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FEATURED TOPIC

Fiber Bundle Fan-in/Fan-out for Four-Core Multi-Core Fiber

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Next-generation transmission systems using multi-core fiber (MCF) for data center applications require fan-in/fan-out (FIFO) devices with low insertion loss (IL) and high return loss (RL). A fiber bundle FIFO can achieve low IL and high RL by high-precision core eccentricity control of the fiber bundle and physical contact connection between the MCF and the fiber bundle. Although our FIFO is designed to allow only rotational alignment*1 between the MCF and the bundle, the optical characteristics of the fabricated FIFO devices achieved IL of less than 0.3 dB and RL of more than 50 dB.

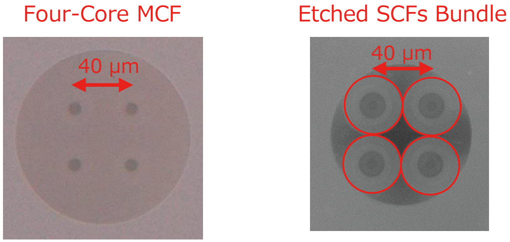
Keywords: space division multiplexing transmission technology, multi-core fiber, fan-in/fan-out

1. Introduction

In recent years, data traffic has rapidly increased with the spread of high-definition video streaming services. Correspondingly, the transmission capacity of single-core fiber (SCF) has been expanded by dense wavelength division multiplexing technology, but it is reaching the fiber input power limit.(1) Since the transmission capacity is expected to reach the limit in the near future, space division multiplexing transmission technology is being developed to increase transmission capacity by spatially dividing transmission paths. Multi-core fiber (MCF), which has multiple cores (light transmission paths) within a single optical fiber, is one promising technology and can increase transmission capacity in proportion to the number of cores without increasing the installation area.(2)

It is assumed that the transmission systems using MCF will start with a configuration that MCF is connected to transceivers with an SCF interface using fan-in/fan-out (FIFO) devices. Since the use of FIFOs in the transmission path increases the number of connection points compared to the current system, FIFOs are required to have low insertion loss (IL) as well as high return loss (RL) above 55 dB to prevent transmission errors due to multi-path interference*2 between connection points.(3),(4)

We have developed a fiber bundle type FIFO (bundle FIFO) to achieve low IL by core eccentricity control and high RL by physical contact (PC) connection. This FIFO is suitable for uncoupled 4-core MCFs that are expected to be adopted for data center applications.(5) This paper introduces the basic design and the characteristics of the FIFO.



MCF	
Core	SM/Uncoupled
MFD	8.6 μm (λ=1.31 μm)
Cladding	125 μm
Core pitch	40 μm

Etched SCF	
Core	SM/Trench
MFD	8.6 μm (λ=1.31 μm)
Cladding	40 μm

Fig. 1. Specifications of 4-core MCF and bundle

2. Design of Bundle FIFO

The bundle FIFO consists of an uncoupled 4-core MCF with a 40 μm square lattice configuration and an SCF bundle. Figure 1 shows the specifications of the 4-core MCF and the bundle. The MCF is a single mode (SM) with a mode field diameter (MFD) of 8.6 μm at the wavelength of 1.31 μm and a cladding diameter of 125 μm. Bend-insensitive SCFs with the same MFD as the MCF were etched from 125 μm to 40 μm in diameter. Four etched SCFs were inserted into the hole of a zirconia ferrule, and then terminated. The hole diameter is designed so that the cores of the SCFs are arranged in a square lattice configuration. The core position of the bundle can be easily matched to that of the MCF.

One feature of this FIFO is the PC connection between the MCF and the bundle. PC connection is a connection technique used in optical fiber connectors. When a pressing force is applied between the ferrules with their tips butted against each other, the fiber ends are elastically deformed, and adhere tightly without gaps, resulting in a high RL at the PC connection.

