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Ultra-compact low loss polarization insensitive silicon waveguide splitter

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Abstract: We observe that the cascaded typical Y junctions will introduce unwanted periodic fringes over the spectrum in practical systems when they link with multimode waveguides. To solve the problem, we design and experimentally demonstrate a wavelength insensitive multimode interferometer (MMI) based 3-dB splitter which has all the merits of Y-splitters such as polarization insensitivity and ultra-compactness. The splitter has a footprint of 1.5 × 1.8 μm^2, nearly one order smaller than the previously reported MMI splitters. The measured excess losses for TE and TM modes at telecom wavelength are as low as −0.11 dB and −0.18 dB respectively.

OCIS codes: (130.3120) Integrated optics devices; (230.7370) Waveguides; (230.1360) Beam splitters.

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1. Introduction

Silicon-on-insulator (SOI) platform holds promise for large scale photonic integration on a highly developed silicon platform for various applications [1, 2]. Optical splitter is one of the critical components which are widely used in integrated photonic system. Many kinds of structures such as Y-junction [3, 4], directional coupler [5] and multimode interference (MMI) waveguide [6, 7] can be used to achieve 3 dB power splitting. Y-junction splitters have the most compact size and polarization insensitive behavior but their sharp junction is unpractical for fabrication due to the limited resolution of etching process, which therefore results in large scattering loss in real application. We also observe another limitation in cascaded Y- junction splitters with multimode waveguide input and output, that is, they may excite the unwanted high order modes so as to squeeze the system bandwidth because of intermodal interference. Recently, Y. Zhang et.al improved the loss performance of Y-junction splitter to −0.28 dB by properly modifying the junction shape [4]. MMI splitters based on self-imaging effect are attractive for beam splitting owing to their advanced properties of low loss, large fabrication tolerance etc. Till now, the best reported excess loss of MMI splitter can reach around −0.1 dB for TE polarization [7]. However, without proper design, MMI splitters are polarization dependent devices. Moreover, the very large footprint of multimode section also limits their practical usage in dense integrated system. Using the conventional design, the demonstrated minimum footprint of MMI splitter is $3.6 \times 11.5\ \mu m^2$ [7]. Tapered MMI splitters are also proposed to decrease the device size but they bring trade-off with the loss performance [8]. In this paper, we demonstrate a splitter by introducing a tiny multimode area to modify the field distribution so that the optical paths are aligned with the output branches for both TE and TM polarization. This design can overcome the fabrication and efficiency limitations in a Y-splitter meanwhile maintaining the compactness, and it will not excite high order modes in the multimode waveguides. We experimentally demonstrate the proposed polarization insensitive 3 dB splitter, and report a very low excess loss in the structures over a fringe free transmission spectrum.

2. Observation of fringes in Y-junction splitter with multimode waveguide

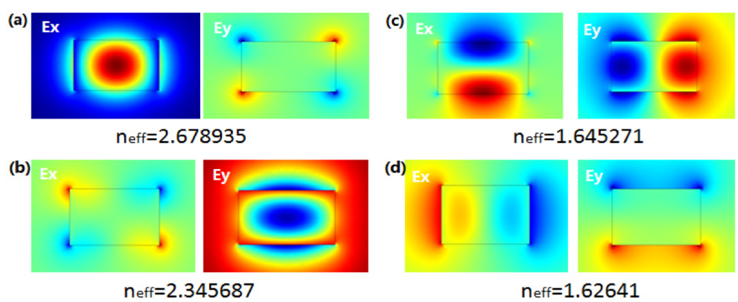

Fig. 1. The supported modes in 500 nm × 300 nm silicon channel waveguide (a) fundamental TE (b) fundamental TM (c) and (d) higher order hybrid modes.

