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Ultra Sharp Photonic Bends: A Review

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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. Thus optical waveguides can be used to carry the information in VLSI circuit e.g. Microprocessors at the speed of light. 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. Hence the design and investigation of high transmission and low bending loss by photonic crystal waveguide has been a subject of strong interest in the past decade. In this paper different technique used for designing optical waveguide bends, the different bending angles along with their transmission efficiency through the bend at various frequencies have been discussed and compared. From the tabular comparison it can be observed that the material is to be chosen with a high refractive index contrast and by adjusting the position, size, structure and refractive index of the holes at the bend to maximize the overall transmission efficiency.

KEYWORDS: Photonic Integrated Circuit, Photonic Crystal waveguide, Bending radius, Transmission efficiency, Bandwidth.

I. PHOTONICS INTRODUCTION

The evolution of optical waveguides is considered here in the paper. For the electrical signals of the order of Hertz cables were used, which were considered as lumped networks since the characteristic length was much less than the wavelength of the signal. But for transmitting the same frequency over longer lines or higher radio frequency signals (3kHz to 300GHz) on smaller lines there was a need of a transmission line. For the length of the wire approaching the wavelength showcased wave like properties of the signal. For transmitting higher microwave signals (300MHz to 300 GHz) we need a shorter dimension of transmission lines called waveguides [1]. A waveguide is a tube of uniform cross-section used for transmitting the electromagnetic waves (EM Waves) by successful reflection from inner walls of the tube. The latest transmission line which makes use of even higher frequency (~THz) in the visible range (i.e. light) is optical waveguide. It has the advantage of large data transfer, minimal power dissipation, bandwidth of multiple terabits-per-second and power dissipation independent of the distance spanned by optical waveguide. There are other motivations for using Optical waveguides are that it is difficult (not impossible) to monitor or tap, so data security is higher. Also it is immune from electromagnetic interference (EMI), induced cross talks, ground loops, etc. Photonics is a science which includes regeneration, transmission, emission, modulation, signal processing, amplification, switching and detection/sensing of light. The use of even higher frequency can also be made possible for transmission on the micrometer distance range on Integrated circuits through the on-chip Optical Waveguides. An optical waveguide used at optical frequencies can be developed through two most profound techniques i.e. firstly the dielectric waveguide in which a dielectric material with high permittivity (i.e. film), and thus high index of refraction, is surrounded by a material with lower permittivity (i.e. surface) and secondly the Photonic Crystal Waveguide. These Optical Waveguides come under the category of Optoelectronics, an application of Photonic Integrated Circuits [2]. 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. For PIC production we need to use a material system by which we can get sharp bend with low loss. In this

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paper the concentration is basically on the bending losses incur by the waveguides at different bending angles. The different techniques and materials for a waveguide which are used to enhance the transmission efficiency at different frequencies are also studied and depicted in a tabular form.

II. SILICON PHOTONICS

Silicon has been for many years the base material for microelectronic devices. Silicon photonics is the study and application 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 Si is the high refractive index which is helpful in attaining high refractive index contrast for the confinement of light within the waveguide as shown in Fig.1 so to utilize the advantages of both hybrid devices are used.

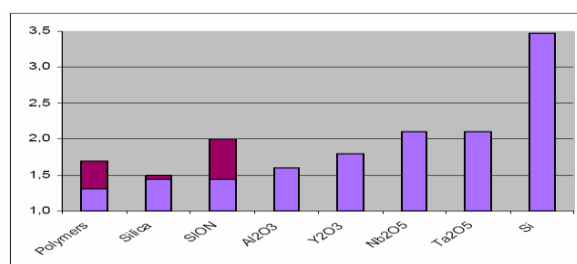


Fig.1 Refractive indexes of materials employed to build optical waveguides

III. BENDING LOSSES

The different types of losses in an optical waveguide can be absorption loss, coupling loss, waveguide loss, bending loss and insertion loss. All the losses mentioned can be minimized. Absorption loss can be minimized by changing the material used for the waveguide, coupling loss by increasing the cross-section of the waveguide, waveguide loss by taking care at the time of manufacturing to reduce the material imperfection and insertion loss by using the material of some other type. But the Bending Loss cannot be much reduced so it contributes a large percent of loss. That's the reason why bending losses need to be studied.

