114 Pbit/s·km Transmission using Three Vendor-Installed 60-km Standard Cladding Multi-Core Fiber Spans with Multiple Fusion Splicing

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Abstract: 63.58 Tbit/s transmission has been experimentally demonstrated over 1,800-km standard cladding trench-assisted profile 4-core fiber (TA-4CF) with multiple connections using installed multivendor TA-4CF optical cables in aerial areas and underground ducts for practical deployment.

1. Introduction

Multi-core fiber (MCF), a spatial division multiplexing (SDM) technology, has been widely investigated to overcome the theoretical limitation of transmission capacity in a standard single-mode fiber (SMF). In particular, a 125-μm standard cladding MCF [1-6] is attractive for early deployment of the SDM system, since it is expected to have high mechanical reliability and applicability to conventional optical cable structures, similar to standard SMF. To date, evaluations of the optical characteristics using MCF cables deployed in the field has been reported for the practical application of MCF [1-3]. In addition, transmission experiments using multivendor MCF wound on spools have been demonstrated to verify compatibility between different vendors [4]. However, high-capacity long-haul transmission experiments using the installed multivendor MCF cables have not been reported thus far.

In this paper, trench-assisted MCF (TA-MCF) cables with suppressed core-to-core crosstalk, which were fabricated by several vendors, were placed in an underground duct and on an aerial installation. In addition, a testbed was constructed to simulate the outdoor installation environment of an actual terrestrial transmission system by performing multiple connections using fusion splicing and connector connections at intervals of several kilometers. Moreover, we evaluated the insertion loss, core-to-core crosstalk characteristics, and fusion splicing loss in cables from each vendor. We also demonstrated 1,800-km full C-band WDM transmission using installed multivendor TA-4CF cables, achieving a transmission capacity of 63.58 Tbit/s and capacity–distance product of 114 Pbit/s·km.

2. Installation of TA-4CF Optical Cables

The installed TA-4CF and TA-4CF cables were fabricated by three different vendors (vendors A, B, and C). In the optical specifications for the TA-4CF, the cladding diameter was 125 μm, core pitch was 40 μm, and transmission loss was less than 0.25 dB/km at 1550 nm. Figure 1 shows the cross-sectional images of the fabricated TA-4CF. A snapshot of a typical MCF cable fabricated using these TA-4CFs is shown in Fig. 2. The diameter and length of the MCF optical cables with a slot-less structure were 12 mm and 3 km, respectively. The total number of fibers in these cables was 200, including 20 fibers for TA-4CF and 180 fibers for conventional SMF.

Figure 3 shows the route for installing the TA-4CF cables, expanding on previous work [3], to construct the outdoor verification environment consisting mainly of an aerial area and underground ducts. Figures 4 (a) and (b) show photographs of the installed TA-4CF cables at the underground duct and aerial area, respectively. First, three TA-4CF cables (cables A, B, and C) manufactured by three different vendors were launched from the test room and pulled up into the aerial area via four poles with a spacing of approximately 35 m or 17 m and a height of 7 m. Then, we installed an underground duct with a length of approximately 42 m and an inner diameter of 200 mm via a

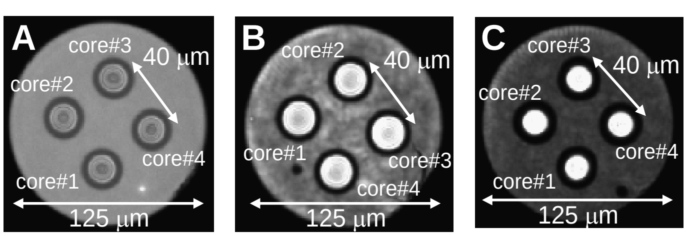

Fig. 1. Cross-sectional images of the TA-4CFs fabricated by vendors A, B, and C.

Fig. 2. A snapshot of the prototype MCF cable fabricated using these TA-4CFs.

