Authors' Submitted Version - IWCS 2023 Cable & Connectivity Industry Forum, pp. 193–197, paper 8-6, Orlando, Florida, USA.

Crosstalk Characteristics of 200-µm-Coating 4-Core Fibers in 288-Fiber/864-Fiber Freeform Ribbon Cables

Tetsuya Hayashi, Ayumi Inoue, Yohei Suzuki, Takuji Nagashima, Yuki Shimoda, and Fumiaki Sato
Sumitomo Electric Industries, Ltd.
Yokohama, Kanagawa, Japan
t-hayashi@sei.co.jp

Abstract
Multicore fiber can significantly increase the spatial density of optical fiber cables, and would realize light-weight ultra-high-density cable suitable for low-cost cable installation. To realize MCF cables with better optical performance, the crosstalk change due to cabling is nonnegligible. In this study, we fabricated 288-fiber and 864-fiber partially-bonded-ribbon cables with 200-µm-coating MCFs, which can suppress the XT increase due to cabling.

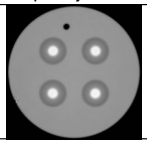
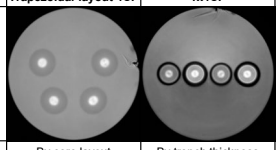
Keywords: multi-core fiber; partially-bonded ribbon; freeform ribbon; optical fiber; microduct cable

1. Introduction
In recent years, with the dramatic increase of data capacity among all over the world due to expanding of crowd computing, the demand for high-fiber-count and high-density optical cable increases. To construct optical networks more economically, it is necessary to make effective use of existing ducts and spaces for the installation of optical fiber cables. Several studies on ultra-high-density optical fiber cable with partially-bonded ribbons have been reported. Recently, the multi-core fiber (MCF) has been actively studied for further improvement of spatial channel density and an MCF cable with partially-bonded ribbons was also reported. A 200-fiber partially-bonded-ribbon cable with 250-µm-coating MCFs (100f/250µm-MCF cable) [1], and a 288-fiber partially-bonded-ribbon cable with 200-µm-coating MCFs (288f/200µm-MCF cable) have been reported [2]. The crosstalk (XT) increase due to cabling was well suppressed in the 100f/250µm-MCF cable, but was somewhat higher in the 288f/200µm-MCF cable.

In this paper, we present 288-fiber and 864-fiber partially-bonded-ribbon cables with 200-µm-coating MCFs, which can suppress the XT increase due to cabling.

2. 125-µm-cladding 4-core fibers and related MCF technologies
In this section, we review the 125-µm-cladding 4-core fibers and related MCF technologies. For practical use of MCFs, 4-core fibers with the standard 125-um cladding have been proposed [3], [4]. Table 1 shows the examples of the 125-µm-cladding 4-core fibers. The square- and trapezoidal-layout 4CFs were fabricated using simple G.652/G.657.A1 compatible cores. The square 4CF has XT for counter-propagating signals (XT_{bidir}) ≤−40 dB/10km at 1550 nm, which provides future compatibility to wavelength band migration from O-band to C-band. In fact, Soma *et al.* demonstrated the transoceanic distance bidirectional transmission over step-index 4-core fibers with the standard cladding diameter [5]. The other short-reach MCFs are optimized for O-band transmissions and have XT_{bidir} << −40 dB/10km at 1310 nm. The trapezoidal 4CF realizes core identification without additional marker and easier rotational alignment. The 1x4CF can pack 8.6-µm MFD cores on a linear array in the 125-µm cladding and can be coupled to PLC-based fan-in/fan-out (FIFO) (i.e., simple waveguide pitch converter) and edge couplers of photonic integrated circuits. Heterogeneous index trench thickness also realizes core identification without additional marker. All of these 125-µm-cladding 4-core fibers are compatible to either of 250-µm coating or 200-µm coating.

Table 1. 125-µm-cladding 4-core fibers [4].

