Loss performance of a field-deployed cable link with 288 four-core multicore fibers

Takuya Oda[1], Shota Kajikawa[1], Katsuhiro Takenaga[1], Kentaro Ichii[1]
Okimi Mukai[2], Daiki Takeda[2]

A high-density optical fiber cable link with 288 four-core multicore fibers (MCFs) and 288 pairs of fan-in-fan-out devices was deployed in the field, and its losses were evaluated. No excess losses were observed from the MCF-related components during the field installation.

1. Introduction

With the rapid expansion of data center services, the necessity for high-capacity optical fiber networks between buildings is increasing, and the effective use of limited space is a key issue. For example, by increasing the core density of optical fiber cables, more information can be transmitted without changing the duct size. There have been initiatives to reduce the diameter of optical fiber cables and single-core fibers (SCFs) to increase density [1) 2)]. Recently, multicore fibers (MCFs) have attracted attention as a solution for achieving a higher core density than SCFs. In particular, a weakly-coupled 4-core MCF (4c-MCF) with a standard cladding diameter of 125 μm is expected to be in practical use at an early stage of space-division multiplexing (SDM) technology [3)]. Various reports have been made on MCFs, peripheral technologies, transmission characteristics, and systems. However, there have been only a few reports on the characteristics of field-deployed MCF cable links. In addition, previous field experiments have shown that the number of MCFs in a cable is limited to a few to several dozen, and no reports have been made on the field characteristics of MCF cable links with a practical number of fibers exceeding 100 [4)].

We constructed a 1152-channel MCF link in a test field constructed with cables having 288 4c-MCFs and evaluated its insertion loss characteristics. The MCF cable achieved 5.2 times density compared to the SCF cables with the same core count of 1152. After deploying the MCF cable in the microduct in the test field, 288 pairs of fan-in-fan-out (FIFO) devices were terminated at both ends of the cable via MCF splicing. The insertion losses (IL) of the constructed MCF link were measured using optical loss test sets (OLTS). The measured ILs in the field were in good agreement with the estimated ILs based on the losses of each component, i.e., the average attenuation of the MCF cable, IL of the FIFO device, and MCF splice loss, confirming that no excess loss was observed owing to field installation.

2. Loss characteristics of MCF-related components

2.1. MCF cable

We fabricated Air-Blown Wrapping Tube Cable™ (AB-WTC) using 288 4c-MCFs. The AB-WTC was designed to be efficiently laid in a microduct with an inner diameter of approximately 10–16 mm by using compressed air [5)]. The combination of the AB-WTC and MCF enables numerous fiber cores to be laid with higher efficiency over longer distances than conventional methods. The 4c-MCF has a cladding diameter of 125 μm, coating diameter of 200 μm, and cores with an optical design compliant with ITU-T G.657.A1 [6)]. Figure 1 shows a cross-sectional image of the MCF cable and photographs of the fabricated MCF cable and 4c-MCF. The four cores arranged at equal intervals in a square lattice are individually distinguished by a marker with a different refractive index from that of the core placed at a position that breaks the core pattern symmetry. Each core number can be assigned based on the difference

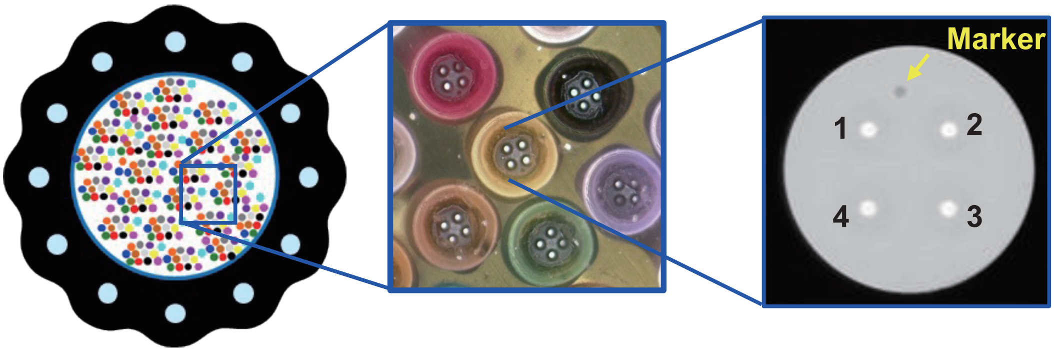

Fig. 1. Cross-sectional images of the fabricated MCF cable.

