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Ultra Sharp Photonic Crystal Hybrid Bends

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ABSTRACT: The information carrying capacity of Electronics circuits is of the order of GHz whereas the optical waveguides on integrated circuits can carry the information using light (Optoelectronic) i.e. using a frequency of the order of THz. The optical waveguide empowers not only an enormous bandwidth increase i.e. in the range of multiple terabits per second, but causes a decrease in power consumption, reduced immunity to temperature variations, immunity to electromagnetic noise interference, etc. This paper presents and analyzes the study by optical simulation, the impact of introducing a 2D Photonic Crystal (PhC) lattice made of air rods embedded within a Si core and placed on the Silica (SiO_2) confining layer at the bend section of waveguide. The goal is to create a light-trapping Hybrid waveguide (consisting of straight dielectric strip waveguide and bend photonic crystal waveguide) which offers minimum bending loss. Different bending angles (i.e. 60^o and 90^o) along with their transmission efficiency through the bend at waveguide width of 0.5µm has been discussed and compared. The results show that the Hybrid configuration has a real potential for enhancing the efficiency. Well known Finite Difference Time Domain (FDTD) method has been used to optimize the efficiency and structure of Silicon-on-Insulator (SOI).

KEYWORDS: Photonic Integrated Circuit, Hybrid Photonic Crystal waveguide, Silicon-on-Insulator, Transmission efficiency, Waveguide width.

I. INTRODUCTION :SILICON PHOTONIC CRYSTAL

An optical waveguide used at optical frequencies can be developed through two most profound techniques i.e. firstly a high refractive index contrastrectangular dielectric waveguide and secondly the Photonic Crystal Waveguide. These Optical Waveguides come under the category of Optoelectronics, an application of Photonic Integrated Circuits (PICs).

As the number of components grow on a PICs (generally in µm or nm) so in establishing a connection between two components (i.e. though routing) sharp bends are required. So the bend is considered to achieve high packaging density for PIC [1]. For PIC production there is a need to use a material system by which a sharp bend with low loss can be attained. Keeping low loss in mind Silicon has been used as a base material for microelectronic devices.

Silicon photonics is the study of photonic systems which use silicon for optical switching and optical waveguide for data transfer. Silicon photonic devices are considered because Si is abundantly available and devices can be made using existing semiconductor fabrication techniques. An additional advantage for using high refractive index Siliconshown in Figure.1 isit's ability to confine the light to the core of the waveguide [2].

To utilize both the advantages Silicon based waveguides are preferred. Hence Silicon on Insulator (SOI) technology is used to design waveguides which are discussed in this paper. The Si is used as a substrate of height 100 µm and a core (where light propagates) of height 0.215 µm. The confining layer of $SiO_2$with height of 3 µm is sandwiched betweenthe substrate and core.

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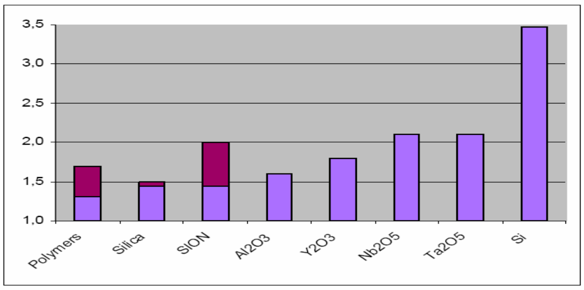
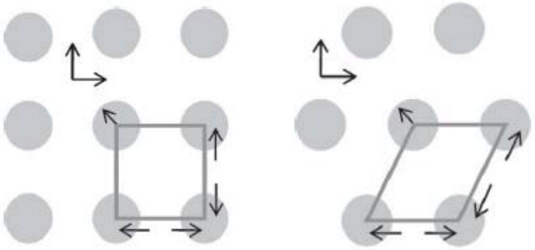


Fig. 1. Refractive indexes of materials employed to build optical waveguides

Photonic crystals are periodic structures with a large contrast of dielectric constant. The lattice can prohibit the propagation of certain electromagnetic waves. There may be gaps in the energy band structure of the crystal, meaning that electrons are forbidden to propagate with certain energies in certain directions. If the potential is strong enough, the gap can extend for all directions in some energies (or frequencies), resulting in a complete band gap, called photonic band gap (PBG) or Electromagnetic Band Gap (EBG). The photonic crystals are array of elements with high dielectric constant immerse in a low dielectric constant media, or holes with low dielectric constant in a high dielectric constant media. The dielectric cylinders of air can be arranged in Triangular or Square lattices as shown in Figure 2. In other words they can also be termed as hexagonal or Rectangular lattice.



