

# Crosstalk analysis in homogeneous multi-core two-mode fiber under bent condition

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**Abstract:** We analyze the inter-core crosstalk in homogeneous multi-core two-mode fibers (MC-TMFs) under bent condition by using the coupled-mode equations. In particular, we investigate the effects of the intra-core mode coupling on the inter-core crosstalk for two different types of MC-TMFs at various bending radii. The results show that the inter-core homo-mode crosstalk of  $LP_{11}$  mode is dominant under the gentle fiber bending condition due to its large effective area. However, as the fiber bending becomes tight, the intra-core mode coupling is significantly enhanced and consequently makes all the inter-core crosstalk levels comparable to each other regardless of the mode. A similar tendency is observed at a reduced bending radius when the difference in the propagation constants between modes is large and core pitch is small.

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## References and links

1. T. Morioka, Y. Awaji, R. Ryf, P. J. Winzer, D. Richardson, and F. Poletti, "Enhancing optical communications with brand new fibers," *IEEE Commun. Mag.* **50**(2), S31–S42 (2012).
2. R. Ryf, N. K. Fontaine, H. Chen, B. Guan, S. Randel, N. Sauer, S.J.B. Yoo, A. Koonen, R. Delbue, P. Pupalaiakis, A. Sureka, R. Shubochkin, Y. Sun, and R. Lingle, "23 Tbit/s transmission over 17-km conventional 50  $\mu$ m graded-index multimode fiber," *OFC/NFOEC 2014*, paper Th5B.1.
3. C. Xia, R. Amezcua-Correa, N. Bai, E. Antonio-Lopez, D. M. Arrijoja, A. Schulzgen, M. Richardson, J. Linares, C. Montero, E. Mateo, X. Zhou, and G. Li, "Hole-assisted few-mode multicore fiber for high-density space-division multiplexing," *IEEE Photon. Technol. Lett.* **24**(21), 1914–1917 (2012).
4. T. Mizuno, T. Kobayashi, H. Takara, A. Sano, H. Kawakami, T. Nakagawa, Y. Miyamoto, Y. Abe, T. Goh, M. Oguma, T. Sakamoto, Y. Sasaki, I. Ishida, K. Takenaga, S. Matsuo, K. Saitoh, and T. Morioka, "12-core x 3-mode dense space division multiplexed transmission over 40 km employing multi-carrier signals with parallel MIMO equalization," *OFC/NFOEC 2014*, paper Th5B.2.
5. Y. Sasaki, K. Takenaga, N. Guan, S. Matsuo, K. Saitoh, and M. Koshiba, "Large-effective-area uncoupled few-mode multi-core fiber," *Opt. Express* **20**(26), B77–B84 (2012).
6. K. Mukasa, K. Imamura, and R. Sugizaki, "Multi-core few-mode optical fibers with large  $A_{eff}$ ," *ECOC 2012*, paper, P1.08.
7. J. Tu, K. Saitoh, K. Takenaga, and S. Matsuo, "Heterogeneous trench-assisted few-mode multi-core fiber with low differential mode delay," *Opt. Express* **22**(4), 4329–4341 (2014).
8. T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Design and fabrication of ultra-low crosstalk and low-loss multi-core fiber," *Opt. Express* **19**(17), 16576–16592 (2011).
9. J. M. Fini, B. Zhu, T. F. Taunay, and M. F. Yan, "Statistics of crosstalk in bent multicore fibers," *Opt. Express* **18**(14), 15122–15129 (2010).
10. M. Koshiba, K. Saitoh, K. Takenaga, and S. Matsuo, "Analytical expression of average power-coupling coefficients for estimating intercore crosstalk in multicore fibers," *IEEE Photon. J.* **4**(5), 1987–1995 (2012).
11. M. Koshiba, K. Saitoh, K. Takenaga, and S. Matsuo, "Multi-core fiber design and analysis: coupled-mode theory and coupled-power theory," *Opt. Express* **19**(26), B102–B111 (2011).
12. K. Ogawa, "Simplified theory of the multimode fiber coupler," *Bell Syst. Tech. J.* **56**(5), 729–745 (1977).
13. J. H. Chang, S. H. Bae, D. H. Sim, H. Kim, and Y. C. Chung, "Analysis of inter-core crosstalk in homogeneous multi-core two-mode fiber under bent condition," *OFC/NFOEC 2015*, paper W41.4.
14. W.-P. Huang, "Coupled-mode theory for optical waveguides: an overview," *J. Opt. Soc. Am. A* **11**(3), 963–983 (1994).
15. D. Marcuse, "Coupled mode theory of round optical fibers," *Bell Syst. Tech. J.* **52**(6), 817–842 (1973).

