Low Loss Fiber-to-Waveguide Converter With a 3-D Functional Taper for Silicon Photonics

Qing Fang, Junfeng Song, Xianshu Luo, Xiaoguang Tu, Lianxi Jia, Mingbin Yu, and Guoqiang Lo

***Abstract*— We demonstrate a low-loss and broad-bandwidth fiber-to-waveguide converter with a 3-D functional SiO_2 taper for silicon photonics. The converter is composed of a cantilevered SiO_2 waveguide and Si nano-tapers. In order to reduce the loss from the cleaved fiber, a 3-D functional SiO_2 taper is designed to compress the size of optical mode field. Using cleaved optical fibers with a mode field diameter of 10.5 μm at 1550 nm, we characterized the optical performances of the converter. With an index-matching liquid, the lowest coupling loss of TE mode is 1.5 dB/facet and the lowest coupling loss of TM mode is 2.1 dB/facet. For both TE and TM modes, the 1-dB bandwidth is more than 100 nm, and the alignment tolerances for 1-dB excess loss are, respectively, ±2.5 and ±2 μm in horizontal and vertical directions.**

***Index Terms*— Integrated optics, silicon photonics, fiber-to-waveguide converter, 3D functional taper, low coupling loss.**

I. Introduction

IT IS potential to provide low-cost and high-reliability silicon photonics products for our current optical communication system. Owing to the compatibility with CMOS fabrication technology, silicon photonics devices can be potentially integrated with IC circuits. These kinds of silicon-based opto-electronics circuits monolithically integrated with IC design have better reliability and lower cost, compared to other material platforms. Over the past decade, many researchers made lots of efforts to the waveguide devices in silicon photonics and achieved many good results. Both of passive devices and active devices of silicon photonics are greatly developed [1]–[5], especially high-speed SiGe-based photodetector and pn-type silicon modulator. Many performances of silicon photonics devices can meet the requirements of commercial products. The devices of silicon photonics are compact because of the high refractive index of silicon for potential large-scale integration, but the mode size of silicon waveguide is not big enough to match with the standard cleaved optical fiber. Currently, the coupling between the submicron silicon waveguide and the standard cleaved fiber is still a bottleneck for the future silicon photonics products. It is highly demanded to reduce the coupling loss and enhance the bandwidth between the silicon photonics devices and the cleaved optical fiber for silicon photonics production. The alignment tolerance is also important to improve for the operation convenience during the fiber assembly.

One kind of converters for silicon photonics devices is the vertical grating coupler [6], [7]. Such vertical grating coupler has a low loss and a big alignment tolerance with the standard cleaved optical fiber. However, the vertical grating coupler has an obvious shortcoming, which is sensitive to the operation wavelength. Moreover, the vertical grating coupler is a polarization-dependent device. Thus, it is limited in some application areas. Several other kinds of mode-size converters for silicon photonics were reported recently [8]–[11] with low-loss coupling by using lensed fiber with a small mode field diameter, which is not cost-effective solution for silicon photonics products. A dual-tapered converter with double core was reported in 2012 and its coupling losses with standard cleaved optical fiber were 2.7dB/facet and 3.0dB/facet for TE and TM modes, respectively [12]. An O-band metamaterial converter was reported by IBM and this converter had good performances with a standard cleaved optical fiber [13]. However, this cantilevered converter is quite long for silicon photonics devices. We reported a fiber-to-waveguide converter on silicon-on-insulator (SOI) wafer in 2010 [14]. Our reported converter has a 6×6 μm^2 cross-sectional area which coupled with the cleaved fiber with slight mode-size mismatch between the coupler and the cleaved fiber, resulting in a relatively high coupling loss. Bell Lab reported the similar cantilevered mode-size converter [15] with a relatively low coupling loss by using a matching liquid. In 2011, we reported another cantilevered coupler based on a-Si waveguide and achieved a good coupling performance [16]. For this kind of cantilevered coupler, the symmetry of silicon nano-tapers in the cantilevered SiO_2 waveguide was very critical. In order to match the size of cleaved fiber, it is better to use a SOI wafer with 4∼6 μm-thick buried oxide (BOX) layer to fabricate the cantilevered coupler. However, the maximum BOX thickness of commercial SOI wafer is 3μm.