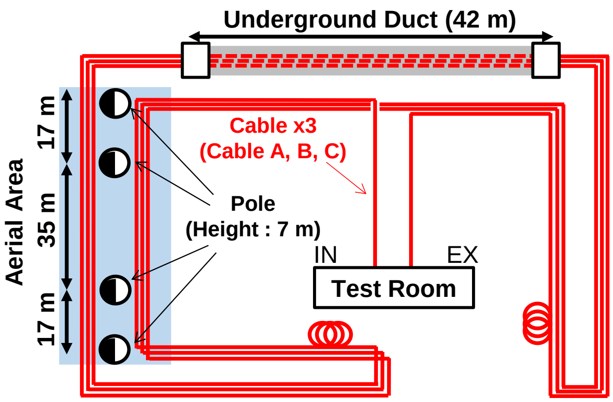

Fig. 3. Cable route of the installed TA-4CF cables.

maintenance hole. Eventually, the cable ended at the test room after three rounds of aerial area and underground duct placement, as shown in Fig. 3.

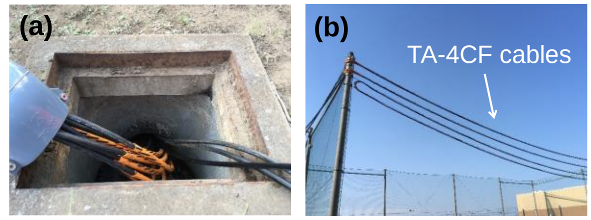

Fig. 4. Photographs of the installed TA-4CF cables at (a) the underground duct area and (b) the aerial area.

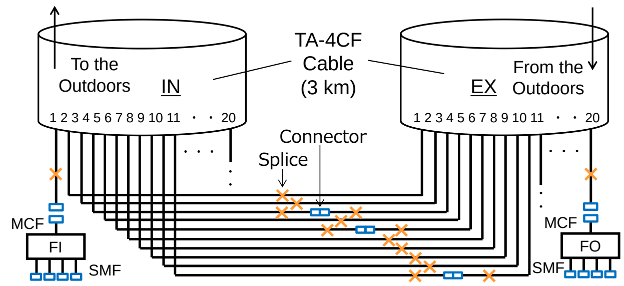

Fig. 5. 60-km TA-4CF configuration with splices and connectors.

3. Multiple connections of TA-4CFs

To evaluate the installed TA-4CF cables, 60-km MCF transmission lines were constructed by fusion splicing and connectors connecting 20 TA-4CFs in cables A, B, and C. Figure 5 shows the connection configuration diagram of the 20 TA-4CFs. In the same manner as in the previous work [3], the IN- and EX-termini of the cables were connected from TA-4CF #1 to #20. To simulate the effects of not only fusion splicing but also connector connecting, six connector points were arranged at the input, 9 km, 15 km, 30 km, 45 km, and 60 km using conventional SC connectors and adapters. Therefore, the total number of connections was 31 for each cable, including 25 fusion splices and 6 connector connections.

First, the losses per fusion splicing point for each TA-4CF core were measured using an optical time domain reflectometer (OTDR) via a fan-in/fan-out (FIFO) device at a wavelength of 1550 nm. Figure 6 shows the histograms of the losses per fusion splicing point for all cores in cables A, B, and C, except for the connector connection points. The average fusion splicing loss over the three cables and all cores was 0.10 dB. Furthermore, fusion splicing losses of less than 0.3 dB can be achieved at almost all connection points. Note that in cable C, the fusion splicing losses of some cores increased due to the mismatch in core pitch between the TA-4CFs, and connection losses exceeding 0.4 dB were observed. Table 1 shows the span losses in each core at 1550 nm in cables A, B and C. The difference in span loss between cores in each cable of less than 2 dB was caused by the difference between the cores in insertion losses of the FIFO devices and accumulated connection losses. The difference in span losses between the cables was mainly due to the difference in transmission losses of the TA-4CFs. Table 2 shows the crosstalk between adjacent cores at 1550 nm in cables A, B and C. The crosstalk between adjacent cores was suppressed to less than -30 dB in each 60-km span.

