A Compact Polarization Independent Power splitter for Mid IR Range

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Abstract
Photonic crystal based Power splitters being associated with significant advantages related to dimensions have been widely explored in literature in last few years. However these devices are associated with a serious drawback of polarization dependency which restricts their operation in various optical interconnects. This paper designs compact Photonic crystal based polarization independent Power splitter for Mid IR Range. The proposed structure has very small footprints with dimensions of 10×10µm² shows a transmission efficiency of efficiency of 97% at wavelength of 1430 nm. Such a small footprint power splitter can help significantly while designing optical setups in areas of spectroscopy and security.

Keywords
Bandgap, Photonic crystal, Photonic integrated circuits, Power splitter, Polarization

Introduction
Photonic crystals (PhCs) have created opportunities where all optical devices can be created to realize all optical communication systems. Creation of miniaturized photonic integrated circuits (PICs) was a challenge till it was difficult to confine optical light in compact space. However PhCs have opened the path where light confinement and control can be done at micro scale and nano scale [1]. This can be attributed to fact of photonic band gap (PBG) which is wavelength or frequency region restricting optical modes inside PhCs. Literature finds various PhC structure based miniaturized photonic devices like de-multiplexers [2-4], optical- filters [5-7], switches [8-10], waveguides [11], and logic- gates [12-14]. Amongst these miniaturized photonic devices power splitter being the major component for dividing input power to equal power has received remarkable attention of researchers in recent past. Power splitter proposed by Xuan Zhao et al. changes the direction of emitted light by modulating the period of air holes [15]. In another structure by T. Sridarshini et al. power splitter uses ring resonator along with waveguide using dielectric rods of silicon in air background. The structure implemented for 1x2, 1x4, and 1x8
generated an output efficiency of 87.12%, 87.06%, and 86.27% [16]. Mohammad Danaie et al. proposes triangular lattice based Y junction power splitter on GaAs substrate and an air hole array with output efficiency of 49 % in each arm of 60° bend [17].

Polarization splitter with self-collimation features of PhCs is proposed with transmission efficiency of 35% for Transverse magnetic (TM) and 30 % for Transverse electric (TE) polarization of light [18]. Haung et al. uses hybrid combinations of PhCs waveguides to realize power splitter with normalized frequency ranging from 0.3904 $\omega a/2\pi c$ to 0.4199 $\omega a/2\pi c$ is in $-3$ dB [19]. The transmission efficiency at normalized frequency of 0.4112 $\omega a/2\pi c$ is $-0.13$ dB with extinction ratio 31.76 dB for TM transmissions and $-0.04$ dB with extinction ratio 80.54 dB for TE transmissions. Ring resonator with PhC structure is used by Ghaffari et al. to produce T bends having high performance characteristics in third optical window with large bandwidth [20]. Five output power splitter is designed with dimension of 21µm x 10 µm by Simranjit Singh et al. with efficiency of 52.2%, 16.9%, 14.6%, 12.1% and 3.4% in each arm [21]. Power splitter which is polarization independent and appropriate for TE and TM propagation is introduced by Hadi Razmi et al. with PBG ranging between 0.4 - 0.5 and transmission efficiency of 45% at 1.56 µm [22]. Several photonic crystal ring resonator based existing structures of optical multiplexers and demultiplexer with their individual advantages and disadvantages have been discussed. Further, the correlation of their relating structural and performance parameters has been presented. Future design considerations based on the existing techniques and comparison survey has also been suggested for the specialists which would be useful for them in planning better structure with improved execution [23]. In this a polarization free 1xN splitter based on 2D high index difference gratings has been presented. It is based on the distribution of incident light into N spots in the desired wavelength region. 1x3 and 1x4 splitters have been realized based on coupled wave analysis (CWA) through numerical simulation and fabricated on SOI wafer. Polarization free splitting has been achieved with high transmission at 1.55µm [24].

Y-splitter with dimension 21 × 21µm reports reduction in radiation losses for TM mode, efficiency of 44% and splitting-ratio 50 [25]. Microstructured polarization splitter using polyethylene fiber based on photonic crystals is optimized with air holes to achieve broadband for terahertz frequency. Structure is optimized for extinction-ratio and length of device to produce very low bending loss. [26]. 1 × 2 power splitters using meta-material structure are designed to meet requirements of PICs for very small footprints. Results indicated that the devices can provide excess loss less than 3.3dB over 100 nm bandwidth centered at 1550 nm [27]. PhCs based power splitter structures in literature having dielectric rods in air suffer serious drawback of plane losses due to insufficient vertical confinement and fabrication issues.

Designs based on square and rectangular lattice have small PBG and results in scattering of light due to sharp bends. Literature finds few designs based on elliptical air holes but they are difficult
to fabricate. Recent era of smart PICs demands high performance power splitters with miniaturized dimensions. Their performance is hindered due to polarization dependence. This paper presents a power splitter design that handles these challenges using model with additional defects at corners. It presents a compact polarization independent power splitter allowing polarization independent transmission in mid IR range. This is based on PhC structure with careful design of defects at corners and split in two arms for equal power split. Section 2 of this paper presents design procedure, followed by results and discussion in section 3 and finally in section 4 we present conclusions to our work.