16. P. Sillard, M. Bigot-Astruc, D. Boivin, H. Maerten, and L. Provost, "Few-mode fiber for uncoupled mode-division multiplexing transmission," ECOC 2011, paper. Tu.5.LeCervin.7.
17. T. Mori, T. Sakamoto, M. Wada, T. Yamamoto, and F. Yamamoto, "Few-mode fibers supporting more than two LP modes for mode-division-multiplexed transmission with MIMO DSP," J. Lightwave Technol. **32**(14), 2468–2479 (2014).

## 1. Introduction

Recently, the space-division-multiplexing (SDM) technology has attracted a great deal of attention as a viable solution to overcome the fundamental capacity limit of the conventional single-mode fiber. Various types of multi-mode fibers (MMFs) and multi-core fibers (MCFs) have been developed for the demonstrations of this technology [1]. For the SDM system utilizing MMFs, it is necessary to compensate for the mode coupling among the spatial modes by utilizing the multiple-input multiple-output (MIMO) processing technique at the coherent receiver. However, the complexity of the MIMO processing increases drastically as the number of the supported modes is increased. For example, the number of the MIMO sub-equalizers increases in proportion to the square of the number of the supported modes [2]. The size of these sub-equalizers should also be increased with the number of the supported modes to accommodate the large temporal walk-offs between modes. Thus, it is difficult to utilize a large number of spatial modes in the MMF-based SDM system due to the increased complexity of the coherent receiver. On the other hand, there is no need to utilize the complicated MIMO processing for the SDM system utilizing uncoupled MCFs (since the core pitch of the MCF is designed to be large enough to make the inter-core crosstalk insignificant). Thus, there have been some efforts to scale up the transmission capacity of an optical fiber with a manageable implementation complexity by utilizing multi-core few-mode fibers (MC-FMFs) [3–7]. However, the spatial efficiency of the MC-FMF can be limited by the inter-core crosstalk. Thus, an accurate estimation of this crosstalk is critical for the optimization of the MC-FMF system. Recently, there have been several reports on the inter-core crosstalk of the multi-core single-mode fiber (MC-SMF) [8–11]. However, to the best of our knowledge, there has been no report yet on the inter-core crosstalk of the MC-FMF under the bent condition. In this paper, we analyze the crosstalk occurring in two different types of multi-core two-mode fibers (MC-TMFs) by using the coupled-mode equations. In particular, we identify the dependence of the inter-core crosstalk on various fiber parameters (such as the index difference and core pitch) as well as the bending radius and intra-core mode coupling. We also investigate the accumulation of the inter-core crosstalk occurring in these MC-TMFs for various transmission distances.

## 2. Simulation model for evaluating the crosstalk in MC-TMF

In MC-TMFs, there are two types of crosstalk; intra-core and inter-core crosstalk. The intra-core crosstalk is caused by the coupling between the fiber modes within each core due to the fiber imperfections such as index perturbations, bends, and twists. The inter-core crosstalk arises from the mode coupling between the neighboring cores and is composed of the hetero-mode coupling (e.g.,  $LP_{01@core A} \rightarrow LP_{11@core B}$ ) and homo-mode coupling (e.g.,  $LP_{11@core A} \rightarrow LP_{11@core B}$ ). To illustrate the inter-core mode coupling occurring in an MC-TMF, we investigate the power transfer from the  $LP_{11@core A}$  to the  $LP_{01@core A}$ ,  $LP_{01@core B}$ , and  $LP_{11@core B}$  when the  $LP_{11}$  mode is launched into core A. Figure 1 shows the relative power of each mode obtained by using the beam propagation method. The cores A and B are assumed to be identical, having the core diameter of 16.76  $\mu\text{m}$  and the index difference of 0.3%. The core pitch (i.e., the distance between the core centers) is assumed to be 25  $\mu\text{m}$ . The figure shows the optical power of each mode oscillates with three different periodicities. It is interesting to note that the coupling length between mode  $\mu$  in core A and mode  $\nu$  in core B in a multi-mode fiber coupler can be expressed as [12]

