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Broadband TM-mode-pass polarizer and polarization beam splitter using asymmetrical directional couplers based on silicon subwavelength grating[☆]

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ABSTRACT

In this paper, an on-chip polarizer passing the transverse-magnetic mode and a polarization beam splitter are proposed. The polarizer achieves an extinction ratio exceeding 20 dB within a spectral range from 1500 nm to 1610 nm, and has a value of 24dB at 1550 nm with a coupling efficiency of 84%. By employing a specific wavelength of 1570 nm, the polarizer behaves as the polarization beam splitter with extinction ratio for the transverse-electric mode and the transverse-magnetic mode of 29dB and 24 dB, respectively. In addition, the coupling efficiency of 95.98% and 78.18% for above two polarizations, demonstrate that our approach has a potential to efficiently control coupling splitting ratio via silicon subwavelength grating.

1. Introduction

In the past decades, special attention has been taken to the on-chip integration of optical, opto-electronical and electronical devices at the nano-scale, to achieve which the silicon-on-insulator (SOI) platforms with high refractive index contrast have been witnessed, in addition to have high compatibility with the Complementary Metal–Oxide–Semiconductor (CMOS) technology, and mature fabrication methods [1]. Moreover, differ from the amorphous silica fibers that have isotropic property, photonic integrated devices based on SOI nanowires are severely polarization-sensitive, that is, with a strong structural birefringence. Such a birefringence is induced by the boundary condition difference between the transverse-electric (TE) mode and the transverse-magnetic (TM) mode, while the corresponding researches focus on two different aspects. On one hand, polarization-independent devices [2–5] aim to achieve same refractive index contrast for both the TE mode and the TM mode, which is often realized by carefully designing the cross-sectional dimension of the SOI nanowires. On the other hand, polarization-handling devices including the polarization beam splitters (PBSs) [6–8], polarization rotators [9–11], and polarizers [12–14], are also developed for special applications.

The polarizer, which is also called polarization filter, is used to produce linearly polarized beam with high extinction ratio and broad bandwidth. Ref. [13] demonstrates a polarizer with length of 9 μm, extinction ratio of 27 dB and excess loss of 0.5 dB at 1550 nm. However, the wavelength range with extinction ratio over 20 dB is only 60 nm. An 18 μm-long polarizer based on nanophotonic waveguide is proposed in Ref. [15], which contains two tapered waveguides sandwiching a narrow section to pass the TM mode only. However, the height of the silicon core is 300 nm, which differs from that in general SOI waveguides of 220 nm, hence it is limited for widespread applications. An ultracompact TE-mode-pass polarizer is reported in Ref. [16] with a length of only 1 μm, yet the extinction ratio of only 15 dB is invalid for industrial applications that often require a value of more than 20 dB.

PBS is another significant polarization-handling device which requires high extinction ratio as well. A PBS structure with a coupling length of only 1.3 μm is demonstrated in Ref. [17], where the numerical simulation presents that a broadband spectral range of 160 nm with an extinction ratio of larger than 10 dB can be achieved. Ref. [18] introduces an 8.13 μm-long PBS structure that enables a bandwidth of 100 nm to have extinction ratio of larger than 10 dB. While such extinction ratio is not large enough for actual use, it additionally remains a problem that the single function of the device may broaden the foot-print of the whole on-chip system. Therefore, we propose an asymmetrical directional coupler with subwavelength grating that behaves as both a TM-mode-pass polarizer and a polarization beam splitter. The proposed structure

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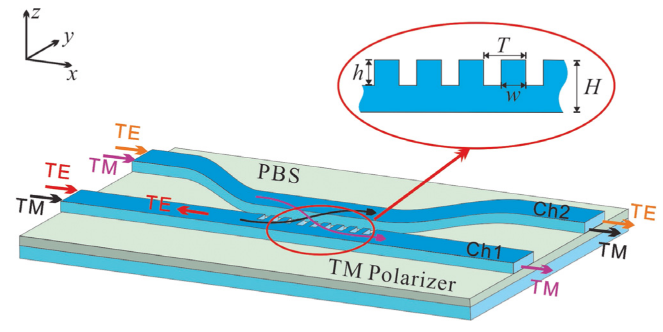

Fig. 1. The structure of TM-mode-pass polarizer and polarization beam splitter, which consists of two channels named as Ch1 and Ch2, respectively.

includes two waveguides with the height of 220 nm based on SOI wafer, and their widths are 480 nm and 500 nm, respectively.

Fig. 1 shows the schematic of the TM-mode-pass polarizer and polarization beam splitter. We define the waveguide with subwavelength grating as channel 1 (Ch1), while the other waveguide is channel 2 (Ch2). When a co-polarized beam is injected into Ch1, the TE-polarized component is reflected by the grating, while the TM-polarized component is coupled into Ch2 due to the phase-matching. Here, Ch1 is used as a polarizer. When a co-polarized beam is injected into Ch2, the TE-polarized passes through the waveguide, while the TM-polarized is coupled to Ch1. Here, Ch2 is used as the input of a PBS, where the other side of Ch1 and Ch2 are used as the output of TE-polarized component, and TM-polarized component, respectively.

