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Parametric Analysis of Silicon Optical Bend Waveguide Tailoring for Straight and L-shape optical Interconnect in photonics Integrated Circuits (PICs)

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Abstract

In Photonics Integrated circuit (PIC), the effort is going on to completely replace conventional copper interconnects with optical interconnects. Optical interconnects throw challenges in form of connecting two optical devices placed at different positions that are not aligned to each other. Moreover, on a PIC, the interconnects have to undergo tight bends that may adversely affect their performance when high data rates are used. The focus of respective work model and design optical interconnects based on straight and L-Shape bend silicon waveguides as interconnects.

The results show that both Straight and U – bend waveguides when properly designed (in x– z plane), provide Coupling Characteristic as well as tolerable total loss (sum of bending and coupling losses) for small bending radius (~ 10 µm) in a wide ITU grid wavelength range for PICs.

Keywords: photonics Integrated Circuits (PICs), Silicon Optical Waveguide, Bend Waveguide, Optical Interconnects, optical design.

I. Introduction

In This paper introduces Photonics Integrated Circuits (PICs), silicon optical waveguides can play a key role as interconnects [1, 2]. They allow elevated efficient on-chip dissemination (nanometre and micrometre scale) of optical signals which forms the backbone of silicon-based PIC [3-4]. Various standalone optical devices have been developed using on silicon waveguides and now they are being integrated to make a complete optical signal processing circuit [5]. In PICs, optical devices/components are placed at various locations on silicon wafer that should be optically connected using optical interconnects [6,7]. For the last two decades, researchers and scientists are working on various types of optical interconnects based on optical waveguides [8,9]. In an optical circuit, it may be required to connect ports of two optical devices that are placed 90^0 degree and parallel. Such situation Straight and L–shape bending in silicon waveguides incurs bending losses and deformation in modal field resulting in coupling and bending losses. will be thoroughly studied.

In L-shape Silicon waveguides to guide power into various optical components and devices integrated on a single layer of PICs. For bend optical interconnects, radiation losses in bending region and coupling losses at device interface have been considered as major issues. The issue becomes more complex as interconnects are subjected to tight bends (upto ~ 10 µm) pertaining to small bending radius of few microns. First, the basic parameters of a mode field is shifted (Δx) of various L– bend waveguides are studied and then the parameters are optimized to yield minimum bending and coupling losses.

II. Methodology

The schematic diagram of silicon straight rectangular waveguide on the silicon substrate is as shown in Fig.1. The various parameters of rectangular waveguide are refractive index of core (n_{f0}), substrate (n_{S0}), cover (n_c), height (h) and width (w) of core waveguide. The refractive index of substrate (nso), cover (n_c) and core (n_{f0}) are 1.46, 1.7 and 3.48 respectively at 1550 nm. The height (h) of the silicon waveguide is chosen as 220 nm due to current standard wafer technology of SOI 220 nm platform on 200 mm [8,9]. The width (w) of the waveguide can be varied from 200 to 500 nm.

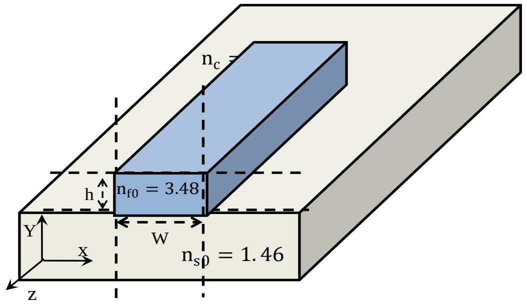

Fig. 1. Straight rectangular waveguide geometry.

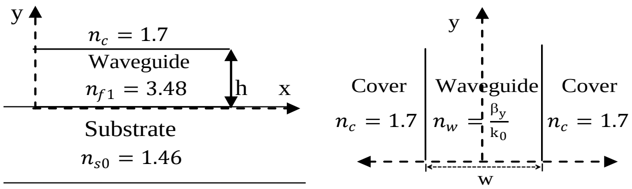

Fig. 2(a) Asymmetric planar waveguide and (b) Symmetric planar waveguide.

conventional Effective Index Method (EIM) [10] with perturbation terms [5,11] is used to obtaining the composite normalized propagation of a rectangular waveguide. The rectangular waveguide splitting into two orthogonal planar slab waveguides for analyzing the composite structure as shown in Fig. 2(a) and (b). Hence, two-dimensional rectangular waveguide problem converts into one dimension problem. The thin one dimension planar waveguide can be calculated by the propagation constant (β) and component of the electromagnetic field of TE (H_y, E_x and E_z) and TM Mode (E_y, H_x and H_z) [12,13]. These components of TE and TM modes are obtained by solving the Maxwell equation [5].

