TE_0-to-TE_2 Silicon-on-Insulator Internally Dielectric Waveguide Mode Converter

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***Abstract*—A dielectric waveguide, that acts as a fundamental to second-order mode converter with dual polarization capability, is proposed. The proposed device has a very simple structure, low insertion loss, and low crosstalk.**

I. INTRODUCTION

Simultaneous mode- and polarization-division multiplexing (PDM-MDM) is an innovative technology for improving on-chip data capacity in optical communications systems [1]–[3]. Combining polarization-division multiplexing with other types of multiplexing techniques while maintaining both TE and TM modes (rather than suppressing one of them) allows doubling the number of orthogonal degrees of freedom for carrying data [4]. These hybrid-multiplexing techniques provide higher data rates than that when using each method individually.

These techniques require the mode conversion process from fundamental mode to a specified higher order mode before multiplexing modes in one multimode waveguide [5], [6]. The topology optimization (TO) method has been used to design a device that allows the conversion between the transverse electric fundamental even (TE_0) mode and the second higher order odd mode (TE_2) [7].

In this paper, a dielectric waveguide mode converter is proposed in silicon-on-insulator (SOI) with dual polarization capability. The device converts a fundamental TE_0 (TM_0) mode in a silicon waveguide to second-order TE_2 (TM_2) mode. The structure is composed of a $1.8\,\mu m \times 220\,nm$ silicon strip multimode waveguide etched with two dielectric substrips of length $0.6\,\mu m$ and width $0.6\,\mu m$. These dielectric substrips divide the fundamental modes into three equal parts. Introducing a phase shift of π to the light propagating through them, the dielectric substrips would readjust the relative phase differences among these three parts and excite the desired second-order mode. The proposed device has a very simple structure, low insertion loss of -1.28 dB, and low crosstalk of -13.5 dB for the TE polarization.

II. DESIGN AND MODELING

The proposed structure is schematically illustrated in Fig. 1. The device consists of a $1.8\,\mu m \times 220\,nm$ silicon strip multimode waveguide. The waveguide is etched with two dielectric substrips on top of a SiO_2 box layer with a SiO_2 cladding. In addition, a circle of the same dielectric material is etched in the propagating waveguide after phase mask of the mode converter which makes an enhancement in the insertion loss and reduces the crosstalk to fundamental mode.

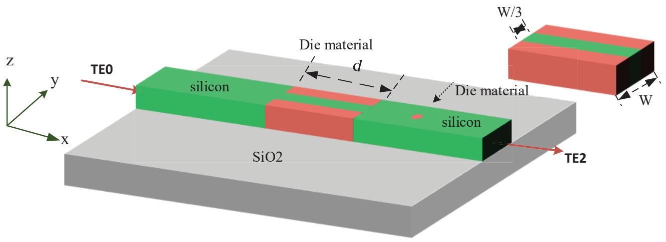

Fig. 1: Schematic diagram of proposed structure.

The phase mask of the mode converter would introduce a suitable phase distribution ($\pi - 0 - \pi$) in the path of fundamental mode propagation through the waveguide so that it is converted to a second-order mode. The pattern of the dielectric phase mask is formed internally inside the propagating waveguide by ditching two substrips of the silicon waveguide with another dielectric material. Each of the two substrips has a length d and a width $W/3$, where W is the width of the multimode waveguide.

The transmittance function of this phase element can be represented by:

$$T(y,z) = \begin{cases} -1; & \text{if } W/2 > |y| > W/6, \\ 0; & \text{if } |y| = W/6, \\ 1; & \text{if } |y| < W/6. \end{cases} \tag{1}$$

where, the center point of the designed waveguide is located at $(y, z) = (0, 0)$ and the phase pattern of the proposed mode converter starts at position $x = 0$. The transmittance function affects the fundamental mode in both y and z directions during distance d and the phase distribution of the resultant field after this phase pattern matches that of second-order mode.

The cross-sectional area of etched dielectric substrips is a design parameter to convert light from fundamental to higher-order mode at a specific wavelength. Specifically, at a wavelength λ, its length d, which produces a phase jump of π to the light passing through it relative to the other silicon

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part of phase mode converter, is given by:

$$d = \frac{\lambda}{2\left(n_{\text{Si}} - n_{\text{Die}}\right)}, \qquad (2)$$

where n_{Si} and n_{Die} are the refractive indices of Si and the other dielectric material, respectively. The width of the dielectric substrip must be $W/(m+1)$, where m is the mode number of the higher-order mode. It should be noticed that $m+1$ is the number of peaks in the higher-order mode, which specifies the number of parts that the fundamental mode will be divided to before introducing the phase shifts.