In this letter, we optimized and fabricated a cantilevered converter with a SiO_2 3D functional taper coupling to cleaved fiber for enhanced performances. We used an 8 μm × 12 μm SiO_2 waveguide of the cantilevered coupler to reduce the coupling loss between the SiO_2 waveguide and the cleaved fiber. Overlapped vertical SiO_2 tapers are used to further compress the optical field in vertical direction, and a horizontalSiO_2

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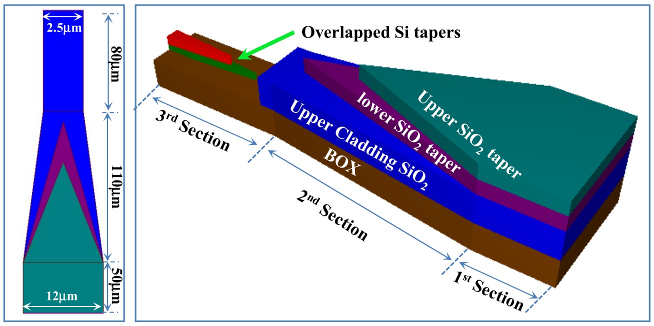

Fig. 1. Core structure of the fiber-to-waveguide cantilevered converter. Left: top view of the converter; Right: perspective view of the converter (part of upper cladding near nano silicon tapers and beams/air-trenches are omitted for better review and simplicity).

taper is used to compress the optical field in horizontal direction. We used a matching liquid (n=1.37) to characterize the coupling losses between the cleaved optical fiber and this converter. The lowest TE-mode coupling loss is 1.5 dB/facet and the lowest TM-mode coupling loss is 2.1 dB/facet. A big alignment tolerance for the assembly with cleaved optical fiber is achieved.

II. Design and Fabrication

Figure 1 shows the schematic of the core structure of the cantilevered fiber-to-waveguide converter. For a better understanding, the upper cladding SiO_2 layer atop the overlapped Si tapers is omitted in the right of Fig. 1. The core structure includes 3 sections, shown in the same figure. The first section is a big cross-sectional SiO_2 waveguide, which is designed as an input waveguide to couple with the standard cleaved fiber. The second section is the 3D functional SiO_2 taper, which is used to compress the big mode-spot size in both horizontal and vertical directions into the small mode-spot size to match Si nano-taper. The third section is the small cross-sectional SiO_2 straight waveguide and the Si overlapped nano-tapers. The 3D functional SiO_2 taper is comprised of overlapped tapers (including an upper SiO_2 taper and a lower SiO_2 taper) and a horizontal taper. The horizontal SiO_2 taper is comprised of the box layer and upper cladding SiO_2 layer in the second section of the cantilevered converter. The overlapped SiO_2 tapers can be used to compress the optical field in the vertical direction and the horizontal SiO_2 taper can be used to compress the optical field in the horizontal direction. Therefore, the 3D functional SiO_2 taper can be used to resolve the mismatch question of mode size. The core structure of the converter is isolated by air-isolation trenches which are formed by etching the adjacent SiO_2 and the underlying silicon. SiO_2 beams are designed to support the core structure. For simplicity, the beams are omitted in Fig. 1. The signal launched from standard cleaved optical fiber comes into the big cross-sectional SiO_2 waveguide. The 3D functional taper compresses the signal. The optical signal compressed by the 3D functional taper further propagates into the small cross-sectional SiO_2 waveguide. Finally, the optical signal enters Si waveguide by Si nano-tapers.

Considering the fiber's mode size and the manufacturing process, we design the SiO_2 waveguide with the cross-section of 8 μm (height) $\times$ 12 μm (width) at the 1st section.

