2-dimentional fiber array with reflow compatibility for high-density optical interconnection

Tsutaru Kumagai, Hajime Arao, Hong C. Nguyen, and Tetsuya Nakanishi
Optical Communications Laboratory, Sumitomo Electric Industries, Ltd., 1, Taya-cho, Sakae-ku, Yokohama, Kanagawa, 244-8588 Japan.
kumagai-tsutaru@sei.co.jp

Abstract: We developed a 2-dimensional fiber array (2D-FA) as an optical interconnection device for co-packaged optics. The 2D-FA was capable of maintaining a low connection loss of < 1.0 dB after reflow process at 260°C.

1. Introduction

The continual growth of internet traffic requires increasingly higher bandwidth for the data transmission to and from the servers in datacenters. Today, inside a datacenter switch, signaling from the switch application-specific integrated circuit (ASIC) to a pluggable optical transceiver on the front panel is performed electrically through a printed circuit board (PCB), as shown in Fig. 1(a). However, there is intensive discussion that such high-speed electrical connections are approaching their fundamental limitations in terms of data rate and energy consumption. Co-packaged optics (CPO), a technology which integrates the optical transceiver function (optical engine) with the ASIC [1], is attracting attention as an alternative. Fig. 1(b) illustration the CPO concept. Placing the optical engine next to the switch ASIC shortens the electrical connections that would otherwise run all the way to the front panel, thus reducing the overall energy consumption.

Silicon photonics (SiPh) is a key component of the optical engine of CPO, as it enables the on-chip integration of optical transceiver functions as well as the packaging of the chip with the ASIC, economically. Assuming a 51.2 Tb/s switch bandwidth supported by 8 SiPh-chips operating at 100 Gb/s per lane, the Tx + Rx channel number per SiPh chip can be 128. Since the compactness of the SiPh-fiber package and low chip-to-fiber coupling loss are crucial for the economic and technical viability of CPO, a high-density and low-loss optical interconnection device (OID) that can scale to >100 channels is required. The OID also needs to withstand operating temperatures that exceed the standard 70°C in telecom, as it is packaged with the heat-generating ASIC. Furthermore, it is desirable that the OID withstand solder reflow process, which could be required for the large-volume packaging and assembly of CPO and other semiconductor devices. In this paper, we demonstrated a two-dimensional fiber array (2D-FA) as a proof-of-concept OID for CPO. The low loss, high channel density and heat resistance, were achieved by combining simple glass plates with heat-durable injection-molded ferrules.

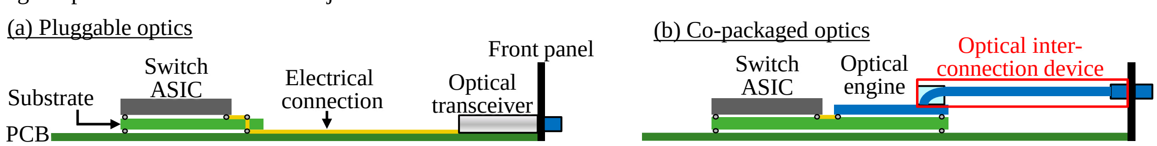
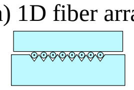
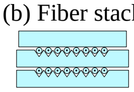
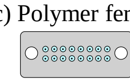
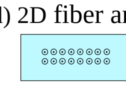


Fig. 1 Conceptual illustration of (a) Pluggable transceiver and (b) Co-packaged optics

2. Design benchmark for OID

Table 1 compares the suitability of the possible candidates for OID. From the perspective of channel density and scalability, technologies that can support two-dimensional (2D) fiber arrangement is preferred over conventional, one-dimensional fiber arrays. Among 2D-capable candidates, fiber stacks (Table 1(b)) [2,3], and polymer ferrules such as multi-row MT ferrules (Table 1(c)) [4], have been reported or are available in the market. However, these have critical drawbacks on the accuracy of fiber core position and/or heat resistance. To overcome these issues we propose the 2D-FA, which consists of a glass plate with high-precision holes for core position accuracy [5], as well as a liquid crystal polymer (LCP) ferrule that act as a heat-resistant fiber support (Table 1(d)). By employing the glass plate as a fiber position aligner, glass will be the interface material to the SiPh chip. This is also beneficial as it offers excellent CTE-matching with the SiPh chip, while its UV transparency enables the bonding between the OID and SiPh chip using UV-curable resin.

