Multi-Core Optical Fibers for the Next-Generation Communications

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Communication systems based on conventional single-mode optical fiber transmission technologies may face a “capacity crunch” in the near future. To address this, Sumitomo Electric Industries, Ltd. has been conducting the R&D on various types of the multi-core fibers (MCFs) for the space-division multiplexed (SDM) transmission. Since the very beginning of the SDM R&D, we have continuously contributed both to revealing the behavior and characteristics of the optical properties—such as inter-core crosstalk— of MCFs, and to proposing various MCFs for practical applications. This paper reviews our MCF R&D history.

Keywords: space-division multiplexing (SDM), multi-core fiber (MCF)

1. Introduction

To meet the ever-growing demand for communication channel capacity, space-division multiplexing (SDM) technology has been vigorously researched in recent years in the field of fiber-optic communications. Various types of optical fibers have been proposed.[1] Among diverse kinds of SDM transmission fibers, the most typical fiber is the multi-core fiber (MCF). This paper is based on our invited talk[2] in a symposium on SDM held at the annual meeting of the Laser Society of Japan (Jan 24-Jan 26, 2018) and provides further information describing MCF-specific design parameters and the efforts made for MCF R&D at Sumitomo Electric Industries, Ltd.

2. MCF-Specific Design Parameters

MCF is an optical fiber that contains multiple cores in one common cladding, as illustrated in Fig. 1. Conventional single-core fiber has a limited design frexibility, in which only the core has some degree of design freedom, with the core being placed at the center of a 125-µm diameter cladding. With MCFs, not only core design, but also the number of cores, core layout, outer cladding thickness (OCT: the minimum distance between the center of the outer cores and the cladding-coating interface), and cladding diameter can be optimized from the perspective of optical and mechanical properties. Desirable fiber design differs depending on the application, because desirable properties differ between applications.

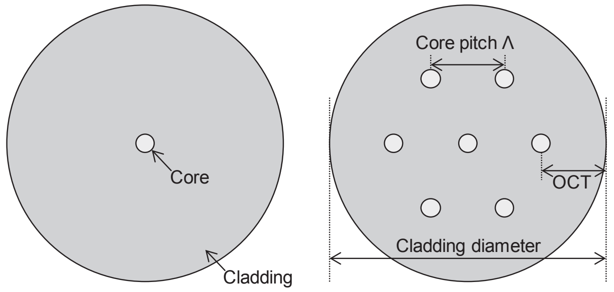

Fig. 1. Schematic optical fiber cross-sections.

2-1 Crosstalk-related parameters

Regarding the number and layout of cores, a smaller core pitch Λ is more desirable for providing a higher core density within the cross-sectional area of the fiber. However, to reduce inter-core crosstalk (XT), a suitable amount of core pitch must be provided.[3] At the initial stage of the MCF R&D process, the MCF XT was believed to be predicted with a simple mode-coupling equation.[4] However, after the fabrication and evaluation of prototype MCFs, we found that the prediction does not hold due to the effect of bends in the fiber, and we proved that a mode-coupling equation, taking the effects of bends and twists in the fiber into account, can accurately predict the actual MCF XT.[5] (Around the same time, Fini *et al*. made a similar discovery through theoretical analysis and published it slightly earlier.[6,7])

When an optical fiber has a bend radius of R_b, the refractive index distribution of the optical fiber can equivalently represent the elongation of the outer optical path of the bend as tilted refractive index, as shown in Fig. 2.

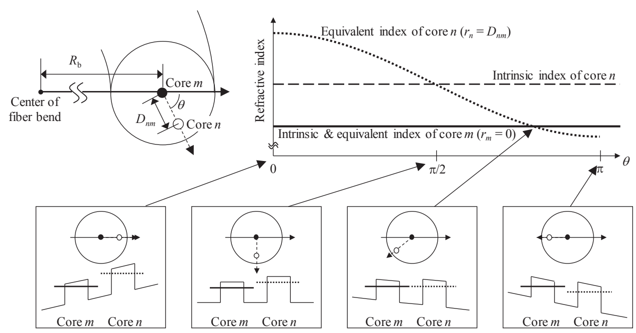

Fig. 2. Equivalent refractive index of MCF affected by bend and twist. (Upper left) Parameters relating to bend in MCF. (Upper right) Equivalent effective refractive indexes of two cores. (Lower) Relative positions and equivalent refractive index distributions of two cores. (The line drawn across a core represents the height of equivalent effective refractive index.)