III. FDTD SIMULATIONS AND RESULTS

In this section, we present FDTD simulation results of proposed device. Both 2D- and 3D-FDTD simulations are studied. First, the proposed waveguide mode converter is designed using silicon nitride (Si_3N_4) material. Next, we replace the Si_3N_4 by silicon dioxide (SiO_2) material.

A. 2D-FDTD Simulation Results

In our 2D-FDTD simulation, a fundamental TE mode is launched at the input of a multimode waveguide of width $W = 1.3\,\mu\text{m}$. The refractive indices of Si strip, Si_3N_4 phase plate, and SiO_2 cladding are $n_{\text{Si}} = 3.477$, $n_{\text{Si}_3\text{N}_4} = 2.016$, and $n_{\text{SiO}_2} = 1.44$, respectively. Using (2), we determine the design parameter $d = 0.4\,\mu\text{m}$. The width of the silicon nitride substrip is $W/3 = 0.44\,\mu\text{m}$. In order to increase the coupled power to second-order mode, two symmetrical Si_3N_4 circles, each of radius $r = 91\,\text{nm}$, are drilled internally at the center points of the propagating waveguide on both sides of the mode converter. Specifically at positions $x = \pm 1.8\,\mu\text{m}$.

The simulation results for TE_0 to TE_2 mode conversion is shown in Fig. 2. The figure shows that at a wavelength of $1550\,\text{nm}$, the conversion is achieved with a low insertion loss (IL) of $-1.17\,\text{dB}$ and low crosstalks of $-13.37\,\text{dB}$ and $-12.5\,\text{dB}$ to both fundamental TE_0 and TE_4 modes, respectively.

In addition, the proposed device can also convert fundamental TM_0 to TM_2. Figure 3 shows the corresponding results. Specifically, at $1550\,\text{nm}$, the insertion loss is about $-1.23\,\text{dB}$, while the crosstalks are $-13\,\text{dB}$ and $-8\,\text{dB}$ to both TM_4 mode and TM_0 modes, respectively.

It is also clear that in both cases, the performance improves when the operating wavelength is decreased, indicating a wideband operation of proposed device.

B. 3D-FDTD Simulation Results

Figures 4 and 5 show 3D-FDTD simulation results for light propagation through the device after being excited by a TE_0 mode at the input section of the waveguide. A $1.8\,\mu\text{m} \times 220\,\text{nm}$ silicon strip waveguide is used with one Si_3N_4 circle of radius $175\,\text{nm}$ after phase plate at position $x = 1.9\,\mu\text{m}$. From the figures, we can clearly observe the conversion into TE_2 mode with an insertion loss of $-1.4\,\text{dB}$ and crosstalks of $-12.8\,\text{dB}$ and $-11\,\text{dB}$ to both fundamental TE_0 and TE_4 modes, respectively, at $1550\,\text{nm}$.

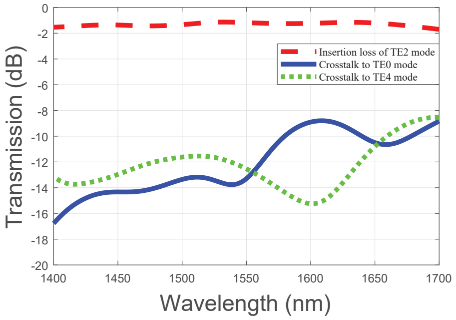

Fig. 2: Insertion loss and crosstalks for TE_0 to TE_2 mode conversion.

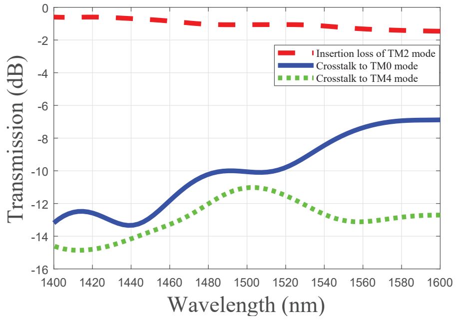

Fig. 3: Insertion loss and crosstalks for TM_0 to TM_2 mode conversion.

It should be noticed that the length and width of the etched Si_3N_4 phase plate is about $0.6\,\mu\text{m}$ only, which is very small and simple compared with other mode converters.

