

125- μ m-Cladding 8-Core Multi-Core Fiber Realizing Ultra-High-Density Cable Suitable for O-Band Short-Reach Optical Interconnects

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Abstract—A novel multi-core fiber (MCF), having 8 cores within a 125- μ m-diameter cladding and suitable for short-reach transmissions, is proposed. By optimizing O-band transmission, the proposed MCF realized the high-density core packing simultaneously achieving the optical characteristics comparable to those of the standard single-mode fiber in O-band, where low material dispersion can be leveraged. The standard 125- μ m-diameter cladding is compatible with conventional cabling/connecting technologies and has the tightly-bendable mechanical reliability proven by the widely-installed standard optical fibers. An ultra-high-density 12-MCF cable was fabricated with the proposed MCF, and achieved 13.6 cores/mm² (96 cores in the 3-mm-diameter cable). The transmission characteristics of the cabled MCF were evaluated using a 100GBASE-LR4 transceiver, and error-free 8-SDM $\times$ 4-WDM $\times$ 25-Gb/s (800-Gb/s/fiber) signals in O-band were successfully transmitted over the 1.11-km-long cabled MCF.

Index Terms—MCF, Multi-core optical fibers, Optical fiber communication, Optical fibers, Optical interconnects, SDM, Space division multiplexing

I. INTRODUCTION

IN the field of optical interconnects, demands for the larger bandwidth (BW) and higher-density parallel transmission link technologies are eagerly increasing. Thus, various transmission media and connecting technologies have been proposed for short reach (<100 m) applications, such as the 1310-nm-optimized multimode fiber (MMF) leveraging low material dispersion and affinity to silicon photonics [1]; high-density optical connectors using 125- μ m-diameter and small-diameter MMFs [2], [3]; spatially multiplexed transmission using a multi-mode multi-core fiber (MCF), a vertical-cavity surface-emitting laser (VCSEL) array, and a photo detector (PD) array (6 channels) [4]; and so on. The BW demands are also rising in transmission up to $\sim$ 500 m—a few 10s of km reach, such as large-scale data-center networks, and standards using a standard single-mode fiber (SSMF) with wavelength-division

multiplexing (WDM) [5]–[8] or parallel SSMFs [9] have been published to realize longer reach and scalable BW interconnects by avoiding the pulse spreads due to the differential modal delay in MMFs. Space-division multiplexing (SDM) using single-mode MCFs has also been studied for the short-reach applications [10]–[12]. However, including the MCFs for long-reach applications, no MCF has been reported which simultaneously achieves the core count of 8 or more, the core optical characteristics at least comparable to the SSMF, the cladding diameter of 125 μ m, and the XT less than -30 dB even after only 1 km [10]–[21], because there is a tradeoff between the shortening of core-to-core and core-to-coating distances, the suppression of inter-core crosstalk (XT) and leakage loss to the high-refractive-index coating, and the enlargement of the mode field diameter (MFD) or the effective area (A_{eff}).

In this study, we developed a 125- μ m-cladding single-mode 8-core fiber that is suitable for short-reach transmission by designing the transmission band up to O-band (1260–1360 nm) [22], where low material dispersion can be leveraged. We also fabricated a 3-mm-diameter 12-MCF cable with the highest core density of 13.6 cores/mm². Finally, error-free, 8-SDM $\times$ 4-WDM $\times$ 25-Gb/s (800-Gb/s/fiber) transmission was demonstrated in O-band over the cabled MCF, and no significant power penalty due to the MCF XT was observed.

II. MOTIVATIONS FOR DEVELOPING THE 125-MICROMETER-CLADDING 8-CORE FIBER

In this study, we adhered to simultaneously realizing (A) the core count of eight, (B) the optical characteristics comparable to those of the SSMF, and (C) the cladding diameter of 125 μ m. In this section, we describe the reasons why we adhered to such design target.

A. The core count of eight

8 cores can transmit the full-duplex 100-Gb/s/ λ signal using the conventional 25-Gb/s transceiver (TRX) technology. If we consider the deployment of the MCF in the short-reach

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applications, most part (except fiber coupling part) of the TRX should be the same with the TRX for non-MCF transmission link, for cost reduction. Expecting TRX manufacturers to design new short-reach TRXs fully-customized (including modulation format, baud rate, spatial channel count, etc.) for MCFs may not be realistic. To make the MCF more realistic and deployable solution, the MCF should be designed so as to minimize the MCF-specific customization of the TRX. From such point of view, as the existing standards using parallel SSMFs [9] requires 4 cores for 100-Gb/s/ λ transmission and 8 cores for full-duplex 100-Gb/s/ λ , we adhered to the core count of 8—if 25-Gb/s/ λ technology is used, 7-core fibers are equivalent to 4-core fibers because 2 fibers are necessary for full-duplex 100-Gb/s/ λ transmission.