Figure 2 shows how to assemble a FI or FO device (FO device). The MCF and the bundle are rotated and aligned in a zirconia split sleeve, and then placed in housing to complete the PC connection. For PC connection, the housing design is based on LC connector*3 parts. The housing size is 63 mm × 5.6 mm × 5.6 mm, including the boot components. Photo 1 shows a picture of a FIFO pair with FO devices connected to both ends of the MCF.

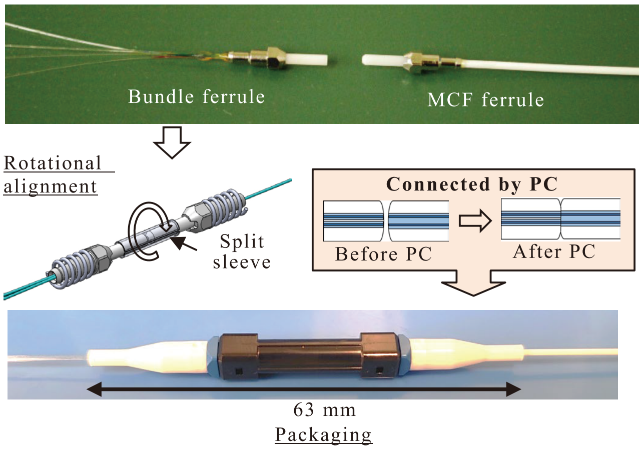


Fig. 2. FO device assembly and PC connection

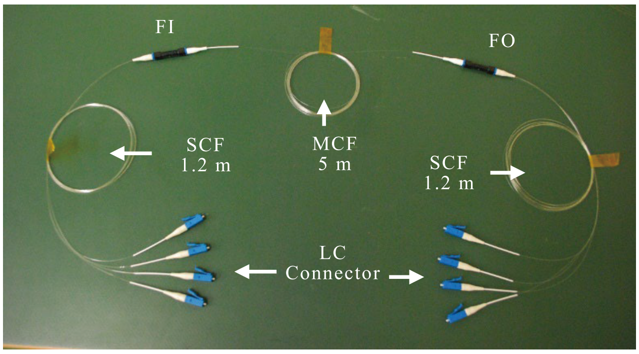


Photo 1. Picture of FIFO pair

The optical characteristic targets for the FO devices are set to IL <0.5 dB, RL >55 dB, and crosstalk (XT) <-50 dB.

3. Core Eccentricity Control

3-1 Core Eccentricity

The IL of the FIFO is degraded mainly by the core position mismatch between the MCF and the bundle, which is caused by core eccentricity of the bundle due to manufacturing variations. Figure 3 shows an overview of the bundle core eccentricity. In this bundle FIFO design, the ferrules of the MCF and bundle are inserted into a split sleeve to fix the XY axis for ease of assembly, and only rotational alignment can be performed. Since ferrules, which have been developed in the field of optical connectors, have high coaxiality of inner and outer circumference and high accuracy of inner and outer diameter, rotational alignment in SCF connection is easily achieved by aligning the outer circumference of the ferrule. However, in the case of bundles, eccentricity control is more difficult due to (1) eccentricity of the ferrule hole relative to the ferrule outer circumference, (2) misalignment of the fiber due to clearance in the ferrule hole, and (3) variation in the outer diameter of the etched fiber. The core eccentricity of bundles and MCFs is defined here as the deviation of the actual core position from the designed core position at the apex of a square of 40 µm per side placed at the center of the ferrule outer circumference.