Using core m as a reference, the equivalent n_{eff} ($n_{\mathrm{eq},n}$) of core n is expressed, as follows.

$$n_{\mathrm{eq},n} \approx n_{\mathrm{eff,c},n} \frac{D_{nm}\cos\theta_{nm}}{R_{\mathrm{b}}} \quad \text{(1)}$$

where, D_{nm} is the distance between the center of core n and the center of core m, $n_{\mathrm{eff,c},n}$ is the intrinsic effective refractive index of core n, and θ_{nm} is the angle that core n and core m form with respect to the direction of the bend radius. If an MCF is straight and its cores differ in effective refractive index $n_{\mathrm{eff,c}}$, phase matching does not occur (with the cores differing in the speed of propagation of light waves), and inter-core crosstalk is reduced. If, in a bent MCF, R_{b} becomes equal to or smaller than R_{pk}:

$$R_{\mathrm{pk}} \approx D_{nm}\, n_{\mathrm{eff,c},n} \Big/ \left| n_{\mathrm{eff,c},n} - n_{\mathrm{eff,c},m} \right| \quad \text{(2)}$$

$n_{\mathrm{eq},n}$ might become equal to $n_{\mathrm{eq},m}$, resulting in increasing XT.[5] Figure 3 presents the calculation results of simulated XT ("coupled power" in Fig. 3) of MCF with a bend and twist. The results reveal that rapid changes in XT occur at phase matching points where $n_{\mathrm{eq},n}$ equals $n_{\mathrm{eq},m}$ ($\delta n_{\mathrm{eq}} = n_{\mathrm{eq},n} - n_{\mathrm{eq},m} = 0$), while mere non-dominant vibration-like changes occur at other points. The reason for this is that

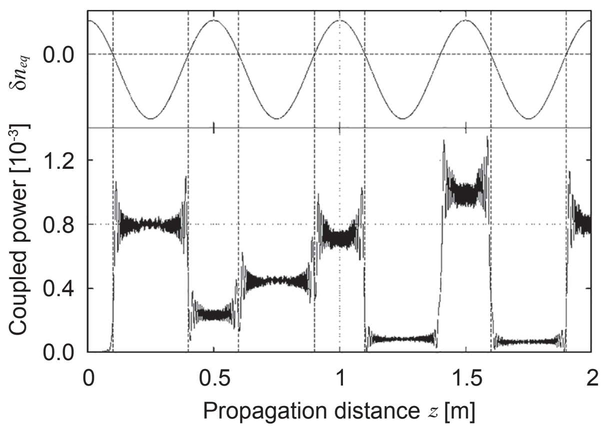

Fig. 3. Effects of fiber curvature ($1/R_{\mathrm{b}}$) and inter-core propagation coefficient mismatching (δn_{eq} in figure) on XT (coupled power in figure) of MCF[5]

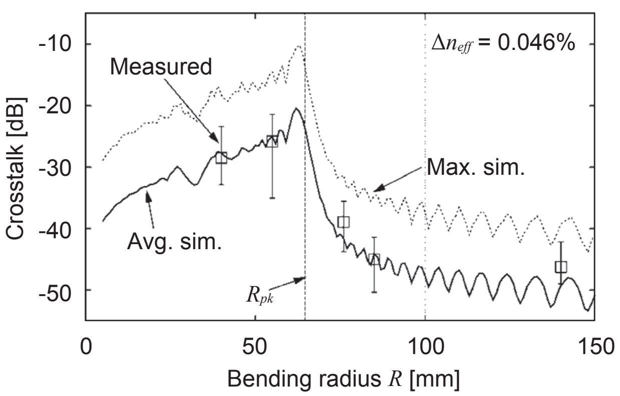

Fig. 4. Effects of fiber curvature ($1/R_{\mathrm{b}}$) and inter-core propagation coefficient mismatching ($\Delta\beta_{\mathrm{c}}$) on XT of MCF[5]

