Paired interference 3-dB coupler based on SOI rib waveguides with anisotropic chemical wet etching

Zhiyong Li (李智勇), Jinzhong Yu (余金中), Shaowu Chen (陈少武), Jingwei Liu (刘敬伟), and Jinsong Xia (夏金松)

State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083

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A 3-dB paired interference (PI) optical coupler in silicon-on-insulator (SOI) based on rib waveguides with trapezoidal cross section was designed with simulation by a modified finite-difference beam propagation method (FD-BPM) and fabricated by potassium hydroxide (KOH) anisotropic chemical wet etching. Theoretically, tolerances of width, length, and port distance are more than 1, 100, and 1 μm, respectively. Smooth interface was obtained with the propagation loss of 1.1 dB/cm at the wavelength of 1.55 μm. The coupler has a good uniformity of 0.2 dB and low excess loss of less than 2 dB.

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In recent years, multi-mode interference (MMI) based couplers[1,2] have been used as one of the key components in integrated optics due to their compactness, large fabrication tolerance, inherent balance, and low optical loss[3]. Their excellent properties have led to growing applications in photonic integrated circuits (PICs) such as Mach-Zehnder switches[4] and modulators[5], variable optical attenuators (VOAs)[6,7]. In this letter, a paired interference (PI) based 3-dB coupler was designed with simulation analysis and fabricated on silicon-on-insulator (SOI) wafer by anisotropic chemical wet-etching of silicon.

So far, the most widely used MMI couplers are based on general interference (GI), few on paired or symmetric interference (SI). In fact, it is proved that in the case of PI the length of the coupler would decrease greatly. Furthermore, PI couplers have better imbalance performance than GI couplers, give the same fabrication tolerances and length constraint for both types[8]. Under PI configuration, input waveguides are placed at $\pm W_e/6$, as shown in Fig. 1, $W_e \approx W_{MMI}$ refers to the effective width of the multi-mode waveguide. The 2×2 3-dB PI couplers have been demonstrated in InP/InGaAsP with the widths of MMIs 15.92—18.81 μm and the lengths of waveguides 358—500 μm[8]. Extremely small PI couplers were realized in 107-μm-long InP-based waveguides with 0.9-dB excess loss and 0.2-dB unbalance[9].

In fact, SOI technology offers the potential of low cost one-chip integration of various optoelectronic devices. Moreover, most of GI based MMI couplers on SOI wafer were made by the conventional dry-etching techniques such as reactive ion etching (RIE). In order to obtain smooth interfaces with less scattering, wet-etching of silicon was used. The root mean square (RMS) roughness of interfaces is less than 2 nm. At the same time, chemical etching has the advantages of very low cost and easy to control with high accuracy of etching depth. However, the waveguide along the ⟨110⟩ crystalline direction of the wafer made by wet etching has trapezoidal cross sections, which is difficult to be accurately simulated. The bottom angle of the sidewall is 54.74°.

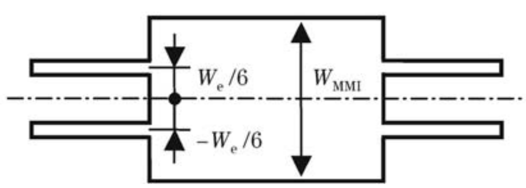

Fig. 1. Schematic of a PI based 3-dB coupler.

The traditional analysis methods, such as effective index method (EIM) for two-dimensional planar waveguides and normal finite difference (FD) beam propagation method (BPM) developed for parallel or vertical interfaces, are not suitable to the case, because these methods cannot describe the sloping sidewall accurately. Recently, Xia *et al.* presented a modified FD-BPM based on a new derived discretization scheme for waveguides with tilted interfaces[10]. The optimal length of MMI coupler was obtained from the simulation results as shown in Fig. 2. Heights of the inner and outer ribs are designed to be 4.8 and 3.3 μm, respectively. The top width of MMI is 40 μm and two images of the input optical field appear at $z = 2850$ μm, as shown in Fig. 2, which is the

