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Low insertion loss and high return loss fiber bundle fan-in/fan-out for four-core multi-core fiber

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Abstract: *We have developed a fiber bundle fan-in/fan-out for four-core multi-core fibers based on physical-contact design. It demonstrates insertion loss less than 0.6 dB, crosstalk less than -55 dB and return loss more than 50 dB.*

Keywords: *Space division Multiplexing, Optical fiber devices, Multi-core fiber, Fan-in/fan-out*

I. INTRODUCTION

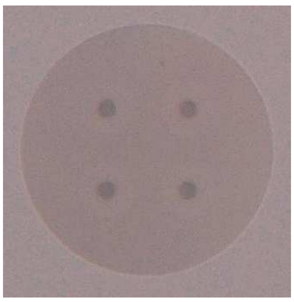
In recent years, data traffic has been rapidly expanding. Ultra-high-fiber-count optical fiber cables have been developed for inter-data center communication, whereas the capacity demand for increasing data traffic is even higher. In order to further increase communication capacity, Spatial Division Multiplexing (SDM) technologies using multi-core fiber (MCF) are expected for the next generation inter-data center network as well as terrestrial and submarine cable networks [1].

In SDM communication systems, Fan-in/Fan-out (FIFO) is an indispensable component to connect MCFs with a transmission system using single-core fibers (SCFs). Several configurations of fiber bundle FIFOs have been reported up to now for four-core MCFs [2] and seven-core MCFs [3]. The most important characteristic of FIFO for keeping power penalties low in a system is low insertion loss (IL). High return loss (RL) is also getting more and more important, as the deployment of 400 Gbps Ethernet links using PAM4 modulation increases in inter-data center network. RL of more than 55 dB is desirable to reduce the impact of multi-pass interference due to reflection [4, 5].

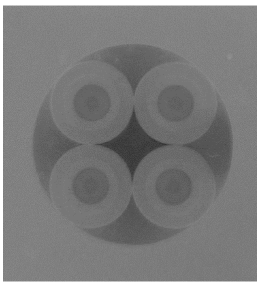
In this paper, we propose and demonstrate fiber bundle FIFO for four-core MCFs based on a physical-contact (PC) design for data center applications. This structure simultaneously allows for low IL and high RL, because the cores of MCF and fiber bundle are rotationally aligned and directly connected to each other by PC. After assembling the FIFOs, we measure IL, RL, crosstalk and IL variation over a temperature range of -40 to 85 ºC at the wavelengths of 1.31 and 1.55 µm.

II. DESIGN OF BUNDLE FIFO

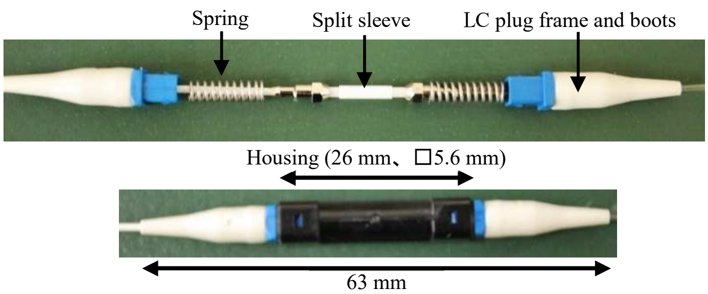
We used an un-coupled four-core MCF (single-mode, MFD: 8.6 µm@1.31 µm, cladding diameter: 125 µm). The MCF cores were arranged on a square lattice with a core pitch of 40 µm as shown in Fig. 1 (a). The MCF was terminated with a zirconia ferrule (outer diameter: 1.25 mm). We also used trench assisted SCFs for the fiber bundle to minimize bending loss in the ferrule. The SCFs were reduced from 125 µm to 40 µm in diameter with chemical etching. The diameters were equivalent to the MCF core pitch. When the etched SCFs were inserted into a ferrule hole with a suitably designed diameter, which is about 96.5 µm, their core positions matched with the core arrangement of the MCF as shown in Fig. 1 (b). The FIFO structure is shown in Fig. 1 (c). The MCF and the fiber bundle were polished to achieve PC. The MCF and the fiber bundle were connected inside a split sleeve after rotational alignment. The ferrule pairs were floated inside a housing designed based on an LC connector structure to connect MCF with a fiber bundle by PC. Hence, RL can be expected to be higher than that of MCFs connected with adhesive. The size of the FIFO is 5.6 mm square × 63 mm long.



