Novel ultra-short and ultra-broadband polarization beam splitter based on a bent directional coupler

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Abstract: A novel ultra-short polarization beam splitter (PBS) based on a bent directional coupler is proposed by utilizing the evanescent coupling between two bent optical waveguides with different core widths. For the bent directional coupler, there is a significant phase-mismatch for TE polarization while the phase-matching condition is satisfied for TM polarization. Therefore, the TM polarized light can be coupled from the narrow input waveguide to the adjacent wide waveguide while the TE polarization goes through the coupling region without significant coupling. An ultra-short (<10 µm-long) PBS is designed based on silicon-on-insulator nanowires and the length of the bent coupling region is as small as 4.5 µm while the gap width is chosen as 200nm (large enough to simplify the fabrication). Numerical simulations show that the present PBS has a good fabrication tolerance for the variation of the waveguide width (more than ± 60nm) and a very broad band (~200nm) for an extinction ratio of >10dB.

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References and links

1. Introduction

As a basic functional element, a polarization beam splitter (PBS) is very useful for many applications when polarization control is desirable [1]. A short PBS with high performance is desired especially for coherent receivers and for ultra-dense on-chip networks. There have been reports of several kinds of waveguide-type PBSs with various structures, e.g., multimode interference (MMI) structure [2–5], directional couplers (DCs) [6–10], Mach-Zehnder interferometers (MZIs) [11–14], photonic crystal (PhC) structures [15,16], and out-of-plane gratings [17-18]. In order to achieve a short PBS, one usually needs highly birefringent waveguides by introducing some additional stress [19], or choosing a material with a relatively high birefringence, e.g., III-V semiconductor compounds [20]. However, such PBSs are still relatively long because the birefringence is not high.

It is well known that a submicron waveguide with an ultra-high index contrast can provide a giant birefringence due to the geometrical asymmetry, e.g., silicon-on-insulator (SOI) nanowires [21] and nano-slot waveguides [22]. Therefore, it is possible to implement a short PBS based on such a platform with a high index-contrast. For example, an ultra-short PBS is realized by using the strong polarization dependence of the PhC structures (e.g., ~50μm [15], ~20μm [16]) or out-of-plane gratings (e.g., ~14μm [17-18]). However, the design of the PhC structure is quite complex and the fabrication is relatively difficult while the out-of-plane grating is not good for planar lightwave circuits. Furthermore, PhC or grating structures usually introduce a relatively large loss due to the scattering. An MMI structure, which is often used for optical couplers/splitters, could be also used for realizing PBSs [2-3]. However, the length of an MMI PBS is usually very long. MZI structures have also been used for...
realizing polarization splitting [11–13]. When using submicron SOI waveguides, one can obtain a short MZI-PBS [14]. However, it is still hard to make an ultra-short PBS (<10µm).

A DC is also very popular for PBSs because of its structural simplicity and easy design [23-26]. In Ref [23], the reported Si-nanowire PBS is as small as 7 × 16 µm². Asymmetrical directional couplers are often used to realize PBSs [24]- [27]. In Ref [24]- [26], the coupling between an SOI nanowire and a nano-slot waveguide was used to realize an ultrasmall PBS. For these structures, the difficulty is the fabrication of the nano-slot. In Ref [27], a polarization splitter-rotator (~37 µm long) is realized by using the coupling between two SOI nanowires with different core widths. In our previous work, we proposed a novel design for a polarization splitter-rotator by combining an adiabatic taper and an asymmetrical directional coupler [28].

In this paper, we propose an ultra-short broadband PBS based on a bent DC structure. A <10µm-long PBS with a 4.5µm-long coupling region is designed as an example based on SOI nanowires and the designed PBS shows a broad band and good tolerance to fabrication errors.

2. Principle, structure and design

Figure 1 shows the schematic configuration of a coupler with two parallel bent waveguides. These two bent waveguides have different core widths and could be designed to satisfy the phase-matching condition for the coupling of TM polarization and consequently TM polarized light could be coupled to the cross port completely when choosing the length of the coupling region appropriately. On the other hand, for TE polarization, the phase-matching condition is not satisfied due to the birefringence of the waveguides. Thus, TE polarized light goes through without any significant coupling. In this way, TE- and TM- polarized light are separated within a very short length which is close to the coupling length of TM polarization.

