Polarization-Insensitive Vertically Curved Si Surface Optical Coupler Bent by Ion Implantation

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***Abstract*— For input coupling from single-mode optical fibers to photoreceivers made with silicon photonics integrated circuits (Si-PICs), we constructed a polarization-insensitive optical surface coupler with a vertically curved silicon waveguide. The polarization insensitivity was attained by the equalization of the radiative transmission losses of TE and TM polarizations in the vertically curved waveguide (VCW) structure while keeping the straight structure of the spot-size converter (SSC) connected above the curved structure. Numerical simulations revealed that the radius of curvature of 6 μm or larger nearly enabled the equalization, and thus we developed a bending technology using ion implantation to realize simultaneously a VCW radius of curvature of 6 μm and a straight SSC of length 7 μm by varying the implantation angles. The bent silicon core was subsequently coated with SiO_2 by plasma-enhanced chemical vapor deposition to function as a collimation lens. The coupling properties of the fabricated coupler and the single-mode fiber with a mode-field diameter of 5 μm exhibited a polarization dependence loss of less than 0.25 dB, a 1-dB bandwidth of 180 nm, and coupling losses of about 1.6 dB at 1550 nm wavelength. A sharp inversely tapered Si waveguide that affects these characteristics significantly can be formed by applying ArF-immersion lithography on the 45-nm-node and hence fabrication is compatible with mass production processes.**

***Index Terms*— Ion implantation, optical surface coupler, opto-electronic device, silicon photonics.**

I. Introduction

INTENSE polarization sensitivity is an almost unavoidable attribute found in silicon photonics integrated circuits (Si-PICs). The architecture of today's Si-PIC device technology is based on it. This sensitivity is acceptable for the optical transmitter where a specific polarization is used for signal processing through outputs to the single-mode optical fibers (SMFs). However, a serious problem for optical receivers is the randomly mixed polarized light input to a Si-PIC via the SMFs. The input light must be treated by applying various methods, using polarization diversity technologies and depending on the data transmission systems employed. For most purposes, optical couplers that couple to SMFs of a Si-PIC are desired to be polarization-insensitive. For this reason, various approaches have been tried to achieve polarization-insensitive couplers [1], [2].

The optical couplers are categorized as either chip-edge couplers or chip-surface couplers. Using adiabatic spot-size converters (SSCs), edge couplers have low polarization dependence loss (PDL) over a broad wavelength range [3], [4]. Owing to the diffraction principle, grating couplers (GCs), which are representative of chip-surface optical couplers, show strong polarization sensitivity over a limited bandwidth. A polarization splitting grating coupler (PSGC), which couples each polarization to different paths, provides a completely polarization-insensitive operation derived from its geometric symmetry but suffers a loss in coupling at the same time [5]–[7].

When properties other than PDL are compared between edge couplers and surface couplers, the surface couplers are superior to the latter in regard to the availability of wafer-level testing and the feasibility of implementing a planar arrangement of multiple fiber cores, including multicore fibers. In addition, surface couplers can provide an input/output port at any location on the chip surface. However, the GC has a strong wavelength dependence, which constrains bandwidth.

The elephant coupler is a surface coupler based on a vertically curved Si waveguide (VCW) fabricated by the ion implantation bending (IIB) method. Compared with GCs, the elephant coupler has an inverse-tapered SSC at the top, with a lens-shaped SiO_2 dome, and has advantages of low coupling loss, broadband coupling, and flexibility in beam direction. [8]–[10] Recently, we have reported on a coupler with a beam-spot size of 5 μm for coupling with high numerical aperture single-mode fibers (HNA-SMFs). The device fabricated using electron-beam (EB) lithography demonstrated broadband coupling operations with coupling losses of 2.4 dB at a wavelength of 1550 nm and a 0.5-dB spectrum bandwidth of more than 220 nm with TE-polarization light. [11]–[13] However, in this demonstration, the minimum coupling loss of the TM polarization was 1 dB larger than that of the TE polarization. Reducing the PDL as much as possible remains an important problem.