(a) (b)

Fig. 2(a) Square or Rectangular Lattice (b) Triangular or Hexagonal Lattice

If a defect is inserted in a two-dimensional photonic crystal lattice, removing or changing the radius or dielectric constant of elements from a line, it creates a photonic crystal waveguide, a region surrounded by reflecting walls [3].

In this paper the concentration is basically on the transmission efficiency incur by the waveguides at different bending angles for a particular waveguide width of 0.5μm.

In this paper comparative analysis of three different types of waveguides (straight, 60^o bend and 90^o bend) is presented.

II. HYBRID OPTICAL WAVEGUIDES

The evolution of Hybrid optical waveguides is considered here in this paper. A waveguide used at optical frequencies is an optical waveguide. Those optical waveguides developed through the combination of two already mentioned techniques i.e. Rectangular Dielectric Waveguide and Photonic Crystal Waveguide are Hybrid Optical waveguides. These two waveguides been discussed extensively in the previous paper [4].

A major drawback of conventional dielectric waveguides is that their bending radii are limited to several millimeters due to the degradation of total internal reflection. Since the guiding of light in a Photonic Crystal defect waveguides is not given through total internal reflection but the photonic bandgap (PBG) effect they can provide bending within the sub-wavelength range.

As far as straight waveguide is concerned, the photonic crystal are yet to prove their advantage for guiding and routing applications over conventional channel waveguide (also referred to as a wire or strip waveguide) which are comparable in size and much easier to design. But photonic crystal waveguide outcast strip waveguide in terms of light confinement, dispersion and losses for a bend waveguide [5].

But the Photonic crystal waveguide cannot be used as both straight and bend waveguide because of its large area so it can only be used at the bends and for the straight waveguides there is need for some other waveguide to get a Hybrid waveguide.

So to inculcate the advantages of both the strip waveguide (in straight section) and photonic crystal waveguide (in bend section) a Hybrid Waveguide (combination of both to form a single waveguide) is used to obtain losses at different angles and to achieve high power efficiency.

III. DESIGN OF HYBRID WAVEGUIDE

The photonic crystal waveguide i.e. used at the bend section of Hybrid waveguide contains air holes to maintain high refractive index contrast. The lattice constant for the crystal is set as a=430nm. The hole diameter is set to be as 0.5a i.e. 215 nm, where a represents the lattice constant. The hole diameter is varied for some of the holes at the bends. The one line defect enables the light from the source to be guided to the end of the waveguide.

The position of holes to be varied at the bend is first randomly assumed. Then for that particular position, the size of the holes is changed to attain highest efficiency. These efficiencies are compared with efficiencies obtained for different positions to get a particular design of the bend waveguide. So in order to design a Hybrid 60° bend with waveguide width of 0.5 µm, the efficiencies obtained were 83.74 %, 92.896 %, 95.44% and 81.62 % for hole radius 0.05 µm, 0.1 µm, 0.11 µm and 0.15 µm respectively. The hole radius of 0.11 µm which shows highest possible efficiency for the implemented hole position is selected. Similarly 90° bend waveguide was designed from the possible efficiencies of 82.79 %, 87.81 % and 95.14 % for hole radius of 0.23 µm, 0.24 µm and 0.25 µm. So hole radius of 0.25 µm is the one selected for achieving high efficiency. This shows how the structures of hybrid 60° bend and hybrid 90° bend waveguide been designed.

All the results obtained throughout are 2D FDTD analysis of the design. When creating a line or a point defect in 2D photonic crystal, one must not forget that the structure, although 2D is only periodic, is still a 3D object. The concept of photonic insulator (or photonic bandgap) works very well in the plane but does not apply in all the three dimensions; for the third dimension total internal reflection (TIR) is to be relied on. So in these obtained results losses due to TIR are indistinguishly added to the photonic crystal losses.

IV. PARAMETERS STUDIED

The waveguides are simulated and compared for some parameters which are angle subtended by the waveguide, mode profile and power efficiency to see the performance of the waveguides.

1. *Angle of Waveguide Bend*

With the advancement in time the chip density increases. As the number of cores grow on such a miniaturePICs (generally in µm or nm) so in establishing a connection between two components (i.e. though routing) sharp bends are required. The connections between the cores are established with the help of Optical Waveguide. But every waveguide need for interconnection cannot be a straight one hence sharp bends of every angle are required to make the Routing easier. Different angle of bend designed are 0° (i.e. straight waveguide), 60° and 90°.

