Randomly-Coupled Multi-Core Fibre Cable with Flattened Spatial Mode Dispersion over S-L Band

Takayoshi Mori[(1)], Ryota Imada[(1)], Taiji Sakamoto[(1)], Yusuke Yamada[(1)], Kazuhide Nakajima[(1)]

[(1)] Access Network Service Systems Laboratories, NTT Corporation, Tsukuba, Ibaraki, 305-0805 Japan, takayoshi.mori@ntt.com

Abstract *We revealed for the first time that the wavelength characteristics of spatial mode dispersion (SMD) can be effectively flattened by implementing 4-, 8-, and 12-core randomly-coupled multi-core fibres in high-density cables. Sufficiently low and stable SMD properties were confirmed independent of the number of cores.*

Introduction

Space division multiplexing (SDM) technology has emerged as a promising solution to address the capacity limitations of conventional single-mode fibres (SMFs) [1]. Among various types of SDM fibres, randomly-coupled multi-core fibres (RC-MCFs) with 125-μm cladding have gained attention for high-density and long-haul SDM transmission, offering reduced mode-dependent loss, delay spread, and fibre nonlinearities compared with weakly-coupled MCFs [2]. However, managing spatial-mode-dispersion (SMD) remains a significant challenge for RC-MCFs, as it impacts multiple-input multiple-output digital signal processing (MIMO-DSP) complexity and transmission distance. Previous studies have shown that SMD is affected by fibre design, bending, and twisting effects [3-5], and have reported wavelength dependence of SMD, which further complicates MIMO-DSP complexity [6].

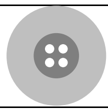
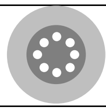
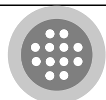
While RC-MCFs with up to 19 cores have been proposed [4-9], SMD reduction through cabling has only been reported for 2-core high-density cables, as well as 3- and 4-core loose tube cables [10-12]. Investigation of SMD suppression for RC-MCFs with more than 2 cores in high-density optical cables remains unexplored.

In this study, we demonstrated the first successful implementation of 4-, 8-, and 12-core RC-MCFs in a high-density optical fibre cable subjected to random bending and twisting, which mitigates the wavelength dependence of SMD due to uniform bending of the spooled fibre. We also confirmed low SMD regardless of the number of cores, notably achieving a low SMD of 3.4 ps/$\sqrt{\text{km}}$ at 1550 nm for the 12-core fibre, representing an advancement in cables with more than 10 cores using RC-MCFs.

Design and Fabrication

We designed and fabricated three RC-MCFs with 4-, 8-, and 12-cores (MCF-4, MCF-8, and MCF-12) and experimentally investigated their optical characteristics. Table 1 summarizes the core layout and measured geometrical and optical properties. In our design, the RC-MCFs have pure-silica glass cores and a fluorine-doped common depressed layer associated with the W-shaped index profile. We used a design method [13] that takes into account the average bending-loss characteristics for unique bending angle and core pitch dependence of the RC-MCFs. It has been reported that the bending loss of an RC-MCF increases as the number of cores increases

Tab. 1: Properties of fabricated pure silica-core 4-, 8-, 12-core RC-MCFs.

Parameters	Wavelength (nm)	MCF-4	MCF-8	MCF-12
Cross-section	-			
Cladding diameter (μm)	-	125.2	125.0	124.8
Core pitch (μm)	-	18.2	18.1	17.8
Cut-off wavelength (nm)	-	1469	1477	1456
Bending loss (dB/turn)*	1625	< 0.1	< 0.1	< 0.1
Attenuation (dB/km)	1550	0.21	0.34	0.28
	1625	0.23	0.36	0.31
Spatial mode dispersion (ps/$\sqrt{\text{km}}$)	1550	5.3	15.3	14.4

*At bending radius of 15 mm

[13], and we adopted the W-shaped index profile to achieve sufficiently low bending loss. The cladding diameter was set to 125 μm, and the mode field diameter was set to 10.8 μm at a wavelength of 1550 nm. The core pitch was set to 18 μm to achieve the desired random coupling.