In this work, we addressed this problem in the following manner: (1) Elucidating the cause of the PDL and through a 3D-FDTD simulation investigating the device structure to reduce it. The radiation loss of the TM polarization in the bent structure of the Si waveguides is known to be more sensitive to the bending radius than that for TE polarization because of a weak optical confinement in the waveguide. Therefore, we conducted simulations to reduce the radiation loss by

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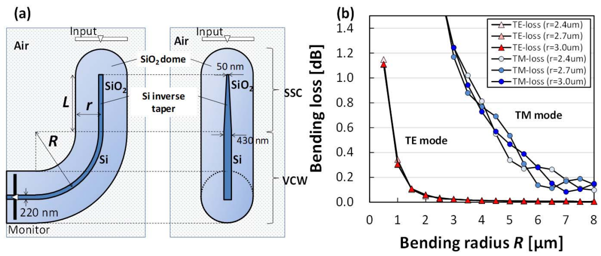

Fig. 1. (a)Schematic views of the elephant coupler. (b)Calculated bending loss as a function of bending radius at a wavelength of 1550 nm.

adjusting the bending radius. (2) Improving the fabrication process to achieve an optimized design structure. The simulation results show that the radius of curvature of the VCW should be more than 7 μm, but the previous IIB method was unable to straighten the SSC structure at the tip at the same time. To overcome this problem, the IIB method was improved by adding a new process in which the implantation angle was varied.

We used ArF-immersion lithography to pattern the Si waveguide instead of EB lithography used in the previous work to confirm whether the designed elephant couplers can be fabricated using commercially available mass production technology. The fabricated device showed a minimum coupling loss of 1.4 dB and a 1-dB-bandwidth of more than 180 nm with a PDL of less than 0.25 dB.

Previous to this work, we presented at a conference results reporting high-efficiency optical coupling with 2.3 dB minimum coupling loss and a 1-dB-bandwidth of more than 150 nm, with low polarization dependence produced by increasing the radius of curvature of the VCW section of the elephant coupler. [14] In this paper, we provide further details of the design and fabrication of the device, and moreover, report an improved result obtained after the conference.

II. Device Design

The elephant coupler is composed of two sections: a VCW and an SSC [Fig. 1(a)] [11]. The VCW section bends light through a right angle towards the surface of a chip, and the SSC enlarges the optical profile of the Si waveguide to match that of the optical fiber.

Some of the coupling loss of the TM mode results from bending losses from the VCW. This is because, whereas the waveguide width is changeable using a tapered structure, the waveguide is often fixed at thickness as small as 220 nm, which is conventional in Si-photonic device research. This small thickness makes the confinement of TM-polarized light in the Si core more difficult and often generates large bending losses.

Generally, the bending loss can be suppressed by adopting a large bending radius. We evaluated the bending loss of the vertical curved waveguide using the 3D-FDTD method by calculating the overlap integral of light just after the vertical bend for various light inputs of both TE and TM fundamental modes [Fig. 1(b)]. The waveguide width and height are 430 and 220 nm, respectively, and the SiO_2 thickness surrounding the Si waveguide was set at 2.4, 2.7, and 3.0 μm as determined in previous work [11]. With a larger bending radius, the bending losses for both polarization modes diminished. Fluctuations were observed for the TM mode, which may be due to multi-mode excitations in the air-cladded Si/SiO_2 hybrid waveguide. We obtained a relatively suppressed loss of about 0.2 dB for the TM mode with bending radii larger than about 7 μm. From the viewpoint of fabrication reliability, the bending radius should be as small as possible because, before the IIB process, with a larger bending radius, the Si cantilever is longer. The loss for the TE mode is negligible compared with that for the TM mode because its optical confinement in the Si core is strong.

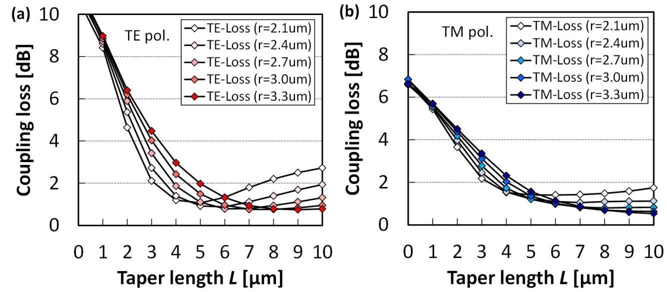

Fig. 2. Taper length dependence of coupling loss of the SSC section for various SiO_2 thicknesses: (a) TE and (b) TM modes.