A Y-junction splitter with multimode waveguide inputs can be used for high speed communication and effective integration with an on-chip Photo Detector (PD). However, we observe the fringes in these structures, which limit its operation to very narrow bandwidth. In our design, we have used a silicon waveguide with width and thickness of 500 nm and 300 nm, respectively. The waveguide layer is sitting on the BOX layer and covered with SiO_2 cladding layer. The waveguide mainly supports the fundamental TE and TM modes, but it also supports two higher order modes which are shown in Finite Element Method (FEM) simulation results in Fig. 1. In the device design, we have varied the bending radius(*r)* of the output waveguide branches as 20 μm (YI), 10 μm (YII) and 5 μm (YIII) to tune the splitting angle of the Y-junction, as shown in Fig. 2. For each type structures, five splitters are cascaded to characterize the performance. The fabrication process of this group of Y-splitters is described in section 4. Figures 2(a), 2(b) and 2(c) show the measured spectral behavior of each port of the three types of cascaded Y-junction splitters. From port p2 to p5, it is obvious that there exist periodic fringes over the spectrum. This is because the non-ideal branch point due to the limited etching resolution excites high order modes (ie. the tangential wavevector component of the fundamental mode equals to the wavevector of higher order mode) which further interference with the fundamental mode and finally merge at the next Y-junction. It can be observed that the fringe periodicity, ie. free spectral range (FSR) increases with the decrease of the distance between two neighbor splitters. In Fig. 2, the measured fringe FSR is around 20 nm, 25 nm and 28 nm for the splitter type YI, YII and YIII, respectively. Based on the interference principle, the fringe FSR, $\Delta\lambda$ can be estimated using the equation $\Delta\lambda = 1.55^2/(\Delta n_{\mathrm{eff}} \cdot L)$, where Δn_{eff} is the effective index difference between fundamental mode and higher order modes, L is the beating length, ie. the distance between two neighboring Y-junction splitters. The calculated FSR for the cascaded Y-junctions YI, YII and YIII is 21 nm, 24.5 nm and 26.8 nm, which are in good agreement with the measurement results. The observed spectral fringes make the Y-junction splitter applicable for only a very narrow bandwidth. The power splitting is not uniform for the nearly entire wavelength of interest.

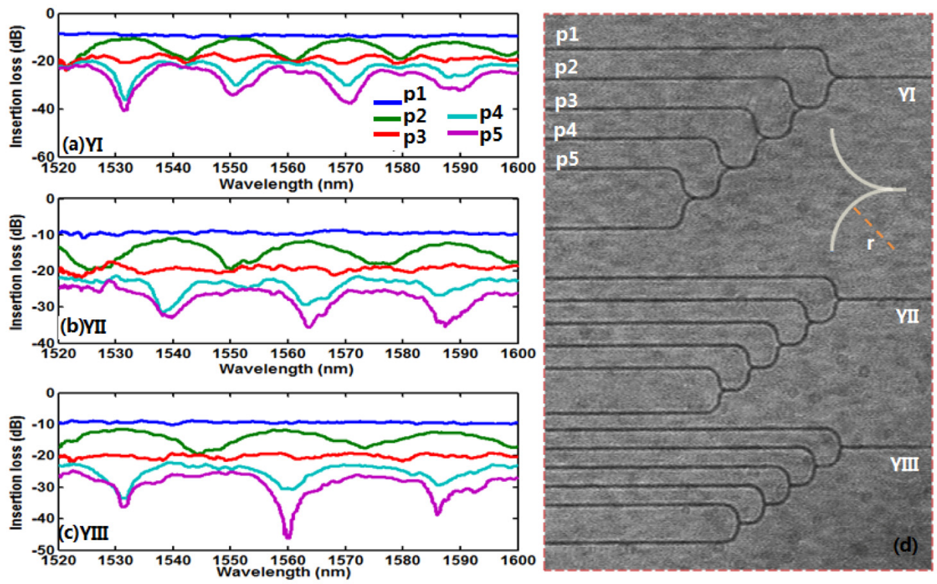

Fig. 2. The spectrum of the cascaded Y-junction splitters (a) YI, (b) YII and (c) YIII; (d) The microscope picture of the three types of Y-junction splitters.

