A Polarization Diversity Circuit for Silicon Photonics

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Abstract — A polarization diversity circuit in silicon waveguide was developed. The polarization dependent loss is 0.5dB. The insertion loss from the polarization diversity components is 3dB. The extinction ratio of the ring circuit is 20dB.
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1. Introduction

Silicon photonics received much attention in the recent years. Silicon waveguides have great potential as a platform for ultra-small photonic circuits [1][2][3]. However, silicon waveguide has large structural birefringence which causes polarization mode dispersion, polarization dependent loss, and polarization dependent wavelength characteristics. The polarization mode dispersion will affect devices application in high data rates. The difference in the effective polarization modes indices makes the filters' resonance wavelengths different. The polarization dependent characteristics limit the application of silicon photonics devices.

To make a photonic circuit polarization independent, the simplest way is to use a square core waveguide. However, for high-index-contrast waveguides, such as silicon waveguide, fabrication errors of just a couple of nanometers are critical and result in birefringence. Another way is to implement polarization diversity scheme. The light with arbitrary polarization from the source will be split into orthogonal component by polarization splitter. By further rotating one of the components, a single polarization is achieved. The two paths may be operated in parallel with identical structures. Fukuda *et al.* designed and fabricated mode-coupling-based polarization splitters [4] and rotators [5] in silicon waveguides. They applied their polarization splitter and rotator in a wavelength filter and achieved improvement for 10Gbps data transmission [6]. Watts *et al.* in MIT published mode-evolution-based polarization splitters [7] and rotators [8]. Their designs were silicon nitride based. The waveguides had core indices of 2.2 and dimensions of 800nm(w)×400nm(h) for TE mode waveguide and 400nm(w)×800nm(h) for TM mode waveguide. A silicon nitride based integrated mode-evolution-based polarization splitter and rotator (PSR) was first reported in [9]. In 2006, a polarization-transparent add-drop filter was demonstrated with the mode-evolution-based polarization splitter-rotator (PSR) in silicon nitride waveguide [10]. In 2008, Romagnoli *et al.* in Pirelli demonstrated an integrated PSR in silicon channel waveguide with cross-section of 450nm×220nm [11].

The mode-coupling-based splitter and rotator have the advantage of single layer of silicon waveguide. However, the mode-evolution-based splitter and rotator have larger wavelength operation window and larger fabrication tolerances. In this paper, we present a polarization diversity ring resonator circuit which is scaled down in 400nm×200nm silicon waveguide. The key polarization diversity components are a mode-coupling-based splitter to split TE and TM modes, a polarization mode converter to convert the TM mode in horizontal waveguide to vertical waveguide, a polarization rotator to rotate the TM mode in vertical waveguide to TE mode in horizontal waveguide. Experimental results are presented.

2. Designs the polarization diversity ring resonator circuit

Figure 1 shows the overall structure of the polarization diversity circuit. The functional component is a ring resonator. There are two types of silicon waveguides in the circuit. One is horizontal waveguide, with the dimension of 400nm (w) by 200nm (h). The other is vertical waveguide, with the dimension of 200nm (w) by 400nm (h). The horizontal waveguide is the main waveguide in the circuit, which makes the input waveguide, ring resonator, and output waveguide. The vertical waveguide is used between the polarization rotator and TM mode converter.

The ring resonator in silicon waveguide has different wavelength response for TE and TM polarization modes. The light with arbitrary polarization from the source is split into orthogonal components by a polarization splitter. Generally, there are two kinds of polarization splitter in silicon waveguide. The mode coupling based polarization splitter is easier to fabricate than the mode-evolution based polarization splitter in the waveguide of 200nm by 400nm due to the wider gap between the two waveguides. Therefore, a mode-coupling based polarization splitter and a combiner are used in the circuit. After the splitter, the TE part of the light (TE1) propagates to the ring resonator, while the TM part of the light (TM2) is rotated to TE mode (TE2) and propagates to the ring resonator. The polarization rotator is an ultra-small polarization rotator. A single polarization is achieved at the ring resonator. The dropped wavelength passes the ring resonator. The TE1 is rotated to TM1 and combined with the TE2 at the combiner. Figure 1 shows the paths of the components propagating in the circuit to the drop output. Figure 2 shows the paths of the components propagating in the circuit to the through output.

