Optical-Fiber Cable Employing 200-μm-Coated Four-Core Multicore Fibers

Yusuke Sasaki, Ryohei Fukumoto, Katsuhiro Takenaga, Shogo Shimizu, and Kazuhiko Aikawa

(Top-Scored Paper)

***Abstract*—Combining small-diameter optical-fiber technology and space-division multiplexing employing multicore fiber (MCF) is a promising method for further increasing the transmission capacity of optical networks. In this work, four-core MCFs with a 200-μm coating diameter (200-4CFs), reduced from 250 μm, were fabricated. The 200-4CFs had featured almost the same characteristics as the 4CFs with a 250-m cladding diameter. The 200-4CFs were ribbonized and cabled. This cabling represents the first time approach employing an MCF with a 200-μm coating. The attenuation increase caused by the cabling was compared with that of 4CFs with 250-μm coating diameter and SMFs. The effective bending radius of the 4CFs in a cable employing partially bonded ribbons was investigated and determined to be smaller than the cable-drum radius. Mechanical and environmental tests based on IEC standards were performed on the cable employing 200-4CFs, and the cable exhibited excellent performance. The scalability of high-fiber-count cables employing 200-4CFs was also demonstrated. Finally, the applicability of an automatic splice with core identification via side-view alignment is presented.**

***Index Terms*—MCF, multi-core fiber, optical fiber, optical fiber cable, SDM, space-division multiplexing.**

I. Introduction

THE traffic in data center networks is increasing drastically. Consequently, higher fiber-count cables are required to improve the transmission capacity. However, the size of the conduits connecting the datacenter sites and the available datacenter floor space for storing cables remain limited. Nevertheless, to meet this growing demand, higher-fiber-count, lighter-weight and smaller-diameter optic cables are required.

Slot-less cables with partially bonded optical-fiber ribbons are suitable for the solution. This optical fiber ribbon is advantageous in that its shape can be altered and it can be packed inside a cable freely. This leads to higher density cables with a smaller cable diameter, which are difficult by slot cables or loose-tube cables. Smaller diameter cables can be wound on a drum with a longer length, which leads to a reduction in the splicing points over a span. As another advantage, it can be easily divided into individual fibers using a simple tool or manually. Moreover, the ribbons can be spliced with each other, as well as with conventional rigid ribbons. Recently, thin 200-μm-coating single-mode fibers (SMFs) with a standard 125-μm cladding diameter have been developed. Reducing the coating diameter from 250 μm to 200 μm reduces the area per fiber by 36%. This drastic reduction enables the development of higher fiber-count cables with smaller cable diameters and lighter weights. For example, by employing 200-SMFs in partially bonded ribbons, a cable with a fiber count of up to 6,912 has been achieved with a cable diameter of 33 mm [1].

Space-division multiplexing (SDM) employing new fibers, such as few-mode fibers (FMFs) and multi-core fibers, has been actively developed to further increase the transmission capacity of optical networks. Single-mode multi-core fibers (MCFs) are promising candidates for SDM. An MCF has multiple single-mode cores in a common cladding, and the signal-transmitting cores can be treated independently, due to the very significantly low crosstalk. A transmission system employing MCFs does not require complex digital signal processing, such as a large-scale multiple-input multiple-output (MIMO), to compensate for crosstalk between cores. The cladding diameter of a standard single-mode fiber is 125 μm. MCFs with a cladding diameter of 125 μm are compatible with the existing optical-transmission systems and are expected to be easily incorporated into practical applications. Using such MCFs will be a breakthrough for achieving much higher density cables in data center networks. Trench-assisted and step-index four-core MCFs with 125 μm claddings have been developed [2], [3]. The results of cable field trials employing four-core MCFs and five-core MCFs have been reported [4], [5]. However, all MCFs with 125-μm claddings reported thus far have a 250-μm coating, which is the same as that in standard SMFs. By reducing the coating diameter of the MCFs to 200 μm, further high-density cables can be designed and developed.

