Improving coupling efficiency of fiber-waveguide coupling with a double-tip coupler

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Abstract: A double-tip coupler that comprises two inversely and laterally tapered waveguides is experimentally demonstrated for efficient light coupling between a fiber and a sub-micron silicon nitride waveguide. The coupling efficiency of the fabricated double-tip coupler can be improved by as much as over 2 dB per coupling facet, compared with that of a single-tip one with the same tip width of 180 nm. The effect of the gap width of the double tips on the coupling efficiency is studied both in experiment and simulation.

OCIS codes: (060.1810) Couplers; (060.2300) Fiber measurements; (220.0220) Optical design and fabrication.

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1. Introduction

In recent years, nano-photonic devices fabricated with complementary metal oxide semiconductor (CMOS)-compatible technology have become a choice for next-generation high-speed and high–volume communication and computation applications. Silicon nitride (SiN) material is a promising candidate for photonic integrated circuits, as it can be conveniently deposited with low-pressure chemical vapor deposition or plasma enhanced chemical vapor deposition (PECVD) and has good optical properties around 1550 nm. Its refractive index can vary from ~2.0 to 2.4. Thus, for a SiN waveguide enclosed in silicon dioxide, both the width and thickness of the waveguide can be in sub-micron scale for single-mode propagation. The propagation loss of a sub-micron SiN waveguide can be as low as 2-3 dB/cm and the bending loss is negligible when the bend radius is in several tens of microns. With the developments in nanofabrication and highly dense integration, photonic devices are made more compact. However, due to unavailability of a CMOS-compatibly integrated light source, an external light source has to be utilized for nano-photonic circuits. Commonly, a single-mode fiber (SMF) is employed to couple light from an external light source to a sub-micron waveguide. However, owing to the differences in size and refractive index, the modes output from a fiber and in a sub-micron waveguide mismatch. As a result, the coupling efficiency for the direct coupling between a fiber and a sub-micron waveguide is normally in tens of dB.

To solve the low coupling efficiency problem, researchers have proposed many structures. Generally, there are mainly two categories of coupling methods, the vertical coupling and the edge coupling. The vertical coupling is that the light is coupled to the waveguide through vertically incident or leaked light, and can be found in slanted gratings [1-3], vertically superimposed microring [4], parabolic reflector [5], metal layers [6], prism [7], and so on [8]. These structures can achieve high coupling efficiency and large alignment tolerance, but the broadband operation could be limited and the fabrication might be complicated. The edge coupling usually involves various spot-size converters [9-15]. Inversely tapered waveguides are commonly used due to their simple design, easy fabrication, broad transmission bandwidth, and high coupling efficiency. The coupling loss can be as low as 0.8 dB for a coupler with a 60 nm-wide silicon tip enclosed in a box of polymer cladding [9]. However, fabrication of such a narrow and long tip would pose a challenge to the current deep UV lithography systems. An inverse taper was fabricated with deep UV lithography and achieved a coupling efficiency of 1.9 dB. However, the coupler was realized with a silicon taper enclosed in a cladding box of benzocyclobutene and polymer [15]. Reference [11] reported a coupler that consisted of a vertically stepwise parabolic graded index profile combined with a lateral taper. The achieved coupling efficiency was also 1.9 dB. However, the reported sub-micron waveguide core is made of SixOyNz with index of 1.7 and the fabrication of the three-dimensionally varying taper is complicated. Researchers [16, 17] proposed to use combined multiple tapered waveguides to improve the coupling efficiency, but no experimental verification has been reported.

In this letter we experimentally demonstrate that a double-tip coupler, composed of two inversely and laterally tapered SiN waveguides, is more efficient for fiber-waveguide coupling than a single SiN taper, whereas the tapers have the same tip width of 180 nm. We study the impact of the gap between the two tapered waveguides on the coupling efficiency both in simulation and experiment. For comparison, an inversely and laterally tapered SiN waveguide, which is named as single-tip coupler, is also investigated.

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2. Design and fabrication

In our design of the double-tip coupler, two identical inversely and laterally tapered waveguides are arranged in parallel. When their width returns to normal, two S-bends combine the tapered waveguides into a single waveguide. Both the lengths of the tapered waveguides and the S-bends are 200 μm. The tip width is 180 nm. The thickness of the SiN layer is 400 nm, and the width of the waveguides is chosen as 700 nm or 400 nm. The gap between two tapered waveguides is varied from 500 nm to 900 nm. Actually, when the gap value is less than the waveguide width, parts of the double tapers and the S-bends are merged. A schematic drawing is shown in Fig. 1(a), which displays the top-view of a schematic double-tip coupler. The coupling facet of the double-tip coupler is shown in Fig. 1(b), where the two small squares are the tip facets of the inversely tapered SiN waveguides. The layers from bottom to top are silicon substrate, 5 μm buried silicon dioxide, 400 nm SiN core layer, and 3 μm silicon dioxide top cladding, respectively. It is worth mentioning that the top cladding is designed as uniform for fabrication convenience. With such a design, both the mode field size and the effective index of the double-tip coupler can be optimized to match the mode output from a lensed fiber by varying the gap between the two tips.