Design Procedure

The design proposed in this paper aims splitting of all optical power for both TM and TE transmissions so that, there is no restriction in its operations on different optical interconnects. This design is proposed considering small footprints requirements in present era for spectroscopy in mid IR range. This requires a structure based on PhC with joint PBG region. Y- Shaped Power splitter is realized with creation of Y- shaped optical waveguide in PhC structure for one input and two outputs. It follows with insertion of line defects in shape of Y by removing holes from the symmetric PhC. The angle between output ports is carefully selected to be 60 ° with horizontal for symmetric power distribution between the two arms. Further there occurs losses and modal mismatching across the junction resulting reflections and reduction in transmission efficiency. These losses and mode mismatching can be tackled by enhancing resonance at the junction as shown by fig. 1. This has been catered in the design by incorporating point defects (shown as green) of air holes (refractive index 1.009) at the junction whose radius has been optimized to produce minimum losses and maximum transmission. This enhancement of contrast between refractive index in interstitial sites results in longer resonance and better transmission.

Figure 1: Resonance and losses at the junction
This power splitter has dimensions of $10 \times 10 \mu m^2$. It has been found that for proposed design of radius to lattice constant ratio ($r/a$) falls in range 0.35 to 0.42, it support polarization independent transmissions. Thus in order to design power splitter for all optical transmission this range has to be followed.

There are severe modal mismatching and losses across the bends in the structures existing in state of art. The proposed structure is carefully designed to tackle these two issues that result in reduction in transmission efficiency. This is based on insertion of certain defect rods whose position, radius and arms lengths of splitter is optimized to enhance transmission efficiency of power splitter at 1430 nm. Fig. 2 shows proposed structure which uses silicon (refractive index $n_1$ 3.42) as substrate with air (refractive index $n_2$ 1.009) holes as dielectric. Design places four defects rods across the bend (shown by red). As $n_2 < n_1$, the introduction of these defects lowers refractive index across the bends which in results lowers the signal losses across these points.

The length of branches has been carefully configured so that coupling of modes takes place appropriately. When light is injected in one arm it propagates certain distance ($L$) before it gets coupled to other arms. $L_c$ is the distance which results in accumulation of phase difference $\pi$ between the two modes represented by eq. 1 [28].

$$L_c = \frac{\pi}{\beta_o - \beta_e}$$  \hspace{1cm} (1)

Signal need to propagate length $L_c$ so that it is best coupled to other arms else more losses take place due to modal mismatch. $L_c$ is related to coupling constant $k$ as shown in eq. 2[29]:

$$k = \frac{\pi}{L_c}$$  \hspace{1cm} (2)
The transmission in output port 1 and output port 2 can be written as eq. 3 and eq. 4.

\[ P_A = \sin^2 \frac{2\pi L}{2\pi c} \]  

\[ P_B = \cos^2 \frac{2\pi L}{2\pi c} \]  

(3)  

(4)

As PhC structure is discrete L is always integral multiple of lattice constant a. Hence the proposed design is optimized for the arm length to reduce these modal mismatches which are major reason for reduction in transmission efficiency.

Results and discussions

After incorporating the steps of design procedure the proposed model of power splitter is tested by simulation for its functionality. Fig.3. presents the band diagram where TE and TM propagation co-exits. The bandgap for TE polarization exists from \(0.29 \frac{\omega a}{2\pi c}\) to \(0.43 \frac{\omega a}{2\pi c}\), where ‘c’ represents free space speed of light. The bandgap for TM polarization exists from \(0.35 \frac{\omega a}{2\pi c}\) to \(0.43 \frac{\omega a}{2\pi c}\). The region which supports all optical transmission with no restriction to its operation is from \(0.35 \frac{\omega a}{2\pi c}\) to \(0.43 \frac{\omega a}{2\pi c}\). This can be attributed to the fact that in this region both TE and TM mode exits.
Table 1 summarizes the output efficiency obtained over varying lattice constant ratio (r/a) when it is being varied from 0.35 to 0.42 in step of 2. The output efficiency computed for the designed power splitter increases from 78% to 97%. But beyond that with further rise in r/a ratio there is fall in efficiency to 94 % to 85 %.

| Radius to lattice constant ratio (r/a) | Output efficiency (%) |
|--------------------------------------|-----------------------|
| 0.35                                 | 78                    |
| 0.37                                 | 97                    |
| 0.39                                 | 94                    |
| 0.42                                 | 85                    |

It signifies that the proposed design outperforms when r/a is 0.37. This can be attributed to the fact that these dimensions are best suiting for modal propagation with reduced mismatch and reflections. This is result of cautious selection of various design parameters. Careful design with optimization of radius, arm length and defects has made this power splitter suitable for all optical transmissions. It has applicability in different optical interconnects without any hindrance as both TE and TM modes are coexisting. The additional defects introduced with reduced refractive index across junction points and across the bends has led to enhanced confinement and reduced modal mismatching. The outperformance behaviour can be reasoned to the fact that defect rods with reduced refractive index enhance the contrast between refractive index. This enhanced
contrast enhances resonance and thus results in better transmissions. Selection of arm length is another attribute which is integral multiple of lattice constant and is optimized to reduce these modal mismatches for reduction in transmission efficiency.

Conclusions

This paper presents miniaturized power splitter suitable for spectroscopy at the wavelength of 1430nm with footprints of $10 \times 10 \mu m^2$. The design of splitter has been proposed such that it supports all optical transmission allowing both TE and TM modes. This makes this splitter suitable for all optical interconnects without any hindrance. The design has been optimized by introducing certain point defects with reduced refractive index in order to enhance refractive index contrast. It is optimized for position, radius of defects along with arm length of splitter. This splitter provides the output with maximum efficiency of 97% when $r/a$ ratio are 0.37. This splitter finds its usability in PICs for spectroscopy or other application which demand miniaturized power splitters. The design of this power splitter can be further enhanced to explore for tunability to various wavelength.

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