Silicon-on-Insulator Fundamental to First-Order Dual Polarization Mode Converter based on Si-Si3N4 Phase Plate Waveguide

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Abstract

A silicon-on-insulator fundamental to first-order mode converter with both polarization capability is proposed. The device is based on ditching half-width of propagating silicon waveguide with a silicon nitride substrip of length $0.8\,\mu\mathrm{m}$. The proposed device has a very simple structure, a low insertion loss of $-1.5\,\mathrm{dB}$, and a low crosstalk of $-12.81\,\mathrm{dB}$ at a wavelength of $1550\,\mathrm{nm}$ for transverse electric (TE) polarization.

Keywords: Mode converters, phase plates, waveguides.

1. Introduction

Mode-division multiplexing (MDM) is an enabling technology for increasing on-chip data capacity in optical communications [1]. Simultaneous mode-and polarization-division-multiplexing (PDM-MDM) technique is an innovative technology for further improvement of on-chip data transmission rates in optical communication systems [2, 3]. Furthermore, utilizing both polarization and multimode multiplexing schemes would lead to a reduction in the potential power. Indeed, only one laser source can be used for both polarized MDM channels at the same time.

Normally these techniques require mode conversions from fundamental modes to higher-order modes. One of the most commonly used methods for mode conversion in optical communication systems is based on the use of phase plates due to its simplicity and good selectivity at the design wavelength [4–6].

Another technique for mode conversion depends on introducing a nanoscale periodic perturbation in its effective index along the propagation direction and a graded effective index profile along its transverse direction [7]. This nanoscale mode converter is enabling the conversion of TE_0 to TE_1 mode in a $1\,\mu\mathrm{m} \times 220\,\mathrm{nm}$ silicon strip waveguide with 88% transmission and has a length of $23\,\mu\mathrm{m}$. Topology optimization has also been used for fundamental to first-order mode conversion of transverse electric (TE) polarization [8]. A $1.4\,\mu\mathrm{m} \times 3.4\,\mu\mathrm{m}$ device with insertion loss $< 2\mathrm{dB}$ and extinction ratio $> 9.5\mathrm{dB}$ has been attained.

In this paper, a silicon-silicon nitride (Si-$\mathrm{Si_3N_4}$) dual polarized phase plate mode converter is proposed for silicon-on-insulator (SOI) technology. The device converts a fundamental TE_0 (TM_0) mode in a silicon waveguide to a first-order TE_1 (TM_1) mode. The idea of this mode converter is based on slicing the propagating fundamental mode into two equal parts and introducing a phase shift π to one part in order to re-adjust the relative phase differences among two halves and thus excite the desired output mode. The structure is composed of an etched silicon nitride substrip of length $0.8\,\mu\mathrm{m}$ on half width of a $1\,\mu\mathrm{m} \times 220\,\mathrm{nm}$ silicon strip waveguide.

2. Design and Modeling

The proposed structure is schematically illustrated in Fig. 1. The device consists of a silicon multimode waveguide, that is etched with an $\mathrm{Si_3N_4}$ substrip on top of a $\mathrm{SiO_2}$ box layer with a $\mathrm{SiO_2}$ cladding. In addition, a circle of silicon nitride is etched in the propagation waveguide after phase mask. This would improve the insertion loss and reduce the crosstalk to fundamental mode. For fundamental to first-order mode conversion, a phase pattern of first-order mode is used as shown in Fig. 2. This pattern

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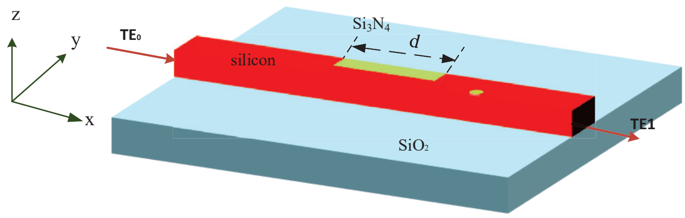

Fig. 1. Schematic diagram of proposed structure.

