Coupled Multi-Core Optical Fiber Suitable for Long-Haul Transmission

Tetsuya HAYASHI*, Yoshiaki TAMURA, Takemi HASEGAWA, Tetsuya NAKANISHI, and Toshiki TARU

Sumitomo Electric Industries, Ltd. has developed a 125-µm-cladding coupled four-core optical fiber achieving the lowest spatial mode dispersion (SMD) and attenuation among optical fibers for space-division multiplexed transmission. The standard 125-µm-diameter cladding offers high mechanical reliability equivalent to that of field-proven standard fibers. The low SMD reduces the computational complexity of multiple-input-multiple-output (MIMO) digital signal processing. The low transmission loss comparable to that of conventional ultra-low-loss fibers contributes to the increase of the transmission capacity without sacrificing the per-core capacity. Furthermore, the transmission characteristics of this coupled multi-core fiber (MFCF) were experimentally confirmed to outperform those of an equivalent single-mode fiber (SMF). The present results demonstrate that the coupled MCF is suitable for ultra-long-haul transmission systems.

Keywords: space division multiplexing, SDM, coupled multi-core optical fiber, MCF, modal dispersion

1. Introduction

Transmission capacity through single-mode fiber (SMF) was shown to have reached its fundamental limit of around 100 Tbit/s/fiber in research activities,(1),(2) and spatial division multiplexing (SDM) technologies are being intensively studied to overcome that capacity limit.(3) In deployed transpacific transmission systems, the system capacity has been increasing exponentially as shown in Fig. 1, and a full-duplex 144 Tbit/s/cable system is scheduled to launch in 2018.(4) Extrapolating from the growth of capacity shown in Fig. 1, demand for full-duplex multi-petabit/s systems by 2025 can be predicted.

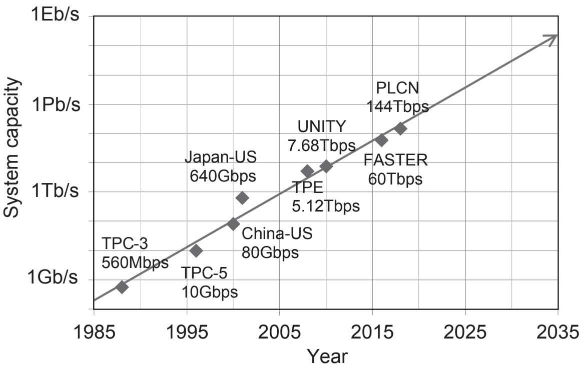

Fig. 1. Capacity growth of transpacific fiber optic transmission systems

To realize such an ultra-high capacity system, we have to increase the fiber pair count in a cable and the capacity of each fiber. However, a fiber count increase is very challenging in submarine cables because a thick and heavy cable significantly increases the cable installation cost due to the limited loading capacities of vessels. Fiber identification is another difficulty for high-count jelly-filled loose-tube submarine cables. Furthermore, transmission experiments in research(2),(5),(6) indicate that there is a limit to the capacity of SMF systems, as shown in Fig. 2. In this situation, the "capacity crunch" of transoceanic SMF transmission systems is likely to become a reality in the next ten years, and SDM fiber is a possible solution that can simply multiply the spatial channel count while using conventional submarine cables.

To deploy SDM fiber in ultra-long-haul submarine systems, SDM fiber must achieve the following conditions:

- ✓ Ultra-low transmission loss for improving optical signal-to-noise ratio
- ✓ Higher spatial-mode density for increasing the spatial channel count within standard 125-µm cladding
- ✓ Lower differential group delay (DGD) between spatial modes (spatial mode dispersion, or SMD) for suppressing digital signal processing (DSP) complexity.

