

Mode-size converter with high coupling efficiency and broad bandwidth

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Abstract: An ultralow coupling loss and broad bandwidth fiber-to-waveguide mode-size converter is demonstrated for nano-scale waveguides on SOI platform using CMOS technology in this paper. The mode-size converter consists of a cantilevered PECVD SiO₂ waveguide and a-Si nanotapers by removing the adjacent SiO₂ layer and underlying substrate Si. The a-Si waveguide is located at the center of the cantilevered SiO₂ waveguide. We characterized the cantilevered mode-size converter using cleaved optical single mode fiber with 10.5 μm mode field diameter. With refractive index (1.375) matching oil, the measured coupling efficiencies between the cleaved optical fiber and this converter are higher than 80% per facet and 70% per facet for TE and TM modes at 1600 nm, respectively. The polarization dependent loss and the coupling loss variation of this converter are less than 1.0 dB at the wavelength range of 1520 ~1640 nm. The 1-dB bandwidths for both TE and TM modes are more than 120 nm. The alignment tolerances for TE and TM modes are ± 2.8 μm and ± 2.1 μm at 1-dB excess loss in horizontal direction and vertical direction, respectively.

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OCIS codes: (130.3120) Integrated optics devices; (130.0250) Optoelectronics; (130.2790) Guided waves.

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1. Introduction

Silicon photonic has been developed rapidly in the past decade, due to the perfect material properties and the mature fabrication process which is compatible with complementary metal-oxide-semiconductor (CMOS) technology. Many good results have been achieved, such as passive devices [1–3], low power thermo-optic devices [4,5], high speed modulators/photodetectors [6,7], and integrated silicon photonic circuits [8–10]. However, there are two bottlenecks which have restricted the development of silicon photonic. One is the polarization dependent loss; the other is the coupling loss. Although the small waveguide cross-section and high refractive index make silicon photonics devices very compact and cost effective, the waveguide spot size is also very small. The mode-size mismatch between the cleaved standard optical fiber and the silicon photonic waveguide makes the coupling loss very high. Furthermore, the effective index difference between the optical silica fiber and the silicon waveguide also contributes to the high coupling loss. It is important to decrease the coupling loss between the silicon photonics devices and the cleaved optical fiber. At the same time, it is critical to enlarge the coupling alignment tolerance to reduce the difficulty of fiber assembly to realize the commercialization of silicon photonics.

Up to now, several techniques have been adopted to decrease the high coupling loss. One type of converters is Si nano-taper covered by another waveguide with lower effective index, such as polymer waveguide or SiON waveguide [11,12]. However, the dimension of the cladding waveguide is small, such as $3\mu\text{m} \times 3\mu\text{m}$ or $3\mu\text{m} \times 5\mu\text{m}$. The coupling loss is low with tapered fiber, but high with normal cleaved fiber. This kind of converter is a good choice for characterization in Labs, but not for commercial products. Another converter is reported in [13]. This converter has a very low coupling loss, but it is still a challenge to align the converter to Si waveguide. The most common converter is the vertical grating coupler [14–16]. The latest reported coupling loss for vertical grating coupler is 1.6 dB/facet; and it has a good alignment tolerance with cleaved fiber. However, vertical grating coupler is usually dependent on the polarization and bandwidth.

In 2010, we reported a novel fiber-to-waveguide converter [17]. This converter has a good potential to resolve all issues of the above converters. Subsequently, the similar converter is also reported by Bell Lab [18]. These converters are fabricated on the commercial silicon-on-insulator (SOI) wafer (single crystal Si on the top layer) with 2–3 μm buried oxide (BOX). The coupling loss is ~ 1.5 dB/facet with index matching oil. In principle, this kind of converter should have a lower coupling loss if using a commercial SOI wafer with a thicker BOX. Unfortunately, such SOI wafer with a thicker BOX ($> 4\mu\text{m}$) is not available. In this paper, we fabricate the SOI wafer with a thicker BOX layer by depositing the buried SiO₂ layer and the top Si layer using plasma-enhanced chemical vapor deposition (PECVD) method from a bulk

single crystal Si wafer. Then, we design and fabricate the cantilevered converter using the fabricated SOI wafer. The measurement results show excellent performances of this converter.