C. Design with Silicon Dioxide Material

In this subsection, we investigate the use another dielectric material to form our higher order mode converter. Specifically, the silicon nitride material is replaced with silicon dioxide with same waveguide parameters, except that the circle radius is reduced to $140\,\text{nm}$ and placed at position $x = 2.2\,\mu\text{m}$. The 3D-FDTD simulation of the silicon dioxide waveguide mode converter is illustrated in Fig. 6. It is clear from the figure that the conversion into TE_2 mode is achieved at $1550\,\text{nm}$ with an insertion loss of $-1.28\,\text{dB}$ and crosstalks of $-13.5\,\text{dB}$ and $-26.96\,\text{dB}$ to both fundamental TE_0 and TE_4 modes, respectively.

A comparison between the silicon dioxide and silicon nitride waveguide mode converters is plotted in Fig. 7. The figure indicates that both the two dielectric materials have approximately the same insertion loss for TE_2 mode, but the SiO_2 waveguide mode converter has a better expectation ratio.

Different dielectric materials can be used in the design of higher order mode converters by simply specifying its length according to relation (2) and its width according to the width of the propagating waveguide.

IV. CONCLUSION

A dielectric waveguide for TE_0 to TE_2 mode conversion has been proposed for silicon-on-insulator (SOI). It has an innova-

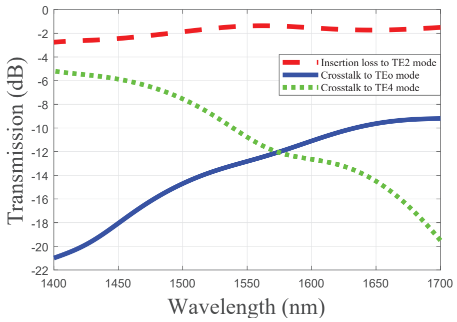

Fig. 4: Insertion loss and crosstalks for TE_0 to TE_2 mode conversion using Si_3N_4 material.

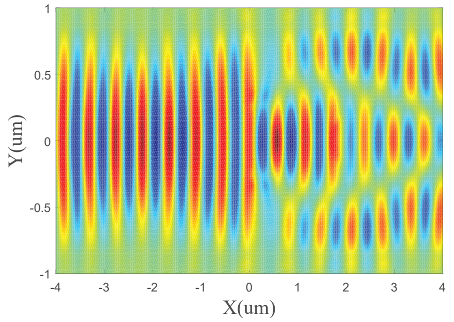

Fig. 5: 3D-FDTD simulation of E_y field propagation.

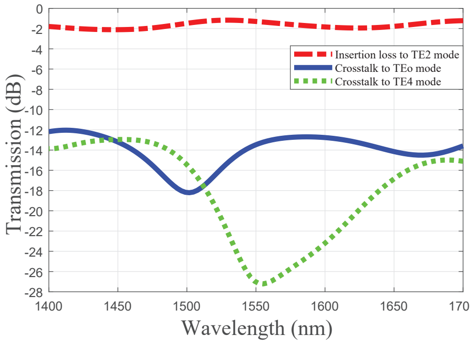

Fig. 6: Insertion loss and crosstalks for TE_0 to TE_2 mode conversion using SiO_2 material.

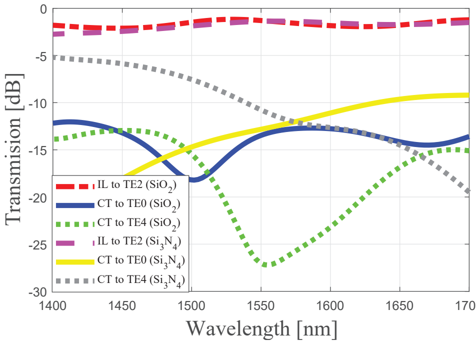

Fig. 7: Comparison between the transmissions through Si_3N_4 and SiO_2 waveguide mode converters.

tive property that it can be optimized to convert both polarized TE_0 and TM_0 modes to TE_2 and TM_2 modes simultaneously; which is very beneficial for PDM-MDM systems. The etched mode converter is very compact and simple; it has a length of $0.6\,\mu\mathrm{m}$ and a width of $1.8\,\mu\mathrm{m}$. In addition, an insertion loss of $-1.28\,\mathrm{dB}$ has been achieved for TE polarization using the SiO_2 material.

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