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Large-effective-area uncoupled few-mode multi-core fiber

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Abstract: Characteristics of few-mode multi-core fiber (FM-MCF) were numerically analyzed and experimentally confirmed. The cores of FM-MCF were designed to support transmission of LP_{01} and LP_{11} modes from the point of bending loss of LP_{11} and LP_{21} modes. Inter-core crosstalk between LP_{11} mode was calculated to determine core pitch of fibers. It was confirmed that the fabricated fibers was two-mode transmission over C-band and L-band with the effective area of LP_{01} mode of about 110 μm^2 at 1550 nm. The crosstalk of the fibers was estimated to be smaller than −30 dB at 1550 nm after 100-km propagation. The crosstalk dependence on wavelength was also measured and matched well with the simulated results.

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OCIS codes: (060.2270) Fiber characterization; (060.2280) Fiber design and fabrication.

References and links

1. T. Morioka, "New generation optical infrastructure technologies: "EXAT initiative" towards 2020 and beyond," *in Proceedings of 15th OptoElectronics and Communications Conference* (Institute of Electrical and Electronics Engineers, 2009), paper FT4.
2. S. Matsuo, K. Takenaga, Y. Arakawa, Y. Sasaki, S. Taniagwa, K. Saitoh, and M. Koshiba, "Large-effective-area ten-core fiber with cladding diameter of about 200 μm," Opt. Lett. **36**(23), 4626–4628 (2011).
3. J. Sakaguchi, B. J. Puttnam, W. Klaus, Y. Awaji, N. Wada, A. Kanno, T. Kawanishi, K. Imamura, H. Inaba, K. Mukasa, R. Sugizaki, T. Kobayashi, and M. Watanabe, "19-core fiber transmission of 19x100x172-Gb/s SDM-WDM-PDM-QPSK signals at 305Tb/s," in *Optical Fiber Communication Conference*, OSA Technical Digest (CD) (Optical Society of America, 2012), paper PDP5C.1.
4. M. Salsi, C. Koebele, G. Charlet, and S. Bigo, "Mode division multiplexed transmission with a weakly coupled few-mode fiber," in *Optical Fiber Communication Conference*, OSA Technical Digest (CD) (Optical Society of America, 2012), paper OTu2C.5.
5. K. Takenaga, Y. Sasaki, N. Guan, S. Matsuo, M. Kasahara, K. Saitoh, and M. Koshiba, "A large-effective-area few-mode multi-core fiber," IEEE Photon. Technol. Lett. **24**(21), 1941–1944 (2012).
6. K. Saitoh and M. Koshiba, "Full-vectorial imaginary-distance beam propagation method based on a finite element scheme: Application to photonic crystal fibers," IEEE J. Quantum Electron. **38**(7), 927–933 (2002).
7. R. Maruyama, N. Kuwaki, S. Matsuo, K. Sato, and M. Ohashi, "Mode dispersion compensating optical transmission line composed of two-mode optical fibers," in *Optical Fiber Communication Conference*, OSA Technical Digest (CD) (Optical Society of America, 2012), paper JW2A.3.
8. K. Takenaga, Y. Arakawa, S. Tanigawa, N. Guan, S. Matsuo, K. Saitoh, and M. Koshiba, "An investigation on crosstalk in multicore fibers by introducing random fluctuation along longitudinal direction," IEICE Trans. Commun. **E94-B**(2), 409–416 (2011).
9. T. Hayashi, T. Nagashima, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Crosstalk variation of multi-core fiber due to fiber bend," in *Proceedings of 36th European Conference and Exhibition on Optical Communication* (Institute of Electrical and Electronics Engineers, 2010), paper We.8.F.6.

1. Introduction

Space division multiplexing (SDM) is expected as a new advanced technology that overcomes the capacity limit of the current optical communication systems [1]. The SDM is realized by multi-core fiber (MCF) and few-mode fiber (FMF). To improve space multiplicity, 10-core fiber with large effective area (A_{eff}) [2], 19-core fiber with small A_{eff} [3], and five-mode fiber [4] have been proposed. However, there are limits in improvement of spacial multiplicity only by using those teqnichues each other from the perspective of inter-

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core crosstalk or inter-mode crosstalk. The combination of MCF and FMF will improve the multiplicity furthermore.

In this paper, we present the characteristics of few-mode multi-core fiber (FM-MCF) that suports LP_{01} and LP_{11} modes over C-band and L-band. The fabricated fibers based on simulations realized the A_{eff} of LP_{01} mode which is about 110 μm^2 at 1550 nm, propagation of both LP_{01} and LP_{11} modes over the bands, and 100-km inter-core crosstalk of smaller than −30 dB at 1550 nm. Finally the crosstalk dependence on wavelength was measured and compared with simulated results.

2. FM-MCF design for two-mode transmission

It is effective to enlarge A_{eff} in order to suppress the non-linearity. Figure 1 shows the calculated results of A_{eff} of LP_{01} and LP_{11} modes at 1550 nm as functions of relative refractive index difference Δ and core radius a [5]. The full-vector finite-element method was used for the calculation [6]. The lower side of a black line is where the bending loss of LP_{21} mode is larger than 1 dB/m at 1530 nm and a bending radius of 140 mm. The upper side of a white line is where the bending loss of LP_{11} mode is smaller than 0.5 dB/100 turn at 1625 nm and a bending radius of 30 mm. The areas which satisfy both conditions support LP_{01} and LP_{11} modes over C-band and L-band and realize the A_{eff} of both modes which is larger than 100 μm^2 at 1550 nm.

