# Mode size converter between high-index-contrast waveguide and cleaved single mode fiber using SiON as intermediate material

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**Abstract:** High-index-contrast (HIC) waveguide such as Si and $Si_3N_4$ has small mode size enabling compact integration. However, the coupling loss with single mode fiber is also remarkable owning to the mode mismatching. Therefore, mode size converter, as the interface between HIC waveguide and optical fiber, takes an important role in the field of integrated optics. The material with refractive index (RI) between HIC waveguide and optical fiber can be used as a bridge to reduce the mode mismatching loss. In this letter, we employ silicon oxynitride (SiON) with RI about 1.50 as the intermediate material and optimize the structure of the SiON waveguide to match with cleaved single mode fiber and HIC waveguide separately. Combined with inverse taper and suspended structure, the mismatching loss is reduced and the dependence to the dimension of the structure is also released. The coupling loss is 1.2 and 1.4 dB/facet for TE and TM mode, respectively, with 3dB alignment tolerance of ± 3.5 μm for $Si_3N_4$ waveguide with just 200nm-wide tip. While for Si waveguide, a critical dimension of 150nm is applied due to the higher index contrast than $Si_3N_4$ waveguide. Similar alignment tolerance is realized with coupling loss about 1.8 and 2.1 dB/facet for TE and TM mode. The polarization dependence loss (PDL) for both platforms is within 0.5 dB.



**OCIS codes:** (130.3120) Integrated optics devices; (060.4510) Optical communications.

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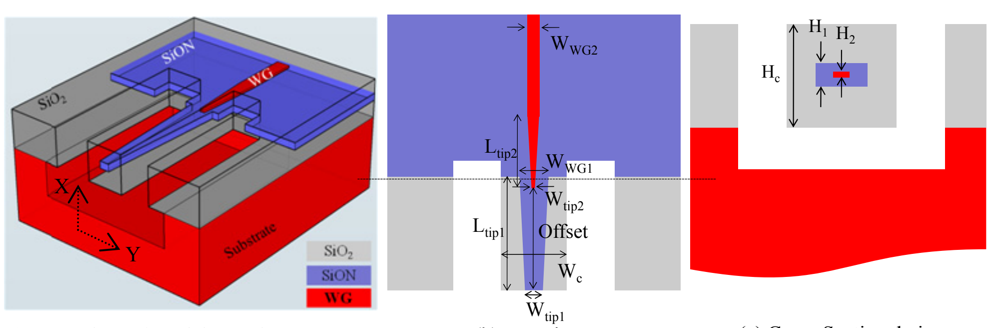
## 1. Introduction

Traditional silica waveguide has almost negligible coupling loss with single mode fiber (SMF) due to their similar mode sizes and reflective index (RI) [1]. On the other hand, high-index-contrast (HIC) waveguide, such as $Si_3N_4$ and Si waveguide, has much smaller mode than SMF, resulting in high coupling loss with SMF. Therefore, mode size converter as the interface to connect integrated optical devices and fibers is very important for the application of optical devices based on Si and $Si_3N_4$ in optical fiber communication networks. Lensed fiber [2–4] and reverse nanotaper [2–7] are commonly used to reduce the coupling loss between SMF and $Si_3N_4$/Si waveguide. However, lensed fiber is not suitable for high volume production because of cost and package issues, and nanotaper usually requires a very tiny tip (100, 60, 80, 120 and 140 nm in [2–5,7] separately), that pushes the fabrication limit and reduces the repeatability and yield of devices. In this letter, we report a structure with common tip width but exhibiting low coupling loss with cleaved SMF. For releasing the dimension of the tip, a material with lower RI than that of HIC waveguide is used to match with fiber. Meanwhile, the RI is higher than that of fiber, which also facilitates the matching with HIC waveguide.

