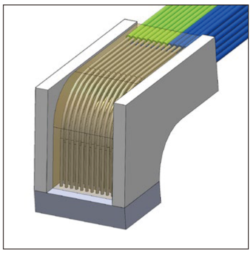

Two-Dimensional Optical Fiber Array with 90-Degree Bend for Next-Generation Datacenter Switches

Tsutaru KUMAGAI*, Haruki KITAO, and Tetsuya NAKANISHI

Co-packaged optics (CPO) switches are attracting attention for their ability to reduce power consumption by integrating electrical and optical functions in a single device using silicon photonics (SiPh) technology. By placing the SiPh chip close to the switch ASIC and shortening the electrical interconnection distance, power consumption can be reduced while maintaining the data rate. For optical coupling with a surface coupling type CPO module in the limited space, new optical interconnection components with a low profile, high density, low loss, and high reliability are necessary. For this purpose, we demonstrated a 72-fiber, two-dimensional optical fiber array with a 90-degree bend (2D-FBGE (FlexBeamGuidE)). We developed a stress-free bending technique of polarization-maintaining fiber (PMF). The stress-free bent PMF shows a small radius (R = 2.5 mm), low loss, and high polarization-maintaining characteristics. By combining 90-degree bent optical fibers with a two-dimensional hole array, we have fabricated the 2D-FBGE with a low profile of 5.5 mm, high density of 24 fibers/mm, low insertion loss of less than 0.5 dB, and high polarization-maintaining characteristics of more than 20 dB. Thus, 2D-FBGE offers robust, space-efficient, and scalable fiber coupling applications for surface coupling type CPO modules.

Keywords: optical interconnection component, Co-packaged optics (CPO), silicon photonics, FlexBeamGuidE (FBGE)

1. Introduction

The power consumption of data center switches is increasing as signal transmission capacity grow. Co-packaged optics (CPO), which integrates electrical and optical functions in a single device using Silicon photonics (SiPh) technology*1, is considered a possible solution to this problem.(1),(2) As shown in Fig. 1, by placing the SiPh chip close to the switch ASIC*2 and shortening the electrical interconnection distance, the power consumption can be reduced while maintaining the data rate.

Grating couplers (GCs) are used for SiPh as a cost-efficient optical coupling technology between the SiPh chip and the single-mode fiber (SMF).(3) However, the fiber coupling to the GC is perpendicular to the chip surface. Therefore, a low-profile feature is required for the optical fiber interconnection components (OICs) for optical fiber coupling in a limited height space, as shown in Fig. 1. In addition, since the CPO modules are expected to support a total bandwidth of 6.4 Tb/s or more, the OIC must provide features such as high density and scalability in the number of fibers.

The concept of an external light source (ELS) module is considered to avoid performance degradation of the laser due to heat generated by the switch ASIC. This requires the use of a polarization-maintaining fiber (PMF) to deliver light from the ELS to the SiPh chip efficiently.

In order to achieve the low profile and high density required for the OIC, a two-dimensional 90°-bent fiber array (2D-FBGE (FlexBeamGuidE)) was fabricated by assembling bent optical fibers into a two-dimensional glass-hole array (2D-GP). In this paper, we summarized the requirements for OICs for CPO switches and demonstrated 2D-FBGEs that meet the requirements.