2. Design and fabrication

Figure 1 shows the schematic structure of the fiber-to-waveguide mode-size converter. The converter includes 3 sections in the left of Fig. 1. The 1st section is a large cross-section SiO₂ straight waveguide which is designed to couple with the cleaved fiber. The 2nd section is the lateral SiO₂ waveguide taper. This middle section is used to compress the large mode spot into the small mode spot which matches with Si nano-taper. The 3rd section is the small cross-sectional SiO₂ straight waveguide and the Si overlapped nano-tapers. The location of overlapped Si tapers is shown in the inset and the upper SiO₂ cladding layer in the 3rd section is hidden to clearly display the overlapped Si tapers. In order to avoid the optical loss, the converter structure is isolated by air-isolation trenches formed by removing the adjacent SiO₂ layer and underlying substrate Si. It is supported by some SiO₂ beams, as shown in the right of Fig. 1. The inset shows the location of the overlapped Si tapers in the converter. It is exactly located in the center of the SiO₂ waveguide of the 3rd section, facing to the 2nd section. The design parameters are shown in the Table 1.

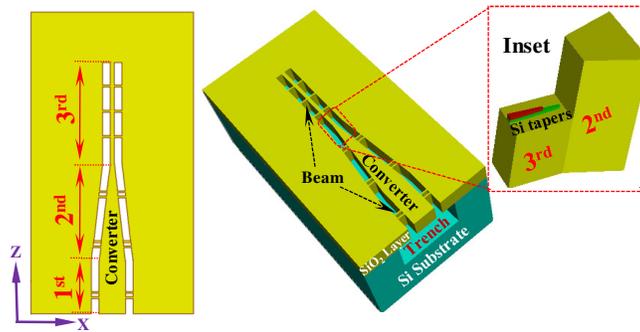


Fig. 1. Schematic structure of the mode-size converter. Left: top view of converter; Right: 3D structure of converter; Inset: the location of Si tapers (beams and air trenches are hidden for simplicity).

Table 1. The Design Parameters of the Mode-Size Converter

| Items | Unit / μm | Items | Unit / μm |
|---|----------------------|---|----------------------|
| Height of lower Si taper | 0.11 | Length of the 1st section | 50 |
| Height of upper Si taper | 0.11 | Length of the 2nd section | 100 |
| Tip width of both Si tapers | 0.1 | Length of the 3rd section | 100 |
| Length of both Si tapers | 50 | SiO ₂ waveguide width of the 1st section | 13 |
| Si waveguide width | 0.5 | SiO ₂ waveguide width of the 3rd section | 3.5 |
| SiO ₂ thickness under Si taper | 5 | SiO ₂ beam width (trench width) | 4 |
| SiO ₂ thickness above Si taper | 5 | SiO ₂ beam length | 1.5 |

According to the parameters in the Table 1, the length of the converter is 250 μm , and the input cross-section of the SiO₂ waveguide in the converter is 10 $\mu\text{m} \times 13 \mu\text{m}$, which matches with the cleaved optical fiber. Based on the designed structure in Fig. 1, we simulate this converter using the RSOFT commercial software. We use the fiber field with 10.5 μm mode field diameter as the input field. The result is shown in Fig. 2. The input optical field is compressed gradually in the 2nd section of the converter. The input optical field forms a compressed optical field in the 2nd section, which matches with the overlapped Si tapers. And then, it is coupled into the Si tapers. The simulated result shows that most of the optical power

is coupled into the Si waveguide from the optical fiber and the SiO₂ beams do not affect the optical field during the transmission. One group of cut-back structures with the mode-size converter are designed to extract the coupling loss.