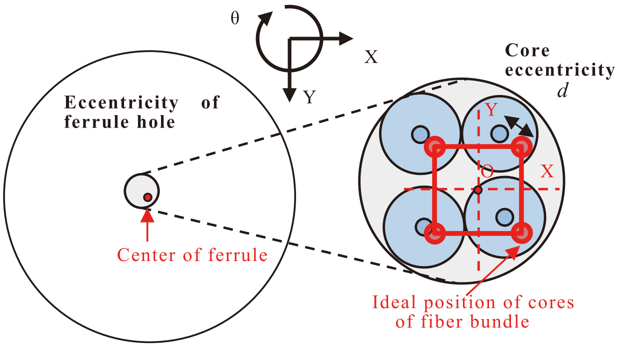


Fig. 3. Eccentricity overview

3-2 Bundle Core Eccentricity Control

We performed simulations to determine the target for the outer diameter variation of etched fibers, which is the main cause of bundle core eccentricity. 40 µm is the ideal outer diameter of the etched fiber to be inserted into the ferrule hole without gaps to match the MCF core pitch of 40 µm. In this case, the ferrule hole diameter would be approximately 96.6 µm. In actual manufacturing, however, slightly larger hole or thinner fibers must be used because clearance is required to insert the fiber into the ferrule hole. Therefore, in the simulation, IL was calculated assuming a fiber with an outer diameter of 39-40 µm for a ferrule hole diameter of Φ97 µm. Based on the Monte Carlo method, cores were randomly positioned so that the distance between cores in the ferrule was larger than the fiber diameter, and the core eccentricity d was calculated. IL can be calculated from the core eccentricity d using Eq. 1.(6) The IL value of the bundle was defined as the maximum IL of the four cores calculated from the core eccentricities.

$$\mathrm{IL} = 10\log\left(\exp\left(\frac{d^2}{MFD^2}\right)\right) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

The cumulative probability of IL obtained as a result of 10,000 calculations is shown in Fig. 4. The result shows that a yield rate of 90% for a target IL <0.5 dB is achievable for a fiber outer diameter of 39.5 µm or larger. Based on this result, we set the fiber diameter control target to ±0.25 µm.

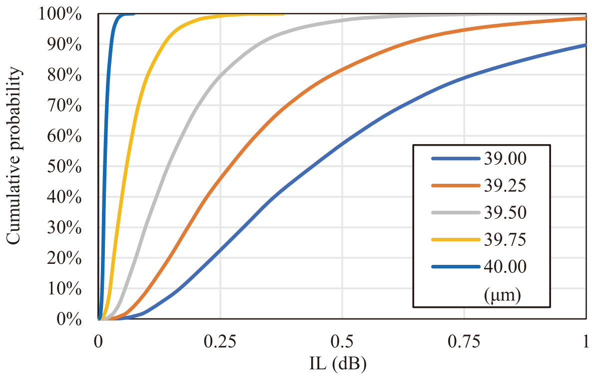


Fig. 4. IL yield rate by fiber diameter

We fabricated eight bundles by preparing etched fibers based on the results of the previous simulation. Figure 5 shows the core eccentricity of the eight bundles measured with an image-processing measuring instrument. The core eccentricity of the bundles was 0.42 μm on average. In addition, the distribution of IL estimates calculated from the core eccentricity with respect to the ideal MCF is shown in Fig. 6. The average IL was 0.06 dB and the maximum IL was 0.30 dB. The core eccentricities were suppressed by using etched fibers with an appropriate outer diameter to the ferrule hole diameter and a small diameter variation.

