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Compact device employed a hybrid plasmonic waveguide for polarization-selective splitting

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ABSTRACT

We proposed an ultra compact polarization beam splitter (PBS) with a short coupling length of 2.82 μm consisting of a horizontally slotted waveguide (HSWG) and a hybrid plasmonic waveguide (HPWG). Only the TM-polarized mode can be supported in the HPWG, and the effective index, corresponding to the TM-polarized mode, in the HPWG is similar to that in the HSWG within a wide wavelength range. Consequently, the TM-polarized mode in the HSWG could be coupled into that in the HPWG. As a result, the TE- and TM-polarized modes are split. Such a PBS exhibits a high extinction ratio of up to −20 dB within an ultra wide wavelength range of 130 nm. Moreover, fabrication tolerances of the PBS are investigated.

1. Introduction

Silicon-on-insulator (SOI) technology has attracted lots of interests as a platform for guiding and manipulating optical signals in photonic integrated circuits. However, SOI waveguides involve highly polarization-dependent guiding owing to the high index difference between silicon and air/silica. As a result, the implementations of polarization beam splitters (PBSs) are essential in the applications of SOI waveguides. Although various configurations, such as multimode interference structures [1–3], Mach-Zehnder interferometers [4–6], photonic crystal structures [7,8], have been demonstrated to split polarization modes, one would prefer to implement PBSs based on directional couplers [9–22] due to their simplicity and easy design. For instance, Dai et al. [14] demonstrated an ultrashort polarization splitter with a strip-nanowire and a vertically slotted waveguide, which took advantage of the completely phase-matching condition for the TM polarization, while significantly suppressed the coupling for the TE polarization. Zhang, et al. presented a compact and efficient PBS using horizontally slotted waveguides with extinction ratio across C+L broadband [15]. Recently, a directional coupler, consisting of a vertically slotted waveguide and a channel waveguide, has been developed to realize polarization splitting with high extinction ratio of 20 dB for through port [16].

In recent years, plasmonic waveguides [23] have attracted intensive research interest due to their excellent ability to break the diffraction limit. Among them, hybrid plasmonic waveguides (HPWGs) are emerging because of their unique advantages of both long propagation length and strong confinement, and, in particular, large birefringence [24–28]. Recently, we demonstrated an on-chip PBS based on directional coupling system consisting of a horizontally slotted waveguide (HSWG) and a HPWG [18], in which only one polarization state was index-matched, whereas the index difference was very high for another polarization so that the effective coupling between the two polarization modes was prevented. Almost at the same time, Gao et al. [19] presented an ultracompact PBS consisting of a HPWG and a strip dielectric waveguide, which showed an extinction ratio of over 14.7 dB for the TE-polarized mode within the whole C band. In addition, Lou et al. [20] demonstrated a compact PBS based on a dielectric-hybrid plasmonic-dielectric coupler. In the meanwhile, Chee et al. [21] designed a similar device by use of Cu as the metal cap and demonstrated an ultrashort integrated polarization splitter with a bandwidth of more than 70 nm and an extinction ratio of less than 15 dB. An asymmetrical coupling system consisting of a hybrid plasmonic waveguide and a silicon nanowire has been proposed by Guan et al. [22].

In this paper, we present a promising PBS based on a directional coupling system consisting of a HSWG and a HPWG. Such a PBS is optimally designed to satisfy the phase-matching condition for TM-polarized modes of the two waveguides, while the TE-polarized mode cannot be supported in the HPWG. In the

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proposed PBS, the two index-curves of the TM-polarized modes in the HSWG and the HPWG have a very small index difference so that strong coupling occurs within a wide wavelength range. In contrast, the effective coupling for the TE-polarized mode is prevented due to the fact that only TM-polarized guided mode can be supported in the HPWG. Consequently, our PBS could be used to split the TM- and TE-polarized modes with a high extinction ratio within an ultra wide wavelength range.

2. Numerical simulation

As shown in Fig. 1, we designed a PBS consisting of a HSWG with a width of w and a HPWG with a width of w_h. The HSWG is composed of a silica spacer with a thickness of h_{slot} and two silicon layers with a thickness of h_s. The HPWG is composed of a metal layer, a silica spacer, and a silicon layer with a thickness of h_m, h_d, and h, respectively. The gap distance between the two waveguides is defined as d. The substrate of the PBS is assumed to be silica with a refractive index of 1.4500. Refractive index of silicon ($n_{silicon}$) is 3.4764. Gold is chose to be the metal layer of the HPWG and its permittivity can be given by [29].

$$\varepsilon_{Au}(\lambda)=\varepsilon_{\infty}-\frac{1}{\lambda_p^2(1-\lambda^2+i/\lambda_p\lambda)}+\sum_{j=1,2}\frac{A_j}{\lambda_j}\left[\frac{e^{i\phi_j}}{(1/\lambda_j-1/\lambda+i/\lambda_j)}+\frac{e^{-i\phi_j}}{(1/\lambda_j+1/\lambda-i/\lambda_j)}\right] \tag{1}$$

where the first and second terms are the contribution from the Drude model, and the third and fourth terms are the contribution from the interband transitions. The parameters in Eq. (1) are listed in Table 1. The default operation wavelength is 1550 nm.

