Multicore Fiber Technology

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(Tutorial Review)

Abstract—Multicore fibers (MCFs) are expected as a good candidate for overcoming the capacity limit of a current optical communication system. This paper describes the recent progress on the MCFs for space-division multiplexing to be utilized in future large capacity long-distance transmission systems. Tradeoff issue between low crosstalk and high core density in MCFs is presented and prospect of large-space multiplicity of MCFs is discussed.

Index Terms—Few-mode fiber, multicore fiber, multimode fiber, space division multiplexing.

I. INTRODUCTION

E experienced Internet traffic growth of about 100 times every 10 years, and this trend is estimated to proceed [1]. The transmission capacity of conventional single-mode single-core fiber (SM-SCF) has also been exponentially increased in the past few decades by a variety of advanced technologies including the expansion of the optical bandwidth of transmission window and enhancement of the spectral efficiency. Recent SM-SCF transmission systems have achieved transmission capacity up to about 100 Tb/s and capacity-distance product over 100 Pb/s·km as shown in Fig. 1 [2]–[7]. However, the capacity of existing standard SM-SCF may no longer satisfy the growing capacity demand and is approaching its fundamental limit around 100 Tb/s owing to the limitation of amplifier bandwidth, nonlinear noise, and fiber fuse phenomenon. Therefore, it is estimated that the current trends of traffic growth will result in capacity crunch in the near future [8].

In order to further increase the fiber capacity or spatial capacity - the capacity per cross-sectional area of the fiber, space division multiplexing (SDM) has been proposed [9] and attracted intensive research efforts as a solution to the problem of saturation of the capacity of conventional SM-SCFs. In SDM transmission systems, several different signals are transmitted simultaneously by providing multiple spatial paths with cost effective ways. From the SDM fiber point of view, there are basically two approaches to introduce multiple spatial paths into a fiber. The first approach is to incorporate multiple separate cores with sufficiently low crosstalk between neighboring cores in a single fiber, which is known as a weakly-coupled multi-core fiber (MCF). The second approach is to utilize multiple different modes in a fiber, which is a few-mode fiber (FMF) or multimode fiber (MMF). From the spatial density perspective, MMF approach is a promising scheme since the spatial channel count (SCC) can be scaled up to more than 30 theoretically with a standard cladding diameter of 125 μm [10], [11], however, the control of group velocity difference between each channel becomes a challenging issue due to structural parameter fluctuation during fabrication if the number of modes increases. On the other hand, from the total SCC perspective, MCF approach is expected as a good candidate since the core multiplicity and mode multiplicity can be combined in MCFs, however, the suppression of crosstalk between neighboring cores becomes an issue if the number of cores increases in a limited cladding size.

In this paper, the state-of-the-art of MCFs as a future large capacity long-distance transmission media for SDM is presented. Firstly, crosstalk estimation and crosstalk suppression techniques in MCFs are described. Next, the core density in MCFs is discussed based on the recently fabricated single-mode MCFs (SM-MCFs). It is shown that there is a tradeoff relationship between low crosstalk and high space multiplicity, therefore the maximum number of cores and the core arrangement have to be carefully determined based on the allowable crosstalk level and upper cladding size. In addition, in order to further increase the space multiplicity in SDM fibers, recently developed MCFs with supporting a few spatial modes in each core, which are few-mode MCFs (FM-MCFs), are also presented.

II. LOW CROSSTALK MULTICORE FIBERS

A. Classification of Multicore Fibers

MCFs for SDM application were firstly proposed in 1979 [12], [13], however, they have not been commercialized then since other cost- and space-efficient network for the subscriber...
lines was utilized. In the late 2000s, the SDM approach with MCFs had come to attract much attention again [9] because the future capacity crunch became an issue with reality [8].