This paper reports on a coupled multi-core fiber

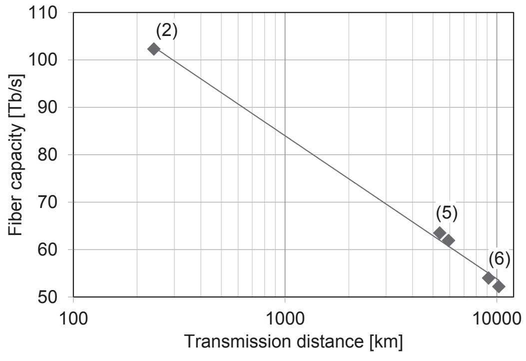

Fig. 2. SMF transmission capacities and distances demonstrated in experiments reported in OFC/ECOC*1 (2),(5),(6)

(C-MCF) having four pure-silica cores with enlarged effective areas (A_{eff}) of 112 μm^2 within the standard 125-μm cladding.[7],[8] The fabricated C-MCF realized an SMD of 3.14 ± 0.17 ps/√km over the C-band and an average attenuation of 0.158 dB/km at 1550 nm, both of which show the lowest values ever reported among optical fibers for SDM transmission. Using the fabricated C-MCF, the transmission performance of the C-MCF was experimentally confirmed to outperform that of SMF having equivalent loss and A_{eff}.[9]

2. Fiber Design

Various kinds of SDM fibers have been proposed with uncoupled multi-core fiber (MCF), few-mode fiber (FMF), and C-MCF being three typical representatives. Figure 3 shows the schematics of the structures of these three fibers and their corresponding transmission systems. The uncoupled MCF has distant cores and low core-to-core crosstalk where each core can transmit the signal in isolation; therefore, conventional receivers for SMF transmission systems can be used without modification. FMF has a core that guides multiple modes, i.e., optical paths, where different modes can transmit different signals. However, it is difficult to suppress the crosstalk between the modes, and the MIMO DSP is necessary for crosstalk compensation. The C-MCF improves core density by accommodating crosstalk compensation using MIMO DSP.

Choosing from among these SDM fibers, we employed a C-MCF to achieve ultra-low loss and low SMD. C-MCF can provide higher spatial channel density compared with uncoupled MCF. [10],[11] Uncoupled MCF tends to have a thicker glass cladding to pack many cores whilst suppressing crosstalk, but the thicker cladding degrades its mechanical reliability, which necessitates a vast amount of validation tests of reliability. On the other hand, C-MCF can pack many cores into the standard 125-μm cladding whose reliability has been proven in the field for many years.

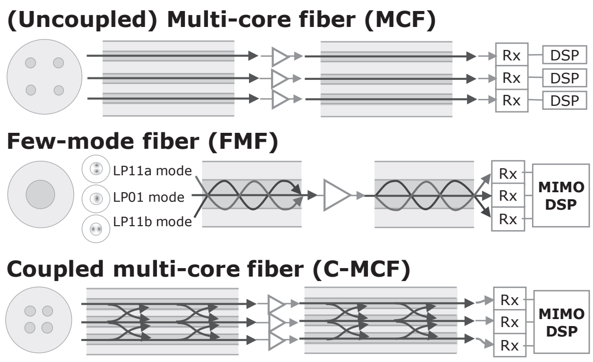

Fig. 3. Major SDM fibers and corresponding transmission systems. (Rx: receiver)

C-MCF can also induce strong random mode coupling that can suppress accumulation of DGD/SMD,[11],[12] mode dependent loss/gain (MDL/MDG),[13] and nonlinear impairment.[12],[13] DGD/SMD suppression is a critical factor for reducing calculation complexity in multiple-input-multiple-output (MIMO) DSP for crosstalk compensation. C-MCF has potential to simultaneously realize low DGD/SMD and ultra-low loss comparable to the lowest loss realized in SMF[16]-[19] because C-MCF can suppress DGD/SMD with simple step-index-type pure-silica cores thanks to random coupling, in contrast to single-core few/multi-mode fiber (FMF/MMF) that needs a GeO_2-doped precisely-controlled graded-index-type core for DGD suppression.

We designed the C-MCF based on the refractive index profile of the ultra-low-loss (ULL) pure-silica-core (PSC) SMF with an enlarged effective area (A_{eff}) of 112 μm^2 (Z-PLUS Fiber ULL[16],[17]). Four cores were arranged on a square lattice with a core pitch of 20 μm for realizing adequate random couplings based on our simulation results. The cladding diameter of the C-MCF was designed to be 125 μm, which is the same as standard optical fibers.