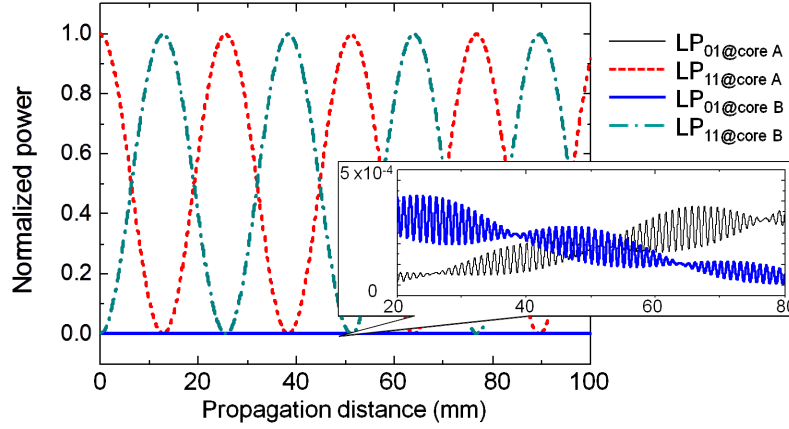


Fig. 1. The optical power of each spatial mode in the two-core two-mode fiber as a function of the propagation distance. The LP<sub>11</sub> mode is launched into the core A, and the results are normalized by the input power of LP<sub>11</sub> mode. Refer to the text for the detailed parameters of this two-core fiber.

$$L_c = \frac{2\pi}{\sqrt{4|\kappa_{(\mu)(v)}|^2 + (\beta_{\mu A} - \beta_{v B})^2}} \quad (1)$$

where  $\beta_{\mu A}$  and  $\beta_{v B}$  are the propagation constants of mode  $\mu$  in core A and mode  $v$  in core B, respectively, and  $\kappa_{(\mu)(v)}$  is the mode coupling coefficient between modes  $\mu$  and  $v$ . Although this equation is derived from two optical modes in two MMFs placed very closely with each other, it can be used to explain the oscillatory behavior of the modes in MC-TMFs. For example, this equation shows that the coupling length of the inter-core homo-mode coupling (i.e.,  $\beta_{\mu A} - \beta_{v B} = 0$ ) is longer than that of the inter-core hetero-mode coupling (since  $\beta_{\mu A} - \beta_{v B}$  is typically much larger than  $\kappa_{(\mu)(v)}$ ). Also, in the case of the inter-core homo-mode coupling, the coupling length is inversely proportional to the coupling coefficient. Thus, we attribute the oscillation with the coupling length of  $\sim 25$  mm shown in Fig. 1 to the inter-core homo-mode coupling of LP<sub>11</sub> modes. On the other hand, the oscillations with the long and extremely short coupling lengths shown in the inset of Fig. 1 are caused by the coupling between LP<sub>01</sub> modes and the inter-core hetero-mode coupling, respectively. In this simulation, the intra-core mode coupling does not exist as we assume no fiber imperfection. Thus, the oscillatory behavior of the LP<sub>01</sub> mode at core A should be attributed to the double inter-core mode coupling (e.g., LP<sub>11@core A</sub>  $\rightarrow$  LP<sub>11@core B</sub>  $\rightarrow$  LP<sub>01@core A</sub>). From this figure, we can also estimate the inter-core crosstalk level by converting some parameters to random variables. For example, when we assume that the propagation constants follow Gaussian distributions, the crosstalk level can be determined by the power coupling coefficient (PCC), which is the ratio between the maximum power conversion efficiency and the coupling length [8, 11]. Then, the PCC between LP<sub>11@core A</sub> and LP<sub>11@core B</sub> is estimated to be  $1/25$  (mm<sup>-1</sup>), whereas it is  $2.5 \times 10^{-4}/1$  (mm<sup>-1</sup>) between LP<sub>11@core A</sub> and LP<sub>01@core B</sub>. These imply that the crosstalk caused by the inter-core homo-mode coupling between LP<sub>11</sub> modes is 160 times larger than the inter-core hetero-mode crosstalk between LP<sub>01</sub> and LP<sub>11</sub> modes.