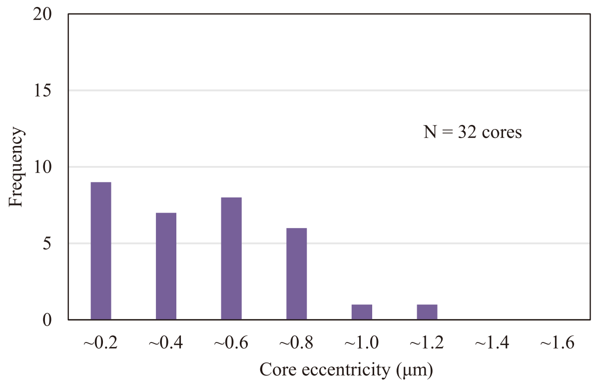


Fig. 5. Core eccentricity of the fabricated bundles measurement

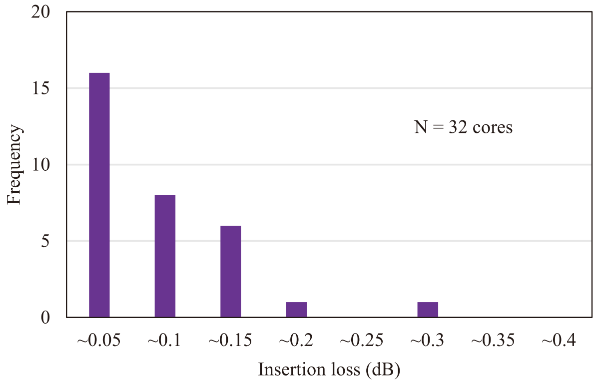


Fig. 6. IL estimates calculated from bundle core eccentricity

3-3 Rotational Alignment

In FIFO assembly, the core eccentricity of the bundle is compensated by rotational alignment with MCFs that also have core eccentricity. A schematic diagram of rotational alignment is shown in Fig. 7. The cores of the MCF and bundle rotate with the center of the ferrule outer circumference in the split sleeve. Since both ferrule hole centers have eccentricity to the outer circumference center, when only rotational alignment is performed, there are positions where the distance between the cores of the MCF and bundle is the largest and the smallest.

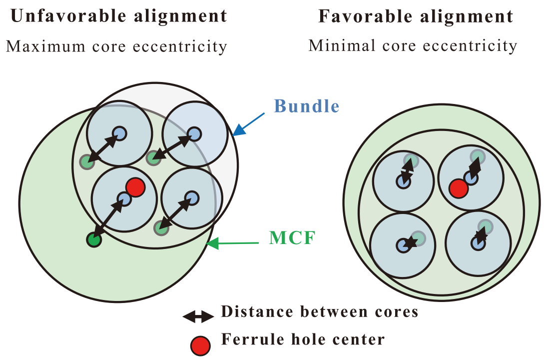


Fig. 7. Schematic diagram of a rotational alignment

The core eccentricity of eight MCFs was also measured to simulate the rotational alignment. The core eccentricity of the MCF was 0.60 μm on average and a maximum of 1.02 μm. Figure 8 shows an example of IL variation by rotational angle when a bundle with an average core eccentricity of 0.85 μm and an MCF with an average core eccentricity of 0.79 μm are rotationally aligned. Since the four cores are arranged in a square configuration, there is an angle at which the total IL value of the four cores becomes small every 90 degrees. Among them, the IL of the four cores is smallest near one direction where the ferrule hole eccentricity direction coincides.

The results of IL estimation simulating rotational alignment with 8 MCFs are shown in Fig. 9. Since the rotational alignment compensated for each other's core eccentricity,

