

Compact Spatial Optical Coupling Fan-in/Fan-out Devices for Multi-core Fibers

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Multi-core fibers (MCFs) have been developed to address the recent surge in communication traffic. Fan-in/Fan-out devices (FIFOs) that connect MCFs to single-core fibers (SCFs) have also been developed at the same time. While various types of FIFOs have been reported so far, types suitable for systems requiring low loss and high reliability are limited. One option is the spatial optical coupling type*¹ FIFO. However, achieving compact FIFOs was challenging due to the complexity of the optical system. We have realized a compact FIFO with a diameter of 3 mm through a new design that utilizes thermally expanded core (TEC) fibers.*²

Keywords: multi-core fiber, fan-in/fan-out, spatial optical coupling

1. Introduction

In recent years, multi-core fibers (MCFs) have been developed to address the recent surge in communication traffic.^{(1),(2)} In the future, the practical application of MCF in submarine optical cable networks and data center networks is anticipated. Regarding submarine, a system partially utilizing MCF is already being deployed.⁽³⁾ While MCF has an advantage in reducing cable space, devices for the system have not yet fully caught up with MCF compatibility and still rely on conventional single-core fiber (SCF) devices. Therefore, fan-in/fan-out devices (FIFO) for connecting MCF and SCF are necessary. For example, in long-haul MCF transmission systems, placing FIFO devices in front and behind optical amplifiers and gain equalizers,*³ as shown in Fig. 1, allows the use of the same optical amplification technology as that used for SCFs. SCF repeaters do not have enough space to accommodate additional devices. Therefore, the development of small-footprint FIFOs is essential. Since the optical power is higher after amplification, high power durability is necessary. When FIFOs are used in submarine systems, long-term reliability beyond that of terrestrial applications is also necessary due to the difficulty of repairs and replacements. The FIFO we have developed is a spatial optical coupling type that does not use resin in optical paths, and owing to the laser-welding assembly, it is advantageous in terms of long-term reliability, including high power resistance. MCF devices, having more channels (chs) compared to SCF devices, usually complicate the

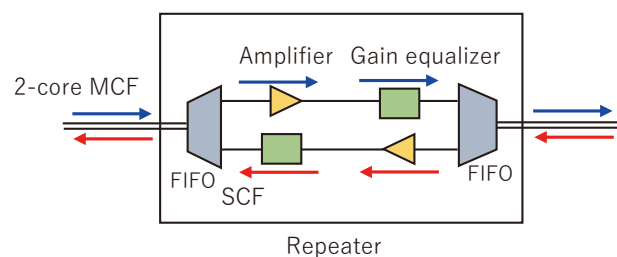


Fig. 1. Schematic diagram of an MCF Repeater

optical system. As a result, they have a disadvantage in miniaturization. On the other hand, our new FIFO has achieved an outer diameter of 3 mm, equivalent to or smaller than that of SCF devices by utilizing thermally expanded core (TEC) fibers.⁽⁴⁾ This paper presents the design and characteristics of two types of FIFO for MCF: a 2-core fiber and a 4-core fiber that have been prototyped.

2. Comparison of Previous and New Optical System Designs

We have previously prototyped spatial optical coupling type FIFO devices.^{(5),(6)} To compare the previous optical system with the new one, schematic diagrams are shown in Figs. 2 (A) and (B), respectively. In the previous design (A), there were four lenses opposing a 4-core SCF array, matching the number of cores. However, since arranging four lenses would considerably increase the outer diameter of the FIFO, a micro-lens array with four integrated lenses was used instead. In this case, if light from an adjacent channel hits the lens, it causes optical loss.