Applications	Short-/medium-reach		Short-reach	
Fiber ID	Square-layout 4CF		Trapezoidal-layout 4CF	1x4CF
Cross section				
Core identification	By marker		By core layout	By trench thickness
Core pitch Λ	40 µm		37 µm	25 µm
Cable cutoff λ	1239–1244 nm		1129–1159 nm	1060–1186 nm
Operation λ (λ_{op})	1310 nm	1550 nm	1310 nm	1310 nm
MFD at λ_{op}	MFD 9.0 µm	-	MFD 8.6–8.9 µm	MFD 8.4–8.7 µm
Loss at λ_{op}	0.327–0.329 dB/km	0.194–0.197 dB/km	0.321–0.325 dB/km	0.317–0.359 dB/km
XT_{dir}[a] at λ_{op}	−68 dB at 1km	−36 dB at 1km	−52 to −51 dB at 1km	−50 to −45 dB at 1km
Total XT_{bidir}[b] at λ_{op}	−84 dB at 10km	−47 dB at 10km	−68 to −65 dB at 10km	−66 to −59 dB at 10km

a) XT_{dir}: Core-to-core XT between co-propagating lights in nearest neighboring cores
b) XT_{bidir}: XT in bidirectional transmission where signals propagate in counter directions between every pair of nearest neighboring cores.

Various MCF technologies necessary to realize MCF links have also been developed. Single-MCF connector (Fig. 1) was demonstrated with the simple structure without additional high-precision components, thus suitable for volume manufacturing [6]. The fabricated MCF LC connectors realized ultralow insertion loss (IL) and high return loss (RL) connections [IL histogram shown in Fig. 1(right)], and passed Telcordia GR-326-CORE mechanical and environmental tests. For the square-layout 4-core fibers, the compact FIFO based on etched fiber bundle technology (Fig. 2) has been well developed with low IL and high RL, and IL variation during temperature cycle was well suppressed [7].



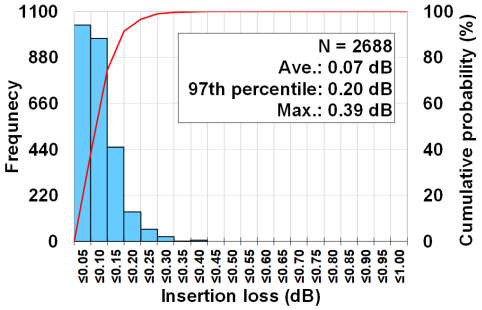


Figure 1. (left) Appearance of the single-MCF LC connector, and (right) the IL histogram for random mating test [6].

The FIFO technologies for these 4-core fibers have also been proposed and developed. For the square-layout 4-core fibers, the compact FIFO based on etched fiber bundle technology (Fig. 2) has been well developed with low IL and high RL, and IL variation during temperature cycle was well suppressed [7]. For the trapezoidal-layout 4-core fibers, the laser-inscribed 3-dimensional waveguide [8] can be a good choice. As already mentioned, the 1x4CF can be coupled to PLC-based FIFO and edge couplers of photonic integrated circuits, which can be easily realized with commercial volume-manufacturable technology.

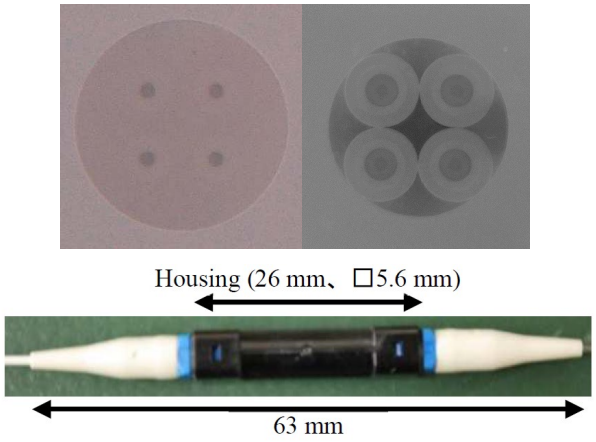


Figure 2. Compact MCF fanout with etched fiber bundle. (top left) End face of MCF, (top right) end face of bundle, and (bottom) appearance of the fanout [7].

