Optics Communications 403 (2017) 234–239

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Low-loss and wide-band polarization converter based on a hybrid plasmonic waveguide with symmetric Ag strips

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ARTICLE INFO

Keywords:
Integrated optics device
Polarization-selective device
Surface plasmon

ABSTRACT

We propose a polarization converter (PC) based on mode coupling in a hybrid plasmonic waveguide (HPW), comprising a Si waveguide, SiO_2 layers surrounding the Si core, and two symmetrically arranged metal strips with respect to the optical axes. In this HPW structure, the surface-plasmon-polariton modes at the metal and SiO_2 interfaces are hybridized with traditional optical modes within the SiO_2 layer Two orthogonal hybrid polarization modes are thus excited. By exploiting the mode characteristics of these two hybrid polarization modes, a compact polarization converter is realized. Simulations indicate that polarization conversion is achieved with a polarization conversion efficiency (PCE) of 99.9%, an insertion loss (IL) of 0.82 dB and an extinction ratio (ER) of 30.4 dB at a wavelength of 155 nm for a conversion length of 4.58 μm. For the C-band, in a wavelength range of 1530–1565 nm the PCE is greater than 99.6% the IL is below 1 dB and the ER is larger than 24 dB. These performance values are an improvement over those reported HPW-based PCs

1. Introduction

Polarization-division multiplexing (PDM) technology has attracted much attention in recent years [1]. This technology uses polarization converters (PC) as key components that convert one polarization state of a light beam to another. Such an optical device can be realized by mode coupling [2–5] or mode evolution [6–8]. Silicon-on-insulator (SOI) devices are considered to be a promising platform for these methods, owing to the advancements in metal-oxide-semiconductor technology and the inherent polarization sensitivity of these materials.

In order to improve integration, surface-plasmon polaritons (SPPs) have also been utilized in SOI-based PC structures. Within these structures, SPP waves were excited at the interfaces between a silicon waveguide core and metal layers. The difference in the propagation constants of the two orthogonal modes is thus increased and the device length is decreased [9]. However, because the SPP modes undergo strong Ohmic loss in the metal, the insertion loss (IL) of the device is usually large. For instance in Ref. [10] although a device length was only 610 nm, the IL is more than 3 dB. Therefore, to reduce the IL, hybrid plasmonic waveguides (HPWs) based PCs have been proposed [11–15]. In an HPW, a thin low-index dielectric layer is sandwiched between the silicon core and the metal layer, thus the excited hybrid mode propagates mostly within the SiO_2 layer and experiences less Ohmic loss from the metal [11]. For example, the simulation results in Ref. [13] achieved a polarization conversion efficiency (PCE) of 99.5% at the wavelength of 1550 nm, while the IL could be decreased to 1.38 dB and the extinction ratio (ER) was 22.4 dB. However, the excited orthogonal fundamental modes inside those works were not very symmetrical around the Si core. Therefore the performance e.g. the ER was unsatisfactory, especially for the entire C-band with wavelength range of 1530–1565 nm.

In the present work, we propose a mode-coupling PC based on an HPW, where two Ag strips are arranged symmetrically with respect to the Si core and the optimal optical axis of the PC. The optimal optical axis of the PC should be rotated by 45° with respect to the original optical axis of input/output waveguide. This symmetrical arrangement of Ag strips ensures an improved excitation of two orthogonal fundamental modes around the Si core inside the PC, which would lead to an improvement of the ER and PCE. Meanwhile, the Ag strips instead of Ag layers used in other works could reduce Ohmic loss and then reduce the IL loss. Numerical simulations show that an optimized PC achieves a high PCE in excess of 99.6%, an ER above 24 dB, and a smaller IL below 1 dB for the entire C-band, while the conversion length is 4.58 μm.

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http://dx.doi.org/10.1016/j.optcom.2017.06.049
Received 18 March 2017; Received in revised form 12 June 2017; Accepted 14 June 2017
0030-4018/

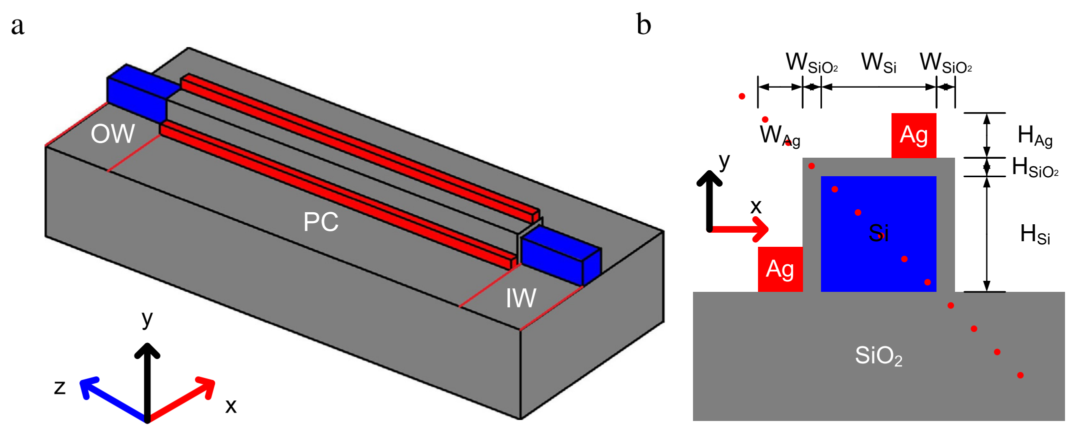

Fig. 1. Schematic of (a) structure and (b) cross section of the proposed polarization converter.