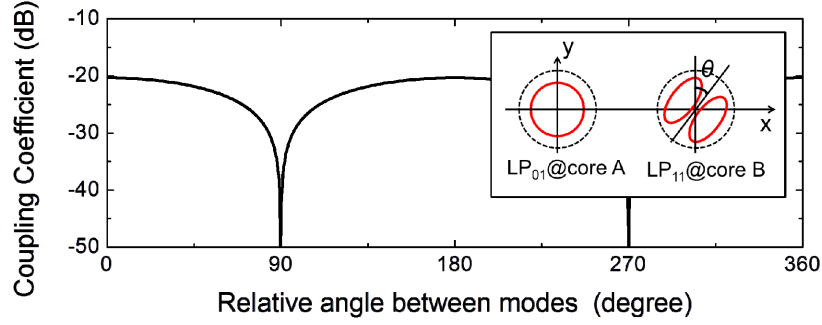


Fig. 2. Coupling coefficient between LP<sub>01</sub> and LP<sub>11</sub> modes as a function of the relative angle between the modes. The cores are assumed to have core diameters of 16.76 μm and the index differences of 0.3%. The core pitch is 55 μm. The inset shows how the relative angle  $\theta$  is defined.

The inter-core crosstalk in the presence of fiber bending can be estimated by using the coupled-mode theory [8–11]. If we assume a homogeneous 7-core TMF, which has a core at the center and six outer cores in a hexagonal layout, the electric fields in core A and B can be expressed as  $E_A = A_{01A}(z) \cdot E_{01}(x, y) + A_{11A}(z) \cdot E_{11}(x, y)$  and  $E_B = A_{01B}(z) \cdot E_{01}(x, y) + A_{11B}(z) \cdot E_{11}(x, y)$ , respectively, where  $A_{\mu m}$  is the amplitude of mode  $\mu$  in core  $m$ ,  $E_{\mu}$  is the transversal field distribution of mode  $\mu$  in undisturbed fiber, and  $z$  is the propagation distance. Then, the inter-core mode couplings in a bent MC-TMF can be described as [13]

$$\begin{pmatrix} A_{01A} \\ A_{11A} \end{pmatrix}' = -j \begin{pmatrix} \kappa_{(01)(01)} e^{j(\phi_{01A} - \phi_{01B})} & \kappa_{(01)(11)} e^{j\Delta\beta z} e^{j(\phi_{01A} - \phi_{11B})} \\ \kappa_{(11)(01)} e^{-j\Delta\beta z} e^{j(\phi_{11A} - \phi_{01B})} & \kappa_{(11)(11)} e^{j(\phi_{11A} - \phi_{11B})} \end{pmatrix} \begin{pmatrix} A_{01B} \\ A_{11B} \end{pmatrix} \quad (2)$$

$$\begin{pmatrix} A_{01B} \\ A_{11B} \end{pmatrix}' = -j \begin{pmatrix} \kappa_{(01)(01)} e^{j(\phi_{01B} - \phi_{01A})} & \kappa_{(01)(11)} e^{j\Delta\beta z} e^{j(\phi_{01B} - \phi_{11A})} \\ \kappa_{(11)(01)} e^{-j\Delta\beta z} e^{j(\phi_{11B} - \phi_{01A})} & \kappa_{(11)(11)} e^{j(\phi_{11B} - \phi_{11A})} \end{pmatrix} \begin{pmatrix} A_{01A} \\ A_{11A} \end{pmatrix} \quad (3)$$

where  $\Delta\beta$  is the difference of the propagation constants between LP<sub>01</sub> and LP<sub>11</sub> modes ( $\Delta\beta = \beta_{01} - \beta_{11}$ ). The prime on the left-hand side of this equation denotes the derivative with respect to  $z$  and  $\phi_{\mu m}$  is the phase of the field for the mode  $\mu$  in core  $m$ . It should be noted that, unlike the inter-core mode coupling between the fundamental LP<sub>01</sub> modes in MC-SMF, the mode coupling relevant to the LP<sub>11</sub> mode depends on its orientation. For example, Fig. 2 shows the mode coupling coefficient  $\kappa_{(01)(11)}$  as a function of the orientation angle of LP<sub>11</sub> mode,  $\theta$ . The coupling coefficient becomes the maximum at  $\theta = n\pi$ , where  $n$  is an integer, whereas it is zero at  $\theta = (2n + 1)\pi/2$ . We assume that the orientation angle is uniformly distributed between 0 and  $2\pi$  to take into account the random variation of  $\theta$  along the fiber and also over time. Also, in order to satisfy the power conservation,  $\kappa_{(11)(01)}$  and  $\kappa_{(01)(11)}$  are set to be identical [14]. In the bent MC-TMF, the deterministic phase of the mode  $\mu$  in core  $m$  can be expressed as  $\phi_{\mu m} = (\beta_{\mu} \Lambda / R_b \gamma) \cdot \sin(\gamma z + \theta_m)$  for the outer cores and  $\phi_{\mu m} = 0$  for the center core, where  $\Lambda$  is the core pitch,  $R_b$  is the bending radius,  $\gamma$  is the twist rate, and  $\theta_m$  is the angle between the radial direction of the bending and the line connecting the center core and core  $m$  [11].

