Ultra-High-Density Microduct Cable with Uncoupled 12-Core Fibers with Standard 250-µm Coating

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Abstract: We developed 12-core fibers suitable for short/medium-reach applications and fabricated a 144-fiber 8-mm-outer-diameter cable using the 12-core fibers, which demonstrates the feasibility of ultra-high-core-count optical cables that can be blown into widely-deployed small-diameter microducts. © 2022 The Authors

1. Introduction

Space division multiplexing (SDM) is a promising technology to increase the transmission capacity of communication networks with improved power efficiency. In a wide sense, increasing the number of single-mode fibers (SMFs) is one of the SDM approaches, and various high fiber count cables have been proposed. In the state-of-the-art cabling technology, partially-bonded fiber ribbons with reduced 200-µm diameter coating enabled 6912-fiber optical cables with ≤30-mm outer diameter (OD) [1]. Recently, in combination with 80-µm thin cladding, 160-µm coating diameter fibers enabled a 1728-fiber cable with 17-mm OD [2]. Toward higher density, the research on further thinner fibers has also been active [3]. However, difficulties in handling and microbending loss suppression are remaining challenges for connections and cabling of such ultra-thin fibers. Another approach of the SDM is increasing the core count with multicore fibers (MCFs). Recent progress in MCF technology has demonstrated the practical MCFs with standard 125-µm cladding [4,5], the improved manufacturability of MCFs [6–8], the practical and manufacturable MCF connectors and fanouts [9–11], and low loss MCF splicing [12,13]. MCF high-density cables have also been demonstrated with 250-µm coating 4-core fibers [14], and 200-µm coating 4-core fibers [15].

In this paper, we propose an ultra-high-core-density microduct (MD) cable with uncoupled 12-core fibers (12CFs) with 250-µm coating. Two types of 12CFs were developed with step-index cores and trench-assisted cores. From the measured core-to-core crosstalk (XT), XT in *bidirectional* transmissions [5] is predicted to be sufficiently suppressed at 1310 nm in the step-index 12CFs and at 1550 nm in the trench-assisted 12CFs for more than 10-km fiber length—even for 100 km in the trench-assisted 12CFs. The microduct cabling had no significant impact on the attenuation and XT of the 12CFs. The results demonstrate that, in combination with MCF technology, MD cables suitable for air-blown installation can be thin, lightweight, and easy-installable ultra-high-core-count optical cables.

2. 12-Core Fibers

We developed 12-core fibers with a standard 250-µm coating diameter for short/medium-reach applications. To simultaneously pack uncoupled standard-compatible 12 cores and keep an adequate coating thickness for coating puncture suppression, we set the cladding diameter to 180 µm. The nominal coating thickness of the present MCF is 35 µm, which is similar to 125-µm cladding fiber with 200-µm coating. Figure 1a shows the schematic core layout of the present 12-core fibers. Thanks to the line-symmetric core layout without any core on the symmetric axis, we can connect the present 12-core fibers without considering connection polarity [5]. Instead of employing a single-purpose marker for core identification, we slightly shifted the positions of Cores 5 and 12, which serve as markers (marker cores) for rotational alignment. By eliminating the single-purpose marker, we can avoid placing the marker in the limited physical cladding space between densely packed optical claddings (and trenches) and avoid the cost increase due to the marker. The marker core shift angle θ was set to be 4 degrees to

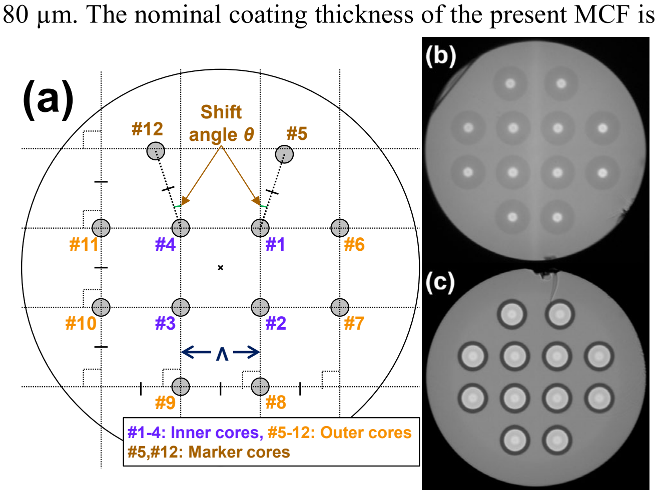

Fig. 1. (a) Schematic core layout of the 12CFs from the starting side of fiber drawing. (b,c) Cross sections of the fabricated SI-12CF (b) and TA-12CF (c).

