Vertically-Curved Si Surface Optical Coupler for Coupling with Standard Single-Mode Optical Fibers

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Abstract:
A vertically-curved-waveguide surface optical coupler for coupling with a 10-µm-MFD standard single-mode optical fiber was developed. The fabricated coupler showed 1-dB bandwidths of >160 nm and >120 nm and coupling losses of 3.9 dB and 4.0 dB for TE and TM polarization.
OCIS codes: (130.3120) Integrated optics devices; (230.7370) Waveguides.

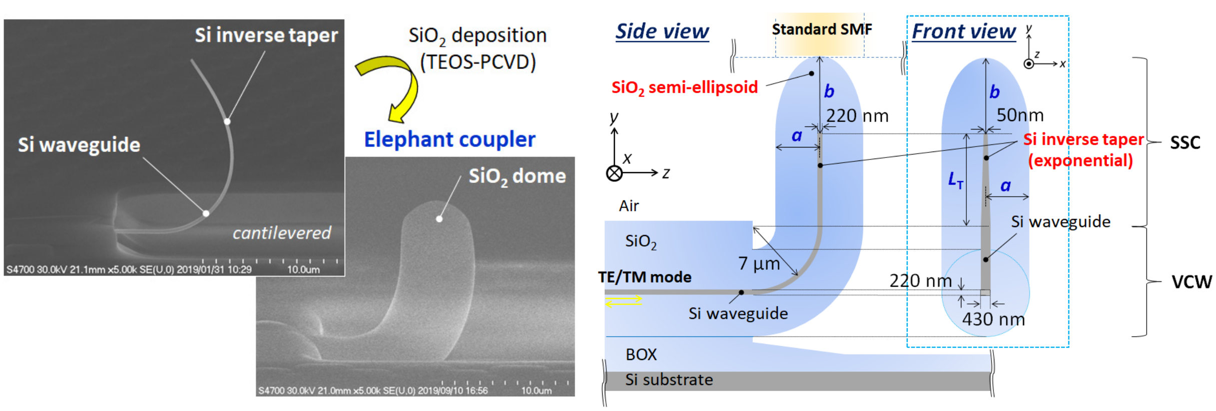
1. Introduction

Chip-surface optical coupling has advantages in wafer-level optical testing and high-density optical fiber assembly for Si photonics integrated circuits (Si-PICs). So far, grating couplers have been extensively developed as representative surface optical couplers. However, these devices have disadvantages in several coupling characteristics, such as coupling efficiency, spectral bandwidth, polarization sensitivity and incident angle sensitivity, because they utilize optical diffraction phenomenon to in/output the optical signal to/from chip surface.

As a different approach to realize surface optical coupling, we have proposed and developed a coupler based on a vertically-curved Si waveguide which is fabricated by ion-implantation into a cantilevered Si waveguide as shown in Fig. 1(a) [1-5]. This device achieves both high-efficiency and broad-band coupling because the propagation path itself is vertically curved. Moreover, the device can be realized in a small device size owing to its unique beam shaping approach where combination of drastic light divergence effect at a short Si inverse taper and light collimation effect at a SiO_2 dome are utilized. We have previously succeeded in demonstration of the coupler designed for coupling with a high-numerical-aperture single-mode optical fiber (HNA-SMF) with a mode-field diameter (MFD) of ~5 µm which is a promising candidate for datacenter interconnection due to its large fiber-bending allowance and good optical connectivity with standard SMFs. The fabricated device showed good polarization-insensitive coupling performance with a coupling loss of less than 2.5 dB and 0.5-dB-spectum-bandwidth of more than 130 nm [5].