3. Freeform Ribbon Cables with 200-μm-coating step-index 4-core fibers

We fabricated 200-μm-coating step-index square-layout 4-core fibers [square-layout 4CF, Table 1(left)] and Freeform Ribbon (partially-bonded ribbon, see Fig. 3) cables with 288 fibers in the cable outer diameter of ~9.5 mm [Fig. 4(left)] and 864 fibers in the cable outer diameter of ~12.8 mm [Fig. 4(right)] using the 4CFs. Table 2 summarizes the properties of the 4-core fibers used for the cable fabrication.

Table 2. Properties of the 4-core fiber spools used for Freeform Ribbon cable fabrication.

MCF samples		4CF-1	4CF-2
Fabricated cables		288f cable	864f cable
Core layout		Square	
Core pitch [μm]		39.5-39.8	39.6-39.8
Cladding diameter [μm]		125 ± 1	
Coating diameter [μm]		205 ± 10	
MFD [μm]	1310nm	8.7-8.8	8.4
λ_{cc} [nm]		1328-1359	1219-1251
Loss [dB/km]	1310nm	0.333	0.332-0.334
	1550nm	0.192-0.193	0.187-0.191
XT [dB at 1km]	1310nm	n/a	-78
	1550nm	-38	-41
Average bend radius [m] in fiber spools		~0.15	~0.09

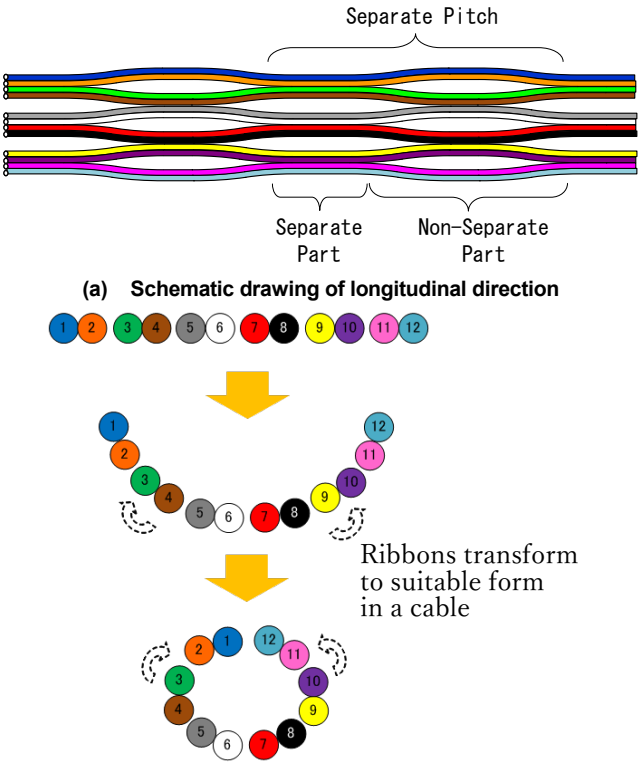


Figure 3. Schematics of 12-fiber Freeform Ribbon [9].

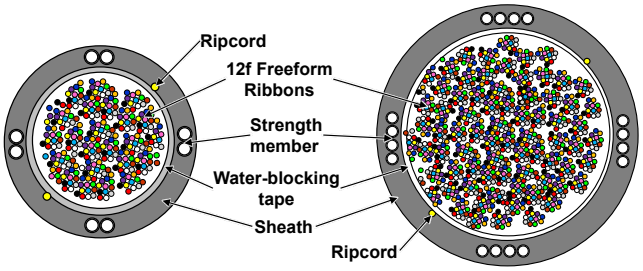


Figure 4. Schematics of (left) 288-fiber and (right) 864-fiber cables using Freeform Ribbons.