(a) End face of MCF



(b) End face of bundle

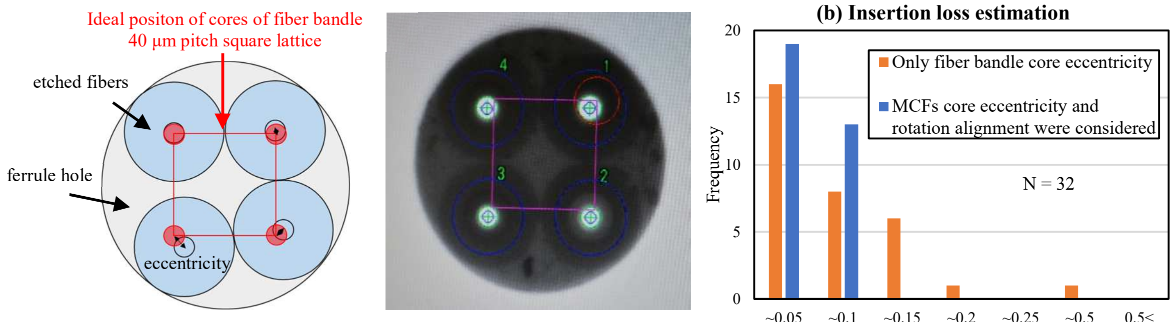


(c) FIFO structure

Fig. 1. End faces of MCF (a) and bundle (b) and FIFO structure (c).

III. ECCENTRICITY OF CORES AND IL ESTIMATION

We prepared 8 terminated MCFs and 8 etched fiber bundles. Core eccentricity of a bundle is mainly caused by a miss-match of etched SCF diameters and the coaxiality of ferrules. We measured the actual core eccentricity of all bundles and MCFs beforehand by an image processing system as shown in Fig. 2 (a). The average core eccentricities of bundles and MCFs were 0.42 and 0.60 µm, respectively. The maximum core eccentricities of bundles and MCFs were 1.12 and 1.02 µm, respectively. IL was estimated from the misalignment between bundles and MCFs by Marcuse's formula [6]. Estimated IL distribution is shown in Fig. 2 (b). The orange bar shows the case with no MCF eccentricities and the blue bar shows the case with actual MCF eccentricities. MCF eccentricity includes not only the MCF itself but also the coaxiality of the ferrule. The mutual rotational positions between the 4 MCF cores and the 4 bundle cores were optimized to gain the lowest IL in the latter case. The estimation result indicates IL of less than 0.5 dB for each FI and FO is possible by the use of well-controlled outer diameter etched fibers. IL less than 0.1 dB for each FI and FO is also possible with an optimized core combination by rotational alignment.



(a) Measurement of core eccentricity of bundle

Fig. 2. Measured core eccentricity (a) and estimated IL from the actual bundles (b).

IV. OPTICAL CHARACTERISTICS OF FIFO

We evaluated the optical characteristics of 4 pairs of the FIFOs at the wavelengths of 1.31 and 1.55 µm. The SCFs were terminated by LC connectors as shown in Fig. 3 (a). IL was evaluated with an optical power source with 1.31 and 1.55 µm and a power detector. The IL distribution of the FIFO pairs is shown in Fig. 3 (b). The maximum IL was 0.57 dB per FIFO pair, or 0.285 dB per FI or FO , assuming both FI and FO have the same loss. The measured ILs were higher than the estimated loss in Fig. 2 (b) . It may be due to IL of the LC connector at the optical power input and the bending loss of the etched fibers in the fiber bundles. The difference in IL between 1.31 and 1.55 µm may be also due to fiber bending loss sensitivity. Therefore, lower IL can be expected by suppressing fiber bending loss.

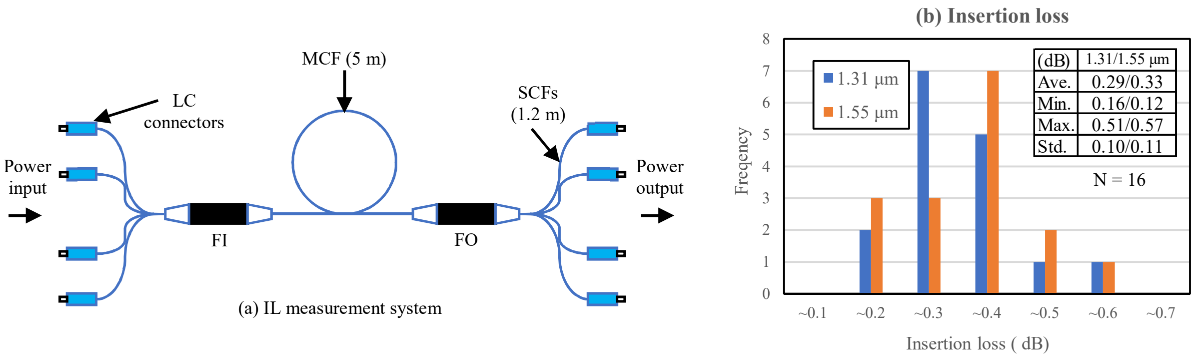


Fig. 3. IL measurement system (a) and IL distribution of FIFO pairs (b).