The polarization splitter is a mode-coupling based polarization splitter. We used the design by NTT in [4]. Basically, it is a directional coupler. It takes longer distance for TE mode to fully couple into the neighbouring waveguide than TM mode. The input light consists of TE and TM modes. Therefore, in this splitter, the TM mode will couple into the neighbouring waveguide, while most of the TE mode will remain in the same waveguide. The TM mode convertor is shown in Fig. 3. It connects horizontal waveguide with vertical waveguide while it maintains light at TM polarization mode. The polarization rotator (Fig. 4) rotates the TM mode in vertical waveguide to TE mode in horizontal waveguide. The rotation region is only 3.6 µm long. Two tapering structures connect the rotation region with the horizontal and vertical waveguides. The mode converter and rotator work in bi-direction.

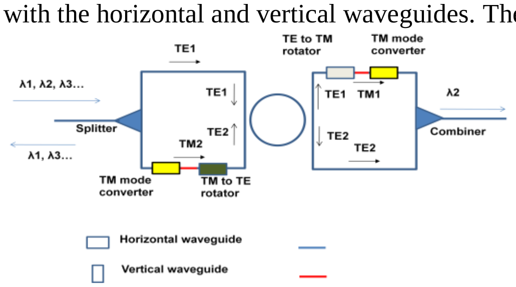

Fig. 1. The ring resonator in a polarization diversity circuit.

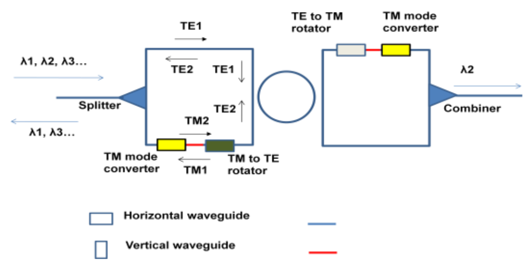

Fig. 2. The ring resonator in a polarization diversity circuit.

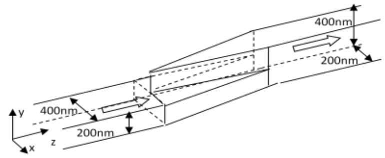

Fig. 3. TM polarization mode converter.

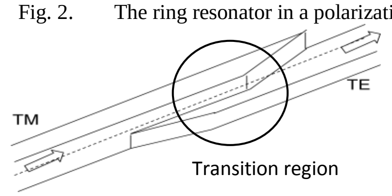

Fig. 4. TM polarization mode converter.

3. Fabricate and characterization of the polarization diversity ring resonator circuit

The polarization diversity circuits were fabricated on SOI wafer. The bottom oxide layer (BOX SiO_2) was 2µm thick. The top silicon was 400nm thick. The two-layer waveguide structure was processed by two-step dry etching. 2um top SiO_2 cladding layer was deposited by High Density Plasma PECVD (HDP SiO_2) in Applied Material PECVD chamber. The total waveguide was 3mm long. The waveguide was tapered to 180nm width at the both ends. The horizontal waveguide was 200nm (w) by 400nm (h), and the vertical waveguide is 400nm (w) by 200nm (h).

The ring resonator in this circuit has a diameter of 20 µm. The waveguide for the ring resonator is horizontal waveguide with a dimension of 400nm (w) by 200nm (h). The gap between the ring and the straight waveguides is 0.3 µm. Figure 5 shows the SEM picture of the ring resonator fabricated.

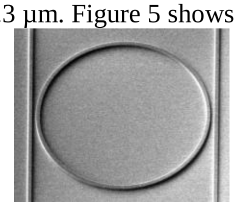

Fig. 5. SEM of the ring resonator fabricated on SOI

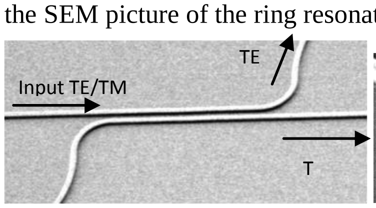

Fig. 6. The mode-coupling based polarization splitter fabricated on SOI

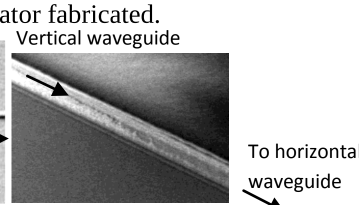

Fig. 7. SEM picture of the transition region of polarization mode converter.