Figure 5 shows the dependence of the core-to-core XT in the 4-core fibers in the fabricated 288-fiber and 864-fiber Freeform Ribbon cables during temperature cycling tests. The XT slightly decreased with temperature decreased. Since the XT of homogeneous MCFs is approximately linear proportional to the fiber bend radius [10], [11], the XT variation with temperature change can be considered due to the fiber bending radius change in cables. We can consider that the cable sheath shrinked and the fiber bending radius in the cables became slightly tighter when temperature decreased. The estimated XT at fiber bending radius (R) is 0.15 m and 0.09 m are also plotted in Fig. 5.

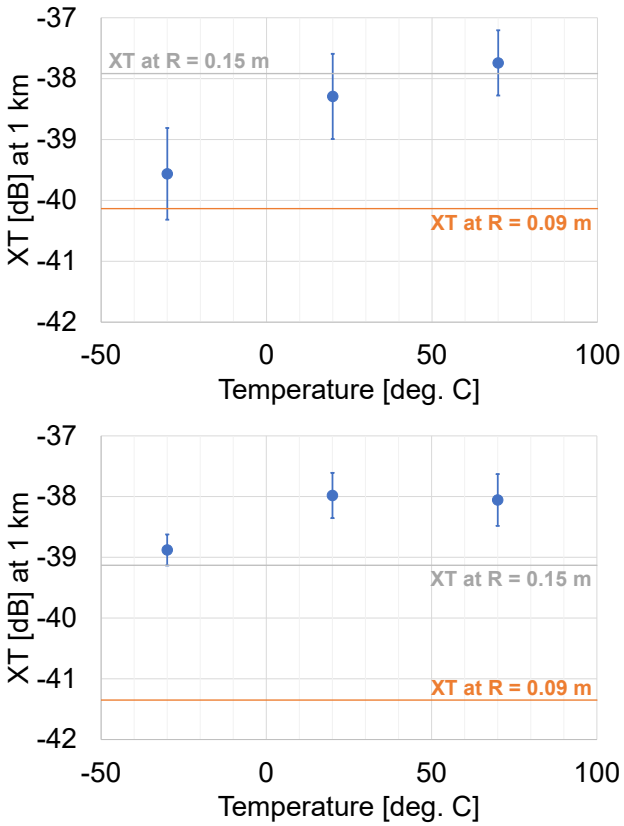


Figure 5. XT at 1550 nm vs temperature of the 4-core fibers in (top) 288-fiber and (bottom) 864-fiber Freeform Ribbon cables.

Using the linear proportionality of the XT to the fiber bending radius, the average fiber bend radius of the MCFs in a cable can be estimated from the XT difference of the MCF between the fiber spool and the cable drum when the drum diameter is much larger than the fiber spool diameter. Using this estimation method, we estimated the average fiber bend radius of the MCFs in the fabricated 288-fiber cable and 864-fiber cable, as shown in Fig. 6. The estimated average fiber bend radius was 0.1-0.15 m in the 288-fiber cable and ~0.2 m in the 864-fiber cable, which realized low XT compared to earlier studies with the estimated average fiber bend radius of ~0.3 m with the 288-fiber partially-ponded-ribbon cables with 200-µm-coating fibers.

Figure 7 shows the XT increase due to cabling, depending on the fiber spool radius before cabling and the fiber bending radius in cables, which clearly shows the proper control of the fiber bending radius in cables is important to realize low XT MCF cables. The fabricated cables demonstrate that partially-bonded-ribbon cables with 200-µm-coating MCFs can also suppress the XT increase due to cabling and can relax the MCF XT requirements.