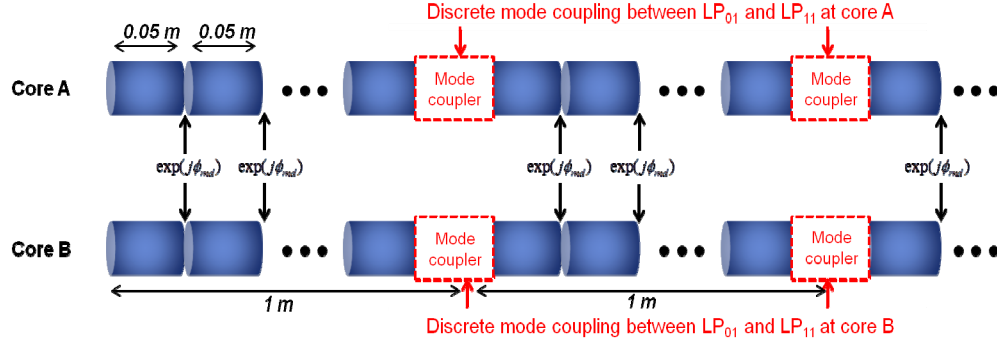


Fig. 3. Simulation model for calculating the inter-core and intra-core crosstalk in multi-core two-mode fiber.

Figure 3 shows the simulation model used to evaluate the inter-core and intra-core crosstalk. In order to emulate the random phase of the coupling between two cores, we divide the fiber into a finite number of small segments so that the random phase shift,  $\exp(j\phi_{rnd})$ , is repeatedly applied at each segment. The random phase  $\phi_{rnd}$  is assumed to be uniformly distributed between 0 and  $2\pi$ . The length of each fiber segment is set to be 0.05 meter [11]. Within each segment, we assume that the fiber modes propagate without the intra-core mode coupling. The twist rate is set to be  $20\pi$  per meter. We then include the effects of the intra-core mode coupling by inserting a mode coupler at every 1 meter of the MC-TMF link. The mode coupler is modeled as a unitary matrix,  $M$ , which can be expressed as

$$M = \begin{pmatrix} \sqrt{1-X} & \sqrt{X} \\ -\sqrt{X} & \sqrt{1-X} \end{pmatrix} \quad (4)$$

where  $X$  is the amount of the power coupling occurring in 1-meter long TMF under the bent condition [15]. To find out how often the mode coupler should be inserted in our simulation model, we calculated the inter-core crosstalk for  $LP_{01}$  mode as a function of the transmission distance while varying the distance between the mode couplers, as shown in Fig. 4. The result shows that the distance between these mode couplers should be much shorter than the propagation distance of our interest. For example, for the propagation distance of 1 meter, the inter-core crosstalk is underestimated to be  $-67$  dB when we utilize only one mode coupler (spaced at 1 meter), while it is calculated to be  $-57$  dB when we place the mode coupler at

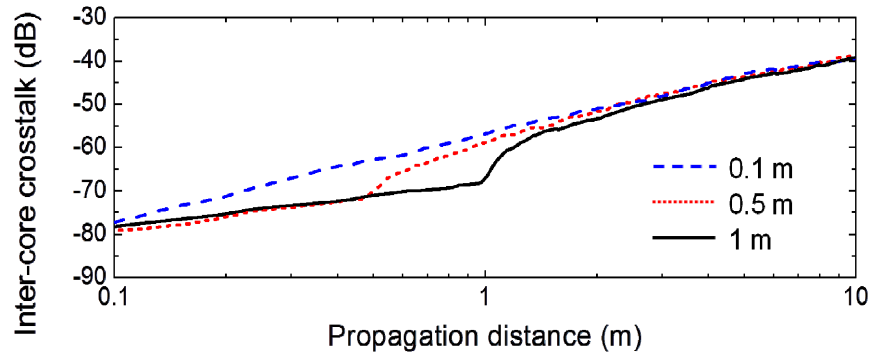


Fig. 4. Inter-core crosstalk for  $LP_{01}$  mode as a function of propagation distances for various distances between mode couplers.

every 0.1 meter. This result indicates that we need to utilize a large number of mode couplers in the link for the accurate estimation of the inter-core crosstalk. In fact, we can reduce the estimation error to be less than 1 dB by placing more than 6 mode couplers in the link regardless of the propagation distance. Thus, in this simulation, we place the mode couplers at every 1 meter. It would be sufficient for the accurate estimation of the inter-core crosstalk as long as the propagation distance is longer than 10 meters.