## 2. Device operating principle

A transition material with RI between fiber and HIC waveguide is commonly used to reduce the large mode mismatching [3,4,6]. In previous works, the dimensions of the transition structures are enlarged to couple with SMF [3,4,6]. However, the large dimension hinders the matching with HIC waveguide, a tiny tip is also necessary to expand the mode of the HIC waveguide [3,4]. Usually, the tip dimension is limited by fabrication capability. If the value exceeds the design rule of the fabrication plant, the structure cannot be formed correctly. In this situation, an alternative method is to compress the mode of the intermediate structure and release the requirement to the tip width. Reducing the thickness of the intermediate material is a feasible method and a tip with normal width can expand the mode effectively as the reduction of the film thickness [8,9]. Meanwhile, a cantilever structure similar to that in [7] is also required at the end of the tip to reduce the leakage loss to the substrate due to the mode expansion. The whole structure will be like the schematics in Fig. 1.



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

Fig. 1. Schematics of the suggested mode size converter.

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## 3. Coupling with $Si_3N_4$ waveguide

We firstly embody this structure on $Si_3N_4$ waveguide. The thickness of the $Si_3N_4$ film is 400 nm [5,10] and the tip width of the $Si_3N_4$ taper is set to 200 nm, which is a conservative value in the platform with 248nm photolithography. For the intermediate material, silicon oxynitride (SiON) of which the RI can be tuned from 1.45 to 2 is an ideal candidate.

*3.1 Design of the mode size converter*

The total insertion loss of the structure is mainly determined by the mode matching in two facets: one is the interface between fiber and the tip of SiON waveguide; another is the interface between SiON waveguide and the tip of $Si_3N_4$ waveguide. Hence, we used the mode mismatching loss in the two facets as the criteria to decide the parameters of the structure. The mode mismatching loss is calculated according to the following equation:

$$\eta(dB) = 10\lg\left(\frac{\left|\int E_1^* E_2 dA\right|^2}{\int |E_1|^2 dA \int |E_2|^2 dA}\right), \tag{1}$$

where $E_1$ and $E_2$ are the electrical field distribution of the two modes.

Firstly, the suitable RI of the SiON should be chosen. The fundamental TE modes of the SiON waveguide in the two facets were calculated under four different RIs: 1.48, 1.5, 1.52 and 1.6 and the width of SiON waveguide was also scanned to get the best matching condition. As stated in the previous paragraph, a thin film is preferred to expand the mode, so we assumed the thickness of SiON was 1 μm in the simulation. Based on the modes, the mode mismatching losses are calculated as shown in Fig. 2. In the first interface, the peak value and tolerance of the width both reduce as the increase of the RI. However, SiON with higher RI has more advantage in the second facet. Combining the results, the SiON with RI in the range of 1.5~1.52 is good choice. RI = 1.5 is utilized in the following simulation.

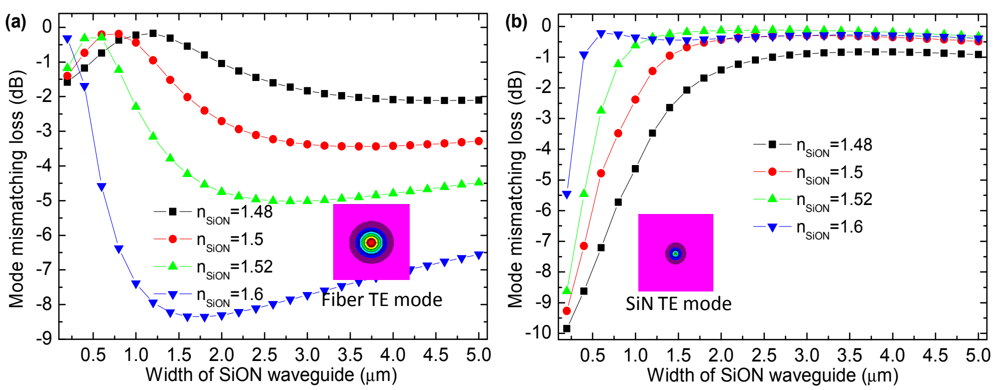


Fig. 2. The mode mismatching losses of SiON waveguide with (a) fiber and (b) $Si_3N_4$ tip under different RI. The insets are the mode distribution of the fiber and $Si_3N_4$ tip in the two facets.