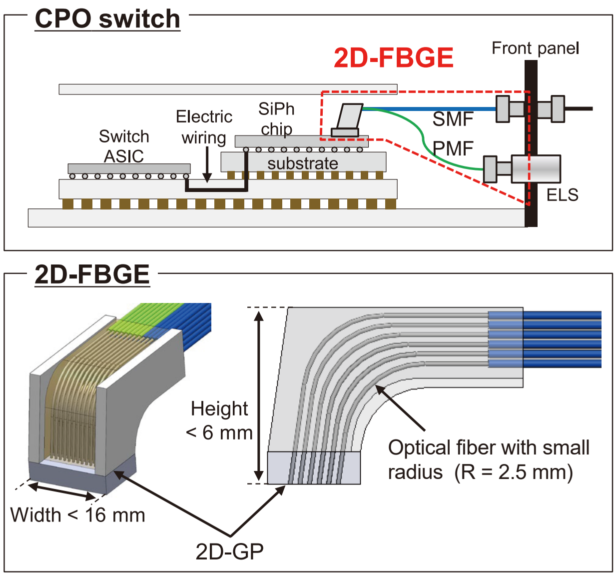

Fig. 1. Schematic diagram of CPO switch and 2D-FBGE

2. Requirements for OICs for CPO switches

Assuming a CPO switch with a total bandwidth of 102.4 Tb/s supported by CPO modules with a total bandwidth of 6.4 Tb/s, 16 CPO modules would be required. In this case, assuming that the CPO module is configured with 200 Gb/lane, 32 channels per direction are required. Therefore, 64 SMFs are required to realize a 6.4 Tb/s CPO module with DR4*3 type for bidirectional transmission. It is also assumed that 8 PMFs are required to deliver light from the ELS to the SiPh chip, thus, OIC with a total of 72 fibers (64 SMFs and 8 PMFs) is a target configuration.

According to reference (1), the maximum allowable width of the OIC of 72 fibers is 16 mm. Therefore, a channel density of 4.5 (= 72/16) fibers/mm or higher is required for the OIC. A conventional one-dimensional (1D) fiber array with 0.25 mm pitch has a density of 4 fibers/mm. Since this value is less than the required density, a more high-density fiber array is required. In addition, the maximum allowable height of the OIC is 6 mm. For the optical coupling with GCs, as shown in Fig. 1, optical fibers are required to be bent to a small radius, such as a bending radius of R = 2.5 mm. However, when an optical fiber with a diameter of 125 µm is mechanically bent at a bending angle of 90° and R = 2.5 mm, the bending stress exceeds 1.8 GPa and the probability of breakage within five years is estimated to be 100%, which is a serious reliability problem.[(4),(5)] Based on the above requirements, we aim to produce a high-density, high-reliability component with a height of less than 6 mm using 72 fibers with a density of more than 4.5 fibers/mm.

To achieve a high density of 4.5 fibers/mm or more, we adopted a 2D-GP.[(6)] By arranging 72 fibers into 12 fibers with 0.25 mm pitch and 6 rows, the density of 24 fibers/mm can be achieved, which exceeds the target of 4.5 fibers/mm and supports future scalability. This density is difficult to achieve with conventional 1D fiber arrays. In addition, 2D-GP has the following advantages: 1) small thermal expansion coefficient difference against SiPh chips; 2) UV-curable resin can be used to bond fiber arrays and SiPh chips; and 3) high heat resistance characteristics are suitable for use near switch ASICs, where the ambient temperature can reach 110°C.

To achieve a height of 6 mm or less, we adopted the "stress-free bending process" (SFB).[(5)] By assembling an SFB-applied bent optical fiber with R = 2.5 mm into 2D-GP, the 2D-FBGE can be realized with high reliability. On the other hand, the 2D-FBGE requires PMFs. Therefore, we first verified the applicability of SFB to the PMF.

3. Bending PMF with Small Radius

3-1 Application of SFB on PMFs

PMFs exhibit polarization-maintaining function due to the birefringence at the core induced by a pair of stress-applying parts (SAPs) on both sides of the core. Therefore, the performance of the PMF may degrade by SFB, in which the stress inside the optical fiber is relaxed by heat. Hence, we investigated the induced or residual stress by mechanical bending and SFB inside SMFs and PMFs (125 µm, R = 2.5 mm). The results of the microscopic visualization of the stress inside the fiber are shown in Fig. 2. In the case of mechanical bending, bending stress is observed in the entire bending area in both SMF and PMF. In the case of SMF with SFB, the bending stress is entirely relaxed. In the case of PMF with SFB, residual stress is observed only around the core. This indicates that it is possible to relax only the bending stress while leaving the birefringence on the core. Thus, both high reliability and polarization-maintaining properties are expected.

