# 400GBASE-FR4 Transmission Test over 2 km 4-core Multiple Multicore Fibers for Intra-Datacenter Interconnects

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*This study demonstrated a transmission test assuming intra-datacenter interconnection using a 400GBASE-FR4 transceiver on a transmission system built using 2 km 4-core multicore fibers, 24 pairs of fan-out devices, and multicore fiber MPO connectors. Error-free transmission was achieved in an environment with inter-core crosstalk, and the results are reported.*

## 1. Introduction

Recently, the demand for artificial intelligence (AI) and machine learning (ML) has surged. Datacenters (DCs) for AI/ML require high-capacity, high-density, and low-latency connections between numerous graphics processing units (GPUs), necessitating extensive fiber optic cabling and connectivity. Thus, the number of fibers installable in server or switch racks has reached the limit of conventional single-core fiber (SCF). Moreover, not only the installation capacity but also the enormous number of connections between GPUs is increasing the wiring workload in the construction of AI/ML data centers. Multicore fiber (MCF), a space-division multiplexing (SDM) technology, has been actively developed to overcome these limitations. Among SDM fibers, weakly coupled 4-core MCF (4c-MCF) with standard cladding diameters is being standardized internationally and used in transmission tests for practical deployment [1)]. Applying 4c-MCF enables a fourfold reduction in fiber and connection footprint compared to SCF, allowing for higher core density.

On the other hand, during the transition phase for MCF deployment, existing SCF systems will be used for transmission equipment such as transceivers, requiring not only MCF-to-MCF connections but also SCF-to-MCF conversion. Figure 1 illustrates the connection concept.

Under this background, this study demonstrated transmission tests using 400GBASE-FR4 transceivers standardized in IEEE802.3 [2)] and in-house-developed 4c-MCF and MCF connection components, assuming wiring in a <2 km optical network in intra-DC using MCFs. In bit-error-rate (BER) tests applying 400Gbps four-level pulse-amplitude modulation (PAM4), we confirmed end-to-end (E2E) error-free transmission. In this paper, the characteristics of the fan-in/fan-out (FI/FO) device and the MPO connector, which are MCF connection components used in the test system, as well as the results of the transmission tests are reported.

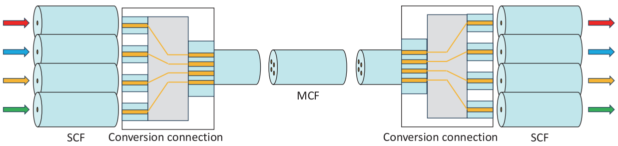


**Fig.1. Schematic of MCF connection.**

## 2. MCF transmission test system

The transmission tests were conducted assuming the situation where MCF is applied to a multi-fiber cable between server racks or switch racks requiring high-density wiring. Accordingly, we used an MCF testbed constructed with a 2 km 4c-MCF as the transmission line between transceivers (Figs. 2(a), 2(b)). The transmission line consisted of twenty-four 4c-MCFs (a total of 96 cores), each end terminated with MPO connectors [3)], which mate with the same type of MPO connector placed on the rear side of a 1U 19-inch rack panel. The 400GBASE-FR4 transceiver connects to the front of the panel via SCF. Within the panel, FI/FO devices—conversion devices necessary to connect MCF and SCF—are installed.

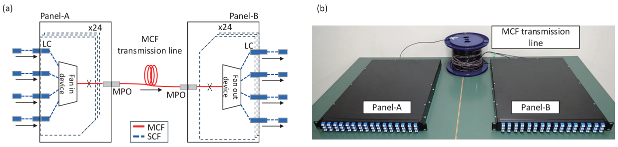


**Fig.2. Testbed for MCF transmission: (a)Schematic, (b) Exterior view.**

### *2.1 Fan-in/Fan-out (FI/FO) Device*

As noted above, FI/FO devices are required to connect MCF into an existing SCF-based system. Figure 3 shows the structure of our in-house, bundle-type FI/FO used in the tests. The 4c-MCF has a cladding outer diameter of

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**Abbreviations, Acronyms, and Terms.**

400GBASE-FR4—400GBASE Forward Reach 4
"A standard for optical communication based on the IEEE 802.3 Ethernet standard.
It uses wavelength division multiplexing (CWDM, 4 wavelengths) and supports transmission of 4 x 100G signals over distances up to 2 km via single-mode fiber."

MT ferrule—Mechanically Transferable Ferrule
A plastic component for connecting multiple optical fibers in a single action with high positioning accuracy.

MPO connector—Multifiber Push-On Connector
A push-pull optical connector with an MT ferrule that connects multiple optical fibers collectively.