Table 1 Comparison of potential high-density optical interconnection method for CPO

Type	(a) 1D fiber array	(b) Fiber stack	(c) Polymer ferrule	(d) 2D fiber array
				
Material	Glass/Silicon	Glass	Engineering plastics	Glass/Silicon
Density	Low	Middle	☑ High	☑ High
Core position accuracy	☑ High	Low	☑ High	☑ High
Heat resistance	☑ Fair	☑ Fair?	Poor	☑ High (with heat-resistant fiber support)
CTE matching to Si	☑ Possible	☑ Possible	No	☑ Possible

3. **Sample preparation and material selection for fiber support**

Figure 2 shows the picture and schematic of a 2D-FA consisting of a 1-mm-thick glass plate and a LCP ferrule. The latter is the fiber support made of LCP, injection-molded into the shape of a standard MT ferrule. The hole pattern of the glass plate is identical to standard 24-fiber MT ferrules (2 × 12 holes with 125 μm diameter and 250 μm pitch, and two guide-pin holes) [6], and the eccentricity of the hole positions from design is within 1 μm. As for the LCP-ferrule material, we selected a LCP containing glass filler as it exhibits small thermal-shrinkage rate at 260°C of less than 0.5%, while keeping <370°C molding temperature for stable manufacturability with standard injection-molding process. Eccentricity of fiber hole positions of the fabricated LCP-ferrule were measured to be less than 3 μm. This is sufficient precision as the LCP-ferrule only acts to support and guide the fiber insertion to the glass plate, which then determines the fiber position accuracy. Figure 3 shows the comparison of the end-facet profiles between the LCP-ferrule and standard MT ferrule using poly-phenylene sulfide (PPS-ferrule), after heat treatment at 260°C for 5 minutes in an electric furnace, simulating the reflow process. After the heat treatment, PPS-ferrule showed large end-surface profile change exceeding 12 μm, and large deformation is observed at the bottom edge of ferrule. On the other hand, the end-surface profile change of LCP-ferrule was comparatively small (<5 μm) and maintained its original shape. These properties of the LCP-ferrule are important because large end-surface profile change cause delamination of the glass plate, and ferrule hole-position change due to deformations cause high stress on the fibers at the plate-ferrule interface, resulting in fiber breakage.

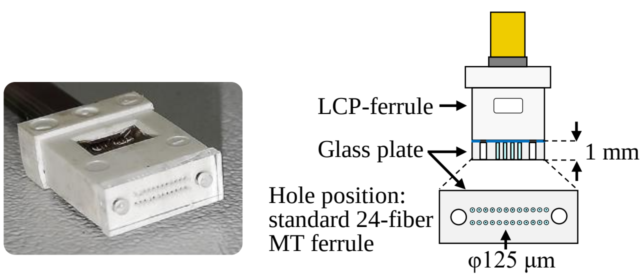


Fig. 2 Picture and schematic of 2D-FA

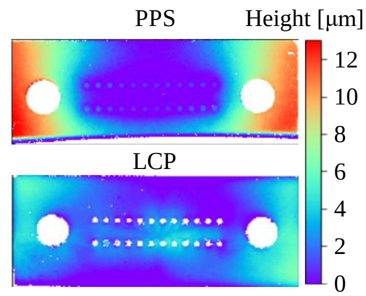


Fig. 3 Facet profiles of PPS- and LCP-ferrule after heat treatment

4. **Experimental results for reflow compatibility**

In order to experimentally examine the reflow compatibility, the 2D-FA and a reference standard MT connector (PPS-MT) were subjected to heat treatments of 260°C for 5 minutes. Figure 4 illustrates the pre- and post-treatment measurement items: 1) core-position eccentricity, 2) connection loss, and 3) warpage of the end face of glass plate.