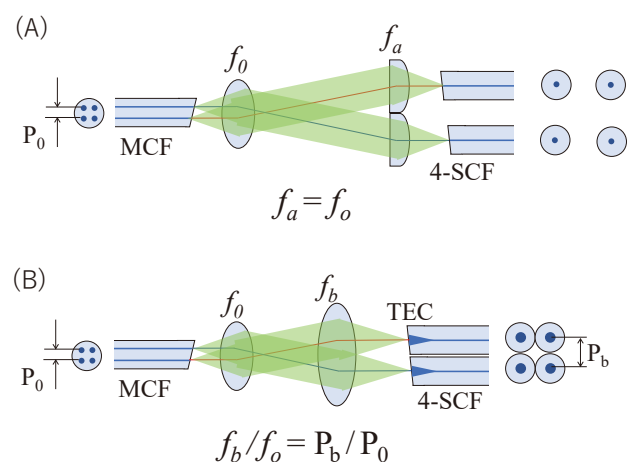


Fig. 2. Schematic of optical systems
(A): previous one and (B): new one

Therefore, the beams between adjacent channels needed to be separated as shown in Fig. 2 (A) before being focused by the micro-lens. Consequently, this requires an increase in distance among the fibers of SCFs, then makes it difficult to be downsized. On the other hand, in the new design (B), a single lens is shared by four SCFs. As shown in Fig. 2 (B), it is possible for the beams between adjacent channels to overlap at the lens and be focused without increasing optical loss. Therefore, the SCF arrays can be formed into bundles where adjacent SCFs come into contact with each other, and this enables the FIFO to be reduced in diameter. In this design, assuming the core pitch of the MCF is P_0 and that of the SCF array is P_b , the magnification of the lens system is P_b / P_0 . Consequently, the mode field diameter (MFD), at the MCF end face should also be enlarged by a factor of P_b / P_0 at the SCF end face. MFD is an indicator of beam size in single-mode fibers. To achieve low-loss coupling, the MFD of each SCF end faces is expanded with TEC treatment technology. In the lens system, in design (A), when the focal lengths of the lenses on the MCF side and SCF side are denoted as f_0 and f_a , respectively, they are set to be $f_a / f_0 = 1$ to achieve 1:1 coupling between the MCF and SCF. On the other hand, in design (B), when the focal lengths of the lenses on the MCF side and SCF side are denoted as f_0 and f_b , respectively, they are set to be $f_b / f_0 = P_b / P_0$.

3. Specifications of Optical Fibers

3-1 Specification of 2-core fiber

Specifications of an MCF and an SCF array used for the FIFO of the 2-core MCF are listed in Table 1. End face photographs of the MCF and the SCF array, along with the near field patterns (NFP)*⁴ of the SCF before and after TEC treatment, are shown in Figs. 3 (A), (B), and (C), respectively. Both the MCF and SCF are designed as single-mode (SM) fibers. The MCF has uncoupled cores with low crosstalk (XT) between the cores.

A core pitch of the MCF is $35.5 \mu\text{m}$, while that of a SCF array is $125 \mu\text{m}$, resulting in a core pitch ratio of 3.5 times. Since the MFD of the MCF at a wavelength of $1.55 \mu\text{m}$ is $10 \mu\text{m}$, SCFs with the MFD of $35 \mu\text{m}$, which is 3.5 times larger, are used. An MFD before TEC treatment is $10.4 \mu\text{m}$.

Table 1. Specifications of 2-core MCF and SCF array

	2-core MCF	2-SCF array
Core type	SM/Uncoupled	SM
MFD@ $\lambda 1.55 \mu\text{m}$ [μm]	10	10.4 35 in TEC
Cradding diameter [μm]	125	125
The nearest core-core pitch [μm]	35.5	125

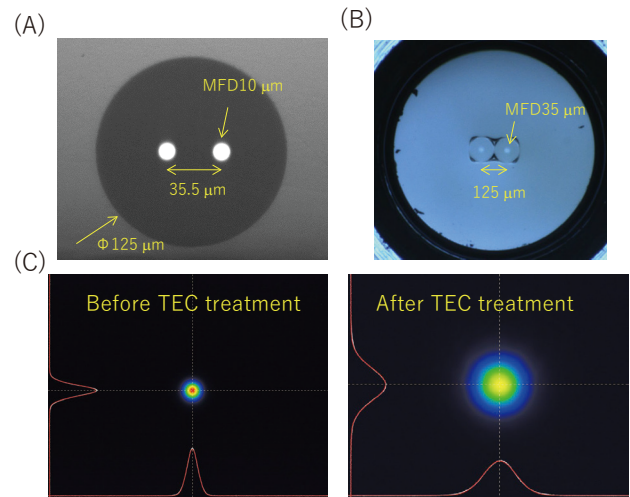


Fig. 3. End face photographs of 2-core MCF and 2-core SCF array, and NFP before and after TEC treatment

3-2 Specification of 4-core MCF

Specifications of the MCF and SCF array used for the FIFO of the 4-core MCF are listed in Table 2. End-face photographs of the MCF and SCF array, along with an NFP of the SCF after TEC treatment, are shown in Figs. 4 (A), (B), and (C), respectively.