MCFs can be fundamentally classified into two different categories as shown in Fig. 2. The first type is a weakly-coupled MCF, in which each core is used as an individual waveguide with sufficiently low interference between neighboring cores. In weakly-coupled MCFs, the optical crosstalk between adjacent cores is an important problem, since a part of the optical power launched into one of the core is coupled with neighboring cores during the propagation, and the crosstalk (XT) is defined as $XT = 10\log_{10}(P^*/P)$ [dB], where $P$ and $P^*$ are the output power from the input core and that from the neighboring core, respectively. In order to keep crosstalk level lower than $-30$ dB, the coupling coefficient $\kappa$ between neighboring cores should be lower than around $10^{-2} \text{ m}^{-1}$ [14] for transmission distance of longer than 10 km by sacrificing the core density and its typical core-to-core distance is around $40 \mu m$. In this case, multiple-input multiple-output (MIMO) digital signal processing (DSP) is not needed at the receiver side for recovering the signals. The second type is a strongly-coupled MCF, in which the crosstalk between cores is intentionally introduced by decreasing the core-to-core distance, resulting in the core density improvement. In theory, the strongly-coupled MCF supports several super-modes and it can be considered a form of MMFs. In practice, these super-modes are strongly mixed due to structural parameter fluctuations and/or bending effect, if the effective index difference $\Delta n_{ef}$ between each mode is relatively small (typically $\Delta n_{ef} < 10^{-5}$). In MMF transmission, group delay spread originating from the modal dispersion is one of the major problems since the magnitude of group delay spread determines the complexity of MIMO receiver (and hence, system reach)[15]. The strong mode mixing in strongly-coupled MCFs is beneficial for reducing the group delay spread and the group delay spread is proportional to the square root of the transmission distance [16]. Recently, this square root dependence of group delay spread was experimentally reported by using a well-designed coupled 3-core fiber up to 4200 km [17], [18] and a coupled 6-core fiber up to 1705 km [19]. The coupling coefficient $\kappa$ between neighboring cores in the strongly-coupled MCFs is in the order of $10^{-1} \text{ m}^{-1}$ or more and the typical core-to-core distance is less than $30 \mu m$. In this case, MIMO DSP with low complexity is needed at the receiver side to undo the signals. It should be noticed that the mode coupling during the propagation between super-modes becomes weak if the coupling between cores is too strong, since the effective index difference $\Delta n_{ef}$ between each mode becomes large (typically $\Delta n_{ef} > 10^{-4}$). In this case, it can be used as an MMF similar to a single-core MMF with high spatial density [20], however, its group delay spread is proportional to the transmission distance and complex MIMO DSP is required as increasing the transmission distance.

Among these two categories of MCFs, SDM based on weakly-coupled MCFs is a simple and promising approach for increasing SCC, resulting in improvement of transmission capacity per fiber. Various kinds of weakly-coupled MCFs have been developed to achieve high-capacity-long-distance transmission. Recent SM-MCF transmission experiments have achieved the transmission capacity well beyond the fundamental limit of SM-SCF as shown in Fig. 1 [21]–[32]. The current maximum transmission capacity per fiber is 1.01 Pb/s [28], the maximum capacity-distance product is 1.032 (0.516+0.516) Eb/s/km [32], and the maximum number of spatial multiplicity is 19 [25], [26] in SM-MCF transmission. The longest span length of MCF transmission reported so far is about 75 km [23], [27].

### B. Crosstalk Estimation in Weakly-Coupled Multicore Fibers

The estimation of crosstalk in MCFs is a very important issue for determining its structural parameters. In order to evaluate crosstalk in MCFs theoretically, coupled-mode theory (CMT) has been introduced [33], [34]. The coupled mode equations for MCFs are written as [35]

$$\frac{dA_m}{dz} = -j \sum_{n \neq m} \kappa_{mn} A_n(z) \exp(j\Delta\beta_{mn} z) f(z)$$

where $A_m$ is the mode amplitude in core $m$, $z$ is the propagation direction, $\kappa_{mn}$ is the mode-coupling coefficient from core $n$ to core $m$, and $\Delta\beta_{mn}$ is the propagation-constant difference between core $m$ and core $n$ expressed as

$$\Delta\beta_{mn} = \Delta\beta_{\text{core},mn} + \Delta\beta_{\text{bend},mn}(z)$$
with $\Delta \beta_{\text{core}, mn}$ being the intrinsic propagation constant difference between core $m$ and core $n$ and $\Delta \beta_{\text{rand}, mn}$ being the bending and twisting induced propagation constant difference. $f(z)$ is the phase function and is given by

$$f(z) = \exp[j(\phi_m - \phi_n)] \delta f(z)$$  \hspace{1cm} (3)

where $\phi_m$ and $\phi_n$ are the phase in core $m$ and core $n$, respectively, and $\delta f(z)$ is the random part. If the random part is missing, Eq. (1) becomes a well-known conventional coupled mode equation. On the other hand, the crosstalk in actual MCFs shows statistical characteristics and this random part $\delta f(z)$ has to be considered accordingly, since there is random fluctuation in longitudinal direction. In order to consider the random part of phase function, $\delta f$, the total fiber length is divided into finite segments of arbitrary but equal length, $d_s$, and random phase-offsets of $\exp(j\phi_{\text{rand}})$ are applied to all cores at every segment. It has been reported that the segment length $d_s$ used in CMT is a stochastic parameter corresponding to the correlation length of phase function [36]. By solving Eq. (1), crosstalk between core $m$ and core $n$ in MCFs can be evaluated, however, in order to obtain sufficiently accurate average values of crosstalk, a large number of simulations are required, since the crosstalk obtained by CMT with random phase-offset shows statistical characteristics.