TABLE I
Design Parameters of the Cantilevered Converter

Parameter	Value
Width of SiO_2 waveguide in 1st section	12 m
Height of SiO_2 waveguide in 1st section	8 m
Length of SiO_2 waveguide in 1st section	50 m
thickness of BOX	2 m
Thickness of Upper cladding SiO_2	3.5 m
Height of lower SiO_2tapper	1.25 m
Height of upperSiO_2tapper	1.25 m
Length of horizontal taper in 2nd section	110 m
Width of SiO_2 waveguide in 3rd section	2.5 m
Length of lower SiO_2tapper	85 m
Length of upperSiO_2tapper	70 m
Height of lower Si taper	80nm
Height of upper Si taper	140 nm
Width of the tip of both Si tapers	100 nm
Width of Si waveguide	500 nm
Width of SiO_2 beam (width of trench)	3.5 m
Length of SiO_2 beam	1.5 m

The detailed design parameters of this cantilevered converter are shown in Table 1 after optimization using RSOFT software. Compared to our previous structures, there are some important parameters improved for better performances. The bigger input SiO_2 waveguide cross-section is designed for higher match with the cleaved fiber and overlapped SiO_2 tapers are selected for lower optical loss. The thinner 1st Si taper is optimized for better match between the silicon waveguide and the SiO_2 waveguide of the 2nd section and the redesigned beams structures is for higher reliability. In order to extract the coupling performances, a set of cut-back Si waveguides were designed. Each Si waveguide between input/output converters is composed of some straight waveguides (220 nm $\times$ 500 nm) and eight 180°-bend waveguides with 10 μm radius. The length difference between two adjacent Si waveguides is 800 μm.

This cantilevered converter was simulated using RSOFT software. A normalized fiber field with a mode field diameter of 10.5μm is launched as the input signal at 1550 nm. The material of matching liquid (n=1.37) was used as the cladding for cantilevered SiO_2 waveguide. The simulation results of TE mode are shown in Fig. 2. X axis is the horizontal direction. Y axis is the vertical direction and Z axis is optical signal propagation direction. As the length of the SiO_2 beam along propagation direction is short and the dimension of SiO_2 waveguide is big, the SiO_2 beams can be negligible in the simulation. In order to simplify the simulation model the SiO_2 beams are elided. The optical field distribution results are shown in Fig. 2. The results show that the big input

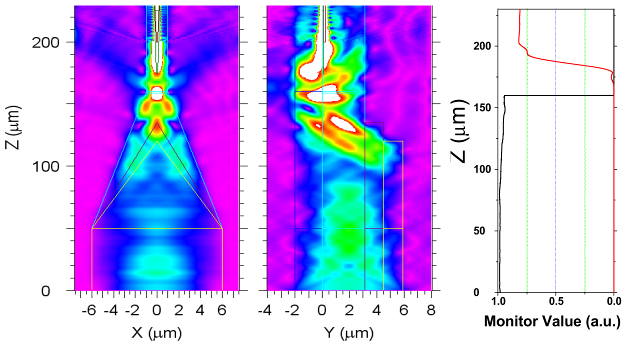

Fig. 2. Simulated optical field distribution in the converter at 1550 nm. Left: Top view; Center: Lateral view; Right: monitored optical power in the converter (black line: the power in both section 1 and section 2, red line: the power in the Si overlapped tapers).

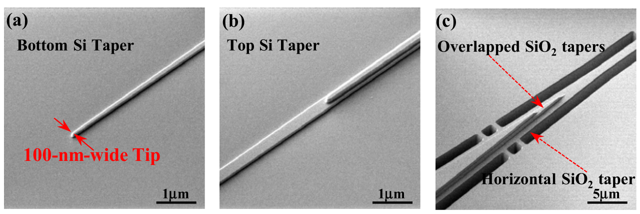

Fig. 3. SEM images of cantilevered mode-size converter during fabrication. (a) bottom Si taper, (b) top Si taper, (c) vertical overlapped SiO_2 tapers.

optical mode size can be compressed into a small one in both horizontal and vertical directions through the 3D SiO_2 taper. The right figure is the results of the monitored optical power in the converter. The coupling loss between the fiber and the 1st section can be negligible. And, the only 4% optical loss exists in the 3D SiO_2 taper. Finally, more than 80% optical power can enter the submicron silicon waveguide from the standard cleaved fiber through the converter in the simulation. The simulated results show the 3D SiO_2 taper can efficiently compress the optical field into the small Si waveguide in horizontal and vertical directions, respectively.

