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Author(s)	Takenaga, Katsuhiro; Arakawa, Yoko; Sasaki, Yusuke; Tanigawa, Shoji; Matsuo, Shoichiro; Saitoh, Kunimasa; Koshiba, Masanori
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A large effective area multi-core fiber with an optimized cladding thickness

Katsuhiro Takenaga,[1,*] Yoko Arakawa,[1] Yusuke Sasaki,[1] Shoji Tanigawa,[1] Shoichiro Matsuo,[1] Kunimasa Saitoh,[2] and Masanori Koshiba[2]

[1] *Optics and Electronics Laboratory, Fujikura Ltd. 1440, Mutsuzaki, Sakura, Chiba, 285-8550, Japan*
[2] *Graduate School of Information Science and Technology, Hokkaido University, Sapporo, 060-0814, Japan*
[*] *katsuhiro.takenaga@jp.fujikura.com*

Abstract: The cladding thickness of trench-assisted multi-core fibers was theoretically and experimentally investigated in terms of excess losses of outer cores. No significant micro-bending loss increase was observed on multi-core fibers with the cladding thickness of about 30 μm. The tolerance for the micro-bending loss of a multi-core fiber is larger than that of the single core fiber. However, the cladding thickness will be limited by the occurrence of the excess loss on outer cores. The reduction of cladding thickness is probably limited around 40 μm in terms of the excess loss. The multi-core fiber with an effective area of 110 μm^2 at 1.55 μm and 181-μm cladding diameter was realized without any excess loss.

OCIS codes: (060.2270) Fiber characterization; (060.2280) Fiber design and fabrication.

References and links

1. K. Takenaga, S. Tanigawa, N. Guan, S. Matsuo, K. Saitoh, and M. Koshiba, "Reduction of crosstalk by quasi-homogeneous solid multi-core fiber," in *Optical Fiber Communication Conference*, OSA Technical Digest (CD) (Optical Society of America, 2010), paper OWK7.
2. K. Imamura, K. Mukasa, and T. Yagi, "Effective space division multiplexing by multi-core fibers," in *Proceedings of 36th European Conference and Exhibition on Optical Communication* (ECOC 2010), paper P1.09.
3. K. Imamura, K. Mukasa, and T. Yagi, "Design optimization of large Aeff multi-core fiber," *in Proceedings of 15th OptoElectronics and Communications Conference* (OECC 2010), paper 7C2–2.
4. K. Takenaga, Y. Arakawa, S. Tanigawa, N. Guan, S. Matsuo, K. Saitoh, and M. Koshiba, "Reduction of crosstalk by trench-assisted multi-core fiber," in *Optical Fiber Communication Conference*, OSA Technical Digest (CD) (Optical Society of America, 2011), paper OWJ4.
5. T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Low-crosstalk and low-loss multi-core fiber utilizing fiber bend," in *Optical Fiber Communication Conference*, OSA Technical Digest (CD) (Optical Society of America, 2011), paper OWJ3.
6. S. Matsuo, M. Ikeda, and K. Himeno, "Low-bending-loss and suppressed-splice-loss optical fibers for FTTH indoor wiring," in *Optical Fiber Communication Conference*, OSA Technical Digest (CD) (Optical Society of America, 2004), paper ThI3.
7. P. Sillard, S. Richard, L.-A. de Montmorillon, and M. Bigot-Astruc, "Micro-bend losses of trench-assisted single-mode fibers," in *Proceedings of 36th European Conference and Exhibition on Optical Communication* (ECOC 2010), paper We.8.F.3.
8. IEC TR-62221, *Optical fibres - Measurement methods - Microbending sensitivity*, 1st ed., (BSI, 2001).
9. K. Saitoh and M. Koshiba, "Full-vectorial imaginary-distance beam propagation method based on a finite element scheme: Application to photonic crystal fibers," IEEE J. Quantum Electron. **38**(7), 927–933 (2002).
10. M. Koshiba, K. Saitoh, K. Takenaga, and S. Matsuo, "Multi-core fiber design and analysis" in *Proceedings of 37th European Conference and Exhibition on Optical Communication* (ECOC 2011), paper Mo.1.LeCervin.5.
11. K. Imamura, K. Mukasa, and R. Sugizaki, "Trench assisted multi-core fiber with large Aeff over 100 μm^2 and low attenuation loss," in *Proceedings of 37th European Conference and Exhibition on Optical Communication* (ECOC 2011), paper Mo.1.LeCervin.1.