2. *Mode Profile*

Mode shows the possible Transverse Electric (TE) mode supported in the waveguide. The mode is observed both in 2D and in 3D (i.e. contour plot). But the plots shown here are 3D contour plots.

3. *Power Efficiency*

Power Efficiency is computed by the ratio of Output Power to the Input Power, shown in Eq (1). To enhance the power efficiency there is a switch from pure dielectric waveguide to hybrid waveguide. So for this Power is monitored by the Power Monitor at the output of a waveguide in watt (W) for input power equal to one watt (1W). Power Monitored is used for comparison as high power monitored accounts for better performance of the waveguide due to low losses.

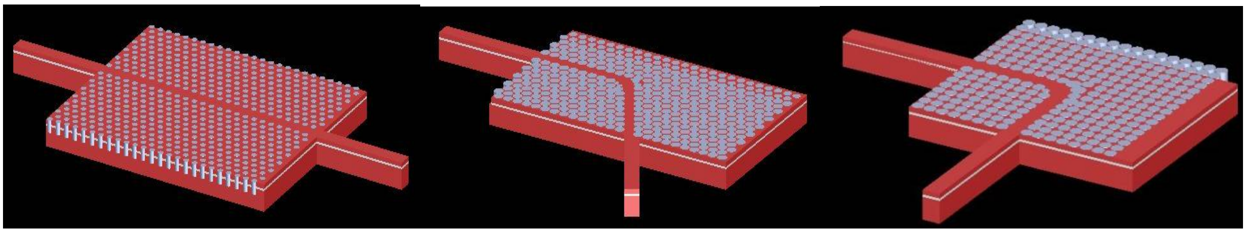
$$\eta = \frac{P_O}{P_I} \qquad \text{eq. (1)}$$

whereη : Efficiency, P_0 : Output Power, P_I : Input Power

V. SILICON BASED HYBRID WAVEGUIDES

1. *Structure*

Below is shown an SOI based Hybrid Si straight waveguide in Figure 3(a), Hybrid 60° bend waveguide in Figure 3(b) and Hybrid 90° bend waveguide in Figure 3(c), in which the bottom most layer is Si substrate of height 100 µm. Above it, is SiO_2 with height 3 µm and the Si core where light propagates is of height 0.215 µm. The 3D view of the design is shown in Figure 3.



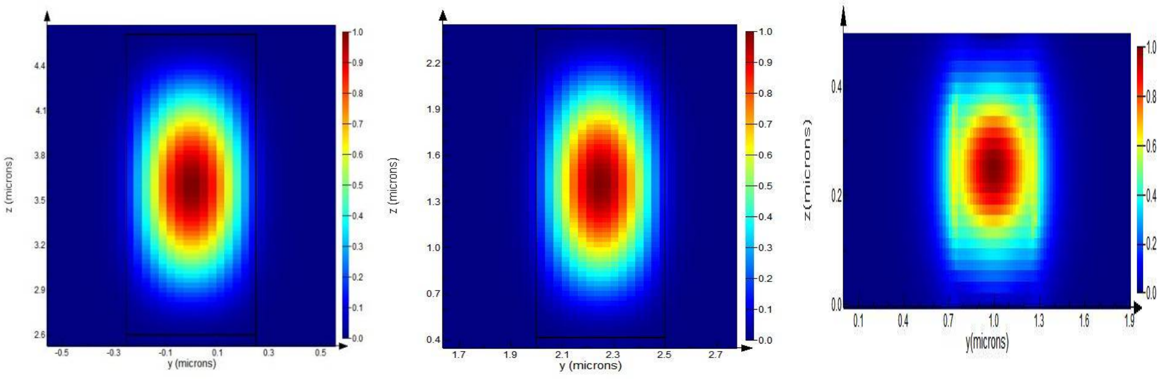
(a) (b) (c)

Fig.3(a) Hybrid Straight Waveguide (b) Hybrid 60° bend Waveguide (c) Hybrid 90°bend Waveguide

2. *Mode*

The various modes that are propagating in the waveguide are shown below in the Figure 4 with waveguide width of 0.5µm.