### 3. Dependency of the inter-core crosstalk on bending radius and intra-core mode coupling

In this analysis, we focus on the inter-core crosstalk occurring in the center core of the homogeneous 7-core step-index two-mode fiber. The inter-core crosstalk for the  $LP_\mu$  mode,  $XT_\mu$ , is defined as the ratio of the optical power coupled to the outer core and the power remained in the center core when only the  $LP_\mu$  mode was launched into the center core. We first investigate the dependence of the inter-core crosstalk on the bending radius. We consider two MC-TMFs having different geometry to investigate the impact of the fiber parameters on the crosstalk. The parameters of these MC-TMFs are listed in Table 1. It should be noted that fiber II has larger  $\Delta\beta$  and shorter core pitch than fiber I. Figure 5 shows the inter-core crosstalk calculated for each mode (i.e.,  $XT_{01}$  and  $XT_{11}$ ) with or without including the effects of the intra-core mode coupling. Due to the stochastic characteristics of the inter-core crosstalk, we repeat the calculation 100 times and obtain their averages. The transmission distance is set to be 100 meters. We first set  $X$  to be zero to isolate the inter-core crosstalk from the intra-core mode coupling. In the absence of the intra-core mode coupling,  $XT_{11}$  is much larger than  $XT_{01}$  under the gentle bending condition. This is because the  $LP_{11}$  mode has a larger effective area than the  $LP_{01}$  mode and the inter-core homo-mode coupling becomes dominant over the inter-core hetero-mode coupling due to the large  $\Delta\beta$  between the two modes [5]. Under the tight bending condition, however, both inter-core crosstalk levels ( $XT_{01}$  and  $XT_{11}$ ) increase drastically and exhibit peaks at the bending radii of  $\sim 130$  and  $\sim 50$  mm for fiber I and II, respectively. This result is attributed to the phase matching between the  $LP_{01}$  and  $LP_{11}$  modes in different cores (i.e., the  $LP_{01@core A}$  and  $LP_{11@core B}$  modes and the  $LP_{11@core A}$  and  $LP_{01@core B}$  modes). In a homogeneous MC-TMF, due to the large difference of the propagation constants between  $LP_{01}$  and  $LP_{11}$  modes, the inter-core hetero-mode coupling is normally very small. However, the bending-induced changes in  $\Delta\beta$  compensate for this difference of the propagation constants, which, in turn, increase the hetero-mode coupling drastically. A similar bending-induced phase matching was also observed in the heterogeneous MC-SMFs [8–10]. For example, it has been reported that the phase matching occurs at the bending radius of  $R_p = \Lambda \cdot \beta_{01} / \Delta\beta$  in heterogeneous MC-SMFs, where  $\beta_{01}$  is  $2\pi n_{eff,01} / \lambda$  [8]. From this equation, we obtain the bending radii of 131 and 51 mm for fibers I and II, respectively, which agree very well with our simulation results shown in Figs. 5(a) and

**Table 1. Fiber parameters at the wavelength of 1550 nm**

Parameter	Symbol	Fiber I	Fiber II
Propagation constant difference	$\Delta\beta$	$3133.5 \text{ m}^{-1}$	$6275.1 \text{ m}^{-1}$
Effective index of $LP_{01}$ mode	$n_{eff,01}$	1.4456	1.4473
Effective index of $LP_{11}$ mode	$n_{eff,11}$	1.4449	1.4457
Core diameter	$d$	$23.70 \text{ }\mu\text{m}$	$16.76 \text{ }\mu\text{m}$
Index difference	$\Delta$	0.15%	0.30%
Normalized frequency	$V$	3.8	3.8
Core pitch	$\Lambda$	$70 \text{ }\mu\text{m}$	$55 \text{ }\mu\text{m}$

Fig. 5(b), respectively. We note that the peak bending radius ( $R_p$ ) is linearly proportional to the core pitch as well as  $1/\Delta\beta$ . Thus,  $R_p$  should be reduced for the densely-spaced MC-TMF with a large  $\Delta\beta$ . On the other hand, the peak would shift to a larger bending radius as the number of supported modes increases in the MC-FMF due to its small  $\Delta\beta$  and large core pitch.