As per convention, such waveguide supports $E_y^{11}$and E_x^{11} modes. For dimensions of the waveguide considered here, quasi-TE mode E_y^{11} mode is supported which is considered to be combination of TE_{01} mode in waveguide of Fig.2a and TM_{01} mode in waveguide of Fig.2b. [5].

$$\tan^{-1}\left[\frac{\sqrt{\left(\beta_y/k_0\right)^2-n_c^2}}{\sqrt{n_{f0}^2-\left(\beta_y/k_0\right)^2}}\right]+\tan^{-1}\left[\frac{\sqrt{\left(\beta_y/k_0\right)^2-n_{s0}^2}}{\sqrt{n_{f0}^2-\left(\beta_y/k_0\right)^2}}\right]-\left[2\frac{h}{\lambda}\sqrt{n_{f0}^2-\left(\beta_y/k_0\right)^2}-m\right]\mu=0$$

To evaluate the propagation constant β_y, the refractive index n_{f0} of the guiding region of Fig. 2.2(a) is replaced with effective refractive index $n_w = \beta_y/k_0$ [14]. Similarly, the overall normalized propagation constant β_0/k_0 of the rectangular waveguide is calculated using transcendental Eq. (1) for TM mode (along x direction) considering boundaries x = 0 and x = w, as shown in Fig. 2(b). The propagation constant of complete rectangular waveguide is obtained by solving transcendental Eq. (2) as

$$\tan^{-1}\left[\left(\frac{n_w}{n_c}\right)^2\frac{\sqrt{\left(\beta_0/k_0\right)^2-n_c^2}}{\sqrt{n_w^2-\left(\beta_0/k_0\right)^2}}\right]+\tan^{-1}\left[\left(\frac{n_w}{n_c}\right)^2\frac{\sqrt{\left(\beta_0/k_0\right)^2-n_c^2}}{\sqrt{n_w^2-\left(\beta_0/k_0\right)^2}}\right]-\left[2\frac{w}{\lambda}\sqrt{n_w^2-\left(\beta_0/k_0\right)^2}-m\right]\mu=0$$

III. System Architecture

SILICON BEND RECTANGULAR WAVEGUIDE

The schematic diagram of silicon bend rectangular waveguide over silicon substrate is shown in fig.3, the angle between waveguide cover and bending angle is 90^0 degree as shown in Fig. 3. Specification of waveguide material is as follow: The reflective index of substrate (n_{so}) is 1.46, reflective index of cover (n_c) is 1.7 and reflective index of rectangular waveguide (n_{fo}) is 3.48. Dimension of the silicon rectangular waveguide are based on standard fabrication technology. The height (h) of rectangular waveguide is 220 nm and width (W) of the rectangular waveguide is varied from 300 to 400 nm

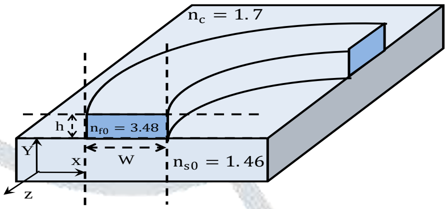

Fig.3. Geometry of silicon rectangular bend waveguide.

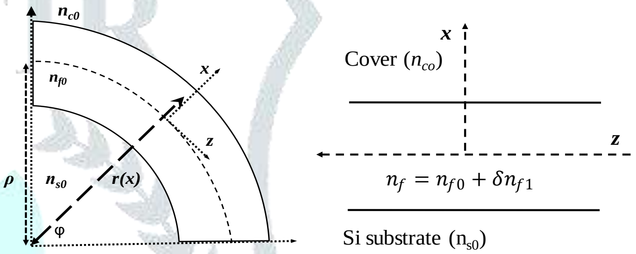

Fig. 4(a) Symmetric planar bend waveguide. b). Planar straight waveguide equivelent to bend waveguide of Fig.3.