To evaluate crosstalk in MCFs more easily, coupled-power theory (CPT) has also been introduced [36]–[38]. The coupled power equations for MCFs are written as [39]

$$\frac{dP_m}{dz} = \sum_{n \neq m} h_{mn}[P_n(z) - P_m(z)]$$  \hspace{1cm} (4)

where $P_m$ is the average power in core $m$ and $h_{mn}$ is the power-coupling coefficient. The averaged power $P_m$ in core $m$ at a point $z$ close to $z = 0$ is given by using the solution of Eq. (1) as

$$P_m(z) = \left\langle |A_m(z)|^2 \right\rangle$$

$$= \left\langle \left[ \kappa_{mn} A_m(0) \int_0^z \exp[j\Delta \beta_{mn} \xi] \delta f(\xi) d\xi \right] \left[ \kappa_{nm} A_n(0) \int_0^z \exp[-j\Delta \beta_{mn} \eta] \delta f^*(\eta) d\eta \right] \right\rangle$$

$$= \kappa_{mn}^2 P_m(0) \int_0^z d\eta \int_0^z \exp[j\Delta \beta_{mn} (\xi - \eta)]$$

$$\left\langle \delta f(\xi) \delta f^*(\eta) \right\rangle d\xi d\eta$$

$$= \kappa_{mn}^2 P_n(0) \int_0^{z-\eta} d\eta \int_{-\eta}^{z-\eta} \exp[j\Delta \beta_{mn} \xi]$$

$$\left\langle \delta f(\eta + \zeta) \delta f^*(\zeta) \right\rangle d\xi d\zeta$$  \hspace{1cm} (5)

where the asterisk and the symbol $\langle \rangle$ indicate complex conjugation and an ensemble average, respectively. The random part of phase function, $\delta f$, is a stationary random process and therefore, it has an autocorrelation function $R(\zeta)$, and Eq. (5) can be rewritten as

$$P_m(z) = \kappa_{mn}^2 P_n(0) z \int_{-\eta}^{z-\eta} \exp[j\Delta \beta_{mn} \zeta] R(\zeta) d\zeta$$  \hspace{1cm} (6)

Since the two quantities, $\eta$ and $\zeta$, are not independent, it is difficult to evaluate rigorously the integral in Eq. (6). If the correlation length of $\delta f$ is much smaller than the increment $z$ of fiber length, the bounds of the integral in Eq. (6) can be neglected and therefore, the upper and the lower integration limits, $z-\eta$ and $-\eta$, are replaced by $+\infty$ and $-\infty$ respectively, and the power-coupling coefficient $h_{mn}(z)$ is written as [36]

$$h_{mn}(z) = \frac{P_m(z)}{z F_n(0)} = \kappa_{mn}^2 \int_{-\infty}^{+\infty} \exp[j\Delta \beta_{mn} \zeta] R(\zeta) d\zeta$$

$$= \kappa_{mn}^2 S(\Delta \beta_{mn}(z))$$  \hspace{1cm} (7)

where $S(\Delta \beta_{mn}(z))$ is the Fourier transform of the autocorrelation function. The autocorrelation function $R(\zeta)$ is an unknown function, but it has been reported that the experimental results of crosstalk in MCFs can be well fitted by using exponential autocorrelation function [36], [40] given by

$$R(\zeta) = \exp(-|\zeta|/d)$$  \hspace{1cm} (8)

where $d$ is the correlation length and its corresponding power coupling coefficient is a Lorenzian function as

$$h_{mn}(z) = \frac{2\kappa_{mn}^2 d}{1 + [\Delta \beta_{mn}(z)]^2}.$$  \hspace{1cm} (9)

If we assume that an MCF is bent at a constant radius $R$ and is twisted continuously at a constant rate $\gamma$, the power coupling coefficient is averaged over a twist pitch as

$$\bar{h}_{mn}(z) = \frac{\gamma}{2\pi} \int_0^{2\pi/\gamma} h_{mn}(z) dz$$  \hspace{1cm} (10)

and the analytical expression of the averaged power coupling coefficient has been derived [40]. Notice that, in this case, the power coupling coefficient is independent of the twist rate $\gamma$, and the crosstalk (XT) between two cores with length $L$ is easily estimated as

$$XT = \tanh(\bar{h}_{mn}(L)).$$  \hspace{1cm} (11)