The other parameters of the converter should be determined after the RI is confirmed. We emphasized the polarization dependence of the structures in the following simulation, both TE and TM modes are involved. The thickness of the SiON film and the widths of the SiON waveguide in the two interfaces are the critical parameters in the structure and their effect to the mode mismatching loss are shown in Figs. 3(a)–3(d). The effect of the SiON thickness on mode mismatching is very similar to that of the RI. The curves in Figs. 3(a)–3(d) show similar variation to those in Fig. 2. Considering the loss and fabrication tolerance, 1μm-thick SiON film is chosen and the widths of the SiON taper are 700 nm and 3 μm separately. All

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the parameters work for TE and TM modes. The calculated mode mismatching loss is 0.5 dB for TE mode and 0.6 dB for TM mode with polarization dependence loss (PDL) just 0.1 dB.

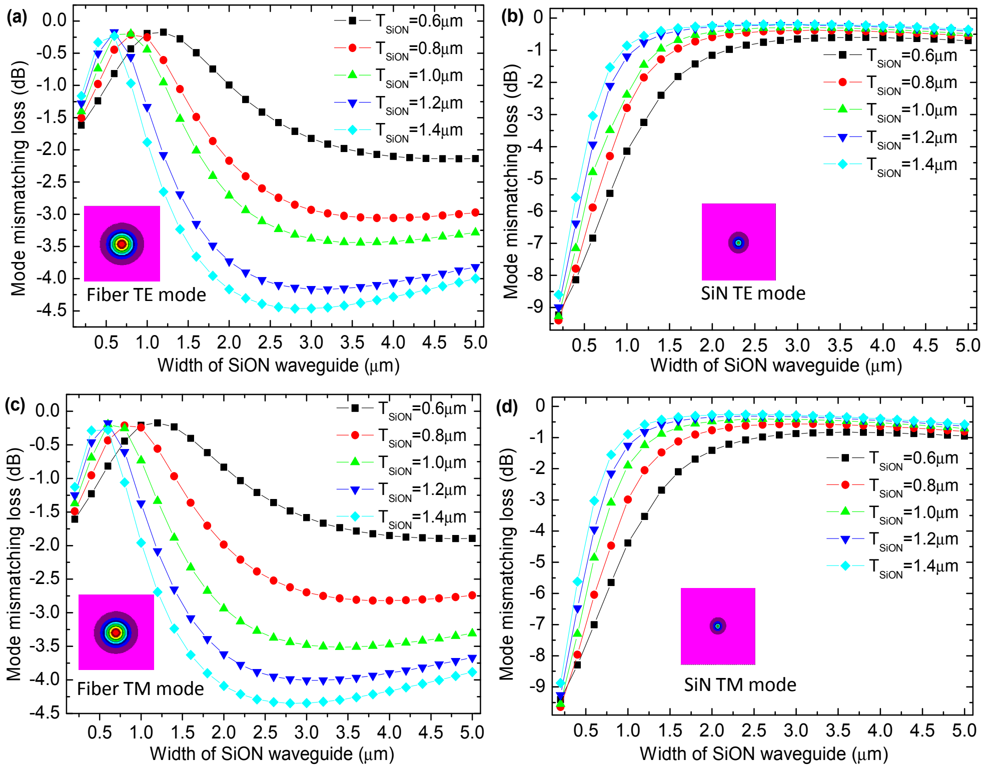


Fig. 3. The mode mismatching losses of SiON waveguide with fiber and $Si_3N_4$ tip under different thickness of SiON film for (a, b) TE mode and (c, d) TM mode.

The mode mismatching calculation is a rough estimation to the coupling loss of the converter. To get the more precise result, we built a model with Rsoft [11] according to the schematics in Fig. 1 and simulated the coupling loss with BeamProp module. The calculated coupling loss is 0.85 dB for TE mode and 1.3 dB for TM mode as shown in Fig. 4. All the parameters in the model are listed in Table 1. The lengths of the tapers are long enough to skip the transition loss and the width of the suspended structure is designed to match with fiber.

