μm	10 μm x 9 μm	10 μm x 9 μm
Spectrum	(1.48 μm-1.80μm)=0.42μm	(1.48μm-1.75 μm)=0.27 μm	(1.45 μm-1.60 μm)=0.15 μm	(1.47 μm-1.58 μm)=0.11 μm

Table2: Comparison of Different 1x4 Power Splitters

Parameter	T-Junction Splitter	Y-Junction Splitter	PCLD-MMI Splitter	MLDPCW Splitter
Configuration	Holes with Rectangular lattice	Same	Same	Same
Max. Power Transmission at Each Output Ports (%)	42(Port1&4)& 32(Port2&3)	38 (Port1&4)& 30(Port2&3)	50(Port1&4)& 31(Port2&3)	38 (Port1&4)& 56(Port2&3)
Equal Splitting	Yes Pair wize	Yes Pair wize	Yes Pair wize	Yes Pair wize
Device Size	12 μm x 11 μm	12 μm x 11 μm	12 μm x 10 μm	12 μm x 11 μm
Spectrum	(1.45 μm-1.56 μm)=0.11 μm	(1.47 μm-1.56 μm)=0.09 μm	(1.48 μm-1.58 μm)=0.10μm	(1.47 μm-1.55 μm)=0.08 μm

Table3: Comparison of Different 1x6 Power Splitters

Parameter	T-Junction Splitter	Y-Junction Splitter	PCLD-MMI Splitter	MLDPCW Splitter
Configuration	Holes with Rectangular lattice	Same	Same	Same
Max. Power Transmission at Each Output Ports (%)	-	-	18(Port 1&6) 22(Port 2&5) 52(Port 3&4)	24(Port 1&6) 42(Port 2&5) 20(Port 3&4)
Equal Splitting	-	-	Yes Pair wize	Yes Pair wize
Device Size	-	-	12 μm x 12 μm	12 μm x 12 μm
Spectrum	-	-	1.48 μm-1.56 μm)=0.08 μm	1.47 μm-1.56 μm)=0.09 μm

5. Conclusion/ Implications

5.1 Achievements

Nano structure based compacted Power Splitter (max. size 100 μm^2) have been designed with photonic crystal. The T-Junction, Y-Junction, PC line defect waveguides integrated with multimode interference block (PCLD-MMI) Splitter, multiple line defect PC waveguides (MLDPCW) Splitter with 1x2, 1x4, 1x6 configuration has been designed & simulates with opti-FDTD software package based on Finite Differential Time Domain method. Hole radius (R), Input port Diameter (D), Input wavelength, λ (with TE and TM), Reflective Index of substrate (n_{sub}) and photonic crystal materials(n_{pcs}), crystal structures(Rectangular, Hexagonal, FCC, BCC) on splitting is demonstrated to get optimize parameters. Furthermore, with optimization of the parameters (Hole Radius, R=0.128µm, Input Diameter, D=1.02 µm, Input wavelength, λ= 1.55 µm, Substrate Reflective Index, n_{sub}= Si (1.52), Photonic Crystal Material, n_{pcs}= InAs (3.45), and Rectangular crystal structure), 1x2 for Y-Junction (100%), 1x4 for T-Junction (92.8%) and 1x6 configuration for MLDPCW (81%) show maximum power transmission. Moreover, with optimize parameters the output power of different and their comparison with different configuration have done.

5.2 Limitations

The splitting limitation of power splitter circuits are more specifically depends on some criteria's that must be considered. Those criteria include the following:

- Broadband – Power splitters should have very small wavelength sensitivity. The ideal device is has no wavelength dependency.

- Uniform Distribution – Except for special applications, power splitters should equally distribute power, and all the outputs should be similar. In the ideal case all outputs are identical.

- Low Insertion Loss – Insertion loss reduces the performance of splitters, and the lower the insertion loss, the better the performance. In general, the return loss and radiation loss should also be minimal, so that almost all the power is transferred to output ports.

- Compactness – If a several devices are used to make a power splitter, the circuit can be very bulky. It is important to use compact devices, or make the circuit as compact as possible. It reduces the manufacturing cost, and makes the circuit easier to combine with other components of the system.

Several devices can be used in power splitter applications, including T-junction, Y-junctions, PCWLD-MMI, and PCWLD. Depending on the requirements of the splitter application, a designer can use any of these devices or a combination of them. Among these devices, Y-junction has better performance considering its insertion loss, size, and similar outputs. But it has only two outputs. Major two issues of limitation need to be solved before it can be used in practical applications: the transmission efficiency should be increased and the grating reflection reduced. The efficiency can be improved by using an optimized grating design and SOI wafers with a buried reflector. The reflection may be reduced by using a properly designed asymmetric grating.