SDM—Space Division Multiplexing
Multiplexing technology utilizing spatial degrees of freedom within optical fibers to expand transmission capacity. Examples include multicore fibers with multiple cores within a single optical fiber.

MCF—Multi-Core Fiber
Conventional optical fibers have one core per fiber. In contrast, MCF has multiple cores within a single fiber.

IC-XT—Inter-Core Crosstalk
Leakage from other cores in multi-core optical fibers. This degrades communication quality as signal noise.

BER—Bit Error Rate
A data transmission quality metric expressed as the ratio of erroneous data to the total data received by the receiving side.

O-band—Original-band
One of the wavelength bands used in optical communication, with wavelengths ranging from 1260 nm to 1360 nm.

QSFP-DD—Quad Small Form-factor Pluggable Double Density
A specification for optical transceivers that connect optical fibers to communication equipment. It features an electrical interface with double the density (8 lanes) compared to QSFP modules.

PAM4—Pulse Amplitude Modulation 4
"Among signal transmission methods, a technique that modulates the signal amplitude into four different values.
Compared to NRZ (Non Return to Zero) modulation with 1 bit per 2 values, it can transmit twice the information. However, the difference between each amplitude becomes smaller, making it more susceptible to noise."

FEC—Forward Error Correction
A type of error correction method that anticipates errors by transmitting redundant data, allowing the receiver to reconstruct the data. PAM4 employs FEC.

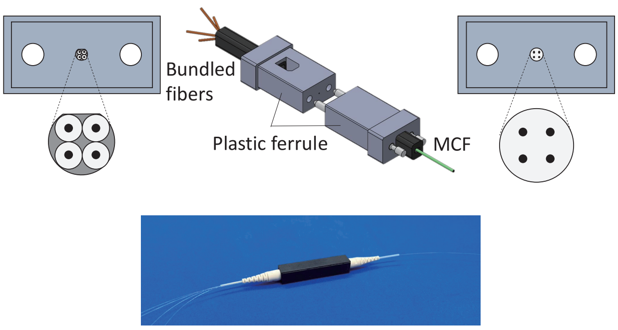


**Fig.3. Structure of bundle-type FI/FO device.**

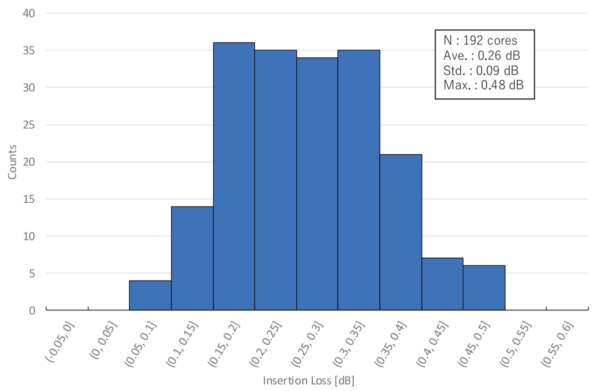


**Fig.4. Insertion loss performance of FI/FO devices.**

125 μm, and four cores arranged in a square lattice with a 40 μm pitch. The bundled fibers are four SCFs whose diameters are reduced from 125 μm to 40 μm by chemical etching. The mode-field diameter (MFD) at the wavelength of 1310 nm is 8.4 μm for the MCF and 8.6 μm for the SCF. Each fiber is inserted into a plastic ferrule formed by injection molding. The rotation angle of the bundled fibers is passively aligned by inserting them into a D-shaped hole formed in the ferrule [4]. Meanwhile, the MCF is rotationally aligned to a specified angle while being observed with a camera. The MCF fixed in the ferrule and the four bundled fibers are optically connected by butting them together. The end faces of both ferrules are polished with an 8° angle to achieve low return loss. The opposite ends of the SCFs are terminated with LC connectors [5]. Figure 4 shows the insertion losses (ILs) at 1310 nm (O-band) for 48 FI/FO devices: the average IL was 0.26 dB per device, with a maximum of 0.48 dB per device. (Here, the IL includes the connection loss of the LC connector.)

*2.2 4c-MCF 24-fiber MPO Connector*

Figure 5 shows a 24-fiber MPO connector using 4c-MCF (24MPO). Each MCF must be rotationally aligned against the two guide pin holes on the MT-ferrule end face, which is the base of the MPO interface. To accurately control the rotation alignment angle, our method fixes twenty-four rotationally aligned MCFs on a holding substrate in advance and inserts them into the MT ferrule together with the substrate as a unit. (For the MT ferrules and MPO connector components, we used our existing products.) For the 96 MCFs fixed in four 24MPO connectors used in the testbed, the average misalignment angle was 0.49°. Figure 6 shows the measured ILs of the 4c-MCF 24MPO connectors used: the average IL was 0.15 dB, and the maximum IL was 0.42 dB. These results correspond to IEC 61753 Grade-C levels (average ≤ 0.25 dB; 97th-percentile ≤ 0.5 dB for IL in random mating [6]).