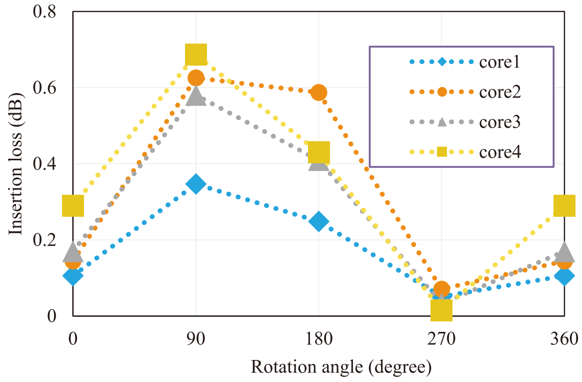


Fig. 8. IL variation by rotation angle in rotational alignment

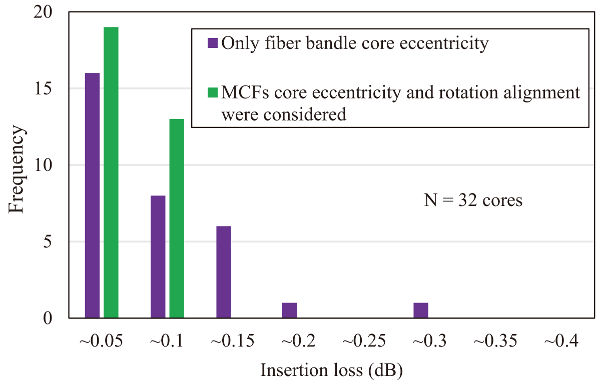


Fig. 9. IL estimates considering rotational alignment

the maximum IL value was estimated to be 0.1 dB. These results suggest that even a simple assembly with only rotational alignment can be sufficient for low IL FIFO production if eccentricity-controlled bundles are used.

4. Optical Characteristics of FIFO

Four FIFO pairs were fabricated by MCFs and bundles whose core eccentricity was measured, and their optical properties were evaluated. Measurements were made at wavelengths of 1.31 μm and 1.55 μm, respectively. Table 1 summarizes the results of the measurements of IL, RL, and XT, which are the main characteristics.

Table 1. Measurement results of optical characteristics

(1.31/1.55 μm) [Unit: dB]

	IL	RL	XT
N	16	32	48
Ave.	0.29/0.33	57.5/58.3	-68.0/-61.6
Min.	0.16/0.12	51.7/54.5	-74.9/-68.4
Max.	0.51/0.57	61.1/61.5	-63.7/-55.8
SD.	0.10/0.11	2.2/1.9	2.4/3.1

Figure 10 shows the distribution of IL for a FIFO pair. Simply multiplying the result of measurements by 0.5 to convert the IL per FO device unit, the maximum value was 0.255 dB at the wavelength of 1.31 μm. The measured ILs were higher than the value of less than 0.1 dB obtained in the rotational alignment simulation. The reasons for this deviation may be the inclusion of LC connector connection loss in this measurement system and fiber bending loss in the bundle ferrule.

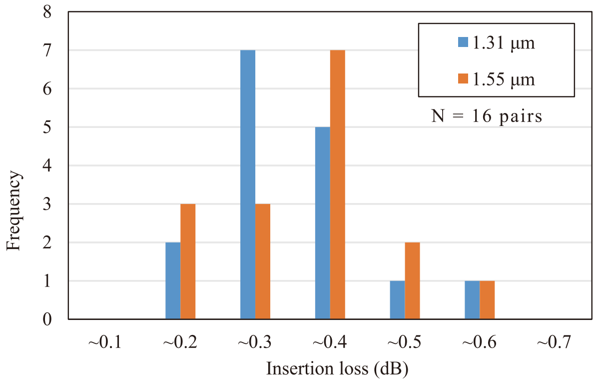


Fig. 10. IL measurement result

Figure 11 shows the measurement results of the RL of the FIFO devices. Note that the RL was measured using the OTDR*4 system and was measured for each FO device. Although some cores failed to the target of 55 dB, the average was 57.5/58.3 dB (wavelength: 1.31/1.55 μm).

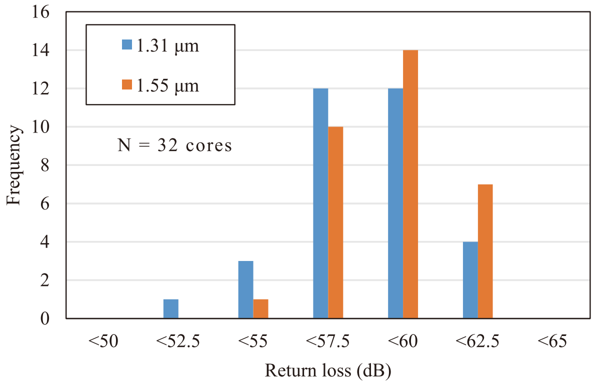


Fig. 11. RL measurement result

Figure 12 shows the XT results for the FIFO pair. XT produced in the nth core with light in the mth core is defined as Eq. 2. XT achieved the target value at both wavelengths.

