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Ultra-broadband fabrication-tolerant polarization splitter and rotator

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Abstract: A polarization splitter and rotator that supports simultaneous O-, C-, and L-band operation is first experimentally demonstrated, with record 1-dB bandwidth over 360 nm, high fabrication tolerance, and high TE-TM conversion efficiency of -0.33 dB.

OCIS codes: (130.0130) Integrated Optics; (130.3120) Integrated optics devices; (230.5440) Polarization-selective devices.

1. Introduction

Polarization splitter and rotator (PSR) is one of the most significant building blocks for silicon photonic circuits with polarization handing capability, including datacom, telecom, quantum photonic chips, etc. [1, 2] In order to fulfill the industry requirement, fabrication-tolerant and broadband PSR with CMOS compatibility is highly demanded for various applications, such as chip-based polarization-entangled photon sources as well as optical high-speed transceivers [3]. Highly efficient PSRs sensitive to fabrication variation or with narrow bandwidth have been reported by using different structures [4, 5]. The first theoretical proposal of a bi-wavelength high-efficient PSR has been presented with simulated insertion loss of 0.9 dB at 1310nm and 1 dB at 1550 nm [4]. The 3-dB bandwidths are ~50 nm for both O- and C- band. CMOS-compatible PSR with even higher efficiency and more compact size has been reported exploiting the advantage of bend structure that confines TE mode better than TM mode [5].

In this work we experimentally realize a fabrication-tolerant CMOS-compatible PSR operating simultaneously in O-, C-, and L-band by exploiting two tapers, for the first time to the best of our knowledge. Limited by the testing setup of laser source, we have verified the performance of ultra-broadband PSR within wavelength range of 1240-1360 nm and 1520-1620nm. The fabricated PSR achieves high TE-TE and TM-TE mode conversion efficiency of -0.15 dB and -0.33 dB at 1310 nm, while the extinction ratio is better than 19 dB. The TE-TE and TM-TE mode conversion efficiency are -0.56 dB and -0.97 dB at 1550 nm, while the extinction ratio is better than 12 dB. Moreover, a width variation of ±20 nm reduces the TM-TE conversion efficiency by only 0.5 dB. Additionally, the wafer level testing shows that there only exists 1-dB variation of TM-TE conversion efficiency in the 8-inch wafer.

2. Design principle and simulations

As shown in Fig. 1, the proposed PSR compromises only two tapers for achieving the ultra-broad bandwidth and large fabrication tolerance. Instead of using mode evolution theory in only one waveguide for polarization rotation, here we place another taper besides it to realize the mode splitting and rotating at the same time.

The light carried by TE mode maintains its polarization status and then exit at the output port of through waveguide. This is achieved by setting fundamental TE mode of through waveguide in both the beginning and ending cross section to possess the highest effective refractive index. At the same time, TM mode needs to be split and rotated to TE mode, so we place another taper as cross waveguide, with a small gap besides the through waveguide. In order to realizing the TM-TE conversion and splitting, the double taper structure is designed so that at the beginning cross section the fundamental TM mode possesses the second highest effective refractive index, while at the ending cross section the fundamental TE mode of the cross waveguide possesses the second highest effective refractive index. Additionally, the cross waveguide is partially etched for breaking the vertical symmetry so that polarization has a freedom to be rotated with SiO_2 as top-cladding, as shown by dark blue area in cross waveguide.

Here we design a sample of proposed PSR with parameters optimized for O-band since O-band have recently attracted more and more attention, especially in the areas of datacom, and quantum communication [5]. The SOI platform has a top silicon thickness H_1 = 220 nm. The width of through waveguide W_1 is tapered from 430nm to 410nm, as the strip bus waveguide operating for O-band normally chooses a width of 420 nm [5]. The gap W_g is 0.2 μm as it is a standard for the photonic circuits fabricated by the 248-nm optical lithography [6]. The rib width W_2 is tapered from 0.2 μm to 0.34 μm, while the slab width W_3 is tapered from 0.3 μm to 0.34 μm.