A pitch between the nearest adjacent cores of the MCF is $40 \mu\text{m}$, while a pitch of the nearest adjacent cores in the SCF array is $125 \mu\text{m}$, resulting in a core pitch ratio of 3.1 times. Since the MFD of the MCF at a wavelength of $1.55 \mu\text{m}$ is $9.8 \mu\text{m}$, SCFs with the MFD of $30.5 \mu\text{m}$,

Table 2. Specifications of 4-core MCF and SCF array

	4-core MCF	4-SCF array
Core type	SM/Uncoupled	SM
MFD@ $\lambda 1.55 \mu\text{m}$ [μm]	9.8	10.4 30.5 in TEC
Cradding diameter [μm]	125	125
The nearest core-core pitch [μm]	40	125

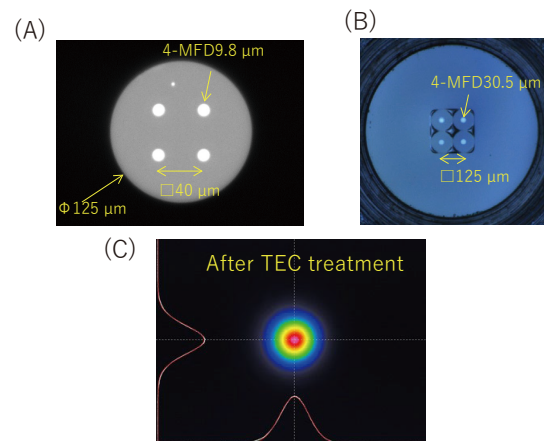


Fig. 4. End-face photographs of 4-core MCF and 4-core SCF array, and NFP before and after TEC treatment

which is 3.1 times larger, are used. An MFD before TEC treatment is 10.4 μm . The NFP before TEC treatment is the same as shown in Fig. 3 (C).

4. Prototyping

Assembly procedures of the FIFOs for the 2-core MCF and the 4-core MCF are almost the same. In both cases, the sub-assemblies*⁵ held in a metal holder are first assembled, and then, the sub-assemblies were actively aligned each other with the optical powers monitored to minimize loss and fixed together using laser welding. The only difference between the two was whether the number of monitored ports for optical power during alignment*⁶ was two or four. As shown in (B) of Figs. 3 and 4, an outer diameter of the ferrule used to hold the fibers was the same for both the 2-core and 4-core. Consequently, both sub-assemblies were made with the same outer diameter. A photograph of the assembled FIFO for the 4-core MCF is shown in Photo 1. An outer diameter of the metal housing is 3 mm, with a total length of the metal tube portion (excluding the boot) being 50 mm, and the total length including the boot being less than 65 mm. Since the metal housing dimensions of the FIFO for the 2-core MCF are the same, the photograph for that is omitted.

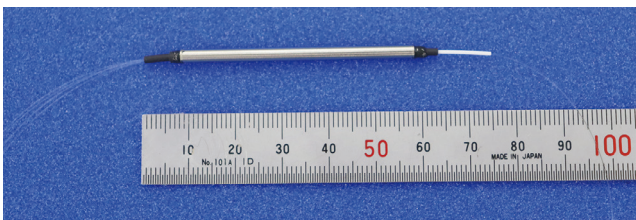


Photo 1. Assembled FIFO for 4-core MCF

A key feature of these FIFOs is that the tips of the SCFs are processed with TEC technology to expand the MFD, thereby allowing the use of a single lens for the SCF array. By utilizing TEC fibers with an MFD 3.5 or 3.1 times larger than non-TEC fibers, the optical system becomes significantly less sensitive to optical loss changes due to axial misalignment. On the other hand, while it is more sensitive to angular misalignment, FIFOs are structurally designed to minimize the occurrence of angular misalignment. Therefore, they not only reduce the risk of assembly failure during laser welding but also offer reliability advantages. The FIFOs have minimal loss degradation, even if optical axis misalignments occur after assembly due to environmental changes like temperature or humidity.