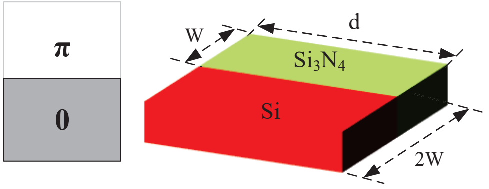

Fig. 2. Phase pattern of first-order mode with cross-sectional area of phase plate.

can be accomplished by etching a substrip of the silicon waveguide with different material so as to introduce a phase shift π to half part of the propagating mode.

In this paper, this pattern is achieved by using silicon nitride (Si_3N_4) material. The pattern of Si-Si_3N_4 phase plate has a cross sectional area of length d and width $2W$, where $2W$ is the waveguide width and d is a design parameter. The width of phase pattern is divided into two substrips. A Si_3N_4 substrip with length d, which produces a phase jump of π to the light passing through it relative to the other silicon substrip of phase plate. This phase coupling element introduces a phase profile that is identical to that of the first-order mode.

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

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

where the center point of the designed waveguide is located at $y = 0$ and $z = 0$. This transfer function of Si-Si_3N_4 phase plate affects the fundamental mode in both y and z directions. After applying it to the fundamental mode for distance d, the phase distributions of the resultant field would match that of first-order mode. For the fields propagating in both substrips to have a phase difference of π:

$$d = \frac{\lambda_0}{2\left(n_{\mathrm{Si}} - n_{\mathrm{Si_3N_4}}\right)}, \tag{2}$$

where n_{Si} and $n_{\mathrm{Si_3N_4}}$ are the refractive indices of Si and Si_3N_4 materials, respectively, and λ_0 is the operating wavelength.

3. FDTD Simulations and Results

In this section, we present the transmission results of both 2D- and 3D-FDTD (finite-difference time-domain) simulations of proposed device.

3.1. 2D-FDTD Simulations

A fundamental TE mode is launched to the input of a multimode waveguide of height 220 nm and width $2W = 2\,\mu\mathrm{m}$. The refractive indices of materials used are $n_{\mathrm{Si_3N_4}} = 2.016$, $n_{\mathrm{Si}} = 3.477$, and $n_{\mathrm{SiO_2}} = 1.44$. Using (2), we determine the design parameter $d = 0.6\,\mu\mathrm{m}$.

The results of our 2D-FDTD simulations are plotted in Fig. 3 versus wavelength. The figure shows that TE_0 to TE_1 mode conversion is achieved at 1550 nm with an insertion loss of -1.8 dB, a crosstalk of -22.4 dB to both TE_2 and TE_4 modes, and a crosstalk of -12.8 dB to both TE_0 and TE_3 modes.

It should be noticed that the proposed device can be operated in both polarizations simultaneously as it converts both fundamental TE_0 and TM_0 modes to first-order TE_1 and TM_1 modes, respectively. Figure 4 shows that the conversion of fundamental TM_0 to TM_1 at 1550 nm is achieved with an insertion loss of -1.56 dB. The crosstalks are about -24.24 dB to both TM_2 and TM_4 modes, and about -13.6 dB to both TM_0 and TM_3 modes.

3.2. 3D-FDTD Simulations

The results of our 3D-FDTD simulations when exciting the device by a TE_0 mode are plotted in Figs. 5 and 6 for a $1\,\mu\mathrm{m} \times 220\,\mathrm{nm}$ waveguide. In the simulations, a silicon strip waveguide is used with a notched circle of radius 125 nm. The circle is filled with Si_3N_4 and placed at position $(x,y) = (2.1, -0.35)\,\mu\mathrm{m}$ after phase plate.

Figure 5 shows the electric field propagation through the device, where it is clear that TE_0 mode is converted to TE_1 mode.