phase matching occurs when $\delta n_{\mathrm{eq}} = 0$ and is reduced at other points. Experimental and computational results shown in Fig. 4 reveal that XT values change substantially at the threshold R_{pk} (when $R_{\mathrm{b}} \leq R_{\mathrm{pk}}$, phase matching occurs due to bend and twist and when $R_{\mathrm{b}} > R_{\mathrm{pk}}$, phase matching does not occur).

If looked at in terms of complex amplitude instead of intensity and if XT is at an adequately low level, random changes, such as represented in Fig. 3, can be approximated by a discrete random walk model expressed by the following equation.[8]

$$A_{n,N} \approx -j\sum_{l=1}^{N} K_{nm,l} \exp\left[-j\varphi_{\mathrm{rnd},l}\right] A_{m,l} \quad \text{(3)}$$

where $A_{m,l}$ is the complex amplitude of core m at the l-th phase matching point, $K_{nm,l}$ is a discrete coupling coefficient from core m to core n at the l-th phase matching point, and $\varphi_{\mathrm{rnd},l}$ is a random variable used to incorporate the randomness of phase shift between phase matching points. According to Eq. (3) and the central limit theorem, the probability distribution of the complex amplitude component of XT converges to a normal (Gaussian) distribution. As the intensity component of XT is the sum of intensities of in-phase and quadrature components of complex amplitudes for two orthogonal polarizations (four components in total), the intensity probability distribution of XT becomes a chi-square distribution with four degrees of freedom.[8] Figure 5 shows a schematic diagram of stochastic behaviors of XT. The statistical average μ_{X} (the ensemble average in Fig. 5) of randomly behaving XT at a wavelength or at a point of time X is approximately equal to the time average or wavelength average of XT. The values of XT in literature on MCFs are often expressed by the values of μ_{X} even if it is not explicitly noted. When the spectrum of a signal light has a flat-top shape, the instantaneous frequency of the light is considered to be varying fast within the signal bandwidth. Consequently, if the signal light band is sufficiently wide, the complex amplitudes of XT components behave as Gaussian noise, which can be treated as noise similar to amplified spontaneous emission (ASE) noise or nonlinear interference noise modeled by Gaussian distribution.[9] Later, Rademacher et al. conducted a detailed study of this. They confirmed by simulations and experiments that, in quadrature amplitude modulation (QAM) and other modulation methods in which signal light has a flat spectrum, the complex amplitudes of XT components can be regarded as Gaussian noise whose average value is constant, if the product of the signal light band and the inter-core group delay difference is not less than a certain value.[10]

The average of XT, μ_{X}, is proportional to fiber length and bend radius if the MCF is the homogeneous-core type in which cores are structurally identical,[8] and can be expressed by the following equation.

$$\mu_X \approx \kappa_{nm}^2 \frac{2R_{\mathrm{b}}L}{\beta_{\mathrm{c},n}D_{nm}} = \kappa_{nm}^2 \frac{\lambda R_{\mathrm{b}}L}{\pi n_{\mathrm{eff,c},n}D_{nm}} \quad \text{(4)}$$

Using this equation, it is extremely simple to accurately predict XT. Accordingly, Eq. (4) is used widely by various groups to conduct MCF R&D.