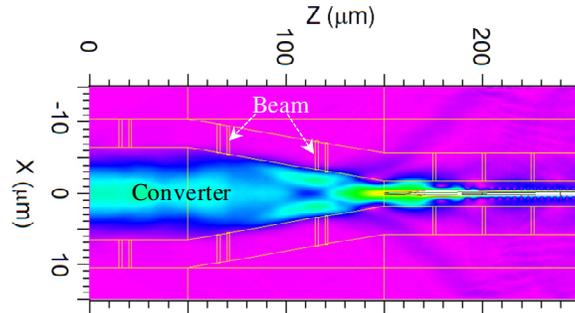


Fig. 2. Simulated optical field distribution in the mode-size converter at 1550 nm (the outline is shown using the yellow lines).

Based on the above design, the mode-size converter was fabricated on an 8-inch Si wafer. We deposited a 5.2 μm -thick SiO₂ layer by PECVD method to form the thicker BOX on the bulk Si wafer. After Chemical Mechanical Polishing (CMP) process where a SiO₂ layer of 0.2 μm was lost, a 300 nm-thick amorphous silicon (a-Si) layer was deposited by PECVD method and also polished to form the 220 nm-thick top Si layer. The SOI wafer with 220 nm top Si layer and 5 μm buried oxide was formed. Atomic force microscope (AFM) images of the PECVD SiO₂ surface are shown in Fig. 3. The left of Fig. 3 is the surface before CMP and the roughness is ~ 5.9 nm. The right is the polished surface and the roughness is less than 0.5 nm. Surface polishing can efficiently reduce the surface scattering of optical light, according to the calculated results in [2].

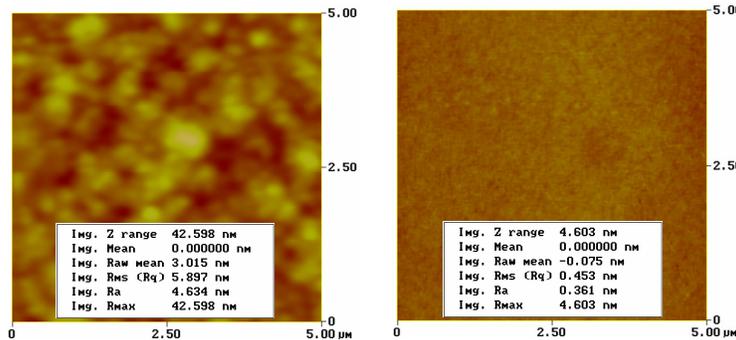


Fig. 3. AFM picture of the surface of PECVD SiO₂ layer before CMP process (left) and after CMP process (right).

The overlapped Si nano-tapers and channel Si waveguides were fabricated by double lithographic/Si-etching processes. This etching process is similar to [17]. The etched overlapped Si nano-tapers are shown in Fig. 4 (Inset 1 and Inset 2). Both of the upper and lower Si nano-tapers are 110 nm high. The tip widths of the two tapers are the same of about 100 nm. After Si nano-tapers formation, another 5.2 μm -thick PECVD SiO₂ layer as the upper cladding layer was deposited on the Si waveguide. In order to further reduce the loss caused by the SiO₂ surface of the upper cladding layer, the deposited SiO₂ layer was also polished to reduce the roughness by CMP process. After CMP, the total SiO₂ thickness is 10 μm and the surface is very smooth. Finally, the air trenches and the beams were patterned. After lithography patterning, the 10 μm -thick SiO₂ layer was etched by octofluorocyclobutane (C₄F₈); and underlying substrate Si layer was etched by sulfur fluoride (SF₆) to form the

cantilevered SiO₂ waveguide and 120 μm-deep Si deep trenches, as shown in Fig. 4. The Si taper exactly lies in the center of the 3rd section of the mode-size converter and its location is shown using the red dashed line in Fig. 4. Both the mode field centers of the cantilevered SiO₂ waveguide and the Si waveguide taper are passing through the same straight line, which enhances the coupling efficiency between the SiO₂ waveguide and the Si taper in the converter, compared to the previous designs [17]. The input cross-section of the mode-size converter is shown in the 3rd inset with 10 μm × 13 μm. The 120 μm Si deep trenches can make the cleaved optical fiber directly couple with the converter without any edge-polishing process after fabrication. Compared to the previous converter [17], the process of this converter is simpler.