The cut-off wavelength, measured in a 22-m-long sample (or cable cut-off wavelength), was about 1470 nm. Bending loss was measured using the experimental setup described in a previous study [13], in which an optical input was provided from the SMF to one core of the MCF, and an integrating sphere power meter received the output light from all cores of the MCF. The bending losses were less than 0.1 dB/turn at a wavelength of 1625 nm with a bending radius R of 15 mm for all three RC-MCFs. The attenuation was measured by OTDR, with the highest loss observed for MCF-8, and MCF-12 had an attenuation of 0.28 dB/km at a wavelength of 1550 nm. SMD was measured in the 1550 ± 5 nm range using the wavelength scanning (fixed analyser) method [3] under the condition of a spooled fibre with a bobbin of R = 140 mm. The smallest SMD was observed for MCF-4, and MCF-12 had SMD of 14.4 ps/$\sqrt{\text{km}}$ at 1550 nm.

The fabricated RC-MCFs were implemented in a curvature-controlled high-density cable. The length of the cable was 1 km and wound on a reel with a drum radius of 500 mm. The cable was composed of units, rip cord, sheath, and strength member. The units were composed of bundled partially-bonded optical fibre ribbons, with each of the four each of MCF-4, MCF-8, and MCF-12 accommodated in another partially-bonded optical fibre tape of a 200-fiber cable. The outer and inner diameters of the cable were 15.2 and 7.8 mm, respectively. The cable diameter was larger than the previous 2-core RC-MCF cable [10] to mitigate the effects of lateral pressure and reduce the increase in micro-bending loss. By applying tension to the bundle tape that binds the fibre unit in the cable, the fibre unit was deformed into a helical shape, and the bundle pitch and bundle tension can be controlled to provide twist and curvature to the fibre. We set the bundle pitch to 60 mm and applied the appropriate bundle tension to achieve a twist rate γ of 33π rad/m and effective fibre bending of 10^2 to 10^4 mm (fibre curvature of 0.1 to 10 m^{-1}) as described in a previous study [10]. These are the conditions that would reduce SMD and prevent bending loss from increasing for the fabricated RC-MCFs.

We numerically investigated the wavelength dependence of the coupling characteristics for bending and twisting. Figure 1 illustrates the calculated power-coupling ratio for phase-matching at a core pitch of 18 μm and γ of 2π and

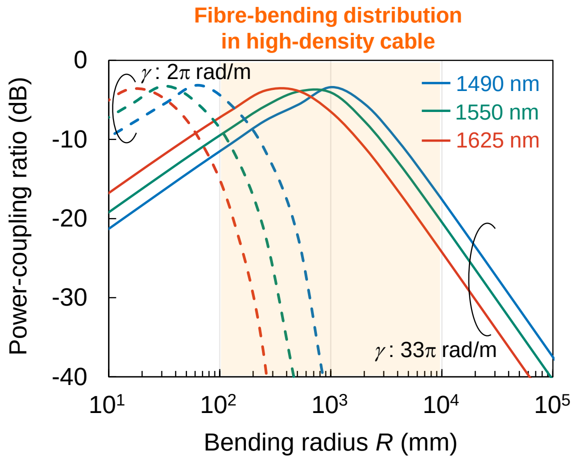


Fig. 1: Calculated power-coupling ratio for bending and twisting for 2-core fibre.

33π rad/m using a 2-core model [3]. In the high-density cable, we consider the fibre-bending distribution in the range of 10^2 to 10^4 mm instead of a uniform curvature as the fibre spooled on the bobbin. Under this fibre-bending distribution, the coupling ratio was low and wavelength dependent on γ of 2π (dotted line). However, with γ of 33π (solid line), the coupling ratios of 1490, 1550, and 1625 nm reached a peak value within the fibre bending distribution. This bending distribution of the cable enhances the coupling over the S-L band. We expected that the fibre-bending distribution and appropriate twisting in the cable would flatten the wavelength characteristics of SMD over the S-L band.