B. The optical characteristics comparable to the SSMF

Also, the optical characteristics comparable to the SSMF are required to minimize the MCF-specific TRX customization. As the single-mode short-reach transmission standards [5]–[9] specify the transmission fibers as the SSMF. The MCF cores should have the optical characteristics comparable to the SSMF.

As the many single-mode short-reach transmission standards utilize O-band for the transmission band [5]–[7], [9], the low dispersion characteristics of the SSMF in O-band can suppress the signal distortions due to the dispersion and enable to remove the electronic dispersion compensation from the TRX, which is beneficial not only for the TRX cost but also for the signal latency.

C. The standard 125- μ m cladding diameter

Though many studies on the MCF have accepted cladding diameters larger than the standard 125- μ m diameter in order to increase core count and improve optical characteristics of the cores [13]–[18], the mechanical reliability is one of large concerns if we consider enlarging the cladding diameter. Fig. 1 shows the cumulative failure probability of one-turn bend of the optical fiber with various cladding diameters, which were calculated using the power law theory [23], [24] with the

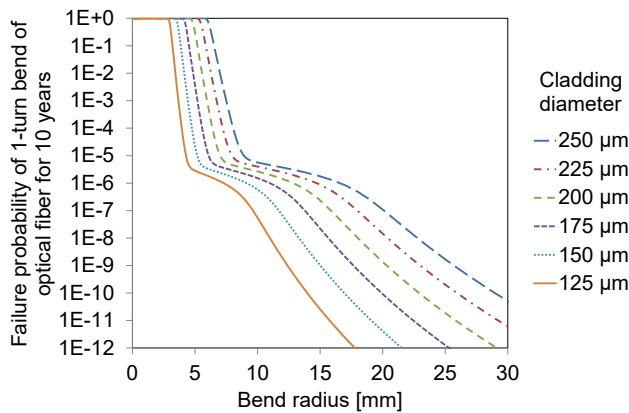


Fig. 1. A relationship between the bend radius, the cladding diameter, and the cumulative failure probability of one-turn bend of the polymer-coated silica optical fiber for 10 years. At the intrinsic region where the steep slopes approach the failure probability of 1, the fiber breakage occurs because the material strength of the silica glass fiber cannot stand the stress. At the extrinsic region where the slopes are gentle, the fiber breakage is induced by the growth of the micro cracks on the cladding surface, as the micro cracks are induced during the fiber drawing process.

literature values of fatigue-related parameters. Though the results may change depending on the fatigue-related parameters, the larger cladding diameter always degrades the failure probability and the smaller cladding diameter can resist tighter bending radius. This is because the bend-induced stress becomes larger in the thicker cladding. In the high-capacity long-haul transmission, the larger cladding diameter may be accepted by increasing the minimum bend radius and by carefully controlling the bend radius in the installation. However, the bend radius may be difficult to control in the short-reach optical interconnects, and the ease of handling may be greatly degraded if tight bends are restricted. The mechanical reliability of the standard 125- μ m-diameter cladding has been already proven in the actual installations of the standard optical fibers in the optical interconnects [25].

The smaller cladding diameter is also preferable from the view point of the fabrication cost, as the longer fiber can be drawn from a same-size preform. Though the cladding diameter of around 200–250 μ m has been assumed as the upper limit in respect of the mechanical reliability [14], [15], the drawable fiber length becomes less than 40% of the standard 125- μ m cladding fiber when the cladding diameter is more than 200 μ m, based on the glass volume.

Additionally, by adopting the standard 125- μ m cladding; mature, reliable, and cost-competitive conventional technologies for the standard optical fibers can be utilized with small modifications or without any modifications—e.g., fiber fabrication technologies, cabling technologies, connecting technologies, etc.

III. DESIGN OF EIGHT-CORE FIBER WITH 125-MICROMETER-DIAMETER CLADDING

We designed an 8-core MCF with identical cores and the cladding diameter of 125 μ m. A trench-assisted (TA) core index profile was employed for simultaneously realizing strong light confinement, single-mode operation, low chromatic dispersion, and low-splice-loss MFD, in O-band. The core was designed so as to have a strong power confinement of the fundamental mode and the optical characteristics comparable to the SSMF—the MFD of 8.6 μ m at the wavelength λ of 1310 nm, the cable cutoff wavelength λ_{cc} of 1200 nm, and zero dispersion wavelength λ_0 of 1312 nm. Fig. 2 shows the refractive index profile of the