From Eq. (9), we can see that the power coupling coefficient becomes peak value when $\Delta \beta_{mn}$ is zero at a particular bending radius, and this critical bending radius $R_c$ is given as

$$R_c = \frac{\beta_m A}{\Delta \beta_{\text{core}, mn}} = \frac{n_{e\text{ff}, mn} A}{\Delta n_{e\text{ff}, mn}}$$  \hspace{1cm} (12)

where $\beta_m$ and $n_{e\text{ff}, mn}$ is the propagation constant and the effective index of the propagating mode in core $m$, respectively, $\Delta n_{e\text{ff}, mn}$ is the intrinsic effective index difference between core $m$ and core $n$, and $A$ is the core-to-core distance. In the case of homogeneous MCFs ($\Delta \beta_{\text{core}, mn} = 0$) with small bending radii, Eq. (9) can be approximated as [35], [36]

$$\bar{h}_{mn}(z) = \frac{2\kappa_{mn}^2 R}{\beta_m A}.$$  \hspace{1cm} (13)

It is clear that, when the mode-coupling coefficient $\kappa$ is obtained, the averaged crosstalk can be easily estimated in homogeneous MCFs. For example, if we target a crosstalk level of $-50$ dB/km with $A<40$ $\mu$m and $R<300$ mm, the $\kappa$ has to be lowered to around 0.002 m$^{-1}$ or less.
In order to decrease crosstalk in MCFs, the coupling coefficient $\kappa$ between cores has to be reduced. Trench-assisted MCFs [41]–[43] and hole-assisted MCFs [44]–[47] have been proposed for reducing the coupling coefficient. Fig. 3(a) shows an example of cross-sectional view of a fabricated trench-assisted MCF with 12 cores [30], [32], where each core has low-index trench layer around the core. In Fig. 3(b), the schematic diagram of an index profile with trench-assisted structure [48] is shown. The relative refractive index differences between core and cladding, trench and cladding are $\Delta_1$ and $\Delta_2$, respectively, and $r_1$, $r_2$, and $W$ are the core radius, the distance from the core center to the inner edge of trench layer, and the trench width, respectively. Due to the existence of low-index trench layer with the thickness of $W$, the overlap of the electromagnetic fields between cores can be greatly suppressed, resulting in the suppression of crosstalk compared with that in an MCF without trench.

Recently, simple analytical expression for crosstalk estimation in trench-assisted MCFs [49] was reported. The crosstalk in a trench-assisted MCF, $XT_{\text{trench}}$, can be accurately approximated as

$$XT_{\text{trench}} = XT_{\text{step}} \Gamma \exp \left[ -4 \left( W_2 - W_1 \right) \frac{W}{r_1} \right]$$  \hspace{1cm} (14)

where $XT_{\text{step}}$ is the crosstalk in a step-index MCF. The parameter $\Gamma$ is given by

$$\Gamma = W_1 / \left[ W_1 + (W_2 - W_1) W / \Lambda \right],$$  \hspace{1cm} (15)

in which $W_1 \approx 1.1428 V_1 - 0.996$ for $1.5 \leq V_1 \leq 2.5$ with $V_1 = 2\pi r_1 n_{\text{core}} \sqrt{2\Delta_1 / \lambda}$, $\lambda$ is the wavelength, $\Lambda$ is the core-to-core distance, and $W_2 = \sqrt{W_2^2 + W_1^2}$ with $W_2 = 2\pi r_1 n_{\text{clad}} \sqrt{2|\Delta_2| / \lambda}$, where $n_{\text{core}}$ and $n_{\text{clad}}$ are the core index and cladding index, respectively. As shown in Eq. (14), the trench width $W$ and the trench depth $\Delta_2$ are key parameters for crosstalk reduction. Fig. 4 shows the crosstalk between two cores as a function of the core-to-core distance in a step-index MCF and trench-assisted MCFs with various relative trench widths of $W/r_1$ at a wavelength of 1550 nm with $R = 140$ mm, where $r_1 = 4.5 \mu m$, $r_2/r_1 = 2.0$, $\Delta_1 = 0.35\%$, and $\Delta_2 = -0.70\%$, as an example. The crosstalk decreases linearly as increasing the core-to-core distance and the amount of crosstalk reduction in trench-assisted structure relative to step-index structure is core-to-core distance independent [49]. It can be seen that more than 30 dB crosstalk reduction is achievable with a typical trench width of $W/r_1 = 1.0$.

