

125- μm -Cladding 8-Core Fiber for Short-Reach Optical Interconnects

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To cope with the growing data traffic in the short-reach interconnects used for parallel processing in supercomputers and data centers, optical interconnect technologies for broadband high-density transmission are intensively researched and developed. Sumitomo Electric Industries, Ltd. developed, for the first time, a multi-core optical fiber (MCF) that has eight cores compatible to the standard single-mode fiber in O-band with low inter-core crosstalk in the standard 125- μm -diameter glass cladding. The developed MCF is suitable for the short-reach interconnects and enables low-distortion signal transmission in O-band. The standard 125- μm cladding provides high mechanical reliability equivalent to the standard optical fibers and enables the use of conventional technologies in cabling and so on. A high-density fiber optic interconnect cable fabricated with the 12 pieces of the developed MCF realized good optical properties and robustness against the mechanical and thermal stresses.

Keywords: space-division multiplexing, SDM, multicore optical fiber, MCF, optical fiber cable

1. Introduction

As demand for broad-band high-density parallel transmission technology has been growing in the area of optical interconnects,^{*1} a variety of transmission media and connection technologies have been proposed in response. For short-reach data transmission of less than 100 meters, many technologies based on multimode fiber (MMF) have been presented. These include high-density connectors with an MMF with 125 μm or less cladding diameter, and space-division multiplexing (SDM) transmission technology utilizing multicore fiber (MCF) with multimode cores together with a vertical cavity surface emitting laser (VCSEL) array and a photo diode (PD) array. The demand for broad-band and high-density data transmission is also rising in the area of short- and medium-reach networks (from 500 m to 10 km) for large-scale data centers etc. In this area, solutions using a single-mode fiber (SMF) are common because SMF is capable of minimizing pulse spreading from mode dispersion^{*2} and meeting requirements for transmission distance and transmission capacity. Solutions also include wavelength-division multiplexing (WDM) standards⁽¹⁾⁻⁽⁴⁾ using a standard SMF (SSMF) as the transmission medium, and the parallel transmission specification over a fiber ribbon etc.⁽⁵⁾ More recently, SDM using MCF made of single-mode cores has also been proposed for short- to medium-reach purposes.⁽⁶⁾ Despite these various technologies becoming available, no report has been made on an MCF that is equipped with all of the said functions—that is, a cable with “eight cores or more,” “optical characteristics equivalent to SSMF,” “125- μm cladding diameter,” and “-30 dB or less inter-core crosstalk (XT) after 1 km transmission.”⁽⁶⁾⁻⁽⁹⁾ This is because there are inherent tradeoffs among the reduction of core spacing, reduction of XT, reduction of leakage loss to cladding (using a high refractive index for cladding mode suppression), and enlargement of the mode field diameter (MFD, or the effective area A_{eff}).

By optimizing the transmission bands to the O-band

(1260–1360 nm), we newly developed a fiber with a 125- μm cladding diameter and 8 cores, each of which is suitable for short-reach transmission and has characteristics equivalent to those of an SSMF. We also created a prototype fiber cable (cord) with an outer diameter of 3 mm and containing 12 of the said MCFs at an extremely high core density of 13.6 core/ mm^2 .⁽¹⁰⁾⁻⁽¹²⁾ This paper discusses the research concerning the developed fiber and cable.

2. Design Targets

In this research, we aimed to develop a fiber equipped with (1) 8 cores, (2) optical characteristics equivalent to an SSMF, and (3) 125- μm cladding diameter, which is equivalent to the diameter of a standard optical fiber. This section summarizes the importance of these features.

2-1 Fiber with 8 cores

When using an MCF for short-reach transmission, conventional data transmission techniques can be used as they are (except for I/O between MCFs), which is important to minimize the costs of building MCF networks. A transceiver of which the modulation system, symbol rate, and number of spatial channels are customized specifically for MCF transmission networks can be a major factor in increasing costs. From this point of view, our 8-core MCF is an ideal material for practical use, as it transmits signals bidirectionally at 100 Gbit/s/ λ per fiber by utilizing conventional 25-Gbit/s transceiver technology, which is currently achievable with an existing specification⁽⁵⁾ using 8 SSMFs.