3. Proposed splitter design

In order to remove the periodic fringes in the spectrum, we consider modifying the field distribution at the branch point of Y-junction by introducing a small multimode area. The input and output waveguides have the same dimensions of 500 nm × 300 nm as the aforementioned Y-junction splitter cases. The schematic main parameters of the proposed splitter are shown in Fig. 3(h). With the added multimode section, the splitter input optical power will excite all the supported symmetric modes in the multimode area, ie. TE_i/TM_i modes, i = 0, 2, ···, 2n, the subscript i indicates the number of field zero point along waveguide lateral direction, n is dependent on the width of the multimode waveguide section [9, 10]. Unlike the conventional large size MMI splitter, in our design, we select the width of the multimode region (W_M) to make it only support the two lowest modes ie. TE_0/TM_0 and TE_2/TM_2 modes. To satisfy this condition, the width value lies in the range of 1.49 µm to 1.95 µm. Through FDTD simulations, we observe that the widths in this range are satisfactory to achieve ultra low loss splitter. However, the excess loss will greatly increase for the width below 1.49 µm. As an intuitive illustration, we take a long multimode section to show the field distribution for TE and TM polarization at different width configurations of W_M = 1.5 µm, 1.25 µm and 1 µm.

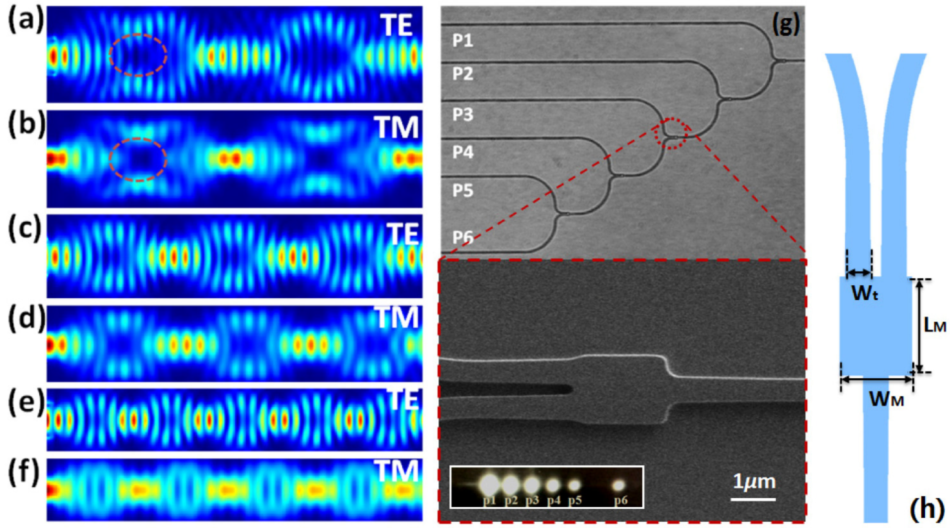

Fig. 3. The E-intensity field distribution for TE and TM polarization (top view) along the multimode section with different width. (a) and (b) for width W_M equals to 1.5 µm; (c) and (d) for width W_M equals to 1.25 µm; (e) and (f) for width W_M equals to 1 µm. (g) The microscope photo of the proposed splitters. Inset: the optical image captured from the output waveguides; (h) The splitter schematic main parameters.

Figures 3(a) and 3(b) illustrate the results for W_M = 1.5 µm which are right in the range to excite the lowest two modes. It can be seen that the two-fold power centers can be clearly formed with good resolution and contrast for both TE and TM modes. The low E-field in the cycled area will reduce the scattering loss, allowing the power to be smoothly divided into two branches. From Figs. 3(a)-3(f), the splitting quality decreases with the reduction of the width of multimode area. It is difficult to find two-fold power centers in the case of W_M = 1 µm as shown in Figs. 3(e) and 3(f). Generally for 1-to-N splitter design, it can also find the corresponding minimum width which allows keeping low loss performance. From Figs. 3(a) and 3(b), it is obvious that the two-fold power centers appear at almost the same plane for TE and TM polarization. It means that this configuration can be used to achieve polarization insensitive power splitting performance. We theoretically verify this according to polarization insensitive condition for multimode waveguide, ie. TE and TM modes can share equal beating length [11, 12].The beating length of TE and TM mode is illustrated as a function of width in Fig. 4(a). The equal beating length for both polarizations is achieved with W_M around 1.5 µm.

