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A high extinction ratio silicon nitride polarizing beam splitter

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Abstract

A silicon nitride polarizing beam splitter is designed and fabricated, using a Mach-Zehnder interferometer consisting of two directional couplers. There is little excess loss for this simple structure and a high extinction ratio and wide operation bandwidth can be achieved. An extinction ratio of 37 dB around 1554-nm wavelength and a 38-nm bandwidth with extinction ratio of higher than 20 dB can be obtained for TE mode coupling to the cross port and TM wave output from the through port. This device could be expected to have more application prospects beyond the polarization splitting in optical communications.

1. Introduction

Silicon nitride (Si_3N_4) is a promising wave-guiding material for integrated photonics applications due to its wide transparency bandwidth and the compatibility with the complementary-metal-oxide-semiconductor (CMOS) technology [1]. Furthermore, Si_3N_4-based passive devices offer a large fabrication tolerance, superior performance in the coupling and propagation loss, and easy to realize three dimensional integration [2]. Though many Si_3N_4 devices such as ring resonators have been demonstrated, to the best of our knowledge, a single-layer high extinction ratio Si_3N_4 polarizing beam splitter (PBS) has not been experimentally developed until now. Several kinds of waveguide-type PBSs for other material platforms have already been reported. For example, an MMI can be used for PBS with the length usually being the common multiple of the self-imaging lengths for TE and TM polarizations. Since an MMI structure is weak polarization dependence intrinsically, the length is usually very long. And a deviation from the optimum MMI length will cause an excess loss [3]. As for the photonic crystal PBS, the design is complex and the fabrication is relatively difficult while the grating coupler PBS is not good for intra chip photonic integration. Moreover, photonic crystal or grating structures usually have a low coupling efficiency and can introduce a relatively large loss due to the scattering [4].

Conventional directional coupler (DC) based PBS is very popular because of its structural simplicity and no excess loss, which takes advantage of the small difference in the coupling coefficients between the two polarizations. Thus the polarization splitting can be realized after travelling a sufficiently long distance. However, the waveguide uniformity is difficult to guarantee, which limits the extinction ratio [5]. By using the birefringence of the arm waveguides, an MZI could be used to fulfill polarization splitting with a high extinction ratio [6]. Therefore, by using a DC based MZI structure, a low signal loss and high extinction ratio PBS can be expected. The DC should work as a 3-dB coupler for TE mode, and can couple TM wave completely to the other pathway, thus its length is almost half of the conventional DC based PBS and has a reduced waveguide uniformity requirement. Two DCs can consist an MZI configuration for polarization splitting, with the TE mode transmitted mostly to the cross port while the TM wave couples completely to the other pathway twice and outputs mainly from the through port.

2. Si_3N_4 Polarizing Beam Splitter

Schematic of the proposed PBS is shown in Fig. 1(a). For the sample structure, an InP substrate was adopted for the potential integration of this type PBS with III-V quantum wells materials [7]. A 3-µm SiO_2 buffer layer was first deposited on the InP substrate by plasma enhanced chemical-vapor deposition (PECVD), then a 200-nm Si_3N_4 film was deposited by electron cyclotron resonance (ECR) plasma enhanced sputtering. By using electron beam lithography and reactive ion etching, the photonic circuits were formed, with the photoresist as an etching mask. After the sample cleaned by oxygen plasma and a wet chemical process, a 2-µm SiO_2 up-cladding layer was deposited by PECVD. The Si_3N_4 thickness was chosen by a trade-off between a minimum value necessary for reducing waveguide bending-related loss and a maximum one to avoid the mechanical rupture caused by a high tensile stress.

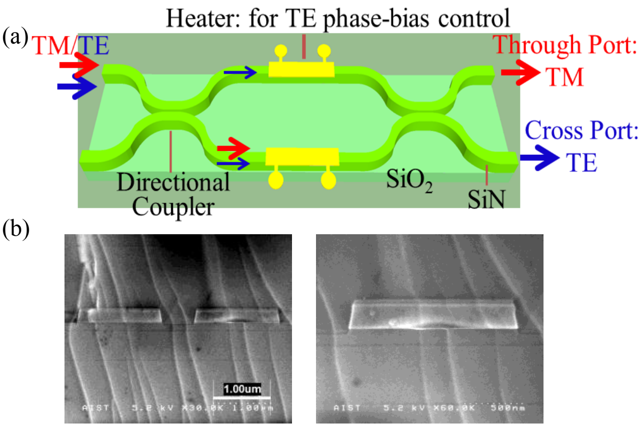

Fig. 1. (a) Schematic of the DC based MZI PBS. (b) Cross sectional scanning electron microscope image at the DC center (left) and a magnified image for a single Si_3N_4 waveguide (right).