2-2 Optical characteristics equivalent to SSMF

To minimize customization for a transceiver, the MCF's cores need to have characteristics equivalent to an SSMF. This is because SMF-based short-reach transmission standards⁽¹⁾⁻⁽⁵⁾ specify an SSMF as the transmission fiber.

In addition, most of the SMF short-reach transmission standards use the O-band (1260–1360 nm) as the transmis-

sion band.^{(1)-(3),(5)} One reason for this is because one of the low chromatic dispersion characteristics*² in the O-band possessed by SSMF suppresses signal distortion during transmission, eliminating the need for electric dispersion compensation at the transceiver. Elimination of the compensation circuit not only reduces transceiver costs but also signal delays.

2-3 Standard 125- μm cladding diameter

Many MCF R&D projects allow a cladding diameter larger than the standard 125 μm in order to increase the number of cores while maintaining and enhancing the optical characteristics of each core.^{(6),(7)} However, this could cause a deterioration in the mechanical reliability of the fiber. Figure 1 shows the failure probability of optical fibers with different cladding diameters along with changes in the bend radius calculated based on references (13) and (14). The larger the cladding diameter, the higher the failure probability is, as well as the bend radius threshold, where failure probability rises significantly in smaller bend radii.

In a long-reach high-volume transmission network, it is possible to alleviate this failure probability by specifying the minimum bend radius of the optical fiber and controlling the actual installation based on this specification. However, doing so in a short-reach transmission network could cause a significant deterioration in operational efficiency. Also, handling thickened and inflexible fibers requires extra work.

Standard 125- μm cladding optical fiber is already in use for short-reach optical interconnects and its mechanical reliability is proven.⁽¹⁵⁾ Utilizing fiber with a standard cladding size also enables the application of mature technologies with high reliability and cost-competitiveness to MCF with minimum or no alteration, and such MCFs can then be used in cables or connectors in the conventional manner.

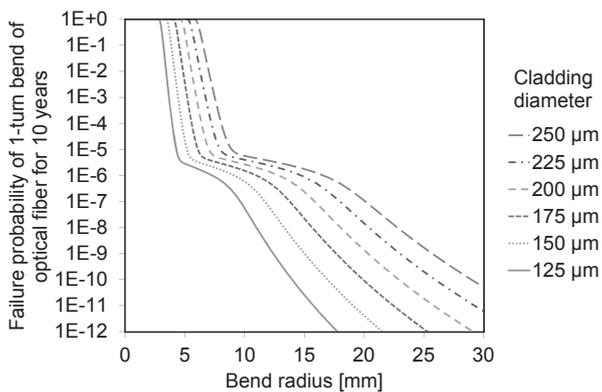


Fig. 1. Example of failure probability of optical fiber by bending and its dependency on bend radius and cladding diameter⁽¹¹⁾

3. Fiber Design

Our 8-core fiber with 125- μm cladding diameter was designed as a homogeneous MCF with identical cores to unify the optical characteristics of each core. We utilized

the trench-assisted (TA) refractive index profile in order to simultaneously achieve, in O-band, optical confinement in the core, single mode transmission, low-wavelength dispersion, and MFD with reduced connection loss. Figure 2 shows the refractive index profile of the design. We designed the MCF to have an MFD of 8.6 μm at 1310 nm, which is equivalent to an SSMF, a cable cutoff wavelength λ_{cc} of 1200 nm, and a zero-dispersion wavelength λ_0 of 1312 nm.

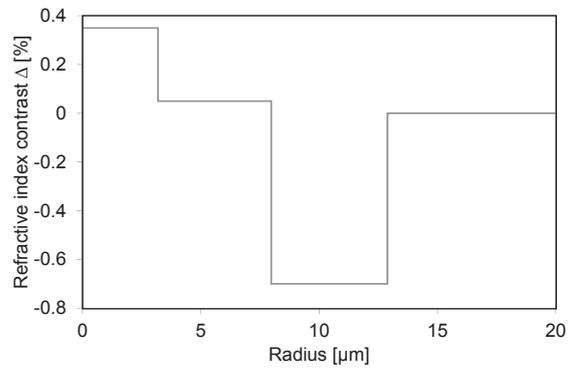


Fig. 2. Designed refractive index profile of the MCF core⁽¹¹⁾

As Fig. 3 shows, the cores are laid out in a circular form at equal intervals. This layout helps unify the optical characteristics of each core taking account of perturbation from each other. This layout also allows all the cores to be accessed easily when coupling an optical chip to a fiber via the chip surface (using grating couplers, VCSELs, or PDs, etc.) as no core is completely surrounded by other cores.

