Highly Reliable and Low-Loss Bent Polarization Maintaining Fiber with High Polarization Extinction Ratio

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Abstract *PMFs with ultra-small bending radius are studied for realizing space-efficient fiber coupling to CPO module. By applying Stress-free bending technique, bent PMF with high PER (>25 dB) and low loss (<0.05 dB), while no residual stress at cladding part demonstrated even at 2.2 mm-radius bending. ©2022 The Author(s)*

Introduction

Power consumption of signal transmission in data centers has been increasing and Co-Packaged Optics (CPO) has been attracting attention as a candidate technology to overcome the issue [1]. CPO integrates optical transmission functions near the switch ASIC and shortens the power-hungry interconnects over electrical wiring thus expected to reduce the power consumption by 30% [2].

In order to deliver light from an external light source module (ELS) to a CPO module, polarization maintaining fibers (PMFs) are required to propagate polarized light from laser chip without polarization-mode coupling and insertion loss (IL). Figure 1 shows the Schematic of CPO switch. In order to realize space efficient CPO modules with surface coupling type silicon photonics chip enabled by grating coupler (GC) [3], it is necessary to bend the PMF at nearly right angle for realizing optical interfaces accessible from side of module.

However, a general optical fiber bent mechanically at an ultra-small bending radius (*R* ≤ 5 mm) is subjected to large stress and the probability of the fiber breakage increases significantly. The probability of the fiber breakage within 5 years when the fiber (ϕ125 μm) is bent at the 90 degrees and a 2.5 mm bending radius can reach 100% [4,5]. In addition, the polarization maintaining characteristics deteriorate as PMF bending radius decrease [6].

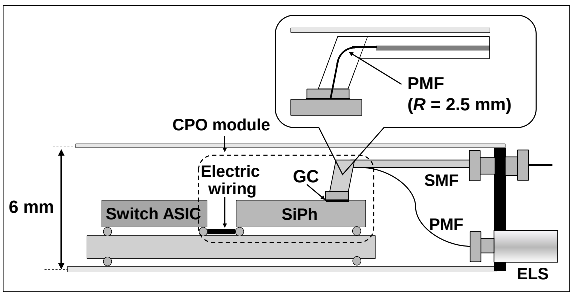
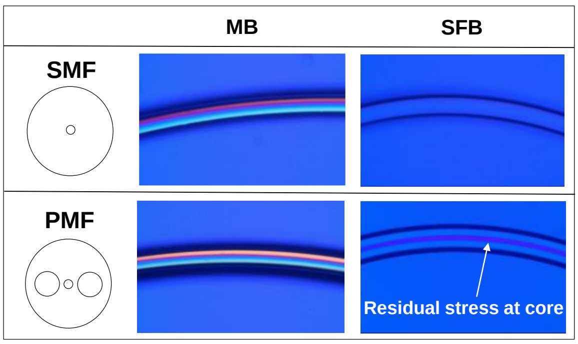


Fig. 1: Schematic of CPO with grating coupler and fiber coupler with bent PMF

In order to address these challenges, we studied stress-free bending technique (SFB) realized by heat treatment [3] and demonstrated PMF bent at an ultra-small bending radius of 2.5 mm with low IL and high polarization extinction ratio (PER).

Influence of heat treatment on bent PMF

As SFB relaxes residual stress by heat treatment, we examined influence of SFB on the stress inside PMF. Figure 2 shows polarizing microscope images of single-mode fibers (SMFs) and PMFs (ϕ125 μm, *R* ≃ 2.5 mm) bent by the mechanical bending (MB) and by SFB. In the case of MB, both SMFs and PMFs showed coloured appearance, indicating stress was applied on the entire bending area. In the case of SFB, the coloured appearance disappeared in the SMF, indicating the stress disappeared completely, whereas the colouring in the core region remains in the PMF. This means the bending stress is relaxed in the clad region of PMF, while the stress and birefringence in the core can be selectively remained. Therefore, bent PMFs by our optimized SFB is expected to have both high reliability features and polarization maintaining characteristics.



(Φ125 μm, *R* ≅ 2.5 mm)

Fig. 2: Polarizing microscope Images of bent fibers

SFB process optimization for PMF

As it is well known that PER deteriorates when a PMF is twisted [7,8], we examined the requirement for SFB process to realize PMF without PER degradation. Figure 3 shows the setup for the twisting test. In this experiment, a straight PMF without bending was fixed on the rotation stage and twisted, thereby for evaluating the twisting effect only. Then, we heated the twisted PMF with length of around 0.2 mm and measured PER. Figure 4 shows the setup for the PER measurement. We used an SLD light source with a wavelength of 1310 nm, two polarizers, and a power meter. The rotational angle of polarizer1 was fixed and so that single polarized light launched into the sample PMF. The polarizer2 was rotated and the transmitted light was detected by the power meter. PER indicates the intensity ratio of two orthogonal polarizations and is expressed by Equation 1:

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

P_{max} represents the maximum light intensity when the two polarizers place parallelly, and P_{min} represents the minimum light intensity when the two polarizers place vertically, respectively.