To include the effects of the intra-core mode coupling, we calculate the coupling coefficient of the discrete mode coupler,  $X$ , for each bending radius [15]. Figure 5 shows that, compared to the results obtained without considering the intra-core mode coupling,  $XT_{01}$  is increased significantly as the bending radius approaches  $R_p$ . This is because fiber bending induces the intra-core mode coupling from  $LP_{01}$  to  $LP_{11}$ , and a portion of the coupled  $LP_{11}$  mode is then transferred to the other cores by the strong inter-core mode coupling between  $LP_{11}$  modes. The efficiency of the intra-core mode coupling from  $LP_{11}$  to  $LP_{01}$  is also greatly enhanced at the bending radii near  $R_p$ . This strong intra-core mode coupling between  $LP_{01}$  and  $LP_{11}$  modes leads to the reduction of  $XT_{11}$  since a significant portion of  $LP_{11}$  mode is coupled into  $LP_{01}$  mode (within the same core) before it is coupled to other cores. Eventually, the optical power of  $LP_{11}$  mode would be equal to that of  $LP_{01}$  mode under the strong intra-core mode coupling. As a result, both the inter-core crosstalk levels,  $XT_{01}$  and  $XT_{11}$ , would become identical. The fiber design is also critical to the efficiency of the intra-core mode coupling. For example, fiber II is more robust to the intra-core mode coupling than fiber I due

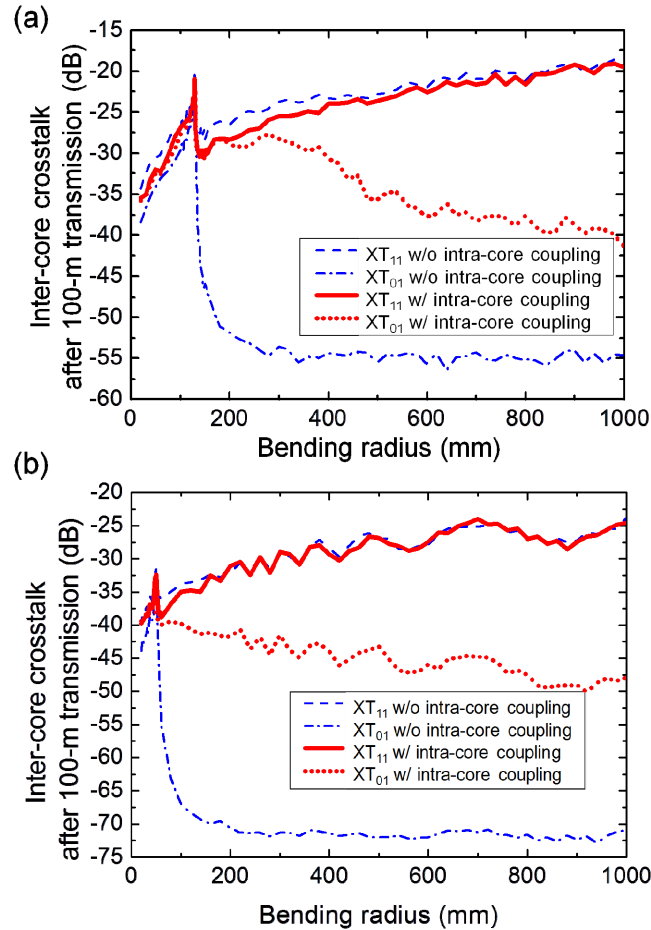


Fig. 5. Inter-core crosstalk as a function of bending radius for (a) fiber I and (b) fiber II.

to its larger  $\Delta\beta$ . Consequently, for fiber II, a considerable difference between  $XT_{01}$  and  $XT_{11}$  is observed even when the bending radius is as small as 200 mm, as shown in Fig. 5(b). However, at the same bending radius,  $XT_{01}$  and  $XT_{11}$  are almost identical for fiber I. Thus, in order to maintain  $XT_{01}$  to be small, it is desirable to utilize the MC-TMF with a large  $\Delta\beta$ .