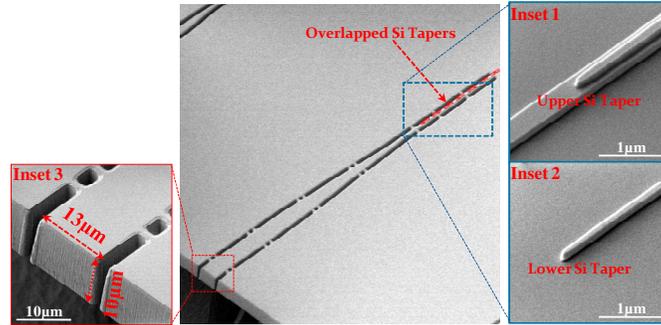


Fig. 4. SEM images of mode-size converter after fabrication. Inset 1: upper Si nano-taper; Inset 2: lower Si taper bottom Si nano-taper; Inset 3: the input of the mode-size converter.

3. Characterization and analysis

After dicing and clean, the end face of the chip doesn't need to polish because of the deep trench. The optical cleaved fiber can be used to directly align with the mode-size converter through the deep trench. This optical fiber is 8/125 μm Corning Panda Polarization Maintaining (PM) fiber which has a mode field diameter of 10.5 μm at 1550 nm. The measurement setup includes a high performance ASE light source with broad band wavelengths, a polarization controller, an optical polarizer, two rotatable fiber holders, a high sensitivity optical power meter and a high precision optical spectrum analyzer. Firstly, we measured the optical spectrum of PM cleaved fiber to PM cleaved fiber with/without the refractive index (1.375) matching oil as a reference. Then, we used the PM cleaved fibers to measure our designed cut-back waveguides integrated with input/output mode converters with/without the same refractive index matching oil for TE/TM modes.

According to the above measured results of cut-back structures, the propagation loss and the coupling loss are calculated, as shown in Fig. 5. The lefts are the propagation loss of PECVD Si waveguide for TE/TM mode with/without the matching oil. The propagation losses for TE/TM modes are 4.0 ± 1.0 dB/cm and 5.0 ± 1.0 dB/cm in the wavelength range of 1530 ~1640 nm, respectively. The propagation loss is relatively high at the short wavelength because of the absorption of the N-H bond formed during the PECVD deposition [19]. Figure 5 also shows that the propagation losses with/without the matching oil are the same for TE/TM modes, respectively. The consistency of the propagation loss with/without the matching oil is in accordance with the fact. The rights are the coupling loss of the mode-size converter for TE/TM modes with/without the matching oil. The coupling losses with the matching oil are 1.2 ± 0.2 dB/facet and 2.0 ± 0.5 dB/facet for TE/TM modes in the wavelength range of 1520 ~1640 nm, respectively. Without the matching oil, the coupling loss are 2.0 ± 0.3 dB/facet and 2.7 ± 0.5 dB/facet for TE/TM modes in the same wavelength range, respectively. At 1600 nm, the coupling losses for TE/TM modes are 1.0 dB/facet and 1.5 dB/facet, respectively. The polarization of the coupling loss with the matching oil is less than 1dB in the above wavelengths. From SEM images in Fig. 4, we can find the very rough

sidewall of SiO₂ waveguide. Using the matching oil, the effective refractive index difference between the SiO₂ waveguide and its cladding layer is decreased. It can contribute to the low coupling loss.