This fiber-to-waveguide converter was fabricated on a SOI wafer with an 8-inch diameter. This wafer had a 220-nm-thick top silicon layer and a 2-μm-thick BOX layer. First, twice lithographic/etching processes were adopted to form the Si tapers and channel Si waveguides with a 70-nm-thick SiO_2 hard mask using. Figure 3(a) is the SEM image of the formed bottom Si taper which is 80 nm in height. Figure 3(b) is the SEM image of the top Si taper which is 140 nm in height. Both of Si tip widths in Fig. 3(a-b) are ~100 nm. A SiO_2 cladding layer at a thickness of 6.2 μm was deposited after Si waveguide formation and clean. Then, Chemical Mechanical Polishing (CMP) process was adopted to smooth the surface of SiO_2 cladding layer. In this step, a thin SiO_2 layer at a thickness of 200 nm was removed. After polishing process, the total SiO_2 height, including the BOX layer, was 8 μm. Figure 3(c) shows the polished surface of the top SiO_2 taper. Later, twice lithographic/SiO_2-etching processes were adopted to form two vertical SiO_2 tapers. The height of each vertical SiO_2 taper was 1.25 μm. This 3D-SiO_2 tapered structure is beneficial to the optical loss in principle. Finally, a thick photoresist layer was used to pattern the air trenches and the beams. After lithography patterning, octofluoro-

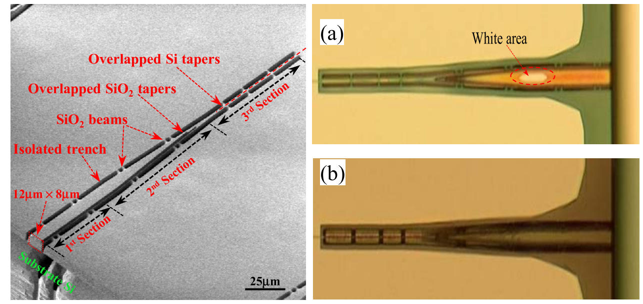

Fig. 4. Left: SEM image of the cantilevered fiber-to-waveguide converter (dot line represents Si overlapped tapers buried in SiO_2 cantilevered waveguide in 3rd section), Right: OM images of non-completely cantilevered structure (a) and completely cantilevered structure (b).

cyclobutane (C_4F_8) gas was used to etch the remained 5.5 μm SiO_2 layer and sulfur-fluoride (SF_6) gas was used to remove the underlying substrate Si layer to form the cantilevered SiO_2 waveguide and the Si deep-trench at the same time. The similar process flow was presented in details in Ref. 14. Figure 4(left) shows the SEM image of the whole converter. We use optical microscope (OM) to estimate the status of cantilevered SiO_2 waveguide. The top-right figure shows the structure which is not completely cantilevered, and the white area in the red circle presents that the substrate Si connects with the SiO_2 waveguide in Fig. 4. The bottom-right shows that the structure of SiO_2 waveguide is completely cantilevered.

III. Measurement and Analysis

The deep trench was formed by etching process and the sidewall was smooth. After dicing and clean, the chip was directly characterized. The used optical fiber is 9/125 μm Corning Panda Polarization Maintaining (PM) fiber, which has a mode field diameter of 10.5 μm at the wavelength of 1550 nm. The characterization tools include a high-performance amplified spontaneous emission (ASE) light source with a broadband wavelength range, a high-sensitivity optical power meter, an optical polarization controller (PC), a high-precision optical spectrum analyzer (OSA) and a linear optical polarizer. In order to ensure a TE mode input, the polarization direction of the linear polarizer is placed to be perpendicular to the chip surface. The output optical light through the polarizer is monitored by a near infrared (NIR) camera. By adjusting the polarization controller and rotating the input fiber, the output power becomes minimum, which suggests the input mode is TE. We can obtain the TM mode by rotating the input fiber by 90°.