1:Optical Technologies R&D Center
2:Optical Cable Division

Abbreviations, Acronyms, and Terms.

MCF—Multi-core fiber
Optical fiber with multiple cores inside the cladding. Weakly coupled multi-core fiber is designed to suprsss core-to-core crosstalk. It can increase the transmission capacity per fiber by the number of cores by having each core transmit a different optical signal.

SCF—Single-core fiber
A conventional optical fiber with one core located in the center of the cladding. Also called as single mode fiber (SMF).

XT—Crosstalk
A phenomenon in which optical signal leakage from one core to another core in a multicore fiber becomes noise, degrading transmission quality. It is desirable to minimize as much as possible in weakly-coupled multicore fiber.

FIFO device—Fan-in-fan-out device
A device for inputt and output optical signals from each core of a multicore fiber to multiple single-core fibers.

ITU-T—International telecommunication union telecommunication standardization sector
The organization prepares recommendations for standards related to telecommunications.

100GBASE-LR4—100GBASE-LR4
A transmission standard compliant with the IEEE 802.3ba designed for single-mode fiber transmission with a maximum transmission distance of 10 km and a transmission bandwidth of 100 Gbps. Four wavelengths in the 1310 nm band are multiplexed.

OLTS—Optical loss test sets
A field-use equipment for optical loss measurement during installation and maintenance of optical fibers. Optical power is input from a light source connected to one end of an optical fiber link, and output optical power is measured with a power meter connected to the other end.

Table 1. Attenuation of the MCF cable (Sample size: 288 fibers, 1152 cores).

Wavelength (nm)	Attenuation (dB/km)			
	Average	Max.	Min.	Target
1310	0.34	0.37	0.31	≤ 0.4
1550	0.20	0.23	0.18	≤ 0.3

of the distance between the marker and each core. Consequently, the direction of core numbering is reversed at both ends of the MCF, resulting in polarity generation [7]. When two MCFs are connected, the number of connected cores changes depending on the combination of their polarity states. Therefore, polarity management is necessary for constructing MCF links with managed core numbering. The details of polarity management are described in Section 3.

The outer diameter of the fabricated MCF cable was 9.3 mm, and its weight was 59 kg/km. The 1152-channel SCF cable with the same number of cores had an outer diameter of 21.3 mm and a weight of 313 kg/km [8]. Thus, the MCF cable achieved a 5.2 times higher core density per unit area and 81% weight reduction. Table 1 lists the attenuations of the MCF cable, whose values are comparable to those of the SCF cables. Figure 2 shows the crosstalk (XT) between adjacent cores before and after cabling, with the XT values increasing and fluctuating more after cabling; these values were measured using the power meter method [9]. The error bars in Fig. 2 indicate the ranges of the maximum and minimum values for the measured 1152 cores. As reported in previous studies, the increase in XT is primarily due to the change in the bending radius from the strand bobbin-wound state to the cable drum-wound state [6]. The main cause of the increased fluctuation in XT is attributed to the variation in the arrangement states of each 4c-MCF in the cable.

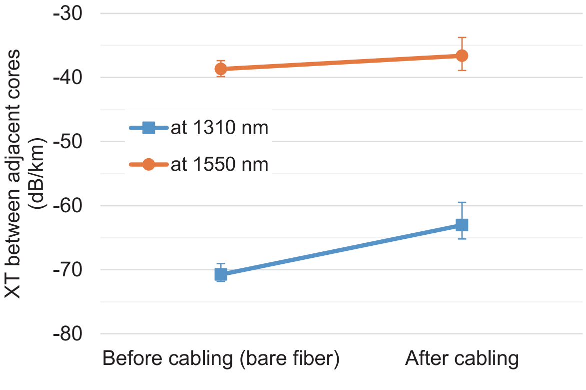

Fig. 2. Changes in XT between the adjacent cores of 4c-MCF before and after cabling (Sample size: 288 fibers, 1152 cores).

