Study on Silicon-Based Polarization Converter Using Asymmetric Slot Waveguide

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Study on Silicon-Based Polarization Converter Using Asymmetric Slot Waveguide

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SUMMARY A compact optical polarization converter (PC) based on slot waveguide has been proposed in this study. Utilizing the high refractive index contrast between a Si waveguide and SiO_2 cladding on the silicon-on-insulator platform, the light beam can be strongly confined in a slot waveguide structure. The proposed PC consists of a square waveguide and an *L*-shape cover waveguide. Since the overall structure is symmetrically distributed along the axis rotated 45-degree from the horizontal direction, the optical axis of this PC lies in the direction with equi-angle from two orthogonally polarized modes of the input and output ends, which leads to a high polarization conversion efficiency (PCE). 3D FDTD simulation results illustrate that a TE-to-TM mode conversion is achieved with a device length of 8.2 μm, and the PCE exceeds 99.8%. The structural tolerance and wavelength dependence of the PC have also been discussed in detail.

key words: *polarization converter, slot waveguide, finite difference time domain method*

1. Introduction

With the rapid progress of the Internet, high-speed and large-capacity data transmission is demanded in the modern communication society. For an optical communication system, polarization division multiplexing (PDM) is an effective method to enlarge the data transmission capacity. Therefore, high-performance optical polarization control devices can improve the overall performance of a PDM system. In recent years, micro-photonic circuits built on the silicon-on-insulator (SOI) platform have attracted much interest due to their low power consumption and the high refractive-index contrast [1]. Moreover, its fabrication is compatible with the complementary metal oxide semiconductor (CMOS) technology, facilitating a cost-effective mass production. Utilizing the high refractive-index contrast between the Si wires and a SiO_2 substrate, micrometer-grade bend waveguide can be manufactured, which leading to a extremely compact optical circuit with a negligible bending loss. However, this property is also results in high-birefringence for the silicon waveguides, and causes the polarization-dependent loss and related waveguide dispersion [2]. Therefore, a polarization diversity system, including polarization beam splitters (PBSs) [3]–[5], polarization converters (PCs) [6]–[11] and single-polarization waveguides [12], is essential for the SOI integrated optical circuits. Until now, various PC elements have been studied and designed, such as PCs using hybrid plasmonic waveguide [6], photonic crystal structure [8] and asymmetric waveguide [9]. Two main design mechanisms are widely used in these PCs, *i. e.*, mode evolution and mode coupling methods. The PC based on the mode evolution method converts the polarization state by rotating the optical axis of incident mode, which generally requires a long device length. On the other hand, the mode coupling PC has an asymmetric structure whose optical axis is 45° tilted relative to the polarization direction of the eigen modes of the input/output waveguide, and the polarization conversion is achieved by the mode coupling between its fundamental and 1st–higher-order modes.

Silicon based slot waveguides were firstly proposed by Almeida *et al* [13], which have a low-refractive index region embedded between two high-refractive index wires. A vertical slot waveguide confines the majority of light into the low-index slot region due to the discontinuous boundary condition on the dielectric interface for the horizontal electric field. Over the last decade, utilizing the large birefringence property, several slot waveguide based polarization diversity devices have been proposed [10]. Moreover, considering the fabrication errors and the mode conversion between a slot waveguide and strip waveguide, asymmetric slot devices have been proposed and investigated [14].

Until now, the PCs based on plasmonic waveguides have a relatively high insertion loss and an extra ohmic loss. The complex fabrication process limits the use of PCs based on photonic crystal structures. On the other hand, devices that can be directly used for polarization conversion of slot waveguides are rarely studied. In this study, a compact PC element based on an asymmetric slot waveguide is designed and investigated. The PC consists of a square waveguide and *L*-shape cover waveguide. By adjusting the appropriate structural parameters, the optical axis of PC having an tilt angle of 45° with respect to the polarization direction of the incident light, lead to a high polarization conversion efficiency (PCE). According to Ref. [7], lithography and one-step etch processes are required to fabricate the PC, and the asymmetric cross section can be achieved by oblique deposition process. A 3D finite difference time domain (3D-

