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Design and Simulation of Unconstrained Coupling and Extinction Ratios in Compact Symmetrical Optical Directional Coupler on SOI Substrate and Study the Polarization Dependent Insertion Loss with Coupling Parameters

Nagaraju Pendam[1], C. P. Vardhani[2]

[1, 2]Department of Physics, Osmania University, Hyderabad, India

Abstract: ***A novel design of slab structured symmetrical optical directional coupler with S-bend waveguides on silicon-on-insulator (SOI) platform has been designed by using R-Soft CAD tool. Beam propagation method is used for light propagation analysis. The simulation results of symmetrical optical directional couplers are reported. We find that the symmetrical directional coupler has lower coupling ratios, higher extinction ratios, and lower insertion losses with waveguide parameters such as width, wavelength, waveguide spacing, and coupling length. Simulation results designate that the coupling efficiency for TE and TM modes can reach about more than 90%, with extinction ratio about 9.7dB when the coupling length is 8mm for both the polarization modes and insertion loss is 0.1dB with same coupling length at 1550nm wavelength. This device is also urgent requirement for communication, high speed computing, optical switch, optical filter, and splitter.***

Keywords: Directional coupler, Silicon-on-insulator (SOI), Integrated Optics, Guided waves, Polarization extinction

1. Introduction

The symmetrical optical directional coupler on silicon-on-insulator (SOI) is one of the key fundamental elements for application in optical switches, power splitters, polarization selectors, optical modulators, and optical filters [1]. SOI based slab structured directional couplers have a low propagation loss and high coupling, extinction ratios compatibility with optical fibers [2]. Therefore, SOI based optical directional couplers are anticipated to be exploited in various low-losses guided integrated devices for optical sensing phenomenon. Optical directional couplers on SOI platform are highly polarization dependant [3]. So, these couplers are usually practice to design devices to operate in both polarization modes such as TE and TM modes.

In this paper, we have shown how the symmetrical directional coupler coupling, extinction ratios, propagation losses could improve the polarization dependent modes with coupling parameters such as width, wavelength, waveguide spacing, and coupling length. In this article, we propose a design of symmetrical directional coupler on SOI platform by using an R-Soft CAD tool and simulated using beam propagation method at 1550nm wavelength.

2. Design of Symmetrical Optical Directional Coupler

The schematic diagram of the proposed symmetrical optical directional coupler is shown in Fig.1. It consists of two waveguides that are straight and S-bend waveguides on SOI substrate with slab structure. S-bend waveguides are separated by 20µm at the input and output ends. Total length is 3cm, input power is 1µW, width is 3µm, height of the device is 5µm, the coupling length of the waveguide is 4000µm, free space wavelength is 1.55µm, and waveguide separation is 2.8µm, under TE and TM polarization modes, which are basic parameters of the directional coupler.

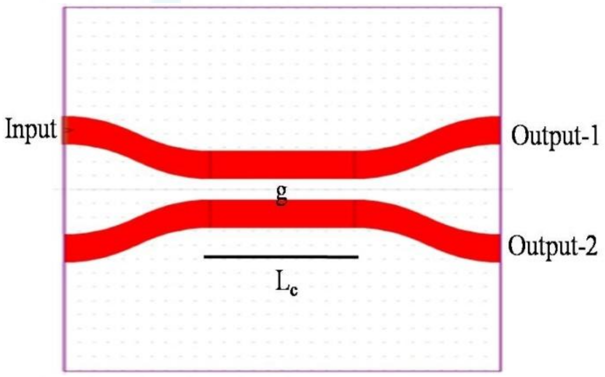

Figure 1: Schematic diagram of symmetrical optical directional coupler (g = waveguide spacing, L_c = coupling length)