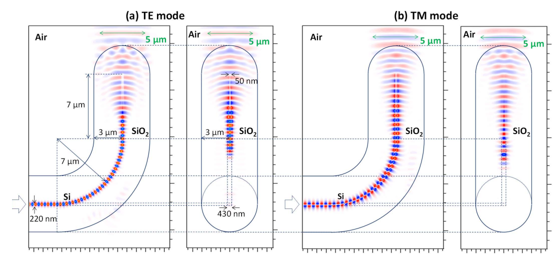

Fig. 3. Electric-field profiles of the designed 5-μm-spot optical coupler for (a) TE and (b) TM-mode polarization.

Next, the characteristics of the SSC were evaluated. In achieving its high-efficiency spot-size conversion from a small footprint, the elephant coupler employs a combination of quite a short Si inversed taper and a dome-like SiO_2 coupler top. For this approach, the former radiates the light that propagates in the Si waveguide, whereas the latter pseud-collimates the radiating light using the lens effect to match the optical profile of the optical fiber. Therefore, the coupling loss depends on both the taper length and the SiO_2 thickness surrounding the Si core. The coupling loss for a 5-μm-spot Gaussian beam as a function of taper length was evaluated for various SiO_2 thicknesses (Fig. 2). These results do not include the loss of the VCW section. The SSC dimensions with minimum losses for the TE and TM modes are independent because of its non-adiabatic mode-conversion mechanism. We designed a polarization-insensitive SSC structure based on the results of both polarization modes [Fig. 2(a) and (b)]. Setting the SiO_2 radius and taper length to 3.0 μm and 7 μm, respectively, the losses for both modes are small at nearly 0.8 dB.

Given these settings for the SiO_2 radius and taper length, the electric field profiles of the coupler were generated (Fig. 3). The bending radius was set to 7 μm [Fig. 1(b)]. We confirmed that light propagating in the optical circuits was bent towards the chip surface along the vertical segment, and the light output of both polarizations was almost collimated with a beam-waist of about 5 μm.

III. Device Fabrication

We first outline the elephant coupler fabrication procedure, which involves: (a) using the AIST-SCR line to pattern

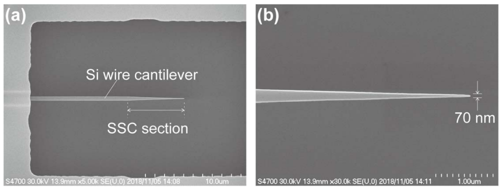

Fig. 4. Typical SEM images of the Si wire cantilever: (a) after formation, (b) closeup view of the tip.

silicon waveguides by ArF-immersion lithography with an inverse-tapered shape for the SSC section on a 300-mm SOI wafer, and by plasma-enhanced chemical vapor deposition (PE-CVD) using tetra-ethyl-ortho-silicate (TEOS) depositing a SiO_2 cladding layer with a thickness of about 1 μm on the silicon waveguide. The wafer is then diced into 20-mm-square chips for fabrication of the elephant coupler using the laboratory line. (b) The terminal of the silicon waveguide, including the inversed taper, is cantilevered using a wet-etching process. (c) The cantilever structure is bombarded by ions thereby bending the silicon waveguide terminal. (d) Using PE-CVD, a SiO_2 cladding is deposited on the three-dimensionally curved silicon waveguide to complete the elephant coupler.

To fabricate the inverse-tapered tip end in the designed SSC section, high precision patterning of ~50 nm is necessary. In our previous studies, [12], [13] we achieved this patterning using EB lithography; however, it is not compatible with mass production processes. In this work, we used ArF-immersion lithography of the 45-nm-node AIST-SCR line to form the Si waveguide, including the SSC section, to confirm whether the designed elephant couplers can be fabricated by commercially available mass production technology. For this node, the finest pattern size is close to optical-resolution limits. We designed a tip end width of 70 nm using a binary mask. Viewing images of the formed shape of the inverse taper of the SSC section (Fig. 4), the Si wire cantilever has a smooth exponentially inverse-tapered shape narrowing from 430 nm to 70 nm, confirming that we had fabricated such structures without advanced lithography such as multiple-patterning.