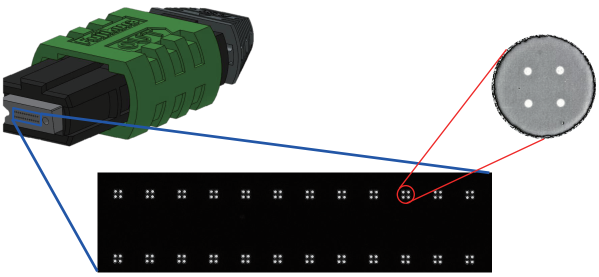

**Fig.5. Schematic diagram of 4c- MCF-24MPO connector.**

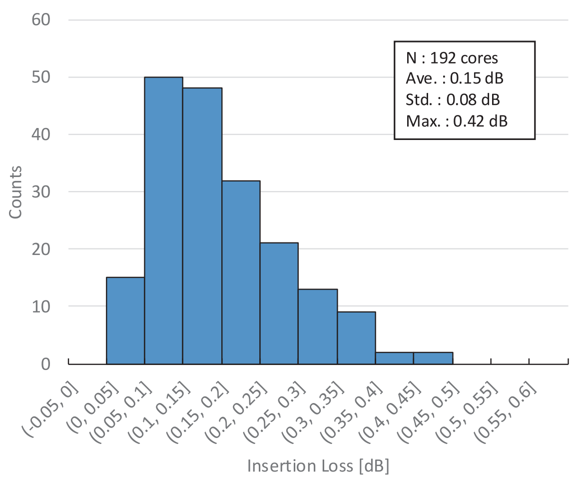


**Fig.6. Insertion Loss performance of 4c-MCF-24MPO Connectors.**

*2.3 Testbed*

Figure 7(a) shows the MCF testbed used for the 400G transmission tests. Ninety-six SCF-LC connector receptacles are arranged on the front of a 1U 19-inch rack panel, to which standard SCF-LC patch cords from the 400GBASE-FR4 transceivers are connected. Each panel (Panels A and B) houses twenty-four FI/FO devices; the rear side of each panel is terminated as a 4c-MCF 24MPO and connected to the MCF transmission line. The fiber link in the MCF testbed includes eight connection/splicing points assuming intra-DC cabling: two MPO connector connections, two FI/FOs, two MCF-to-MCF fusion splices, and two SCF-LC connector connections. By evaluating transmission performance in this testbed, we assessed the feasibility of MCF solutions for intra-DC wiring applications. Figure 8 shows the measured ILs of the MCF testbed in the O-band. In the configuration where the MCF transmission line length was shortened to 50 m to exclude the propagation loss contribution, the average IL was 1.42 dB, and the maximum IL was 2.39 dB. The 400GBASE-FR4 specification requires the total link-loss budget—including fiber transmission, connector losses, and splice losses—to be at most 4 dB. Given that the attenuation of the MCF used here is typically 0.35 dB/km in the O-band, the link-loss requirement can be sufficiently met even when a 2-km MCF is used for the transmission line.

## 3. 400GBASE-FR4 Transmission Test over 2-km MCF

The transmission test setup including the above MCF testbed is shown in Fig. 7(a). By plugging a QSFP-DD-form-factor 400GBASE-FR4 transceiver 1 (TRx1) into a BER tester 1 (BERT1), eight lanes of 50-Gbps electrical signals are input to TRx1, and 400Gbps PAM4 optical signals are transmitted (Tx1, blue arrow). After traversing the MCF testbed, the optical signal is divided by an optical switch (OS) into BERT1 following Rx1 of TRx1 and into a digital sampling oscilloscope for eye-diagram capture, where BER is evaluated. The typical IL of the OS was 3.0 dB. In addition, a second transceiver (TRx2) was used to transmit signals in the same direction to two other adjacent cores in the same MCF to evaluate the effect of inter-core crosstalk (IC-XT) on transmission quality (Tx2, green arrow). (In one of the two cores, the signal is looped back after transmission and reinput, as depicted in Fig. 7(b).)

Figure 9 shows the BER results when the MCF transmission line length was 2 km. The range of each boxplot reflects variation among the eight electrical lanes. For the tests, we selected, respectively, four cores with higher IL and four cores with lower IL in the MCF testbed (IL without the OS: 1.3–2.9 dB), and we compared two conditions: with IC-XT from adjacent cores and without IC-XT. As a result, the pre-FEC BERs were below 10-6 regardless of the IL magnitude or the presence of IC-XT, which is the same level as back-to-back (B2B) connection where two transceivers are directly connected without the testbed. These BERs are roughly two orders of magnitude smaller than the FEC threshold of 2.4×10-4, indicating that error-free communication was achieved for 400 GBASE-FR4 transmission over a 2-km MCF assuming intra-DC interconnection, even in the presence of IC-XT.