TE (Transverse Electric) mode

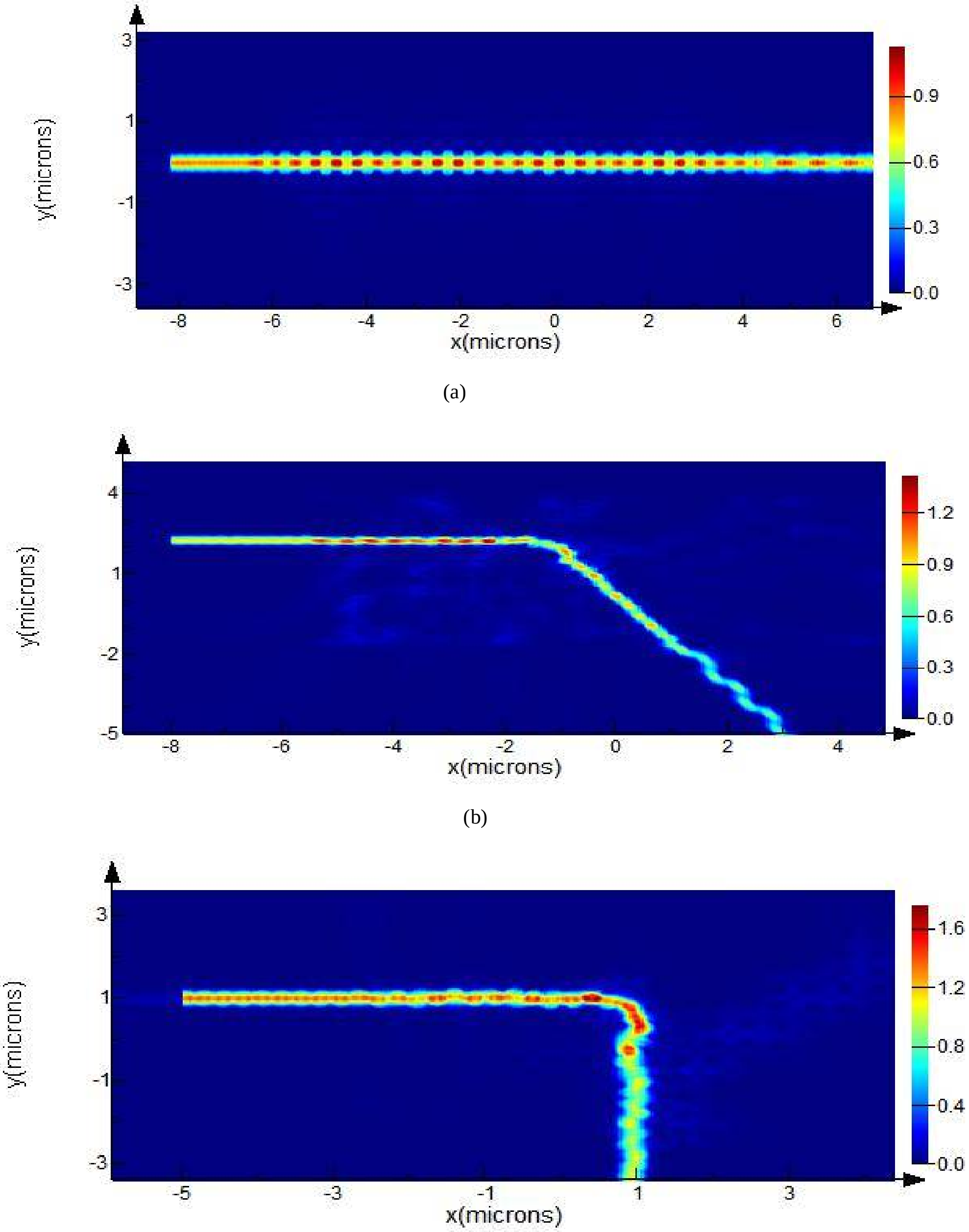


(a) (b) (c)

Fig.4 TE mode profile for Si Hybrid waveguide at waveguide width of 0.5 µm
(a) Straight Waveguide (b) 60° bend Waveguide (c) 90° bend Waveguide

3. *Field Propagation*

The field propagation from source to the end of the waveguide is shown in Fig. 5.



(a)

(b)

(c)

Fig. 5 Power propagation for Si Hybrid waveguide
(a) Straight waveguide (b) 60° bend waveguide (c) 90° bend waveguide

4. *Power Efficiency*

Power efficiency is calculated for Si based Hybrid waveguides at three different angles i.e. 0° bend (straight), 60° bend and 90° bend with waveguide widths of 0.5 µm.

The values of the Efficiencies are shown in Table 1.