3. BPM Simulation Results

The beam propagation method (BPM) is the most powerful method to investigate linear and nonlinear lightwave propagation phenomena in axially varying waveguides. Recently, beam propagation method (BPM) is the most widely used propagation technique for modeling integrated and fiber optic photonic devices. The BPM is essentially a particular approach for approximating the exact wave equation for monochromatic waves, and solving the resulting equations numerically. The basic approach is illustrated by formulating the problem under the restrictions of a scalar field (i.e. neglecting polarization effects) and paraxiality (i.e. propagation restricted to a narrow range of angles). The scalar field assumption allows the wave equation to be written in the form of the well-known Helmholtz equation for monochromatic waves.

$$\frac{\partial^2\Phi}{\partial x^2}+\frac{\partial^2\Phi}{\partial y^2}+\frac{\partial^2\Phi}{\partial z^2}+k(x,y,z)^2\Phi = 0 \quad (1)$$

Here the scalar electric field has been written as $E\,(x,y,z,t) = \Phi\,(x,y,z)e^{-iwt}$ and the notation $k(x,y,z,t) = k_{\circ}\,n(x,y,z)$ has been introduced for the spatially dependent wave number, with $k_{\circ} = {}^{2\pi}/_{\lambda}$ being the wavenumber in free space.

The geometry of the problem is defined entirely by the refractive index distribution n (x, y, z). Assuming that axis is predominantly along the z-direction, it is beneficial to factor the rapid phase variation out of the problem by introducing a so-called slowly varying field u along the direction z

$$\Phi\,(x,y,z) = u\,(x,y,z)e^{i\bar{k}z} \quad (2)$$

$\bar{k}$ is a constant number to be chosen to represent the average phase variation of the field Φ. Then, introducing the expression into the Helmholtz equation yields the following equation for the slowly varying field

$$\frac{\partial^2 u}{\partial z^2}+2i\bar{k}\frac{\partial u}{\partial z}+\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\left(k^2-\bar{k}^2\right)u = 0 \quad (3)$$

$$\frac{\partial u}{\partial z} = \frac{i}{2\bar{k}}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\left(k^2-\bar{k}^2\right)u\right) \quad (4)$$

This is the basic BPM equation in three dimensions (3D), simplification to two dimensions (2D) is obtained by omitting any dependence on y [4].