Figure 5 shows the measured core-position eccentricity of the 2D-FA (left) and PPS-MT (right) before and after the heat treatment. The core position eccentricity of the 2D-FA after heat treatment was within 0.7 μm, and observed almost no change in the core positions. On the other hand, large core-position eccentricity of up to 4.4 μm is observed for the PPS-MT after the heat treatment, over 7 times larger than in the 2D-FA.

The loss were measured by active alignment of the test samples to a 24-fiber MT connector that complies with IEC 61753-1 Grade C [7], in a setup as shown in Fig. 6. Figure 7 shows the measured connection loss results on the same samples shown in Fig. 5. The average connection loss of the 2D-FA before and after the heat treatment were 0.48 and 0.59 dB, respectively, with the maximum loss across all channels less than 1.0 dB. On the other hand, the connection loss of the reference PPS-MT after the heat treatment increased greatly, with an average up to 1.95 dB, compared to 0.44 dB before treatment. These results are consistent with the core position evaluation results shown in Fig. 5. Figure 8 shows the histogram of the connection loss of 2D-FAs after heat treatment for 4 samples (= 96 channels in total), confirmed that the connection loss is less than 1.0 dB for all 96 channels.

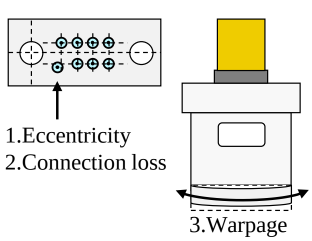


Fig. 4 Evaluation items

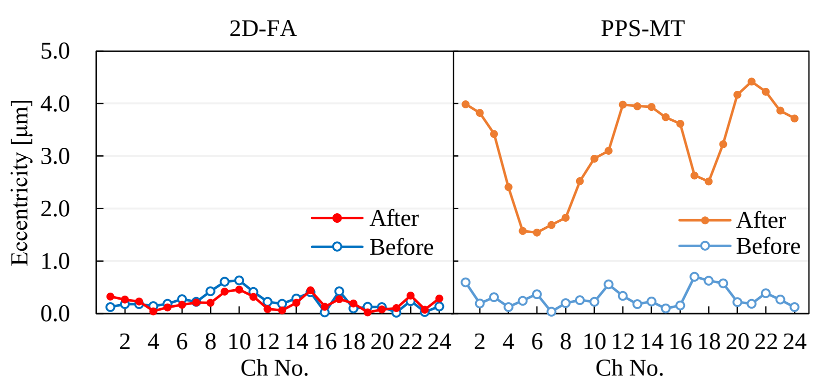


Fig. 5 Core position eccentricity of the 2D-FA and PPS-MT before/after the heat treatment.