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FDTD) method is used to simulate the modal conversation behavior of the transverse electric (TE) mode of a horizontal slot waveguide to the transverse magnetic (TM) mode. Owing to structure of the PC, it can be used for polarization conversion of slot waveguides (the input/output ends are set as two orthogonal slot waveguides) or conventional linear waveguides (the input/output ends are set to linear waveguides). In this paper, we mainly illustrate the propagation characteristics of the PC with input/output ends of slot waveguides. The numerical results show that a PCE of 99.8% is achieved with a device length of 8 μm, and the corresponding extinction ratio (ER) is better than −26.6dB. Moreover, the structural tolerance and wavelength dependence of the PC have also been discussed in detail.

2. PC Based on Slot Waveguide

2.1 Excited Eigen Modes

The 3D and cross-sectional views of our proposed PC are depicted in Fig. 1. For the polarization conversion region, a square Si waveguide (width and thickness are W_1 and H_1, respectively) and an L-shaped cover waveguide (width and thickness are W_2 and H_2, respectively) are symmetrically placed along the $y = x$ plane. The vertical and horizontal slot thicknesses are denoted as g_x and g_y. A horizontal slot and vertical slot waveguides are set to be the input and output ports, respectively. The refractive indices of silica and silicon are set to be 1.444 and 3.478 at the operating wavelength of 1.55 μm.

Owing to the asymmetric distribution of the PC, for each eigen mode, both E_x and E_y components are exist. The rotation angle of the optical axis θ (respect to the x-axis) is defined as follows:

$$\tan(\theta) = \frac{\iint \varepsilon(x,y)E_x^2(x,y)dxdy}{\iint \varepsilon(x,y)E_y^2(x,y)dxdy} \tag{1}$$

where $\varepsilon(x,y)$ is the real part of the permittivity distribution, $E_x(x,y)$ and $E_y(x,y)$ are the horizontal and vertical electrical components of an eigen mode, respectively. By carefully adjusting the structural parameters, the equal intensities for the E_x and E_y components of each mode can be realized, leading to an efficient polarization conversion. According to the coupled mode theory, when a TE (TM) mode is launched into the PC, the fundamental and 1st-higher-order modes (contain both polarizations) will be excited and made a beat with each other. With propagation of the light, an orthogonal TM (TE) mode is generated where the phase difference between these two modes increases to π. The conversion length can be calculated by $L_c = 0.5\lambda/(n_{\mathrm{eff},1} - n_{\mathrm{eff},2})$, where λ is the operation wavelength and $n_{\mathrm{eff},1}$ and $n_{\mathrm{eff},2}$ are the effective refractive indices of the excited fundamental and 1st-higher-order modes, respectively.

In this study, since the overall PC is symmetrically distributed along the $y = x$ plane, we set $W_1 = H_1$, $g_x = g_y = g$ and $W_2 = H_2 = 100$ nm. The variation of conversion length L_c with the different waveguide width W_1 and slot thickness g is given in Fig. 2. It is revealed that a relatively short device length can be achieved with a narrow square waveguide width and a wide slot thickness. Here, the $W_1 = H_1 = 200$ nm and $g_x = g_y = g = 100$ nm are selected to further analyze the excited modes of the PC. Electric field distributions of the lowest two eigen modes are obtained by using the finite element method (FEM), as shown in Fig. 3. It is seen that the field distributions of the two modes are similar to each other for both polarizations, and the light power is mostly confined in the low-index slot region. The calculated tilt angles of the PC optical axis is 45°.

