

Optical Fiber Array with 90-degree Bend for Silicon Photonics Chip Coupling

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Recently, the demand for silicon photonics (SiPh) optical transceivers for data centers has been increasing rapidly. In order to address this situation, we have developed FlexBeamGuideE (FBGE) as an optical interconnection device indispensable for SiPh chips. The FBGE is an optical fiber array with a 90-degree bend, formed using state-of-the-art stress-free fiber bending technology. The developed FBGE is suitable for use in SiPh optical transceivers because of its compact nature with an overall height of less than 3.8 mm, low attenuation loss of less than 0.5 dB, and high reliability.

Keywords: optical fiber array with 90-degree bend, silicon photonics, optical interconnection device

1. Introduction

The demand for optical transceivers used in data centers is increasing rapidly with the growing data traffic.⁽¹⁾ Silicon photonics (SiPh)^{*1} is an attractive technology for increasing the transceiver data rate and performance, leveraging existing complementary metal-oxide-semiconductor (CMOS) process to integrate optical transmitter and receiver functionalities onto a single chip. In SiPh, a grating coupler (GC) has been widely used to couple light between the SiPh chip and an optical fiber.⁽²⁾ The GC emits light perpendicular to the chip surface, and is designed to match the mode field diameter (MFD)^{*2} to that of an optical fiber, in order to reduce the coupling loss. However, as shown in Fig. 1, a sharply bent optical fiber component

is required for the GC-to-fiber coupling, due to the limited space inside the transceiver module. Quad Small Form-Factor Pluggable (QSFP),^{*3} an industry standard for transceiver form factor adopted widely in DCs, generally requires the height of the optical fiber components to be less than 4 mm (Fig. 1 (b)). To meet this requirement, the fibers must be bent to a radius of 2.0 to 2.5 mm. However, bending an optical fiber to such a small radius causes the fiber to fracture due to increased bending stress and increases bending loss.

To solve the above problems, we have developed an optical fiber array (FlexBeamGuideE: FBGE) with a 90-degree bend as an optical interconnection device that exhibits high reliability and low loss while fitting into a limited space. This paper describes the technologies behind the FBGE, which simultaneously achieves the space efficiency, low bend-loss, and high reliability, and presents the suitability of the FBGE for SiPh optical transceivers.

2. Enhancing the Reliability of Sharply Bent Optical Fiber

A bent optical fiber can fracture due to two primary causes: stress concentration at scratches and other micro-defects on the glass fiber surface; and the bending stress exceeding the inherent strength of the glass itself. The failure probability F of a sharply bent optical fiber can be expressed by the following Eq. (1).⁽³⁾

$$F = 1 - \exp \left[-\frac{\pi R}{2} \left[N_p \left\{ \left(1 + \left(\frac{\varepsilon}{\varepsilon_p} \right)^n \left(\frac{t}{t_p} \right)^{\frac{m_1}{n-2}} \right) - 1 \right\} + \left(\frac{\varepsilon_p^n t_p}{k_{02}} \right)^{\frac{m_2}{n-2}} \left\{ \left(1 + \left(\frac{\varepsilon}{\varepsilon_p} \right)^n \left(\frac{t}{t_p} \right)^{\frac{m_2}{n-2}} \right) - 1 \right\} \right] \right] \quad (1)$$

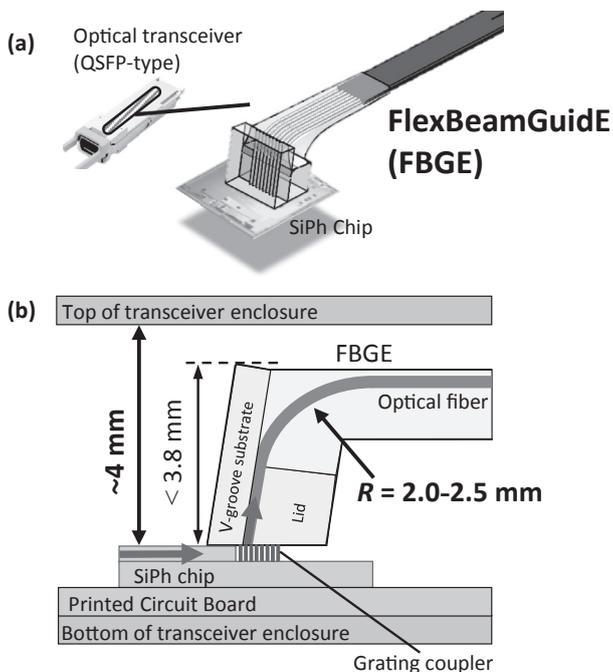


Fig. 1. (a) FBGE installed inside an optical transceiver (QSFP), (b) Schematic of the space allowed for optical fiber coupling inside the transceiver

