Silicon photonics packaging with lateral fiber coupling to apodized grating coupler embedded circuit

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Abstract: We report a novel lateral packaging approach using laser welding technique with angle polished fiber coupling to grating coupler embedded silicon photonic circuit. Measurements show the relax alignment tolerance for fiber packaging process. The packaging excess loss of 1.2 dB is achieved. The use of angle polished fiber for lateral fiber coupling enables an alternative way for cost-effective deployment of silicon photonics packaging in telecommunication systems.

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1. Introduction

With the increasing popularity of internet access, high-definition TV broadcast, 3D displays, and peer-to-peer file sharing, the demand for significantly higher data rates grows. Advanced solutions for high transmission capacity are therefore required, which eventually can only be provided by integrated photonics. Silicon photonics is a rapidly advancing field with a strong potential for realistic dense photonic integrated circuit (PIC) [1] in various applications with the support of mature CMOS-compatible fabrication processes.

In order to realize practical applications of silicon photonics device, the circuits must be packaged with optical single-mode fibers coupling. Although efficient coupling between the optical fiber and the submicron-sized waveguide is a key challenge due to the large modal mismatch, recent inspiring developments have shown that significantly improved coupling efficiencies using grating couplers [2–11] or adiabatic tapers and polished facets [12] is possible. Two strategies have been followed: (1) lateral coupling using mode size converter [12] and (2) vertical coupling using grating coupler [2–11]. Lateral coupling is compatible with standard planar design but requires extremely accurate alignment. Vertical coupling provides larger alignment tolerance but normally obstructs a large part of device surface, which limits further component integration. Vertical coupling may be less favorable than edge coupling given that it does not free the top surface for electrical and thermal connections and active device. Recently, lateral coupling to waveguide grating coupler with angle polished fiber has been proposed [13, 14] as an alternative to overcome the above disadvantages. The angle end facet of fibers that are placed laterally redirects the light by total internal reflection to the waveguide. Furthermore, different techniques have been investigated in emerging research activities on silicon photonics packaging [15]. Among these, laser welding packaging has the potential to be a promising method as it offers better strength, cleanliness, and long-term reliability [16, 17]. However, silicon photonics packaging using laser welding technique has been rarely reported.

Here we demonstrated a fully packaged silicon device using laser welding technique on angle polished fibers as input and output ports coupling to high efficiency silicon double-etched apodized waveguide grating couplers.

2. Device designs and principle

The lateral fiber coupling method using angle polished fibers to couple the light in and out of the double-etched apodized waveguide grating coupler is depicted in Fig. 1(a). In order to minimize coupling loss caused by second-order reflection, the grating coupler is designed to couple light in/out at an angle of 10° off vertical direction. The fiber polish angle $\theta_f$ is thus determined to be 40° when fibers are placed laterally as illustrated in Fig. 1(a). To satisfy the condition for total internal reflection (TIR), $\theta_f$ should be less than $90° - \sin^{-1}(1/1.4862) \approx 47.1°$ [13, 14]. Given $\theta_f$ of 40°, we can have large tolerance to the specification of angle variations without any reflective coating on top of the fiber facet. In order to achieve high fiber-to-waveguide coupling efficiency, a highly directional grating is required whilst the grating coupling strength $\alpha$ needs to be optimized to obtain a Gaussian-shaped field profile that can match the fiber mode. Here the double-etched apodized grating coupler design with engineered coupling strength for each grating period on 340-nm-thick SOI was employed to enhance the coupling efficiency [18]. The grating is designed for TE-polarization with central wavelength of $\sim 1550$ nm. The grating coupler has total 23 periods including 4 periods with shallow etch depth and 19 periods with deep etch depth. The grating width is $10 \mu$m, while
the total length is about 13 μm. The groove width \( g \) closest to the waveguide is 135 nm. The grating period \( \Lambda \) gradually changes from 548 to 610 nm along \( z \)-axis.

Fig. 1. (a) Schematic of angle polished fiber coupling to a double-etched apodized waveguide grating coupler. (b) Top-view scanning electron micrograph (SEM) of the fabricated grating coupler. (c), (d) Zoom-in view SEM images of the device.

The double-etched apodized waveguide grating coupler was fabricated by using standard CMOS-compatible technology on a commercial 8-inch 340-nm-thick SOI wafer with 2-μm-thick buried oxide layer. Figure 1(b) shows the top-view scanning electron micrograph (SEM) of the fabricated double-etched waveguide grating coupler on SOI. Figures 1(c) and 1(d) show the zoom-in view SEM images of the device. The measured shallow etch depth \( e_s \) is \( \sim 85 \) nm and the deep etch depth \( e_d \) is \( \sim 210 \) nm. The fill factor and the period are purposely designed to achieve engineered coupling strength for each grating period (shown in Fig. 1(b)). The minimum feature size is \( \sim 135 \) nm.

Fig. 2. (a) Side-view and (b) top-view optical micrograph of angle polished fiber coupling to grating coupler. (c) Measure insertion loss as a function of wavelength for planar and vertical fiber coupling.

We first studied the lateral fiber coupling method by employing angle polished fibers as shown in Fig. 2. Figures 2(a)-2(d) show the top-view and side-view images when input and output angle polished fibers were aligned with silicon chip. The side-view zoom-in picture is shown in Fig. 2(d), which indicates the angle polished facet of the fiber. A tunable laser (Agilent 8164B) was employed as the input light source. A polarization controller was used to adjust the input light in TE-polarization for the waveguide grating coupler. There is no index-matching liquid applied between the optical fiber and waveguide grating coupler.
The alignment tolerances were measured using a lateral AutoAlign system. The input and output angle polished fibers were aligned to the grating couplers as shown in Fig. 2. The minimum fiber-waveguide-fiber insertion loss of a waveguide with grating couplers at both ends laterally coupling to angle polished fibers as input and output is $-6.5$ dB. Then the wavelength of tunable laser was set at the peak wavelength of 1547.32 nm. The characterized alignment tolerances are shown in Fig. 3 with variations of the fiber position and angular offset. An extra loss of less than 1 dB was measured over a $5 \mu m$ range along the grating or an $8 \mu m$ range across the grating as shown in Fig. 3(a). The insertion loss deviation is within 1 dB with the distance variation of $8 \mu m$ between grating and fiber cladding (shown in Fig. 3(b)).