In this study, we demonstrate the characteristics of step-index 200-μm-coated four-core fibers (200-4CFs) and cabled 200-4CFs [6]. The characteristics of the cabled 4CFs were compared with those of 200-μm-coating SMFs (200-SMFs), which are included in the same cable, and also compared with

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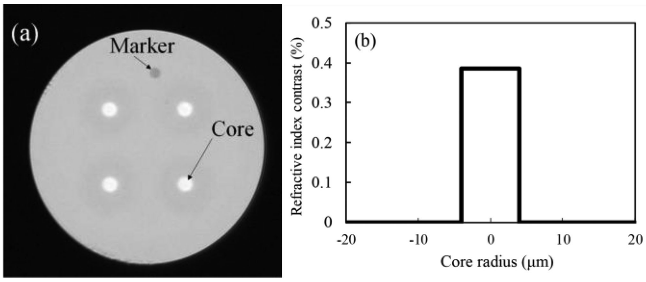

Fig. 1. Cross-section and index profile of a fabricated 200-4CF.

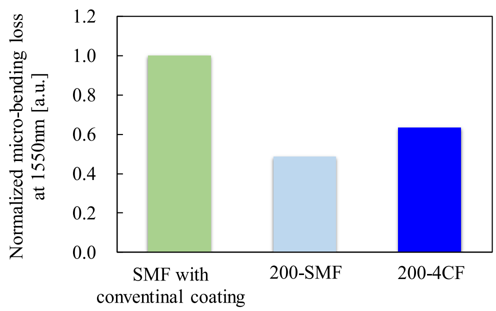

Fig. 2. Measured micro-bending loss at 1550 nm.

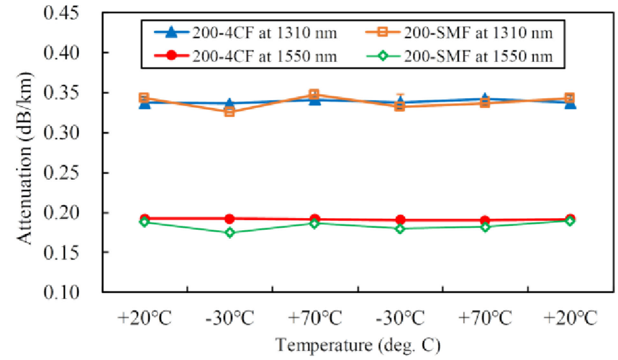

Fig. 3. Temperature cycling test result of 200-4CFs and 200-SMFs before cabling.

250-μm-coating 4CFs. To the best of our knowledge, this is the first report of a cabled, thin, 200-μm-coating MCF. Finally, we demonstrate the low-loss splicing of 200-4CFs using side-view alignment technology.

II. Prepared Fiber Characteristics

Conventional standard SMFs have a cladding diameter of 125 μm and a dual-layered coating with a diameter of 250 μm. Fibers in high-density cables are required to possess low micro-bending loss characteristics because of the high lateral pressure. Generally, the thin coating on the fibers leads to a deterioration of the cushion effect against disturbances and causes an increase in the micro-bending loss. Therefore, we optimized the Young's modulus of resins of the primary and secondary coatings for 200-SMFs for high-density cables [7]. Young's modulus of newly developed primary coating of 200-SMFs was lower than that of 250-SMFs to suppress micro-bending loss. The thicknesses of the primary and secondary of 200-SMFs were also optimized based on the thickness ratio of 250-SMFs. It is reported that micro-bending loss depends on the cladding diameter, and that not on whether the fiber is an MCF or an SMF [8]. Therefore, optimized Yong's modulus and thickness of the primary and secondary coating for 200-SMFs can be directly applicable to 200-4CFs. We employed the same coating for 200-4CFs. Fig. 1(a) shows the cross-section of a fabricated 200-4CF. A dual-layered coating exists outside the glass area. The micro-bending losses of the 200-4CF were measured by conducting fixed-diameter sandpaper drum tests, as described in IEC TR62221. The micro-bending loss of a standard 250-μm-coating SMF with conventional coating resins was also measured for comparison. Fig. 2 shows the measured micro-bending loss at 1550 nm. The values were normalized using the measured value of an SMF with conventional coating. The micro-bending loss of a 200-SMF with the newly developed coating was less than the standard SMF, despite the reduction in the coating diameter. Micro-bending loss of a 200-4CF was almost the same as that of the 200-SMF, which indicates that 200-4CFs can apply to high-density cables as 200-SMFs.