Furthermore, we have also experimentally and theo-

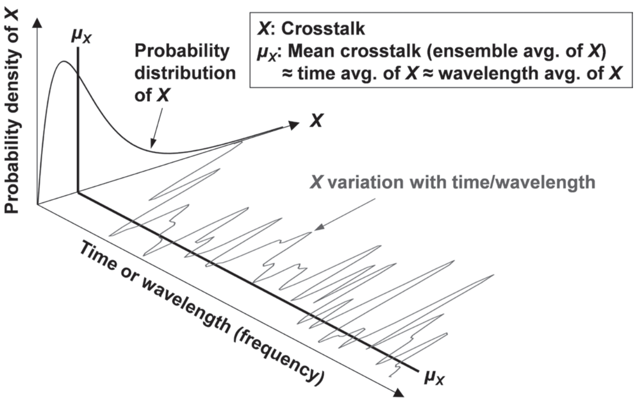

Fig. 5. Schematic diagram explaining stochastic behaviors and statistical parameters of XT in MCF[9]

retically examined and reported the effects of micro-bends and other conditions on XT.[11]

2-2 Outer cladding thickness and loss attributable to leakage through coating

The OCT is an important parameter to ensure favorable optical properties of the outer cores close to the cladding-coating interface. The optical fiber coating is specified to a high refractive index to prevent light leaking from cores propagating in the cladding mode. However, if the cores are excessively close to the coating, light in the cores might be coupled to the leakage mode of the coating, resulting in increasing loss from the outer cores. To reduce this, it is necessary to provide a sufficiently large OCT.[12]

2-3 Cladding diameter

To contain multiple cores while meeting the above requirements, the cladding diameter tends to be large. Many reported ultra-high-capacity SDM transmission experiments use thicker SDM fibers than the standard fibers with a cladding diameter of 125 µm. Their thickness ranges from 200 to 300 µm in cladding diameter.[13]-[16] On one hand, larger cladding diameters contribute to an increasing transmission capacity per fiber; on the other hand, larger cladding diameters are disadvantageous principally in that they result in degraded mechanical reliability and productivity. Regarding mechanical reliability, thicker bent fibers are subject to increasing breaking probability due to the higher strain applied to the glass. It is highly likely that the productivity is affected simply by an increasing glass volume per unit fiber length. Therefore, smaller (standard) cladding diameters are desirable, if possible.

3. Representative Examples of Prototype MCFs Proposed or Fabricated by Sumitomo Electric

We have designed, fabricated prototypes of, and proposed various MCFs for specific applications and purposes by accurately predicting their optical properties. Table 1 presents representative examples of MCFs proposed by Sumitomo Electric and prototype MCFs fabricated by the company through joint research projects. The features of these MCFs are explained below.

3-1 Uncoupled MCF

An uncoupled MCF is an MCF with reduced intercore XT. Each core in it can be handled as an independent transmission channel. This implies a great advantage in that conventional SMF transceivers are usable with uncoupled MCFs without need for any modification.

For long-distance transmission applications, we have proposed and fabricated prototype MCFs with the following features.

(a) Ultra-low XT MCF: We have proven an MCF that is suitable for the C+L bands, contains 7 cores in a 150 µm diameter cladding, and controls XT to −30 dB (10^{-3}) or below even after transmission over a distance of 10,000 km.[8] Extremely low XT has been achieved by providing refractive index trenches around each core and using the longest possible cutoff wavelength λ_{cc}, which are effective for confining light in each core. Using this MCF,