Figure 2 shows the calculated failure probability F of fibers fracturing within five years of being bent mechanically to 90 degrees and fixed in that position. The calculation parameters are shown in Table 1. This figure shows that F increases sharply at a small radius R . For conventional optical fibers with a diameter of 125 μm , F approaches 100% when the fibers are bent to $R < 2.5$ mm. While it is known that the bending stress decreases as the glass diameter decreases, an 80 μm diameter fiber still exhibits $F \sim 5\%$ at $R = 2.0$ mm, which would be impractical from a reliability perspective.

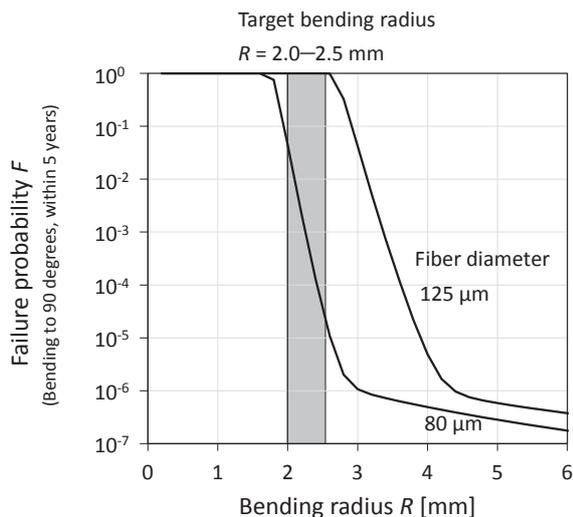


Fig. 2. Calculation result for the relationship between failure probability F and bending radius R

Table 1. Values of parameters used for the calculation

N_p	10^{-6}
n	20
m_1	3
m_2	30
ε_p	0.01
t_p	0.075
k_{02}	10^{-26}

To solve the above problems, we have developed a new stress-free bending process that can relieve the stress at the bends. Figure 3 shows a photograph of an optical fiber with a diameter of 125 μm . It was taken by a polarized light microscope, which can visualize bending stress by coloring the birefringence of light inside the glass. An image of a mechanically-bent optical fiber is shown in Fig. 3 (a), indicating the presence of stress in the bent section. An optical fiber bent using the newly developed stress-free bending process is shown in Fig. 3 (b). The glass is free of stress even when it was bent to $R = 2$ mm, resulting in high reliability as discussed later.

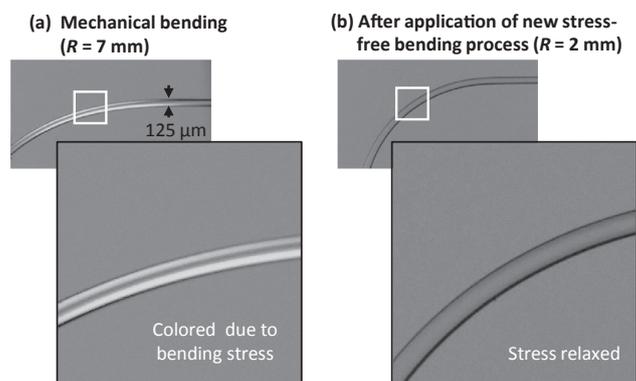


Fig. 3. Polarized light microscope images (stress inside fiber visualized by color change)

- (a) Mechanical bending,
(b) After application of stress-free bending process

3. Reducing Bending Loss

3-1 Low bending loss optical fiber

Other than deteriorating the reliability, a sharply-bent optical fiber also causes increased bend loss. To overcome this problem, we used a bend insensitive fiber (BIF) that has a trench-assisted refractive index profile (Fig. 4). The BIF has a low bend loss, compared to a standard single mode fiber (SMF) with a stepped refractive index profile. The typical characteristics of the BIF fabricated in-house are shown in Table 2. When the BIF is bent by 90 degrees at $R = 2$ mm, it demonstrated a very low loss of ≤ 0.06 dB at a wavelength of 1310 nm, which is widely used for SiPh optical transceivers. We also confirmed that the bent fiber satisfied the requirements of the ITU-T G.657.B3 standard.