2.2. *MCF splicing*

The Fujikura specialty fiber fusion splicer (FSM-100P) was used for 4c-MCF splicing. This splicer enables automatic detection and rotational adjustment of the marker and core positions using the side-view method by standing alone [6]. This method has advantages in terms of the splicer size and cost because of its simpler mechanism than the end-view method, which has been conventionally used for MCF alignment [10]. Figure 3 shows a histogram of the splice loss of 4c-MCFs obtained from 44 splicing tests

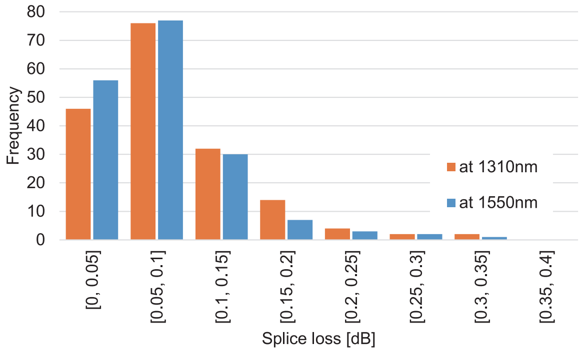

Fig. 3. Splice test result of 4c-MCF (Sample size: 44 connection, 176 cores).

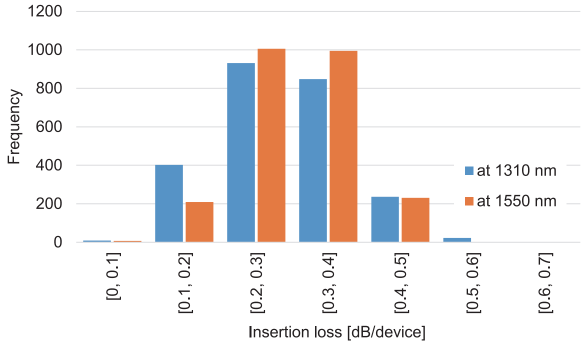

Fig. 4. Insertion loss distribution of the FIFO device (Sample size: 612 pcs, 2448 channels).

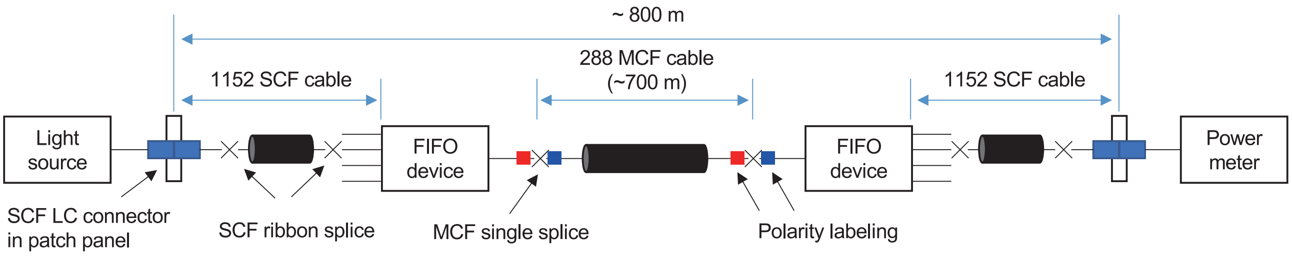

Fig. 5. Schematic of the constructed MCF link and OTSL measurement setup.

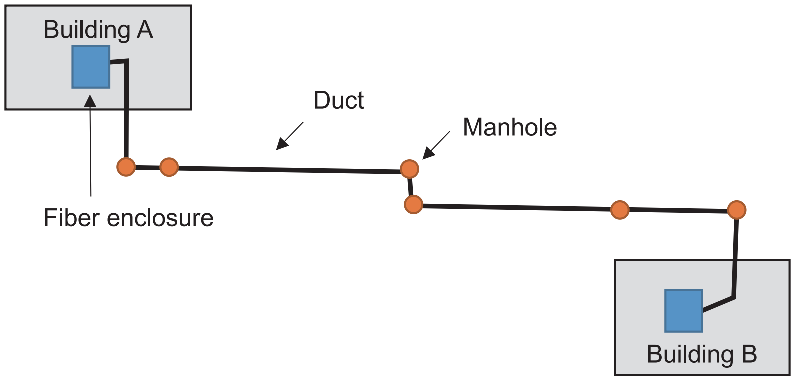

Fig. 6. Schematic map of the test site.

under the same conditions as the field installation. The average and maximum splicing losses were 0.09 dB and 0.35 dB at 1310 nm and 0.08 dB and 0.31 dB at 1550 nm, respectively.