In the meantime, there is a concern that twisting the PMF during the SFB process may cause crosstalk between orthogonal polarizations due to angular misalignment

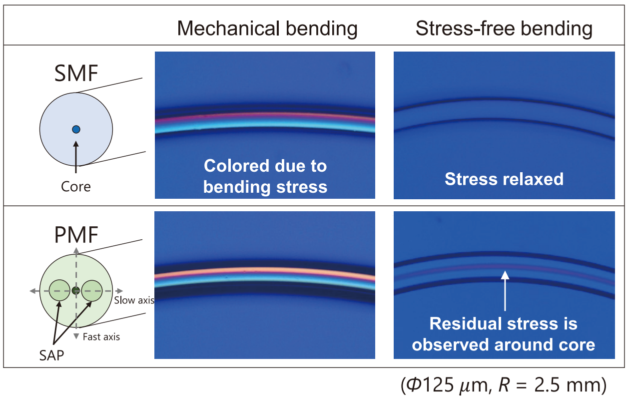

Fig. 2. Polarized light microscope images (stress visualized by color change)

(Fig. 3) and degrade the polarization extinction ratio (PER). Therefore, we investigated the effect of heat on the PER of intentionally twisted samples. The PER was calculated from the ratio of light intensities between orthogonal polarizations using the following Eq. (1):

$$\mathrm{PER} = 10\log(P_{\max}/P_{\min}). \quad \cdots\cdots (1)$$

Where P_{max} and P_{min} are the maximum and minimum intensities of the light after propagation, respectively. As shown in Fig. 4, the measured PER decreases as the twist angle increases and the PER are in accordance with Malus's law.[(7)] This indicates that the PER degradation can only be explained by the angular misalignment and there is no degradation due to the SFB process itself.

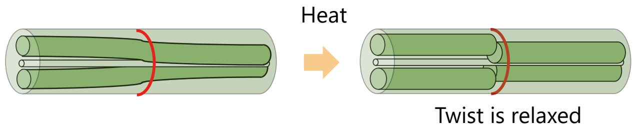

Fig. 3. Effect of heat on twisted PMF

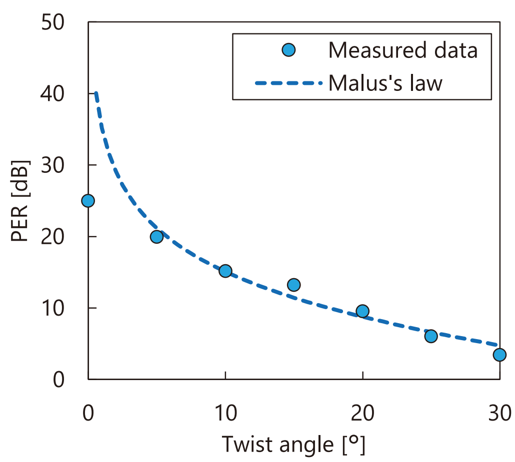

Fig. 4. Result of twist test

3-2 Optical Characteristics of PMF with SFB

To evaluate the optical characteristics of PMF with SFB, bending loss (BL) and PER were measured. In order to obtain low bending loss even at a small bending radius, we prepared a bend-insensitive PMF for this study. PMFs were bent by SFB with bending radii ranging from 1.5 mm to 3.5 mm. The twisting of the PMF during SFB process was suppressed based on the above results. The bending direction was selected for both the 0° direction, where the two SAPs were aligned parallel to the bending plane, and the 90° direction, where two SAPs were aligned perpendicular to the bending plane.

The BL was obtained from the difference between the input and output light intensities. Table 1 shows the results of the BL measurements. For all bend radii and directions, the BL showed a low loss of less than 0.1 dB.

Table 1. BL measurement results of SFB applied PMFs

Bending radius [mm]	BL [dB] (0° direction)	BL [dB] (90° direction)
1.5	0.03	0.08
2.5	0.01	0.01
3.5	0.00	0.04