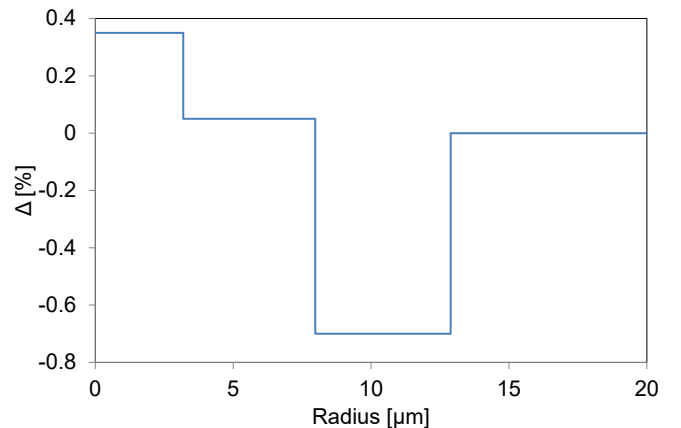


Fig. 2. The refractive index profile of the designed MCF.

designed TA core.

We employed a one-ring core layout where all the cores are equally-spaced on a common circle whose center is the cladding center. With the one-ring layout, all the cores can have identical optical characteristics in design even if the XT and/or the perturbations from the other cores and from the coating are considered. Additionally, every core may be easily accessible from the photonic integrated circuit when surface fiber couplers (grating coupler, VCSEL, PD, etc.) are used, because the optical/electrical passes to any couplers are not obstructed by the other couplers—no coupler is surrounded by other couplers.

To investigate if eight cores that have the designed index profile can be packed into the 125- μm cladding simultaneously avoiding significant degradation of the optical characteristics, we investigated the relationship between the core-to-coating distance d (the minimum distance from the core center to the coating), the core-to-core distance D (the distance between two nearest neighboring core centers), and coating-leakage loss (the power coupling from the core to the coating), and the core-to-core XT (the power coupling between two cores) at λ of 1310 nm, 1490 nm, and 1550 nm, as shown in Fig. 3. The coating-leakage loss was calculated using the full-vector finite-element imaginary-distance beam-propagation method [26]. The XT was calculated using the simple analytical approximate expression of the power-coupling coefficient h for the homogeneous MCF [13], [27]:

$$h \approx \kappa^2 \frac{2R_b}{\beta D} = \kappa^2 \frac{\lambda R_b}{\pi n_{\text{eff}} D}, \quad (1)$$

by assuming the average bend radius as one meter for design, where κ is the mode-coupling coefficient, R_b the fiber bend radius, β the propagation constant, and n_{eff} is the effective refractive index. In the one-ring core layout, the XT between the two nearest neighboring cores (XT_{nearest}) and the XT between the two second-nearest neighboring cores (XT_{second}) can be expressed as (see appendix):

$$XT_{\text{nearest}} \approx hL, \quad XT_{\text{second}} \approx \frac{h^2 L^2}{2}, \quad (hL \ll 1), \quad (2)$$

where h is the power-coupling coefficient between the nearest neighboring cores, and L is the fiber length. Power coupling between the second-nearest neighboring cores is governed by indirect power coupling via the middle core, and hardly affected by the direct coupling. According to Fig. 3, we cannot find d or D that simultaneously realize the XT less than -40 dB and the coating-leakage loss less than 0.1 dB/km at λ of 1490 nm and 1550 nm. However, at $\lambda = 1310$ nm, the coating-leakage loss can be suppressed to be ≤ 0.01 dB/km when d is ≥ 21.9 μm (D is ≤ 31.0 μm), and ≤ 0.001 dB/km when d is ≥ 25.3 μm (D is ≤ 28.5 μm). The XT between the nearest neighboring cores can be suppressed to be ≤ -40 dB after 10-km propagation when D is ≥ 30.9 μm (d is ≤ 22.1 μm), and the XT between second-nearest neighboring cores can be suppressed when D is ≥ 24.7 μm or more (d is ≤ 30.2 μm). Therefore, by optimizing the MCF for O-band transmission, we can realize the 8-core fiber with optical characteristics comparable to the SSMF and having the cladding diameter of 125 μm . In this study, we chose d of 22.0 μm (D of 31.0 μm), as shown in Fig. 4, so that we can evaluate