5. Optical Characteristics

5-1 Example of optical characteristics of 2-core MCF

An insertion loss (IL), a polarization-dependent loss (PDL), a crosstalk (XT), and an isolation (ISO) of the FIFO

for the 2-core MCF were measured in the C-band.*⁷ A setup of the measurement system is shown in Fig. 5.

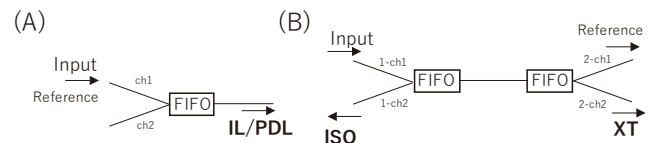


Fig. 5. Optical characteristics measurement system setup for the FIFO for the 2-Core MCF

As for the IL and PDL in (A), measurements were taken with a single FIFO, while XT and ISO in (B) were measured with two FIFOs connected. In this measurement, XT represents the amount of signal light leaking into adjacent channels, and ISO indicates the performance in blocking light that returns in the opposite direction to the signal light. IL is an indicator representing optical loss, or efficiency, where lower values are preferable. PDL indicates how much IL can fluctuate depending on the polarization state of the light signal, where a lower value is also preferred for stable IL. Lower XT is desirable as it does not degrade the signal quality of adjacent channels. In the case of the 2-core MCF, it is assumed that one core is used for upstream and the other for downstream signals. If light leaks to the opposite direction in an adjacent channel, it could degrade the signal quality of that channel. Therefore, a larger ISO value (which has an opposite sign to XT) is preferred.

Characteristics examples for IL, PDL, XT, and ISO are shown in Figs. 6 (A), (B), and (C). As shown in (A), the IL showed flat spectrums with minimal wavelength dependency in the C-band. The PDL was below 0.1 dB. The XT and ISO, as shown in (B) and (C), were below -55 dB and above 55 dB, respectively. Regarding XT of the FIFO, it includes not only the XT inherent to the spatial optics section in the FIFO but also the XT inherent to the MCF itself. However, since the MCF in this FIFO is only 10 m or shorter, the influence of the MCF is expected to be minimal.

The IL distribution for $N = 38$, totaling 76 channels, is shown in Fig. 6 (D). The values used for the IL distribution are the maximum and average values within the C-band for each sample. Both values were below 0.35 dB, with averages of 0.22 dB and 0.2 dB, respectively. The reflection loss at a wavelength of 1.55 μm for each channel was measured with two FIFOs connected. All of them were more than 50 dB. These results are at a practical level of use.

5-2 Example of optical characteristics of 4-core MCF

Characteristics of IL, PDL, XT, and ISO of the FIFO for the 4-core MCF were also measured in the C-band. A setup of the measurement system is shown in Fig. 7, and characteristic examples are shown in Fig. 8 (A), (B), and (C).

IL and PDL in (A) were measured with a single FIFO, while XT and ISO in (B) and (C) were measured with two FIFOs connected as similarly to the FIFO for 2-core MCF.

The definitions for XT and ISO are the same as those of the FIFO for the 2-core MCF. While the IL of the FIFO for the 4-core MCF is higher than that for the 2-core MCF, it still shows low loss at below 0.3 dB, with flat spectrums and minimal wavelength dependency in the C-band. PDL, XT, and ISO results are at also the same level as those of the

FIFO for the 2-core MCF. These results are at a practical application level, as well as the FIFO for the 2-core MCF.