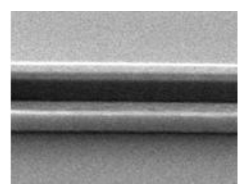

Fig. 8. SEM picture of the transition region of polarization rotator.

Figure 6 shows the polarization splitter. The waveguides are horizontal waveguides. The gap between the two waveguide in the coupling region is 480nm. The length of the coupling region is 10 µm. The polarization splitter has polarization extinction ratio (PER) of more than 12dB at 1550nm. The TM mode converter is shown in Fig. 7. Figure 8 shows the transition region of the polarization rotator.

A broadband ASE source was used to characterize the circuit. It covered the wavelength range from 1520nm to 1610nm. Polarization maintenance fibers were used in connection. The polarization status of from the light source was adjusted using a polarization controller. The output power after the polarization controller was -1dBm. The power fluctuation caused by changing the polarization status was less than 0.1dB.

We measured an individual ring resonator on this wafer. Figure 9 shows the spectra at the drop output of the individual ring resonator without polarization diversity circuit. The TE mode has 12 dB loss which is mainly due to the coupling loss and propagation loss. The filter's extinction ratio (ER) is 10dB in TE mode near 1550nm wavelength. The TM mode has 8 dB loss which is much less than the TE mode. The TE mode and TM mode have different spectral characteristics. The TM mode has wider bandwidth at each resonance peak than TE mode. The free space range (FSR) of TM mode is larger than TE mode. Hence, this ring resonator doesn't work properly if the polarization status of the input light is not well controlled. However, in the real optical system, it is difficult to predict the polarization status of the incoming light. The polarization transparent circuit becomes necessary.

The polarization diversity circuit with the ring resonator worked at TE mode. The polarization status of the input light was adjusted by the polarization controller to be TE, TM and 45 degree linear polarization, respectively. The optical spectra at the drop output were recorded with TE, TM and 45 degree linear polarization inputs, respectively. Figure 10 shows the spectra of the ring resonator with polarization diversity circuit. The circuit had the same wavelength response in the range from 1540nm to 1610nm regardless of the input polarization status. With polarization diversity circuit, the extinction ratio of the filter is improved to be more than 20dB in the range of 1545nm to 1600nm. The total loss of the circuit is about 15 dB. Considering the 12 dB loss from the ring resonator and the coupling loss between the fibers and the waveguide for TE mode, the insertion loss from the polarization diversity components at the peak wavelength is about 3dB. Figure 11 shows the resonance peak at 1552nm wavelength after taking out the coupling loss and propagation loss of the ring filter. The polarization dependent loss (PDL) at the peak wavelength is 0.5dB.

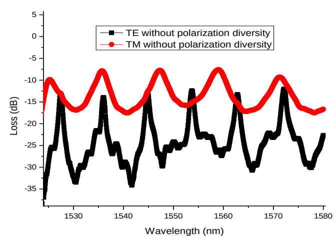

Fig. 9. Spectra of the ring resonator at TE mode and TM mode without polarization diversity circuit

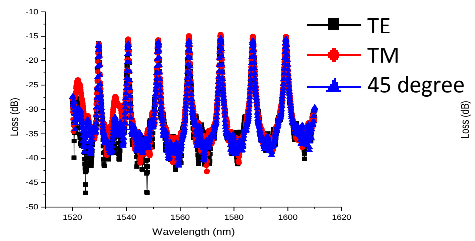

Fig. 10. Spectra of the ring resonator with polarization diversity circuit

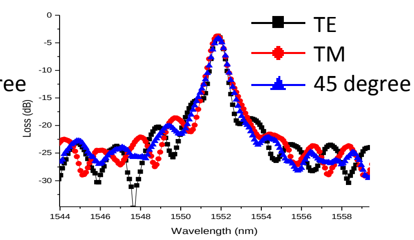

Fig. 11. Resonance peak of the ring resonator with polarization diversity circuit at 1552nm wavelength.

4. Conclusions

A polarization diversity circuit with a ring resonator in 200nm by 400nm silicon waveguide was developed. The polarization dependent loss is less than 0.5dB. The insertion loss from the polarization diversity components in the circuit is 3dB. The extinction ratio of the circuit is more than 20dB. With the polarization diversity circuit, silicon photonics can be connected with fiber optics and will have more applications.

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