Table 1. Representative examples of reported MCFs

		Ref.	# of cores	Core layout	Cladding diam. [µm]	λ_{cc} [µm]	MFD [µm]	A_{eff} [µm^2]	XT [/km]	λ band	Potential applications	Feature
Uncoupled	(a)	(8)	7	Hexagonal	150	≤1.51	9.8^a	80^a	$6.0\times10^{-9\,b}$	C~L	Long-haul	Ultra-low XT
	(b)	(17)	7	Hexagonal	188	≤1.47	12.2^a	124^a	$8.0\times10^{-7\,b}$	C~L	Long-haul	High OSNR
	(c)	(18,19)	31	Hexagonal	225	~1.47	n/a	57^a	9.3×10	C~L	Long-haul	High SSE
	(d)	(20,21)	4	Square	125	≤1.19	8.6^c	n/a	$5.0\times10^{-5\,b}$	O~L	Long-haul	Standard diam. clad. + Full wavelength band
	(e)	(22)	8	Circular	125	≤1.24	8.4^c	n/a	$3.2\times10^{-7\,c}$	O	Short-reach	Standard diam. clad. + 8 cores
	(f)	(23)	8	2×4	180	≤1.20	8.4^c	n/a	$\leq6.3\times10^{-5\,a}$	O~C	Short-reach	Si photonics TRx mounted
	(g)	(24)	4	1×4	98×200	≤1.34	9.7^a	n/a	$3.0\times10^{-4\,a}$	C~L	Short-reach	Non-circular clad.
		Ref.	# of cores	Core layout	Cladding diam. [µm]	λ_{cc} [µm]	MFD [µm]	A_{eff} [µm^2]	SMD [ps/√km]	λ band	Potential applications	Feature
Coupled	(h)	(25)	3	Equilateral triangular	125	~1.35	n/a	129^a	≤ 30	S~L	Long-haul	4,200-km MIMO transmission and real-time MIMO transmission achieved.
	(i)	(26)	4	Square	125	≤1.47	n/a	112^a	3.1	C~L	Long-haul	Has set low space mode dispersion (SMD) and low-loss records for SDM fibers. 10,000 km transmission achieved.

Values at wavelengths of a) 1550nm b) 1625nm and c) 1310nm.

the National Institute of Information and Communications Technology (NICT) conducted a transmission experiment, in which the MCF achieved a transmission capacity of higher than 100 Tbit/s per optical fiber for the first time.[27]

(b) High-OSNR MCF: We demonstrated that, in repeated long-haul transmission with ASE and nonlinear interference (NLI) noises, to improve the optical signal-to-noise ratio (OSNR) of each core, it is important to ensure the equilibrium of the enlargement of the effective area A_{eff}, XT reduction, and core density (to reduce nonlinear noise and XT in a well-balanced manner) rather than to specifically reduce XT.[17]

(c) High-SSE MCF: In terms of spatial spectral efficiency [SSE: spectral efficiency (SE) per unit cross-sectional area of fiber], it is desirable to use high-Δ small-diameter cores for stronger confinement in the core and raise the core density by reducing Λ. This is because even with degraded nonlinearity due to higher Δ and smaller core diameter, the benefit from the effect of a higher number of linear-proportional cores is large, since the SE of each core is log-proportional to A_{eff}.[18],[19] This design concept is suitable for the SDM transmission technique,[28] which maximizes the transmission capacity per unit power consumption by reducing the SE of each core and incorporating a higher number of cores.

(d) 125-µm cladding 4-core fiber for O-L bands: This is an MCF proposed by Nippon Telegraph and Telephone Corporation (NTT), which contains 4 cores in a standard 125-µm-diameter cladding while keeping the optical properties of each core compatible to the standard SMF in all wavelength bands (O/E/S/C/L bands: 1260–1625 nm).[20] Sumitomo Electric, Fujikura Ltd., and Furukawa Electric Co., Ltd. fabricated MCFs in accordance with common specifications. The results of a transmission experiment interconnecting their MCFs were reported by NTT, the three companies, and others.[21]

For short-distance transmission applications, we have proposed MCFs with the following features.

(e) 125-µm cladding 8-core fiber for O-band: This MCF contains 8 cores in a standard 125-µm-diameter cladding while keeping the optical properties in O-band comparable to the standard SMF. O-band (1260-1360 nm) has low chromatic dispersion and is suitable for short-reach transmissions using intensity-modulation direct-detection.[22] Though it is optimized for O-band transmission, this MCF has recorded the highest density of an MCF that contains standard-SMF-equivalent cores in a standard-diameter cladding, and realized prototypes of a 96-core MPO connector (8 cores × 12 MCFs)[29] and a 256-core MPO connector (8 cores × 32 MCFs),[30] proving its scalability for future ultra-high-density installation.