The second approach to suppress the crosstalk is to introduce intrinsic index difference between adjacent cores [50], [51], which is called heterogeneous MCFs. The heterogeneous MCF consists of several kinds of cores whose propagation constants are different from each other, and the bending perturbation plays an important role for predicting the crosstalk in heterogeneous MCFs [33], [34]. Fig. 5 shows the averaged power coupling coefficient as a function of the intrinsic effective index difference $\Delta n_{\text{eff}}$ between cores and the bending radius $R$ at 1550 nm wavelength, where the core-to-core distance is $\Lambda = 40 \mu m$ and the coupling coefficient is $\kappa = 0.01 m^{-1}$. The bending radius of the MCF in a cable will be depending on the cable design and it can be assumed to be from several tens of mm to 1000 mm [52]. It is shown that, when the bending radius is smaller than a critical bending radius $R_c$ given by Eq. (12), there is a linear relation between a bending radius in a logarithmic scale and a crosstalk values [51]. On the other hand, over the bending radius...
larger than the critical bending radius, the crosstalk decreases rapidly. This is because, if the bending radius is smaller than $R_c$, the bent induced effective index variation is larger than the intrinsic index difference $\Delta n_{eff}$ between heterogeneous cores, namely $\text{Max}[|\Delta \beta_{bend}(z)|] > \Delta \beta_{core}$, and large crosstalk degradation occurs many times during the propagation at the phase matching points of $\Delta \beta'_{mn}(z) = 0$. On the other hand, in the non-phase-matching region of bending radii $> R_c$, the bent induced effective index variation is smaller than the intrinsic index difference $\Delta n_{eff}$, namely $\text{Max}[|\Delta \beta_{bend}(z)|] < \Delta \beta_{core}$, therefore the crosstalk is dominated by the statistical properties [33], [36], [53], [54]. In this non-phase-matching region, the heterogeneous MCFs can be used as a bending insensitive fiber in terms of crosstalk. If the effective index difference between cores is sufficiently large, the value of $R_c$ can be pushed toward small range lower than an effective bending radius in MCF cables.

Recently, a heterogeneous MCF with 30 cores has been reported [55]. Fig. 6(a) and (b) show a schematic structure and cross-sectional view of the fabricated 30-core fiber with heterogeneous core arrangement, respectively. The fiber structure is based on a hexagonal closed-pack structure (HCPS) with 37 cores. Six outermost cores were removed to reduce the cladding diameter. The center core was also removed because the cutoff wavelength lengthening of the center core due to the trench-assisted structure was unavoidable. Four kinds of cores were used to produce a heterogeneous relation for all the adjacent cores under the limitation of the similar effective area ($A_{eff}$) for all the cores. Cores 1, 2, and 3 employed a trench-assisted index profile shown in Fig. 3(b) to reduce the crosstalk, whereas Core 4 has a step-index profile without trench layer to avoid the cutoff wavelength lengthening of the inner cores surrounded by trench-assisted cores. Their core parameters were determined based on the effective index difference as shown in Fig. 7, where the normalized trench position is $r_2/r_1 = 1.7$ and $\Delta_2 = -0.7\%$ for trench-assisted cores. All the cores were selected so that the effective index difference between adjacent cores becomes larger than 0.0005 with the similar $A_{eff}$ of 80 $\mu$m$^2$.

The fabricated fiber length was 9.6 km, and it had the core-to-core distance of 29.7 $\mu$m, the cladding diameter of 228 $\mu$m, and the averaged $A_{eff}$ of 77.3 $\mu$m$^2$ at 1550 nm wavelength. In addition, the critical bending radius $R_c$ was less than 100 mm for all the core combinations. The measured crosstalk was less than $-50$ dB. Fig. 8 shows the characteristics of the fan-in/fan-out (FI/FO) device for the 30-core fiber [56].

Another option for crosstalk suppression in MCFs is to utilize propagation-direction interleaving (PDI) technique [57]–[59],
where adjacent cores are assigned to opposite direction. We can reduce the number of adjacent core in which the signal propagates to the same direction to one for all cores by using PDI. Accordingly, effective crosstalk is expected to be reduced. In the unidirectional propagation scheme, the inputted power in excited core is coupled to adjacent cores and the crosstalk given by Eq. (11) is forward propagated crosstalk, \( XT_f \), as shown in Fig. 9(a). On the other hand, in the bidirectional propagation scheme, the crosstalk from the adjacent cores is generated when the back-scattered light is coupled with the opposite direction as shown in Fig. 9(b), and the dominant factor in back-propagating signals is Rayleigh backscattering [59]. The backward propagated crosstalk, \( XT_b \), is given by

\[
XT_b = \frac{S_{R_{h}}}{2n} \bar{h}_{m,n} \left[ \frac{1 - \exp(-2\alpha L)}{\exp(-h_{m,n} L) \cosh(h_{m,n} L) \exp(-\alpha L)} \right] \tag{16}
\]

where \( S \) and \( \alpha_R \) are the recapture factor of the Rayleigh scattering component into the backward direction and the attenuation coefficient due to Rayleigh scattering, respectively. \( \alpha \) and \( L \) are the fiber attenuation coefficient and fiber length, respectively.