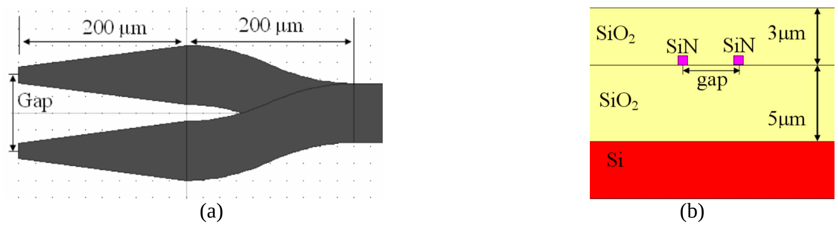

Fig. 1. (a). Top-view and (b) cross-section of a schematic double-tip coupler.

We started the fabrication on an 8-inch crystalline silicon wafer. 5 μm thick silicon dioxide with the refractive index of ~1.46 was deposited on the wafer with PECVD. Then, we deposited 400 nm SiN with PECVD. The refractive index of the SiN layer was measured as ~2.07. To decrease the SiN surface roughness, we applied the chemical mechanical polishing. After patterning with 248-nm lithography, the SiN layer was etched with inductively coupled plasma. Then, we cleaned the wafer with diluted HF and sulfuric acid-hydrogen peroxide mixture solutions. Finally, the wafer was clad with PECVD deposition of 3 μm silicon dioxide. The scanning electron microscope pictures of the fabricated double-tip, combined region of double-tip coupler, and single-tip without top cladding are shown in Figs. 2(a), 2(b), and 2(c), respectively. The diced samples were polished with diamond films for exposing and smoothing the coupling facets of the couplers.

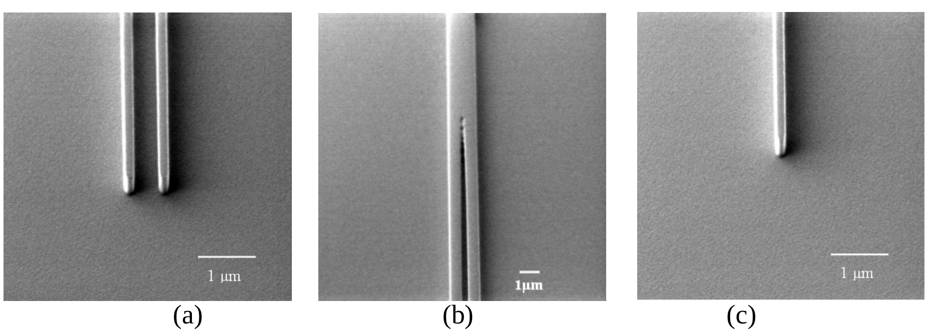

Fig. 2. (a). Double tips of a double-tip coupler; (b) the combined region of the double-tip coupler; (c) the tip of a single-tip coupler.

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3. Characterization and simulation

In the characterization, we measured the insertion losses of the devices at wavelength of 1550 nm. The insertion loss referred to the total loss from the laser source to the power meter. Firstly, we characterized the insertion loss of the setup as the reference loss. The setup consisted of a 1550 nm laser, a polarization controller, and a power meter, which were connected with polarization-maintaining fibers. Then we used lensed polarization-maintaining fibers (LPMFs) to align with the input and the output of the device under testing, respectively. The focus spot size of the LPMF was ~2.5 μm in diameter. We adjusted the polarization controller to choose a quasi-TE (the electric field parallel to the device substrate) or –TM (the electric field perpendicular to the device substrate) mode as the input light. Two types of devices were characterized: a double-tip coupler device that contained a 2200 μm-long straight waveguide and a 400 μm-long double-tip coupler at each end of the straight waveguide, and a single-tip coupler device that contained a 2600 μm-long straight waveguide and a 200 μm-long single-tip coupler at each end of the straight waveguide. The total length of each device is 3 mm. For the double-tip coupler devices with gap widths of 500 nm, 600 nm, 800nm, and 900nm, the measured insertion losses for the TE mode were 4.9 dB, 4.8 dB, 5.0 dB, and 5.1 dB, respectively. The measured insertion losses for the TM mode were 7.7 dB, 6.5 dB, 7.9 dB, and 8.0 dB, respectively. For a single-tip coupler device with the same tip width and waveguide width, the measured insertion losses were 7.0 dB for the TE mode and 9.4 dB for the TM mode, respectively. The waveguide width for these couplers was 700 nm.