Fig. 2 illustrates the calculated effective refractive indices (N_{eff}) and propagation distances of the TM-polarized mode in the HPWG as a function of the HPWG width of w_h, where the propagation distance of the TM- and TE-polarized modes is defined as a distance over which the guided power drops to 1/e of its initial magnitude. As shown in Fig. 2(a) and (b), the effective index and the propagation length of the TE-polarized mode decreases and increases, respectively, with the decrease of w_h. It can be seen from that the TE-polarized mode is gradually coupled into the silica substrate with the decreases of w_h (Fig. 2(e)), while the TE-polarized mode is confined in the HPWG (Fig. 2(f)). Simulation results show that the TE-polarized mode is completely leaked into the silica substrate while w_h is less than 240 nm. In other words, the TE-polarized mode cut off in the HPWG with a width of less than 240 nm. On the other hand, as shown in Fig. 2(c) and (d), both the effective index and the propagation length of the TM-polarized mode decrease with the decrease of w_h. We also calculated the effective refractive indices and the propagation lengths of the TM- and TE-polarized modes in the HPWG with different silica spacer thicknesses, h_d, of 60, 80, and 100 nm in order to find an optimal silica spacer thickness of 80 nm, as described below.

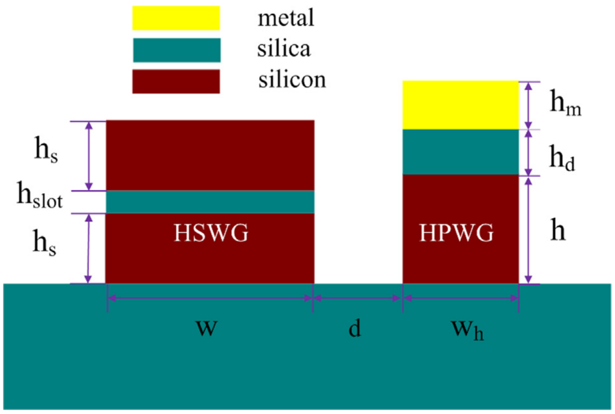

Fig. 1. Schematic diagram of the cross section of a proposed PBS consisting of a HSWG and a HPWG.

As shown in Fig. 3(a), the refractive index differences between the TM- and TE-polarized modes in the HSWG with a silicon layer thickness of 150 nm and a silica layer thickness (h_s) of 30, 45, and 50 nm are 0.568608, 0.592991 and 0.596920, respectively, at the wavelength of 1550 nm. As shown in Fig. 3(b), in case the silicon layer thickness is 200 nm, the refractive index differences above are decreased by 0.384813, 0.444664 and 0.459149, respectively. As a result, smaller silicon layer thickness and larger silica layer thickness are best except larger silica layer thickness may lead to higher order guided-modes.

Based on the above analysis, we improve the parameters of the desired PBS to be $w=450$ nm, $w_h=200$ nm, $h_m=100$ nm, $h_d=80$ nm, $h_{slot}=36.5$ nm, $h=250$ nm, $h_s=150$ nm, and $d=100$ nm. The parameters above will be used in all simulations below. We calculated the effective indices of the fundamental modes in a HSWG and a HPWG with the parameters above, as shown in Fig. 4. Obviously, only the TM-polarized mode can be supported in the HPWG. It can be easily found from Fig. 4 that the index difference between the TM-polarized modes of the two waveguides is very small in an ultra wide wavelength range from 1.45 μm to 1.65 μm. Therefore, the TM-polarized modes in the HSWG and the HPWG are index-matched in the wide wavelength range. On the other hand, the evanescent coupling of the TE-polarized light is entirely suppressed due to the cutoff of the TE-polarized mode in the HPWG.

The reason for choosing a HSWG, rather than a single silicon waveguide (SWG) could be described as follow. As shown in Fig. 5, although the HSWG and the SWG have the same index-matching point with the HPWG, each waveguide exhibits different index curves. And effective index difference of the TM-polarized modes between the SWG and the HPWG is quite larger than that between the HSWG and the HPWG. As a result, the coupling efficiency of the TM-polarized mode from the HSWG to the HPWG is much higher than that from the SWG to the HPWG [30]. So a HSWG, rather than a SWG, is integrated in our PBS.

Operation principle of our PBS could also be explained in terms of the supermode theory for the TM-polarized modes. In case each core of a coupler is a single-mode-guided waveguide, such a coupler structure can support two modes, including one odd mode and one even mode, and the coupling length, L, can be calculated by:

$$L_c^{TM}=\frac{\lambda}{2({n_e}^{TM}-{n_o}^{TM})} \tag{2}$$

where ${n_e}^{TM}$ and ${n_o}^{TM}$ are the effective indices of the even and odd supermodes, respectively. Electric field distributions of the guided modes in the PBS with a gap distance of 100 nm were simulated by finite element method. As shown in Figs. 6(a) and (b), antisymmetric

Table 1
Parameters used in Eq. (1) for gold.

Parameter (units)	Data of Johnson and Christy
ε_∞	1.54
λ_p(nm)	143
γ_p(nm)	14500
A_1	1.27
ϕ_1(rad)	$-\pi/4$
λ_1(nm)	470
γ_1(nm)	1900
A_2	1.4
ϕ_2 (rad)	$-\pi/4$
λ_2(nm)	325
γ_2(nm)	1060