Low loss/Large tolerance mode converter between SiN waveguide and cleaved single mode fiber

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Abstract: A mode converter is fabricated with SiON to reduce the coupling loss between SiN waveguide and cleaved single-mode-fiber. The coupling loss is 1.2dB/facet and 1.4dB/facet for TE and TM mode, respectively, with 3dB alignment tolerance of ±3.5µm.
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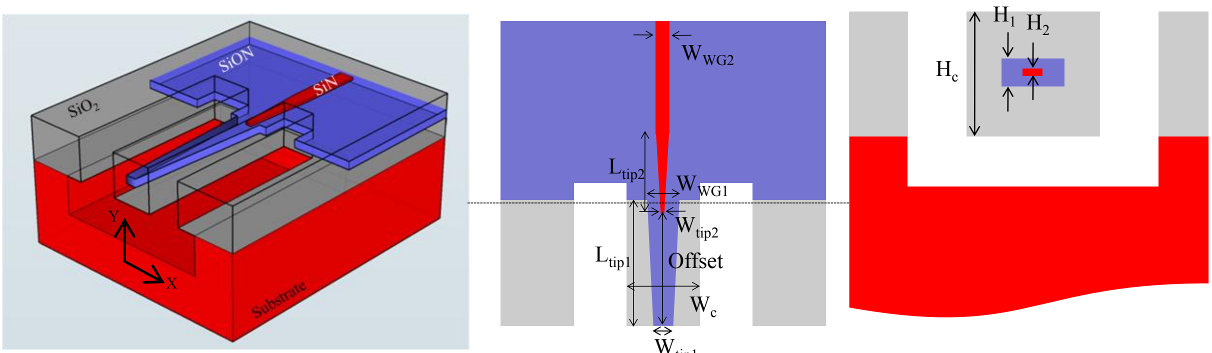
1. Introduction

Mode converter as the interface of connecting integrated optical devices and fibers is very important for the application of integrated optical devices in optical fiber communication networks. Traditional silica waveguide has almost negligible coupling loss with the single mode fiber (SMF) due to their similar mode size. On the other hand, SiN/Si waveguide due to its high index contrast are much smaller in mode size than SMF, resulting in high coupling loss. Lensed fiber [1,2] and reverse nanotaper [1-4] are commonly used to reduce the coupling loss between SMF and SiN/Si waveguide. However, lensed fiber is not suitable for high volume production due to cost issue, while nanotaper usually requires a very tiny tip (100, 60, 80 and 120 nm in reference 1-4 separately), that pushes the fabrication limit and reduces the repeatability and yield. In this letter, we report a structure with tip width of 200 nm but exhibiting low coupling loss with cleaved SMF.

2. Principle

A transition material with refractive index between fiber and high index waveguide is commonly used to reduce the large mode mismatching [2,3]. In this letter, SiON with index of 1.5 is selected as the transition material. Unlike previously reported works to enlarge the dimensions of the transition structure [2,3], the thickness of SiON layer is just 1µm with a tip width of 700 nm and the simulated mode mismatching loss with cleaved SMF is just 0.3 dB. The mode size of the SiN waveguide is first expanded through a reverse taper with tip width of 200 nm. To match with this expanded SiN mode, a waveguide with width of 3µm is designed on the 1um-thick SiON layer with simulated mode mismatching loss about 0.2 dB. Another reverse taper in SiON is used to connect the SiON tip and waveguide with a length of 300µm for adiabatic conversion of the mode. A cantilever structure similar to that in reference 4 is also required at the end of the SiON reverse taper for reducing the leakage loss to the substrate due to the mode expansion. The schematics of the structure are shown in fig. 1(a)-(c) and the parameters are listed in Table 1.



(a) 3D Schematics of the mode converter (b) Top view (c) Cross-Sectional view

Figure1. Schematics of the mode converter.

Table 1. The value of the parameters in the design.