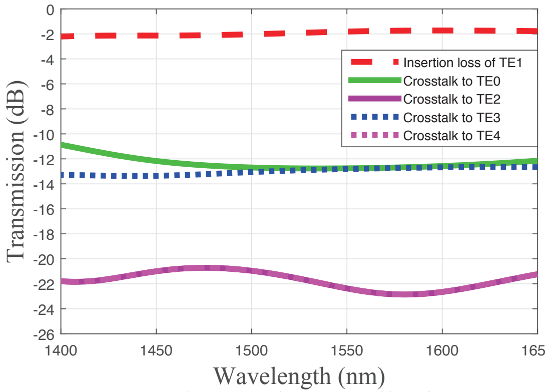

Fig. 3. Insertion loss and crosstalks for TE_0 to TE_1 mode conversion.

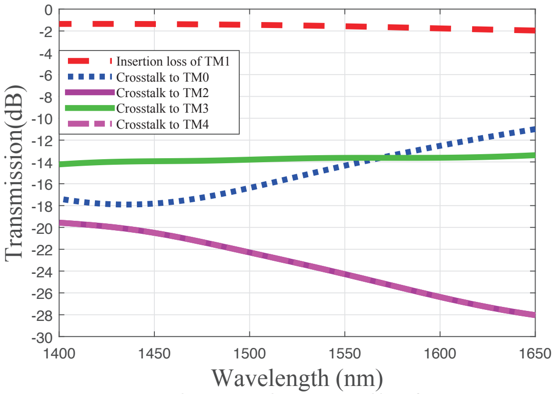

Fig. 4. Insertion loss and crosstalks for TM_0 to TM_1 mode conversion.

Figure 6 shows the corresponding transmission in dB versus wavelength. Specifically at an operating wavelength of 1550 nm, we can clearly observe the conversion into TE_1 mode is achieved with an insertion loss of -1.5 dB. The crosstalks to TE_2 and fundamental TE_0 modes are -16.42 dB and -12.81 dB, respectively.

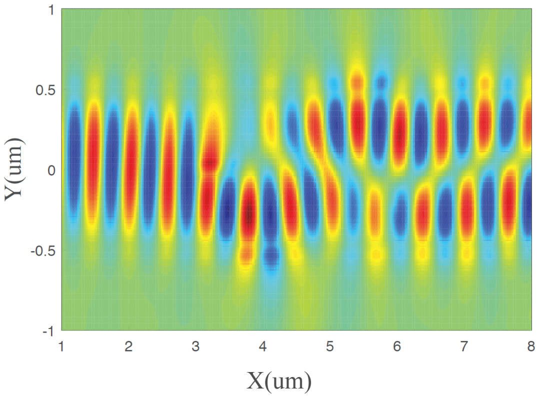

Fig. 5. 3D FDTD simulation of the E_y field propagation.

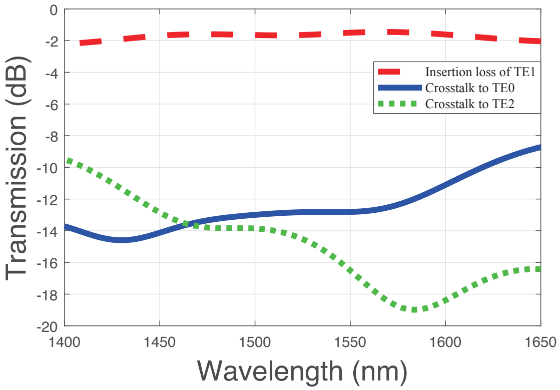

Fig. 6. Insertion loss and crosstalks for TE_0 to TE_1 mode conversion.

It should be mentioned that here the length of the etched Si-Si_3N_4 mode converter waveguide is about $d = 0.8\,\mu$m only, which is very small and simple compared to the spatial mode converter in [7], which has a length of 23 µm.