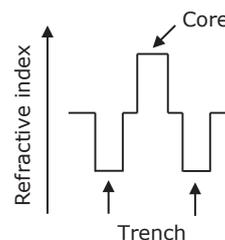


Fig. 4. Schematic of refractive index profile of BIF used for FBGE

Table 2. Optical characteristics measurement result for BIF

Wavelength [nm]		1310	1550
MFD [μm]		8.5–8.7	9.5–9.7
Transmission loss [dB/km]		0.333–0.340	0.201–0.212
Bending loss [dB/turn]	$R = 10$ mm		≤ 0.03
	$R = 5$ mm		≤ 0.15
	$R = 2$ mm	≤ 0.24	
	$R = 2$ mm (1/4 turn)	≤ 0.06	
Cable cutoff wavelength [nm]		1205–1225	

3-2 Analyzing the bend profile of optical fiber

It is known that perturbation at sharply bent fiber causes a mode conversion from the fundamental mode to higher-order modes. This increases the coupling loss between the optical fiber and the SiPh chip. We performed a beam propagation method (BPM) analysis to determine the optimal bend profile for the BIF, to reduce the fiber-to-chip coupling loss. In this analysis, we used a longitudinal position z , curvature C ($=1/R$), and the change rate of curvature dC/dz as the calculation parameters and studied the propagation behavior of the light inside the fiber when it is bent to $R \approx 2$ mm. In this calculation, the maximum value of C for conditions (I) to (III) was assumed to be constant at 0.5 mm^{-1} ($R = 2.0$ mm) as shown in Fig. 5 (a), while the maximum values of dC/dz_{max} , for conditions (I), (II), and (III) were assumed to be 0.61 mm^{-2} , 1.96 mm^{-2} , and 5.99 mm^{-2} , respectively (Fig. 5 (b)).

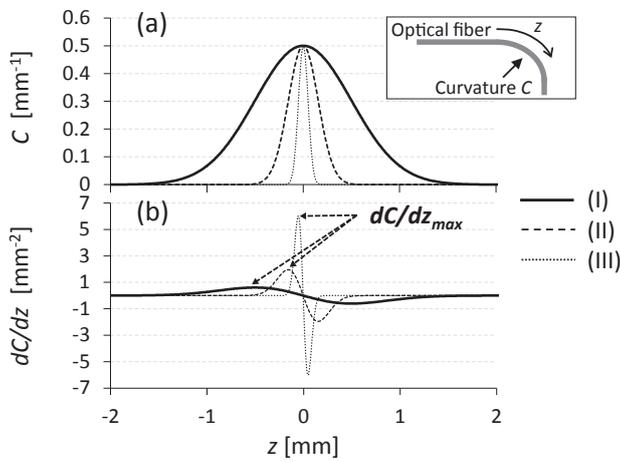


Fig. 5. Curvature of optical fiber assumed in BPM calculations (a) Curvature C , (b) Curvature change rate dC/dz

Figure 6 shows the simulation results of the evolution of the electric field distribution as the light propagates along the bent fiber. For the calculation, a straight wave-

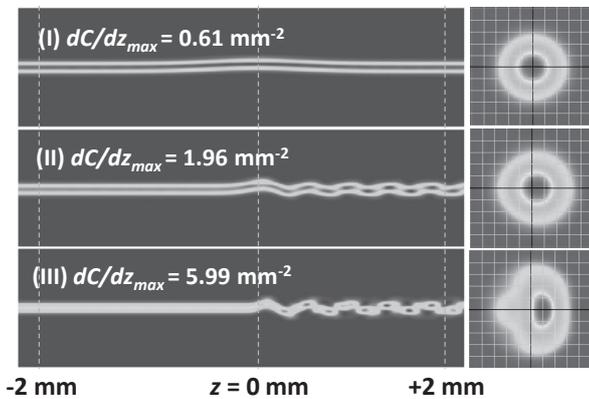


Fig. 6. BPM calculation results

guide having a refractive index distribution equivalent to each bending shape was assumed. In condition (I) where dC/dz_{max} is small, it was confirmed that a symmetrical electrical field distribution is maintained throughout the bend, indicating that dominance of the fundamental mode. On the other hand in condition (III), where dC/dz_{max} is large, disturbance of the electrical field distribution implies the excitation of a higher order mode. The GC on a SiPh chip is usually designed so that the coupling loss with a fundamental mode of standard SMF is minimized. Therefore, the occurrence of a higher order mode results in an increased coupling loss.