Fig. 10 shows the forward propagated crosstalk, \( XT_f \), and the backward propagated crosstalk, \( XT_b \), as a function of the fiber length in a trench-assisted MCF at a wavelength of 1550 nm with \( R = 140 \) mm, where \( r_1 = 4.5 \) \( \mu m \), \( r_2/r_1 = 2.0 \), \( W/r_1 = 1.0 \), \( \Delta_1 = 0.35\% \), and \( \Delta_2 = -0.70\% \).

By adopting combination of these crosstalk suppression techniques, low crosstalk and high core count MCFs can be designed, such as heterogeneous trench-assisted MCFs [55] and trench-assisted MCFs with PDI [59]. The allowable crosstalk is depending on the transmission distance as well as the modulation format to be used. In Ref. [61], the effect of the crosstalk on the optical signal to noise ratio was numerically investigated by assuming the crosstalk as a static coupling, and experimentally by realizing the crosstalk as an effectively static coupling using optical couplers and variable optical attenuators. It has been reported that the crosstalk-induced penalty at the bit-error rate of \( 10^{-3} \) is less than 1 dB, when the crosstalk is less than \(-18 \) dB for quadrature phase-shift keying (QPSK), \(-24 \) dB for 16 quadrature amplitude modulation (QAM), \(-32 \) dB for 64 QAM [61]. Similarly, in Ref. [59], the crosstalk penalty in Q-factor for QPSK, 16 QAM, and 32 QAM signals were experimentally measured by using 50-km 12-core fiber. It has been reported that the allowable crosstalk for 0.3-dB Q-penalty was \(-18 \) dB for QPSK, \(-25 \) dB for 16 QAM, and \(-29 \) dB for 32 QAM. Based on these relations between the allowable crosstalk level and the modulation format, a relation between the achievable transmission distance and the allowable crosstalk level for different modulation format can be plotted as shown in Fig. 11. If the modulation format is QPSK, the crosstalk level of \(-40 \) dB/km is acceptable for 100 km transmission. On the other hand, if the modulation format is 64 QAM, the crosstalk level of around \(-55 \) dB/km is required for 100 km transmission. Therefore,
the crosstalk level in MCFs should be carefully designed based on the transmission distance and the modulation format for the transmission experiment.

We should also notice that the crosstalk given by Eq. (11) is the averaged crosstalk between two cores and it is not the worst case crosstalk. In actual MCFs, each core generally has several adjacent cores and it is affected by the nearest cores [23]. If all cores carry equal signal power, the worst case crosstalk of inner cores is larger than that of outer cores, since the number of nearest neighbor cores is larger for inner cores. For example, in the case of the HCPS, the inner core has six nearest neighbor cores, while the outer cores have three or four nearest neighbor cores. The worst crosstalk, $XT_{\text{worst}}$, in [dB] is given by

$$XT_{\text{worst}} = XT - 10 \log n$$

where $XT$ is the crosstalk between two cores in [dB], and $n$ is the number of nearest neighbor cores. Fig. 12 shows the crosstalk increment due to nearest neighbor cores ($\Delta XT$) for HCPS, one ring structure (ORS), and dual ring structure (DRS), where $\Delta XT = XT_{\text{worst}} - XT = 10 \log n$. In HCPS, the $\Delta XT$ of inner cores is 7.8 dB and that of outer cores is 4.8 dB for three nearest neighbor cores or 6.0 dB for four nearest neighbor cores. On the other hand, in ORS, $\Delta XT$ is 3 dB for all the cores. The allowable crosstalk level in MCFs should be determined by considering $XT_{\text{worst}}$.

### D. Core Density and Spatial Channel Count

MCFs for SDM applications should have high spatial efficiency (SE) compared with a conventional SM-SCF. The number of cores to be multiplexed in a fiber is related to the core-to-core distance, and the core-to-core distance can be determined by considering the allowable crosstalk based on the transmission distance and the modulation format. The upper limit of the core number is also limited by a cladding diameter (CD), since a small cladding diameter is preferable for maintaining high mechanical reliability for bending. Fig. 13 shows the failure probability after 20 years as a function of cladding diameter for bending diameters of $D = 30$ mm and $D = 60$ mm [62].

