Silicon on Insulator based Directional and Multimode Interference Optical Coupler design

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***Abstract*—A new and innovative interconnection technology in opto-electronics based chip fabrication is presented. This technology gives the advantages over existing technology of electrical interconnection in terms of greater speed. After giving overview of different types of optical coupler design with planer light wave circuit, the focus of this paper is on to develop such optical coupler, gives maximum coupled optical power and reduce the back hand coupled power losses.**

***IndexTerms*—Silicon on insulator, Directional coupler, Multimode interference coupler, Cross gap coupler, Optical coupler design.**

I. INTRODUCTION

Planar light wave circuits are opticalintegrated circuits (ICs) or optical circuit boards which usually perform their functions in the optical domain. Planar light wave circuits uses optical waveguides to route photons in the the similar way as the metal traces are used to route electrons in electronic ICs and circuit boards .Planar light wave circuits are analogous counterpart of electronic ICs in optical domain. They are usually of nanometer size and can act as splitter, switches, couplers etc. efficiently with less space required and with greater speed. They are optical circuits patterned on Si wafer and are useful because of their small size and their potential for integration of multiple devices.

To make these planar light wave circuits of smaller size, the waveguide components have to be reduced considerably[2].Hence with the advent of photonic integration nowadays strongly guiding ridge waveguides are used as building blocks for optical devices such as small length couplers (with coupling length of few micrometers). So to design these optical devices we use high index contrast waveguides, with very small cross-section, popularly known as Si photonic wire waveguides.

II. SI PHOTONIC WIRE WAVEGUIDE

Silicon photonics is receiving much interest because it enables the use of well-developed Si processing technologies as well as Si substrates that are cheaper than the compound semiconductor (GaAs or InP) substrates to fabricate a broad range of optical devices (light emitters, photo-detectors , optical switches, optical passive components, and nonlinear optic devices)[2-5]

However in Silicon on Insulator based waveguide at several hundred micrometer range of banding waveguide causes the maximum bending loss. There for it could not be bending to small curvature. For the requirement of sharp bends in waveguide it is necessary to have high index contrast of reflection (high Δ).

As shown in Fig. 1 the schematic diagram of waveguide structure with Si wire core is in nanometer size. The index contrast between the Si core & silica cladding is of 40% order. This structure makes it possible to bend the wave guide with micrometer or nanometer curvature.

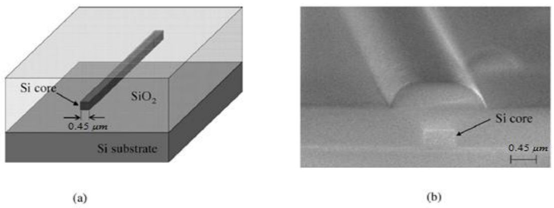

Fig. 1: Si photonic wire waveguide (a) Layered structure. (b) Picture of cross section[1]

The design of the two types of coupler namely Directional Coupler and Multi-Mode Interference Coupler (MMI) were based on Si photonic wire waveguide with refractive index of the core and cladding material were 3.48 and 1.46 respectively and the width and height of the Si core was 0.45 µm and 0.21 µm.

III. FUNDAMENTALS, TYPES AND APPLICATIONS

Optical coupler of N×N coupler (with N≥2) can be used as power splitter, power tap etc. For the design of coupler by using planar waveguide like lithiumniobate($LiNbO_3$), silica and various polymers. When discussing about coupler and splitters it is customary to refer to them in terms of number of input and output device [10].

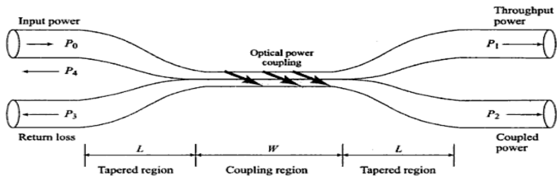

Fig. 2: Fused fiber coupler [10]

The optical power of coupler is given as

$$P_2 = P_0 \sin^2 (kz) \qquad (1)$$

Where z is axial distance and k is coupling co-efficient .Here P_2 is depends on axial length, coupling region size and the difference in radii of the two fiber in coupling region[14]. For identical core fiber we have equation is

$$P_1 = P_0 - P_2 = P_0 [1 - \sin^2 (kz)] = P_0 \cos^2 (kz) \qquad (2)$$

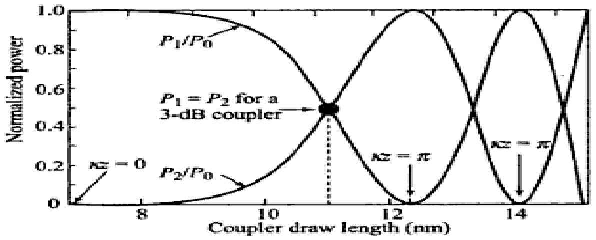

Fig. 3: Normalized coupled powers as a function of the coupler draw length[10]

The basic parameter id to require for to design 2×2 coupler is gap between waveguide, waveguide width and refractive index between waveguides in coupling region.