1. Introduction

A multi-core fiber (MCF) is expected to be a next generation transmission fiber that overcomes the capacity limit by space-division multiplexing technique. Many types of MCFs

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have been proposed [1–5]. Crosstalk between cores is a critical issue for MCF. Additionally, low attenuation and large effective area (A_{eff}) characteristics are also important for a transmission fiber to improve OSNR. A MCF with A_{eff} of about 110 μm^2 at 1.55 μm has been reported [3]. However, the cladding diameter of the MCF was about 220 μm for suppressing a micro-bending loss. The large cladding diameter is undesirable in terms of a reliability issue and a high density core arrangement.

In this paper, we investigate cladding thickness effect on a micro-bending loss and an excess loss of outer cores to realize a large A_{eff} and small-cladding MCF. The cladding thickness is determined in consideration of the micro-bending loss and the excess loss of outer cores. The micro-bending characteristic of MCFs is compared to that of single-core fibers (SCFs) for various cladding thicknesses. It is confirmed that the tolerance for the micro-bending loss of a multi-core fiber is larger than that of the single core fiber. The excess loss is estimated by the confinement loss of cores and experimentally confirmed. We clarify that the limit of the cladding thickness in the case of the large A_{eff} MCF is about 40 μm. Our fabricated MCF with a trench index profile realizes A_{eff} of more than 110 μm^2, cladding diameter of 181-μm and crosstalk of lower than −30 dB at 100 km, simultaneously.

2. Fiber design

We employed a trench-assisted MCF (TA-MCF) design to realize a low crosstalk and dense core arrangement simultaneously. The trench-assisted fiber (TAF) can reduce not only a macro-bending loss [6] but also a micro-bending loss [7]. Figure 1 shows a cross section of a seven-core TA-MCF and an index profile of a core element. The TA-MCFs with A_{eff} of 80 μm^2 have been reported [4]. We targeted the TA-MCF with A_{eff} of about 110 μm^2 for long transmission lines. The fiber parameters were determined to achieve A_{eff} of 110 μm^2 and crosstalk of lower than −30 dB at 100 km. An outer cladding thickness (*OCT*) affects micro-bending loss characteristics and excess loss of outer cores. We fabricated MCFs with *OCT*s of about 30 μm and 50 μm based on the following consideration on micro-bending loss and excess loss.

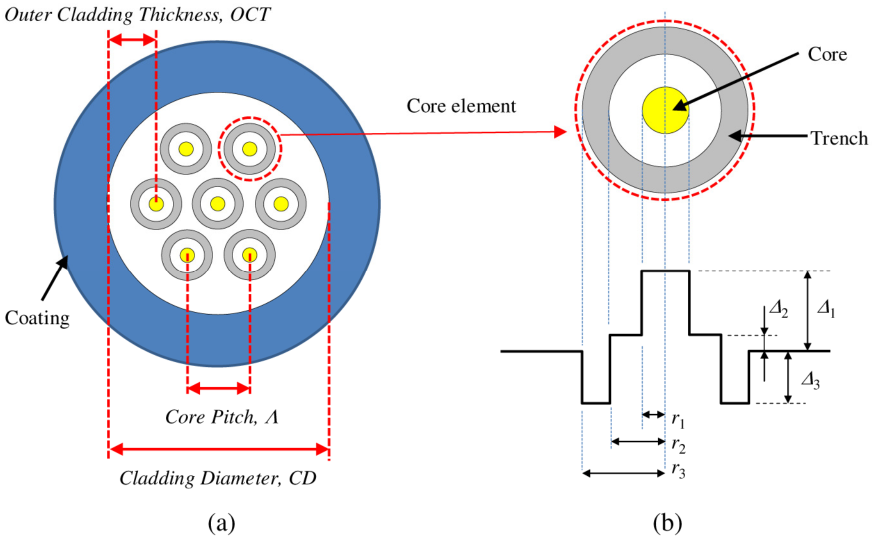

Fig. 1. (a) Cross section of a seven-core trench-assisted multi-core fiber. (b) Trench index profile.