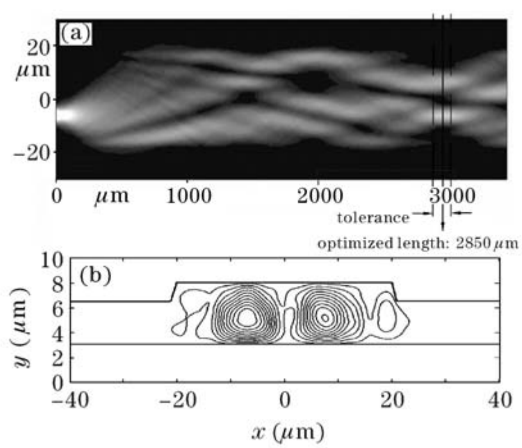

Fig. 2. (a) Self-image of the MMI obtained by simulation and (b) mode field distribution at optimal length.

Table 1. Comparison of Self-Image Lengths from Different Methods

Simulation Method		Self-Image Length (μm)
EIM		2374
Normal BPM	$W_{\text{e}} = W_{\text{top}}$	2740
	$W_{\text{e}} = W_{\text{bottom}}$	2979
New FD-BPM		2850

optimal MMI length for PI based 3-dB couplers. Table 1 gives the results from EIM, normal FD method, and the new FD-BPM. If EIM is used, the result will be inaccurate because the method is very simplistic and not suitable to the simulation of trapezoidal cross section. As for the normal FD method, the different results would be obtained when the width of MMI was selected as the top width or the bottom width of about 42.12 μm. It results in design difficulty for MMIs that the range of the self-image length exceeds 200 μm. So the modified FD-BPM is very desirable and more accurate for tilted surfaces. According to the results from the modified method, the tolerance is also obtained. Assuming that the critical uniformity is 0.5 dB, the tolerances of width, length, and distance between the two input/output ports of the multi-mode section are more than 1, 100, and 1 μm, respectively.

The microscope image of the fabricated coupler is shown in Fig. 3. In measurement, 1.55-μm light from the single-mode fiber was directly coupled into the rib input waveguides through the cleaved facet. The light emerging from the output ends was projected onto an infrared charge coupled device (CCD). The measured image of the output near field of one sample was displayed on the monitor, as shown in Fig. 4. According to the data from the otptical powermeter (EXFO FOT-90A),

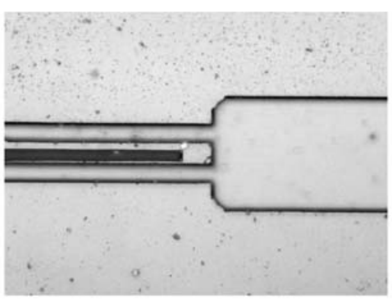

Fig. 3. Local microscope image of the fabricated device.

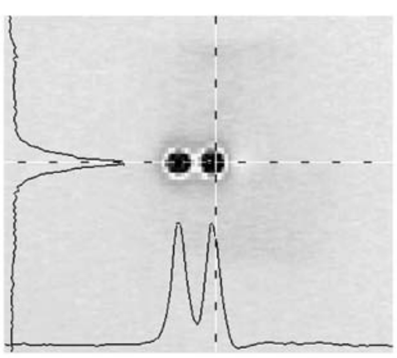

Fig. 4. Output near field of the coupler.