simultaneously assure the distinguishability of the marker cores and adequate outer cladding thickness (OCT) for leakage loss suppression. We designed two types of 12-core fibers: step-index 12-core fiber (SI-12CF, Fig. 1b) for O-band transmissions and trench-assisted 12-core fiber (TA-12CF, Fig. 1c) for O to C band transmissions. Table 1 summarizes the target properties and fabricated results of the SI-12CFs and TA-12CFs. We fabricated three preforms (A/B/C) for each design (SI/TA). Each of the fabricated 12-core fibers has a 180-µm diameter cladding as designed. The uncolored and colored coating diameters were controlled to be within the standard range of 245 ± 10 µm and 250 ± 15 µm, respectively. The core pitch Λ was designed to be 37 µm for SI-12CF and 35 µm for TA-12CF. The SI-12CF requires a longer Λ for suppressing inter-core crosstalk (XT) without index trenches, and the TA-12CF requires a longer OCT for suppressing the coating leakage loss in C-band. The variation of Λ of the fabricated 12CFs was still somewhat large but can be suppressed by process optimization. The fabricated SI-12CFs have the mode field diameter (MFD), cutoff wavelength (λ_{cc}), zero dispersion wavelength (λ_0), and zero dispersion slope (S_0) compliant with ITU-T G.652.D, except for 4 cores of SI-B having λ_0 of more than 1324 nm, which can be easily adjusted by process optimization. The fabricated TA-12CFs have the MFD, λ_{cc}, and λ_0 compliant with ITU-T G.652.D; and S_0 compatible with ITU-T G.657.B. The attenuation and XT are well suppressed at 1310 nm for both SI-12CFs and TA-12CFs. In the SI-12CF, the core-to-core XT at 1310 nm was specified as ≤−34.2 dB at 1 km, which corresponds to the aggregate XT of ≤−40 dB at 10 km in bidirectional transmissions (including backscattered, indirect, and reflection XT with ≤−26-dB TRx reflectance, see [5]). The attenuation and XT of the TA-12CFs are also suppressed at 1550 nm. The core-to-core XT at 1550 nm was specified as ≤−29 dB at 1 km, corresponding to the aggregate XT of ≤−30 dB at 10 km in bidirectional transmissions. The measured XTs were much lower than the targets, and both SI-12CF and TA-12CF designs have sufficient XT margins for manufacturing tolerance. Figure 2a shows the bidirectional XT vs. fiber length, which was calculated from the measured core-to-core XT and other values using equations in [5]. The aggregate bidirectional XT of the SI-12CFs at 1310 nm (blue curves) was <−40 dB up to 50 km at least, which should be sufficiently low for IM-DD PAM4 transmissions. The aggregate bidirectional XT of the TA-12CFs at 1550 nm (red curves) was <−30 dB for TA-A, and <−20 dB for TA-B and TA-C, even after 100 km fiber (link) length. XT of <−30 dB and <−20 dB may permit dual-polarization higher-order (≤64-ary) QAM and (≤4-ary) QPSK transmissions, respectively, with <1-dB SNR penalty [16,17].

Table 1. Target characteristics and fabricated results of the present SI-12CF and TA-12CF.