To determine whether or not it was possible to include eight of the designed cores in the 125- μm cladding diameter, we made a calculation based on references (16) to (18). This calculation evaluated the relationship of core pitch D (center-to-center distance between neighboring cores), outer cladding thickness d (minimum distance between the core center and the border of the cladding and coating), inter-core crosstalk XT (when the bend radius R_b is assumed to be 1 meter), and leakage loss to coating when the cores are laid out as shown in Fig. 3. The calculation results showed that there is no value of D or d that achieves -40 dB or less crosstalk after 10 km transmission and 0.1 dB/km or less leakage loss simultaneously at wavelengths of 1490 nm or 1550 nm. However, at 1310 nm, it is possible to achieve 0.01 dB/km or less leakage loss and -40dB or less crosstalk between two neighboring cores when d is $\sim 22 \mu\text{m}$ (i.e. D is $\sim 31 \mu\text{m}$).

These results suggested that 8 cores with SSMF-equivalent characteristics can be included in the 125- μm cladding by optimizing the transmission wavelengths to the O-band, and thus we selected $d = 22.0 \mu\text{m}$ ($D = 31.0 \mu\text{m}$) for the fiber in this research. In this case, the leakage loss at 1310 nm wavelength is estimated to be approximately 0.01 dB/km, which is sufficiently low in short-reach communications of less than several kilometers data transmission.

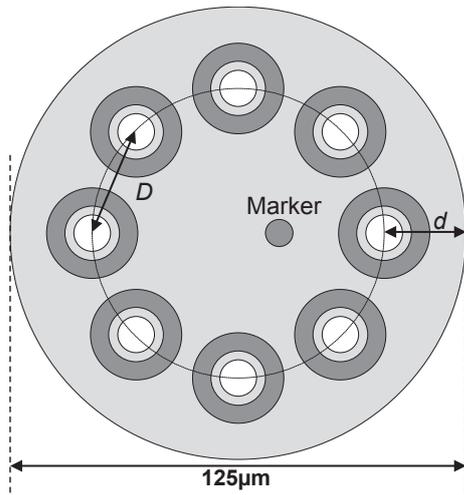


Fig. 3. Section view of the designed MCF⁽¹⁰⁾
(Refractive index is low in dark colored edges)

4. Fabrication of 125- μ m-Cladding 8-Core Fiber Prototype

We fabricated a prototype of the 8-core fiber based on the design described earlier. Figure 4 shows a section view of the MCF prototype. We were able to control the core pitch D precisely within an error of $\pm 0.3 \mu\text{m}$ due to the simple circular core layout with high rotational symmetry, and the actual value of D was between 30.8 to 31.3 μm compared to the designed figure of 31.0 μm . The outer cladding thickness d was $\sim 22 \mu\text{m}$, as designed. As shown in Fig. 5, the transmission loss spectrum indicates that the loss increases in long wavelengths due to the leakage to the coating. However, the window of transmission is clearly open in the O-band as we expected. Figure 6 shows the crosstalk after 13.14 km transmission at the 1310 nm wavelength in the MCF that was wound on a bobbin with a radius of approximately 8 cm. A superluminescent diode (SLD) with a center wavelength of 1308 nm and a 3-dB bandwidth of $\sim 32 \text{ nm}$ was used as the light source. We used the time average of received optical power as the measurement values to obtain the average wavelength of the crosstalk (this becomes an approximate value of the statistical