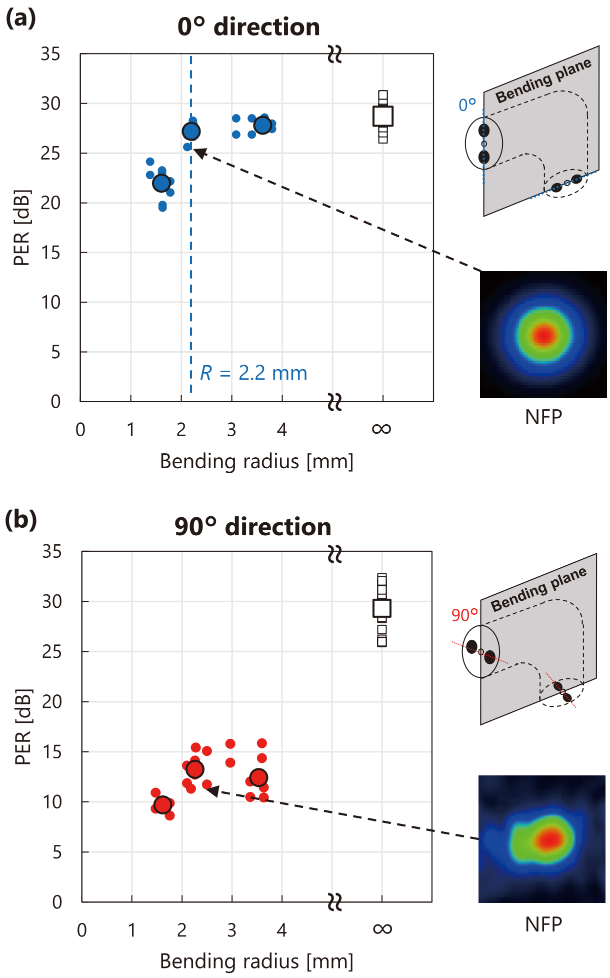

Fig. 5. Bending radius dependence of PER in (a) 0° and (b) 90° directions

Figure 5 (a) shows the measured PER in the 0° direction plotted against the bend radius *R*. For *R* = 2.2 mm or larger, the PER was higher than 25 dB, demonstrating that the bending radius of SFB applied PMF is sufficient to realize the space-efficient CPO module package. The near field pattern (NFP) image in Fig. 5 (a) shows that the mode profile is symmetric and maintains single-mode propagation. On the other hand, as shown in Fig. 5 (b), the PER decreases to 10-15 dB in the 90° direction. The NFP image shows an asymmetric mode profile, indicating higher-order mode excitation. The optical confinement to the core in the 90° direction is weaker than that of in the 0° direction because the SAP, which has a negative refractive index, is not in the bending plane. Therefore, the generation of a higher-order mode causes the degradation of the polarization-maintaining characteristic.

These results confirm that PMFs bent in the 0° direction can achieve high reliability, low bending loss of less than 0.1 dB, and high polarization-maintaining characteristics of more than 25 dB, simultaneously.

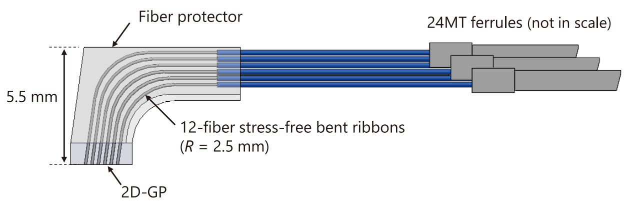

Fig. 6. Schematic diagram of 72-fiber 2D-FBGE

4. Fabrication and Evaluation of 2D-FBGE

4-1 Fabrication of 2D-FBGE

Figure 6 shows a schematic diagram of a 72-fiber 2D-FBGE. The 2D-FBGE consists of a 2D-GP, SFB-applied 12-fiber ribbons (*R* = 2.5 mm), a fiber protector, and 24MT ferrules.[8] The holes of 2D-GP are arranged in a 12×6 array configuration with a pitch of 0.25×0.3 mm. The hole angle was set to 8° to suppress return loss. The total height of the fabricated sample is 5.5 mm, which meets the height requirement of less than 6 mm. Seventy-two fibers are arranged within a width of 3 mm, resulting in a fiber density of 24 (= 72/3) fibers/mm. This meets the target density of 4.5 fibers/mm and is 6 times higher than conventional 1D fiber arrays with 0.25 mm pitch. This density can be further increased by increasing the number of rows.

Figure 7 shows an end-face view of a 2D-FBGE with 64 SMFs and 8 PMFs assembled into the 2D-GP. The misalignment of the PMF rotation angle, which results in excess loss due to a mismatch with the polarization axis of the GC, was less than ± 3°. The misalignment of the PMF in the MT ferrule was also less than ± 3°.