The alignment tolerance of the optical converter is a critical parameter for the fiber assembly. Here, the tolerances of our converter in both X and Y axes were characterized using the cleaved optical fiber with 10.5 μm mode field diameter. The measured alignment tolerances are shown in Table 2. The coupling loss between cleaved fibers with the matching oil is very low with only ~0.1 dB/facet. The corresponding alignment tolerance for 1-dB excess loss is ± 2.65 μm for both horizontal and vertical directions. Without the matching oil, the tolerance between fibers is ± 2.40 μm. With the matching oil, the tolerances between the converter and the fiber are ~ ± 2.8 μm and ~ ± 2.1 μm in the horizontal and vertical directions, respectively. Compared to the results without matching oil, the matching oil cannot efficiently enhance the mode size and the alignment tolerance for this converter.

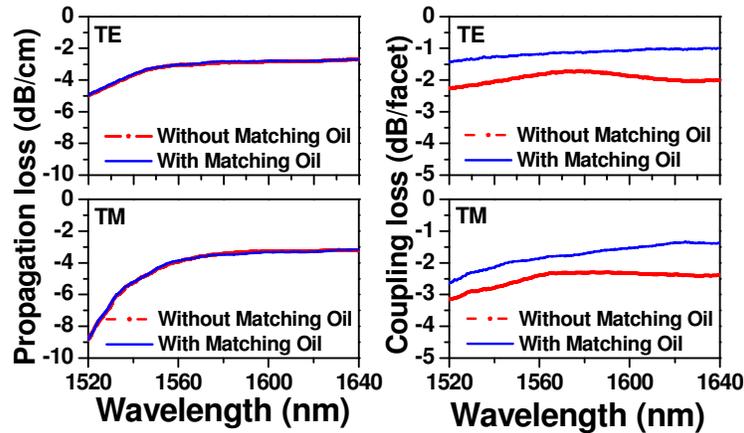


Fig. 5. Measured results using cut-back structures integrated with input/output mode-size converter. Left: propagation loss of PECVD Si waveguide for TE/TM modes with/without matching oil. Right: coupling loss of mode-size converter for TE/TM modes with/without matching oil.

Table 2. Measured Results of Coupling Loss and Tolerance at 1600 nm

| Items | With matching oil | Coupling loss /(dB/facet) | | Alignment tolerance @ 1dB excess loss /μm | | | |
|--------------------------------|-------------------|---------------------------|------|---|----------|------------|----------|
| | | TE | TM | TE | | TM | |
| | | | | horizontal | vertical | horizontal | vertical |
| Cleaved fiber to Cleaved fiber | Yes | ~0.1 | ~0.1 | ± 2.65 | ± 2.65 | ± 2.65 | ± 2.65 |
| | No | ~0.3 | ~0.3 | ± 2.40 | ± 2.40 | ± 2.40 | ± 2.40 |
| Cleaved fiber to converter | Yes | 1.0 | 1.5 | ± 2.75 | ± 2.14 | ± 2.85 | ± 2.12 |
| | No | 1.8 | 2.3 | ± 2.65 | ± 2.15 | ± 2.70 | ± 2.12 |

4. Conclusion

We have demonstrated a high performance mode-size converter for silicon photonic devices using CMOS compatible technology on SOI platform. We used the bulk Si wafer to fabricate a SOI wafer with a 5 μm-thick BOX layer by PECVD method. The cantilevered mode-size converter was designed and fabricated on the above SOI wafer. This mode-size converter has a low coupling loss and it is independent on the operated wavelengths. The coupling loss measured with matching oil is 1.0 dB/facet (~80% coupling efficiency) for TE mode and 1.5 dB/facet (~70% coupling efficiency) for TM mode. The polarization dependent loss and the

coupling loss variation of this converter are less than 1.0 dB at the wavelength range of 1520 ~1640 nm. 1-dB bandwidth is more than 120 nm for both TE and TM modes. The alignment tolerance for 1-dB excess loss is $\sim \pm 2.8 \mu\text{m}$ in horizontal direction and $\sim \pm 2.1 \mu\text{m}$ in vertical direction for both TE and TM modes.

Acknowledgments

The authors would like to thank National Natural Science Foundation of China (61177064) for financial support.