	Unit	λ [nm]	SI-12CF				TA-12CF			
			Target	SI-A	SI-B	SI-C	Target	TA-A	TA-B	TA-C
Cladding diameter	µm	-	180	180	180	180	180	180	180	180
Uncolored coating diameter	µm	-	245 ± 10[a]	243	241	241	245 ± 10[a]	241	242	242
Colored coating diameter	µm	-	250 ± 15[a]	n/a	252	n/a	250 ± 15[a]	250	250	252
Core pitch Λ [µm]	µm	-	**37**	36.9–38.0	36.2–36.8	36.4–37.4	**35**	35.0–36.0	34.0–34.8	33.9–34.6
MFD	µm	1310	8.6 ± 0.4[b]	8.7–8.9	8-6–8.8	8.5–9.0	8.6 ± 0.4[b]	8.5–8.6	8.6–8.7	8.7–8.8
Cutoff wavelength λ_{cc}	nm	-	≤1260[b]	1148–1169	1050–1160	1070–1172	≤1260[b]	1198–1219	1165–1183	1171–1199
Zero-dispersion wavelength λ_0	nm	-	1300–1324[b]	1319–1321	1322–1327	1308–1324	1300–1324[b]	1322–1324	1313–1316	1312–1313
Zero-dispersion slope S_0	ps/nm²/km	λ_0	**≤0.092[b]**	0.085–0.086	0.083–0.086	0.084–0.089	**≤0.11[c]**	0.091–0.092	0.092–0.093	0.093–0.094
Attenuation	dB/km	1310	≤0.40[b]	0.337–0.353	0.314–0.317	0.314–0.321	≤0.40[b]	0.322–0.331	0.314–0.321	0.318–0.326
		1550	**n/a**	>0.250	>0.250	>0.250	**≤0.30[b]**	0.186–0.203	0.188–0.200	0.186–0.203
Core-to-core XT (unidirectional/co-propagating)	dB at 1 km[d]	1310	**≤−34.2**	−55 to −52	−50 to −42	−50 to −42	**n/a**	−81 to −77	−68 to −64	−67 to −65
		1550	**n/a**	−25 to −23	−22 to −15	−22 to −16	**≤29**	−48 to −45	−37 to −35	−37 to −35
Aggregate XT in bidirectional transmission[e]	dB at 10 km[e]	1310	**≤−40**	−69 to −62	−62 to −53	−65 to −53	**n/a**	−94 to −87	−83 to −74	−81 to −75
		1550	**n/a**	n/a	n/a	n/a	**≤−30**	−61 to −54	−48 to −41	−47 to −42
	dB at 100 km[e]		n/a	n/a	n/a	n/a	n/a	−44 to −38	−29 to −22	−29 to −23

Bold) Targets different between SI-12CF and TA-12CF. (a–c) Targets compatible with (a) IEC 60793-2-50:2018, (b) ITU-T G.652.D, and (c) ITU-T G.657.B. (d) Direct XT between co-propagating modes of nearest neighboring cores grows linearly (10 dB/decade in dB scale). (e) Bidirectional XT grows nonlinearly (See [5] for details). Calculated from the measured core-to-core XT and other values using equations in [5].

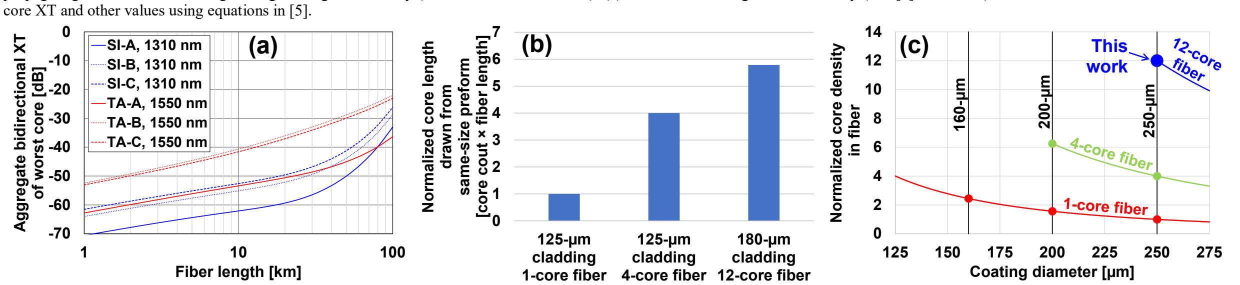

Fig. 2. (a) Bidirectional XT vs. fiber length, calculated from the measured core-to-core XT (see [5] for details of the nonlinear growth). (b) Normalized core length drawn from same-size preforms. (c) Normalized core density in optical fibers.

The thicker 180-µm glass diameter is beneficial for suppressing microbending loss. Based on [18], the present 12CFs should have >10-times better microbending insensitivity than the standard SMFs with 250-µm coating. The total fiber length of a 180-µm cladding fiber drawn from a same-size preform becomes shorter than that of a 125-µm cladding fiber, but the total core length (the product of core count and fiber length [km·core]) can be increased by the present 12CFs as shown in Fig. 2b, which can improve per-core drawing productivity. Of course, the 12CF can realize simultaneous 12-core splicing, which can be comparable to 12-SMF ribbon splicing and more efficient than 4-core fiber splicing. Despite the thicker coating, the present 12CFs have much higher core density than 200-µm coated 4CF, as shown in Fig. 2c. The disadvantage of the thicker glass diameter is the potential degradation of mechanical reliability against bending stress. The very tight bend with a few- to several-millimeter radius should be avoided to suppress the bending stress less than the intrinsic strength of glass. However, based on the power law theory [19], the mechanical reliability degradation in gentle bend situations (like non-tight coils) can be suppressed by increasing the minimum bending radius by a factor of 180/125 = 1.44 or increasing the proof stress by a factor of $(180/125)^{(n-2)/(n-2-m)}$ where n is the stress corrosion susceptibility parameter and m is the Weibull parameter for extrinsic flaw—for example, $(180/125)^{(n-2)/(n-2-m)} = (180/125)^{1.2} \approx 1.55$ for $n = 20$ and $m = 3$.