To establish a connection between two components (i.e. through routing) in a Photonic Integrated Circuit (PIC) there are two possibilities:

One can imagine a series of straight waveguide joined together at the junction abruptly but there would be losses at each abrupt junction.

Second method is to introduce a curved waveguide between two straight waveguides which allows a gradual transition from one direction to other and reduce the losses. Along the bend in order to maintain phase relationship across the mode, the light at outer arc of the bend moves quicker as compared to the one travelling along the inner arc of the bend. But the material within the circular waveguide is same so light cannot travel at two different velocities in same refractive index material.

This is the main reason for losses at the bend [3].

IV. OPTICAL WAVEGUIDES

A waveguide used at optical frequencies is an optical waveguide. It can be developed through two most profound techniques, which are:

1. Rectangular Dielectric Waveguide

There are three main types of Rectangular Waveguide shown in Fig.2

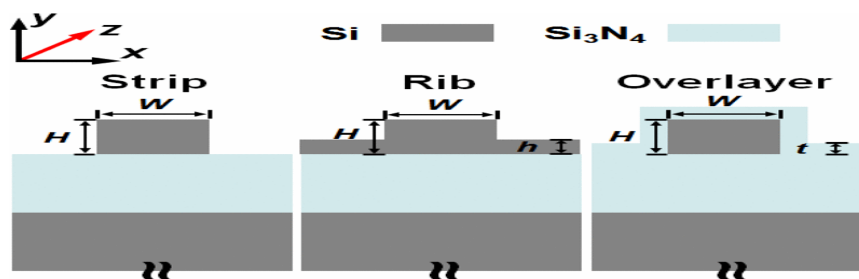


Fig.2 Types of Rectangular Waveguides

A **buried channel waveguide** (also known as **overlayer waveguide**) is formed with a high-index wave guiding core buried in a low-index surrounding medium.

A **strip waveguide** has a structure that looks like a strip/wire/ridge waveguide. Strip on top of the planar structure has a high refractive index and is actually the wave guiding core. A strip waveguide has a strong optical confinement because it is surrounded on three sides by low-index air (or cladding material).

A **rib waveguide** has its structure similar to that of a wire or strip or ridge waveguide, but the strip has the same index as the high index planar layer beneath it and is part of the wave guiding core [4].

Of these three waveguides, Rib waveguide has larger cross-section as compared to the other two waveguides so it provides high coupling efficiency but on the contrary it requires the larger area hence the chip density decreases so overall performance decreases. This is the main reason why rib waveguide is not used and other two waveguides are mainly taken into consideration.

In the recent past, various methods were proposed by different authors to determine the bending loss. The authors present a low loss, hybrid silicon waveguide consisting of a straight rib section and compact photonic wire bends. The rib and wire waveguides are both single mode and are connected through a short double-etched linear taper section. Due to the introduction of spline much improvement in bending losses comes forth for first 10° spline angles and bending radius less than $3.5 \mu\text{m}$ [5]. Another authors determined the bending loss in hybrid (Rib/wire) waveguide where bend rib section and straight wire section is used. In this paper transmission efficiency is increased to 90% but the bending radius also increases [6]. All the observations from different papers are depicted in the tabular form in Table.1

2. Photonic Crystal Waveguide

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 PC defect waveguides is not given through total internal reflection but the photonic bandgap (PBG) effect they can provide bending within the sub-wavelength range.

Photonic crystals are periodic structures with large refractive index contrast and the lattice prohibits the propagation of certain EM waves due to the gaps in the energy band structure of the crystal, i.e. the 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). This is much similar to the semiconductors theory where the valence band and the conduction band are separated by the band gap.