Experiments and Discussion

Figure 2 shows the cabling-losses of the fabricated RC-MCF cable, where the cabling loss is the difference in the attenuation coefficient between the fibres spooled on a bobbin and the cable spooled on the reel. The solid blue, red, and green plots respectively denote the cabling losses of MCF-4, MCF-8, and MCF-12, while the solid black diamond denotes that of the conventional SMF for reference. Although the maximum cable loss at 1625 nm for MCF-8 was 0.07 dB/km, the average cabling losses were less than 0.05 dB/km at each wavelength and for all fibres. Figure 3 shows the wavelength dependence of SMD for the spooled and cabled RC-MCFs. For the cabled RC-MCFs, they were each fusion-spliced with four fibres and the SMD was measured at 4 km. The wavelength was swept from the S- to the L-band using a wavelength tuneable light source, and SMD was measured at a width of 10 nm. For the spooled RC-MCFs, the SMD values changed for MCF-4, MCF-8, and MCF-12 and decreased to less than

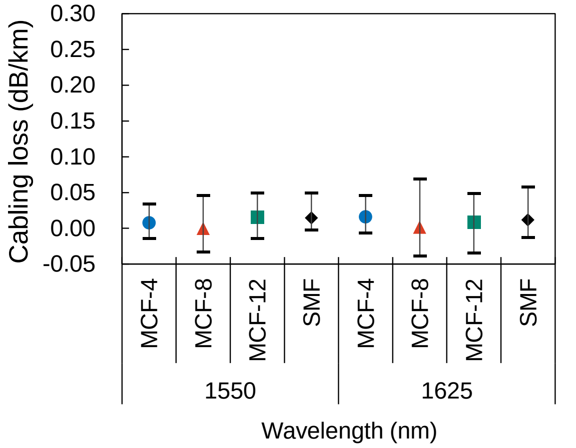


Fig. 2: Cabling-losses of RC-MCFs and conventional SMF.

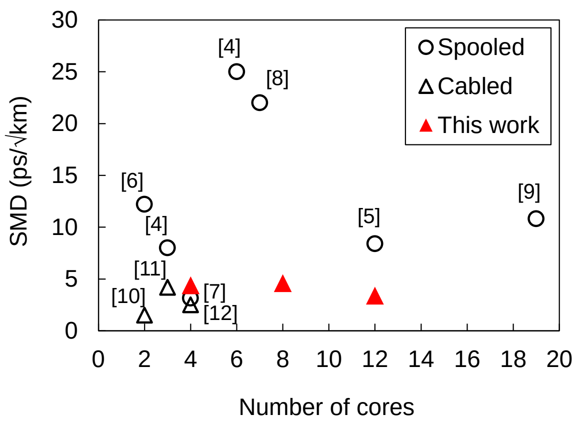


Fig. 4: Reported SMD of spooled and cabled RC-MCFs.

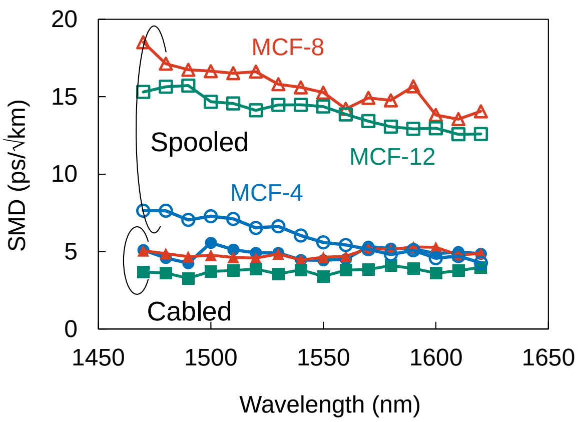


Fig. 3: Wavelength dependence of spooled and cabled RC-MCFs.