Next, we describe the development of the advanced IIB process. In our designed device, the straight SSC section is connected to the VCW section with a larger bending radius. The formation of this shape is impossible with the original IIB method, where we irradiate ion-beam only from the vertical direction. The only way to form a straight SSC section is to increase the ion dose, which only reduces the radius of curvature of the VCW section, and only forms a wavy shape [15]. To overcome this difficulty, we introduced the IIB process with tilted ion-beam implantation. By changing the angle of incidence of the ions, we were able to control separately the formation of the straight SSC section and an extension of the radius of curvature of the VCW section. (This tilted-angle ion implantation is a standard method in extending doping of a fin field-effect transistor.) [16] Figure 5(a) shows an SEM image of a silicon VCW after the modified IIB process. Although it is slightly smaller than the ideal design value, we constructed a VCW section with a radius of curvature of about 6 μm, and an SSC section that was almost straight. Because the shape of the VCW section is deformed through stress generation and relaxation during PE-CVD using TEOS, the IIB conditions were adjusted so that the desired shape is obtained after the next PE-CVD of SiO_2. To obtain high-device fabrication uniformity and reproducibility for the VCW, we used the high-accuracy IIB requiring a metal mask that partially shields ions during implantation [17]. This method would be integrated into the Si-PICs including the electrical wiring layers.

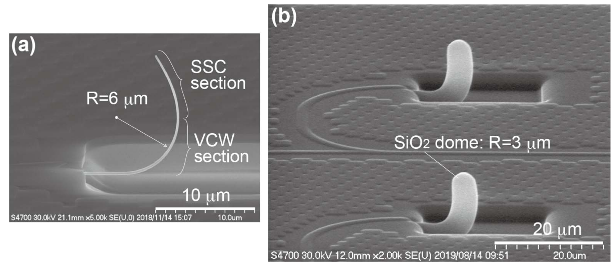

Fig. 5. Typical SEM images during fabrication of the elephant coupler: (a) after the IIB process, (b) after the PE-CVD.

Finally, we describe the SiO_2 cladding process with PE-CVD over the VCW section. The PE-CVD process is crucial in shaping the lens to collimate the light, and not solely for cladding the VCW section. The SiO_2 on the needle-like VCW tip end forms a nearly hemispherical SiO_2 dome as a result of the conformal SiO_2-deposition, and the radius of SiO_2 dome is controlled by SiO_2 deposition thickness. [Fig. 5(b)]. Fig. 5(b) indicates a pair of neighboring couplers with the same design parameters. As mentioned before, we adjusted the IIB conditions to ensure the desired shape is formed after the PE-CVD because stress generation and relaxation during SiO_2 deposition deforms the VCW. The SiO_2 radius, the taper length, and the bending radius of the fabricated elephant coupler are about 3.0 μm, 5 μm, and 6 μm, respectively. These values were slightly different from the design values. To realize the design values, further optimization of the IIB recipe is necessary.

IV. MEASUREMENT

We measured the coupling characteristics of the fabricated elephant coupler using a vertically accessed tip-lensed SMF and a polarization-maintaining fiber (PMF). Both the SMF and PMF have a spot-size of about 5 μm. The test waveguide was composed of two elephant couplers connected by a 5-mm-long Si waveguide. In this measurement, we vertically accessed the incident side PMF closest to one of the pair of elephant couplers to couple the inputted light. The emission side SMF was then vertically approached to the other of the pair to couple to the emitted light. We used a broadband TE- and TM-polarization light from a superluminescent diode (SLD) light source. Each fiber was aligned by detecting the peak output power using an optical power meter. The coupling loss was measured next, using an optical spectrum analyzer. We also measured the loss spectrum per unit length of the Si waveguide employing the cutback method.