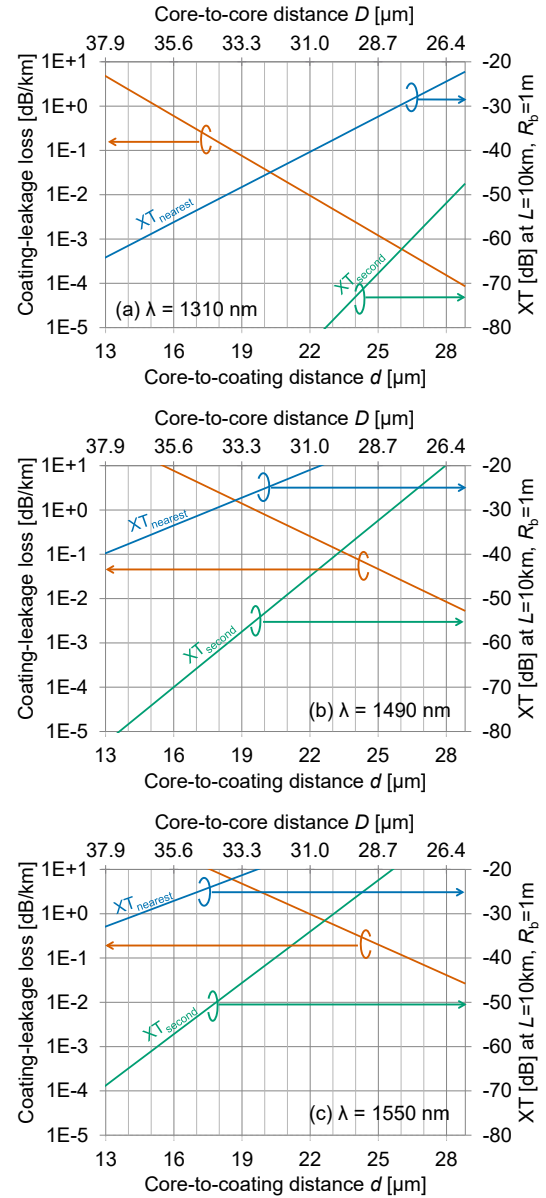


Fig. 3. The relationship between core-to-core distance D , core-to-coating distance d , the core-to-core XT, and the coating-leakage losses, when 8 cores having the designed index profile are equally spaced on a common circle whose center is the center of the 125- μm -diameter cladding.

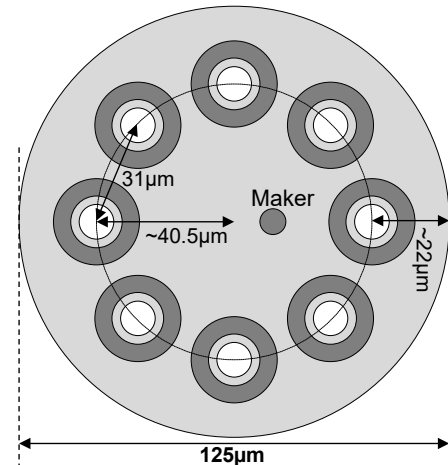


Fig. 4. The cross section of the designed MCF.

the severe case for the coating-leakage loss of ~ 0.01 dB/km at $\lambda = 1.31 \mu\text{m}$ —however, ~ 0.01 dB/km loss increase is still very low for short-reach ($\leq$ a few kilometers) applications. If we optimize the MCF for bidirectional transmission where the signal lights counter-propagate between all pairs of the nearest neighboring cores and where the XT between second-nearest neighboring cores should be cared for, we can enlarge d , and thus can further suppress the coating-leakage loss in O-band.

IV. FABRICATION OF THE MCF

Based on the design, an 8-core MCF was successfully fabricated as shown in Fig. 5. The core-to-core distances ranged from $30.8 \mu\text{m}$ to $31.3 \mu\text{m}$, and the pitch deviation from the design ($31.0 \mu\text{m}$) was well controlled to be less than $\pm 0.3 \mu\text{m}$ owing to the simple one-ring core layout. The minimum core-to-coating distance was fabricated to be $22 \mu\text{m}$. As shown in Fig. 6, the attenuation spectra reflect the impact of the high

leakage loss in the longer wavelength bands. However, we can see that the transmission window is still open in the O-band as we designed. Fig. 7 shows the XT at $1.31 \mu\text{m}$, measured with a 13.14-km MCF sample wound on a bobbin at the bend radius of ~ 8 cm. The XT was measured as a wavelength-averaged XT—that can approximate the statistical mean of the XT [28]—using a superluminescent diode (SLD) whose center wavelength was 1308 nm and whose 3-dB bandwidth was $\sim 32 \text{ nm}$, and time-averaged optical power measurement. The average of the values of the XT between each pair of the nearest neighboring cores of the MCF was -53.7 dB after 13.14 km (-64.9 dB after 1 km , according to the 10 dB/decade dependence of the XT on the fiber length [27]). The optical characteristics in O-band and the λ_{cc} of each core are shown in Table I, which are compatible with ITU-T G.652 as far as in O-band.

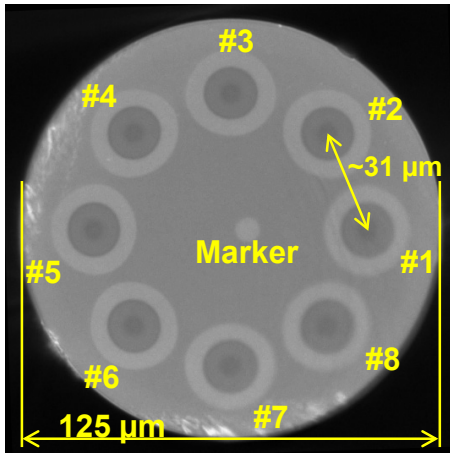


Fig. 5. The cross section of the fabricated MCF.