2. Structure design and operation principle

2.1. Structure design

The structure of the proposed polarization rotator is outlined in the schematic as shown in Fig. 1. The entire device is based on an SOI platform and is surrounded by air. As shown in Fig. 1(a), the structure consists of three sections: the input waveguide (IW), the polarization converter (PC), and the output waveguide (OW). Fig. 1(b) shows the PC cross section, which is composed of a Si core, a SiO_2 layer, and two identical Ag wires. The Si core is embedded within the SiO_2 layer. Two identical Ag wires are located on top and on one side of the SiO_2 layer. The dotted line represents the symmetry line of the cross section. The upper Ag strip is clearly aligned with one side of the Si core, such that the two Ag strips are arranged symmetrically with respect to the dotted line. This arrangement ensures that the optical axes of the fundamental modes of the PC are rotated by 45° relative to those of the IW, and that the electric and magnetic fields of these modes are also symmetrically distributed.

2.2. Operation principle

The operation principle of the PC is as follows. As light (E_{input}) is introduced into the HPW (more specifically, into the PC section), two orthogonal hybrid modes E_{M1} and E_{M2} become excited, with the subscripts M1 and M2 denoting the modes with the greater and smaller propagation constants, respectively. When traveling through the PC section, the two modes produce a beating effect and accumulate a phase difference $\Delta\varphi_{\text{M1}} - \Delta\varphi_{\text{M2}}$. Ideally, when a phase difference of π is accumulated through the PC section, the polarization of the light (E_{output}) in the output waveguide is rotated by 90°. Fig. 2 illustrates this polarization conversion, when the input light (E_{input}) is assumed to be in the quasi-TE state of polarization, with its amplitude normalized by the power flow. When the accumulated phase difference between the two eigenmodes E_{M1} and E_{M2} is π, mode E_{M1} is equivalently rotated to be a new mode E'_{M1}. Consequently, the output light (E_{output}) is in the quasi-TM state of polarization.

First, the mode characteristics of the input and output waveguides were analyzed by simulation. The wavelength range was set from 1450 to 1650 nm, and the refractive indices of Si and SiO_2 were $n_{\text{Si}} = 3.48$ and $n_{\text{SiO2}} = 1.44$, respectively. The width and height of the Si core, W_{Si} and H_{Si}, were both 310 nm [14]. The permittivity of silver is derived from the Drude model as $\varepsilon(\omega) = \varepsilon_\infty - \omega_p^2/(\omega^2 + i\omega/\tau)$, with $\varepsilon_\infty = 1.0$, $\omega_p = 1.37 \times 10^{16}$ rad/s, and $\tau = 33$ fs [10]. The size of the input and output waveguides is strictly limited to ensure that there are two lowest-order modes, namely the quasi-TE and quasi-TM polarization modes. In a two-dimensional (2D) simulation of the input and output waveguides,

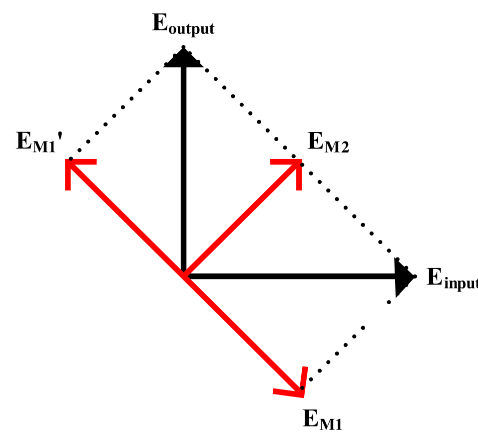

Fig. 2. Polarization conversion from a quasi-TE to a quasi-TM state of polarization at the center of the Si strip.

the effective indices of these two modes, n_{TE} and n_{TM}, were 1.9966 and 1.9174, respectively.

Second, the mode characteristics of the HPW-PC section were analyzed. The conversion length L_C is defined as

$$L_C = \frac{\pi}{\beta_{\text{M1}} - \beta_{\text{M2}}} = \frac{\lambda}{2\Delta n} \tag{1}$$

where β_{M1} and β_{M2} are the propagation constants of the two excited hybrid modes inside the HPW, $\Delta n = n_{\text{M1}} - n_{\text{M2}}$ is the difference between the hybrid-mode indices, and λ is the wavelength. After propagating through a distance L_C, a relative phase shift π appears between the two modes. An important figure of merit for the PC is the PCE, which is related to the rotation angle θ of the hybrid-mode optical axis and L_C:

$$\text{PCE} = \sin^2(2\theta)\sin^2\left(\frac{\pi L}{2L_C}\right) \times 100\%. \tag{2}$$

The rotation angle θ is defined by the transverse electric fields:

$$\tan(\theta) = R = \frac{\iint \varepsilon(x,y) E_x^2(x,y)\,\mathrm{d}x\mathrm{d}y}{\iint \varepsilon(x,y) E_y^2(x,y)\,\mathrm{d}x\mathrm{d}y} \tag{3}$$

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 electric components of the excited eigenmode with the greater propagation constant. Therefore, $\theta = 45°$ is needed to achieve a PCE of ∼100%.

The calculated electric and magnetic fields of the two hybrid modes are shown in Fig. 3. It is clearly seen that the asymmetry of the structure has ensured an asymmetric field profile. While the electric fields are confined mostly in the SiO_2 layer, the magnetic fields are mainly located