2.1 Micro-bending loss

Figure 2 shows the measurement results of micro-bending loss of SCFs. Three types of fibers were prepared for the measurement. The coating thicknesses of the fibers were set to be same

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as the standard single-mode fiber. A Step80 is a conventional single-mode fiber with a step index profile and A_{eff} at 1.55 μm of 80 μm^2. A Step110 and a TAF110 realize A_{eff} at 1.55 μm of 110 μm^2 with a step profile and a trench-assisted profile, respectively. The step110 is a conventional large A_{eff} fiber. We fabricated the TAF110 to verify the micro-bending reduction due to a trench. The *OCT* of a SCF corresponds to half of a cladding diameter. The micro-bending loss is a loss increase at 1.625 μm when the fiber was wound on a bobbin whose surface is covered with a sand paper (grade 40 μm) based on the IEC standard [8]. The tension on the fiber during winding was 100 gf. The length of the fiber was 400 m.

The micro-bending loss of Step80 was about 0.1dB/km. The micro-bending loss reduction thanks to a trench was clearly observed from the measurement data of Step110 and TAF110. The micro-bending loss of TAF110 with 50-μm *OCT* is the similar level with that of Step110 with 62.5-μm *OCT*.

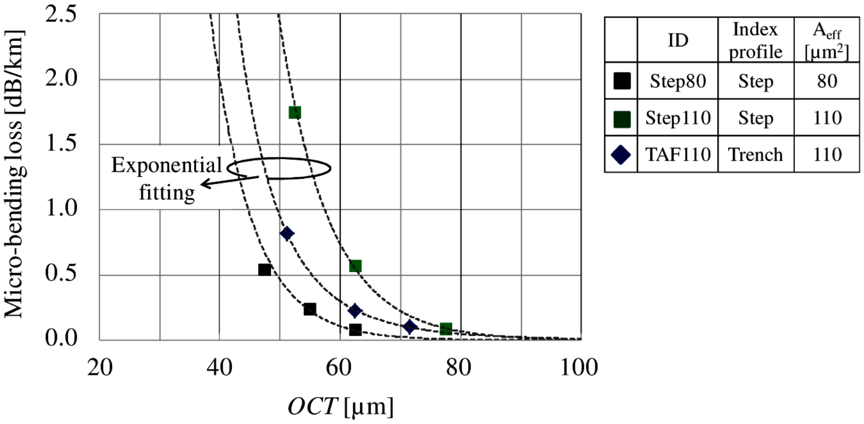

Fig. 2. Micro-bending loss of different kinds of single-core fibers as a function of cladding thickness: Symbols are measurement results. Dashed lines are exponential fitting lines on the measurement results.

2.2 Excess loss in outer cores

In the case of transmission fibers, the refractive index of the coating n_{co} is larger than that of glass region of a fiber. The high index coating causes the excess loss in outer cores for small *OCT* [5]. To estimate the excess loss in outer cores is important in terms of homogeneous optical properties of all cores. The excess loss can be evaluated with the difference of confinement loss between cores. We simulate the confinement loss of a center core (CL_c) and an outer core (CL_o) with full vector finite element method [9] and define a simulated excess loss in outer cores (EL_{sim}) by the following equation.

$$EL_{sim} = CL_o - CL_c \tag{1}$$

Figure 3 shows simulation results of CL_o and CL_c as a function of *OCT*s. r_1 = 5.13 μm, r_2 = 11.10 μm, r_3 = 16.00 μm, Λ = 40.7 μm, Δ_1 = 0.260%, Δ_2 = 0.00%, Δ_3 = –0.70% and n_{co} = 1.486. The wavelength of the simulation was 1.625 μm. The simulated CL_o was about six-digit larger than the CL_c for the simulated structure. Figure 4 shows EL_{sim} as a function of *OCT*. The *OCT* dependence of EL_{sim} was well fitted with an exponential function. The *OCT* should be larger than 38 μm to suppress EL_{sim} less than 0.001 dB/km.