Crosstalk increases with the transmission length. However, in data center networks, the transmission length is generally less than 100 km. Therefore, an ultra-low crosstalk characteristic, which is achieved by introducing a deep index trench, is not necessary. Thus, a simple step-index core profile without a trench was employed for the 200-4CFs as shown in Fig. 1(b). This core profile can be manufactured using the vapor-phase axial deposition (VAD) method, suitable for mass production and cost reduction. The core pitch and outer-cladding thickness were designed to be 40.0 μm and 34.2 μm, respectively, to suppress the crosstalk and excessive losses, caused by the absorption of light into the coating [3]. Table I summarizes the optical characteristics of the fabricated 200-4CFs. We also prepared 4CFs with a 250-μm coating (250-4CFs), SMFs with a 250-μm coating (250-SMFs), and a 200-μm coating (200-SMFs) for comparison. The 200-SMFs had the same coating resins as the 200-4CFs, whereas the 250-SMFs and 250-4CFs had conventional coating resins. The same core profile was employed for all the fibers. The optical properties of each core of all the fibers satisfied the ITU-T G.657.A1 recommendation as designed. All the fibers passed 1% proof strength test. The crosstalk distributions of the 4CFs were measured using the wavelength sweeping method, and the crosstalk values were obtained [9]. The crosstalk of the 200-4CFs was –67 dB/km and –36 dB/km at 1310 nm and 1550 nm, respectively. The crosstalk at 1310 nm was sufficiently low for O-band transmission, and that at 1550 nm was also sufficiently low to support coherent QPSK transmission over 10–40 km [3]. Furthermore, crosstalk values of 200-4CFs were lower than or almost identical to those of 250-4CFs. The diameter of the fiber spool was 310 mm for both 200-4CFs and 250-4CFs. It was confirmed that the coating thickness had a minimal effect on the crosstalk.

A temperature-cycling test was carried out on the 200-4CFs and 200-SMFs from -30 to $+70$ °C for two cycles before cabling. Fig. 3 shows the attenuation variations of the 200-4CFs and 200-SMFs. The averaged attenuation variations of

TABLE I
MEASURED OPTICAL CHARACTERISTICS AND DIMENSIONS OF A FABRICATED 200-4CF AND PREPARED FIBERS

Attribute	Wavelength	ITU-T G.657.A1	200-4CF Core 1	200-4CF Core 2	200-4CF Core 3	200-4CF Core 3	250-4CF Average	200-SMF	250-SMF
Attenuation (dB/km)	1310 nm	< 0.4	0.339	0.339	0.338	0.338	0.330	0.327	0.334
	1550 nm	< 0.3	0.192	0.192	0.193	0.192	0.191	0.188	0.186
MFD (μm)	1310 nm	8.2-9.6	8.3	8.3	8.3	8.3	8.5	8.5	8.6
	1550 nm	-	9.3	9.3	9.3	9.3	9.6	9.5	9.6
Macro-bending loss at ϕ 30 mm (dB/10 turns)	1550 nm	< 0.25	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.04	< 0.01
	1625 nm	< 1.0	0.01	0.01	0.02	0.02	0.04	-	-
Macro-bending loss at ϕ 20 mm (dB/1 turn)	1550 nm	< 0.75	0.03	0.04	0.03	0.03	0.10	-	-
	1625 nm	< 1.5	0.12	0.15	0.16	0.14	0.41	0.23	0.25
Zero-dispersion wavelength (nm)		1300-1324	1314	1314	1312	1315	1315	1313	1313
Cable cutoff wavelength (μm)		<1.26	1.21	1.20	1.21	1.21	1.20	1.21	1.23
PMD (ps/km$^{1/2}$)		< 0.20	0.08*	0.06*	0.06*	0.06*	0.08*	0.02	0.02
Total crosstalk (dB/km)	1310 nm	-	−67				−67	-	-
	1550 nm	-	−36				−33	-	-
	1625 nm	-	−28				−24	-	-
Outer cladding thickness (μm)			34.4				34.2	-	-
Cladding diameter (μm)		124.3-125.7	124.9				125.0	125.0	125.0
Coating diameter (μm)		-	194				243	194	239
Core pitch (μm)		-	39.8				40.0	-	-

*Measured on spool.