In order to have a complete coupling for one polarization, the two bent waveguide should be optimized to satisfy the phase-matching condition [29], i.e., their optical path lengths (OPL) are equal. Thus,

\[ OPL = N_1 k_0 R_1 \theta = N_2 k_0 R_2 \theta, \]

where \( k_0 \) is the wavenumber in vacuum, \( N_1 \) and \( N_2 \) are the effective indices of the fundamental polarized modes of the two bent waveguides, respectively, \( R_1 \) and \( R_2 \) are the corresponding bending radii, \( \theta \) is the arc-angle for the coupling region. From Fig. 1, one has

\[ R_1 = R_2 = \left( w_1 / 2 + w_2 + w_g / 2 \right). \]

In this paper, we use a SOI wafer with a silicon thickness of \( h_{co} = 220\text{nm} \) as an example. The refractive indices of Si, SiO₂, and air are \( n_{Si} = 3.455 \), \( n_{SiO_2} = 1.445 \), and \( n_{air} = 1.0 \) respectively. The bending radius \( R_2 \) is chosen according to the following two rules: (1) \( R_2 \) should be large enough to guarantee a low bending loss for both polarizations; (2) Smaller \( R_2 \) is desired to increase the phase mismatching for the polarization (e.g., TE here) to be non-coupled. For the design here, we choose \( R_2 = 20\mu m \) by making a trade-off. Figure 2(a) and 2(b) respectively show the calculated optical path lengths OPL (\( \theta = 1 \text{ rad} \)) for the TE and TM
fundamental modes as the waveguide width varies for when choosing $R_2 = 20\,\mu\text{m}$. Here we use a commercial software (FIMMwave, Photon Design) for the mode solving [30]. In order to make the fabrication easier, a larger gap width is desirable. On the other hand, a narrow gap is needed for sufficient evanescent coupling. With these two considerations (i.e., relatively easy fabrication and sufficient coupling), here we choose $\Delta R = R_2 - R_1 = 0.7\,\mu\text{m}$, so that the gap width will be around 200nm if the Si core width is chosen as $w_{co}\approx 500\text{nm}$ to be singlemode as usual. It is well known that TM polarization has a much stronger evanescent coupling than TE polarization for $500\text{nm} \times 220\text{nm}$ SOI nanowires. Therefore, in order to make a short PBS, in our design we make the phase matching condition satisfied for TM polarization. The dashed line in Fig. 2 (a) gives the optimal widths ($w_1$, $w_2$) to have equal optical path lengths for TM fundamental modes in waveguides #1 and #2. We choose ($w_1$, $w_2$) = (0.534\,\mu\text{m}, 0.46\,\mu\text{m}) as an example. Figure 2(b) shows the optical path lengths for TE fundamental modes in waveguides #1 and #2. From this figure, one sees that the phase-matching condition is satisfied for TM polarization only when choosing the optimal widths ($w_1$, $w_2$).

![Fig. 2. The optical path lengths (OPL) as the waveguide width varies when $R_2 = 20\,\mu\text{m}$, (a) TM; (b) TE.](image)

Figure 3(a) and 3(b) respectively show the 3D view and the top view for the proposed ultra-short PBS based on a bent directional coupler. We connect S-bends at the end of the coupling region to make the two waveguides separated. The offsets for the S-bend are $L_x = 0.8\,\mu\text{m}$ and $L_z = 4\,\mu\text{m}$. Considering the bending loss is polarization dependent, i.e., TM fundamental mode has a higher bending loss than TE fundamental mode, we choose a sharp bending at the through port to realize a compact TE-through polarizer, which helps filter out the undesired TM polarization at this port and improves the extinction ratio. The bending radius $R_0$ (see Fig. 3) is chosen as $R_0 = 4\,\mu\text{m}$. We use a commercial software (FIMMPROP, Photon Design) employing an eigenmode expansion and matching method [30] to simulate...
the light propagation in the present structure. The calculated transmissions at the through and cross ports for the TM and TE polarizations are shown Fig. 4(a) and 4(b), respectively, as the length \( L_{dc} \) of the coupling region varies. Here the length \( L_{dc} \) is given by \( L_{dc} = R_2 \sin(\theta) \), where \( \theta \) is the arc angle (as shown in Fig. 3(b)). The corresponding parameters are: \( w_1 = 0.534 \mu m \), \( w_2 = 0.46 \mu m \), \( R_1 = 19.3 \mu m \), and \( R_2 = 20.0 \mu m \). One sees that there is an optimal coupling length \( L_{dc0} \) for a maximal output at the cross port for TM polarization and \( L_{dc0} = 4.5 \mu m \) for the present case. In contrast, for TE polarization, the transmission is not sensitive to the coupling length because the coupling is very weak and incomplete due to the mode phase mismatching. Therefore, we choose \( L_{dc0} = 4.5 \mu m \) as our optimal design for the PBS.