One can consider it as an array of elements with high dielectric constant immerses a low dielectric constant media or in other words the holes with low dielectric constant in a high dielectric constant media.

If we insert defects in a two-dimensional photonic crystal lattice we create a waveguide. There are three ways of introducing a defect in crystal lattice to make a Waveguide. They are: removing a line of holes from lattice; changing the radius of holes; changing the dielectric constant of holes [7]. It has a width in the size of lattice constant. The lattice constant is in the order of operating wavelength. Such waveguide in the size of few microns makes it a promising solution for the interconnection between functional blocks in ultra-compact photonic integrated circuits (PICs). Therefore, the design and the investigation of high transmission and low bending loss by photonic crystal waveguide has been a subject of strong interest in the past decade.

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Different authors stressed on various materials to decimate the bending radius and thereby the bending loss at distinct bending angles to enhance the transmission efficiency shown in Table 1.

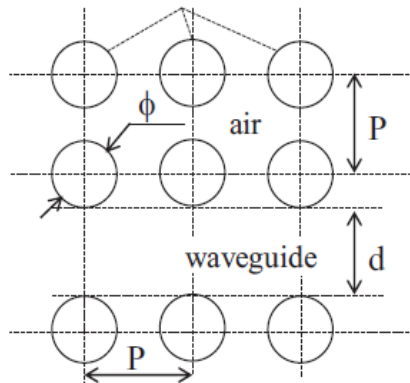
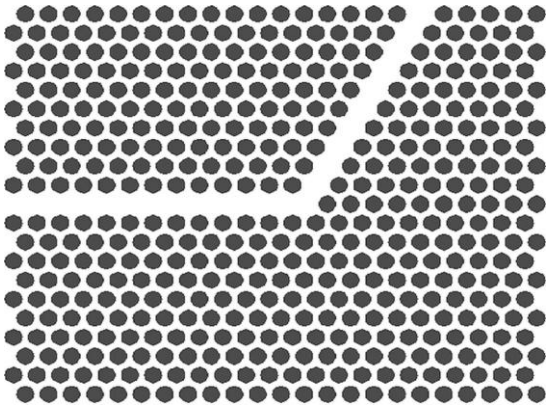


Fig.3 Schematic view of the simple 2-D photonic crystal waveguide bend
Fig.4 Top view of fundamental square lattice and waveguide bends photonic crystal waveguide

Schematic view of a Square lattice 2D photonic crystal waveguide with 60° bend is shown in Fig.3 [8]. The same figure in magnified form is shown in Fig.4 [9] in which we can see holes or rods in a cluster forms a photonic crystal. These rods can be of different materials which are contained in a substrate. The difference between two rods is P i.e. lattice constant. Generally the transmission efficiency for a photonic crystal waveguide is 90% for entire C band. To enhance the efficiency various steps can be taken like choosing a proper guided mode in the bend waveguide, which has a mode pattern similar to the guided mode in the straight waveguide. Then, alter the band structure of the waveguide bend by adjusting the size and position of the air holes near the bend corner in order to have a wider frequency region. In this region, the wave number of the mode in the bend waveguide matches that of the straight waveguide. The Optimized waveguide is shown in Fig.5 [8].

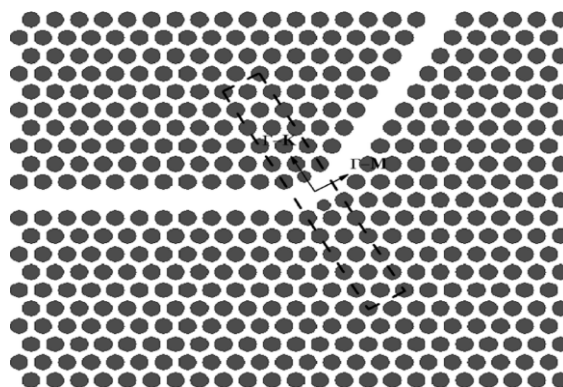


Fig.5 Schematic view of the optimized 2-D Photonic Crystal waveguide bend

By adjusting the size and the position of rods/holes at the bend corner affects the transmission efficiency.