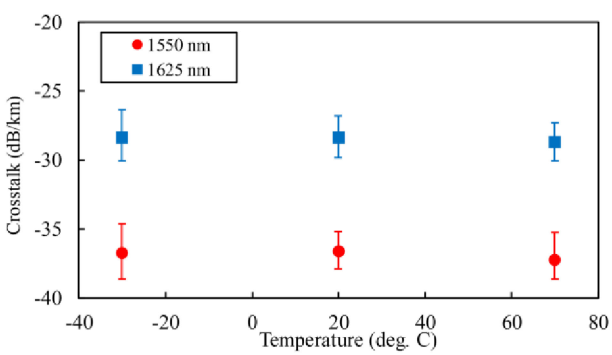

Fig. 4. Temperature dependence of core-to-core crosstalk of 200-4CFs before cabling.

the 200-4CFs were confirmed to be less than 0.01 dB/km at 1550 nm, which was less than that of the 200-SMFs. Fig. 4 shows the temperature dependence of the core-to-core crosstalk of the 200-4CFs before cabling. The average crosstalk at 1550 nm was −36.7 dB/km, −36.6 dB/km, and −37.3 dB/km at −20 °C, +20 °C, and +70 °C, respectively. There was no clear relationship between the crosstalk and temperature before cabling.

III. Cable Characteristics

Two types of partially bonded optical-fiber ribbons employing 4CFs and SMFs were fabricated. One ribbon had 200-μm-coated fibers, and the other had 250-μm-coated fibers. Each ribbon was then cabled and labeled as Cable A and B, with lengths of 5 km and 2 km, respectively. The unit structure was the same as those of conventional cables. Cable A was comprised of 200-μm-coated fibers, 12 of which were 200-4CFs, and 276 of which were 200-SMFs. Similarly, Cable B was comprised of 250-μm-coated fibers, 50 of which were 250-4CFs and 90 of which were 250-SMFs. Fig. 5 shows an external view of the fabricated Cable A and a schematic view of the fiber ribbon inside Cable A. The cable was composed of a polyethylene sheath, water-blocking tapes, strength members, and fiber ribbons. We measured the attenuation of each SMF and the core of every 4CF after the cabling process and compared it with the before-cabling condition. The cables were wound onto drums. Fig. 6 shows the attenuation before and after the cabling process for Cables A and B at 1550 nm. The differences in the attenuation of the 250-4CFs and 250-SMFs before cabling could be attributed to the additional fabrication processes, such as the drilling process. The attenuation of both the 4CFs and SMFs after the cabling process increased, as compared to that before the cabling process. We believe this is due to the micro-bending loss caused by fiber compression in the longitudinal direction of

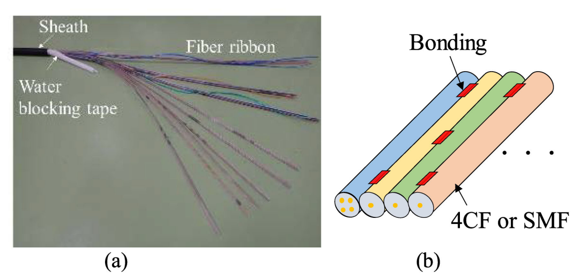

Fig. 5. Structure of fabricated cable A. (a) Outlook of cable, (b) External view of a fiber ribbon inside the Cable A.

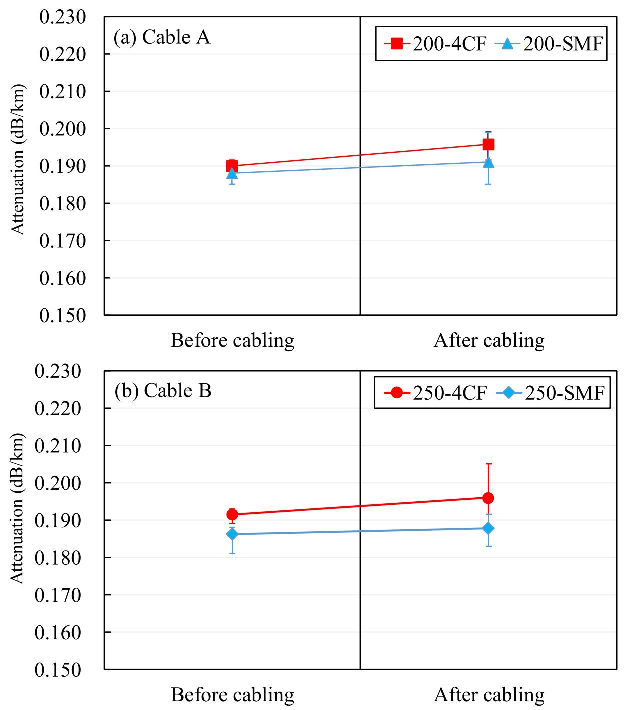

Fig. 6. Variation in attenuation due to cabling process of (a) Cable A and (b) Cable B.