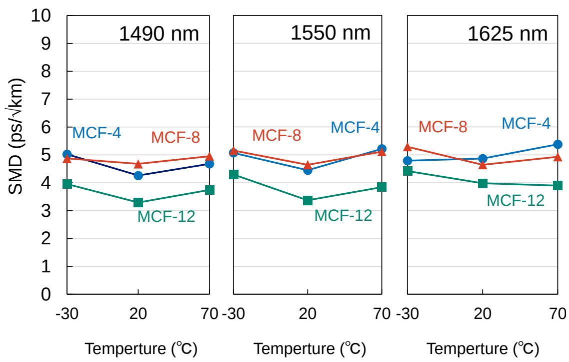


Fig. 5: Heat-cycle test results for SMD at 1490, 1550, and 1625 nm.

5 ps/√km for all of them after cabling. The wavelength dependence of the S-L band varied by about 4 ps/√km for the spooled fibres, but only about 1 ps/√km for the cabled fibres thanks to enhancing the coupling within the S-L band by bending distribution and sufficient twisting in the cable, as shown in Fig. 1. Figure 4 summarizes the relationship between the number of cores and SMD among the reported spooled and cabled RC-MCFs. MCF-4, 8, and 12 achieved SMD of 5 ps/√km or less. For MCF-12, SMD was the lowest at 3.4 ps/√km at 1550 nm and 3.3 to 4.1 ps/√km in the S-L band, making it possible to fabricate an RC-MCF cable with more than 10 cores.

Next, we investigated how temperature change affects SMD, considering that SMD change is due to the fibre curvature variation. Figure 5 shows the SMD results at 1490, 1550, and 1625 nm when heat-cycle tests of -30 to 20°C and 20 to 70°C were conducted. For the wavelength of 1550 nm, SMD varied from 4.4 to 5.2 ps/√km for MCF-4, 4.6 to 5.2 ps/√km for MCF-8, and 3.4 to 4.3 ps/√km for MCF-12, with variations of less than 1 ps/√km for all wavelengths, confirming stable characteristics within the entire S-L band.

Conclusions

We revealed that the wavelength dependence of SMD can be mitigated by controlling the implementation conditions of a high-density optical cable consisting of 4-, 8-, and 12-core RC-MCFs through random bending and proper twisting of the cable. We also confirmed low SMD independent of the number of cores for RC-MCFs with more than two cores. Specifically, we achieved SMD values of 3.4 ps/√km at 1550 nm and 3.3 to 4.1 ps/√km in the S-L band for the 12-core MCF. We also conducted heat-cycle tests, which confirmed that SMD remains stable even when changing from -30 to 20 °C and from 20 to 70°C, with a variation of less than 1 ps/√km.

Acknowledgements

Part of this research is supported by the National Institute of Information and Communications Technology, Japan under commissioned research No. 01001.

References

[1] W. Klaus, P. J. Winzer and K. Nakajima, "The Role of Parallelism in the Evolution of Optical Fiber Communication Systems," Proceedings of the IEEE, vol. 110, no. 11, pp. 1619-1654, 2022. DOI: 10.1109/JPROC.2022.3207920

[2] T. Hayashi, T. Sakamoto, Y. Yamada, R. Ryf, R.-J. Essiambre, N. Fontaine, M. Mazur, H. Chen, and T. Hasegawa, "Randomly-Coupled Multi-Core Fiber Technology," Proceedings of the IEEE, vol. 110, no. 11, pp. 1786-1803, 2022. DOI:10.1109/JPROC.2022.3182049

[3] T. Sakamoto, T. Mori, M. Wada, T. Yamamoto, F. Yamamoto, and K. Nakajima, "Fiber Twisting and Bending Induced Adiabatic / Nonadiabatic Super-mode Transition in Coupled Multi-core Fiber," Journal of Lightwave Technology, vol. 34, no. 4, pp. 1228–1237, 2016. DOI: 10.1109/JLT.2015.2502260

[4] T. Hayashi, H. Chen, N. Fontaine, T. Nagashima, R. Ryf, R.-J. Essiambre, and T. Taru, "Effects of Core Count/Layout and Twisting Condition on Spatial Mode Dispersion in Coupled Multi-Core Fibers," 42nd European Conference on Optical Communication (ECOC) 2016, W.2.B.5, 2016.