We also characterized the propagation losses of the SiN waveguides with the cutback method. Eight clip-like waveguides with lengths from 6.8 mm to 24.3 mm were measured and the propagation loss was deduced by linearly fitting the insertion losses. The propagation losses were 2.5 dB/cm for the TE mode and 2.6 dB/cm for the TM mode, respectively. The lowest coupling loss was 2.0 dB/facet for the TE mode, achieved with a double-tip coupler with the gap width of 600 nm and the tip width of 180 nm. For the single-tip coupler device with the same tip width of 180 nm, the coupling loss was 3.1 dB/facet for the TE mode, which was 1.1 dB lower than that of the corresponding double-tip coupler. Obviously, the coupling efficiency can be increased significantly with a double-tip coupler. The whole double-tip coupler device that was integrated with double-tip couplers at the input and the output ends had totally 2.2 dB (TE) and 3.0 dB (TM) higher coupling efficiencies than the one with single-tip couplers. We also used a tunable laser and an optical spectrum analyzer to evaluate the spectrum responses of the devices. The scanning range was from 1510 nm to 1612 nm with the scanning step of 40 pm. The spectral responses of the double-tip coupler devices and the single-tip one are present in Fig. 3. It can be observed that there is a dip in ~1510 nm, due to the material absorbance. The curves from top to bottom are for the double-tip coupler devices with gap widths of 600 nm, 500 nm, 800 nm, and 900 nm, and for the single-tip coupler device, respectively. The fluctuations in the curves could be caused by the surface reflections of the devices and the perturbation of the measurement stage. The widening waveguide in the combined S-bend segment would induce multimode interference, which could also contribute to the fluctuation. We found that the double-tip coupler devices had lower polarization dependence loss (PDL) than the single-tip one. The measured PDL for the whole double-tip coupler device with a gap width of 600 nm was less than 1 dB in the whole scanning range. Furthermore, it can be observed from Fig. 3 that the spectral responses of the double-tip coupler devices are not deteriorated due to the use of double tips.

We have also fabricated double-tip and single-tip coupler devices with waveguide width of 400 nm on SiN material of refractive index ~2.33. All the other structure parameters remained. The measured spectral transmissions are present in Fig. 4, where the curves from top to bottom are for the double-tip coupler devices with gap widths of 600 nm, 500 nm, 900 nm, and 800 nm, and for the single-tip coupler device, respectively. The insertion losses in Fig. 4 are much higher than those in Fig. 3 due to the roughness of polished surfaces varying from sample to sample and higher propagation loss resulting from the narrower waveguide. As all the coupler devices displayed in Fig. 4 have the same length and propagation loss, we

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can deduce that the double-tip couplers have higher coupling efficiencies than the single-tip one. Compare the couplers with the tip width of 180 nm and waveguide width of 400 nm and we can find that the double-tip coupler achieves ~2 dB higher coupling efficiency per coupling facet. The total coupling efficiency for the whole double-tip coupler device increases ~4 dB in the broad band from 1510 nm to 1612 nm. Comparing Figs. 3 and 4 we can observe that both the double-tip couplers with the gap width of 600 nm have the highest coupling efficiency in the 102 nm-bandwidth.

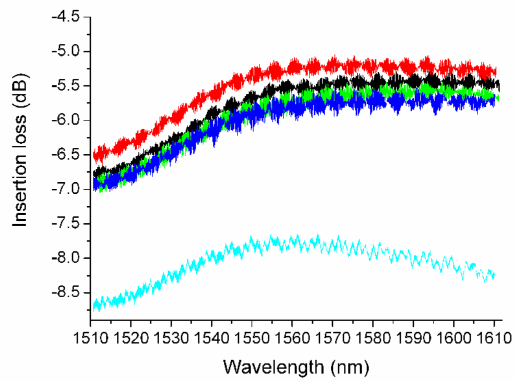

Fig. 3. (a). Transmission spectra (from top to bottom) for the double-tip couplers with gap widths of 600 nm, 500 nm, 800 nm, and 900 nm, and for the single-tip coupler, respectively. The waveguide width is 700 nm and the tip width is 180 nm.

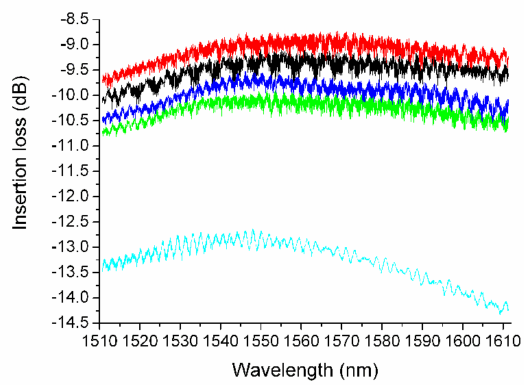

Fig. 4. Transmission spectra (from top to bottom) for the double-tip couplers with gap widths 600 nm, 500 nm, 900 nm, and 800 nm, and for the single-tip coupler, respectively. The waveguide width is 400 nm and the tip width is 180 nm.