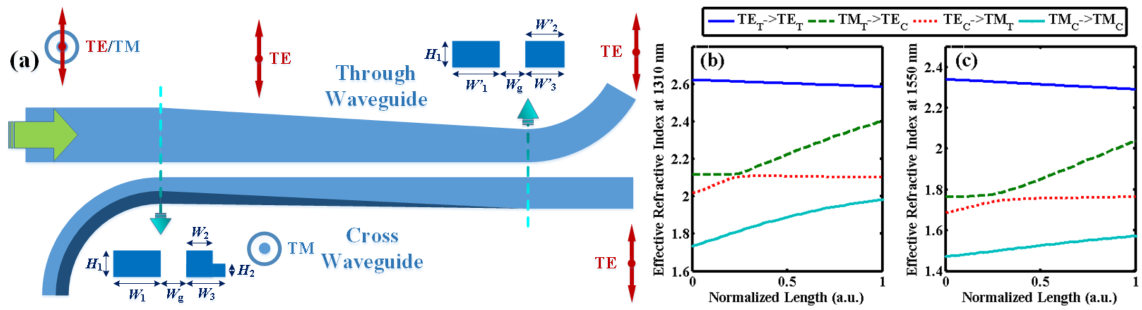

Fig. 1. (a) Schematic structure of the PSR with ultra-broadband and large fabrication tolerance. The cross section of left and right part of the PSR is shown in the bottom left and top right respectively. The SiO_2 cladding is not shown for clarity. The effective refractive index evolution of different modes at a wavelength of (b) 1310 nm and (c) 1550 nm.

Figure 1 (b) and (c) show the mode evolution of light propagating along the double taper structure. As depicted by the blue curve, the TE mode stimulated at the input port of through waveguide maintains its mode property in the through waveguide and then exit at the output port of through waveguide. The dashed green line demonstrates the mode evolution from TM mode in through waveguide to TE mode in cross waveguide. The mode conversion exists at the region with a length about one quarter of the total length when light wavelength is 1310nm, while this region moves right when light wavelength is shifted to be 1550nm. This indicates that 240-nm increase of operation wavelength moves the location of mode conversion region to the right within a quite small and tolerant range, meaning that the conversion efficiency would not be affected a lot when wavelength changes greatly. This also shows that the performance of proposed PSR operating from 1310nm to 1550nm will be in between.

We numerically verify the design by using Lumerical three-dimensional finite-difference-time-domain (3D-FDTD) solutions, with the results shown in Fig. 2. Figure 2 (a) depicts that the light is well confined in the through waveguide when fundamental TE mode is stimulated at the input port of through waveguide. When TM mode is injected, the light is highly coupled to cross waveguide and converted to TE mode, as demonstrated in Fig.2 (b). The TM-TE mode conversion is further illustrated by Fig. 2(c)-(f).

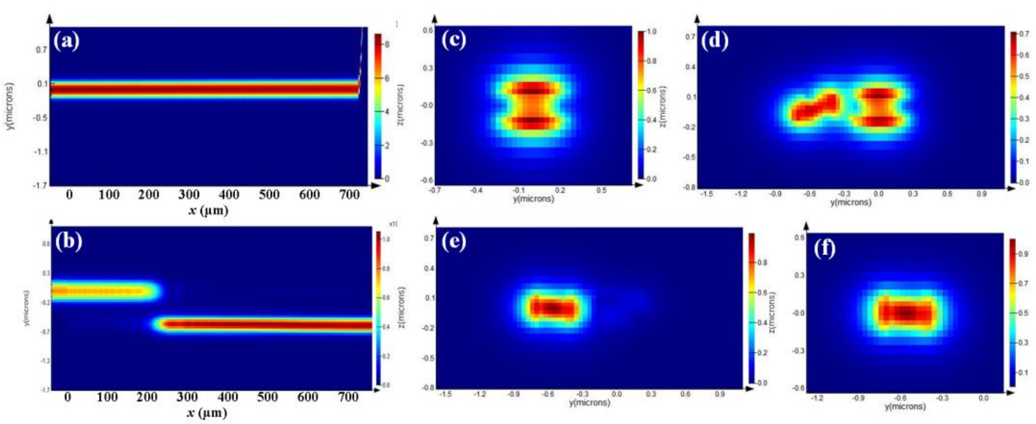

Fig. 2. The light propagation when (a) TE mode and (b) TM mode is stimulated at the input port of through waveguide. The mode conversion is further illuminated by (c)-(f). (c) The TM mode at the input port of through waveguide. (d) The hybrid mode at the middle of the tapers, where the energy carried by TM mode starts to convert into TE-like mode in the cross waveguide. (e) Most energy is coupled into TE mode in the cross waveguide. (f) Converted TE mode at the cross output of the cross waveguide. The light wavelength is set to be 1310 nm.