We can also observe that the difference in beating length for TE and TM modes is not very sensitive to variation of width in this design, providing good tolerance. The width value of 1.5 µm is large enough to conquer the fabrication limitation by the etching resolution (As the deep ultra-violet (DUV), 248 nm photolithography is adopted with minimum feature size of 200 nm, the multimode width needs to be at least 1.4 µm). Actually, this design is also the most compact 3 dB design which can simultaneously satisfy the fabrication limitation, loss limitation (ie, the minimum width value that can exert two-fold clear power centers) and polarization insensitive condition, provided that the thickness of the multimode section is also taken into account for optimisation. The result is shown in Fig. 4 (b). In Fig. 4(b), only the values above the fabrication and loss limitation curves can be used for a good design. It can be seen that the most compact design can be achieved with h = 300 nm and W_M = 1.5 µm. In this case, the corresponding multimode area length L_M is 1.8 µm optimized by numerical calculation.

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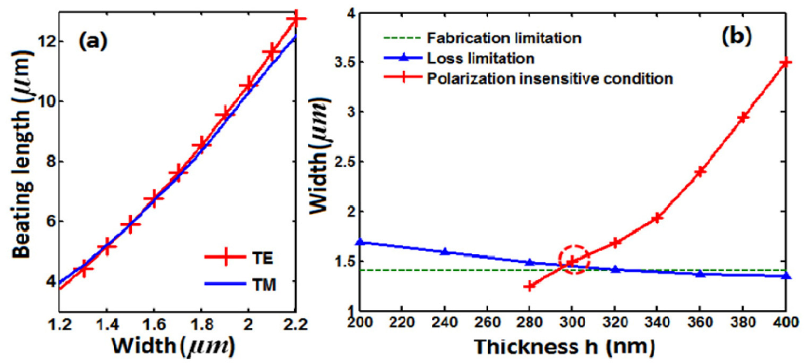

Fig. 4. (a) TE and TM beating length versus the width of multimode section; (b) The fabrication and loss limitation and the polarization insensitive condition.

4. Fabrication and measurements

We fabricated the polarization insensitive splitter in silicon-on-insulator (SOI) platform through Institute of Micro Electronics (IME) CMOS fabrication process. The fabrication is done on an 8 inch SOI wafer with a 340 nm top silicon layer thickness and 2 μm buried oxide (BOX) layer. Thermal oxidation is adopted firstly in order to thin down the silicon layer to 300 nm. The device is patterned by DUV photolithography, followed by a two-step silicon reactive ion etching (RIE) down to the BOX layer. To increase the coupling efficiency between lensed fibre and the device, the waveguide ends were terminated with Spot Size Converters (SSC) having a length 200 μm and tip width 180 nm. The whole structure is finally covered by 1.1 μm silicon dioxide (SiO_2) cladding layer. The microscope photos of the fabricated structures are shown in Fig. 3(g). Five splitters are cascaded in order to measure the splitter excess loss. It can be seen that the proposed splitters have almost the same size as Y-junction splitter. The inset shows the optical image captured from the output waveguides. Referring to the lensed fiber to fiber coupling loss, the measured insertion loss at each output waveguide for TE and TM mode is given in Figs. 5(a) and 5(b), respectively. When compared to the Y-junction splitter, the spectrum measured at each port of the proposed splitter is smooth curve without any fringes from wavelength 1520 nm to 1600 nm, which offers wide operation bandwidth. In Fig. 5, it should be noted that the insertion loss includes the fiber-to-chip facet coupling losses, splitter excess loss and waveguide propagation loss. We linearly fit the insertion loss of each output ports to calculate the excess loss of the designed splitter. The