![Fig. 4](image)

**Fig. 4.** The transmissions at the through and cross ports as the length of the coupling region for:
(a) TM input; (b) TE input.

In Fig. 5(a) and 5(b), we show light propagation in the designed PBS for TE and TM polarizations, respectively. It can be seen that TM polarization is coupled and output from the cross port while TE polarization is output from the through port without any coupling almost. In this design, we choose the bending radius \( R_3 \) of the second arc section in the cross port as \( R_3 = 18 \mu m \), which is large enough to have a low-loss for TM polarization. At the through port, the S-bend is designed so that the bending loss is negligible for TE polarization and the end separation (~2\( \mu m \)) of the two output ports is large enough to avoid any undesired coupling. The small bending radius \( (R_0 = 3 \mu m) \) at the through port helps to filter out the residual TM polarization and consequently the extinction ratio is improved. The total length for the PBS is less than 10\( \mu m \), which is one of the smallest PBS reported until now.

![Fig. 5](image)

**Fig. 5.** The light propagation in the designed PBS with \( L_{dc} = 4.5 \mu m \), \( R_1 = 19.3 \mu m \), \( R_2 = 20.0 \mu m \), \( w_1 = 0.534 \mu m \), \( w_2 = 0.46 \mu m \), and \( w_{gap} = 203 \text{nm} \). (a) TE; (b) TM.

Figure 6(a) and 6(b) show the wavelength dependence of the output powers at the cross port and the through port when the input is the TM fundamental mode (TM\(_0\)), and the TE fundamental mode (TE\(_0\)), respectively. From these figures, one sees that the output is not sensitive to the wavelength variation when the TE fundamental mode (TE\(_0\)) is launched. This is because phase mismatching for the input TE\(_0\) mode, which makes a very weak coupling...
over a large wavelength range. In contrast, for the input TM fundamental mode, the response is a little more sensitive to the wavelength, which is due to the wavelength dependences of the coupling length in the evanescent coupling. From Fig. 6(a), the designed PBS has a very large bandwidth, which is about 200nm for an extinction ratio of 10dB.

Figure 7(a) and 7(b) show the output powers at the cross port and the through port when there is a waveguide width variation $\Delta w$ for the cases of inputting the TM fundamental mode ($\text{TM}_0$), and the TE fundamental mode ($\text{TE}_0$), respectively. According to the analysis given in Ref [31], the waveguide fabricated with CMOS technologies has a linewidth uniformity of 0.76% (i.e., the deviation $\Delta w=3\text{nm}$) over a wafer. Therefore, it is reasonable to assume that the two adjacent bent waveguides in the coupling region have the same width variance $\Delta w$. Therefore, the gap width variance is then given by $\Delta w_g = \Delta w$ correspondingly. From Fig. 7(a) and 7(b), one sees that the present PBS has a very large fabrication tolerance. When the fabrication error is as large as $\pm 60\text{nm}$, the PBS still works very well, which makes an easy fabrication.

3. Conclusions

In summary, we have proposed an ultra-short PBS by utilizing a bent directional coupler. TM polarization is coupled to the cross port by choosing the length of the coupling region appropriately while TE polarized light goes through the directional coupler without any coupling almost. A 9.5$\mu$m-long PBS based on a SOI platform has been designed as an example, in which the length of the coupling region is only 4.5$\mu$m. To the best of our knowledge, it is one of the shortest PBSs reported to date. The numerical simulation shows that the present PBS has a very broad band (~200nm) for an extinction ratio of >10dB. It also
shows that there is a relatively large fabrication tolerance (e.g., more than ± 60nm) for the variation of the waveguide width.

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