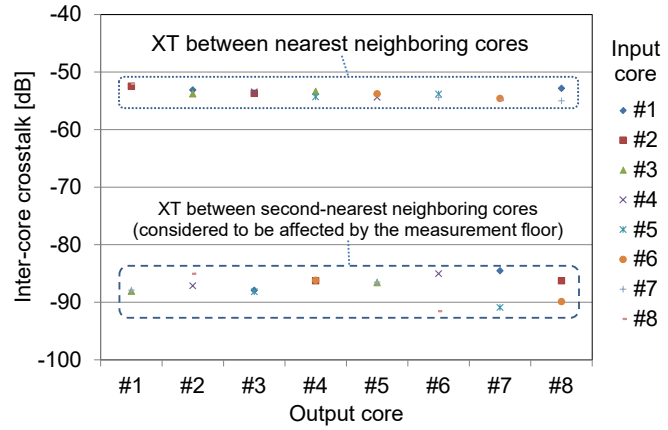


Fig. 7. The inter-core XT of the fabricated MCF at $\lambda = 1.31 \mu\text{m}$ after 13.14-km propagation.

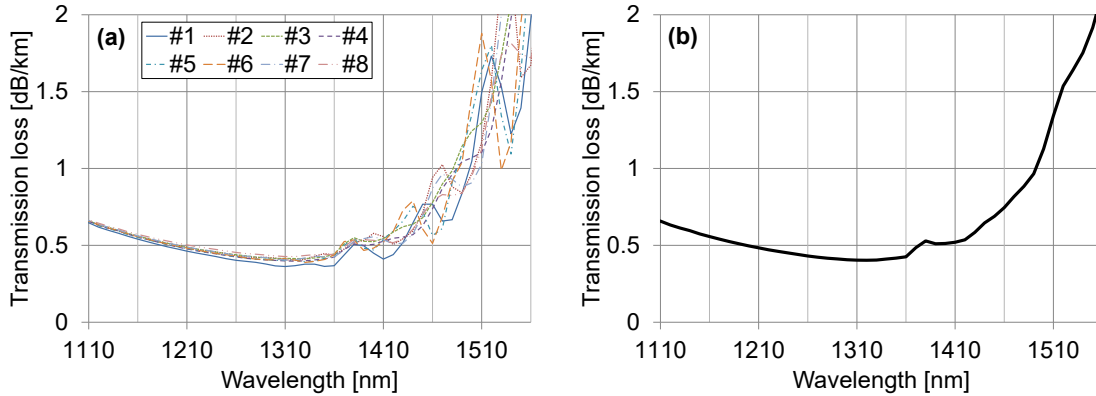


Fig. 6. The transmission loss spectra of the fabricated MCF.

TABLE I
THE OPTICAL CHARACTERISTICS OF THE CORES OF THE FABRICATED MCF

	Transmission loss [dB/km]	λ_{cc} [nm]	MFD [μm]	λ_0 [nm]	Macrobend loss [dB/turn] at R=3mm
λ [nm]	1310	n/a	1310	n/a	1310
#1	0.346	1238	8.5	1317.7	0.034
#2	0.397	1231	8.3	1320.0	0.027
#3	0.394	1228	8.3	1320.2	0.031
#4	0.388	1226	8.4	1319.8	0.023
#5	0.386	1225	8.5	1319.6	0.027
#6	0.389	1217	8.3	1319.7	0.032
#7	0.395	1229	8.3	1317.6	0.027
#8	0.412	1236	8.4	1317.9	0.028
ITU-T G.652	≤ 0.5	≤ 1260	$8.6\text{--}9.5 \pm 0.6$	1300–1324	n/a

V. ULTRA-HIGH-DENSITY MCF CABLE

We fabricated a 1.11-km-long ultra-high-density cable using the fabricated MCF, whose schematic cross-section is shown in Fig. 8(a) and photos in Figs. 8(b,c). The cable includes 12 MCFs, i.e., 96 cores, within the cable diameter of 3 mm. The core density of the cable achieved 13.6 cores/mm², which is more than 2 times higher than the highest value (6 cores/mm² [29]) ever reported, to the best of our knowledge. Owing to the standard 125- μ m cladding diameter, we were able to fabricate the cable by using our manufacturing facilities for current optical fiber cable products without any modifications, and able to use standard ferrules for connectorization. The transmission losses of the cable are shown in Table II and no significant degradation due to the cabling was observed. Tapered-type [30] MCF fan-in/out (FI/FO) were used for accessing each core of the MCF. The link losses of the 8 cores—including the cabled MCF, the MCF-FI/FO pair, 2 MCF connections between the MCF and the FI/FO using SC connectors, and 1 SMF connection at the launching—were 1.5–3.6 dB at $\lambda = 1.31 \mu\text{m}$. The link loss variation may be due to the core-dependent losses of the MCF FI/FO and the MCF connections. Fig. 9 shows the XT characteristics of the cabled MCF and the MCF-FI/FO. The MCF cable was wound on a 14-cm-radius bobbin. The average of the XT between the nearest neighboring cores of the cabled MCF was -61.2 dB after 1.11 km (-61.6 dB after 1 km). The XT change from the non-cabled MCF can be explained by the 10 dB/decade dependence of the XT on the average bending radius [27] and the cable winding thickness on the bobbin—the average bending radius is estimated to be $\sim 16.2 \text{ cm}$.