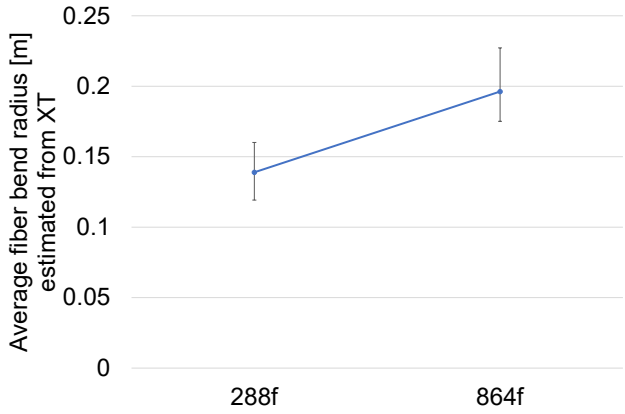


Figure 6. Fiber bending radius in the fabricated Freeform Ribbon cables, estimated from the XT change in the 4-core fibers before/after cabling.

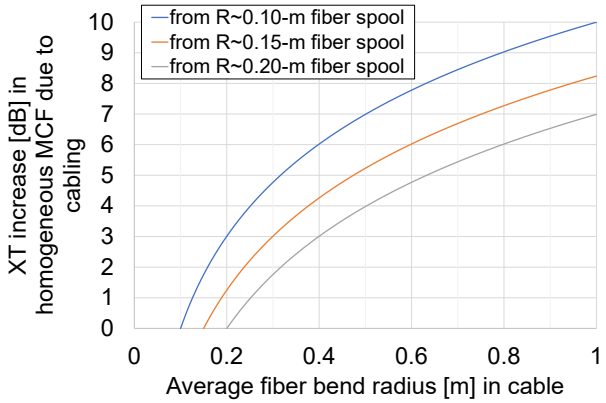


Figure 7. XT increase in homogeneous MCFs due to cabling

4. Conclusions

We reviewed the recent progress of the MCF technologies for practical realization, and presented newly fabricated 288-fiber and 864-fiber partially-bonded-ribbon cables with 200-µm-coating MCFs, which can suppress the XT increase due to cabling, thanks to the proper control of average fiber bending radius in the cables. Our cabling technology will enable low XT MCF cables and help the practical realization of optical communication networks with thin and lightweight high-density MCF cables.

5. References

[1] T. Hayashi *et al.*, "Crosstalk Characteristics of Multi-Core Fibers with Different Cladding Diameters in High-Density Optical Cable with Freeform Ribbons," in *Int. Wire Cable Symp. (IWCS)*, Providence, 2018, p. P-6.

[2] Y. Sasaki *et al.*, "Optical-Fiber Cable Employing 200-µm-Coated Four-Core Multicore Fibers," *J. Lightwave Technol.*, vol. 40, no. 5, pp. 1560–1566, Mar. 2022.

[3] T. Matsui *et al.*, "Step-index profile multi-core fibre with standard 125-µm cladding to full-band application," in *Eur. Conf. Opt. Commun. (ECOC)*, 2019, p. M.1.D.3.

[4] T. Hayashi *et al.*, "Uncoupled Multi-core Fiber Design for Practical Bidirectional Optical Communications," in *Opt. Fiber Commun. Conf. (OFC)*, San Diego, 2022, p. M1E.1.
[5] D. Soma *et al.*, "Transoceanic-Class Transmission over Step-Index Profile Standard Cladding 4-Core Fibre with Bidirectional Transmission Technology," in *Eur. Conf. Opt. Commun. (ECOC)*, Basel, 2022, p. Th1D.2.
[6] T. Morishima *et al.*, "Simple-structure low-loss multi-core fiber LC connector using an align-by-contact method," *Opt. Express*, vol. 29, no. 6, pp. 9157–9164, Mar. 2021.
[7] T. Kikuchi *et al.*, "Low insertion loss and high return loss fiber bundle fan-in/fan-out for four-core multi-core fiber," in *OptoElectron. Commun. Conf./Photonics in Switching and Computing (OECC/PSC)*, 2022, p. TuC4-2.
[8] S. Gross and M. J. Withford, "Ultrafast-laser-inscribed 3D integrated photonics: challenges and emerging applications," *Nanophotonics*, vol. 4, no. 3, pp. 332–352, Nov. 2015.
[9] F. Sato *et al.*, "Characteristics of Ultra-High-Fiber-Count and High-Density Optical Cables with Pliable Ribbons," in *Int. Wire Cable Symp. (IWCS)*, Orlando, Florida, 2017, pp. 304–311.
[10] T. Hayashi, "Multi-Core Fiber Technology from Design to Deployment," in *Eur. Conf. Opt. Commun. (ECOC)*, Basel, 2022, p. Mo4D.1.
[11] T. Hayashi *et al.*, "Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber," *Opt. Express*, vol. 19, no. 17, pp. 16576–16592, Aug. 2011.