(f) 2×4-core MCF: Sumitomo Electric and Luxtera, Inc. co-designed an MCF and grating coupler array for MCF coupling to a silicon photonics chip, developed a fully-functional transceiver (TRx) in which MCFs are directly coupled to a photonic die, and realized the first end-to-end single-mode MCF transmission link.[23]

(g) Noncircular cladding MCF: We have realized noncircular cladding for easy rotational alignment of MCFs at a practical drawing speed.[24] This fiber also has a linear core arrangement for easy coupling to a chip edge.

Through the development of these MCFs, we are delivering value propositions for potential MCF applications.

3-2 Coupled MCF

A (randomly) coupled MCF is an MCF that allows for (or rather, encourages) random coupling between cores on the assumption that XT is compensated by multiple-input-multiple-output (MIMO) digital signal processing (DSP)*1. A coupled MCF can achieve higher core density than an uncoupled MCF, even with a simple core structure. Moreover, the random coupling in the coupled MCF can reduce the accumulation of nonlinearity impairment, group delay difference between modes [spatial mode dispersion (SMD)], and mode-dependent loss/gain. Consequently, the coupled MCF is expected to be applied to long-distance point-to-point communication. While undertaking research on coupled MCFs in collaboration with Nokia Bell Labs (former Bell Laboratories, Alcatel-Lucent USA Inc.), Sumitomo Electric has recently developed and proposed its original fibers.

To reduce the computational complexity of MIMO DSP, the important factors are how random coupling between modes occurs and how SMD can be reduced. Regarding the mode coupling of the coupled MCF, we have elucidated that bends and twists play major roles as with XT in uncoupled MCF and that the mode coupling length can be shortened and SMD can be reduced with a higher twist rate (the number of fiber twists per unit length).[31] Assuming that unintended twists in fiber occur as a Wiener process (with the twist rate observed as additive white Gaussian noise), we have also found that the results of fiber transfer matrix calculation accurately reproduce actual fiber SMD.[32] (This random twist model was adopted by Fujisawa et al. as an XT calculation model for uncoupled MCF[33] and proved itself to be effective.)

Representative coupled MCFs that we have reported on are implemented in the standard 125-µm cladding, as follows.

(h) The first realization of fully randomly coupled MCF.[25] This fiber proved the applicability of MIMO to fiber-optic communications at an ultra-long distance of 4,200 km and realized the first real-time MIMO SDM transmission over optical fiber. [34]

(i) MCF that has set the low-loss low-SMD records as an SDM fiber.[26] This fiber has proven that the coupled MCF can outperform the SMF with comparative loss and A_{eff} in transmission performance with lowered nonlinear noise over a transmission distance of 10,000 km.[35]

3-3 Uncoupled few-mode MCF

The fiber known as few-mode (FM) MCF is a type of uncoupled MCF, each core of which is intended for multi-mode operation, rather than single-mode operation, and performs mode-multiplexed transmission. Sumitomo Electric jointly with NICT and Yokohama National University reported on a 36-core fiber, each core of which operating in 3 modes (108 modes in total),[13] and we also has fabricated prototypes of 19-core fibers[15],[16],[36] with each core operating in 6 modes, for KDDI Research, Inc. (former KDDI R&D Laboratories, Inc.). The latest achievements include a prototype 6-mode 19-core fiber usable in the entire C + L bands (1530-1625 nm) for long-distance communications. In a transmission experiment conducted at KDDI Research, this fiber attained a transmission capacity exceeding 10 Pbit/s per optical fiber.[16]

4. Conclusion

To respond to the continuously growing demand for communications capacity, Sumitomo Electric is working on the research and development of MCFs; has established fundamental technologies for design, manufacture, and evaluation; and has proposed the value of MCFs specifically designed for various applications. We will continue to improve our manufacturing technologies and develop related engineering, aiming at the commercialization of MCFs for communication applications.

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Technical Term

*1 MIMO DSP: MIMO stands for multiple-input-multiple-output and DSP for digital signal processing. In a transmission system that has more than one spatial channel, cross-talk between spatial channels can be compensated for by MIMO DSP to recover the signal without the crosstalk.

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