3. Fabrication Results

Table 1 shows the optical properties of four samples of the fabricated C-MCF. Photo 1 and Fig. 4 show a cross section and the average attenuation spectra, respectively. The cladding diameter and core pitch measured 125 μm and 19.5 to 19.8 μm, respectively. The attenuation was measured using the cutback and backscattering methods.[20] The inter-core crosstalk was so strong that the powers in the core modes could be completely mixed within < 1 m propagation, and therefore the measured attenuation was averaged over the modes and average attenuation measured using both methods. The lowest average attenuation at 1550 nm observed using the cutback method was 0.158 dB/km, which is much lower than those of previously reported MCFs (0.177 dB/km in C-MCF,[11] 0.168 dB/km in uncoupled MCF[21]), approaching those of ultra-low-loss SMFs (0.142–0.154 dB/km).[16]–[19] The difference in the average attenuation between the cutback and backscattering

Table 1. Measured optical characteristics at 1550 nm of the fabricated C-MCF[8]

Sample #	Fiber length [km]	Average attenuation [dB/km]		λcc [nm]	CD [ps/(nm·km)]	CD slope [ps/(nm^2·km)]	Bend loss [dB/turn] at R_b = 15 mm
		Cut-back	Backscattering				
Sample 1	17.3	0.158	0.157	1469	20.1	0.061	0.064
Sample 2	24.2	0.161	0.159	1468	20.1	0.063	0.069
Sample 3	30.1	0.160	0.160	1472	20.1	0.061	0.046
Sample 4	41.2	0.159	0.159	1473	20.0	0.060	0.058

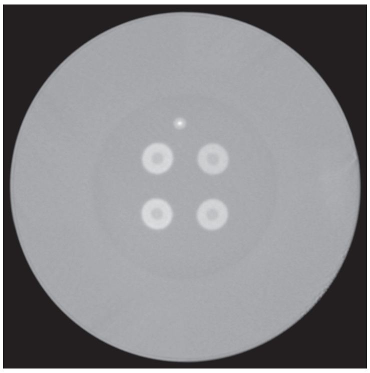

Photo 1. A cross section of a fabricated C-MCF[7]

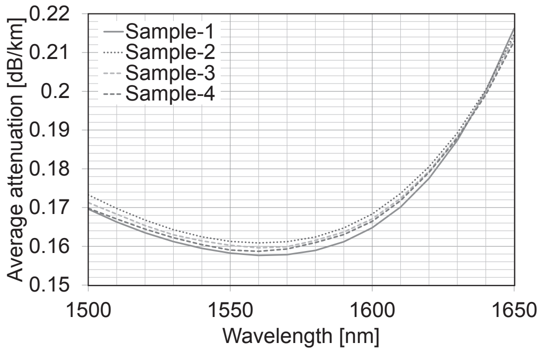

Fig. 4. The average attenuation spectra of the fabricated C-MCFs[8]

methods in the cases of Samples 1 and 2 may be due to slight excess losses induced near the output end of the samples.

The cutoff wavelength (λ_{cc}) was measured using the multimode reference method.[20] The λ_{cc} of the higher-order modes, except the modes corresponding to the fundamental core modes, measured < 1480 nm, as shown in Table 1. The chromatic dispersion (CD) averaged over the spatial modes was measured using the conventional modulation phase shift method.[22] For the CD measurement, we launched and received the light into and from a core. The measured CDs were as expected for the design. The macro-bend loss at R_b = 15 mm was measured to be lower than 0.1 dB/turn at 1550 nm. The strong random mode mixing did not permit us to measure the A_{eff}, but we believe the A_{eff} would be similar to their design values, since the measured values of the other parameters were as expected for their design values. The development of an A_{eff} measurement method for mixed modes is a future issue.