The coupling between two straight waveguides in the overlapping region is considered for design, although there will be some additional mode overlap in the waveguide bends at the entrance and exit of the coupler. For TM wave, the DC should have a coupling length to accumulate a π phase difference for the even and odd DC modes, which can make the TM wave couple completely to the cross pathway. The DC length should also be at a $\pi/2$ phase difference coupling length for the TE mode, to realize a 3-dB coupler for the MZI configuration. Based on the finite element method using optical software *Rsoft*, even and odd DC modes for both polarizations can be calculated with varying coupling gap, at a wavelength of 1550 nm and waveguide width of 1.5 μm (single mode condition). The refractive indices are 1.46, 2.01, and 3.17 for SiO_2, Si_3N_4, and InP, respectively. The corresponding coupling length can be obtained according to the effective index difference between the even and odd modes. With varying coupling gap, there is a cross-point between the calculated coupling length of TE as a 3-dB coupler and the TM complete cross-coupling, where the DC gap is 0.75 μm with a coupling length of 71 μm.

Based on the designed structure, we fabricated PBSs with varying gap and coupling length. The straight waveguides in the DC part were connected to the S-bend waveguides with a length of 150 μm and a lateral offset of 15 μm (with radius of around 406 μm) to separate with each other, as shown in Fig. 1(a). Ti/Au heaters were attached to the MZI arms, in order to adjust the phase imbalance caused by the waveguide non-uniformity and thus guarantee a high extinction ratio for TE mode. The heaters have little influence on TM wave extinction ratio due to the complete cross-coupling by one DC. Finally, the wafer was backside polished and cleaved for measurement. The optimum polarizing beam splitter can be obtained with a DC gap of 0.6 μm and coupling length of 23 μm. The cross-sectional scanning electron microscope image is shown in Fig. 1(b). Both the gap and length are smaller than the designed values, indicating that the coupling contribution of the S-bend waveguides plays an important role for the actual device performance.

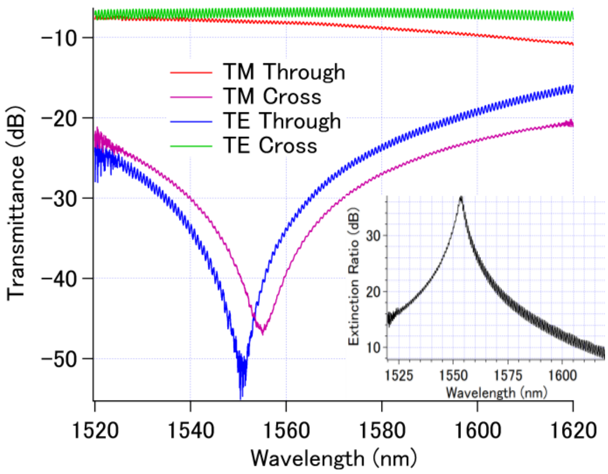

Fig. 2. Output Spectra for both polarizations of an experimental optimized PBS with a 23-μm coupling length and 0.6-μm DC gap. Inset: device extinction ratio spectrum.

The transmission spectra of TE and TM polarizations for an optimum PBS were measured by optical spectrum analyzer (Fig. 2), with applying a heater voltage to obtain a minimum TE through port output. The input light polarization state was controlled by a polarization controller. It can be clearly seen that a maximum polarization splitting ratio (defined as the absolute transmittance difference between two output ports) for TE mode is about 48 dB at a 1550-nm wavelength, while TM wave has the peak point at a 1555-nm wavelength with the splitting ratio of 39 dB. For TE mode, a 41-nm bandwidth (1531–1572 nm) can be realized with the splitting ratio of more than 20 dB, while for TM, that is around 39 nm (1536–1575 nm).

The PBS extinction ratio is defined as a minimum value of TE and TM splitting ratio, as shown in the inset of Fig. 2. An extinction ratio of 37 dB around 1554-nm wavelength and a 38-nm bandwidth with extinction ratio of higher than 20 dB can be obtained, for TE mode coupling to the cross port and TM wave output from the through port. As the fiber coupling loss of about 6.2 dB for TE and 4.5 dB for TM, it can be seen from Fig. 2 that this PBS can still achieve a low excess loss for TE mode but a little loss for TM wave, due to the different bending-related loss.

3. Conclusion

To summarize, a Si_3N_4 high extinction ratio DC based MZI PBS is experimentally demonstrated. This simple structure has little inherent excess signal loss due to the use of DCs. An extinction ratio of 37 dB around 1554-nm wavelength and a 38-nm bandwidth with extinction ratio of higher than 20 dB can be obtained, for TE mode coupling to the cross port and TM wave output from the through port. The beam splitting ratio of TE mode can be controlled through adjusting the heater voltage. Further work can be done for a potential application of this PBS as an all-optical intersubband switch, with InGaAs/AlAsSb coupled double quantum wells vertically integrated on the MZI arms, while no additional TE/TM beam combiner is needed [8]. This device could be expected to have more application prospects beyond the polarization splitting.

Acknowledgements

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Appendix

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