(1) Directional coupler(DC)

Directional coupler is as shown in below Fig.4 with 2×2 type and that have mainly four pot design. The main aim to design directional coupler is to give power from any one of port and get maximum coupled output at two port which is in opposite side and make minimum power output at isolated back port. All the power is expressed in db.

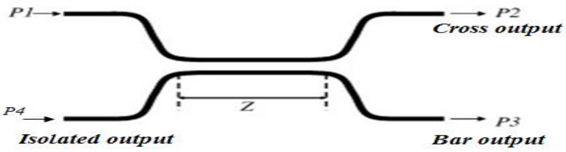

Fig.4: Schematic core pattern of a directional coupler [11]

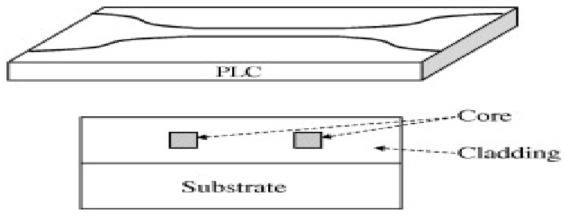

Fig.5: Schematic pattern of directional coupler in PLC and its cross-section [11]

The DC considered as consist of two parallel symmetric wave guides[14]. The transfer of the light is proportional to the propagation distance (z). The Bar and Cross output of DC is given as followed equations.

$$P_b=P_{in}\cos^2 (z\pi/2L_c) \quad (3)$$

$$P_c=P_{in}\sin^2 (z\pi/2L_c) \quad (4)$$

The coupling length which is as small as possible is given as [8]

$$L_c=\pi/\beta_e-\beta_{o}= \lambda_0/2(n_e-n_0) \quad (5)$$

n_e and n_0 is effective indexes of even and odd super nodes. In this the TE and TM mode of polarization operation is possible.

(2) Multimode interference coupler(MMI)

Multimode interface coupler has attracted much interest in the past decade, owing to it compact structure, low loss, easy and large fabrication tolerances. Many functions realize using MMI such as power splitter[7], optical switching etc.

IV. Effective Index And Mode Polarisation

The effective index is used to find approximate solutions for the propagation constants of two dimensionalwaveguides. This is done without dealing with the electric fields within thewaveguide, and so this method, known as the effective index method, is very simple. [5]The approach to finding the propagation constants for the waveguide shown as an example inFig. 6 is to regard it as a combination of two planar waveguides, one horizontal and onevertical, shown respectively in Fig. 7(a) and 7(b). We then successively solve the planarwaveguide eigenvalue equations first in one direction and then the other, taking the effectiveindex of the first as the core refractive index for the second.

So, when considering, for example, the previously defined strip waveguide, with the indexdistribution shown in Fig. 6, and considering a TE mode.

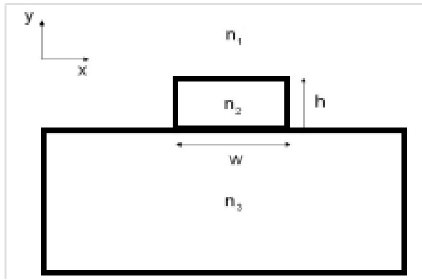

Fig.6: waveguide cross section and index distribution.

We start by calculating the effective index in the y direction, and obtain the effective index in this direction,n_{eff} as shown in Fig. 7(a).