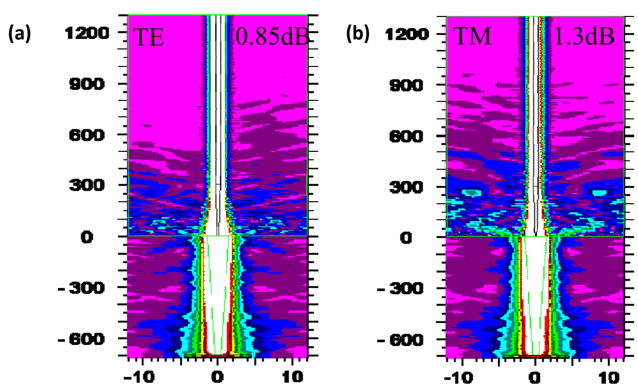


Fig. 4. The calculated electrical field distribution of the mode size converter at Y = 0 surface for (a) TE and (b) TM mode.

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**Table 1. 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 | $L_{tip1}$ |

As shown in Fig. 1(c), the centers of $Si_3N_4$ and SiON waveguide should overlap in the design, but there are inevitable errors such as overlay misalignment and film thickness error making the center of the two layers deviate and increasing the mode mismatching loss. The effect of the center deviation to the mode mismatching loss is analyzed and the results are shown in Fig. 5. Compared to the TM mode, the TE mode is more sensitive to the deviation in Y direction, while the deviation in X direction shows similar effect to the mode mismatching loss for both polarization states.

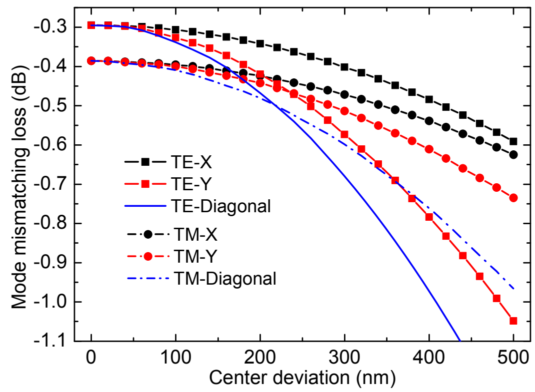


Fig. 5. The effect of center deviation to the mode mismatching loss. The deviation in X, Y and diagonal directions are calculated under different polarization states.

### *3.2 Fabrication and characterization*

We fabricated the structure on a commercial 8-inch Si wafer with the CMOS compatible process of IME Singapore. 4μm-thick $SiO_2$ 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. Then, 500nm-thick SiON is deposited with PECVD and polished to 300nm-thick. The measured RI of the SiON is in the range of 1.5~1.51. Following is the deposition of 400nm-thick $Si_3N_4$ using low pressure chemical vapor deposition (LPCVD). The $Si_3N_4$ waveguide is patterned with 248nm ultra-violet lithography and etched with inductively coupled plasma etching. Figure 6(a) shows the SEM image of $Si_3N_4$ tip. Then, another layer of 800nm-thick SiON is deposited and polished to 700nm-thick to cover the $Si_3N_4$ waveguide so that the $Si_3N_4$ core is in the center of the SiON layer. Following is the SiON waveguide formation, the tip of SiON waveguide is shown in Fig. 6(b). Another 4μm-thick $SiO_2$ is deposited as up-cladding layer. Finally the cantilever structure is patterned and formed with dry etching as shown in Fig. 6(c).

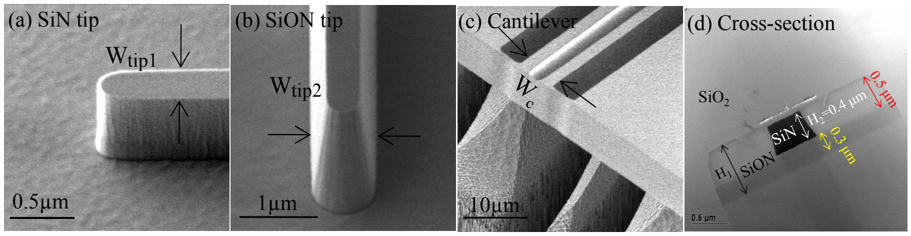


Fig. 6. SEM images of the mode size converter. (a) Tip of $Si_3N_4$; (b) Tip of SiON; (c) Cantilever of $SiO_2$; (d) Cross-SEM image of the mode size converter.