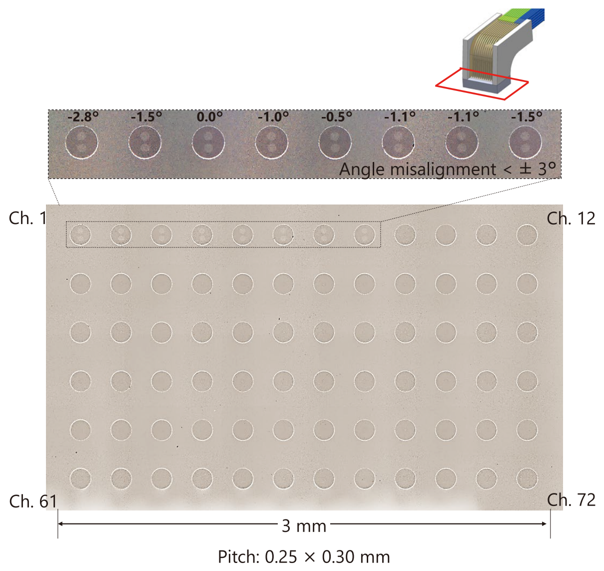

Fig. 7. End face view of a 2D-FBGE

4-2 Optical Characteristics of 2D-FBGE

Insertion loss (IL) and core position error of the optical fiber were measured to estimate the loss when connecting 2D-FBGE and SiPh chips. IL was measured by active alignment. An SMF was aligned to the end-face of the 2D-FBGE and the light intensity propagated from the MT ferrule side was detected with a power meter. The results of the IL measurement are shown in Fig. 8. The ILs of all fibers were less than 0.5 dB, with an average of 0.33 dB.

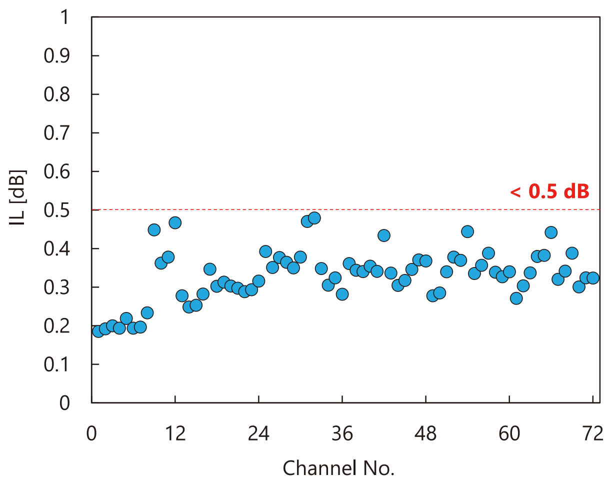

Fig. 8. Result of IL measurement

Figure 9 shows a histogram of the core position error measurements. The average, 97th percentile*4, and maximum core position errors were 0.5, 1.4, and 2.1 μm, respectively. The following Eq. (2) was used to estimate the coupling loss (CL) with the GC[9]:

$$\mathrm{CL} = -10\log\left(\frac{2w_1w_2}{w_1^2+w_2^2}\right)^2 \exp\left(-\frac{2s^2}{w_1^2+w_2^2}\right) \quad \cdots\cdots (2)$$

where $2w_1$ and $2w_2$ are the mode field diameters (MFD) of the optical fibers and GCs, respectively. Since the MFD of the GC is usually designed to match the MFD of the SMF (= 8.6 μm), $2w_1$ and $2w_2$ were assumed as 8.6 μm. The s is the value of relative position error between the optical fiber core and GC. Since GCs are usually manufactured with very high precision and the position error is considered to be negligibly small, the value of s can be considered as the measured core position errors of the optical fibers inside 2D-GP. Based on the above assumptions, CL was calculated and shown on the second axis of Fig. 9. In the case of s = 0.5 μm (average), CL is 0.06 dB. In the case of s = 1.4 μm (97th percentile), the CL is 0.46 dB. The major origin of core position error is due to glass hole diameter deviation and inaccurate hole position. Further CL reduction can be expected by improving the precision of the 2D-GP manufacturing process.