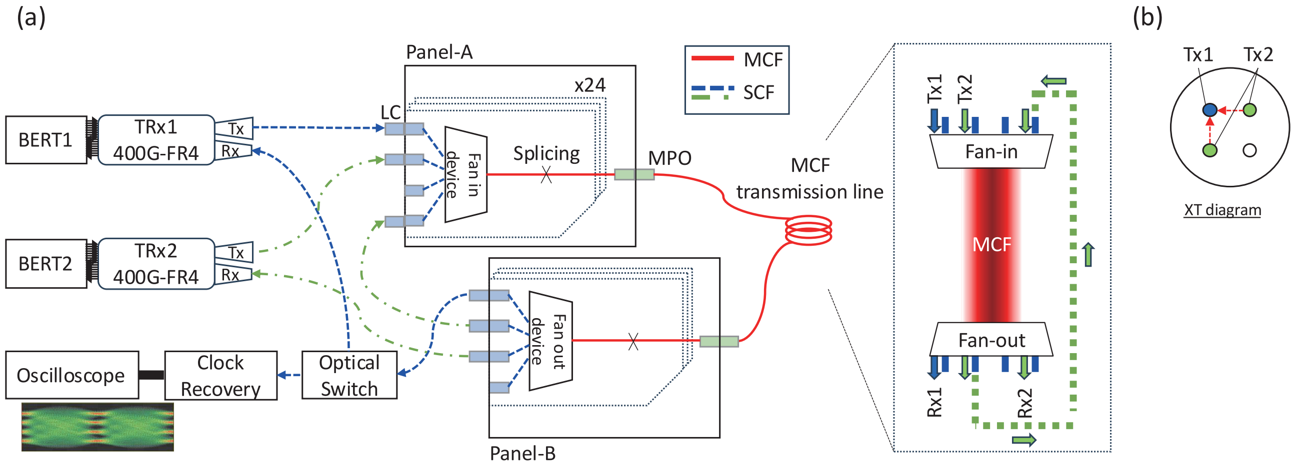


Fig.7. Setup for 400 Gbps transmission MCF testbed.

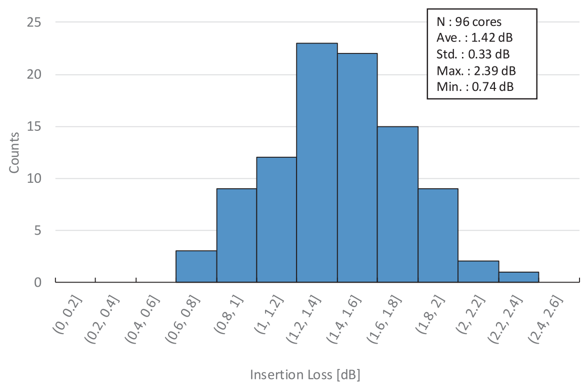


Fig.8. Insertion loss performance of MCF testbed (50 m MCF).

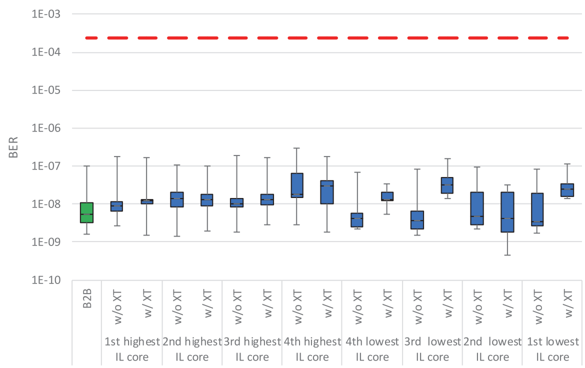


Fig.9. BER of the transmission over 2 km MCF line with/without IC-XT

## 4. Conclusion

We constructed a testbed for intra-DC cabling using a weakly coupled 4c-MCF with a standard cladding outer diameter as the transmission line, together with our FI/FO devices for MCF–SCF conversion and 4c-MCF 24-fiber MPO connectors, and we experimentally demonstrated 2-km transmission tests using a 400GBASE-FR4 transceiver. The results confirmed error-free transmission under conditions with IC-XT with BERs < 10-6—below the FEC threshold— and indicated the feasibility of realizing high-density intra-DC optical cabling using MCF and MCF connection components. We will continue to develop MCF solutions, including connection components such as FI/FO devices and MCF connectors, to meet the needs of the DC market.

## References

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