2.3. FIFO device

For this trial, we prepared 612 pieces of FIFO devices, including some spares. They were fabricated by Chiral Photonics using the vanishing-core technique [11). Figure 4 shows the ILs of the FIFO devices for 612 pieces. The average and maximum ILs were 0.29 dB and 0.58 dB at 1310 nm and 0.30 dB and 0.50 dB at 1550 nm, respectively. These low and stable ILs were achieved through an accurate assembly process and precise core positioning in MCF (approximately 0.1 μm error) [12). The average and maximum return losses were -66 dB and -60 dB at 1550 nm, respectively. The XT between the adjacent cores was well below the detection limit (approximately -70 dB) at 1310 nm. The maximum XT was -45 dB at 1550 nm.

3. Construction of MCF link and loss evaluation

Figure 5 shows a schematic of the constructed MCF link. Approximately 800-m distance between the patch panels (PPs) in two buildings was routed using the MCF cable, FIFO devices, and SCF cables. They were connected through MCF single-fusion splices, SCF ribbon splices, and SCF connectors. First, an MCF cable was laid in microducts buried underground with outer and inner diameters of 15 mm and 13 mm, respectively, by using the air-blown technology. It was laid from one end toward Building A from a manhole near the center of the site map, as shown in Figure 6, followed by the other end toward Building B. The MCFs in the cable and MCF pigtails attached to the FIFO devices were fusion-spliced under the same condition described in Section 2.2. The SCF attached to the FIFO device was then fusion-spliced with approximately 25 m of SCF cable in the building. The FIFO devices and surrounding splicing points were housed in splice trays in enclosures for protection.

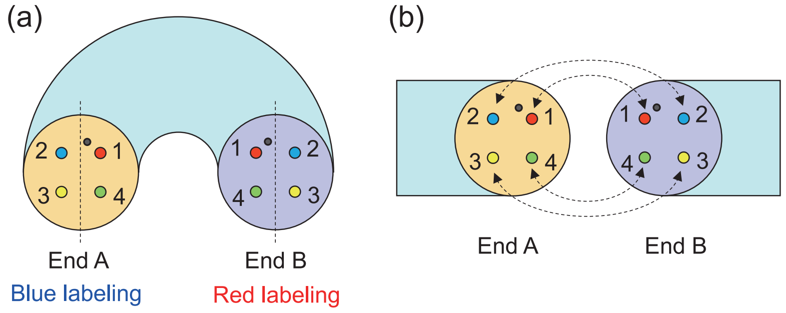

**Fig. 7. (a) Definition of MCF polarity and labeling color,
(b) Connected core numbers in the MCF-MCF connection.**

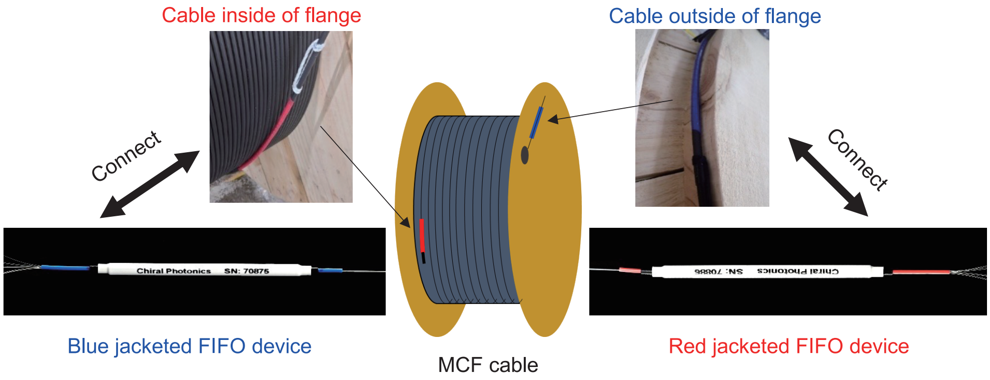

Fig. 8. Photos of the MCF cable and FIFO devices with polarity labeling.