Here, n_{f0} is refractive index of the core without effect of bending obtained by EIM and δn_{f1} is first order perturbed index that depends on bending radius and given as [9].

$$\delta n_{f1}=\frac{1}{4\left(\rho k_0\right)^2}+\left[2\left(\left(\beta_y/k_0\right)^2-\frac{1}{4}\left(\rho k_0\right)^2\right)\Big/\rho k_0\right]^3\left(r(x)-\rho k_0\right)$$

$$for\left(\rho-w/2\right)\le r(x)\le\left(\rho+w/2\right)$$

Here,k_0 is wave number, β_0 represent propagation constant, ρ represent the radius of curvature of the bend waveguide. Variable r(x) represents radial distance form origin at any position x in the region of ρ – w/2 ≤ r(x) ≤ ρ + w/2 in Fig. 4(a).

IV. Results

In figure 5. shows the first order singular perturbed index ($\delta\beta_1/k_0$) with respect to various bending radius from 2 to 100 μm using Single perturbation Technique and Rsoft. The width of the waveguide is varying from 300 to 450 nm. It is depicted that perturbed index is exponentially decreases for tight bending radius 2<r<15 μm. After increasing the bending radius beyond 15 μm the value of perturbed index is obtained which is less than 0.002. When waveguide width is increases at fixed radius of curvature, the perturbed index has been increasing.

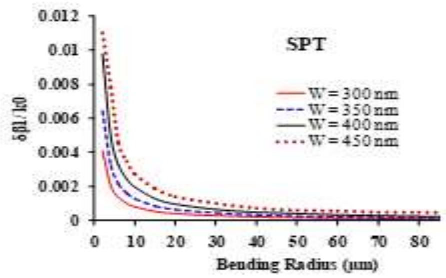

Fig.5. Singular perturbed index with respect to bending radius for various width of Silicon bend waveguide

Figure 2.10 shows that the electric field of fundamental TM mode has been propagating in straight silicon rectangular waveguide and coupled in same dimensional bend waveguide. Due to effect of bending on physical material parameter, the maximum value of electric field is shifted (Δx) outwards in bend waveguide [5,8]

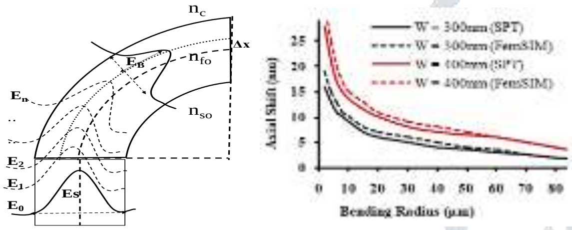

Fig. 6. Axial shift (Δx) with respect to different bending radius of different width of silicon waveguide

The modal distribution of the fundamental TM mode of straight and bend waveguide at bending radius is 4 μm of same dimension is shown in Fig. 6(a) and (b) respectively. It is observed that the peak value of mode field is shifted (Δx) from center of the bend waveguide

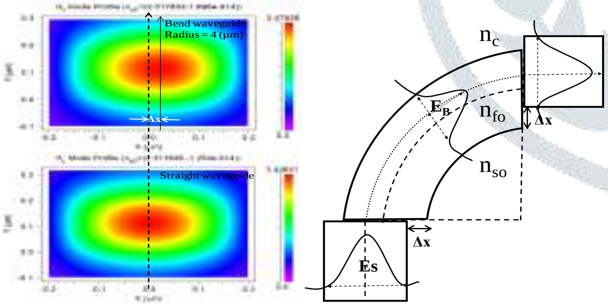

Fig. 7.

To compensate the coupling loss, a tolerable lateral shift is evaluated

As discussed above, axial shift and asymmetric electric field distribution in a bend waveguide are major cause of transition or coupling loss when two straight waveguides are connected by compensate the coupling loss, a tolerable lateral shift is evaluated and is schematically shown in Fig.7. The coupling loss is calculated using the relation given below [5]

$$\alpha = 10*\log\left(\frac{T_{\max}-T}{T_{\max}}\right)$$

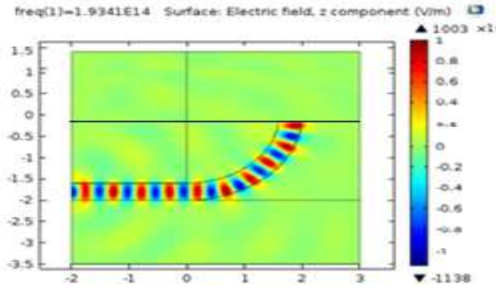

Fig. 8. Modal field propagate in L-bend silicon waveguide

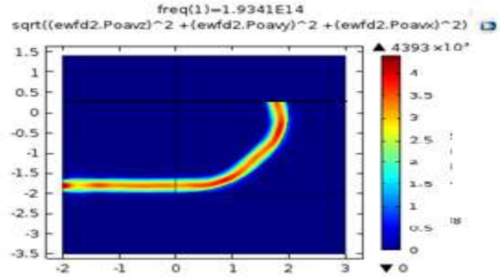

Fig. 9. Power transmits in L bend waveguide.