4. Modal Dispersion Measurement

As discussed above, SMD suppression is very important for reducing the calculation complexity of MIMO DSP for crosstalk compensation. After Sakamoto et al.,[23] spatial mode dispersion (SMD) was measured in the range of 1520 to 1580 nm using a method similar to the fixed analyzer technique —can also be referred to as the wavelength scanning technique/method — with Fourier analysis for the polarization mode dispersion (PMD) measurement,[24] as detailed in (8).

The measured DGD $\Delta\tau$ distribution was Gaussian-distributed as shown in Fig. 5. SMD was defined as the square root of the second moment of the DGD distribution, i.e., the standard deviation σ_R of the autocorrelation function of the impulse response, as in the case of the PMD measurement.[24] The σ_R is twice the standard deviation σ_I of the impulse response.[25] The measured SMD $\langle\Delta\tau\rangle$ values and the SMD evolution over the fiber length are shown in Table 2 and Fig. 6, respectively. The SMD of the samples fit well with the square-root curve having an SMD coefficient of 6.1 ps/√km, calculated from $((\sum\sigma_R{}^2)/(\sum L))^{1/2}$ of Samples 1–4.

Next, we obtained 1 km pieces from Sample 4 and investigated the dependence of the SMD on the fiber

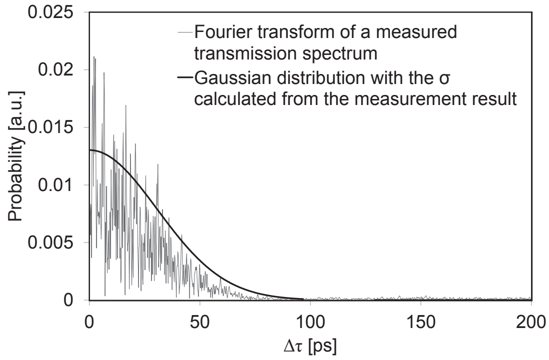

Fig. 5. An example of measured DGD distribution[8]

Table 2. SMD of the fabricated C-MCF[8]

Sample	Length [km]	SMD [ps]*	SMD coeff. [ps/√km]*
Sample 0	2.975	12.05±0.31	7.99±0.18
Sample 1	17.31	26.05±0.48	6.26±0.12
Sample 2	24.24	32.28±0.50	6.56±0.10
Sample 3	30.06	33.41±0.02	6.09±0.00
Sample 4	41.22	36.67±0.52	5.71±0.08

*The samples were wound on a 140-mm-radius bobbin, and measurement wavelength range was 1520–1580 nm. Each value shows the average ± the standard error.

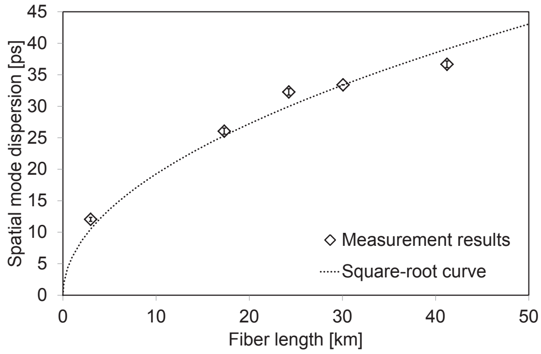

Fig. 6. The SMD of the fabricated C-MCFs (Error bars represent the standard errors of the measurements with different core launching)[8]

bending radius R_b. We measured the SMD at R_b of 8 cm, 14 cm, and 31 cm. The results are shown in Table 3 and Fig. 6. The linear proportionality of SMD on the fiber curvature ($1/R_b$) was clearly observed, and the SMD at R_b of 31 cm was further suppressed to be 3.14 ± 0.17 ps/√km, which is 10-times lower than the lowest value[(12)] in earlier reports.

Based on the measurement results, the SMD after 10,000-km transmission is expected to be 6.1 × 10^2 ps for the 6.1-ps/√km case and to be 3.14 × 10^2 ps for the 3.14-ps/√km case, sufficiently low for suppressing MIMO calculation complexity. Assuming a 25-GBaud symbol rate (50-GHz sampling), the required tap counts for MIMO DSP for transmission over the fabricated C-MCF for covering most of the power of the impulse responses were estimated for the 6.1-ps/√km and 3.14-ps/√km cases, as shown in Table 4. Even after 10,000-km transmission, the required tap count can be quite a reasonable value for suppressing MIMO calculation complexity.