We also evaluate the inter-core crosstalk accumulated in a 10-km long transmission link. Figure 6 shows the inter-core crosstalk estimated as a function of the transmission distance for three bending radii for fiber I. When we exclude the effects of the intra-core mode coupling, the inter-core crosstalk for both modes is increased linearly with the transmission distance regardless of the bending radius. This is similar to the case of MC-SMFs [8]. However, when we include the intra-core mode coupling,  $XT_{01}$  is increased rapidly with the transmission distance and converged to  $XT_{11}$ . This is because the intra-core mode coupling serves to equalize the optical powers of two modes and eventually make these two inter-core crosstalk levels to be equal, as described above. The results also show that  $XT_{01}$  could be negligible compared to  $XT_{11}$  in an extremely short transmission system unless the fiber is bent sharply (i.e.,  $R_b < R_p$ ). However, both the crosstalk levels become identical in a long transmission system (i.e., the transmission distance is longer than a few kilometers) even under the gentle bending condition. A similar tendency of the inter-core crosstalk is observed for fiber II.

By comparing the results of fibers I and II, we can predict the crosstalk behavior of an MC-FMF in which each core supports more than two spatial modes. In general, the difference in the propagation constants between modes ( $\Delta\beta$ ) tends to be reduced as the number of modes increases [16, 17]. As a result, the intra-core mode coupling and  $R_p$  are increased with the number of modes. The increased number of modes in each core can also create multiple peak bending radii, when the inter-core crosstalk is plotted as a function of the bending radius (e.g., Fig. 5). The number of the peak bending radii (i.e.,  $R_p$ ) could be determined by  ${}_N C_2$ , where  $N$  is the number of modes in each core. For these reasons, in the case of MC-FMF (i.e., each core supports more than two modes), the crosstalk level of each mode would become identical even if the transmission distance is not long and/or the fiber is bent slightly.

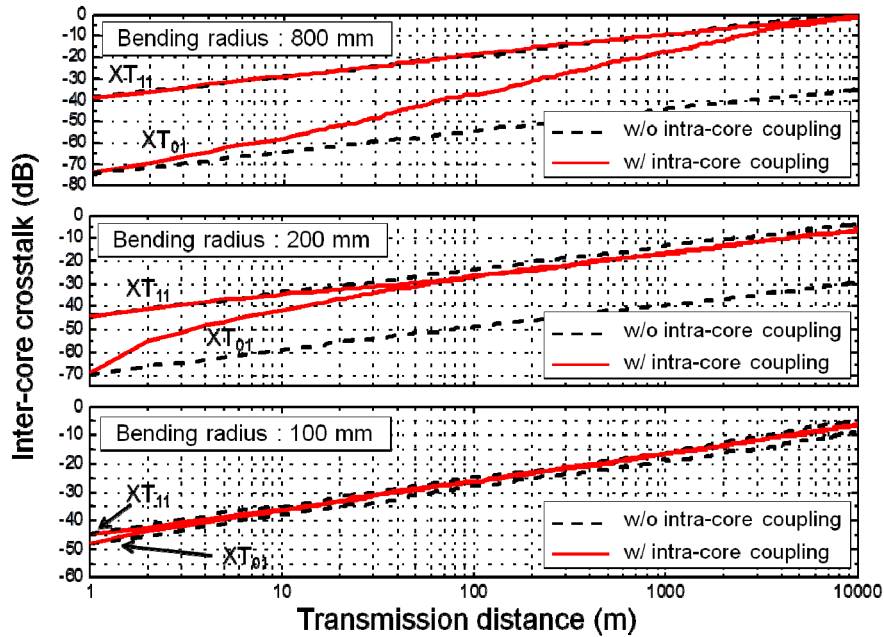


Fig. 6. Inter-core crosstalk of fiber I as a function of the transmission distance for various bending radii.



#### 4. Summary

We have evaluated the inter-core crosstalk in the homogeneous MC-TMFs under bent condition. For this purpose, we have analyzed the mode coupling occurring between the cores and within each core by solving the coupled-mode equations for successive short segments of MC-TMFs. The results show that, when the bending radius is much larger than the peak bending radius ( $R_p$ ), the inter-core homo-mode coupling of the  $LP_{11}$  is dominant. On the other hand, when the bending radius is close to  $R_p$ , the inter-core hetero-mode coupling can be drastically increased due to the phase matching between the modes. The results also show that the fiber bending tends to make the inter-core crosstalk uniform across the modes due to the strong intra-core mode coupling (caused by bending). This tendency is reinforced when we increase the transmission distance or employ the MC-TMFs with a small  $\Delta\beta$ .

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