3. Experimental demonstrations

We fabricated and tested the devices in IME of A*STAR. Limited by the facilities in the testing lab, the O-band and C+L-band ASE source were used as the laser source. Figure 3(a) and (b) depict the different mode conversion efficiencies for O-band and C+L band respectively. The blue and red lines showing the TM-TE and TE-TE mode conversion efficiency are quite flat across the O-, C-, and L- bend, which proves the ultra-broad bandwidth of proposed PSR. The small fluctuations in the curve may be due to the instability of polarization or the edge coupling. Lots of deeps shown by the green and cyan line in Fig. 3(a) may be because that there exist some mode beating between several TE modes with different time delay at the output. Since the PSR is specially designed for O-band operation, the fabricated PSR achieves a high TM-TE and TE-TE mode conversion efficiency of -0.33 dB and -0.15

dB at 1310 nm, respectively, whose extinction ratio is better than 19 dB. As shown in Fig. 3 (b), the TM-TE and TE-TE conversion efficiency at 1550 nm is -0.97 dB and -0.56 dB, while the extinction ratio is better than 12 dB. According to the design theory and simulation results, the performance of proposed PSR operating between these two band regions will not be worse, which indicates a 1-dB bandwidth of exceeding 360 nm. Moreover, we experimentally tested the fabrication tolerance by varying the slab width W_3 by ±20 nm. As shown in Fig. 3(c), the TM-TE mode conversion efficiency only decreases by 0.5 dB for a width variation of 20 nm. This is because that only the mode conversion region is simply shifted and the mode conversion efficiency is almost maintained, which has the same situation as the wavelength shift explain in the section of design principles. Since the PSR is highly fabrication-tolerant, we further tested the performance of PSR across the whole wafer. As depicted in Fig.3 (d), chip 1 is selected in the center area of the 8-inch wafer, chip 2-4 are chosen in the different corners. It shows a 1-dB variation of TM-TE conversion efficiency across the 8-inch wafer.

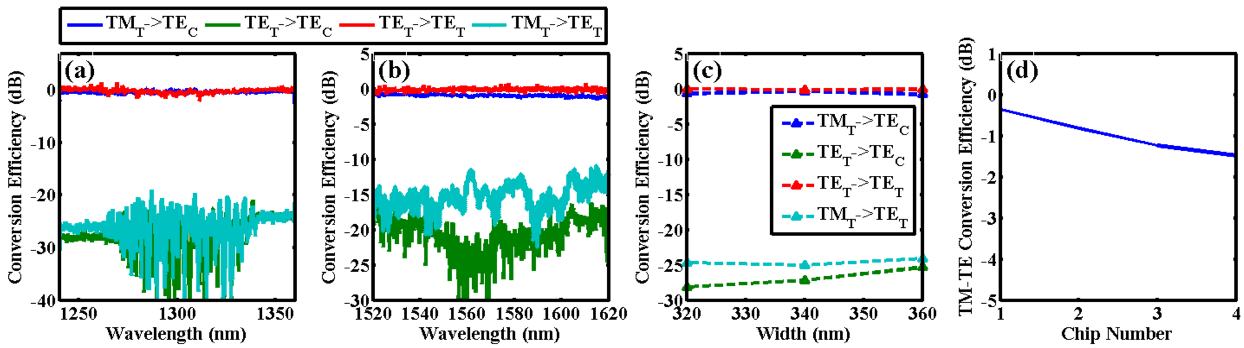

Fig. 3. (a) and (b) shows the mode conversion efficiency as a function of the wavelength for O-, C-, and L- band. (c) The mode conversion efficiency as a function of W'_3. (d) The TM-TE mode conversion efficiency for four different chips in the same wafer. The light wavelength is set to be 1310 nm for testing the fabrication tolerance in (c) and (d).

4. Conclusions

In summary, a fabrication-tolerant CMOS-compatible PSR has been experimentally demonstrated with operation wavelength covering O-, C-, and L-band, for the first time to the best our knowledge. The 1-dB bandwidth exceeds 360 nm. The fabricated PSR has a high TE-TE and TM-TE mode conversion efficiency of -0.15 dB and -0.33 dB at 1310 nm, whose extinction ratio is better than 19 dB. The TE-TE and TM-TE mode conversion efficiency are -0.56 dB and -0.97 dB at 1550 nm, while the extinction ratio is better than 12 dB. Moreover, a width variation of ±20 nm reduces the TM-TE conversion efficiency by only 0.5 dB. Additionally, the wafer level testing shows that there only exists 1-dB variation of TM-TE conversion efficiency in the 8-inch wafer. This PSR design potentially provides a practical solution for polarization handing in future large-scale system integration of photonic integrated circuits.

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