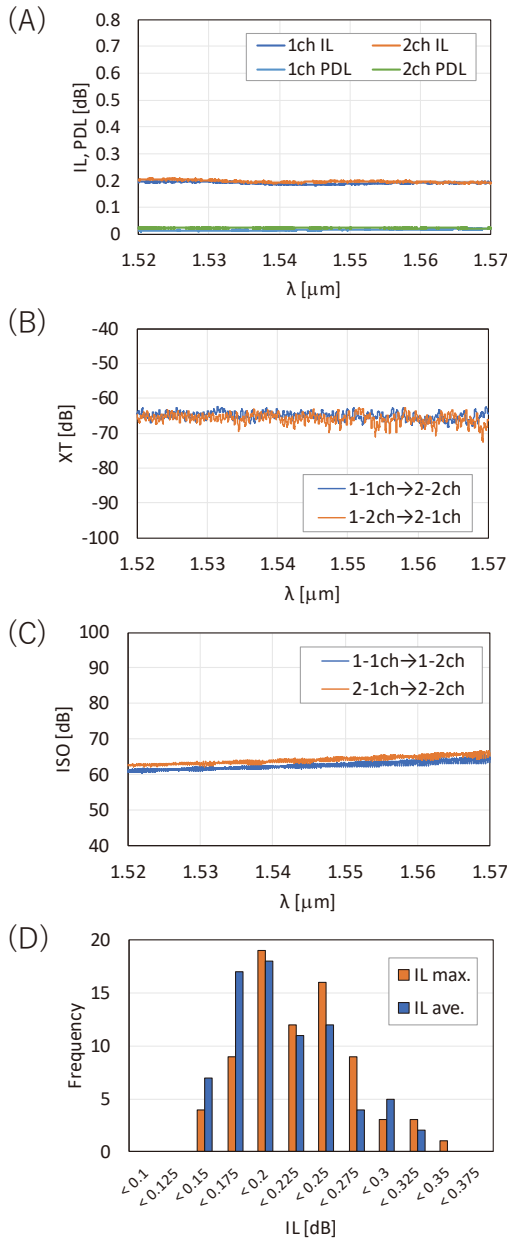


Fig. 6. Example of optical characteristics of the FIFO for the 2-core MCF, (A) IL, PDL; (B) XT; (C) ISO; (D) IL distribution

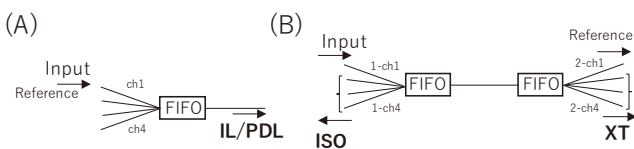


Fig. 7. Optical characteristics measurement system setup of the FIFO for the 4-core MCF

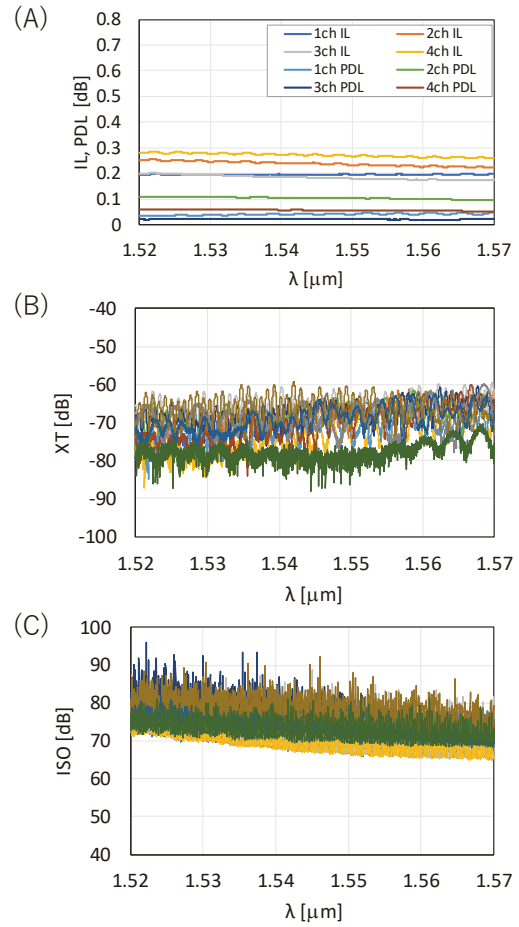


Fig. 8. Optical characteristics of the FIFO for the 4-core MCF, (A) IL, PDL; (B) XT; (C) ISO

6. Reliability

6-1 Environmental test

As for the FIFO for the 2-core MCF, main environmental tests compliant with the Telcordia[®] reliability standard GR-1221-CORE for passive optical components were conducted, and confirmed that they met the criteria. The results are summarized in Table 3. Each test of damp heat, temperature cycling, high temperature storage, and low temperature storage were conducted using 11 FIFOs / each test. The IL variations before and after each testing were sufficiently smaller than the target of 0.3 dB.