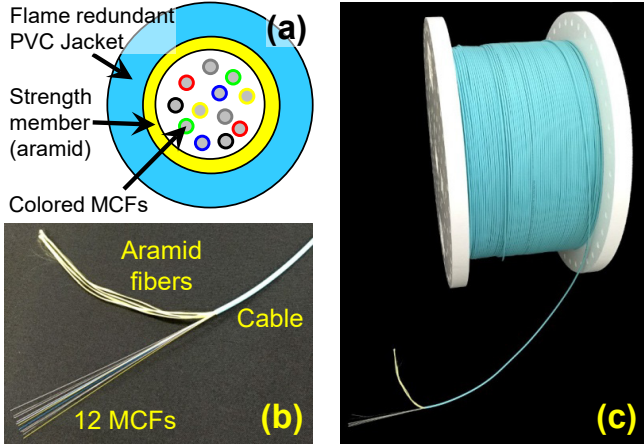


Fig. 8. The fabricated MCF cable. (a) A schematic cross-section, and (b,c) photos of the cable.

TABLE II
TRANSMISSION LOSS OF THE MCF AT 1310 NM
BEFORE AND AFTER THE CABLING

	Transmission loss [dB/km]		
	Before cabling	After cabling	Variation
#1	0.346	0.349	+0.003
#2	0.397	0.399	+0.002
#3	0.394	0.393	-0.001
#4	0.388	0.386	-0.002
#5	0.386	0.389	+0.003
#6	0.389	0.383	-0.006
#7	0.395	0.392	-0.003
#8	0.412	0.406	-0.006

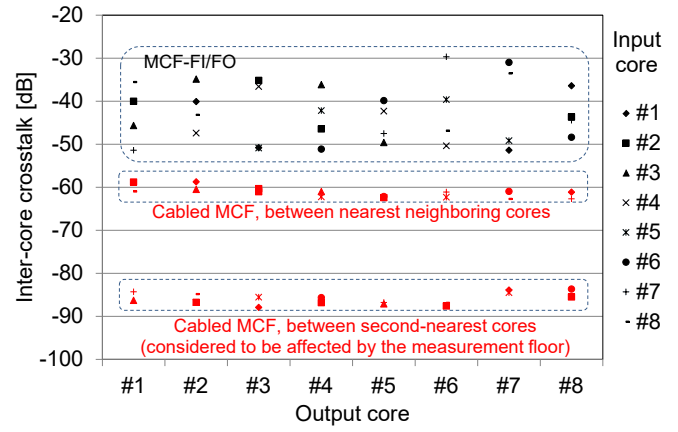


Fig. 9. The XT of the fabricated MCF cable and the MCF-FI/FO at $\lambda = 1.31 \mu\text{m}$.

VI. TRANSMISSION CHARACTERISTICS OF THE CABLED MCF

Transmission characteristics of the fabricated MCF link were experimentally evaluated using a 100GBASE-LR4 [5] transceiver as the transmitter (Tx) and receiver (Rx), for two cases of unidirectional and bidirectional transmissions. In the unidirectional transmission case, the signal lights co-propagate in all the nearest neighboring cores. In the bidirectional transmission case, the signal lights counter-propagate between all the nearest neighboring cores. The unidirectional transmission is more severe in respect of the XT but the bidirectional transmission may be more realistic because the 8-core fiber can transmit full-duplex 100-Gb/s/ λ signal within one fiber using the conventional 25-Gb/s/ λ transmission technologies [5]–[7], [9].