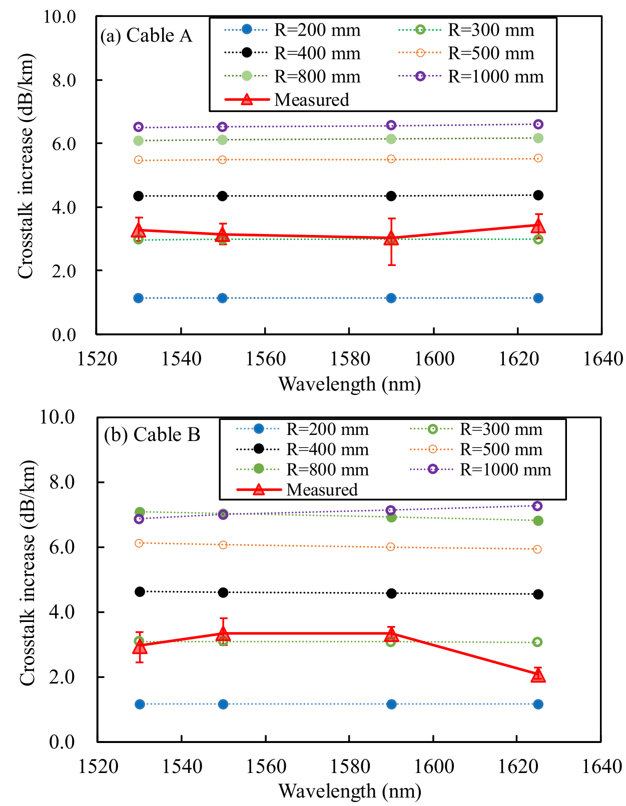

Fig. 7. Crosstalk increment after cabling as compared to before cabling for (a) Cable A (200-4CFs) and (b) Cable B (250-4CFs).

the cable. However, the average variation in the attenuation of the 200-4CFs and 250-4CFs was less than 0.01 dB/km. Therefore, we can conclude that the difference in the coating diameters had a negligible impact on the attenuation.

It has been reported that the crosstalk of a 4CF with a 250-μm coating in a loose-tube cable increased by 5–6 dB due to the cabling, and the increment was mainly caused by the change in the fiber bending radius [4]. For cabling 200-4CFs or 250-4CFs, we chose a high-density cable structure employing partially bonded ribbons. The fibers inside a high-density cable are subject to receive high lateral pressure because the fibers in a high-density cable are packed into a smaller space than in a loose-tube cable. This might deteriorate the crosstalk characteristics of the MCFs in a high-density cable. If the crosstalk deteriorates due to the cabling, it must be considered when designing an MCF. Therefore, we measured the crosstalk of the 4CFs after cabling and compared it with the crosstalk before cabling. Before cabling, the fiber-spool radius of the 4CFs was 155 mm. The cables were wound onto large-diameter cable drums. The cable-drum radii for cables A and B were 500 and 600 mm, respectively. The crosstalk of an MCF increases as the bending radius increases in the phase-matching region with bending radii smaller than a critical bending radius (R_{pk}) [10]. The R_{pk} was calculated to be approximately 1 m from the index profiles of each core of 4CFs. Therefore, the crosstalk of a cabled 4CF wound onto a cable drum would be larger than that before cabling. Fig. 7 shows the measured core-to-core crosstalk increase after cabling, along with the simulation results using multiple bending radii (R), assuming that all the crosstalk variations are caused by the variations in R. The simulated crosstalk increase in the 200-4CFs in Cable A and the 250-4CFs in Cable B was 5–6 dB, as expected from the variation in the fiber-spool radius of 155 mm to the cable-drum radius of 500 or 600 mm. However, it was observed that the measured crosstalk increase for both 200-4CFs and 250-4CFs was almost identical at 3 dB. The coating-diameter difference had a minimal impact on the crosstalk behavior due to cabling. The measured 3-dB increase was smaller than the expected values and matched well with the assumption that R was approximately 300 mm for both cables. This can be explained by the deformation of the fibers in the cable, which may have resulted in a smaller effective bending radius. This led to a suppressed crosstalk increase in the 4CFs after cabling. It is confirmed that the crosstalk does not deteriorate, owing to the cabling process, even if the cable is a high-density type employing partially bonded ribbons. Because the deformation and the small effective bending diameter are maintained even after the cable installation, the crosstalk of the 4CFs will be suppressed, regardless of the coating diameter.