The positions of holes need to be changed such that the wave number of the mode in the bend waveguide matches that of the straight waveguide. In other sense the field intensity of both the straight and the bend waveguide should overlap hence the difference between their peaks to be equal to the shift in the lattice points [10].

Other method that can be used for the upliftment of transmission efficiency is the introduction of Drop Holes whose structure is shown in Fig.6 and is utilized to attain high efficiency in 180° waveguide bend shown in Fig.7 [11].

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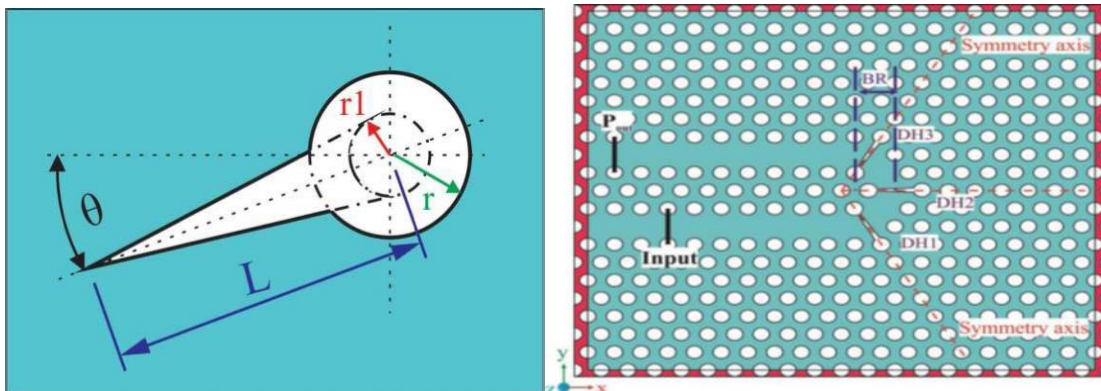


Fig.6 Layout of the drop hole used for structure tuning in the Fig.7 Schematic drawing of 180° bend waveguide
180° waveguide bends

Normalized transmission as high as 99.4% is achieved at 1550 nm optical wavelength and it is greater than 94% for nearly the entire optical C-band. Such a high transmission efficiency can be attained for large frequency band but drop holes is rarely used because it is difficult to fabricate. Hence the structure of the rods at the bend must be an easy one to fabricate.

Different losses are experienced by varying the material of rods. Two distinct photonic crystal structure consisting of dielectric (i.e. ceramic) and metallic (i.e. aluminium) rods are compared with respective straight waveguides and the efficiency is computed [9]. This shows that the transmission efficiency varies with the material of the rods.

Implicitly single line defect is taken to make a waveguide but with the increase in the number of lines of defect the overall efficiency also increases. The improvement in the efficiency is greater if the number of holes displaced at the bend corner increases [12].

The Photonic crystal waveguide because of its large area cannot be used as both straight and bend waveguide so it can only be used at the bends and for the straight waveguides there is need for some other waveguide As nano-wire waveguide offers less propagation loss for straight waveguides so a hybrid waveguide consisting of bend photonic crystal waveguide and straight nano-wire waveguide designed with low index trenches is presented in the Fig.8 [13].