A. Unidirectional transmission

Fig. 10 shows the experimental setup for the unidirectional transmission test. In the Tx, the 4 wavelength channels were excited and modulated by 4 electro-absorption modulator integrated laser diodes (EMLs) with a 25.78125-GBaud pseudo-random binary sequence (PRBS) with $2^{31} - 1$ bits, and the 4 wavelength channels were combined by a wavelength-division multiplexing (WDM) coupler. The WDM signal output from the Tx was split to 8 SSFMs by using a fused fiber coupler,

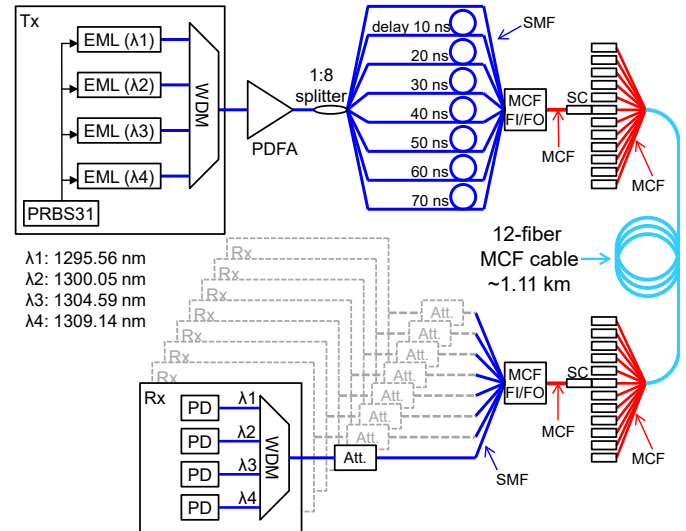


Fig. 10. A setup for the unidirectional transmission experiment.

and different time delays were introduced to each spatial channel for the decorrelation. The launching power (the power after the splitter) per wavelength channel averaged over 8 spatial channels was adjusted to be ~ 2 dBm by using a Praseodymium-doped fiber amplifier (PDFA) inserted before the splitter. The MCF-FI/FO were used for accessing each core of a fabricated MCF in the cable. After being transmitted over the cabled MCF, the signal was demultiplexed by another WDM coupler and received by photo detectors (PDs) in the Rx. Fig. 11 shows the bit error rate (BER) performance of the unidirectional transmission over the cabled MCF. The points indicate the measured performances of individual channels, and the lines are regression lines calculated from the measured performance of all the spatial channels. Black series indicate the back-to-back performance which was measured by connecting the splitter output and the attenuator input. Red and blue series show the MCF transmission performances respectively in the cases where only 1 core was excited and all the cores were excited. The cabled MCF successfully transmitted error-free 8-

SDM $\times$ 4-WDM $\times$ 25-Gb/s (200-Gb/s/ λ /fiber $\times$ 4 λ) signals. Though slight XT-induced penalties were observed for Core #6 and Core #8 at 1305 nm, the penalties came from the MCF-FI/FO and no significant penalty was induced by the MCF XT.

B. Bidirectional transmission

The experimental setup for the bidirectional transmission test was the same as the setup shown in Fig. 10 except that the SMF pigtails of the MCF-FI/FO were connected so as to alternate the signal propagation directions between all pairs of the nearest neighboring cores. Fig. 12 shows the BER performance of the bidirectional transmission over the cabled MCF. The cabled MCF successfully transmitted error-free full-duplex (2 $\times$) 4-SDM $\times$ 4-WDM $\times$ 25-Gb/s (full-duplex 100-Gb/s/ λ /fiber $\times$ 4 λ) signals. In the bidirectional transmission test, no significant penalty was observed.

VII. CONCLUSION

We developed a 125- μ m-cladding 8-core fiber suitable for O-band short reach transmission by employing trench-assisted cores and by designing the transmission band within O-band. The cores of the developed MCF have the MFDs of around 8.6 μ m and XT values of about -60 dB after 1 km propagation at 1310 nm, the cable cutoff wavelengths less than 1260 nm, and the zero dispersion wavelengths within 1300 nm–1324 nm. A 3-mm-diameter 12-MCF cable was fabricated using the developed MCF, and error-free 800-Gb/s/fiber (200-Gb/s/ λ /fiber, 25-Gb/s/ λ /core) signal was successfully transmitted over the cabled MCF. The fabricated MCF cable has the capability to propagate at least 9.6 Tb/s (2.4 Tb/s/ λ). The MCF induced no significant penalty, and further high BW transmission may be easily achieved by increasing signal baud rate and/or modulation order—e.g., the uses of the baud rate of ~ 50 GBd and/or 4-level pulse-amplitude modulation (PAM4) have been proposed for realizing 400 Gb/s Ethernet [31]. Since the developed MCF has the standard 125- μ m cladding, the core density and cable capacity can be easily improved by cabling the MCF with the high-density SMF cabling technology [32]. The 125- μ m cladding can also realize ultra-high-density connectors with the existing standard connectors such as MT, MPO, etc. Though we used tapered MCF-FI/FO in this study, further reductions of the size and cost of the input/output interface of the MCFs are expected to be realized by developments on fiber coupling technologies such as the grating couplers using silicon photonics [10], [33], single-mode VCSELs operable in O-band [34], and so on.