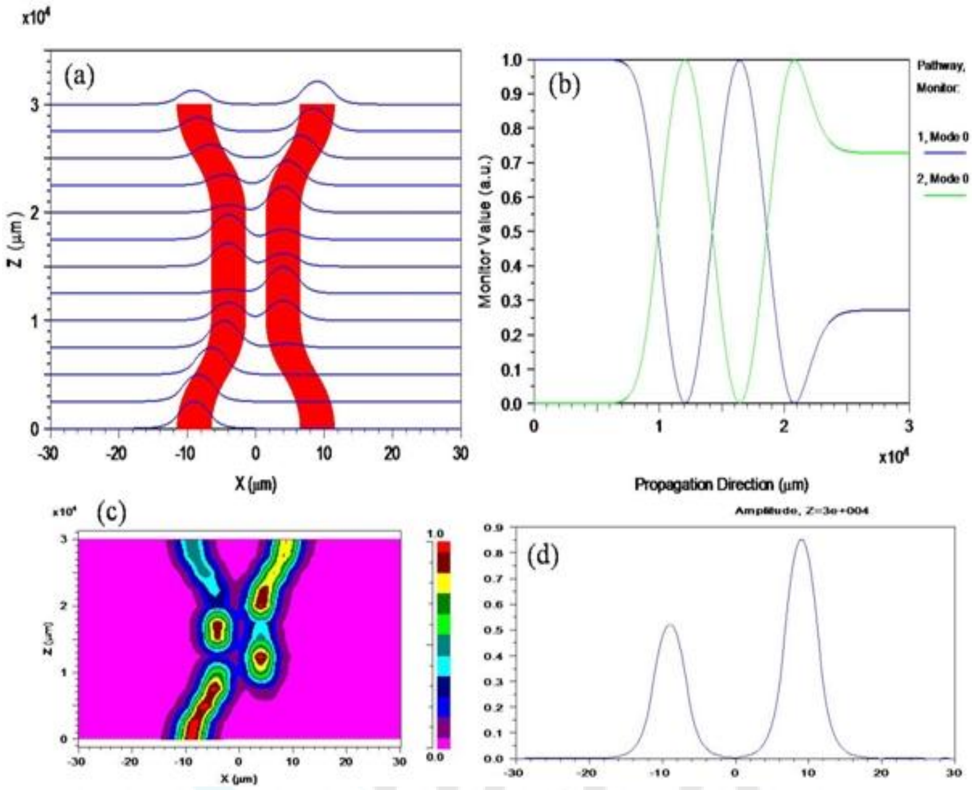

Figure 2: Simulated profiles for symmetrical optical directional coupler (a) launching profile with slice structure type, (b) propagation field view, (c) mode field view, (d) amplitude view.

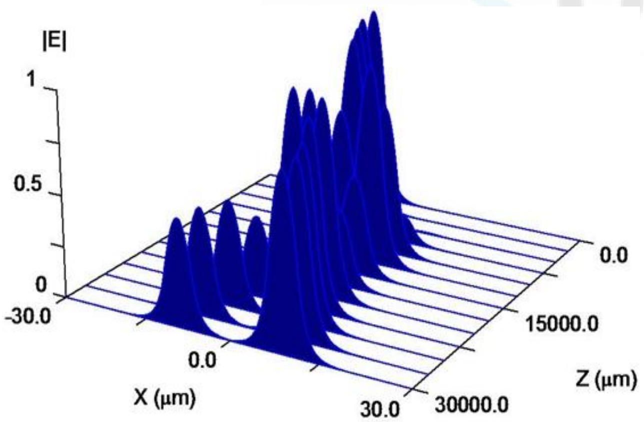

Figure 3: power launching field view in 3D.

Simulations have been carried out by BPM tool by considering the propagation of an optical signal of fundamental TE and TM modes through the symmetrical optical directional coupler. Here we depicted some of the simulation profiles in Fig 2 and Fig 3. Fig. 2 (a) shows the launching field of the optical directional coupler with slice approach. Fig. 2 (b) shows the light propagation direction of the optical directional coupler, from this profile we can calculate the transmitted power. Fig. 2 (c) shows the mode profile of the optical directional coupler. Fig. 2 (d) shows the propagation of amplitude view throughout the optical directional coupler, from this profile we can confirm the light propagate through other port. Fig. 3 shows the 3D view of simulation of symmetrical optical directional coupler with 5μm width, 1550nm wavelength, 3cm length, 10000 coupling length, and 20μm gap between the two output ports.

Simulation results enable the extinction ratio (ER) and coupling ratio (R) which is used to calculate these values by using the following formulae.

$$ER_{TM} = 10\log_{10}\frac{P_{TM}}{P_{TE}}\ dB \quad (5)$$

$$ER_{TE} = 10\log_{10}\frac{P_{TE}}{P_{TM}}\ dB \quad (6)$$

$$R = \frac{P_2}{P_1} = \frac{\text{Output Power at coupled waveguide}}{\text{Input Power}} \quad (7)$$

Where ER is the Extinction ratio (dB) of an optical directional coupler, is defined as the ratio between the transmitted powers of two polarizations at the same output port. P_{TM} is the transmitted power at TM-mode, P_{TE} is the transmitted power at TE-mode [5-6].

The coupling parameter (w) takes part in an imperative task in symmetrical optical directional coupler for changes the coupling ratio, extinction ratio, and insertion loss. Fig. 4 shows the coupling and extinction ratios with component width of the directional coupler for TE polarization mode. The coupling ratio is decreased with width, which has got more than 90% at 8 and 9μm at port-I in TE and TM modes also because of the higher widths enable the good mode confinement of the light. The extinction ratio is increased with width, which has got maximum that is 0.02dB at 8μm width of the directional coupler because of the coupling efficiency of the polarization decreases with width. Fig. 5 shows the insertion loss with width of the symmetrical optical directional coupler for two different modes. The minimum insertion loss achieved 3.85dB at 7μm for both TE and TM modes at 1550nm wavelength through port-II.