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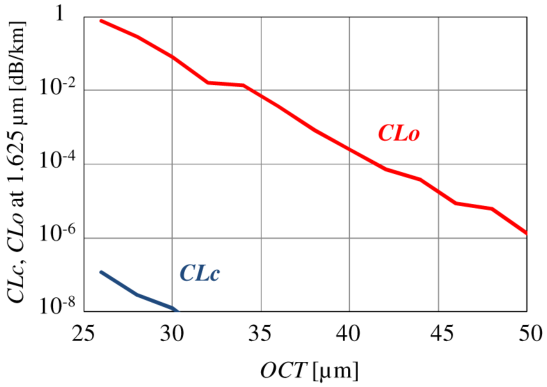

Fig. 3. Simulated confinement loss of a center core and an outer core as a function of *OCT*: A blue line is the confinement loss of a center core (CL_c). A red line is the confinement loss of outer core (CL_o).

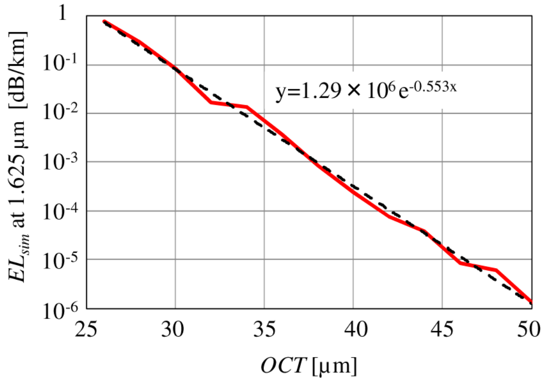

Fig. 4. Simulated excess loss of an outer core as a function of *OCT*: A red solid line is simulation results. A black dashed line is an exponential fitting line to the simulation results.

3. Characteristics of fabricated fibers

We fabricated three kinds of 7-core TA-MCF. Table 1 shows measurement results of fabricated fibers. Figure 5 shows a cross sectional view of a fabricated fiber (Fiber A). The *OCT*s of Fiber A, Fiber B and Fiber C were 31.6 μm, 33.6 μm and 47.7 μm, respectively. The coating thicknesses of the fabricated fibers were set to be same as the standard single-mode fiber. The outer-core crosstalk at 1.55 μm was measured on a fiber wound on a spool with a diameter of 210 mm according to the same measurement setup with Ref [1]. Figure 6(a) shows simulated cutoff wavelength as a function of core pitch Λ. The FEM [9] was used for the simulation. We selected Λ to be as small as possible while suppressing the lengthening of the cable cutoff wavelength [4]. Figure 6(b) shows 100-km crosstalk as a function of Λ. Three lines are the simulation results by the coupled power theory [10] for each fabricated MCF. Symbols indicate 100-km crosstalks that are estimated from the measured crosstalks on the fabricated fibers of a few km lengths by the coupled power theory. All the fibers have crosstalks of less than −30 dB at 100 km as designed.

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Table 1. Measurement results of fabricated fibers. (* Optical properties of center core)

Item		Fiber A	Fiber B	Fiber C
Core pitch [μm]		40.7	42.6	43.0
Cladding thickness [μm]		31.6	33.6	47.7
Cladding diameter [μm]		144.6	152.4	181.3
Coating diameter [μm]		272	272	302
MFD* [μm]		12.1	12.2	12.1
A_{eff}* [μm^2]		111.3	114.1	112.4
Attenuation* at 1.55 μm [dB/km]		0.202	0.198	0.198
Attenuation* at 1.625 μm [dB/km]		0.211	0.207	0.210
Cable cutoff wavelength* [μm]		1.33	1.38	1.37
Bending loss* at 1.625 μm (r = 10mm) [dB/m]		2.6	1.6	1.5
Length [m]		2765	1765	1905
Crosstalk at 1.55 μm [dB] (outer core)	average	−45	−55	−56
	max	−44	−54	−54
	min	−47	−56	−57

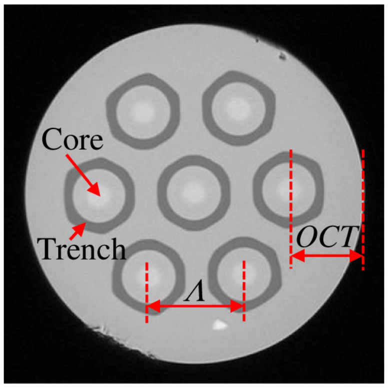

Fig. 5. Cross section of a seven-core TA-MCF (Fiber A).