We also tested IL variation during a temperature cycle in the range of -40 to 85 °C. Figure 4 shows the IL variation in ten cycles at the wavelengths of 1.31 and 1.55 µm. The IL variation was within ± 0.1 dB at both wavelengths. More stable operation can be expected under a controlled environmental temperature range, which is -10 to 60 °C.

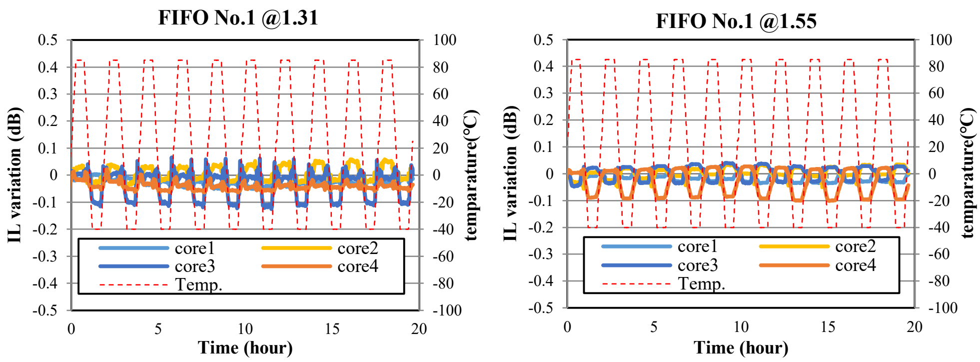


Fig. 4. Optical power variation during temperature cycle.

Crosstalk was evaluated with a 4-ch optical power detector. Figure 5 (a) shows the distribution of crosstalk of FIFO pairs. The average crosstalk was -68.0 dB at 1.31µm and -61.6 dB at 1.55 µm. The maximum crosstalk was -63.7 dB at 1.31 µm and -55.8 dB at 1.55 µm.

Figure 5 (b) shows the distribution of RL measured with an OTDR system. The average RL was 57.5 dB at 1.31 µm and 58.3 dB at 1.55 µm. The minimum RL was 51.7 dB at 1.31 µm and 54.5 dB at 1.55 µm. A RL more than 50 dB is equivalent to a UPC polishing in the optical connector standard. There were some lower RL cores. It may be caused by scratches or contamination occurring during rotational alignment or the surface shape of polished MCFs and bundles end faces did not meet the PC condition [7]. RL more than 55 dB can be achieved by solving these challenges in the future.

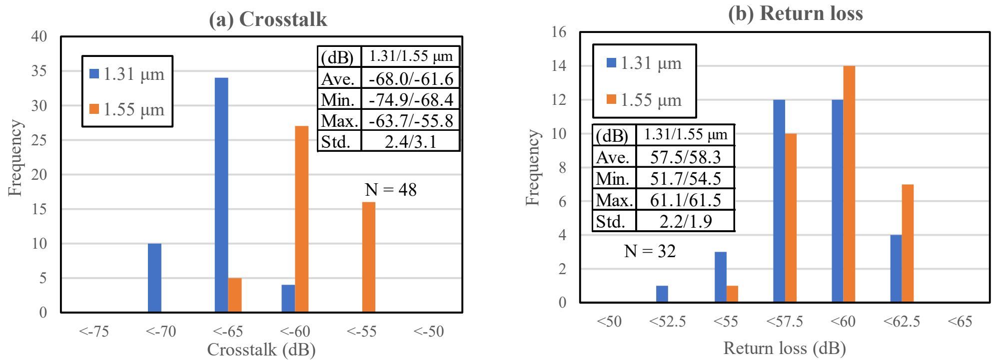


Fig. 5. Histograms of crosstalk (a) and return loss of FIFOs (b).

V. CONCLUSIONS

In this study, we fabricated the FIFOs for four-core MCF based on physical-contact design. To connect the cores directly by physical contact, we achieved IL less than 0.6 dB per FIFO pair and confirmed low IL variation of ±0.1 dB over a temperature cycle test at both 1.31 and 1.55 µm. We also demonstrated crosstalk less than -55 dB per FIFO pair and a return loss more than 50 dB at the both wavelengths of 1.31 and 1.55 µm.

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