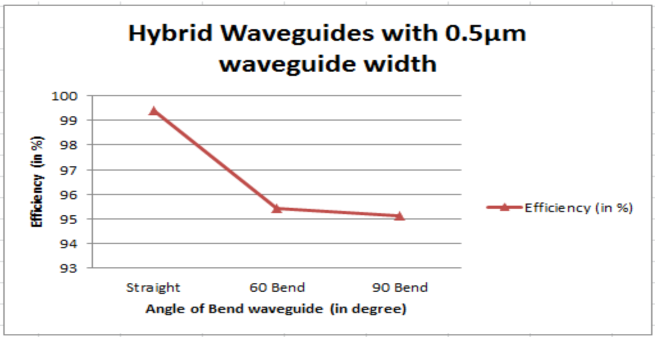


Fig. 6. Power Efficiency vs Angle of bend Waveguide plot for Hybrid waveguide

Table 1: Comparison of Power Efficiency of Si based waveguide on the basis of angle of waveguide

Angle of Waveguide (degree)	**Efficiency (Si)** (%)
Straight	99.372
60^o Bend	95.4433
90^o Bend	95.1446

The result of Table 1 has been shown graphically shown in Figure 6. The graph has been plotted to highlight the fact that the efficiency decreases with increase in the angle of bend of waveguide. In the graph on the horizontal axis is the angle of bend waveguide (in degree) and on the ordinate is the efficiency calculated (in %). The line drawn in the graph shows the efficiency of design using SOI technique (Si substrate). From graph it can be seen that with 0.5 µm waveguide width the efficiencies show largest difference from straight to 60^{o}bend waveguide, which gradually decreaseswith the increase in angle of waveguide bend.

Table 2:Comparison of Proposed Results with Previous Paper Results

Material	**Technique**	**Angle**	**Efficiency** (%)	**Analysis**
Si based [6]	Photonic Crystal Waveguide	90^o	90.9%	QMR and FMM (reduce computational complexity) Global Optimising Algo.)
GaAs substrate & $Al_{0.9}Ga_{0.1}As$ (vertical confinement) [7]	Photonic Crystal Slab	60^o	90%	2D FDTD
SOI [8]	Cubic Photonic Crystal (Adding 3 holes at corners)	90^o	96.8%	2D FDTD

GaAs substrate [9]	Photonic crystal	90^o	95%	2D FDTD with PML boundaries. Also hold true for 3D Photonic crystals
GaAlAs [10]	Photonic crystal (Mode pattern and wave no. match)	60^o	> 90% for entire C band	2D FDTD
InGaAsP (guiding layer) n+ InP (substrate) [11]	Photonic crystal	60^o	96.8%	2D FDTD, 2D MMP, 3D FDTD
Si substrate [12]	Photonic crystal Dielectric (ceramic) & Mettalic (Aluminium) rods	Double 90^o Crank shaped bend	89% 65%	FDTD method and Vector network analyser
Si substrate [13]	Photonic crystal Overlapping fields of straight and bend waveguide	60^o	72.7 - 87.5%	2D FDTD
GaAs substrate [14]	Photonic Crystal Waveguide (3 line defect)	60^o	70%	Electron beam Lithography
Si Substrate SiO_2 Confining layer (Proposed Results)	Hybrid Photonic Crystal Waveguide (Single line defect) with variation in size and position of rods at bends	0^o	99.372%	2D FDTD Analysis
		60^o	95.4433%	
		90^o	95.1446%	

Table 2 shows the efficiencies obtained for Photonic Crystal Waveguides for 60^o and 90^o bending angles using different techniques or structures. Results obtained for Hybrid Photonic Crystal Waveguide with width of 0.5µm is shown as proposed results at the end of the table.

All the efficiencies of proposed results for Hybrid waveguides are obtained through 2D FDTD analysis are far better than previously obtained efficiencies by other authors as described in Table 2. The best possible efficiency for a 60^o bend from Table 2 is approximately 90% whereas obtained efficiency through Hybrid Waveguide is greater than 95%. Similar is the case with 90^o bend waveguides. Table 3 also emphasizes on the efficiency for a straight waveguide that is approximately 100%.

VI. CONCLUSION

This paper is giving a precise knowledge of Si based Hybrid optical waveguide bends. The material of the waveguide is chosen to be Si which has a high refractive index contrast and by adjusting the position and size of the holes at the bend to maximize the overall transmission efficiency. With the help of hybrid waveguide the transmission efficiency greater than 95% (for straight, 60^o bend and 90^o bend) is attained using the designed waveguide of width 0.5

µm. All these obtained efficiencies through 2D FDTD analysis are far better than previously obtained efficiencies by other authors described in the previous paper. Finally, it can be concluded that with the help of Si based hybrid optical waveguides the efficiency of transmission for a particular waveguide width increases significantly with decrease in bending angles.

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BIOGRAPHY

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His research focuses on Bending Losses of Hybrid photonic crystal waveguides.

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