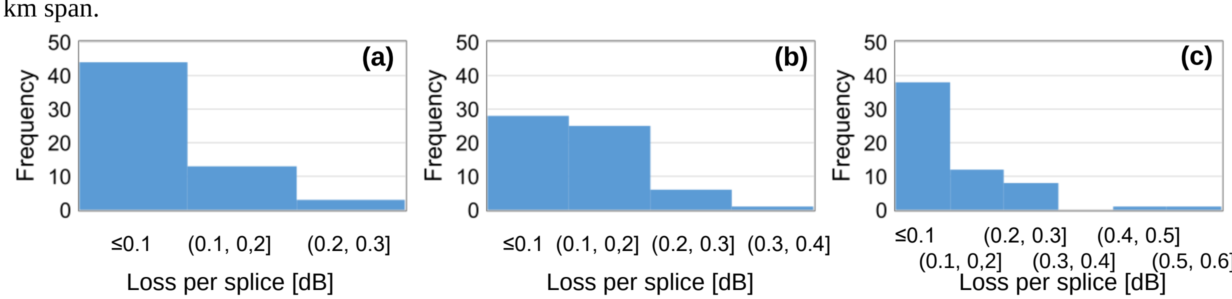

Fig. 6. Histograms of the losses per splice at 1550 nm in (a) Cable A, (b) Cable B, (c) Cable C.

Table. 1. Span losses in each cable at 1550 nm.

Unit : dB	core#1	core#2	core#3	core#4
Cable A	16.44	15.62	14.88	15.80
Cable B	13.54	14.95	15.45	15.40
Cable C	17.76	17.84	18.04	16.95

Table. 2. Core-to-core crosstalk characteristics in each cable at 1550 nm.

Unit : dB	core#1 > core#4	core#1 > core#2	core#2 > core#1	core#2 > core#3	core#3 > core#2	core#3 > core#4	core#4 > core#3	core#4 > core#1
Cable A	-40.23	-40.59	-41.57	-42.30	--42.01	-41.63	-41.66	-40.66
Cable B	-33.37	-32.87	-32.38	-31.27	-31.75	-33.26	-33.28	-31.18
Cable C	-35.39	-33.92	-33.86	-34.97	-35.18	-33.99	-33.86	-35.23

4. Transmission Potential of Installed TA-4CF with Multiple Connections

We evaluated the transmission potential of TA-4CFs with multiple connections using the installed MCF cables. Figure 7 shows the experimental setup based on our previous MCF transmission experiments [5, 6]. In the transmitter, the 25-GHz-spaced 24-Gbaud 190-channel WDM Nyquist-shaped DP-QPSK signals were generated in the same manner as in previous work [5, 6]. The generated WDM signals were split into 4 paths, with a relative delay of 200 ns for decorrelation, and fed into a recirculating loop system consisting of three spans of installed 60-km TA-4CFs, C-band optical amplifiers and 2×2 optical switches (SWs), and C-band wavelength selective switches (WSSs). In the receiver, the transmitted WDM signals were detected by four individual digital coherent receivers. For offline processing, the stored samples were processed by four individual adaptive 2×2 MIMO equalizers. The MIMO tap coefficients were updated based on a decision-directed least-mean square (DD-LMS) algorithm [7].

Figure 8 shows the Q^2-factors of 752 (4 core × 188 WDM) SDM/WDM channels after 1,800-km transmission. Note that two WDM channels at both edges in the C-band were removed due to insufficient characteristics. In this experiment, we assumed three different soft-decision FECs based on low-density parity-check codes: a 6.5 dB FEC limit [8] with 12.75% overhead (OH), a 5.7 dB FEC limit [9] with 20% OH, and a 4.95 dB FEC limit [10] with 25.5% OH. In the results shown in Fig. 8, the Q^2-factors of 668, 82, and 2 SDM/WDM channels exceeded the thresholds of 12.75%, 20%, and 25.5% OH FEC, respectively. The worst Q^2-factor was 5.45 dB at 1565.19 nm in core #2, which was higher than the FEC limit of 4.95 dB for the 25.5% OH FEC. The maximum difference in the Q^2-factors between the 4 cores for each WDM channel was 0.86 dB at 1560.50 nm. As a result, we achieved a transmission capacity of 63.58 Tbit/s with the 188-WDM 24-Gbaud DP-QPSK signals over a full C-band after the 1,800-km transmission using installed multivendor TA-4CFs.