In addition, PC with a rectangular waveguide ($W_1 \neq H_1$) also can provide a 45° tilt angle of the optical axis to achieve a high PCE. Here, we consider the PC with $H_1 = 200$ nm, $g_x = 100$ nm and $W_2 = H_2 = 100$ nm. The variation of θ with different horizontal slot thickness g_y is illustrated

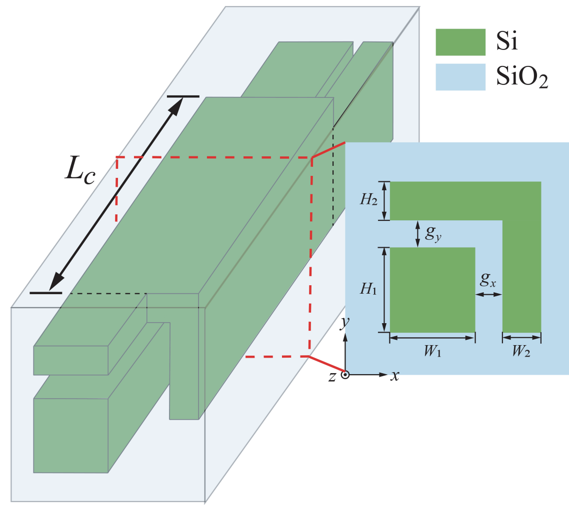

Fig. 1 3 dimensional schematic and cross-section view of the PC element based on slot waveguide. The input/output ports are set to horizontal/vertical slot waveguides.

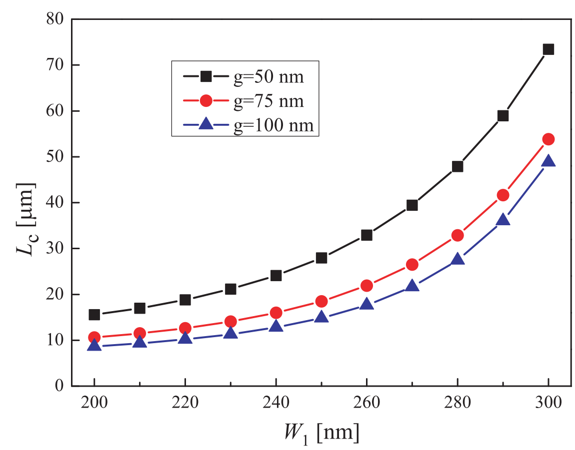

Fig. 2 The variation of conversion length L_c with different square waveguide width W_1 and slot thickness g ($W_1 = H_1$, $g_x = g_y = g$ and $W_2 = H_2 = 100$ nm).

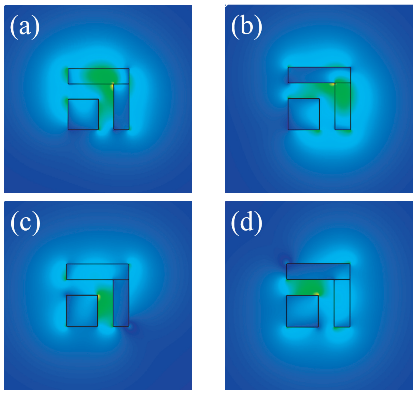

Fig. 3 Electric field distributions of the two lowest modes in the PC with $W_1 = H_1 = 200$ nm, $W_2 = H_2 = 100$ nm and $g = 100$ nm at wavelength of 1.55 μm. (a) E_x and (b) E_y for the fundamental mode; (c) E_x and (d) E_y for the 1^{st}-higher-order modes.

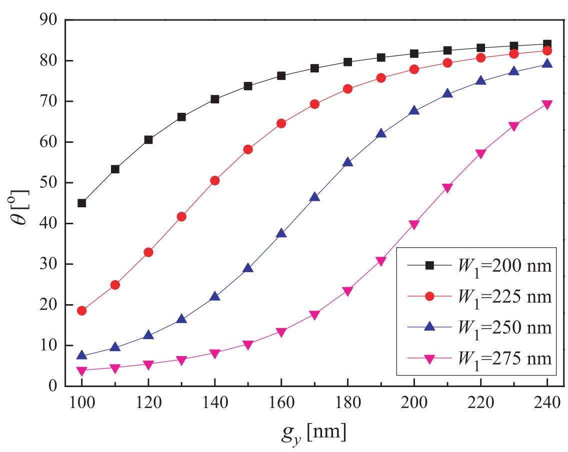

Fig. 4 The tilt angle of the optical axis θ as a function of horizontal slot thickness g_y.

in Fig. 4. It is obvious that for a wide width ($W_1 > H_1$) PC element, the optical axis can be tilted up to 45° by properly enlarging the horizontal slot thickness.