Figure 5 shows the measured dependence of PER on twist angles. The solid circles are the result of the measurement and the dashed line represents the calculated result using Malus's law [9]. Measured PERs are in good agreement with the Malus's law and degraded as the twist angle increased. Hence, the PER degradation by SFB is explained by only angle rotation mismatch at twisted region and influence of birefringence induced by elastic formation is negligible. As bending fiber length for 90º bent at R = 2.5 mm is around 4 mm, the bending part consist of 20 parts of heated zone. Since the worst-case scenario for PER degradation is the case where each rotation angle error accumulated, twisting angle of each heated part must be less than 0.25° (= 5°/20 parts) for maintaining PER more than 20 dB [10]. Hence, we optimized SFB process so that PMF is not twisted more than this threshold during the process.

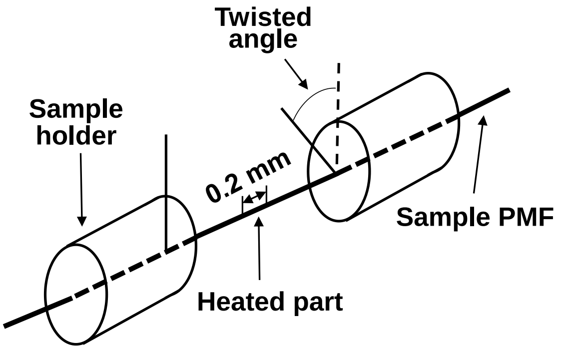


Fig. 3: Set up for the twisting test

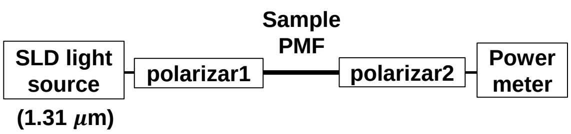


Fig. 4: Set up of PER measurement.

Dependence of PER on bending radius and bending direction

In order to obtain low bending loss even at a small bending radius, we prepared a bend-insensitive PMF (MFD = 7.7 μm, R = 5 mm bending loss < 0.03 dB / turn at wavelength 1310 nm) for this study. PMFs were bent by SFB with bending radii ranging from 1.5 mm to 3.5 mm and without twist as described above. As shown in Fig. 6, we made two types of bent PMFs by controlling bending directions. The 0° direction referred to the case where two stress-applied parts (SAP) were arranged parallelly to the bending plane, whereas the 90° direction referred to the case where they were arranged vertically.

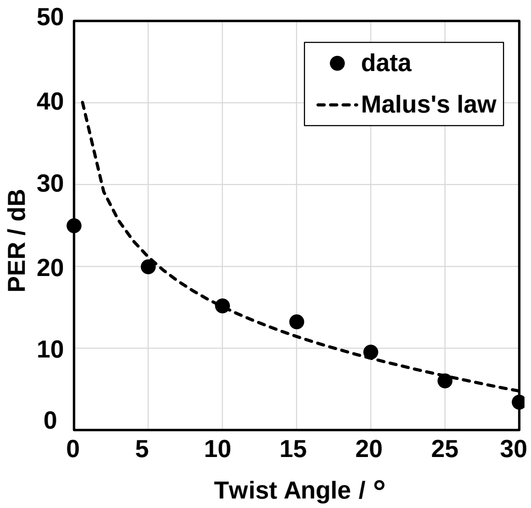


Fig. 5: Measured dependence of PER on twist angles

Tab. 1: Measured dependence of IL on bending radius

Bending method	Bend radius /mm	IL /dB (0°direction)	IL /dB (90°direction)
SFB	1.5	0.00	0.21
	2.5	0.02	0.04
	3.5	0.01	0.03
MB	1.5	0.03	0.08
	2.5	0.01	0.01
	3.5	0.00	0.04

Table 1 shows the measured IL of all bending conditions. In almost all cases, IL was less than 0.1 dB, except the condition of R = 1.5 mm with MB.

The Figure 6(a) shows the measured PER plotted as a function of bending radius for the 0° direction case. In the figure, small circles represent measured raw data, while large circles are the averaged values for each bending radius. In the case of SFB, PER more than 25 dB was successfully confirmed at $R \geq 2.2$ mm, which is considered the sufficient bending radius for realizing the space efficient CPO module package. At R = 1.5 mm, PER degraded to 19.7 dB, which is worse than the PER obtained by the MB case. However, PER of 19.7 dB can still be considered high enough, as it corresponds to less than 0.1 dB coupling loss due to polarization mismatch between PMF and GC.