IV. Mechanical and Environmental Tests

Mechanical characteristic tests were conducted on Cable A. Because Cable A was fabricated as a high-density cable for microducts, mechanical tests were performed considering the IEC60794-1-21 standard [11]. The measured wavelength of the tests was 1550 nm. Table II summarizes the test results. The 200-4CFs and 200-SMFs inside the same cable A were compared. The loss variation of each 200-4CF and 200-SMF

TABLE II
AVERAGED LOSS VARIATION OF CABLE A AFTER ENVIRONMENTAL TEST

Attribute	Test condition	200-4CF	200-SMF
Tensile	IEC60794-1-21 E1	< 0.03 dB/core	< 0.01 dB/fiber
Crush	IEC60794-1-21 E3	< 0.01 dB/core	< 0.01 dB/fiber
Impact	IEC60794-1-21 E4	< 0.01 dB/core	< 0.01 dB/fiber
Bend	IEC60794-1-21 E11	< 0.01 dB/core	< 0.01 dB/fiber
Repeated bending	IEC60794-1-21 E6	< 0.01 dB/core	< 0.01 dB/fiber
Torsion	IEC60794-1-21 E7	< 0.01 dB/core	< 0.01 dB/fiber

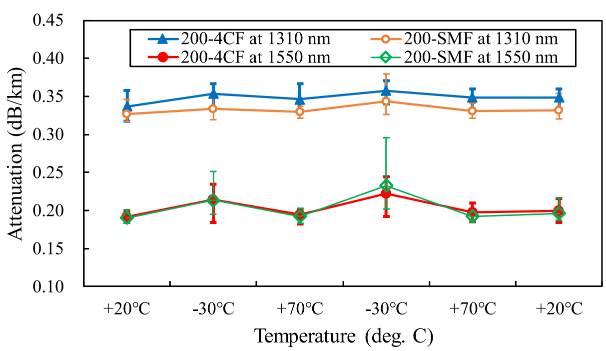

Fig. 8. Result of temperature cycling test after cabling.

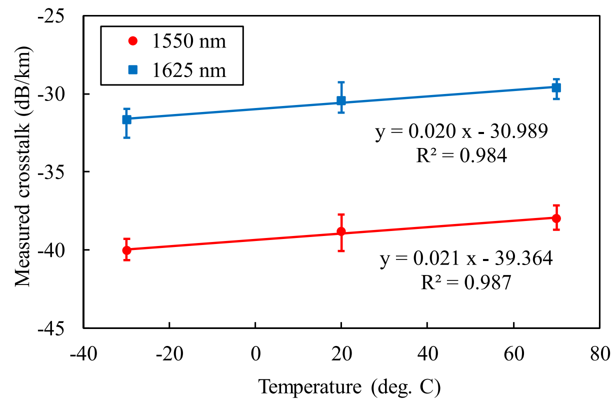

Fig. 9. Temperature dependence of crosstalk after cabling. Lines are collinear approximate straight lines.

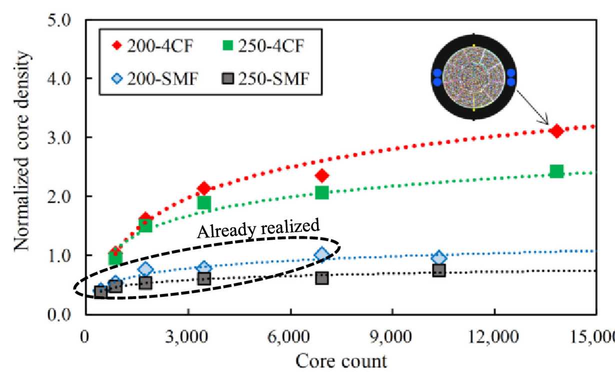

Fig. 10. Relationship between the core density and core count. (Dotted lines are approximated curves).

sample after each test was less than 0.05 dB; therefore, they passed the tests. In all the tests, favorable results were obtained. It was confirmed that the fabricated 200-4CFs exhibited the same mechanical performance as 200-SMFs. 200-SMFs have been already commercially available for high-density cables. There are no problems with using 200-4CFs in a high-density cable.