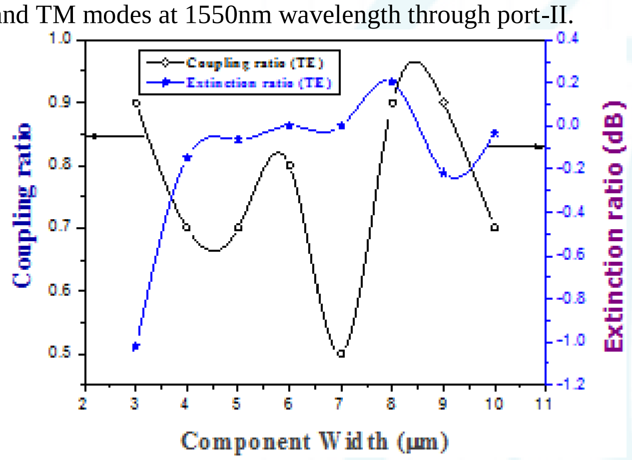

Figure 4: Waveguide width as function of coupling and extinction ratios for TE mode

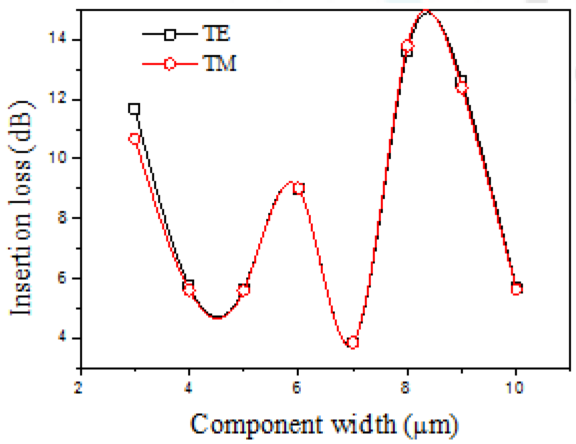

Figure 5: Waveguide width as function of insertion loss for different modes

The coupling parameter (λ) takes part in an imperative role in symmetrical optical directional coupler for changes the coupling ratio, extinction ratio, and insertion loss. Fig. 6 shows the coupling and extinction ratios with wavelength of the directional coupler for TE polarization mode. The coupling ratio is decreased with wavelength, which has got highest value is 99% at 1.55μm wavelength at port-II in TE and TM modes also because of its central wavelength in photonic spectrum band. The extinction ratio is increased with wavelength upto 1600nm, which has got maximum that is 0.08dB at 1.66μm wavelength of the directional coupler because of equal distribution of transmitted power on the both output ports. Fig. 7 shows the insertion loss with wavelength of the symmetrical optical directional coupler for two different modes. The minimum insertion loss achieved 0.0086dB for both TE and TM modes at 1500nm wavelength through port-II.

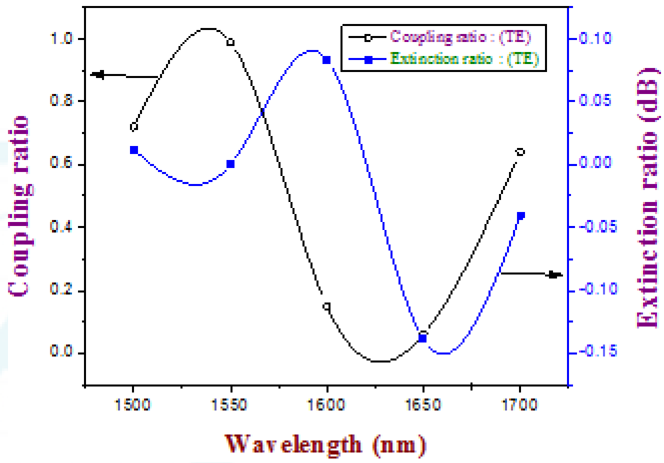

Figure 6: Wavelength as function of coupling ratio and extinction ratio for TE mode.