In the test, 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 state of the input light for the characterization of polarization-dependent property of the devices. Firstly, the propagation loss of $Si_3N_4$ waveguide is extracted with a cutback structure on the same wafer. Then the transmission loss of the waveguide with mode size 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 2.5 μm separately, are used as comparison, and index matching gel with RI of 1.37 is applied in the test with cleaved SMF.

Figure 7 shows the measured coupling loss. For cleaved SMF, the coupling loss is between 1.2~1.5 dB/facet for TE mode and 1.4~1.7 dB/facet for TM mode in the range of 1510~1610 nm. While for lensed SMF, the coupling loss is larger than 3.5 dB/facet for both polarization states. Actually, the $Si_3N_4$ tip has a smaller mode size than lensed fiber. However, the coupling loss with cleaved SMF is better than that with lensed SMF in our design, which proves that the mode of SiN tip is effectively expanded close to that of cleaved SMF through the converter. The oscillation in the spectrum of coupling loss with lensed fiber is the resonance due to the reflection in the facets between fiber and converter.

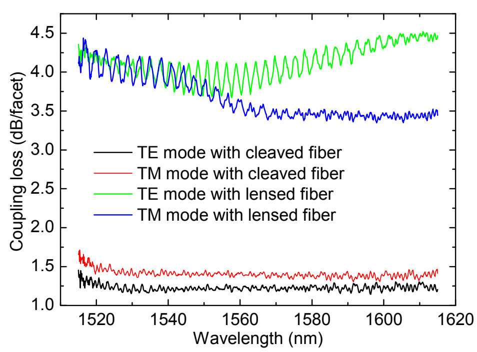


Fig. 7. The measured coupling loss between $Si_3N_4$ waveguide and cleaved/lensed SMF in the C + L band with the designed mode size converter.

As comparison, five other mode size converters are fabricated and tested: 1. $Si_3N_4$ nanotaper with 200nm-wide tip (the same below), 2. $Si_3N_4$ nanotaper and cantilever, 3. $Si_3N_4$ nanotaper and SiON taper without offset, 4. $Si_3N_4$ nanotaper and SiON taper with offset, 5. $Si_3N_4$ nanotaper and SiON taper with cantilever but without offset. The test results at 1550nm are listed in Table 2 with the result of the suggested mode size converter together. It is shown that the nanotaper in $Si_3N_4$ waveguide works to couple with lensed SMF with coupling loss about 1.9 dB/facet and 1.7 dB/facet for TE and TM mode. However, the coupling loss is larger than 4.5 dB/facet for cleaved SMF. It is proven that 200nm-wide tip is not sufficient to expand the mode to match with cleaved SMF and narrower tip is needed [5]. With the assistance of another taper with 700nm-wide tip in the SiON layer, the coupling loss with

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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 2.9 dB/facet coupling loss of TM mode in structure 4 is the result of this effect. Therefore, a cantilever is essential to the structure with effectively expanded mode.

**Table 2. Coupling Loss (dB/facet) of Different Mode Size Converters with Lensed and Cleaved SMF at 1550 nm***

| Fiber | Mode | $Si_3N_4$ | $Si_3N_4$ + Cantilever | SiON + $Si_3N_4$ | SiON + $Si_3N_4$ + offset | SiON + $Si_3N_4$ + Cantilever | SiON + $Si_3N_4$ + 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 | 4.5 | 5 | 4 | 1.9 | 3.9 | **1.2** |
| | TM | 4.9 | 5.25 | 4.7 | 2.9 | 4.6 | **1.4** |

*$Si_3N_4$ and SiON denote reverse taper in the $Si_3N_4$ and SiON waveguide.