$$XT_{m,n} = \frac{Pout_n}{Pout_1 + Pout_2 + Pout_3 + Pout_4} \quad (m \neq n) \quad \cdots (2)$$

The FIFO pair was placed in a thermostatic oven to evaluate the IL temperature dependence. The evaluation conditions were -40°C to 85°C, referring to the “Category OP+^{HD}” conditions of IEC61753-1. Figure 13 shows the IL variation at the wavelength of 1.31 μm for one sample. In

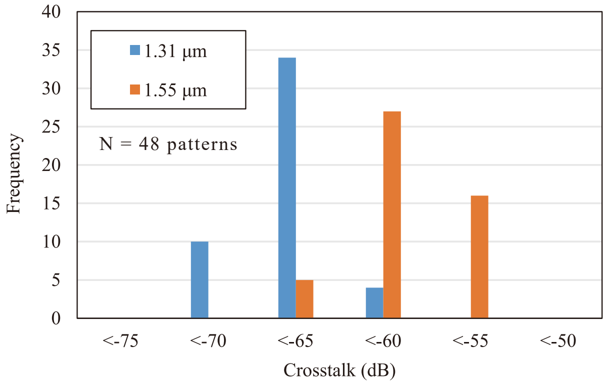


Fig. 12. XT measurement results

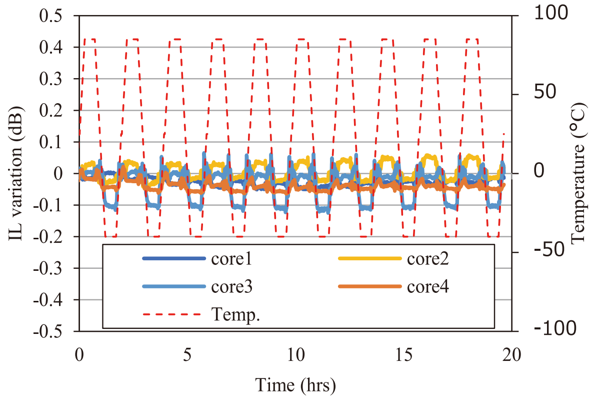


Fig. 13. Temperature-dependent loss

all cores, the IL followed the temperature change, but the fluctuation range was within ±0.1 dB.

5. Conclusion

We introduced the design and optical characteristics of a bundle FIFO suitable for data center transmission systems using 4-core MCFs. Low IL by high-precision core eccentricity control and high RL by PC connection were achieved.

The core eccentricity data of the fabricated bundles showed that the core eccentricity can be suppressed by controlling the etched fiber diameter. The core eccentricities of the bundle and MCF are compensated by the rotational alignment, and an IL less than 0.1 dB due to the core eccentricity is possible.

The bundle FIFO achieved the target in IL and XT, and RL missed the target by 55 dB in some cases but achieved the target in the average value.

In the future, we would like to contribute to the spread of MCF transmission systems by further improving FIFO characteristics.

Technical Terms

*1	Alignment: To align the optical axis in the assembly of an optical device. Adjustments are made in the vertical, horizontal, forward/backward, rotational, and tilt directions by usually monitoring optical power.
*2	Multi-path interference: Interference between multiple modes and reflected light of an optical signal propagating in an optical fiber, leads to degradation of transmission quality due to fluctuations of optical power in time.
*3	LC connector: A compact PC connector used in places where high-density wiring is required, such as rack-to-rack wiring in servers.
*4	OTDR: Optical Time Domain Reflectometer (OTDR) is a measuring instrument used to evaluate loss and reflection measurements of optical fiber transmission paths.

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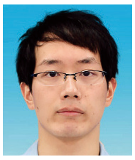

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