6. Pictures of Authors



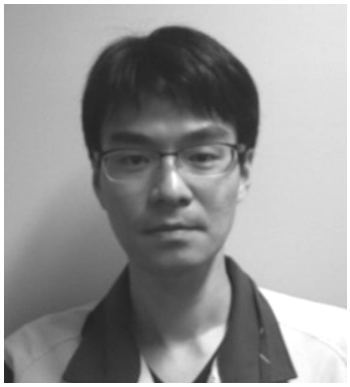
Tetsuya Hayashi received the B.E. and M.E. degrees in electronic engineering from the University of Tokyo, Japan, in 2004 and 2006, respectively, and the Ph.D. in engineering from Hokkaido University, Sapporo, Japan, in 2013.

In 2006, he joined Optical Communications Laboratory, Sumitomo Electric Industries, Ltd., Yokohama, Japan. He has been engaged in research and development on optical fibers and fiber optics. He is currently a Group Manager for advanced optical fiber R&D. He has authored and coauthored more than 120 publications in international journals and conference proceedings, and four book chapters.

Dr. Hayashi is a Senior Member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan, the Institute of Electrical and Electronics Engineers (IEEE), and Optica (formerly OSA). He received various awards and prizes including the Tingye Li Innovation Prize from OSA at Optical Fiber Communication Conference (OFC) 2017.

Ayumi Inoue received the B.E and M.E. degrees in Applied Chemistry from Keio University, Kanagawa, Japan, in 2017 and 2019, respectively.

In 2019, she joined Optical Communications Laboratory, Sumitomo Electric Industries, Ltd., Yokohama, Japan, and since then has been engaged in research and development of optical fibers.



Yohei Suzuki received his M.S. degree from Tokyo University of science in 2006. He joined Sumitomo Electric Industries, Ltd. in 2006 and he has been engaged in plant and process engineering of optical cables and in development of optical fibers and cables since then.

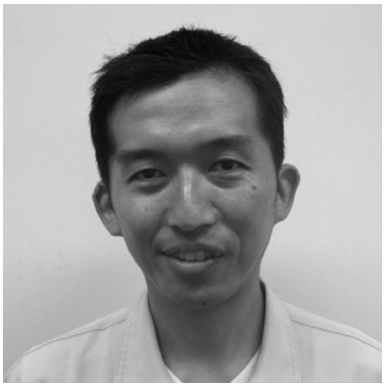


Takuji Nagashima received the B.E. and the M.E. degrees in electronic engineering from Kyoto University, Kyoto, Japan, in 2005 and 2007, respectively.

In 2007, he joined Optical Communications Laboratory, Sumitomo Electric Industries, Ltd., Yokohama, Japan, and since then has been engaged in research and development of optical fibers.



Yuki Shimoda received his M.S. degrees from Osaka University in 2001. He joined Sumitomo Electric Industries, Ltd. in 2001 and has been engaged in engineering and development of optical fibers and cables since then. He is a Project Manager of Data Center Optical Cable Engineering Group in Optical Fiber and Cable Division.



Fumiaki Sato received his M.E. degrees from Tohoku University in 2000. He joined Sumitomo Electric Industries, Ltd. in 2000 and he has been engaged in design and development of optical fibers and cables since then. He is a Group Manager of Data Center Optical Cable Engineering Group in Optical Fiber and Cable Division.