2.2 Light Propagation Behavior

Here, the electric field evolution along the propagation distance through the PC is simulated using the 3D FDTD method, as shown in Fig. 5. Taking the TE-to-TM mode conversion as an example, the incident mode is set to the TE mode of a horizontal slot waveguide. With $W_1 = H_1 = 200$ nm, $W_2 = H_2 = 100$ nm and $g_x = g_y = g = 100$ nm, the calculated conversion length is $L_c = 8.2\ \mu$m at $\lambda = 1.55\ \mu$m. The incident TE mode is converted into a TM mode at the output port of the PC. The ER, PCE and insertion loss (IL) of the PC are defined as [9],

$$\mathrm{ER} = 10\log_{10}(P_{\mathrm{TE,out}}/P_{\mathrm{TM,out}}), \tag{2}$$

$$\mathrm{PCE} = \frac{P_{\mathrm{TM,out}}}{(P_{\mathrm{TE,out}} + P_{\mathrm{TM,out}})} \times 100\%, \tag{3}$$

$$\mathrm{IL} = -10\log_{10}(P_{\mathrm{out}}/P_{\mathrm{in}}), \tag{4}$$

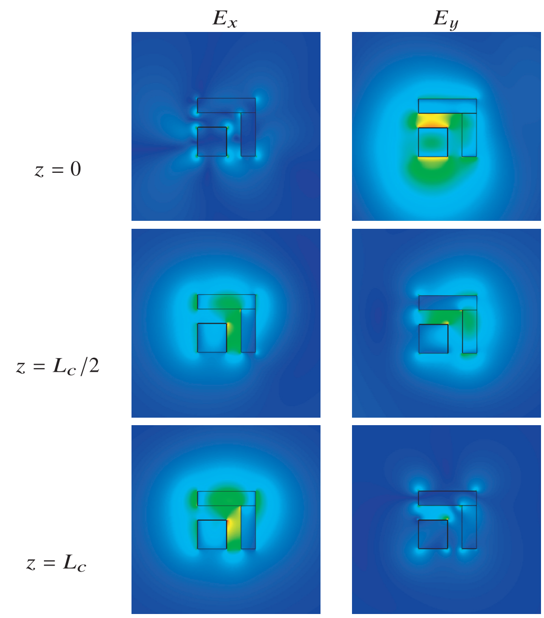

Fig. 5 Light propagation behavior of TE-to-TM mode conversion through the designed PC using 3D-FDTD method.

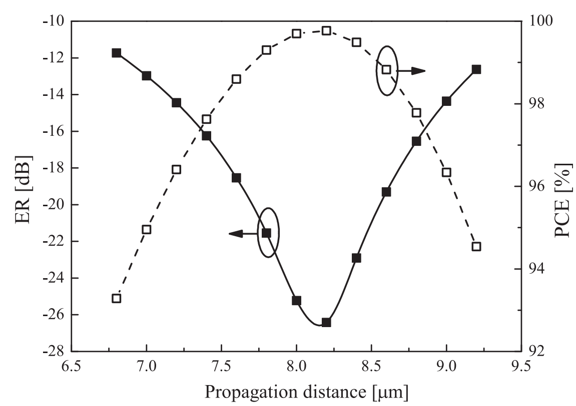

Fig. 6 The ER and PCE as functions of the propagation distance from 6.8~9.2 μm.

where $P_{\mathrm{TM,out}}$ and $P_{\mathrm{TE,out}}$ are the output power of the TM and TE modes for a TE-to-TM mode conversion; P_{out} and P_{in} are the power of input and output ports, respectively.