With the matching liquid, the optical spectra of TE/TM modes from the input PM cleaved optical fiber to the output PM cleaved optical fiber were measured first as a reference. Then, the same input/output optical fibers were used to measure the designed cut-back waveguides which were integrated with cantilevered converters using the same matching liquid for TE mode and TM mode. Based on the above measured data, the bend loss and the propagation loss of the waveguides were extracted. In the bandwidth of 1520~1620 nm, the TE-mode propagation loss is about 2.5 dB/cm and the TM-mode propagation loss is about 2.9 dB/cm. For the bend waveguide of 10 μm radius, the 180° bend losses of TE and

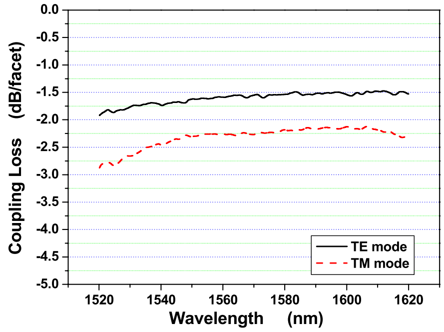

Fig. 5. Measured coupling loss of mode converter using cleaved optical fibers with a mode field diameter of 10.5μm.

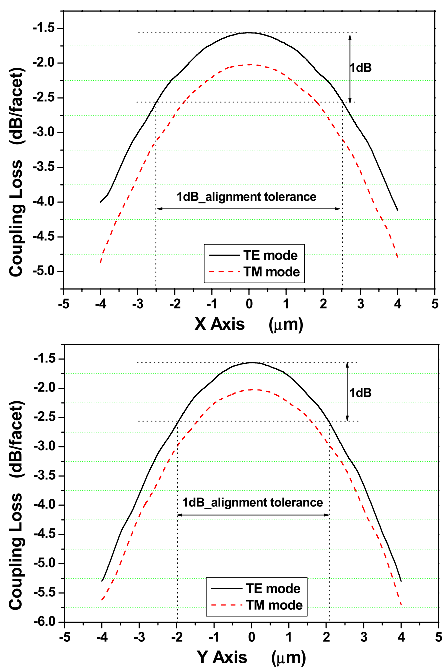

Fig. 6. Alignment tolerance between mode size converter and cleaved optical fiber in both horizontal (X) and vertical (Y) directions.

TM modes are about 0.01 dB. By deducting the propagation/bend losses of waveguides and the fiber-fiber loss, the coupling spectra of the cantilevered converter were achieved for TE and TM modes in Fig. 5. The results show that the lowest coupling loss of TE mode is only 1.5 dB/facet and the lowest coupling loss of TM mode is 2.1 dB/facet. The coupling dependent loss of the converter is less than 1 dB at the wavelength range of 1520$\sim$1620 nm. In the same wavelength range, the 1-dB bandwidth for TE mode and TM mode is very broad, $>$100 nm. The coupling loss without any matching liquid was also characterized. Without the matching liquid, the lowest coupling loss of TE is about 2.6 dB/facet and the lowest coupling loss of TM mode is 3.0 dB/facet. As the sidewall roughness of SiO_2 waveguide is little high after all processes, the matching liquid is used to mainly reduce the scattering of rough SiO_2 waveguide sidewall. At the same time, the matching liquid is also used to reduce the reflection at the interface of converter/fiber. For a commercial converter, a big alignment tolerance greatly benefits the package of optical products. Hence, we measured the alignment data of this cantilevered converter. Figure 6 shows the measured results about the alignment tolerances. Using the above cleaved fiber and matching liquid, the tolerance in X axis is ± 2.5 μm and it in Y axis is ± 2.0 μm for 1-dB excess loss.

IV. Conclusion

In conclusion, we demonstrated a high-performance cleaved fiber-to-waveguide mode-size converter for silicon photonics devices on SOI platform. This mode-size converter with a 3D taper has a low coupling loss and it is independent on the operated wavelengths. The lowest coupling loss is 1.5 dB/facet for TE mode and 2.1 dB/facet for TM mode. 1-dB bandwidth is more than 100 nm for both TE and TM modes. The alignment tolerance for 1-dB excess loss is ± 2.5 μm in horizontal direction and ± 2.0 μm in vertical direction for both TE and TM modes. It is a candidate as a converter for the future silicon photonics productions.

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