The coupling loss between a bent-BIF and a GC was estimated by assuming that the mode profile of the GC is the same as that of SMF. Below we study the coupling loss between a bent-BIF and a standard SMF (hereafter referred to as SMF coupling loss). Figure 7 shows the relationship between the electrical field distribution obtained for respective dC/dz_{max} conditions and the coupling loss with the fundamental mode of an SMF. From the almost-linear relationship between dC/dz_{max} and the SMF coupling loss, we found that $dC/dz_{\text{max}} < 2 \text{ mm}^{-2}$ is required to maintain an SMF coupling loss < 0.5 dB (and hence between the BIF and GC).

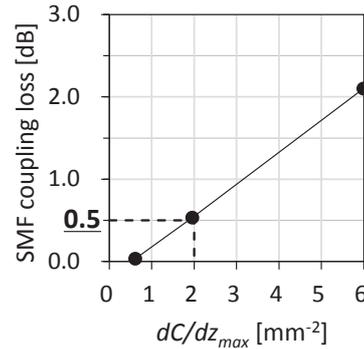


Fig. 7. Relationship between dC/dz_{max} and SMF coupling loss

4. Characteristics of FBGE

Based on the study results discussed above, we fabricated an 8-fiber FBGE with a mechanically transferable (MT) connector and measured their characteristics. A fabricated FBGE is shown in Fig. 8. With an overall height of

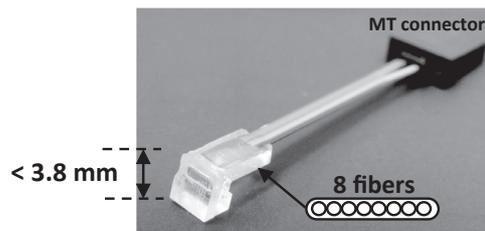


Fig. 8. Photograph of 8-fiber FBGE with MT connector

3.8 mm or less, the FBGEs were compact enough to fit inside an optical transceiver enclosure. Figure 9 shows typical C and dC/dz profiles of a bent optical fiber that was fabricated using the stress-free bending process described above. The maximum value of C ranged from 0.4 to 0.5 mm^{-1} ($R = 2.0$ to 2.5 mm), verifying that the target bending radius could be achieved. Furthermore, dC/dz maintained within ± 2 mm^{-2} over the entire length of the bend, thus, SMF coupling loss < 0.5 dB is expected.

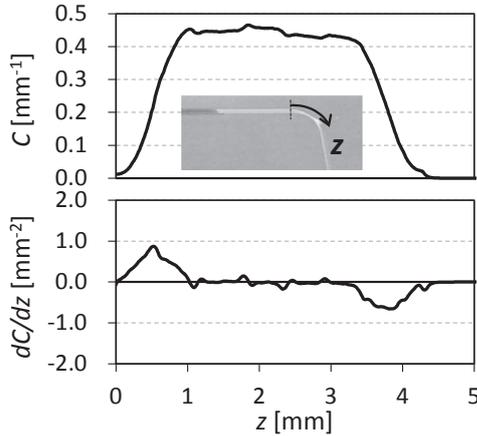


Fig. 9. Measurement result for curvature C and curvature change rate dC/dz of bent optical fiber

In order to evaluate the coupling loss with an SMF (and hence a GC) experimentally, we actively aligned an SMF optical fiber array with the end face of an FBGE as shown in Fig. 10, and measured the SMF coupling loss. Figure 11 shows the histogram of the measurement result for $N = 1224$ ch (8 ch \times 153 samples). Considering that this result includes the connection loss of the MT connector shown in Fig. 10, we confirmed that the overall insertion loss of the FBGEs is < 0.5 dB. This verifies that the newly developed FBGE can be coupled with SiPh chips with low loss.