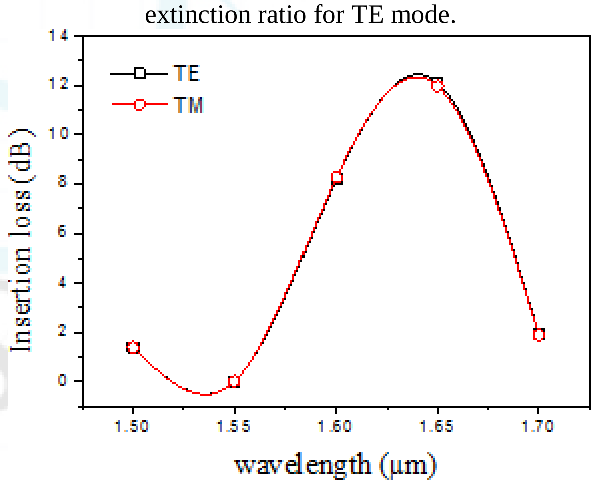

Figure 7: Wavelength as function of insertion loss for different modes.

The coupling parameter (g) takes part in a key role in symmetrical optical directional coupler for changes the coupling ratio, extinction ratio, and insertion loss. Fig. 8 shows the coupling and extinction ratios with waveguide spacing of the directional coupler for TE polarization mode. The coupling ratio is decreased with waveguide spacing, which has got highest value is 89% at 2μm waveguide spacing at port-I in TE and TM modes also because of its lesser distance. The extinction ratio is increased with waveguide spacing, which has got maximum that is 0.09dB at 4.4μm waveguide spacing of the directional coupler because of equal distribution of propagation of light on the both output ports. Fig. 9 shows the insertion loss with waveguide spacing of the symmetrical optical directional

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coupler for two different modes. The minimum insertion loss achieved 0.0086dB for both TE and TM modes at 4.4μm waveguide spacing through port-II.

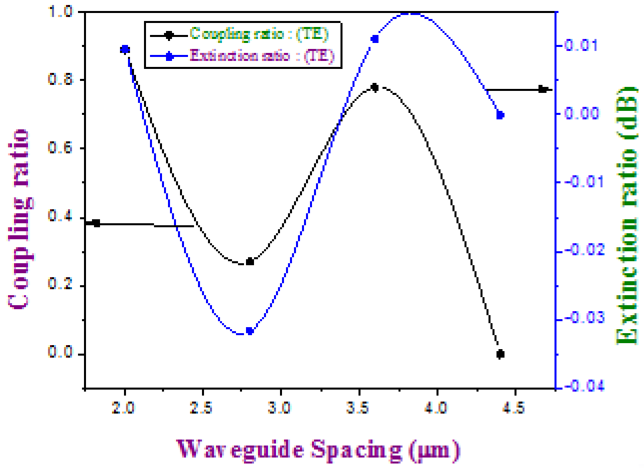

Figure 8: Waveguide spacing as function of coupling ratio and extinction ratio for TE mode.

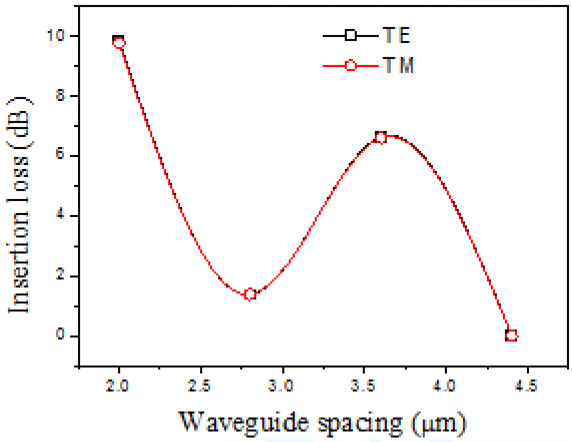

Figure 9: Waveguide spacing as function of insertion loss for different modes.