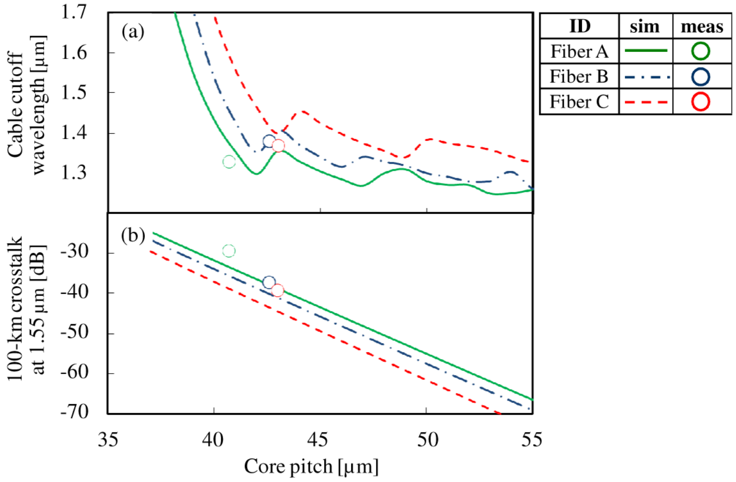

Fig. 6. Core pitch Λ dependence of (a) cable cutoff wavelength and (b) 100-km crosstalk: Lines are simulation results. Symbols are measurement results.

4. Consideration of the effect of coating thickness on micro-bending loss and excess loss

4.1 Micro-bending loss

Figure 7 shows measured micro-bending losses of the fabricated MCFs and SCFs. The micro-bending losses were measured at the condition as described in section 2.1. Open symbols were averaged micro-bending losses between outer cores and error bars denote maximum and minimum micro-bending losses of outer cores. The measured micro-bending losses of MCFs were smaller than those of SCFs with the same *OCT* and A_{eff}. No significant loss increase was observed even at the *OCT* of about 30 µm. We think that large glass diameter and the twisting along the longitudinal direction of MCFs would play a role in the reduction of micro-bending losses with comparison to SCFs. The micro-bending losses of the fabricated MCFs were slightly larger than that of a standard single-mode fiber (Step80, cladding diameter = 125 µm) and were smaller than that of a commercially available large A_{eff} fiber (Step110, cladding diameter = 125 µm). As the results, we can conclude that fabricated MCFs have enough performance for actual use in terms of micro-bending performance. The variations with micro-bending of crosstalk values were smaller than 2dB at the condition as described in section 2.1.

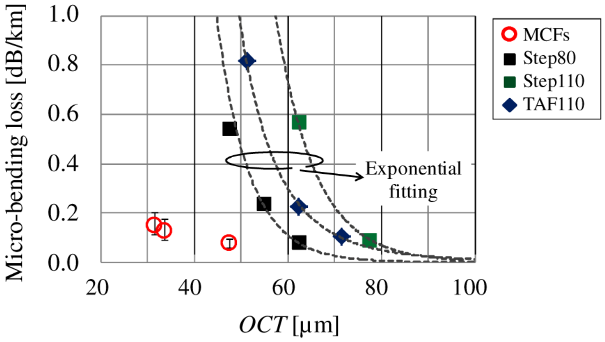

Fig. 7. Cladding thickness dependence of measured micro-bending loss of MCFs and single-core fibers at 1.625 µm: Red open symbols are averaged loss of the outer cores of MCFs. The error bar indicates maximum and minimum values of outer cores. Solid symbols and dashed line are data shown in Fig. 2.

4.2 Excess loss in outer cores

Figure 8 shows measured excess loss of outer cores at 1.625 µm as a function of *OCT*. The circle symbols were averaged excess losses of outer cores and error bars denote maximum and minimum excess losses of outer cores. A measured excess loss is defined by

$$EL_{meas} = \alpha_{outer} - \alpha_{center}, \tag{2}$$

where α_{outer} is an attenuation of an outer core and α_{center} is an attenuation of a center core. The dashed line is the approximated line of simulated results in Fig. 4. The solid line is an approximate line on the measured data with the same slope as the simulation line. Large excess loss was observed on outer cores of the MCFs with the *OCT* less than 35 µm and the trend of the measured excess loss well agreed with the simulation results. The reduction of *OCT* is probably limited around 40 µm in terms of the excess loss.