5. Conclusions

We installed TA-4CF optical cables fabricated by three different vendors in an aerial area and underground duct and constructed a testbed that simulates the actual outdoor environment by multiple connections using fusion splicing and connector connections. We also evaluated the insertion loss, core-to-core crosstalk, and fusion splicing loss and demonstrated 63.58 Tbit/s transmission over 1,800 km using installed multivendor TA-4CF cables.

We would like to thank the staff of Furukawa Electric Co., Fujikura, Ltd., and TOHO ELECTRICAL CONSTRUCTION CO., LTD., for their assistance in this study. A part of this research was supported by the National Institute of Information and Communications Technology (NICT)/No.20301, Japan.

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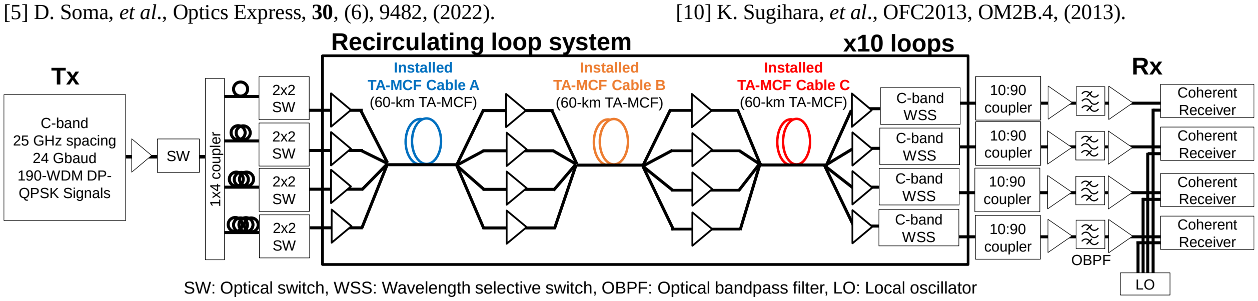

Fig. 7. Experimental setup for evaluating the transmission potential of TA-4CFs.

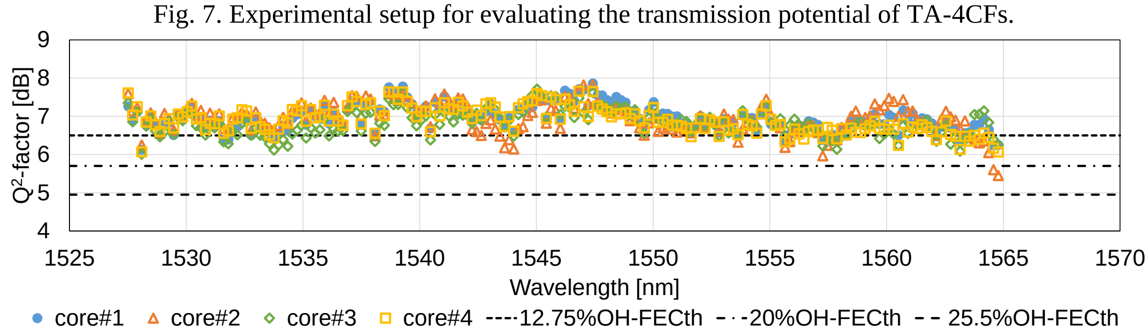

Fig. 8. Q^2-factors for all 4-SDM/188-WDM channels after 1,800-km transmission.