Figure 6(b) shows the dependence of PER on a bending radius in the case of 90° direction. On the contrary to the 0° direction case, PER of the PMF bent by SFB decreased to 15 dB or less. Figure 7 shows NFP images observed at the end face of samples bent in the 0° and 90° directions. In the MB, regardless of the bending direction, NFP images stayed concentric circle shapes and this means single mode propagation maintained. In SFB, the NFP image of the 0° direction kept a concentric circle, while that of the 90° direction showed an irregular shape. Therefore, it is considered that the PER deterioration seen in SFB at the bending direction of 90° is relating to higher-order mode excitation. The reason for higher chance of higher-order mode excitation in the 90° direction is because in the 0° bending direction, the SAP with negative refractive index is in the bending plane and the separation between the fundamental and higher-order modes is greater, whereas in the 90° direction the SAP is not in the bending plane and the separation between the modes is smaller. Although further study required, as it is known that higher-order mode excitation occurs due to bending curvature discontinuity in SFB technique [5], the PER degradation can be suppressed even for 90° direction case by careful bending curvature distribution tailoring and PMF design optimization.

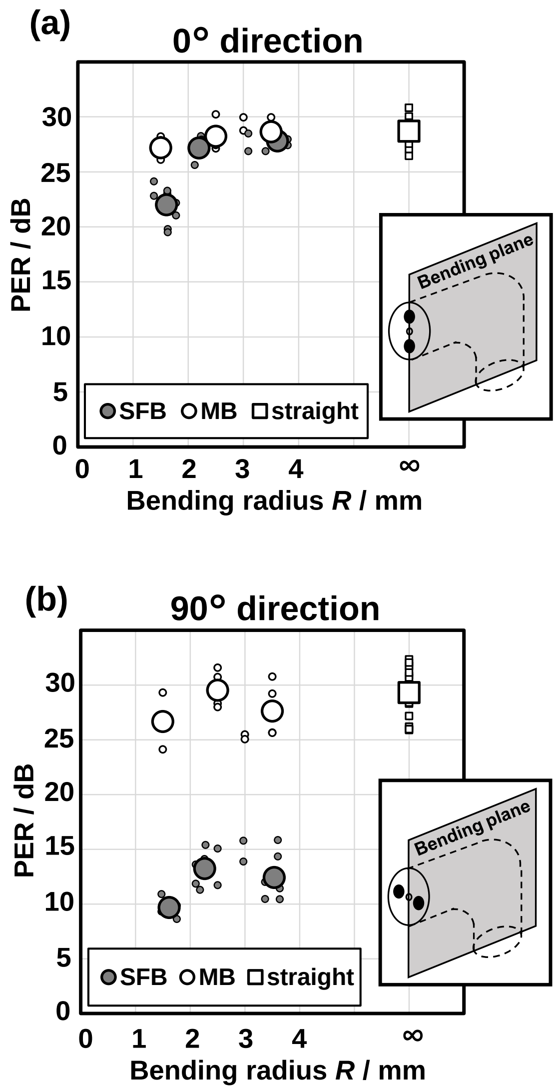


Fig. 6: Measured dependence of PER on bending radius in the **(a)** 0° and (b) 90° direction

Conclusions

We studied the applicability of stress-free bending technique on PMFs and demonstrated the low-loss and high PER more than 25 dB in the 0° bending direction, while residual stress at cladding relaxed completely even at a bending radius of 2.2 mm. Therefore, bent PMFs with stress-free bending technique can offer highly reliable and space efficient solution for PMF coupling to CPO modules with surface coupling type silicon photonics chips.

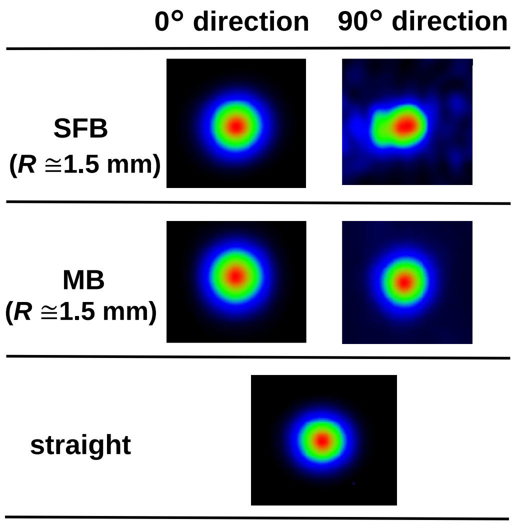


Fig. 7: NFP images of the bent and straight PMF

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