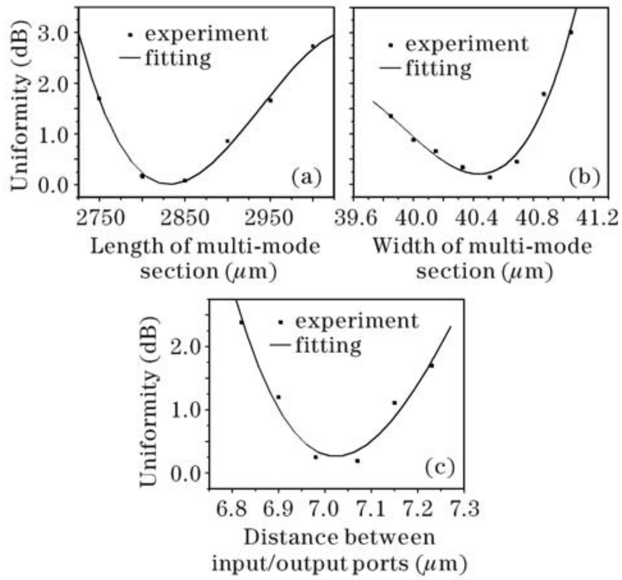

Fig. 5. Power uniformity of the coupler versus tolerances of (a) length, (b) width, and (c) port distance.

the measured uniformity in the two output ports is less than 0.2 dB, demonstrating highly uniform output of the couplers. Figure 5 shows the power uniformity of the coupler with different tolerances of length, width, and port distance. Figure 5(a) indicates that the minimum of uniformity is about 0.09 dB and the designed length of the couplers should be about 2830 μm with the designed MMI width of 40.15 μm and the selected port distance of 6.82 μm, which accords with the simulation result. The optimal width and port distance of multi-mode sections should be about 40.5 and 7.05 μm, respectively, as can be seen in Figs. 5(b) and (c). These results show that the underetching is not negligible. Besides, according to the experiment results, the tolerances of the two parameters are only about 0.5 and 0.2 μm. Nevertheless, they would be caused by the small sizes of couplers and could be relaxed by using wider access waveguides[1].

The insertion loss of the straight waveguides in the same wafer was measured, which is about 9.2 dB for the total length of about 2 cm. The value consists of propagation loss of 2.2 dB for rib waveguides and dominant coupling loss of 3.5 dB for each end due to facet reflection and modal mismatch. The insertion loss of the coupler with the same length is about 14.3 dB for one port. Therefore, excluding the 3-dB energy separation, the excess loss of about 2 dB is induced by light scattering and leakage in the couplers because of design and fabrication. The polarization and wavelength dependent losses (PDL and WDL) of one coupler can be seen in Fig. 6, obtained by Newport PM500 and Agilent 8164A systems. The data show that the insertion loss fluctuates from 14.2 to 15.9 dB with the wavelength range of 1535—1640 nm, almost covering the C- and L-band for optical fiber communication. But the minimal loss of the coupler emerges at the wavelength of 1609.5 nm, not 1550 nm as designed. And the PDLs in the wavelength ranges are about 1.68 ± 0.61 dB, a little greater than that of straight single-mode waveguides. These results indicate that PDLs originated from MMIs are excessive to the couplers and need to be diminished in new designs.

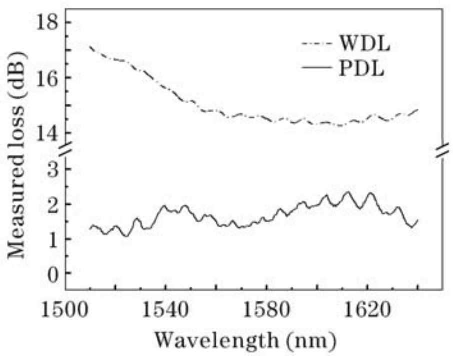

Fig. 6. Polarization and wavelength dependent losses (PDL and WDL) of one coupler.

In conclusion, a PI 2 × 2 3-dB coupler based on SOI rib waveguides with trapezoidal cross section was demonstrated for the design of silicon based optical switches. The modified FD-BPM was used to simulate the multi-mode rib waveguides with tilted sidewalls and optimize the design parameters. Couplers with different lengths, widths, and port distances of multi-mode waveguides were fabricated. The output near field images show that the PI-based couplers have large fabrication tolerance and good power uniformity. These devices are suitable for silicon photonic application. Compared with GI-based couplers, they have shorter multi-mode waveguides and therefore lower propagation loss, showing promise to fabricate more compact and low-loss SOI devices such as large-scale optical switch arrays.

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