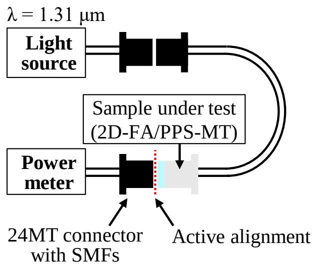


Fig. 6 Setup for the connection loss measurement

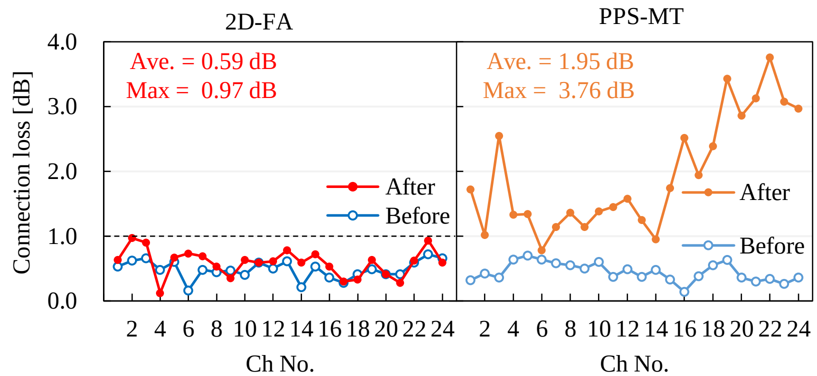


Fig. 7 Connection loss of the 2D-FA and PPS-MT before and after heat treatment.

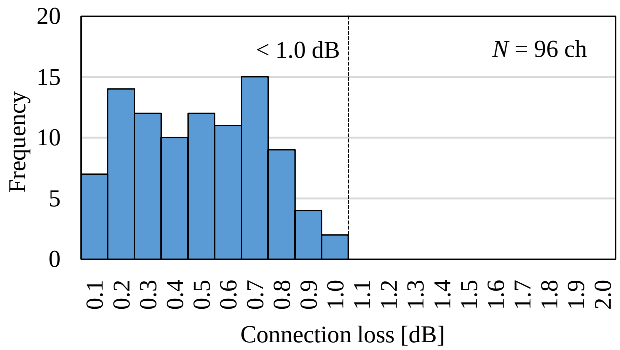


Fig. 8 Histogram of connection loss

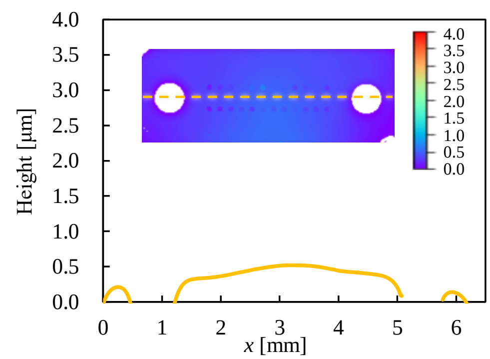


Fig. 9 Surface profile of 2D-FA after heat treatment.

Increased warpage of the glass plate is a concern as the light propagation angle from the end face may divert and coupling loss to SiPh chip may increase, since the coupling efficiency of grating couplers (GCs) have a relatively large angle dependence. Figure 9 shows the surface profile of the 2D-FA after heat treatment. From the representative height profile extracted from the dashed line on the inset 2D profile image, the warpage of the glass plate is measured to be within 0.6 μm. The curvature of the profile can be translated to a light propagation-angle error of within 0.03 degree. As GCs tolerate one order magnitude larger angle error generally, this flatness of the 2D-FA end face ensures to avoid additional connection loss to the SiPh chip after the reflow process.

5. **Confirmation of delamination and fiber breakage by high temperature and humidity test**

Finally, in order to verify the basic reliability of the proposed 2D-FA configuration, we performed pressure cooker test (PCT) at 110°C/100%RH for 80 hours as an acceleration test. As a result, no delamination was observed at the interface between the glass plate and LCP-ferrule after PCT (Not shown). We also confirmed no fiber breakage in entire 2D-FA structure. Although we plan to perform complete Telcordia GR-326-CORE test on 2D-FA and need to be verified all items, this PCT results indicate that the 2D-FA, by combination of glass plate and LCP-ferrule, is a robust design and can be used as the OID reliably.

6. **Conclusion**

We demonstrated a 2D-FA using glass plate with high precision holes and fiber support ferrule with LCP. This structure achieves low core-position eccentricity of less than 0.7 μm and low connection loss of less than 1.0 dB, even after heat treatment of 260°C for 5 minutes which simulate the solder reflow process. As there is no fundamental limitation in increasing the number of fibers per row or the number of rows in this structure, the demonstrated 2D-FA concept enables a scalable, high-density OID required for CPO.

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