We can see that there is a trade-off relationship between high $RSE$ and low crosstalk. Fig. 14 shows the SCC as functions of the 100-km worst crosstalk and the CD for MCFs listed in Table I. For SM-MCFs, the reported maximum $RSE$ and the maximum SCC are, respectively, 9 and 30 [55] with the worst crosstalk of about 10 dB/100 km so far. It should be noted that the crosstalk of MCFs increases with increasing the wavelength and the slope of crosstalk over wavelength regimes was measured to be about 0.1 dB/nm [30], [66], [69], [70]. Therefore, the worst case crosstalk at the longer edge of L band is about 10 dB larger than that at the shorter edge of C band.
III. FEW-MODE MULTICORE FIBERS FOR HIGH SCC

Mode division multiplexing (MDM) over MMFs/FMFs is an attractive approach for SDM with high SE. Various FMFs have been reported for large-capacity MDM transmission with reduce differential mode group delay (DMD) [71]–[75]. However, for long-distance transmission using MMFs/FMFs, complex MIMO DSP is required to separate coupled modes during propagation in most cases. The number of multiplexed modes may be limited regarding the signal processing system complexity and controllability of mode dependent loss. In addition, scalability of SCC in MMFs is also limited in terms of the fabrication tolerance of the DMD characteristics [11], since it would be very sensitive to structural parameter fluctuation during fabrication with increasing the number of multiplexed modes.

The combination of core multiplexing and mode multiplexing, which is FM-MCF, is also promising candidate for SDM, since it can directly increase the SCCs by increasing the core and mode multiplicity. For example, 19-core fiber supporting 2-LP mode (3 spatial modes) in each core can achieve SCC of 36, and in 12-core fiber with 4-LP mode (6 spatial modes), SCC becomes 72. In FM-MCFs, required core-to-core distance becomes large compared with that in SM-MCFs, since the crosstalk between higher-order modes is larger than that between fundamental modes. Fig. 15 shows the numerically simulated crosstalk between LP01 modes (XT01−01), LP11 modes (XT11−11), and LP02 modes (XT02−02) in single-mode core, 2-LP-mode core, and 4-LP-mode core, respectively, as a function of core-to-core distance at 1565 nm wavelength.

Table II summarizes characteristics of weakly-coupled FM-MCFs for achieving similar crosstalk compared with SM-MCFs.

![Figure 14](image1.png)

**TABLE I**

<table>
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<tr>
<th>Reference</th>
<th>SCC</th>
<th>Aeff [μm²] at 1550 nm</th>
<th>CD [μm]</th>
<th>CT [μm]</th>
<th>100-km worst crosstalk [dB] at 1550 nm</th>
<th>RSE</th>
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<td>S. Matsuo et al. [66]</td>
<td>12</td>
<td>80</td>
<td>225</td>
<td>39</td>
<td>-42</td>
<td>3.7</td>
</tr>
<tr>
<td>H. Takahashi et al. [29]</td>
<td>7</td>
<td>99</td>
<td>200</td>
<td>55</td>
<td>-39.6</td>
<td>2.73</td>
</tr>
<tr>
<td>J. Sakaguchi et al. [26]</td>
<td>19</td>
<td>72</td>
<td>200</td>
<td>30</td>
<td>-14.3</td>
<td>7.42</td>
</tr>
<tr>
<td>T. Sakamoto et al. [46]</td>
<td>6</td>
<td>72.7</td>
<td>125</td>
<td>30.9</td>
<td>-32.5 (at 1625 nm)</td>
<td>6</td>
</tr>
<tr>
<td>A. Sano et al. [30]</td>
<td>12</td>
<td>105.8</td>
<td>230</td>
<td>35</td>
<td>-45</td>
<td>3.56</td>
</tr>
<tr>
<td>J. Sakaguchi et al. [67]</td>
<td>19</td>
<td>85</td>
<td>220</td>
<td>34.8</td>
<td>-36.8</td>
<td>6.13</td>
</tr>
<tr>
<td>Y. Amma et al. [55]</td>
<td>30</td>
<td>77.3</td>
<td>228</td>
<td>33.8</td>
<td>-42</td>
<td>9</td>
</tr>
<tr>
<td>T. Hayashi et al. [68]</td>
<td>8</td>
<td>~55 (at 1310 nm)</td>
<td>125</td>
<td>22</td>
<td>-42 (at 1310 nm)</td>
<td>8</td>
</tr>
</tbody>
</table>

![Figure 15](image2.png)

Fig. 14. SCC as functions of the 100-km worst crosstalk and the CD for SM-MCFs listed in Table I.

Fig. 15. Crosstalk between LP01 modes (XT01−01), LP11 modes (XT11−11), and LP02 modes (XT02−02) in single-mode core, 2-LP-mode core, and 4-LP-mode core, respectively, as a function of core-to-core distance at 1565 nm wavelength.
TABLE II
CHARACTERISTICS OF REPORTED WEAKLY-COUPLED FEW-MODE MULTICORE FIBERS