Table 3. Reliability test items and results

Test	Condition	Time or cycle	Sample size	Criteria	Judge
Damp heat	85°C/85%RH	2000 hr	11	Δ IL < 0.3 dB	Pass
Temp cycling	-40°C/85°C	500 cycle	11		Pass
High temp storage	85°C	2000 hr	11		Pass
Low temp storage	-40°C	1000 hr	11		Pass

6-2 High power test

A high optical power transmission test was conducted with a FIFO pair for the 2-core MCF to verify its durability. While the optical power within repeaters is typically expected to be below 23 dBm, a 100-hour test at an optical power of 34 dBm, which is over 12 times higher, was conducted as shown in Fig. 9. No decrease in optical power output from the FIFO pair was observed.

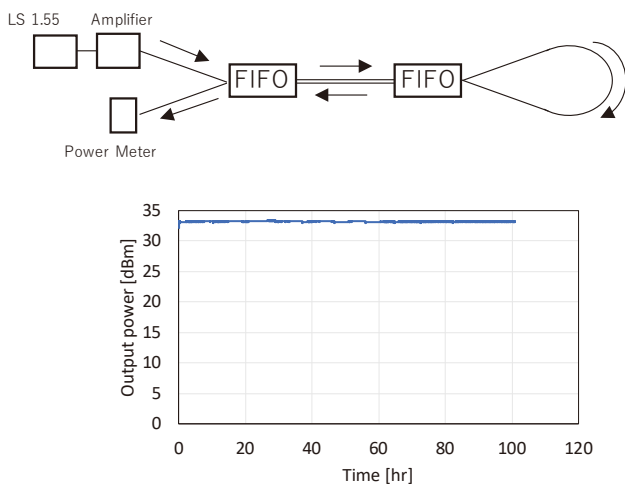


Fig. 9. High power test setup and output optical power stability

7. Conclusion

This paper presented the results of the prototyping and evaluation of FIFOs for MCF designed for applications that require compact size, low loss, and high reliability. The external dimensions are $\phi 3.0 \text{ mm} \times \text{L}65 \text{ mm}$, making it compact. The insertion loss (IL) was below 0.3 dB, with no wavelength dependence in the C-band. Other characteristics of PDL, XT, ISO, and RL also demonstrated a practical use level performance. We conducted main environmental tests in compliance with the Telcordia reliability standard GR-1221-CORE, and confirmed that the characteristics remained stable. A 100-hour high optical power test was also conducted with over 12 times the light power of practical use, and no degradation of IL was observed.

The combination of high optical power and environmental durability is attributed to the spatial optical coupling design and the use of laser welding technology in assembly. Additionally, the use of TEC fibers has contributed to the miniaturization of the device.

We anticipate that this FIFO will play an important role with the widespread adoption of MCF transmission systems.

Technical Terms

- *1 Spatial optical coupling type: An optical system using lenses and/or mirrors that propagates light in a space. A light can be controlled more flexibly in free space than inside an optical fiber. Therefore, spatial optical coupling type devices are popular.
- *2 Thermally expanded core (TEC) fiber: TEC is an abbreviation for "Thermally Expanded Core". In TEC fiber, a core section that transmits light is expanded by heating.
- *3 Gain equalizer: When amplifying optical signals, the amplification gain varies depending on the wavelength. A gain equalizer is a device to equalize this variation.
- *4 Near field pattern (NFP): The intensity distribution of optical output at the end face of optical fibers or laser devices.
- *5 Sub-assembly: A collection of components that make up an entire device. By combining multiple assemblies (sub-assemblies), a single device is formed.
- *6 Alignment: The process in the assembly of optical devices. Aligning the position and angle of optical fibers or lenses so that the optical axis (the axis along which light propagates) coincides. When this adjustment is performed while allowing light to pass through to minimize loss, it is called active alignment.
- *7 C-band: Abbreviation for "Conventional-Band," one of the wavelength bands used in optical communications. The wavelength range is from 1.53 to 1.565 μm , where optical fiber transmission loss is lowest.
- *8 Telcordia: This standard originated from specifications established by Bell Labs in the United States for optical communication equipment. Telcordia standards are widely used as standard specifications today.

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