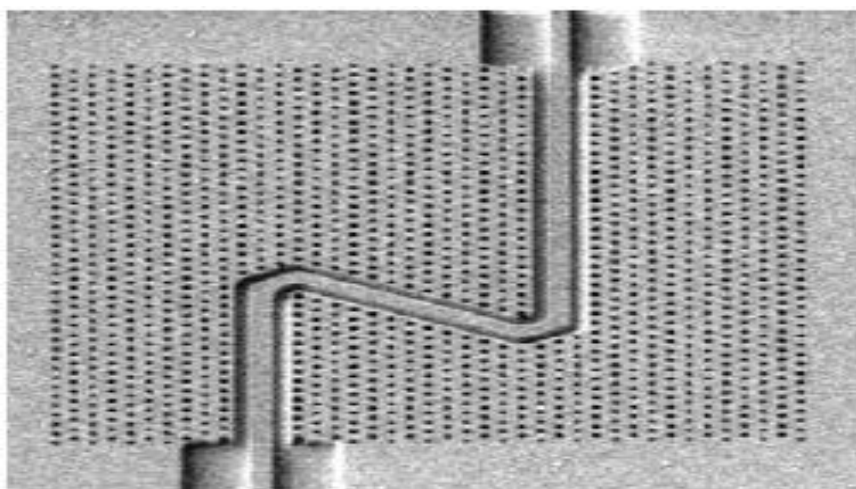


Fig.8 Top view of fabricated Hybrid waveguide

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TABLE I.COMPARATIVE ANALYSIS OF DIFFERENT TECHNIQUES

Material	Technique	Bending Radius (μm)	Angle	Bending Loss (dB/90°)	Efficiency (%)
SOI Hybrid (Rib/Wire) waveguide [5]	Double etched taper (Spline)	5	90° α=20°	0.0273	-
		3	90° α=10°	0.037	
SOI Hybrid [6]	Asymmetric Rib structure with and without outer slab region	200	90°	1.15	90%
		800		4.7	60%
SOS (Wire) waveguide [14]	-	1700	90°	10.34	-
		2550		2	
		4500		0	
SOI (Wire) waveguide [14]	-	10	90°	1.233	-
		20		0.072	
		30		0.004	
Silicon Oxynitride (SiON) [15]	Wire waveguide	2	90°	0.086	-
Si based [16]	Photonic Crystal Waveguide	-	90°	-	90.9%
GaAs substrate & Al _{0.5} Ga _{0.1} As (vertical confinement) [17]	Photonic Crystal Slab	1.5	60°	-	90%
SOI Hybrid (Photonic crystal and nano-wire) waveguide [13]	Hybrid waveguide with Low Index Trenches	-	120°	0.5	-

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SOI [18]	Cubic Photonic Crystal (Adding 3 holes at corners)	-	90°	-	96.8%
Si substrate [11]	Photonic crystal slab with 3 Drop Holes	1	180°	-	99.4%
					> 94% for entire C band
Ga(Al)As [8]	Photonic crystal (Mode pattern and wave no. match)	-	60°	-	> 90% for entire C band
InGaAsP (guiding layer) n+ InP (substrate) [19]	Photonic crystal waveguide	-	60°	-	96.8%
GaInAsP (guiding layer) InP (substrate) [12]	Photonic crystal (More than 1 line defect + Displacing 3 holes)	-	Double 60°	-	99%
Si substrate [9]	Photonic crystal Dielectric (Ceramic) & Metallic (Aluminium) rods	-	Double 90° Crankshaped bend	-	89%
					65%
Si substrate [10]	Photonic crystal overlapping fields of straight and bend waveguide	-	60°	-	72.7 - 87.5%
			120°		5.7 - 87.5%

V. CONCLUSION

This review paper is giving a precise knowledge of optical waveguides bends. Dielectric Waveguide experiences large losses at the bend whereas the Photonic Crystal Waveguide incurs less loss at the bend and is also a suitable choice to get sharper bends so chip density increases. The material of the waveguide is to be chosen with a high refractive index contrast (preferably Si as abundantly available) and by adjusting the position, size, structure and refractive index of the holes at the bend to maximize the overall transmission efficiency. With the help of photonic

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crystal waveguide the transmission efficiency of 94% (for entire C band) and approximately 99% for particular frequencies can be obtained. 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 of some other waveguide to get a Hybrid waveguide. Finally, it can be concluded that a serious research work in the field of hybrid optical waveguide is going on to enhance the efficiency of transmission, bandwidth with low bending loss at different bending angles for different waveguide materials.

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