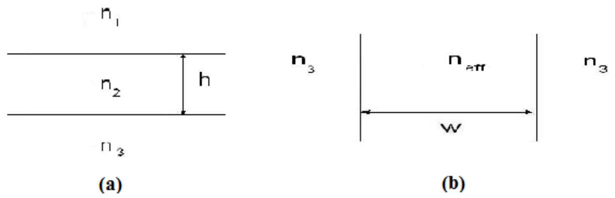

Fig. 7: (a) vertical (b) horizontal calculation of effective index

For the first decomposition of the waveguide, equation

$$k_0 n_1 h \cos\theta_1 - m\pi = \tan^{-1}\frac{\sqrt{\sin^2\theta_1-\left(\frac{n_2}{n_1}\right)^2}}{\cos\theta_1} + \tan^{-1}\frac{\sqrt{\sin^2\theta_1-\left(\frac{n_3}{n_1}\right)^2}}{\cos\theta_1} \quad (6)$$

With$k_0 = {2\pi}/{\lambda_0}$the propagation constant in free space and $h$the height of the core layer. For TE modes, has to be solved inorder to obtain the propagation angle θ_1.Then, from the definition of the effective index of the mode, we obtain that:

$$n_{eff} = n_1 \sin\theta_1 (7)$$

Then the analogous equation for TM modes has to be solved for the other decomposition inorder to find the effective index of the mode.The polarisation has to be chosen carefully. If we are considering an electric field polarized in the*x* direction (TE polarisation), then when solving the three-layer planar waveguide in the *y*direction we use the TE eigenvalue equation. However, when we subsequently solve thevertical three-layer planar waveguide, we must use the TM eigenvalue equation because, withrespect to this imaginary vertical waveguide, the field is polarised in the TM direction.

The general solution to the wave equation for TE modes in planar waveguides [5], which is of the form:

$$\nabla^2 E = \mu_m \varepsilon_m \frac{\partial^2 E}{\partial t^2} \quad (8)$$

With$v = {1}/{\sqrt{\mu_m \varepsilon_m}}$ the velocity of wave is following:

$$E_x = E_c\, e^{-\gamma k_y} e^{-j\beta z} e^{j\omega t} \quad (9)$$

The $e^{-j\beta z}$corresponds to a propagating sinusoidal type field, while the $e^{-\gamma k_y}$ represents fields propagating in the y direction through the claddings. That means that the field penetrates the cladding with a decay constant k_y, so part of the field is propagating through the cladding. So after obtaining this solution, it is possible to plot the field distribution, $E_X(y)$ or the intensity distribution, $|E_X(y)|^2$ for the different modes, in order to have an idea of how the field propagates through the waveguide [5].

V. DESIGN AND ANALYSIS

(1) Directional Coupler:

The most fundamental component in optical device for add-drop multiplexer, power combiner and switches [8-9] is directional coupler. The DC was having silicon insulator material with 0.45µm thick single crystal Si surface fabrication. The surface was first patterned by using electronic beam lithography to wave guide core pattern of DCs[12]

TABLE 1: SPECIFICATIONS USED FOR MODELING THE DIRECTIONAL COUPLER

Power of the input light	1mw(0 dbm)
Polarization and wavelength of the incident light	TM MODE, 1.55 μm
Width and height of the core	0.45 μm, 0.21 μm
Refractive index of the core	3.48
Refractive index of the cladding	1.46
Radius of curvature for s-shaped waveguide	10 μm
Coupling length	5 μm
Gap between two linear waveguide	0.20 μm

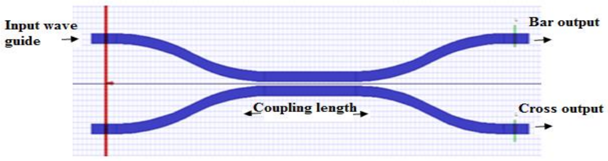

Fig. 8: Design of Directional Coupler

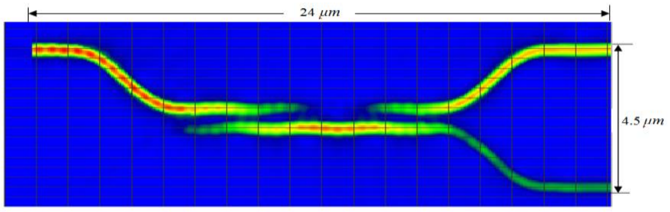

Fig. 9:Planar view of H_y component of light in directional coupler

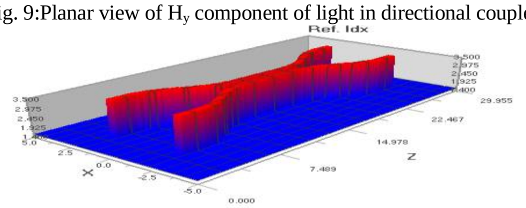

Fig.10: Refractive index distribution

(2) MMI Coupler:

MMI coupler having smaller size compare to DC and design is robust less parameters like pitch (Pt), coupling length, and width [6].