APPENDIX: DERIVATION OF XT_{SECOND} IN (2)

When we consider Cores 1, 2, and 3 in Fig. 5 and neglect the other cores for simplicity, the coupled-power equations can be written as

$$\begin{cases} \frac{dP_1}{dz} \approx h_{\text{nearest}} (P_2 - P_1) + h_{\text{second}} (P_3 - P_1), \\ \frac{dP_2}{dz} \approx h_{\text{nearest}} (P_1 - P_2) + h_{\text{nearest}} (P_3 - P_2), \\ \frac{dP_3}{dz} \approx h_{\text{nearest}} (P_2 - P_3) + h_{\text{second}} (P_1 - P_3), \end{cases} \quad (\text{A1})$$

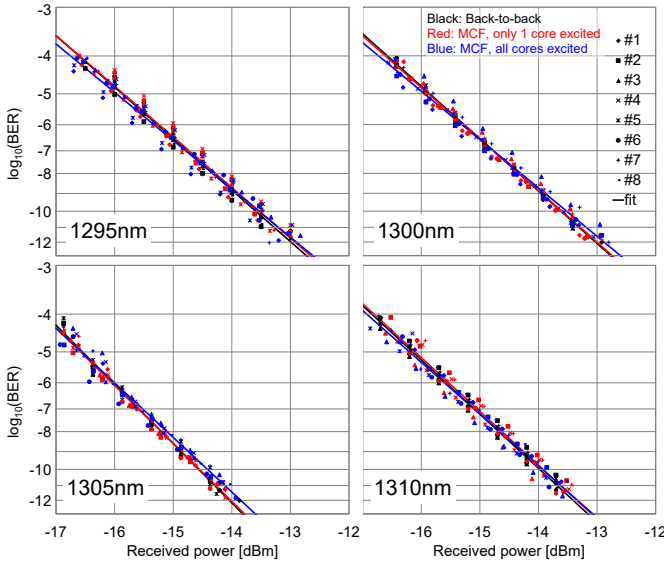


Fig. 11. The BER performance of the unidirectional transmission over the 1.11-km-long cabled MCF.

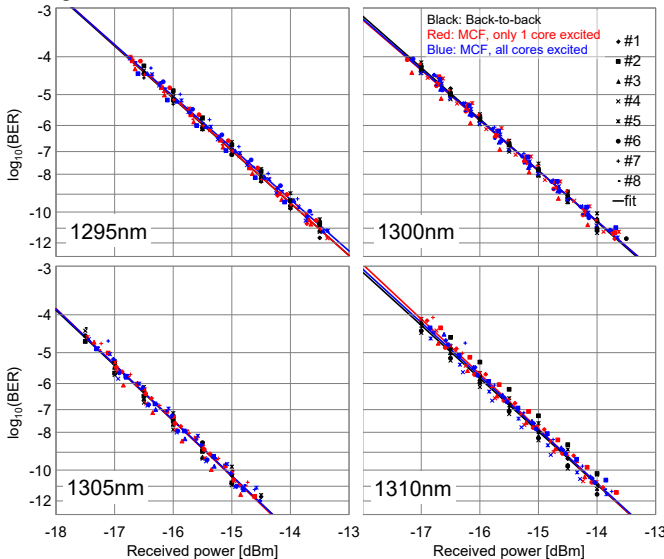


Fig. 12. The BER performance of the bidirectional transmission over the 1.11-km-long cabled MCF.

where P_n is the power of Core n , h_{nearest} is the power-coupling coefficient between the nearest neighboring cores, and h_{second} is the power-coupling coefficient between the second-neighboring cores. When $P_1(0) = 1$, $P_2(0) = 0$, $P_3(0) = 0$, and $1 \gg h_{\text{nearest}} \gg h_{\text{second}}$; and when $P_1 \gg P_2 \gg P_3$ ($z \neq 0$) are assumed, (A1) can be reduced to

$$P_1 \approx 1, \quad \frac{dP_2}{dz} \approx h_{\text{nearest}}, \quad \frac{dP_3}{dz} \approx h_{\text{nearest}} P_2 + h_{\text{second}}. \quad (\text{A2})$$

(A2) is further rewritten as

$$P_1 \approx 1, \quad P_2 \approx h_{\text{nearest}} z, \quad P_3 \approx h_{\text{nearest}}^2 \frac{z^2}{2} + h_{\text{second}} z. \quad (\text{A3})$$

Because h exponentially decreases with the core-to-core distance increase, $h_{\text{nearest}}^2 \frac{z^2}{2} \gg h_{\text{second}} z$ holds for the designed MCF, and we obtain (2) from

$$XT_{\text{nearest}} \equiv \frac{P_2}{P_1}, \quad XT_{\text{second}} \equiv \frac{P_3}{P_1}. \quad (\text{A4})$$

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