Figure 6 gives the variation of ER and PCE with the propagation distances from 6.8~9.2 μm. It is observed that the ER and PCE reach the minimum and maximum values respectively at $z = 8.2\ \mu$m. The FDTD simulation results show that the ER is better than −26.6dB, the PCE is 99.8% and the IL is 1.47dB. Moreover, considering actual production processes, the ER is better than −20dB even if the PC device length is deviated within 7.8~8.6 μm.

3. Tolerance and Wavelength Dependence

So far, the PC element based on slot waveguide has been designed. In this section, the structural tolerance and wavelength dependence of the proposed PC are discussed.

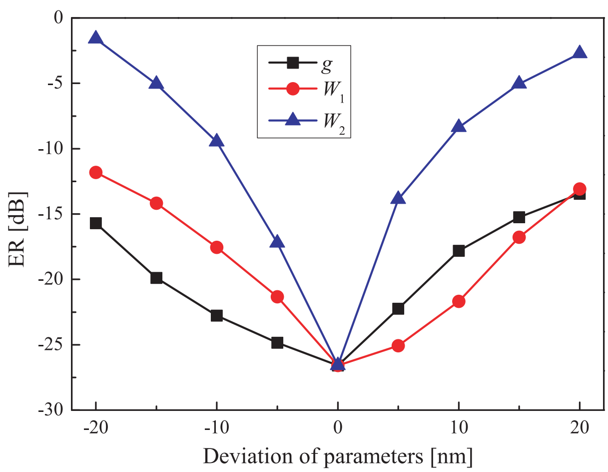

Fig. 7 ER variation with the deviation of all the parameters.

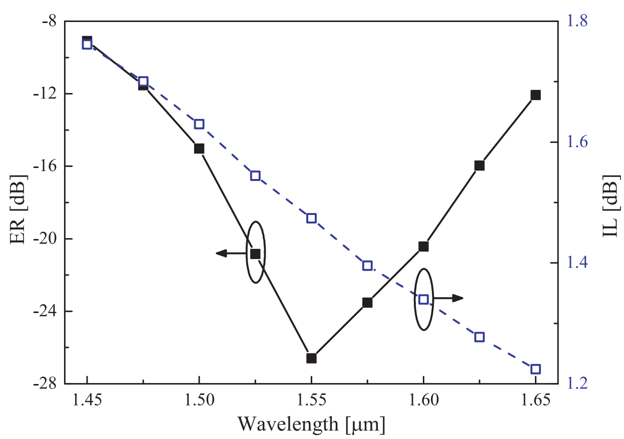

Fig. 8 Wavelength dependence of the ER and IL for a TE-to-TM mode conversion.

Firstly, the ER variation with the each parameter range within ±20 nm is shown in Fig. 7. The ER is sensitive to the *L*-shaped cover waveguide width W_2, because the width directly affects the amount of light that penetrates the cladding, and a slight change may cause a variation of the electric field distribution which means the conversion length will no longer be the original designed value of 8.2 μm. Numerical simulation results give that the ER is better than −20dB when W_2 varies from −4 ∼ +3 nm, or the square waveguide width W_1 varies from −7 ∼ +12 nm, or the slot thickness g varies from −15 ∼ +8 nm.

Additionally, the wavelength dependence of the PC has also been investigated, as shown in Fig. 8. For the TE-to-TM mode conversion, the ER is better than −20dB from 1.525 to 1.600 μm (bandwidth is 75 nm). The corresponding IL decreases as the operation wavelength increases, and the IL = 1.35 dB at λ = 1.6 μm.

4. Conclusion

In this paper, a novel PC element based on slot waveguide has been proposed. FDTD simulation results show that an incident TE mode of horizontal slot waveguide can be converted into a TM mode with a device length of 8.2 μm. The ER is better than −26.6dB, the PCE is 99.8% and the IL is 1.47dB. Moreover, the structural tolerance and wavelength dependence have also been discussed in detail. In the future, we will further investigate the properties of this PC used in a simple rectangular waveguide.

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