5.3 Future Scope

Photonic devices lie at the heart of the communications revolution, and have become a large and important part of the electronic engineering field. Photonics is discipline concerning the control of light, or photons, for useful applications, much as electronics has to do with electrons. Light is electromagnetic radiation of frequencies in the range from 1 THz to 10 PHz, corresponding to wavelengths between 300 μm and 30 nm in free space. This optical spectral range is generally divided into infrared, visible, and ultraviolet regions. The spectral range of concern in photonics communication is usually in a wavelength range between 1.50μm to 1.60μm. The primary interest in the applications of photonic devices is in an even narrower range of visible and near infrared wavelengths. Experimental results have demonstrated that an input signal can arbitrarily be split into two or more signals output ports by uploading optimized multicasting phase holograms onto the Opti-FDTD simulator. Generally speaking, the photon nature of light is important in the operation of photonic splitter devices for generation, amplification, frequency conversion, or detection of light, while the wave nature is important in the operation of all photonic devices but is particularly so for devices used in transmission, modulation, or switching of light. Moreover that, a bandwidth exceeding 50 nm over the C-band of optical telecommunications has been measured, making the adaptive splitter attractive for many optical network applications. The point of view this thesis is to optimize and analyze the power distribution & transmission characteristic of the different types of power splitter structures which configuration is formed in 2-D and 2-D slab photonic crystals. To achieve the equal power at each output channel all configurations are optimized by 2-D FDTD computational method with vary of different wavelength and bandwidth spectrum. Photonic crystal based power splitter can be used in wide application area such as on-chip optical interconnect, nano-technology, data control in high speed optical communication link and also beam formation in Phased Antenna Array (PAA). For further research to design and practical implementation of photonic devices are needed for better and fast performance in nano advanced technology.

5.4 Conclusion

T-Junction, Y-Junction, PCLD-MMI Splitters and PCLDW splitters in different lattice configurations (like rectangular, hexagonal, FCC and BCC structures) with TE and TM mode have been designed, simulated with FDTD method. Performance of each structure was characterized and compared with each other by maximum power transmission. It has shown the different types splitter have relatively higher transmission efficiency in contrast with others. Finally, with optimize parameters the output power of differentiation and their comparison with different configuration have been done. Based on these structures optimizations higher efficiency power splitters were designed which can be used in networking, modulation, transmission, switching etc. application.

References

Joannopoulos, J. D., Johnson, S.G., Winn, J. N., and. Meade, R. D. (1999), *Photonic Crystals: Molding the Flow of Light*, Princeton University Press, USA.

Dey, R. (2011),'Optical Power Splitting Techniques Using Photonic Crystal Line Defect Waveguides' Ph.D Thesis, The University of Western Ontario, Canada.

Forbes, M., Gouly, J., and Desmulliz, M. (2001), 'Optically interconnect electronic chips: A tutorial and review of the technology', *J. Elect. and Comm. Engg*, 13, 221-223, viewed Oct 2001 < http://ieeexplore.ieee.org>.

Yu, T., Zhou, H., Yang, J., Jiang, X., and Wang, M. (2008), 'Ultracompact multiway beam splitters using multiple coupled photonic crystal waveguides', *J.Phys.D:Appl. Phys*. 41, 1-5 <http://iopscience.iop.org/0022-3727/41/9/095101>.

Fan, S., Johnson, S. G., Joannopoulos, J. D., Manolatou, C., and Haus, H. A. (2001), 'Waveguide branches in photonic crystals', *J. Opt. Soc. Am. B.* 18, 162-165 < http://www.opticsinfobase.org/josab/abstract.cfm?uri=josab-18-2-162>.

Chowm, E., Lin, S. Y., Johnson, S. G., and Villeneuve, P. R. (2000), 'Three-dimensional control of light in a two-dimensional photonic crystal slab', *Nature*, 407, 983, viewed 26 Oct 2000, <http://www.ncbi.nlm.nih.gov/pubmed/ 11069173>.

Notomi, M., Shinya, A., Yamada, K., and Takahashi, J. (2001), 'Single mode transmission within photonic bandgap of width-varied single-line-defect photonic crystal waveguides on SOI substrates', *Electron. Lett*. 37, 293, viewed 1st March 2001, <http://ieeexplore.ieee.org>.

Taflove, A. (1995), *Computational Electrodynamics: The Finite-Difference Time-Domain Method,* Artech House, Boston.