A temperature-cycling test was performed on Cable A after cabling. The temperature was varied from −30 °C to +70 °C for two cycles. Fan-in/fan-out devices (FIFOs) and fusion-spliced points for looping were set outside the climate chamber. We used waveguide type FIFOs whose insertion loss was about 2 dB/pair at 1310 nm, 1550 nm and 1625 nm. Fig. 8 shows the attenuation variations of the 200-4CFs and 200-SMFs. The attenuation fluctuation of the 200-4CFs was almost the same as that of the 200-SMFs. Compared with before cabling, as shown in Fig. 3, the attenuation fluctuation of the 200-4CFs was larger after cabling. However, the fluctuations were less than 0.05 dB/km for both 1310 nm and 1550 nm. This is a favorable level for practical use. Fig. 9 shows the temperature dependence of the core-to-core crosstalk of the 200-4CFs. The values were averaged over two cycles. A strong correlation was found between the crosstalk and temperature, which was not exhibited before cabling, as shown in Fig. 4. The appearance of the dependency was not due to the 4CF itself but due to the cabling. The crosstalk improved as the temperature decreased. This is because a low temperature causes cable shrinkage. This shrinking might lead to a smaller effective bending radius of the 4CFs in the cable, leading to lower crosstalk.

V. CORE-DENSITY AND HIGH CORE COUNT CABLE

The fabricated Cable A had 288 fibers, consisting of 12 strands of 200-4CFs and 276 strands of 200-SMFs. If the fibers were all 4CFs, a 1,152 core-count cable could be achieved. We estimated the number of core count in a cable or how a high-density cable can be achieved, if the cable consists of all 200-4CFs, instead of SMFs. This demonstrates the effectiveness of reducing the coating diameter to 200 μm and employing 4CFs. Thus far, as many as 6,912 core count cable employing 200-SMFs and a 3,456 core count cable employing 250-SMFs [12] have been reported. Fig. 10 shows the relationship between the core density and core count for various types of fibers. The core density was normalized to that of a 6,912-fiber cable with 200-SMFs. The cable diameter and core density of the cable are 33 mm and 8 cores/mm^2, respectively [1]. The 4CFs can realize significantly higher core-density cables than 250-SMFs and 200-SMFs. Utilizing 200-4CFs can enable the development of higher core-density cables, compared with those fabricated using 250-4CFs. This tendency becomes remarkably large as the core count increases. Fig. 11 shows a comparison of the cable diameter and core count of high-density cables. By employing 200-4CFs, 13,824 core count cables can be achieved with a cable

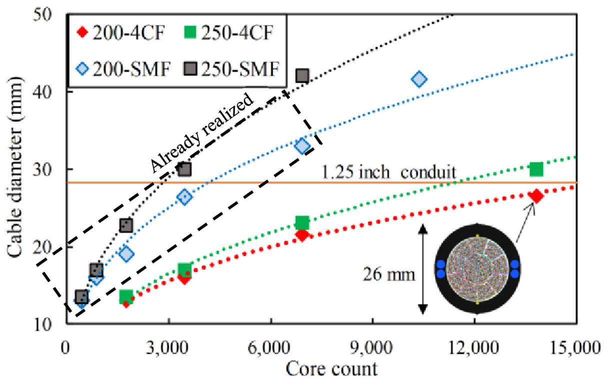

Fig. 11. Comparison of cable diameter and core count. (Dotted lines are approximated curves; orange lines are the allowable outer diameter of conduits to install the cables.

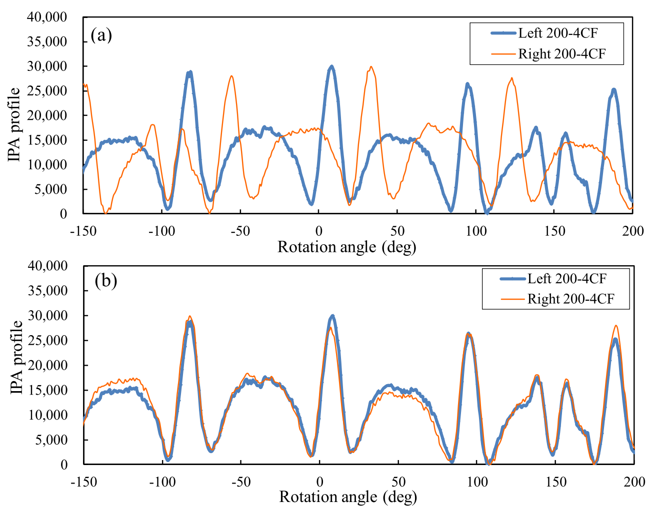

Fig. 12. Obtained IPA profiles (a) before and (b) after alignment.

diameter of 26 mm and a density of 25 cores/mm^2. This cable can be installed in existing 1.25 inch conduits, which is difficult to achieve using 250-4CFs.