Table 3. The effect of the fiber bend radius on the spatial mode dispersion of the fabricated C-MCF[(8)]

Bend radius [cm]	Length [km]	SMD [ps]*
8	1.00	15.05±0.11
14	1.00	8.55±0.21
31	1.00	3.14±0.17

* Measurement wavelength range was 1520–1580 nm. Each value shows the average ± standard error.

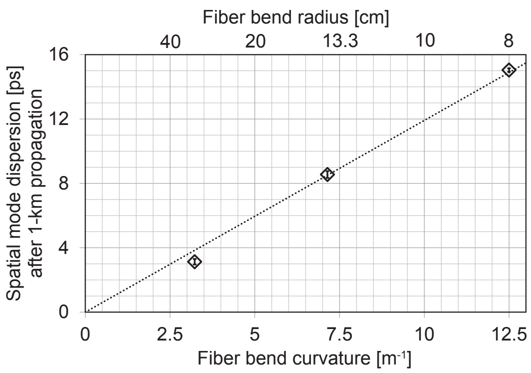

Fig. 7. The relationship between the fiber bend curvature and the SMD of 1 km pieces obtained from the fabricated C-MCF.[(8)]
(Error bars represent the standard errors of the measurements with different core launching. The line is the linear regression from the origin.)

Table 4. The required tap count for MIMO DSP for the fabricated C-MCF after 10,000-km transmission[(8)]

Tap-covered interval	Normalized power covered by taps	Required tap count	
		6.1 ps/√km SMD case	3.14 ps/√km SMD case
$\pm 2\sigma_I = 2\sigma_R$	~0.95	61	32
$\pm 4\sigma_I = 4\sigma_R$	~0.99994	1.2×10^2	63
$\pm 6\sigma_I = 6\sigma_R$	~0.999999998	1.8×10^2	95

5. Conclusion

We developed a coupled four-core fiber achieving a record-low SMD of 3.14 ± 0.17 ps/√km over the C-band and an ultra-low average attenuation of 0.158 dB/km at 1550 nm, both of which show the lowest values ever reported among optical fibers for SDM transmission. Attenuation comparable to ultra-low-loss SMF will enable the realization of a spatial channel increase without the degradation of per-channel capacity. Using a fabricated C-MCF, it was experimentally confirmed that C-MCF can outperform SMF having equivalent loss in transmission performance.[(9)] The results in this paper demonstrate that C-MCF is best suited to ultra-long-haul submarine transmission systems considering the limited valuable cross section of the cable. With further research progress in the MIMO DSP field, C-MCF can become a realistic optical fiber candidate for next–generation, ultra-high-capacity, ultra-long-haul transmission systems.

Technical Terms

*1 OFC/ECOC: The Optical Fiber Communication Conference (OFC) is the world's largest conference on optical fiber communication held annually in March in the United States. The European Conference on Optical Communication (ECOC) is the largest conference on optical communication in Europe held annually in September.

*2 Tap count: Tap count or the number of taps represents the memory length of an equalizing filter in digital signal processing, since the digital filter can be implemented in a tapped delay line structure.

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Contributors

The lead author is indicated by an asterisk (*).

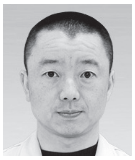
T. HAYASHI*

- Ph. D.
  Assistant Manager, Optical Communications Laboratory
  Received the Tingye Li Innovation Prize from the Optical Society (OSA) at OFC2017 for his post deadline paper related to this study presented at OFC2016(7).

Y. TAMURA

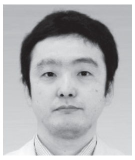
- Assistant Manager, Optical Communications Laboratory

T. HASEGAWA



- Group Manager, Optical Communications Laboratory

T. NAKANISHI



- Group Manager, Optical Communications Laboratory

T. TARU

- Assistant General Manager, New Business Marketing and Promotion Division