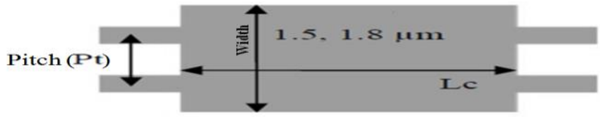

Fig. 11: Structure of the MMI Coupler[14]

Here we design for two widths 1.5 and 1.8 with pitch distance is 0.735µm and 0.882µm respectively.

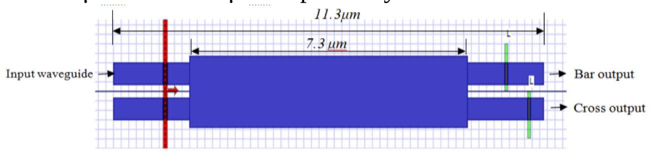

Fig. 12: Structure of the MMI Coupler (width 1.5µm)

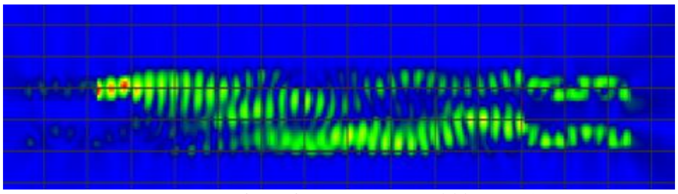
Fig. 13: Planar view of H_y of light in MMI (width 1.5µm)

VI. RESULT AND COMPARISON

TABLE 2: BAR AND CROSS OUTPUT FOR DIFFERENT WAVELENGTH DIRECTIONAL COUPLER

Bar Output (dBm)	*Cross Output (dBm)*	*Wavelength (µm)*
-2.345	-3.998	1.5
-2.678	-3.542	1.52
-2.768	-3.413	1.53
-2.888	-3.288	1.54
-3.08	-3.08	1.55
-3.245	-2.908	1.56
-3.535	-2.655	1.57
-3.775	-2.415	1.58
-4.12	-2.15	1.6

TABLE 3:BAR AND CROSS OUTPUT FOR DIFFERENT WAVELENGTH MMI COUPLER(WIDTH=1.5µm)

Bar Output(dBm)	*Cross Output(dB)*	*Wavelength (µm)*
-4.86	-3.464	1.5
-4.664	-3.635	1.52
-4.389	-3.785	1.53
-4.134	-3.948	1.54
-3.95	-3.95	1.55
-3.48	-4.02	1.56
-3.346	-4.05	1.57
-3.211	-4.08	1.58
-2.94	-4.234	1.6

TABLE 4:BAR AND CROSS OUTPUT FOR MMI COUPLER (WIDTH=1.8μm)

Bar Output(dB)	*Cross Output (dB)*	*Wavelength (μm)*
-4.89	-3.32	1.5
-4.81	-3.45	1.52
-4.634	-3.67	1.53
-4.45	-3.98	1.54
-4.09	-4.09	1.55
-3.96	-4.19	1.56
-3.79	-4.28	1.57
-3.56	-4.35	1.58
-3.08	-4.8	1.6

TABLE 5: TYPES OF LOSSES AND RATIO

Types of losses and ratio parameter	*Equation of loss*
Coupling Ratio	$SR = \frac{P_2}{P_1 + P_2} \times 100\%$
Excess Loss	$Excessloss = 10\log\left(\frac{P_0}{P_1 + P_2}\right)$
Insertion Loss	$Insertionloss = 10\log\left(\frac{P_i}{P_j}\right)$
Return Loss and Reflectance	$Returnloss = 10\log\left(\frac{P_3}{P_0}\right)$

TABLE 7: EXCESS LOSS OF DC AND MMIS FOR DIFFERENT WAVELENGTH

Wavelength(μm)	*E.L. of DC (in dB)*	*E.L. of MMI of 1.5 μm width(in dB)*	*E. L. of MMI of 1.8 μm width(in dB)*
1.5	0.083	1.125	1.024
1.52	0.0782	1.1	1.066
1.53	0.0764	1.066	1.115
1.54	0.073	0.9	1.198
1.55	0.0697	0.8	1.0797
1.56	0.06293	0.75	1.063
1.57	0.06244	0.695	1.018
1.58	0.0316	0.68	0.9269
1.6	0.02435	0.528	0.8457