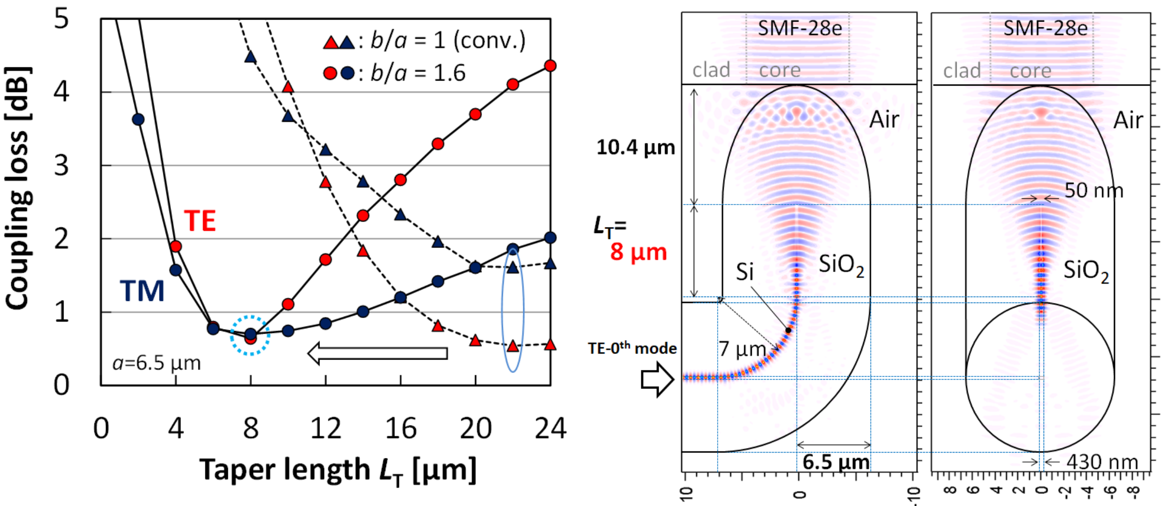
While assembly with HNA-SMFs has merits as noted above, assembly with SMFs with further large MFDs (e.g. 10-µm-MFD standard SMF and ~7-µm-MFD fiber) is also important. This is because optical coupling with the large MFD enhances the optical alignment tolerance, and that results in reduction of assembly cost of Si-PICs [6].

In this work, we designed and fabricated a coupler having a spot-size of 10 µm toward coupling with standard SMFs. In this device, a semi-ellipsoid SiO_2 coupler top was introduced to form a large spot-size beam effectively compared to the conventional semi-sphere coupler top. This effect leads to shortening of the Si taper and prevention of Si cantilever stiction onto the substrate during the fabrication. The fabricated device had a taper length of as short as 9 µm and showed almost polarization-insensitive coupling with the loss of less than 4.0 dB at a wavelength of 1550 nm and 1-dB spectrum bandwidth of more than 120 nm.



(a) (b)

Fig. 1 (a) SEM images of vertically curved Si waveguide before (upper left) and after (bottom right) SiO_2 deposition. (b) Calculation model of the coupler for coupling with standard SMF.



(a) (b)

Fig. 2 (a) 3D-FDTD-simulated coupling loss as a function of Si taper length for coupling with 10-µm-spot Gaussian beam. The half-width of SiO_2 semi-ellipsoid was fixed to be 6.5 µm (b) Electric-field profiles of the TE-fundamental-mode transmission in the coupler and butt-joint coupled SMF-28e.

2. Device design

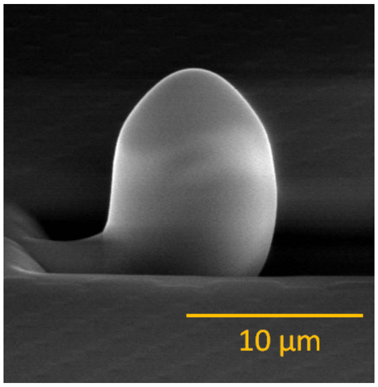
Figure 1(b) describes the schematic model of the device, where a 3D-FDTD simulation was applied. This device is composed of a vertical curved waveguide (VCW) part and a spot-size-conversion (SSC) part. In the VCW part, a 220 × 430 nm Si wire waveguide with a 7-µm-radius vertical bend is introduced to suppress the radiation losses for TE and TM modes. Then, in the SSC part, the width of Si waveguide exponentially narrows down from 430 nm to 50 nm using an inverse-tapered structure. The Si waveguide is entirely covered with a SiO_2 cladding, and the rounded coupler top acts as a collimation lens for the diverged light from the short Si inverse taper. In this work, to shorten the Si taper length, we introduced a semi-ellipsoid-shaped coupler top. Generally, the optical collimation effect becomes large by increasing the ratio for b/a, where a and b indicate half-width and half-length of ellipsoid, respectively.