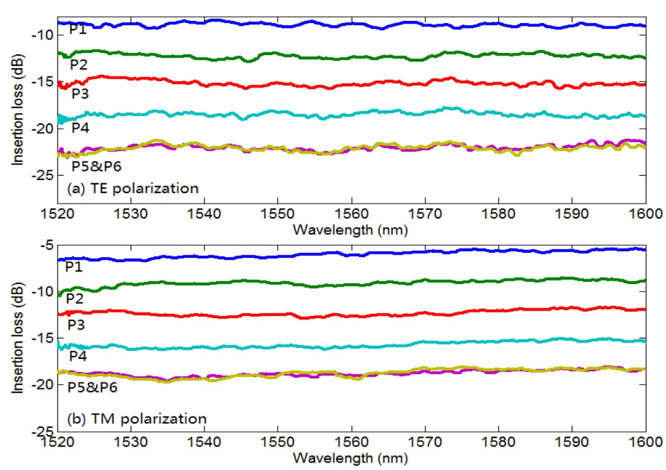

Fig. 5. The normalized spectrum at each output waveguide for (a) TE and (b) TM polarization light from ASE source referring to fiber to fiber coupling loss.

results are shown in Fig. 6(a) for TE polarization, Fig. 6(b) for TM polarization and Fig. 6(c) for unpolarized light. The slope of the linear formula is the excess loss plus the 3 dB beam-splitting drop, and the interception mainly reflects the fiber-to-chip facet coupling loss. The excess loss is −0.11 dB for TE polarization, −0.18 dB for TM polarization and −0.14 dB for unpolarized light. To the best of our knowledge, this is the best experimental result for polarization insensitive splitter till now. The access width of the input and output waveguides is also optimized to obtain the optimum performance in our design. Figure 6(d) illustrates the relationship of splitter excess loss versus the access taper width W_t. It can be seen that the optimum loss performance is obtained while W_t = 540 nm. There exists some difference between the measurement and simulation values, which mainly comes from the fabrication variation like the geometry deformation and round edges etc. Although our proposed splitter has tiny footprint, the device has good fabrication tolerance. In our study, we find that only 0.1 dB extra loss is introduced by ± 100 nm variation in multimode area length or by ± 20 nm variation in its width.

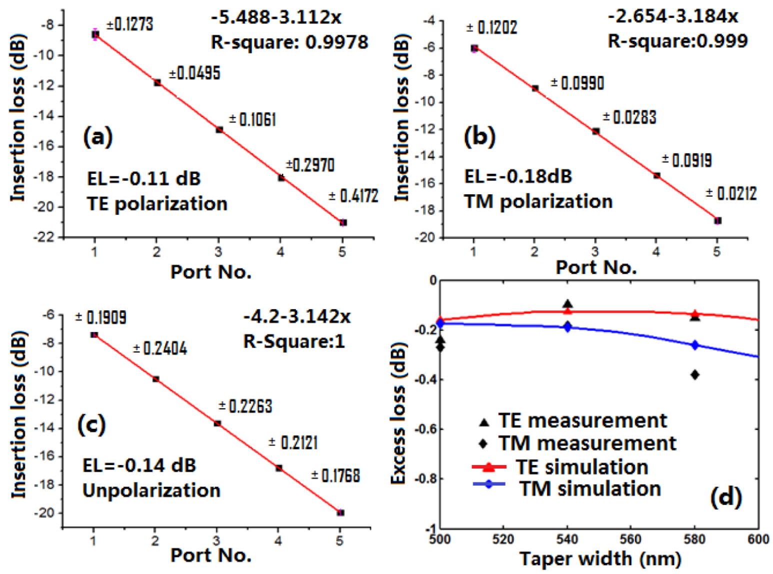

Fig. 6. The measured insertion loss from the output ports for (a) TE polarization, (b) TM polarization and (c) unpolarized light at 1.55 µm wavelength; (d) The relationship of splitter excess loss versus taper width.

5. Conclusion

In summary, we design and experimentally demonstrate an ultra-compact low loss MMI 3-dB power splitter. The design has all the merits of Y junction such as polarization insensitivity and ultra-compact size, and it also solves problems of the periodic fringes introduced by Y-junction for multimode waveguide applications. The device footprint takes only 1.5 × 1.8 μm^2. The excess losses for TE and TM mode are −0.11 dB and −0.18 dB, respectively. This is expected to be a practical power splitter design on SOI platform for large scale photonics integration.

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