Table 3 summarizes the reliability evaluation results of the FBGE. The evaluation test was carried out in compliance with Telcordia GR-1221-CORE. For the 18 samples, the change in insertion loss before and after the test was equal to or less than the standard value of 0.5 dB. No damage to these samples were found after the test. After 2,000 hours of damp-heat and 500 thermal cycles, which are specified in the standard as extended reference test items, the samples were free of fracture and change in loss. These results confirm the sufficiently high reliability of the FBGE, despite the sharp bend in the fibers.

5. Conclusion

Bending optical fibers using a stress-free process has led to the newly developed FBGE that is space-efficient and has a low height of < 3.8 mm. The FBGE meets the Telcordia GR-1221-CORE standard for reliability and

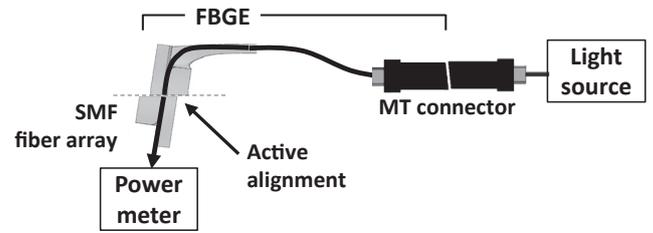


Fig. 10. Measurement setup for coupling loss to SMF

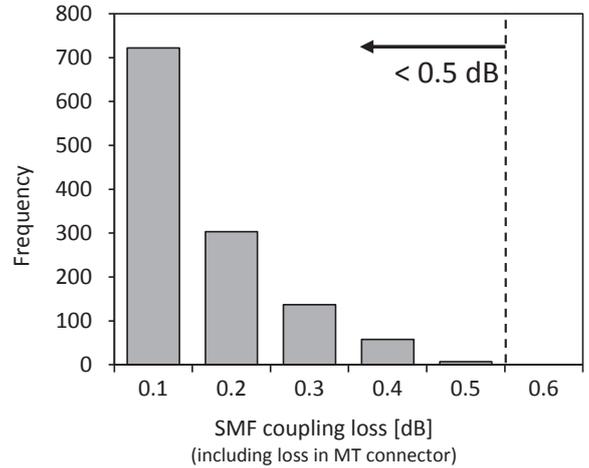


Fig. 11. Histogram of SMF coupling loss (including connection loss at MT connector interface)

Table 3. Reliability test result ($N = 18$) Test conditions comply with Telcordia GR-1221-CORE

Test item	Test condition	Change in insertion loss [dB] hang	Fracture
Mechanical shock	6 directions, 3 times in each direction, 500 G, 1 ms	-0.07-0.03	0
Vibration	10 to 2,000 Hz, Sinusoidal wave, 20 G	-0.11-0.12	0
Thermal shock	0 to 100°C, 5 min, 15 times	-0.11-0.08	0
Fiber integrity twist	0.5 kg, 10 times	-0.11-0.12	0
Cable retention	0.5 kg, 1 min	-0.11-0.11	0
High temp.	85°C, 2,000 h	-0.11-0.12	0
Damp heat	85°C/85% 500 h, 2,000 h (Extended)	500 h: -0.11-0.05 2000 h: -0.11-0.11	0
Temperature cycle	-40 to 85°C, 100 circles, 500 circles (Extended)	100 cyc: -0.08-0.06 500 cyc: -0.07-0.07	0

enables low-loss coupling with SiPh chips. With its compactness, high reliability, and low loss, the FBGE is an ideal optical interconnection device for SiPh optical transceivers.

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

Technical Terms

- *1 Silicon photonics (SiPh): SiPh is a technology for integrating optical transmitter and receiver functions onto a silicon chip. SiPh is generally useful for fabricating highly cost-effective optical transceivers, since this technology uses a smaller number of components than that for conventional optical transceivers.
- *2 Mode Field Diameter (MFD): The MFD is defined as the diameter of the spread of electrical field distribution in the propagation mode of a single-mode optical fiber. In an optical connection, the connection loss increases as the difference in MFD between the two fibers increases.
- *3 Quad Small Form-Factor Pluggable (QSFP): QSFP is an industry standard for optical transceivers.

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