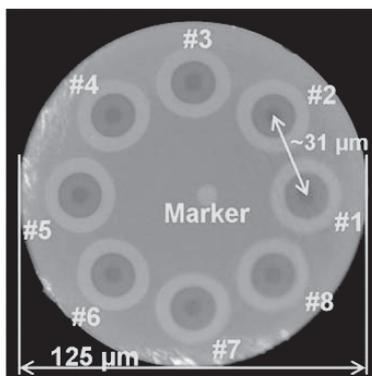


Fig. 4. Section view of MCF prototype⁽¹⁰⁾, ⁽¹¹⁾

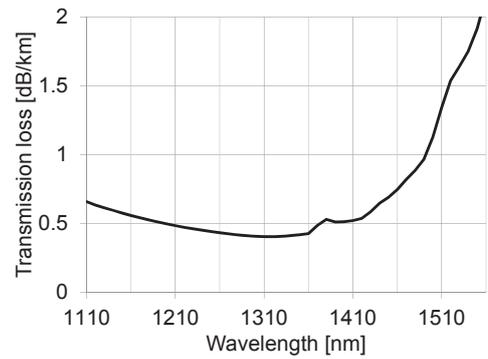


Fig. 5. Average of transmission loss spectra in all cores of MCF prototype⁽¹⁰⁾, ⁽¹¹⁾

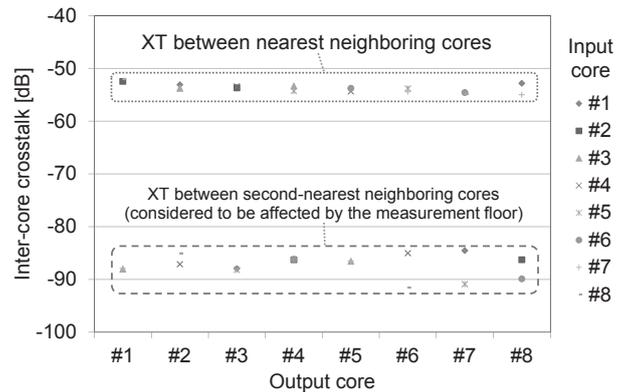


Fig. 6. MCF prototype's inter-core crosstalk at 1.31 μm wavelength after 13.14 km transmission

average of the crosstalk).⁽¹⁹⁾ The average crosstalk measurement between the neighboring cores was -53.7 dB after 13.14 km transmission (equivalent to -64.9 dB after 1 km transmission). Table 1 lists the optical characteristics in the O-band in each core and λ_{cc} , and the values within the O-band are comparable to ITU-T G.652.

Table 1. Optical characteristics of each core in the MCF prototype⁽¹⁰⁾, ⁽¹¹⁾

	Transmission loss [dB/km]	λ_{cc} [nm]	MFD [μm]	λ_0 [nm]	Bending loss [dB/turn] (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

5. MCF Cable and Actual Usage Assessment

Utilizing the fabricated MCF, we also developed a prototype of an ultra-high-density cable of 1.11 km in length. The cable section view is shown in Fig. 7 (a), and the exterior of the prototype cable are shown in Fig. 7 (b) and (c). The cable contains 12 pieces of the 8-core fiber (i.e. 96 cores in total) within an outer diameter of 3 mm. The core density reaches 13.6 core/mm², and this density is more than twice the highest core density (6 core/mm²)⁽²⁰⁾ reported in the area of communication optical fiber cables to date (as of May 2016). Also, thanks to the MCF made in the standard 125- μ m cladding diameter, the cable prototype was fabricated using the current optical fiber cable production facility without any modifications. It was also possible to mate the cable and SC connector using a conventional ferrule. The MCF's transmission loss and crosstalk were measured again after it was assembled into a cable, and no significant deterioration was identified. We then conducted an environmental resistance test on the MCF cable prototype. Table 2 shows the test items and related conditions.

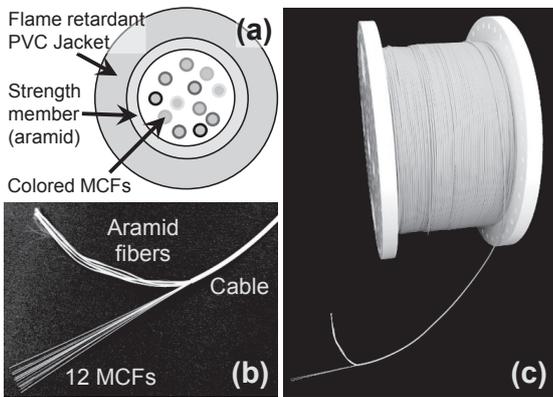


Fig. 7 MCF cable prototype^{(10), (11)}
 (a) Section view diagram,
 (b) & (c) Appearance of cable prototype