However, for the devices 2, the suspended structure increases the coupling loss compared to device 1. It may be due to the scattering loss introduced by the sidewall of the suspended structure. The total effect of the suspended structure will by the two effects: if the leakage loss is larger than the scattering loss, the total coupling loss will be reduced; if the leakage loss to the substrate is ignorable due to the small mode, the scattering loss will dominate as in the case of normal SiN taper. The TE mode undergoes higher loss than that of TM mode, which is also a proof of the explanation, because TE mode is more sensitive to the sidewall roughness.

The measured coupling loss for TE mode is larger than the simulation result with BeamProp, while the TM mode shows coincident result with simulation. One possible reason is the thickness deviation of the up-cladding SiON. The target thickness is 700 nm after CMP, while the XSEM image in Fig. 6(d) just shows 500nm-thick SiON. There are 200 nm deviation in the total thickness of the SiON film and 100 nm deviation between the centers of Si3N4 and SiON films in the vertical direction. These errors, especially the later one, will affect the coupling loss of the TE mode more obviously as the simulation shown in Fig. 5.

The alignment tolerance of the converter is a very critical specification for device packaging. 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 test results are normalized with the peak coupling loss as shown in Fig. 8. For the structure 5, the alignment tolerances for 3dB excess loss in X and Y axes are ± 1.3 μm and ± 1.1 μm, respectively. For our structure, the 3dB alignment tolerances in X and Y axes both exceed ± 3.5 μm. The alignment tolerance of the butt-coupled cleaved SMF to SMF, as shown with dashed line in Fig. 8(a), is calculated, which is very similar to the results of our structure. The results under TM mode are also measured, which is similar to that under TE mode.

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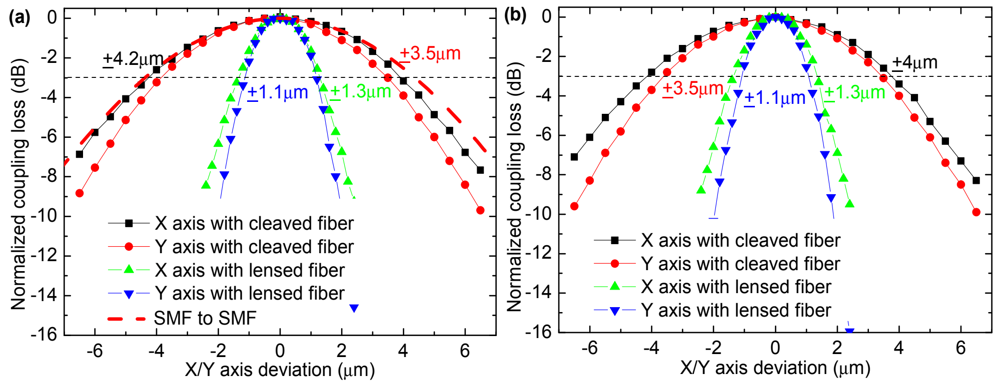


Fig. 8. Alignment tolerances of structure 5 and 6 in both X and Y axes at 1550 nm for (a) TE mode and (b) TM mode.

## 4. Coupling with Si waveguide

Similar structure can be used to couple with Si waveguide. As proof of concept, we used the masks for $Si_3N_4$ waveguide to fabricate the coupler on Si waveguide. The device was fabricated with similar process to that of $Si_3N_4$ waveguide just replacing Si wafer with SOI wafer. Limited by the layer structure of the SOI wafer, the center of the silicon layer cannot overlap with the center of the SiON waveguide as the image shown in Fig. 9(a) and the thickness of the oxide $H_c$ is 7 μm.

For $Si_3N_4$ waveguide, 200nm-wide tip is enough to expand the mode. While for Si waveguide, a tip with width between 120nm to 180nm is needed to restrict the mode mismatching loss within 1 dB as shown in Fig. 9(b). For reducing the width of the Si tip, a trimming process was applied after the lithography of the Si waveguide and the tip width is reduced to 150 nm from 200 nm.