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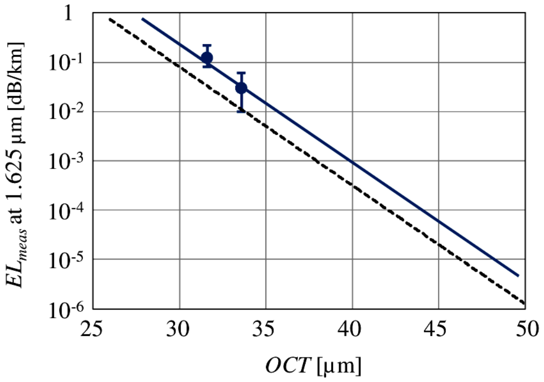

Fig. 8. Outer cladding diameter (*OCT*) dependence of measured excess loss (EL_{meas}) of fabricated MCFs at 1.625 µm: Symbols are averaged excess loss of fabricated MCFs. Error bars denote maximum and minimum EL_{meas}. The dashed line is the exponential fitting line shown in Fig. 4. The solid line is an approximation line on measured data with the same slope as the dashed line.

5. Core multiplicity factor

We introduce a core multiplicity factor (*CMF*) to compare the core density of MCFs. The *CMF* is given by

$$CMF = \frac{nA_{eff}}{\pi (D/2)^2}, \tag{3}$$

where n is a number of core with A_{eff} in a cladding and D is a cladding diameter. The *CMF* indicates the core area ratio in a cladding.

Figure 9 shows the contour plot of relative *CMF* (*RCMF*) on a 7-core MCFs for various A_{eff} and cladding diameter. The *RCMF* is ratio between *CMF* of a MCF and a standard single core single mode fiber with A_{eff} = 80 µm^2 at 1.55 µm and cladding diameter = 125 µm. The *RCMF* of the MCF in [3, 11] was about 3 because of the large cladding diameter. The *RCMF*s of Fiber A, Fiber B and Fiber C were 7.3, 6.7 and 4.7, respectively. Fiber A and Fiber B realize the *RCMF* larger than 6.5. However, the *OCT*s of the fibers are not applicable because the excess losses were observed on the fibers. The *RCMF* of a TA-MCF with A_{eff} about 110 µm^2 and *OCT* of 40 µm will reach to six without any excess loss. The *RCMF* of six is two times larger than the previously reported large A_{eff} MCF.

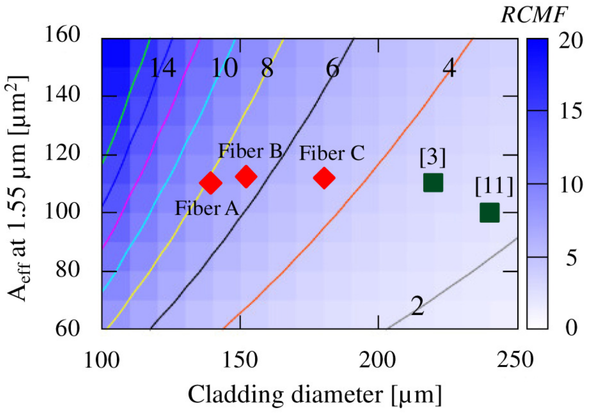

Fig. 9. Contour plot of *RCMF* on a 7-core MCF for various A_{eff} and cladding diameter: Red symbols are measured data presented in this paper. Green symbols are previously reported data. Solid lines indicate counter lines of *RCMF*.

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6. Conclusion

We investigated required cladding thickness of a MCF in terms of a micro-bending loss and an excess loss of outer cores theoretically and experimentally. No significant micro-bending loss increase was observed on MCFs with the cladding thickness of about 30 µm. The tolerance for the micro-bending loss of a MCF is larger than that of the SCF. However, the cladding thickness will be limited by the occurrence of the excess loss on outer cores. Our fabricated MCF realized a *RCMF* of 4.7 without any excess loss of outer cores. The *RCMF* of six, which is about two times larger than that of the previously reported large A_{eff} MCF, will be attainable on a TA-MCF with an optimized cladding thickness.

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