We used a three-dimensional scalar beam propagation method to simulate the effect of the gap between the two tips on the coupling efficiency. The light was output from a fiber with diameter of 2.5 μm. We varied the gap width from 500 nm to 900 nm and calculated the corresponding coupling efficiency. The simulated coupling efficiencies for the double-tip couplers with waveguide widths of 700 nm and 400 nm and with varying gaps are shown in Fig. 5. For comparison, the coupling efficiencies of the single-tip couplers with waveguide widths of 700 nm and 400 nm are also present in Fig. 5. The wavelength in simulation was set as 1.55 μm. The width of all the tips was remained as 180 nm. In Fig. 5 the lines from top to bottom are for the double-tip coupler with the waveguide width of 700 nm, the single-tip coupler with the waveguide width of 700nm, the double-tip coupler with the waveguide width of 400 nm, and the single-tip coupler with the waveguide width of 400 nm, respectively. The coupling efficiency is governed by the mode mismatch loss and mode conversion loss. From

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Fig. 5 we can observe that the coupling efficiencies vary with gap widths and tip widths, as the double-tip couplers with different gap widths and tip widths have different mode fields and effective indexes. When the mode field and effective index of the double-tip coupler match with those of the coupling fiber and the length of the coupler is optimized, the mode mismatch loss and mode conversion loss would be minimized, as also simulated in [17].

It can be observed that the double-tip couplers have higher coupling efficiency than the corresponding single-tip ones; the coupling efficiency of the double-tip coupler varies with the gap width and reaches the highest at the gap width of ~600-700 nm; both the couplers with wider waveguide width have higher coupling efficiencies than the corresponding ones with narrower waveguide width. These observations are in good agreement with the measurement results. However, the improvements of coupling efficiencies with double-tip couplers in the simulations are not as significant as those in the experiments. The greater improvements of the coupling efficiencies achieved in the experiments could be due to the deteriorated coupling efficiencies of the single-tip couplers. The designed 180 nm-wide tips might become narrower in the lithography or etch process. For the light coupling between an LPMF and a sub-micron waveguide, we found both in the experiments and simulations that the coupling efficiencies of the single-tip couplers decreased nearly linearly as the nominal tip width decreased from 220 nm to 150 nm. On the contrary, in the simulations, the coupling efficiencies of the double-tip couplers decreased more slowly with narrower tips.

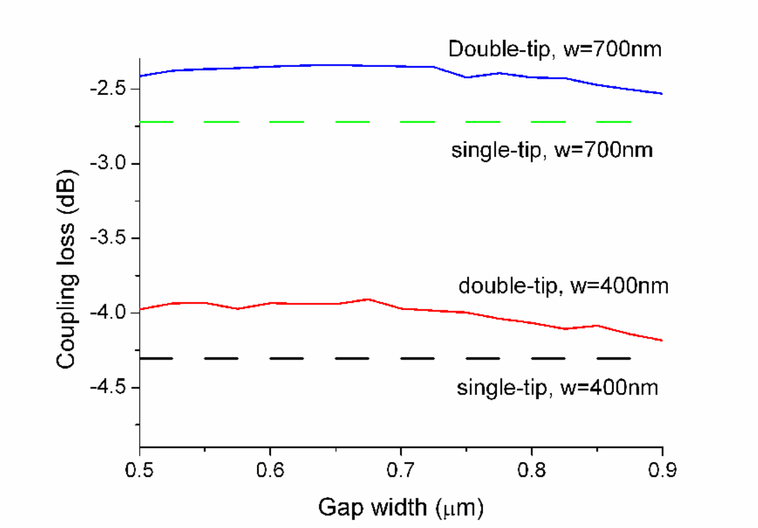

Fig. 5. Simulated coupling efficiencies for the double-tip couplers with varying gap widths (solid lines) and coupling efficiencies for the corresponding single-tip couplers (dashed lines).

4. Conclusion

In summary, optical couplers with double inversely and laterally tapered waveguides have been demonstrated for efficient fiber-waveguide coupling. The double-tip couplers are fabricated on CMOS-compatible SiN material. They can achieve over 2 dB higher coupling efficiency per coupling facet than a single-tip coupler with the same tip width of 180 nm. Fabrication of such couplers would be comfortable with the current lithography systems and the alignment between a double-tip coupler and an LPMF is also convenient. Furthermore, if one of the long and narrow tips of a double-tip coupler is broken or damaged, the other tip can still couple light effectively. The double-tip coupler may find important applications for constructing highly dense and efficient photonics integrated circuits.

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