When the structure operates as polarizer, the extinction ratio reaches 24 dB, with a coupling efficiency of ~84% at 1550 nm. The extinction ratio is larger than 20 dB within 110 nm wavelength bandwidth (from 1500 nm to 1610 nm), which broadens by a factor of 2 compared to that shown in Ref. [13]. When the structure operates as PBS, the extinction ratio for the TE mode and the TM mode are 29 dB and 24 dB, with transmission efficiency of 95.98% and 78.18%, respectively.

2. Theory model

The defects introduced into the dielectric waveguide change the effective refractive index. By utilizing the subwavelength grating as defects, the effective refractive index is calculated by Eqs. (1) and (2) [4]

$$N_{eff}^{TE} = \sqrt{f n_1^2 + (1-f) n_2^2} \quad (1)$$

$$N_{eff}^{TM} = \sqrt{\frac{1}{\frac{f}{n_1^2} + \frac{(1-f)}{n_2^2}}} \quad (2)$$

$$f = \frac{h(T-w)}{HT} \quad (3)$$

where f is filling factor given by Eq. (3) [19], n_1, n_2 are refractive index of silicon and air, which are set as $n_1 = 3.5$ and $n_2 = 1$, respectively. We define h as the height of grating ridge in Y direction, H as the width of waveguide, T as the period of grating, and w as the width of ridge in X direction, as shown in Fig. 1. Moreover, to design a subwavelength grating that reflects the TE-polarized component and passes the TM-polarized components, Eqs.(4) and (5) should be approximately satisfied [13]

$$N_f^{TE} f \times T + N_{(1-f)}^{TE} \times T(1-f) = \lambda_0/2 \quad (4)$$

$$N_f^{TM} f \times T + N_{(1-f)}^{TM} \times T(1-f) < \lambda_0/2 \quad (5)$$

where N_f^{TE} denotes the refractive index of TE-polarized component for etching part within one period, N_{1-f}^{TE} denotes that in medium part, respectively, and the same definitions are applied to the TM-polarized component. In addition, in a two-waveguide coupling system,

Table 1
Calculated values of key parameters (Unit: Micrometers).

Parameters	T	w	h	N
Values	0.632	0.2	0.2	19

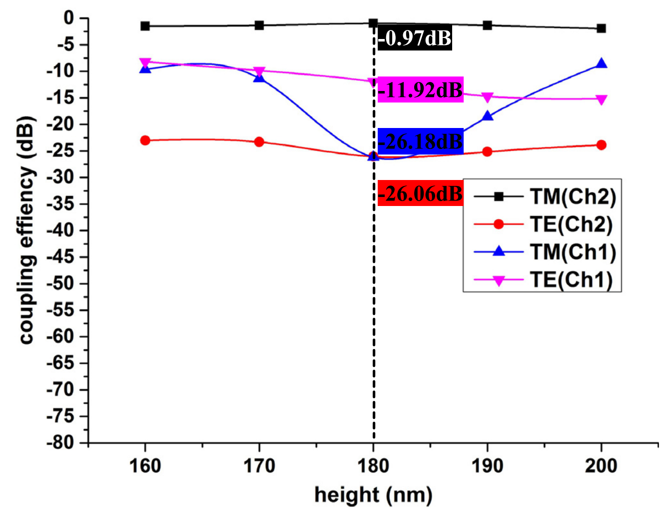

Fig. 2. The coupling efficiency of different polarization in two channels versus the etch height, which has an optimized value of 180 nm.

the coupling efficiency F is given by

$$F = \frac{1}{1 + \left(\frac{\delta}{k}\right)^2} \quad (6)$$

where κ denotes the coupling coefficient, $\delta = (\beta_1 - \beta_2)/2$ denotes the half phase-mismatch (β_1 an β_2 are the propagation constants of two waveguides). According to Eq. (6), when the phase-matching is satisfied, i.e., $\beta_1 = \beta_2$, the cross-coupling of two waveguides reaches 100% [20].

A new structure is designed employing above principles, which can operate as a TM-mode-pass polarizer or a PBS, depending on which channel that beam is injected in. The optimized values of the period (T), the period number N, the width (w), the subwavelength grating etching height (h) are shown in Table 1. According to Eq. (6), we calculate the coupling efficiency of TM polarization is 91%.

3. Simulation results

The detailed optimization of the values shown in Table 1 is demonstrated as follow, where we employ beam at 1550 nm. To design a TM-mode-pass polarizer, we calculate the coupling efficiency when the beam is injected into Ch1.

Fig. 2 shows the coupling efficiency involving the etching height as a single degree of freedom, which varies from 160 nm to 200 nm, while other parameters take the values shown in Table 1. The motivation is to achieve a maximal power of TM-component in Ch2, and a minimal power for other cases. When $h = 180$ nm, the coupling efficiency for the TM (Ch2) reaches −0.97 dB (79.94%), while for the TE (Ch2) it is only −26.06 dB (0.25%), resulting an extinction ratio of ~25 dB calculated by Eq. (7).

$$\eta = -10 \log P_{(max)}/P_{(min)}. \quad (7)$$

Fig. 3 shows the coupling efficiency involving the width of grating ridge as a single degree of freedom, which varies from 100 nm to 350 nm, while other parameters take the values shown in Table 1. The coupling efficiency for the TM (Ch2) is relatively stable and larger than other cases, that is, reaches −1.55 dB (70%) for all widths. When the