W_{tip1}	W_{tip2}	W_{WG1}	W_{WG2}	W_c	H_1	H_2	H_c	L_{tip1}	L_{tip2}	Offset
700 nm	200 nm	3 µm	600 nm	9 µm	1 µm	400 nm	8 µm	250 µm	300 µm	L_{tip1}

3. Fabrication and Characterization

The structure is fabricated on a commercial 8-inch Si wafer with CMOS compatible process. 4-µm SiO_2 is deposited as down-cladding layer with plasma enhanced chemical vapor deposition (PECVD), after which chemical mechanical polishing (CMP) is employed to reduce the surface roughness. After CMP, 500nm-thick SiON is deposited with PECVD and polished also with CMP. This is followed by the deposition of 400-nm thick SiN using low pressure chemical vapor deposition (LPCVD) and the SiN waveguide is patterned with 248nm UV lithography and etched. Fig. 2(a) shows the SEM image of SiN tip. Then another layer of SiON with thickness of 800nm is deposited and polished to cover the SiN waveguide so that the SiN core is within the center of the SiON layer, which is important to reduce the coupling loss. Followed is the SiON tip and waveguide formation as shown in fig. 2(b). Then another 4-µm SiO2 is deposited as up-cladding layer. Finally the cantilever structure is patterned and formed with dry etching as shown in fig. 3(c).

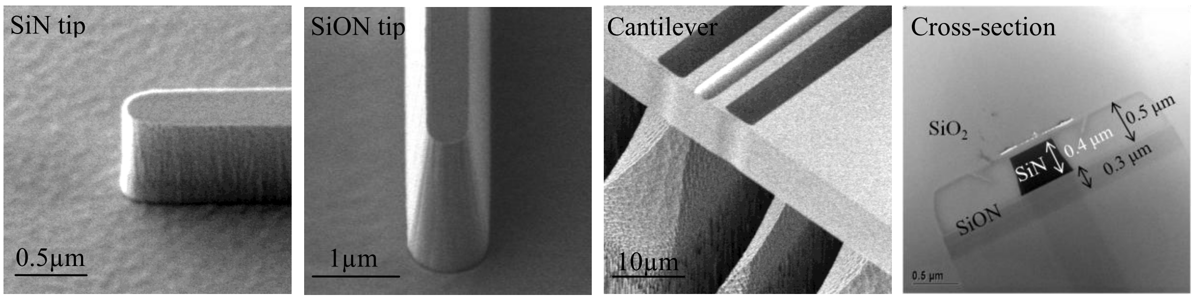


Figure 2. SEM images of the mode converter. (a) Tip of SiN; (b) Tip of SiON; (c) Cantilever of SiO_2; (d) Cross-SEM image of the mode converter.

In the experiment, amplified spontaneous emission (ASE) light source and optical spectrum analyzer (OSA) are used to provide the input light and record the output light. A polarization controller is applied to control the polarization mode of the input light for the characterization of polarization-dependent property of the structure. Firstly, a cut-back structure on the same wafer is used to measure the propagation loss of SiN waveguide. Then the transmission loss of the waveguide with mode converters is normalized with the propagation loss to get the coupling loss with input fiber. Two kinds of fibers, cleaved and lensed SMF with mode diameter of 9.2 µm and 2.5µm separately, are used for comparison, and index matching gel with index of 1.37 is used in the test with cleaved SMF.

Fig. 3 shows the experimental results of the suggested structure. For cleaved SMF, the coupling loss is between 1.2-1.5 dB/facet for TE mode and 1.4-1.7 dB/facet in the range from 1510 to 1610 nm. While for lensed SMF, the coupling loss is larger than 3.5 dB/facet for both polarization modes. Actually, the mode size of the SiN waveguide is smaller than that of lensed fiber, therefore, these results validate that the mode size is effectively expanded towards that of cleaved SMF after the mode converter. The oscillation in the test results with lensed fiber is the resonance due to the reflection in the facets.

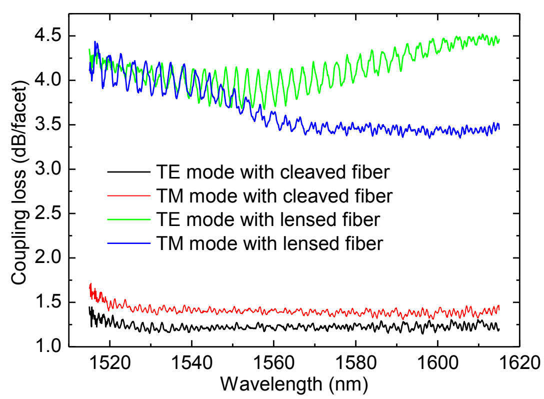


Figure 3. The measured coupling loss of the suggested structure with lensed and cleaved SMF in the C+L band.