TABLE 8: SPLITTING RATIO OF DC AND MMIS FOR DIFFERENT WAVELENGTH

Wavelength(μm)	*S.R.of DC (in %)*	*S.R. of MMI 1.5 μm width (in %)*	*S.R. of MMI 1.8 μm width (in %)*
1.5	43.73	57.97	58.94
1.52	45.04	55.9	57.76
1.53	46.26	53.47	55.53
1.54	47.69	51.07	52.7
1.55	50	50	50
1.56	51.19	46.89	48.67
1.57	55.04	45.93	47.18
1.58	57.76	45.01	45.4
1.6	61.14	42.6	40.29

VII. COMPARISONS OF THE SIMULATION RESULTS

TABLE 9: VARIATION IN EXCESS LOSS OF DIRECTIONAL COUPLER AND MMI COUPLERS

Excess Loss(in dB)	**DC**	**MMI of 1.5 μm width**	**MMI of 1.8 μm width**
Minimum	0.014	0.528	1.198
Maximum	0.083	1.125	0.8457

TABLE 10: VARIATION IN SPLITTING RATIO OF DIRECTIONAL COUPLER AND MMI COUPLERS

Splitting Ratio (In %)	**DC**	**MMI Coupler of 1.5μm width**	**MMI Coupler of 1.8μm width**
Minimum	43.73	57.97	58.94
Maximum	61.14	42.60	40.29

VIII. CONCLUSION

As conclusion Directional coupler having very less transmission losses but it is having large splitting ratio. Multimode interface coupler is very easy in design but it has large excess loss and variation in splitting ratio is large. As per the requirement of less transmission loss we use directional coupler for designing PLCs with silicon on insulator substrate.

REFERENCES

[1] Hirohito Yamada, Member, Tao Chu ,Satomi Ishida, and Yasuhiko Arakawa, "Si Photonic Wire Waveguide Devices," *IEEE Journal Of Selected Topics In Quantum Electronics*, VOL. 12, NO. 6,*November/December* 2006.

[2] L. Pavesi, "Will silicon be the photonic material of the third millennium?," *J. Phys., Condens. Matter*, vol. 15, pp. R1169–R1196, 2003.

[3] B. Jalali, S. Yegna narayanan, T. Yoon, T. Yoshimoto, I. Rendina, and F. Coppinger, "Advances in silicon-on-insulator optoelectronics*,"* *IEEE J. Sel. Topics Quantum Electron.*, vol. 4, no. 6, pp. 938–947, Nov.–Dec. 1998.

[4] L. C. Kimerling, "Silicon micro photonics," *Appl. Surf. Sci.*, vol. 159–160, pp. 8–13, 2000.

[5] G.T.Reed and A.P.Khights, "Silicon photonics: an introduction", *John Wiley&Sons,Ltd,*

[6] 2004.R. A. Forber and E. Marom, "Symmetric directional coupler switches," *IEEE J. Quantum Electron.*, vol. QE-22, no. 6, pp. 911–919, Jun. 1986.

[7] G. Rickman, G. T. Reed, and F. Namavar, "Silicon-on-insulator optical rib waveguide loss and mode characteristics," *J. Lightw. Technol.*, vol. 12,no. 10, pp. 1771–1776, Oct. 1994.

[8] H. Kogelnik and R. V. Schmidt, "Switched directional couplers with alternating Δβ," *IEEE J. Quantum Electron.*, vol. QE-12, no. 7, pp. 396–401, Jul. 1976.

[9] N. Ofusa, T. Saito, T. Shimoda, T. Hanada, Y. Urino, and M. Kitamura, "An optical add-drop multiplexer with a grating-loaded directional coupler in silica waveguides," *IEICE Trans. Communication*., vol. E82-B, pp. 1248–1251, 1999.

[10] Gerd Keiser, "Optical Fiber Communication" *fourth edition, Tata McGraw Hill*.2009

[11] Makoto Fujimaki, Keita Kawabe, Masahiro Suzuki, Koichi Awazu, Yoshimichi Ohki,Junji Tominaga "Control of the properties of directional couplers using proton irradiation,"Volume 264, Issue 2, November 2007, Pages 267–271.

[12] Hirohito Yamada, Member, Tao Chu, Member, Satomi Ishida, and Yasuhiko Arakawa," Optical Directional Coupler Based on Si-Wire Waveguides," *IEEE photonics technology letters*, vol. 17, no. 3, march 2005.

[13] *Tutorials and Background "FDTD" Optiwave Inc*. 2006.

[14] RUI YIN , "Improving the self-imaging in multimode interference (MMI) couplers," *Optical Application*, Vol. XLI, No. 3, 2011.