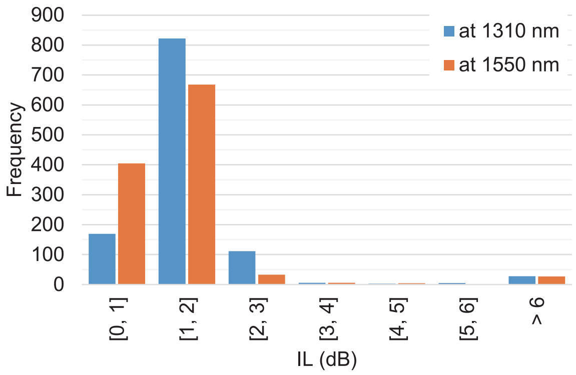

**Fig. 9. IL measurement result of the constructed MCF link
(Sample size: 1152 channels).**

It is necessary to manage the number of cores when building MCF links, as described in Section 2.1. Figure 7(a) shows the definition of the MCF polarity and labeling color. The MCF cables and FIFO devices were labeled to identify the polarity state; blue and red labeling were attached to ends A and B, respectively. As shown in Figure 8, red or blue tapes were attached to both ends of the MCF cable. Similarly, red or blue jackets were attached to the FIFO devices depending on the polarity of the attached MCF pigtail. The MCF cable and FIFO devices were arranged such that their red and blue labels were connected, as shown in Figure 5. To achieve this configuration, the MCF cable was fabricated with individual 288 MCFs arranged such that their polarities faced the same direction. Special polarity process control and inspection were performed for individual fibers, which were not required for the SCF cable. Moreover, the laying direction of the cables and the location of each FIFO device were considered. The MCFs in the cable and FIFO devices were spliced after marker position detection and alignment using the FSM-100P to achieve the arrangement shown in Fig. 7(b). We confirmed that all core numbers were exactly connected, as planned, in the field test. This trial revealed that although the polarity management of MCF is possible in principle, it is a major burden and confusing factor in building a high-fiber count MCF link. Considering the polarity management method is necessary for practical use [13].

The ILs of the constructed MCF link were measured using the OLTS method. As shown in Figure 5, a light source and power meter were connected to the patch panels at both ends and evaluated at wavelengths of 1310 nm and 1550 nm. The average of the two IL values from

Table 2. Loss setting values for SCF-related components used for link loss estimation, which are assumed to have similar values at 1310 nm and 1550 nm.

	SCF LC connector	SCF splice loss	SCF cable
Unit	dB/connection	dB/connection	dB at 25m length
IL average	0.1	0.05	0.01
IL maximum	0.2	0.2	0.01

the bidirectional measurement was used as the measured value. Figure 9 shows the measurement results, in which 1102 channels out of 1152 channels achieved a target value of less than 3 dB. Most of the causes in the remaining 50 channels with high losses occurred at the SCF connectors and SCF ribbon splicing points. The average of the measured IL was 1.46 dB at 1310 nm and 1.17 dB at 1550 nm, focusing on the channels below the target value of 3 dB.

The measured ILs were compared with the expected ILs to verify the effect of field installation. The expected ILs were calculated from the sum of the average ILs of each component in Figure 5. The loss values for each component were the averages of the MCF- and SCF-related components shown in Section 2 and Table 2, respectively. The expected ILs were calculated to be 1.44 dB at 1310 nm and 1.32 dB at 1550 nm, which are significantly close to the measured values. These results indicate that there was no excess loss due to the MCF-related components in this field deployment. The potential transmission range based on the field test results was estimated with reference to a power budget of 6.3 dB for 100GBASE-LR4 transmitted in the 1310-nm band 14). The maximum loss for each component was assumed in the calculation. The MCF cable was set to a target limit of 0.40 dB/km at 1310 nm, as shown in Table 1. The MCF splice loss and FIFO device loss were calculated using the maximum values at 1310 nm, as described in Section 2. The maximum ILs of the SCF-related components are presented in Table 2. Based on these assumptions, the maximum transmission distance is estimated to be 8 km.

Note that the XT measurements after installation could not be performed in this field test. Therefore, the effect of field installation on XT should be further investigated in the future. However, the XT of individual MCF-related components is sufficiently low to not affect the transmission quality in the 1310-nm band with transmission distances of up to 10 km. The transmission quality is not affected even if XT increases owing to field installation 3).

4. Conclusion

The loss performance of a field-deployed 1152-channel MCF link consisting of 288 4c-MCFs was evaluated, and no excess loss was observed in the MCF-related components owing to field deployment. The test results indicate the feasibility of high-density MCF links in the 1310-nm band at distances up to approximately 8 km. For practical use, considering both the individual specifications of MCF-related technologies and the core number management method is necessary.

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