Where, T_{max} is maximum transmission efficient when both the waveguides are straight and axial offset is zero.

Transmission coefficient (T) in case of straight and bend waveguide is given a [5].

$$T = \frac{\left|\int\int_{-\infty}^{\infty} E_{x_{st}}(x,y)\,E_{x_b}(x,y)\,dx\,dy\right|^2}{\int\int_{-\infty}^{\infty}\left|E_{x_{st}}(x,y)\right|^2 dx\,dy\int\int_{-\infty}^{\infty}\left|E_{x_b}(x,y)\right|^2 dx\,dy}$$

Where, $E_{x_{st}}$ and E_{x_b} are the expressions for electric field of straight and bend silicon waveguide.

Figure 2.15 shows the coupling losses evaluated in terms of various bending radius at the coupling point between straight and bend waveguides using Eqs. (23) and (24), respectively

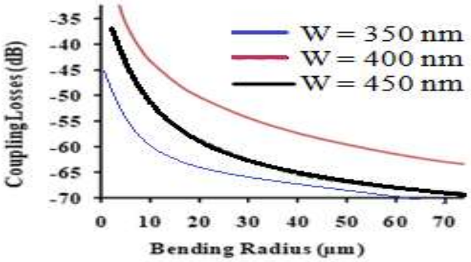

Fig. 10. Copling losses versus bending radius of L-bend silicon waveguide

Figure 10 shows that the Coupling loss between the straight and bend waveguide using Rsoft FTDT. These results show that there is high insertion loss when coupling occurs between straight and tight bend waveguide (2-14 μm radii). Moreover obtained the bending losses in optical interconnect is high for 1 μm to 5 μm radius, then after bending losses decrease from 0.04 to 0.01 dB follow linearly trend for 300 nm and 400 nm wide waveguide as shown in figure 11.

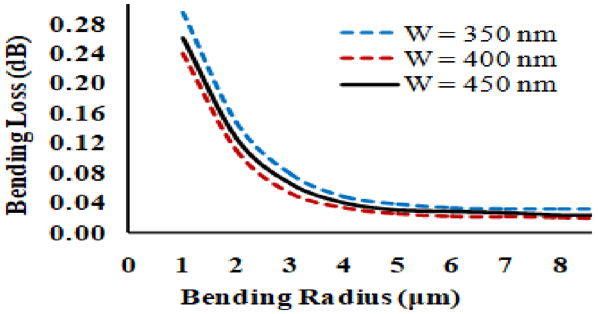

Fig. 11. Bending losses versus bending radius of L-bend silicon waveguide.

In this result the minimum loss is observed at 400 nm waveguide width of S-bend interconnect. These dimensions are most suitable for transmission of optical signal and it is also favorable in fabrication techniques.

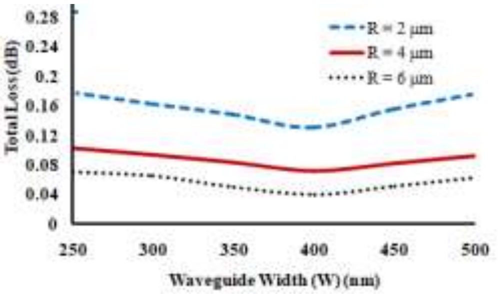

Fig. 12. Total losses versus bending radius of L-bend silicon waveguide.

VII. Conclusion

We present a robust analytical method based on multiple scaling method using singular perturbation techniques to quantitatively obtain normalized propagation constant and modal field profile of rectangular silicon waveguide of dimensions less then operating wavelength. The quantitative estimation of the axial shift and narrowing of width of modal field due to bending are obtained through singular perturbation technique, The results obtained by present approach are compared with that obtained by FTDT based commercial software Rsoft. Compensation of coupling by introducing a lateral offset between straight and bend waveguides is proposed. It is observed that even for tightly bend of silicon waveguide compensation in coupling losses upto 35 dB can be achieved. With compensation of coupling loss and bending loss, quality of transceiver signal can be improved which may result in reduced bit error rate (BER) performance of optical interconnects.

The present analysis provides useful guidelines to design optical interconnect required to connect two devices on silicon photonics integrated circuit and placed at about right angle to each other.

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