Vertical Optical Fiber Assembly on Silicon Photonic Chips Using 3D-Curved Silicon Waveguide Couplers

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Abstract:
Using UV adhesive mixed with glass spacer beads, vertical surface connection of optical fibers to silicon photonic chips via elephant couplers was realized with wavelength and polarization insensitiveness at temperatures from -18.5°C to 90°C.
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1. Introduction

In silicon photonics surface fiber coupling is attractive both for wafer-level testing and fiber assembly. Thus grating surface couplers have been extensively used. However, grating couplers have disadvantages such as strong wavelength dependence, polarization dependence, and slightly inclined coupling angle.

Recently we developed a new type of surface coupler consisting of a vertically-curved silicon waveguide as illustrated in Fig. 1, using ion implantation as a bending method, and called it "*elephant coupler*."[1-3] Elephant coupler enables bending of propagation direction of light to the perpendicular surface direction thanks to the strong confinement of light in the silicon waveguides. In addition, we have developed a method of attaching spot size conversion (SSC) structures at the top of the elephant couplers with inverse-tapered waveguide tip and lens-shaped SiO_2 dome [4-7], as shown in Fig. 2. By appropriate design this SSC can realize broadband spectral window and completely perpendicular coupling, which are difficult to be realized by grating couplers. Recently coupling of < 2.5 dB loss with small polarization dependence was attained for lens-tip optical fibers with 5 µm mode field diameter (MFD).[8] This polarization insensitive result demonstrates a promising potential of the elephant couplers for photoreceiver use.

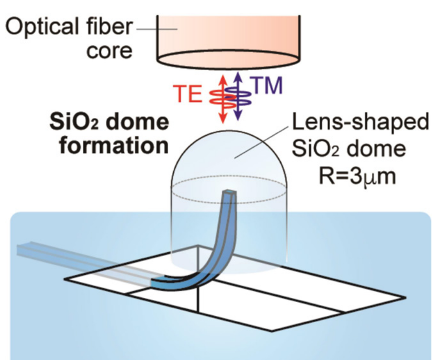

Fig. 1 Schematic illustration of an elephant coupler. Size is deformed.

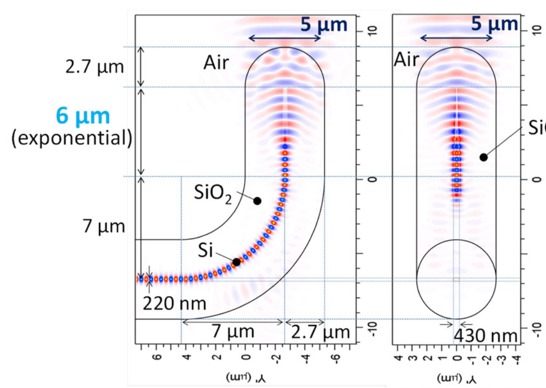

Fig. 2 Propagation profile of optical field simulated by 3D-FDTD.

In practical applications using elephant couplers, firm fixing technology of optical fibers to the elephant couplers with highly accurate position alignment for single mode coupling is crucially necessary. Wide temperature range operation is also expected for many applications. In this work we report an assembly method of high numerical aperture (HNA) optical fibers with a MFD of 5µm to the elephant couplers. As shown in Fig. 2, because quasi-Gaussian beam waist is formed just above the top of the elephant coupler, best assembly position of the fiber edge will be just above the top of the elephant coupler. However, because the elephant couplers protrude from the chip surface with a height of ~ 10 µm, simple butt joint assembly of optical fibers to the chip surface destroys the elephant couplers. Thus, optical fibers have to be fixed ~ 10 µm apart from the chip surface. Moreover, the elephant coupler must not be buried in optical adhesives but in the air in order for the SiO_2 dome to work as lens. We demonstrate our solution that meets these requirements with a simple loop-back fiber assembly for a straight silicon waveguide. We also demonstrate that the assembly method enables wavelength and polarization insensitive operation at temperatures from -20 °C to 90 °C.