3.2.1. TM_0 to TM_1 Conversion

As the two fundamental polarizations are not degenerate in a strip waveguide, some modifications are needed to be able to convert a fundamental TM_0 to first-order TM_1 mode. Specifically, the propagation waveguide has a width of 1.5 µm and the Si_3N_4 substrip length is $d = 1.6\,\mu$m. The reason is that fundamental TM_0 mode requires a longer distance of the etched material to produce a phase shift of π than that required by fundamental TE_0 mode. In addition, the notched circle is placed after phase plate at position $(x,y) = (2.9,-0.2)\,\mu$m with a radius of 225 nm. Figure 7 shows that the conversion into TM_1 mode is achieved with an insertion loss of -2.58 dB. The crosstalks to TM_2 and fundamental TM_0 modes are -10.68 dB and -13.2 dB, respectively.

3.2.2. Simultaneous Transmission of both TE_0 and TM_0 Polarizations

The proposed device can be optimized to convert both TE_0 and TM_0 fundamental modes to corresponding first-order modes simultaneously with fixed design parameters. Producing a phase shift π to the half part of the propagating modes can be attained by setting the length of the Si_3N_4 substrip to be equal to odd multiples of the design parameter d. However, there is a trade-off between simultaneous conversation of both polarized modes and the insertion losses of the two first-order TE_1 and TM_1 modes

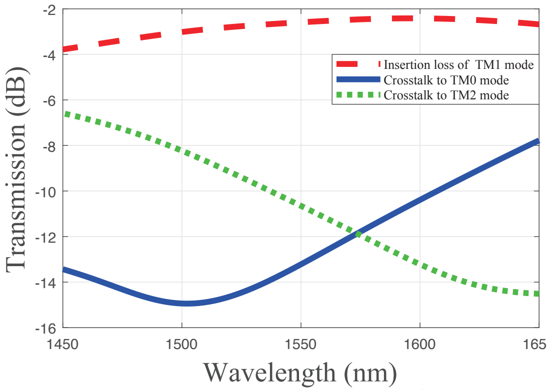

Fig. 7. Insertion loss and crosstalks for TM_0 to TM_1 mode conversion.

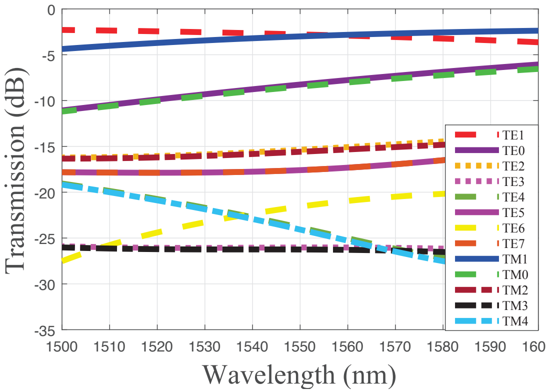

Fig. 8. Transmission of both TE_0 and TM_0 polarizations simultaneously in the mode converter.

as well as the crosstalks, as an optimum length of the design parameter d must achieve acceptable mode conversion for both polarizations at the same time with same device parameters.

Figure 8 shows the results of transmitting both fundamental TE_0 and TM_0 modes simultaneously through the mode converter. Here, the waveguide width is $2.8\,\mu\text{m}$ and the Si_3N_4 length is $d = 1.8\,\mu\text{m}$. The notched circle is placed after phase plate at position $(x, y) = (0.6, -1.2)\,\mu\text{m}$ with radius of $120\,\text{nm}$. The conversion is achieved with an insertion loss of $-2.79\,\text{dB}$ and $-2.98\,\text{dB}$ to both TE_1 and TM_1, respectively. This idea still needs more optimization in order to enhance the insertion loss and reduce the crosstalk.

4. Conclusion

An etched Si-Si_3N_4 binary phase plate waveguide for TE_0 to TE_1 mode conversion has been proposed for silicon-on-insulator (SOI). It has the advantage of being very compact and simple; its length is only $0.8\,\mu\text{m}$ and its width is $1\,\mu\text{m}$. In addition, an insertion loss of $-1.5\,\text{dB}$ has been achieved for the mode conversion. The proposed device can also convert TM_0 to TM_1 mode. Simultaneous conversion of both polarizations is very useful in implementing PDM-MDM systems.

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