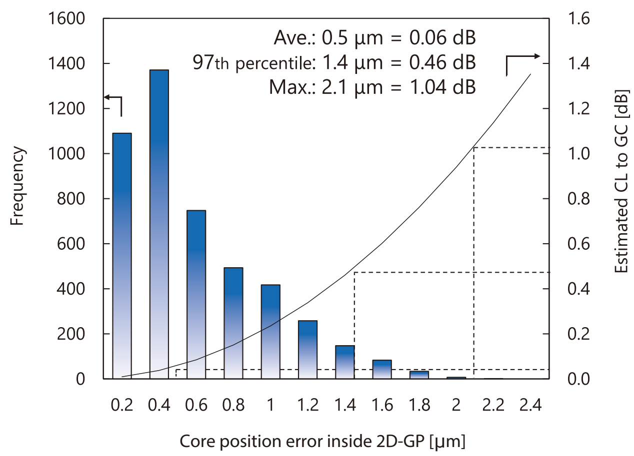

Fig. 9. Measured result of core position error and estimated coupling loss to grating coupler

The PER was measured to evaluate the polarization-maintaining performance of the PMF in the fabricated 2D-FBGE. In general, since the GC of the SiPh chip can only receive light with one polarization state, degradation of PER results in excess loss (EL) at the PMF/GC coupling. EL can be estimated from PER using the following Eq. (3):

$$\mathrm{EL} = 10\log\left(1+10^{-\mathrm{PER}/10}\right). \quad \cdots\cdots\cdots\cdots (3)$$

From this equation, the PER of 16 dB or more is required to keep the EL below 0.1 dB. The measured results of the PER are shown in Fig. 10. The results show that the PER is more than 20 dB for all 8 PMFs, indicating that the 2D-FBGE has a high polarization maintaining performance and the EL of less than 0.1 dB can be expected.

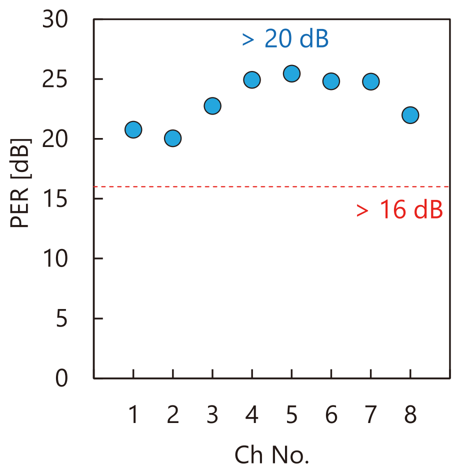

Fig. 10. Result of PER measurement

4-3 Reliability Tests

To confirm the basic reliability of the 72-fiber 2D-FBGE, a heat cycling test (-45 ~ 85°C × 100 cycles) and a dump heat test (85°C/85% RH × 100 hours) were performed. As a result, no fiber breakage was confirmed. In addition, an initial test for 110°C operation was conducted for 168 hours in order to simulate the use near the switch ASIC. The fiber breakage and optical degradation did not occur after the test.

5. Conclusion

A 72-fiber 2D-FBGE is demonstrated as an optical fiber coupling solution for CPO switches used in next-generation data centers. By applying stress-free bending process, we have established a small-radius (R = 2.2 mm) bending technology of PMF with high reliability, low loss of less than 0.1 dB, and high polarization-maintaining characteristics of PER > 25 dB for PMF bent in the 0° direction. The fabricated 2D-FBGE achieves insertion loss of less than 0.5 dB, average core position error of 0.5 µm, and PER of higher than 20 dB. Therefore, the developed 2D-FBGE offers reliable, space-efficient, and scalable fiber coupling technology for surface coupling type CPO modules.

• FlexBeamGuidE is a trademark or registered trademark of Sumitomo Electric Industries, Ltd.

Technical Terms

∗1 Silicon Photonics: Silicon Photonics (SiPh) is a technology that integrates optical transceiver functions on a silicon chip, which is widely used as a semiconductor. Compared to conventional optical transceivers, SiPh transceivers have advantages for economical production because the number of components can be reduced through integration.

∗2 ASIC: Application Specific Integrated Circuit: A generic term for an integrated circuit that combines multiple functions into a single circuit for a specific application.

∗3 DR4: One of the standards for optical transceivers. Four pairs of optical fibers (eight fibers in total) are used for the transmission and reception of optical signals.

∗4 Percentile: Value obtained by arranging the data in ascending order and specifying the value at any given %.

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