2. Assembly method of optical fibers with elephant couplers

We adopted a scheme shown in Fig. 3. Utilization of UV adhesive mixed with glass spacer beads is a basic idea. To UV cure the adhesive, fiber ferrule has to be transparent in UV region. Thus we used glass as the ferrule material. We applied this adhesive only on the peripheral region of the polished flat surface of the fiber ferrule capillaries (Fig. 3(a)). The top of the elephant coupler is in a dome-like form shown in Fig. 2 with a function of collimation lens using the difference of refractive indices between silica and air. Therefore, the space over the dome has to be filled with the air but not the adhesive.

With 6-axis position controller we moved the fiber ferrule down onto the chip surface till landing (Fig. 3(b-c)). The spacer beads kept the distance between the fiber edge and chip surface slightly larger than the height of elephant coupler. We used glass spacer beads with a diameter of 10 μm (CV of 2.5%). These beads are commercial products for liquid crystal displays, and thus very high quality products are available with a diameter step by 0.1 μm. The coupling alignment tolerance of the distance between the fiber edge and the top of elephant coupler is within several microns if MFD is larger than 5 μm. This value is much larger than the manufacturing tolerance of the diameter of the beads, and thus such spacer beads satisfies the fiber alignment requirement in height.

Then the position of the landed fiber ferrule was adjusted along the chip surface (Fig. 3(c)). Active alignment was done by monitoring the transmitted optical power. At the best position, UV light was irradiated to cure the adhesive and the fiber ferrule was fixed on the silicon photonic chip. Because the spacer beads roll along the chip surface, very smooth alignment movement was possible. The transmitted optical power was almost identical before, during and after the UV irradiation. This means that the UV cure process that accompanies small volume shrinkage of the adhesive was well balanced within the coupling alignment tolerance (typically, ~ ± 0.5 μm in surface direction and ~ ± 2 μm for 5 μm MFD).

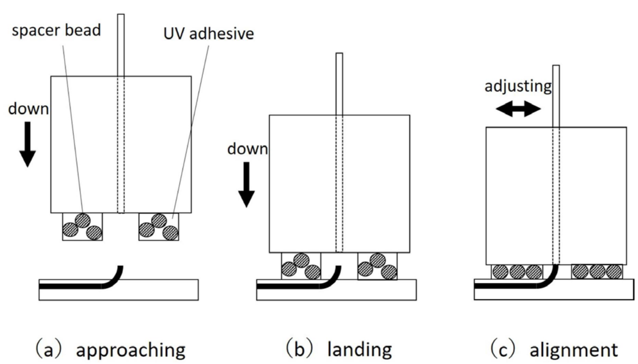

Fig. 3 Assembly scheme of an optical fiber over an elephant coupler. The figure is not in an actual size ratio.

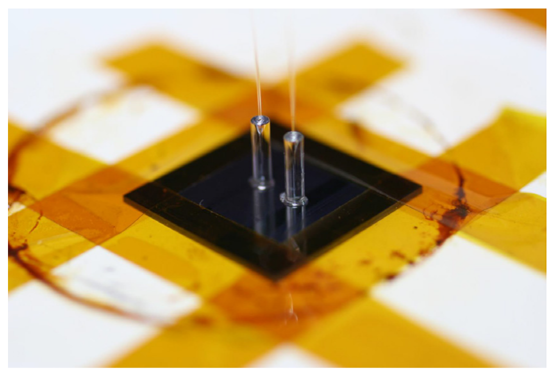

Fig. 4 Loop-back module of a straight silicon waveguide connected with two fibers vertically. Silicon chip is fixed onto a hot plate surface with polyimide tape.