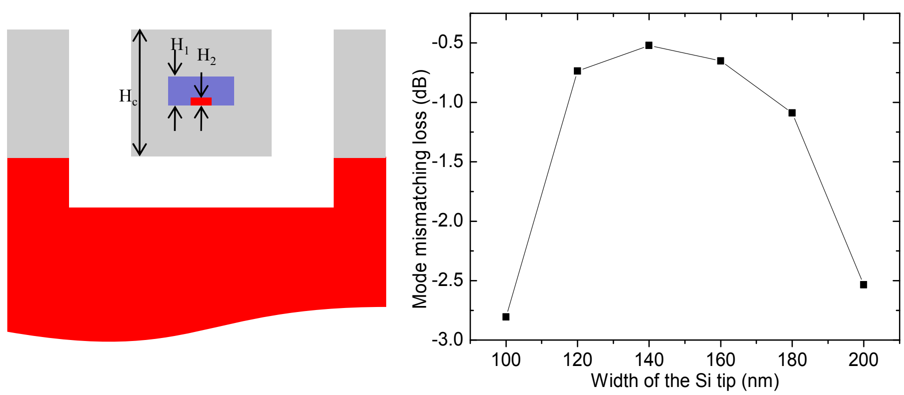


Fig. 9. (a) Cross section of the mode size converter on SOI wafer. (b) The mode mismatching loss of SiON waveguide with Si tip under different width.

The measured results are shown in Fig. 10. The coupling loss is about 1.8 and 2.1 dB/facet for TE and TM mode, a PDL smaller than 0.5 dB is realized. There is fluctuation in the spectrum especially under TE mode, which is due to the multi-mode effect in the waveguide since we used the mask of $Si_3N_4$ waveguide with width of 600 nm. The alignment tolerance is about 3.5 μm in X axis and 3 μm in Y axis for both TE and TM mode.

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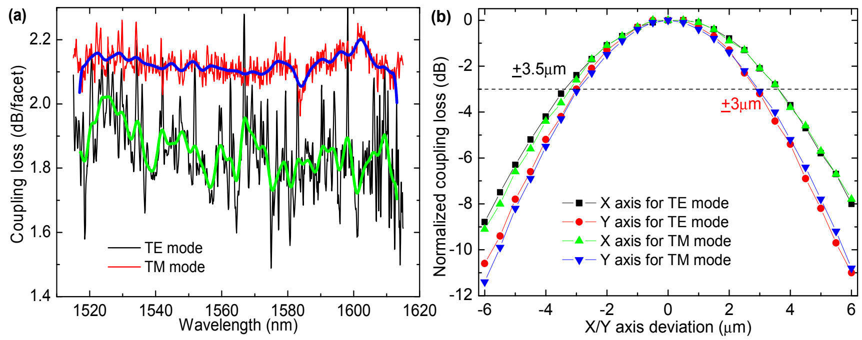


Fig. 10. (a) The measured coupling loss between Si waveguide and cleaved SMF in the C + L band with the designed mode size converter. (b) Alignment tolerance of the mode size converter in both X and Y axes at 1550 nm for TE mode and TM mode.

## 5. Summary and discussion

In summary, we proposed an efficient mode size converter based on intermediate material SiON for the coupling between cleaved SMF and HIC waveguide and embodied the structure on $Si_3N_4$ and Si waveguide separately. For $Si_3N_4$ waveguide with 200nm-wide tip, the coupling loss is about 1.2 and 1.4 dB/facet for TE and TM mode and the alignment tolerances exceed ± 3.5 μm in both X and Y axes. If the tip width can be reduced to below 100 nm, the coupling loss for both polarization states should be smaller than 1 dB/facet.

For Si waveguide with 150nm-wide tip, the coupling loss is about 1.8 and 2.1 dB/facet for TE and TM mode and the alignment tolerances exceed ± 3 μm. The coupling loss with Si waveguide can be further reduced with the following methods without pursing smaller tip: (1) with the double-taper structure in the silicon tip as shown in [7], the silicon mode can be expanded further; (2) with $Si_3N_4$ as second intermediate material, combination with the $Si_3N_4$ to SOI transition structure shown in [12], the coupling loss can be controlled within 2 dB/facet for both polarization states just with 200nm-wide tip. The relevant verification works are in process.