The measurement of angular alignment tolerances were performed by changing the aligned angles in different directions (horizontal, vertical and self rotation). For each measurement, the fiber was realigned to an optimum power. A very large swing angle tolerance with 1 dB excess loss over $+/− 6^\circ$ range is shown in Fig. 3(c). Less than 1 dB power penalty can be expected with the tilt angle variation within $4^\circ$ range. The rotation alignment tolerance measurement indicates that the excess loss is less than 1 dB with the angle deviation of $4^\circ$. In summary, such relax alignment tolerances ease the difficulties for fiber packaging process.

3. Photonic packaging with fiber assembly

After the silicon photonics chips fabrication and alignment tolerances measurements, we employed the well known laser welding technique for the photonic packaging of the chips with fiber assembly. Compared with epoxy approach [13, 14], this can provide significantly enhanced mechanical reliability. Figure 4(a) depicts the schematic of the packaging structure. Figure 4(a) inset shows the laser welding station.
At first, the roll orientation of the first angle polished fiber surrounded by a nickel based metal ferrule was adjusted by using a visible laser and monitoring the distance between the input spot and reflected spot at the chip surface. Secondly, the fiber was aligned to the input grating coupler using a precision vision system. The fiber position fine tune was then performed by monitoring the output spot from the other grating coupler using Infra-Red (IR) camera. After that, the fiber was welded with nickel based weld clips by YAG lasers. The laser welding sequences follows the procedure as detailed in [17]. A total of four welds were placed in pairs at the same height as the center-line of the metal ferrule to minimize Post-Weld-Shift (PWS). The power of YAG laser for joining was 4.6 J. Before this joining, the weld clip was welded on Kovar plate by the YAG laser with power of ~6.9 J.

During the welding process, the PWS between the weld clip and the ferrule caused by rapid solidification of the welded region and the associated material shrinkage resulted in the misalignment between the angle polished fiber and the circuit. In order to compensate this misalignment, we implemented mechanical tuning via monitoring the waveguide output by a high intensity Infra-Red (IR) camera. The mechanical tuning of the lensed fiber was performed using seesaw effects [16] and the jointed weld clip acted as a pivot when the rear side of metal ferrule surrounding the lensed fiber was tuned. This tuning can be performed due to the large angular tolerance as shown in Fig. 3. The second lensed fiber attached by laser welding was then carried out with active alignment. Similarly, misalignment compensation monitored by IR camera was done. The fine tune process could be also done by laser hammering process. For example, the tip of fiber will move to up-side when laser hammering is implemented on the rear side of between the metal ferrule and the weld clip. The pivot is composed of two front welding points in this case. After pigtailig input and output fibers, the additional mechanical tuning can be performed for both fibers to check the misalignment. Figure 4(b) shows the packaged sub-assembly using YAG laser welding. At last, housing process was conducted by loading the sub-assembly in a designed metal box and then they were assembled using thermal epoxy as shown in Fig. 4(c). It takes typically more than 1 hour for curing with over 80 °C in the thermal epoxy process. In our packaging process, the curing temperature and time were 80 °C and 1.5 hours, respectively. Additional micro-tuning process via power monitoring will be required if misalignment is occurred by the thermal curing process.

4. Results and discussion

The optical power of the angle polished fibers coupling to apodized grating coupler embedded silicon chip and packaged module was compared as shown in Fig. 5. The chip measurement was performed by active alignment on the AutoAlign system with precision motorized stages. The angle polished fibers are aligned in plane with the fabricated silicon
chip. The measured fiber-waveguide-fiber insertion loss is ~6.5 dB. The current grating coupler with grating area of only ~10 × 13 um is not optimized for such planar coupling scheme. Therefore higher insertion loss results from larger distance (~60 μm) between the fiber core and waveguide grating compared with the case of vertical fibers coupling to the apodized grating coupler [18].

![Figure 5](image.png)

Fig. 5. Measured spectra comparison between angle polished fibers coupling to chip and packaged module with fiber assembly.

The optical loss of module after performing the mechanical tuning has been measured to be 1.2 dB with respect to the chip data. Due to the laser welding station setup limitation, it is very difficult to fiber tilt angle precisely during the packaging process. The PWS may even introduce extra angle tilting. In order to overcome such issue, a side-view vision system is required to be equipped in the laser welding station. The rotation of the fiber was adjusted by using a visible laser and monitoring the distance between the input spot and reflected spot. However, such process was not well controlled because the fiber rotation can only be manually tuned with the current setup and the resolution of vision system needs to be enhanced. We believe that with improved laser welding station, the excess packaging loss can be further reduced with better repeatability and reliability.

5. Conclusion

We demonstrated silicon photonics packaging with lateral fiber coupling to grating coupler using YAG laser welding technique. The packaging loss was less than 1.2 dB with respect to chip data. The use of angle polished fibers enables in plane coupling scheme with waveguide grating coupler embedded silicon photonic circuit. Relax alignment tolerance can be obtained to achieve enhanced coupling reliability, which is desirable for the fiber packaging process. This will pave way for cost-effective deployment of high efficiency silicon photonics packaging in telecommunication systems.