3. Coupling properties

With the above-mentioned assembly method, we fabricated a simple loop-back module shown in Fig. 4. First, we fabricated a straight silicon waveguide with a length of 4.5 mm with its both terminals processed to elephant couplers with a target MFD of 5 μm. The fabrication process including ArF-immersion lithography of AIST Super Clean Room (SCR) was the same as that reported previously.[8] Before fiber assembly, transmission loss properties of this device were measured using a pair of lens-tip optical fibers with a MFD of 5 μm mounted on 6-axis stages. For device test measurements lens-tip fibers are convenient because their beam waist positions are apart from the fiber tips by the working distance (~ 25μm for a MFD of 5 μm) and thus non-contact measurement is possible with fine alignment accuracy. One lens-tip fiber was PMF and the other was SMF. From the PMF side, measurement light was input to the silicon device and the transmitted light was coupled-out to the SMF side. Since silicon photonic devices usually have strong polarization dependence, the utilization of PM fibers is necessary for the entrance coupling for test purpose. Figure 5 shows whole transmission loss spectra of a device used in the following fiber assembly. The loss includes coupling loss between elephant couplers and fibers and transmission loss of the silicon waveguide (1.0 dB/cm for TE-like mode and 1.6 dB/cm for TM-like mode at 1550 nm). The loss spectra showed wavelength and polarization insensitiveness.

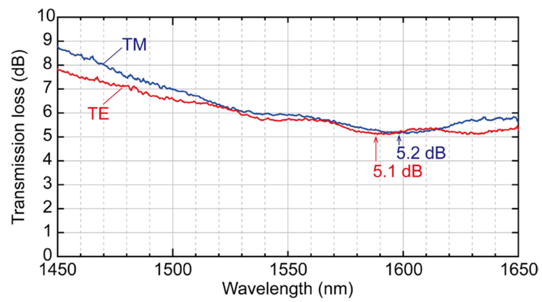

Fig. 5 Whole transmission loss of the silicon waveguide coupled with lens-tip PMF and SMF.

Using the method described in section 2 we assembled the loop-back module shown in Fig. 4 with the silicon device, PMF and SMF. For entrance coupling lens-tip PMF with a MFD of 5 µm was inserted and fixed in glass ferrule capillaries with its tip position ~ 25µm back from the ferrule edge in order for the beam waist to locate at the ferrule edge. For exit coupling HNA SMF with a MFD of 5 µm was inserted and fixed in a glass ferrule capillary with its edge flat-polished. The HNA SMF was TEC-fusion-spliced to standard SMF. The assembled module was fixed onto a hot plate surface with polyimide tape, as shown in Fig. 4. The temperature of the hot plate was raised from room temperature to 90 °C, which was the withstanding temperature of the UV adhesive used in this work. The sample kept stable standing at 90 °C. Figure 6 shows the whole transmission loss. Compared to Fig. 5, 2-3 dB excess loss was observed by the fiber assembly. With increasing temperature the loss increased but its wavelength and polarization insensitive nature remained. When temperature returned to room temperature, the loss became identical to the loss before raising temperature. The loss at -18.5 °C showed almost identical properties to those at room temperature.

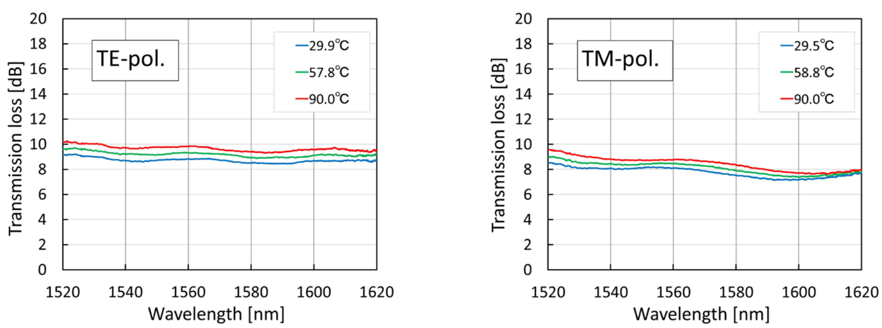

Fig. 6. Temperature dependence of the whole transmission loss of the loop-back module.

4. Conclusion

The assembly method using UV adhesive mixed with glass spacer beads was successful for vertical surface connection of optical fibers to silicon photonic chips via elephant couplers. In this assembly we confirmed that accurate alignment was possible between the fiber cores and the elephant couplers. The demonstrated insensitiveness of the transmission loss in wavelength and polarization in temperature range from -18.5 °C to 90 °C will be useful in a lot of applications.

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