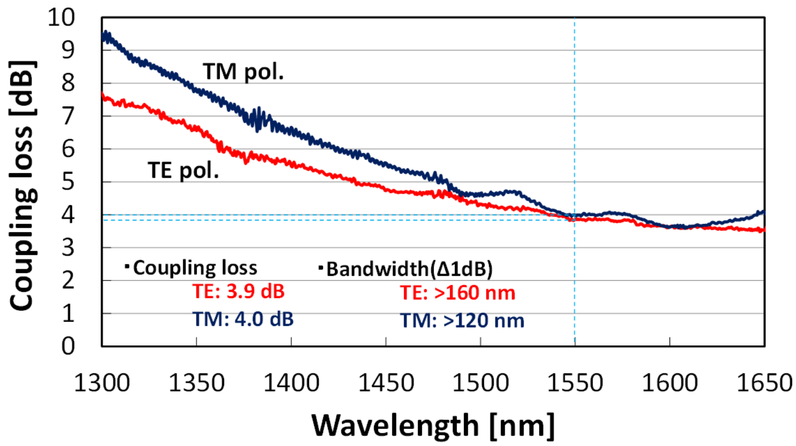
Figure 2(a) shows the taper length dependence of the coupling losses for coupling with TE- and TM-polarized 10-µm-spot Gaussian beam. The red and blue plots indicate the TE and TM polarizations, respectively. For the device with b/a of 1 (i.e. hemisphere shape), a minimum coupling loss was obtained when the taper length is 22 µm for both polarizations. However, such a long taper generates stiction of the cantilevered waveguide onto the substrate from our experience. On the other hand, for the device with b/a of 1.6, a minimum coupling losses of 0.6 dB for TE pol. and 0.8 dB for TM pol. were obtained when the taper length of as short as 8 µm. This taper length was comparable with that of the devices designed for HNA optical fiber coupling [3]. Therefore, compact, low-loss and polarization insensitive optical coupler was numerically obtained by introducing semi-ellipsoid coupler top.

Figure 2(b) shows the propagating electric-field profiles of the designed coupler. The TE-fundamental mode was input from left side. The light certainly changed the direction to the chip-surface along the curved Si waveguide, and it drastically enlarged the optical field by the inverse taper. Then, the arched waveform in the SiO_2 cladding was efficiently converted into flat waveform by the SiO_2 semi-ellipsoid coupler top. The output light coupled into a 10-µm-MFD SMF. We also confirmed the similar behavior for TM-fundamental mode propagation.

3. Fabrication and measurement

In this work, Si optical circuits was formed by ArF-immersion lithography using a 300-mm fab-line at AIST-SCR, and the fabrication process of this coupler was basically compliant to the previous work [5]. We realized a semi-ellipsoid SiO_2 coupler top by TEOS-PCVD under the condition of low temperature (80 °C) and high RF power after isotropic SiO_2 deposition to the vertically curved Si waveguide as shown in Fig.1 (a), where the rounded shape of coupler top was deformed in a sharpened shape due to the balance of the sputtering and depositing effects [7]. Figure 3(a) shows the SEM image of the fabricated device. A bullet-head-like SiO_2 coupler top with the full-width of about 9 µm was realized. The shape of the coupler top must be controlled by adjusting the process condition for these two-step SiO_2 deposition.





(a) (b)

Fig. 3 (a) SEM image of the fabricated coupler having a semi-ellipsoid SiO_2 coupler top. Si taper length was 9 µm. (b) Measured coupling spectra of the coupler device for TE and TM polarized lights via 10-µm spot optical fibers.

We measured the coupling characteristics of the fabricated device. The TE- and TM-polarized lights from SLD light source were coupled into the device using a 10-µm-spot graded-index(GI) tip-lensed optical fiber. Then the light was extracted from the other coupler in the same way after passing through a 4.5-mm-long connecting waveguides. Figure 3(b) shows the coupling spectra of the coupler device for both polarizations where the connecting waveguide loss was excluded. The coupling loss of 3.9 dB at a wavelength of 1550 nm and 1-dB-loss-bandwidth of over 160 nm were obtained for TE polarization. Also, the coupling loss and bandwidth for the TM-polarized light were 4.0 dB and >120 nm, respectively, and thus almost polarization-insensitive performance was obtained. Although the minimum coupling loss appeared in the long-wavelength side and loss was large compared to the simulated result, we consider that sophistication of the device structure (especially for coupler-top shape) will solve these issues. We also succeeded in fabrication of the polarization-insensitive 7-µm-spot coupler which showed minimum loss of 2.5 dB, and thus this approach is applicable to various MFDs of optical fibers.

4. Conclusion

We designed and fabricated a surface optical coupler based on a vertically curved Si waveguide for coupling with standard SMFs with a MFD of 10 µm. This coupler has a semi-ellipsoid SiO_2 coupler top which shows stronger optical collimation effect than the conventional hemisphere top. Such an effect leads to shortening of the Si taper and thus prevents from stiction of the cantilevered Si waveguide during the fabrication. We succeeded in forming the bullet-head -like coupler top using low-temperature TEOS-PCVD. The fabricated device with the taper length of 9 µm showed almost polarization-insensitive performance with coupling loss of <4.0 dB and 1-dB-spectrum-bandwidth of as wide as >120 nm. We also confirmed that the proposed beam-shaping technique was applicable to the optical fibers with various MFDs in a small device footprint.

Acknowledgements

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