In optical directional coupler, coupling phenomenon takes place in the coupling region in which the odd and even normal modes can propagate with propagation constants β_e and β_o. The coupling length of either TE or TM polarization is given by

$$L_c = \frac{\pi}{(\beta_e - \beta_o)} \tag{8}$$

The coupling parameter (L_c) takes part in a key role in symmetrical optical directional coupler for changes the coupling ratio, extinction ratio, and insertion loss. Fig. 10 shows the coupling and extinction ratios with coupling length of the directional coupler for TE polarization mode. The coupling ratio is decreased with coupling length, which has got highest value is 99% at 4mm coupling length with 2.8μm waveguide separation at port-I in TE and TM modes also because of the coupled mode theory. The extinction ratio is increased with coupling length, which has got maximum that is 9.7dB at 8mm coupling length of the directional coupler because of the coupling efficiency is increased with decreasing of coupling ratio. Fig. 11 shows the insertion loss with coupling length of the symmetrical optical directional coupler for two different modes. The minimum insertion loss achieved approximately 0.1dB for both TE and TM modes at 8mm coupling length through port-II at 2.8μm waveguide spacing.

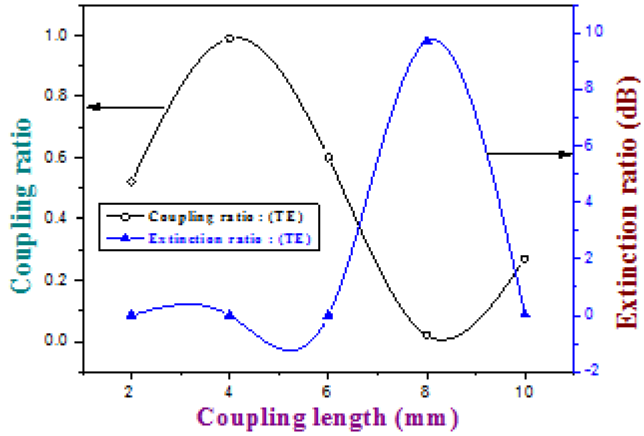

Figure 10: Coupling length as function of coupling ratio and extinction ratio for TE mode.

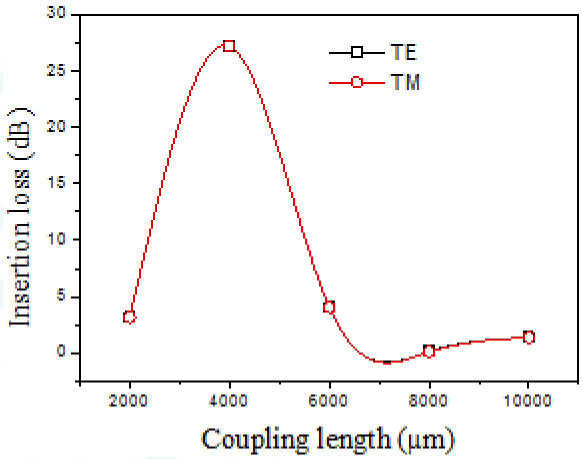

Figure 11: Coupling length as function of insertion loss for different modes.

4. Conclusions

In summary, we proposed a symmetrical optical directional coupler exhibiting switching phenomena for changing waveguide spacing between two waveguides of the coupler. We found from our BPM simulation results the coupling ratio can be reduced with waveguide parameters such as width, wavelength, waveguide spacing, and coupling length, extinction ratio can be increased with waveguide parameter such as width, C-band region wavelength, waveguide spacing, and coupling length, insertion loss can be reduced with width, waveguide spacing, and coupling length, but increased with photonic band region wavelength, and minimum insertion loss at 1550nm wavelength for both polarization modes such as TE and TM. The device shows high extinction ratio, high coupling ratio, and low insertion loss on SOI platform. These symmetrical optical directional couplers can be developed as key components for integrated optical communication devices and useful for build up functional devices, optical clock distribution or arranged as I/O ports on SOI ULSI devices. This work supplies a capable solution for all optical directional couplers on a SOI chip.

5. Acknowledgments

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