3. Microduct Cable

We fabricated a 1-km 144-fiber microduct (MD) cable with the fabricated 12-core fibers. Figure 3a shows the structure of the fabricated cable, which is the same as a newly-developed commercial MD SMF cable suitable for air-blown installations. The cable accommodates 12 partially-bonded fiber ribbons, and each ribbon comprises 12 fibers with 250-µm coating. The outer diameter (OD) of the cable was 8 mm, which is suitable for air-blown installation into widely-deployed MDs with an inner diameter of 10 mm. One of the ribbons contains six strands of SI-12CF (SI-B) and six strands of TA-12CF (TA-C). The remainder of the ribbons consists of the SMFs compatible with ITU-T G.657.A1 for trial fabrication. The fabricated cable was wound on a 500-mm-radius drum, and we measured the attenuation and core-to-core XT of one strand from each of SI-12CF and TA-12CF as an initial test. As summarized in Table 2, we observed no significant degradation of attenuation and XT due to cabling. By assuming a 100% MCF cable, the present MCFs and cable structure can accommodate 1728 cores in 8-mm OD and achieve ≥34 cores/mm^2, as shown in Fig. 3c. The results demonstrate the present 12CFs with state-of-the-art MD cables suitable for air-blown installation will enable ultra-high-core-count easy-installable optical cables for short/medium-reach applications.

Table 2. Average attenuation and XT before and after cabling.

	Unit	λ [nm]	SI-12CF (SI-B)			TA-12CF (TA-C)		
			Target	Fiber	Cable	Target	Fiber	Cable
Attenuation	dB/km	1310	≤0.40[b]	0.316	0.324	≤0.40[b]	0.321	0.321
		1550	n/a	>0.250	>0.250	≤0.30[b]	0.193	0.193
Core-to-core XT	dB at 1 km	1310	≤−34.2	−46.5	−45.0	n/a	−66.3	n/a
		1550	n/a	n/a	n/a	≤29	−36.2	−34.0

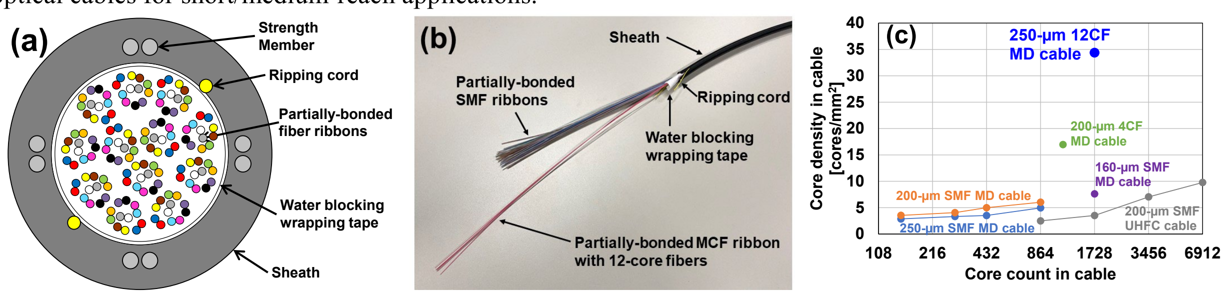

Fig. 3. (a) Structure and (b) appearance of the fabricated MD cable with 12CFs. (c) Core density comparison between the fabricated 12CF cable and typical high-density optical cables, which include 250/200-µm coated SMF MD cables [20], 200-µm coated SMF ultra high fiber count (UHFC) cables [1,21], 160-µm coated 80-µm cladding SMF MD cable [2], and 200-µm coated 4-core fiber (4CF) cable [15]. The core densities of the MCF cables assumed 100% MCF cables for both 4CF and 12CF cables.

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