<table>
<thead>
<tr>
<th>Reference</th>
<th>SCC</th>
<th>$A_{eff}$ [μm$^2$] of LP$_{01}$ mode</th>
<th>$CD$ [μm]</th>
<th>$CT$ [μm]</th>
<th>MaximumDMD [ps/km]</th>
<th>100-km worst crosstalk [dB] at 1550 nm</th>
<th>RSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>D. Qian et al. [76]</td>
<td>216</td>
<td>110</td>
<td>213</td>
<td>98.6</td>
<td>51</td>
<td>2300</td>
<td>7</td>
</tr>
<tr>
<td>C. Xia et al. [77]</td>
<td>218</td>
<td>114</td>
<td>176</td>
<td>51</td>
<td>3000</td>
<td>39</td>
<td>6</td>
</tr>
<tr>
<td>K. Mukasa et al. [79]</td>
<td>440</td>
<td>110</td>
<td>195.4</td>
<td>51.5</td>
<td>2729</td>
<td>−39</td>
<td>4.6</td>
</tr>
<tr>
<td>Y. Sasaki et al. [80]</td>
<td>96</td>
<td>106</td>
<td>229.5</td>
<td>49.8</td>
<td>520</td>
<td>−55</td>
<td>4.6</td>
</tr>
<tr>
<td>Y. Sasaki et al. [81]</td>
<td>110</td>
<td>110</td>
<td>230</td>
<td>47</td>
<td>63</td>
<td>−58</td>
<td>10.6</td>
</tr>
<tr>
<td>T. Mizuno et al. [82]</td>
<td>76</td>
<td>96</td>
<td>306</td>
<td>51</td>
<td>7400</td>
<td>−5</td>
<td>18</td>
</tr>
<tr>
<td>K. Shibahara et al. [83]</td>
<td>318</td>
<td>110</td>
<td>318</td>
<td>35</td>
<td>1000</td>
<td>−19</td>
<td>17.6</td>
</tr>
<tr>
<td>J. Sakaguchi et al. [84]</td>
<td>306</td>
<td>108</td>
<td>229.5</td>
<td>51</td>
<td>7400</td>
<td>−5</td>
<td>18</td>
</tr>
<tr>
<td>K. Igarashi et al. [85]</td>
<td>306</td>
<td>118</td>
<td>318</td>
<td>35</td>
<td>1000</td>
<td>−19</td>
<td>17.6</td>
</tr>
</tbody>
</table>

In Fig. 16, filled circles correspond to the MCFs with $CD$ of smaller than 230 μm, while open circles represent the MCFs with $CD$ of larger than 230 μm. 7-core 2LP-mode homogeneous MCF [81] having a step-index profile with trench showed low worst crosstalk of $−40.2$ dB/100 km, however, its DMD was a few thousand ps/km. 12-core 2LP-mode heterogeneous MCFs having a multi-step index profile with trench and a graded index profile with trench achieved low crosstalk and low DMD, simultaneously [82], [83]. Recently, SCC more than 100 has been also reported by using the 36-core 2LP-mode heterogeneous MCF [84] and the 19-core 4LP-mode homogeneous MCF [85], although their $CD$s were larger than 300 μm.

Fig. 18 (a) and (b) show the experimentally measured wavelength dependence of the DMD for the fabricated 12-core 2LP-mode MCFs with (a) a multi-step index profile [82] and (b) a graded index profile [83].
adopted. This is because only two kinds of cores are required for the heterogeneous core arrangement in the square lattice structure. On the other hand, if we use an HCPS, at least three kinds of cores are needed for the heterogeneous core arrangement.

The square lattice structure is also beneficial in terms of the worst case crosstalk, as the number of the nearest neighboring cores is four, resulting in ΔXΔT of 6 dB. The measured attenuation and ΔAeff for LP11 mode were 0.218 dB/km and 110 μm², respectively, at 1550 nm wavelength. By using this FM-MCF, the 527-km 36-spatial-channels transmission was achieved [83]. These results indicate the high potential of FM-MCFs for further increment of SCC.

IV. CONCLUSION

In this paper, weakly-coupled MCF technology for the application of high-capacity SDM transmission has been described. Crosstalk estimation method was reviewed and three crosstalk suppression schemes, which are trench-assisted structure, heterogeneous core arrangement, and PDI technique, were explained. In addition, the relation between achievable crosstalk, SE, and SCC was presented. It was shown that the core-to-core distance should be carefully determined by considering the allowable crosstalk based on the transmission distance and the modulation format to be used, while the number of cores as well as the core arrangement have to be determined by taking the ΔXΔT and the required CT under the limitation of the CD related to their mechanical reliability. It was also shown that the combination of core multiplexing and mode multiplexing by using FM-MCFs is a very promising approach to realize high SCC over 100. In FM-MCFs, not only crosstalk suppression for the higher-order modes but also the control of DMD in each core during the fabrication are challenging issues as increasing the number of modes. Further researches on design optimization of MCFs and development of related devices such as FI/O and amplifier are highly expected.

REFERENCES


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