These tests were conducted following Telcordia GR-409,⁽²¹⁾ which specifies the methods and conditions for testing optical fiber cables for interconnects, except that the measured wavelength was 1.31 μ m. For MCF I/O, we used a pair of fan-in/fan-out (FIFO) devices with low crosstalk. As shown in Fig. 8, we connected FIFO devices individually to MCFs at one end of the cable, and connected the two MCFs to each other using SC connectors at the other end. This configuration forces the light to travel backward and forward within the 1.11 km cable, creating a total of 2.22 km round-trip transmission. We then measured the finally received optical power. The results of loss variation and crosstalk variation are shown in Table 2. The resulting loss variation and crosstalk variation were both small enough for sufficiently suppressing signal deterioration during transmission.

Based on these results, we confirmed that the MCF cable prototype achieves optical characteristics sufficient for actual use in short-reach interconnects.

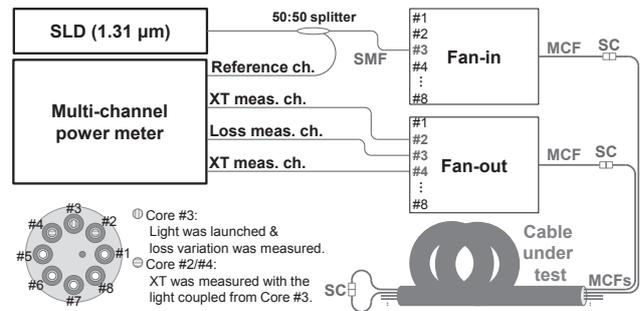


Fig. 8. Experimental setup to measure loss and XT variations in MCF⁽¹²⁾

Table 2. Summary of mechanical characteristics and temperature characteristics test

Test items	Test methods	Loss variation [dB/pass]	XT variation [dB]
Tensile strength	Telcordia GR-409-CORE 30 N, 3 m, 30 min.	< 0.1	-0.1 to 0.2
Twist	Telcordia GR-409-CORE $\pm 180^\circ$ / 30 cm, 10 times	< 0.1	-0.3 to 0.2
Repeated bending	Telcordia GR-409-CORE $R_b = 25$ mm x 6 windings, 25 times	< 0.1	-0.1 to 0.2
Lateral pressure	Telcordia GR-409-CORE 98 N/25 mm	< 0.1	-0.2 to 0.1
Impact	Telcordia GR-409-CORE 0.74 N-m, 3 times	< 0.1	0.0 to 0.1
High/Low temperature bending	Telcordia GR-409-CORE $R_b = 25$ mm x 10 windings 0°C/60°C	< 0.1	-0.3 to 0.2
Temperature cycle	Telcordia GR-409-CORE 0 to 70°C, 2 cycles	< 0.1dB/km	-0.4 to 0.5

6. Conclusion

We developed an MCF prototype that contains 8 cores suitable for short-reach transmission within a standard 125- μ m cladding diameter by using trench-assisted cores and optimizing the transmission window for the O-band transmission. These cores are about 8.6 μ m in MFD, and achieve an inter-core crosstalk of approximately -60 dB after 1 km transmission (at 1310 nm wavelength), λ_{cc} of 1260 nm or less, and λ_0 of 1300 to 1324 nm. We then developed a 3-mm-diameter cable that contains 12 of the said MCF prototypes. As the MCF prototype has the standard 125- μ m cladding diameter, existing cable production technologies can be used as they are and the resulting cable retained the MCF's optical characteristics intact. We assume that the core density in the cable and the transmission capacity can be easily improved by developing a new cable utilizing the said MCF prototype and applying the existing ultra-high-density SMF cable production technology.

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Technical Terms

- *1 Interconnect: Interconnections among multiple chips, servers, server racks, and data centers, etc.
- *2 Dispersion (Modal dispersion or wavelength dispersion): Difference in light speeds depending on the mode or wavelength. This creates fast-travelling elements and slow-traveling elements in the optical signal, causing distortions in the waveforms. Dispersion increases as the transmission distance becomes longer, necessitating optical or electrical compensation.

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