[5] T. Sakamoto, S. Aozasa, T. Mori, M. Wada, T. Yamamoto, S. Nozoe, Y. Sagae, K. Tsujikawa, and K. Nakajima, "Twisting-Rate-Controlled 125 μm Cladding Randomly Coupled Single-Mode 12-Core Fiber," Journal of Lightwave Technology, vol. 36, no. 2, pp. 325-330, 2018. DOI: 10.1109/JLT.2017.2743205

[6] T. Sakamoto, T. Mori, M. Wada, T. Yamamoto, F. Yamamoto, and K. Nakajima, "Strongly-coupled multi-core fiber and its optical characteristics for MIMO transmission systems," Optical Fiber Technology, vol. 35, pp. 8-18, 2017. DOI: 10.1016/j.yofte.2016.07.010

[7] T. Hayashi, Y. Tamura, T. Hasegawa, and T. Taru, " Record-Low Spatial Mode Dispersion and Ultra-Low Loss Coupled Multi-Core Fiber for Ultra-Long-Haul Transmission," Journal of Lightwave Technology, vol. 35, no. 3, pp. 450–457, 2017. DOI: 10.1109/JLT.2016.2614000

[8] R. Ryf, J. C. A.-Zacarias, S. Wittek, N. K. Fontaine, R.-J. Essiambre, H. Chen, R. A.-Correa, H. Sakuma, T. Hayashi, and T. Hasegawa, "Coupled-Core Transmission Over 7-Core Fiber," Optical Fiber Communications Conference and Exhibition (OFC) 2019, Th4B.3, 2019.

[9] G. Rademacher, M. v. d. Hout, R. S. Luis, B. J. Puttnam, G. D. Sciullo, T. Hayashi, A. Inoue, T. Nagashima, S. Gross, A. R.-Adams, M. J. Withford, J. Sakaguchi, C. Antonelli, C. Okonkwo, and H. Furukawa, "Randomly Coupled 19-Core Multi-Core Fiber with Standard Cladding Diameter," Optical Fiber Communications Conference and Exhibition (OFC) 2023, Th4A.4, 2023.

[10] Y. Yamada, T. Sakamoto, M. Wada, S. Nozoe, Y. Sagae, Y. Yamashita, H. Izumita, K. Nakajima, and H. Tanioka, "Design of High-Density Cable Parameters for Controlling Spatial-Mode Dispersion of Randomly Coupled Multi-Core Fibers," Journal of Lightwave Technology, vol. 39, no. 4, pp.1179-1185, 2021. DOI: 10.1109/JLT.2020.3045761

[11] T. Hayashi, T. Nagashima, T. Muramoto, F. Sato, and T. Nakanishi, "Spatial Mode Dispersion Suppressed Randomly-Coupled Multi-Core Fiber in Straightened Loose-Tube Cable," Optical Fiber Communications Conference and Exhibition (OFC) 2019, Th4A.2, 2019.

[12] T. Hayashi, T. Nagashima, T. Nakanishi, T. Morishima, R. Kawawada, A. Mecozzi, and C. Antonelli, "Field-Deployed Multi-Core Fiber Testbed," OptoElectronics and Communications Conference (OECC) and International Conference on Photonics in Switching and Computing (PSC) 2019, PDP3, 2019. DOI: 10.23919/PS.2019.8818058

[13] R. Imada, T. Sakamoto, T. Mori, Y. Yamada, and K. Nakajima, "Unique Bending Loss Properties and Design Consideration for Coupled Multi-core Fiber," Optical Fiber Communications Conference and Exhibition (OFC) 2023, M3B.1, 2023.