VI. Splicing 200-4CFs

Splicing technology is also important for the practical use of 200-4CFs. As side-view alignment is commonly used for SMF splicing, the applicability of side-view alignment to 200-4CFs is crucial. We investigated how precisely the alignment and how small a splice loss could be achieved via automatic side-view alignment. A 200-4CF has a marker to identify the core identifier, made from a low-index rod in a preform. This marker helps to splice the 4CFs with core identification. We used the improved inter-relational profile alignment (IPA) method, available in a conventional splicer (FSM-100P). This method uses captured side-view images while continuously rotating through one revolution. The IPA profile was obtained by analyzing the brightness features obtained at each rotational angle [13]. Fig. 12(a) shows an example of measured IPA profiles obtained from the splicer under the condition that the same fabricated 200-4CFs were set for both right and left sides under the condition before alignment.

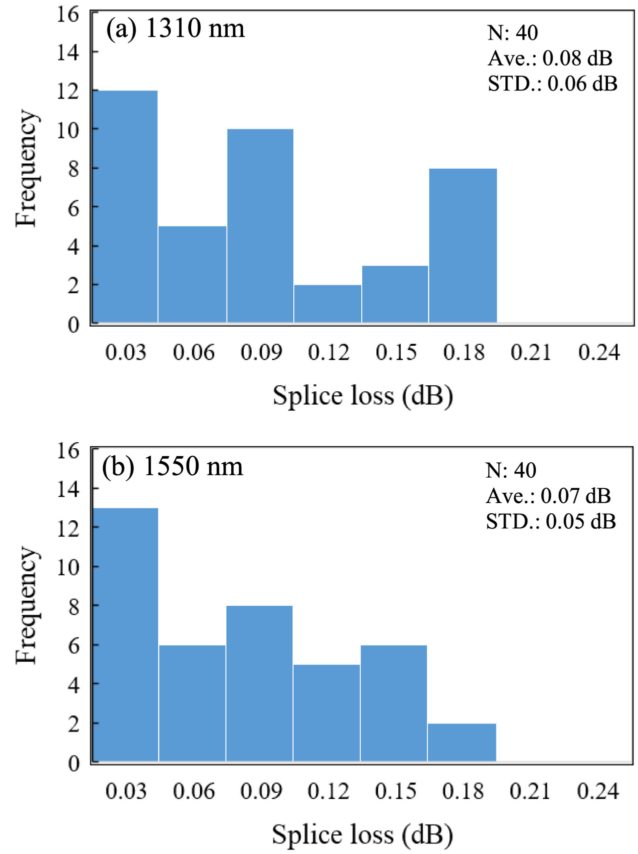

Fig. 13. Histogram of measured splice loss at (a) 1310 nm and (b) 1550 nm.

Four high peaks and four low peaks can be observed. One of the low peaks has a dip due to the marker, which makes an asymmetrical point. The shapes of the left and right profiles were almost the same, although the peak positions were different. The required rotation angle was calculated such that the IPA profiles of both the left and right sides of the 200-4CFs matched, as shown in Fig. 12(b). We attempted splicing ten times. Fig. 13 shows the measured splice-loss distribution of every core at 1310 nm and 1550 nm ($N = 10$ times $\times$ 4 cores). The average splice loss was less than 0.10 dB for both wavelengths. Low splice loss was confirmed to be achievable via full automatic side-view alignment with marker and core identification.

VII. Conclusion

Four-core multicore fibers with a 200-μm coating were fabricated and cabled for the first time in this study. The characteristics of the 200-4CFs and cabled 200-4CFs were compared with those of the SMFs and 250-4CFs. Based on various comparisons and tests, it was confirmed that 200-4CFs can be used practically as 250-4CFs and SMFs.

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