With an elephant coupler having a VCW section of about 6-μm-radius and a 5-μm-length SSC section, loss spectra (Fig. 5) were obtained for wavelengths between 1350 nm and 1650 nm from the SLD light source. The values given were derived from the measured spectra minus the loss spectra of the 5-mm-long Si wire waveguide. The difference in coupling loss between TE- and TM-polarization modes was less than 0.25 dB over a wide wavelength range. Both coupling losses for the two modes were about 1.6 dB at 1550 nm. Minimum coupling losses were about 1.4 dB and 1.6 dB. The 1-dB bandwidths with the 0.25 dB PDL were about 180 nm. The polarization dependence and wavelength dependence of

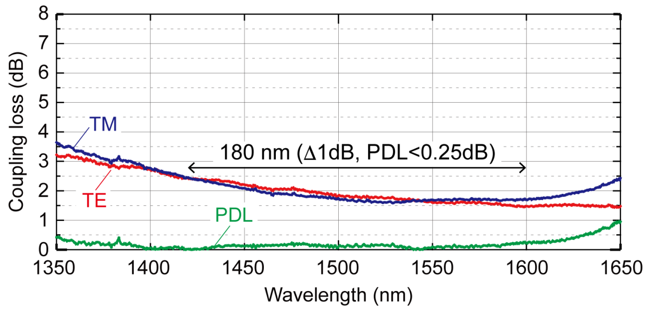

Fig. 6. Coupling spectra for TE and TM polarized light.

the observed spectra were sufficiently smaller than those of previously reported GCs.

The coupling loss (Fig. 6) includes the ion implantation loss. Previously, we reported that the annealing treatment reduces the ion implantation loss caused by the IIB process [10]. According to our estimation, we expect a loss reduction of about 0.5 dB by annealing.

V. Discussion

The small difference in coupling loss between the TE- and TM-polarization modes (Fig. 6) indicates that the elephant coupler has exhibited a polarization-insensitive optical performance. This result is promising for use in optical receivers. The coupling bandwidth of the elephant coupler is superior to any PSGC. [2] The 1.0-dB-loss bandwidth of a PSGC using the bottom mirror is 38 nm. [6] The 180 nm wavelength window of the fabricated elephant coupler is particularly suitable for wavelength division multiplexing (WDM) applications. Moreover, coarse-WDM (CWDM) applications using Si photonics are possible with this surface coupling method. The 180 nm wavelength window corresponds to nine wavelengths in CWDM spaced 20 nm apart. This wavelength window is also obtainable using edge couplers, but the availability of wafer-level testing using the elephant coupler will be of great benefit to silicon photonics manufacturing.

Spatial-division multiplexing (SDM) using multicore fibers (MCF) is another attractive technology that increases the bandwidth of optical interconnects. Surface couplers are superior to edge couplers in attaching MCFs to Si-PICs. For elephant couplers, MCFs can be securely attached perpendicularly. We expect that in the future, elephant couplers will become strategically important optical couplers to function as broadband optical interconnects, combining both SDM and CWDM techniques.

In this work, we used the lensed fibers for the measurements because they are useful for test probing purposes without any physical contact with working distances of approximately 25 μm. When fibers are fixed in the packaging assembly, HNA fibers instead of lensed fibers would be cost-effective. We have already demonstrated a method to put a facet of an HNA fiber just above the top of elephant coupler with a precise and robust fixing durable at temperatures from -18.5 to 90 °C using spacer beads mixed in a UV adhesive. This assembly method can protect elephant couplers from external physical damages. [18].

VI. Conclusion

We developed a polarization-insensitive elephant coupler suitable for optical receiver applications. A PDL of less than 0.25 dB was obtained over a 180-nm bandwidth. The minimum coupling losses were about 1.4 dB (TE) and 1.6 dB (TM), and the 1-dB bandwidth with the 0.25-dB PDL was about 180 nm. Furthermore, the obtained broad coupling spectra show that elephant couplers have high potential as an optical coupler for CWDM. In addition, because the elephant coupler is of surface type, it facilitates the attachment of MCFs, contributing to a broader bandwidth for optical interconnects that combine SDM and CWDM techniques.

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