As comparison, five other structures of mode converter are fabricated and tested: 1. SiN nanotaper with tip width of 200nm (the same below), 2. SiN nanotaper and cantilever, 3. SiN nanotaper and SiON taper without offset, 4. SiN nanotaper and SiON taper with offset, 5. SiN nanotaper and SiON taper with cantilever but without offset. The test results at 1550nm are listed in Table 2 with that of the suggested structure together. It is shown that nanotaper in SiN waveguide works to couple with lensed SMF with a coupling loss about 1.9 dB/facet and 1.7 dB/facet for TE and TM mode. However, the coupling loss is larger than 2.9 dB/facet when the fiber is cleaved SMF. It is proven that 200 nm nanotaper is not sufficient to expand the mode to match with cleaved SMF and smaller nanotaper is needed [4]. With the assistance of another taper in the SiON layer, the coupling loss with cleaved fiber can be much reduced as shown in structure 4 and 6. But the leakage loss to the substrate will increase as the expansion of the mode size and the 2.9 dB/facet coupling loss of TM mode in structure 4 is the result of this leakage. Therefore, a cantilever is essential to the coupling with cleaved SMF after the effective expansion of the mode size.

Table 2. The coupling loss (dB/facet) of different mode converters with lensed and cleaved SMF at 1550 nm. SiN and SiON denote the structures with reverse taper in the SiN and SiON waveguide.

Fiber	Mode	SiN	SiN+Cantilever	SiON+SiN	SiON+SiN+offset	SiON+SiN+ Cantilever	SiON+SiN+offset+ Cantilever
Lensed SMF	TE	1.95	1.9	1.85	6	1.8	4
	TM	1.75	1.75	1.7	7.2	1.7	3.8
Cleaved SMF	TE	2.9	5	4	1.9	3.9	1.2
	TM	3.8	5.25	4.7	2.9	4.6	1.4

The alignment tolerance of the converter is a very critical specification for fiber assembly. Hence, the tolerances of suggested converter in both X and Y axes at 1550 nm are characterized. As comparison, the alignment tolerance of the structure 5, which has best coupling loss with lensed fiber, is also measured. The results for tolerance test are normalized with the lowest coupling loss as shown in fig. 4. For the lensed fiber, the alignment tolerances for 3dB excess loss in X and Y axes are ±1.3 μm and ±1.1 μm, respectively. For the case of cleaved fiber, the 3dB alignment tolerances in X and Y axes both exceed ±3.5 μm. The similar results are obtained for both TE and TM mode.

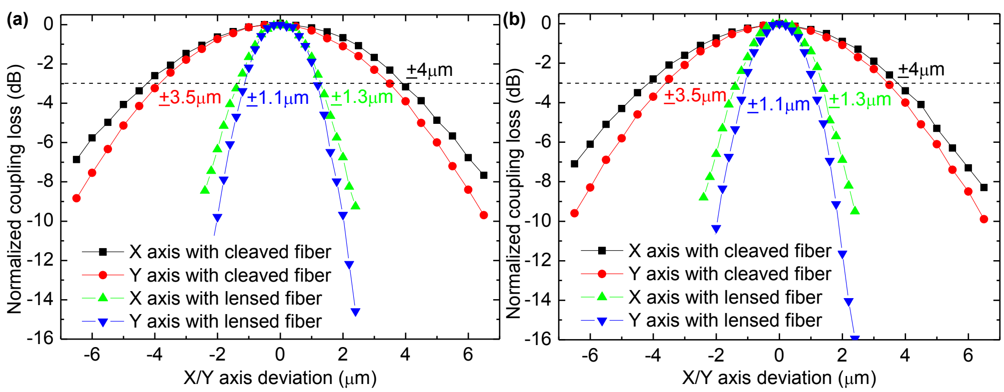


Figure 4. Alignment tolerances of the mode converters in both X and Y axes at 1550 nm. (a) TE mode and (b) TM mode.

4. Discussion

The simulated coupling loss is about 0.7 dB/facet, better than the result of experiment, which may be caused by the asymmetry in the X direction as shown in fig. 2(d). The total thickness of SiON is 0.8 μm and the thickness of SiON on the SiN is just 0.1 μm, which is caused by over-CMP after the deposition of up-cladding SiON.

5.Summary and conclusion

After all, an efficient mode converter between cleaved SMF and SiN waveguide is achieved with loss about 1.2 and 1.4 dB/facet for TE and TM mode respectively and the alignment tolerances exceed ±3.5 μm in both X and Y direction. If the tip width can be reduced to smaller than 100nm, the coupling loss for both polarization mode should be < 1dB/facet. Similar structure can be used for Si waveguide and the relevant experiments are in progress.

6. References

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