The small inter-core crosstalk of MCFs is preferable to reduce the load of signal processing. In the case of FM-MCF, we should concern crosstalk related to higher order mode such as LP_{11}-LP_{11} inter-core crosstalk ($XT_{11\text{-}11}$) and LP_{01}-LP_{11} inter-core crosstalk ($XT_{01\text{-}11}$) in addition to LP_{01}-LP_{01} inter-core crosstalk ($XT_{01\text{-}01}$) that is only crosstalk for a single-mode MCF. Figure 2 shows the simulated 100-km inter-core crosstalk at 1550 nm among modes as a function of core pitch, assuming a = 6.47 μm and Δ = 0.45% [5]. The core supports two-mode propagation as shown in Fig. 1. The 1550-nm A_{eff} of LP_{01} and LP_{11} modes would be 110 μm^2 and 170 μm^2, respectively. The $XT_{11\text{-}11}$ and the $XT_{01\text{-}11}$ depend on the angle of LP_{11} mode of adjacent cores because LP_{11} mode is composed from two spatial degenerated modes and shows asymmetry field distribution. We define LP_{11} mode related crosstalk such as $XT_{11\text{-}11}$ as the worst crosstalk over various angles. A red line, a green line and a blue line indicate $XT_{01\text{-}01}$, $XT_{01\text{-}11}$ and $XT_{11\text{-}11}$, respectively. The worst is $XT_{11\text{-}11}$, because the power of LP_{11} mode distributes more extensively than that of LP_{01} mode. We can realize 100-km $XT_{11\text{-}11}$ smaller than −30 dB for a core pitch of larger than 52 μm.

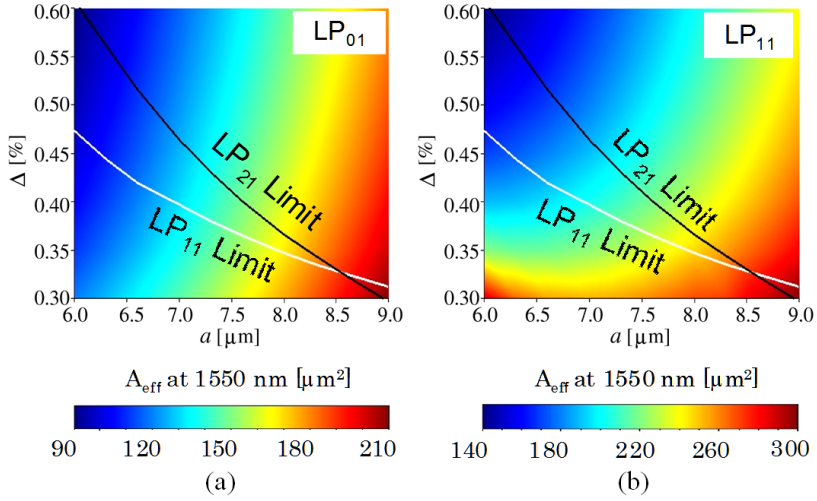

Fig. 1. Structural parameter dependence of A_{eff} of (a) LP_{01} mode and (b) LP_{11} mode.

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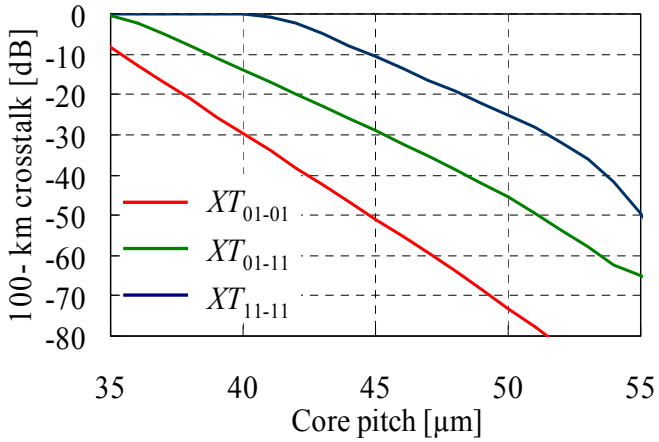

Fig. 2. Simulated inter-core 100-km crosstalk as a function of core pitch assuming a = 6.47 μm and Δ = 0.45%.

3. Fabricated fiber

We have fabricated three kinds of four-core FM-MCF (Fiber A, B and C) with stack and draw method. The core pitch of Fiber A was scaled to be 52 μm for $XT_{11\text{-}11}$ at 1550 nm to be smaller than −30 dB. And the core pitch of Fiber B was scaled to be 44 μm for $XT_{11\text{-}11}$ at 1550 nm to be about −10 dB. Fiber A, Fiber B and Fiber C had almost the same profile. A_{eff} of Fiber C was designed to be about 120 μm^2. Figure 3 shows a cross sectional view of Fiber A. Table 1 and Table 2 summarize the structural parameters and optical properties of LP_{01} mode of fabricated fibers, respectively. The core pitch of fabricated Fiber A and Fiber B, and A_{eff} of Fiber C were as we had designed. The near field pattern (NFP) was measured to confirm two mode transmissions directly. Figure 4(a) is the NFP of Fiber B at 1550 nm, which shows the propagating mode was mainly LP_{11} mode. By adding bends of 20 turns whose diameter was 10 mm, the NFP has changed to Fig. 4(b), which shows the propagating mode was mainly LP_{01} mode. Those results shows both LP_{11} and LP_{01} modes are propagated at 1550 nm. We also measured cable cutoff wavelength of LP_{11} mode and next higher order LP_{21} mode. The definition of cable cutoff wavelength of LP_{11} mode was applied to that of LP_{21} mode. The cutoff wavelength of LP_{21} mode was smaller than 1530 nm and that of LP_{11} mode was larger than 2000 nm. Those results indicate that Fiber A, Fiber B and Fiber C realized LP_{01} and LP_{11} mode operation over C-band and L-band as we had designed. The differential mode group delay (DMGD) between LP_{01} mode and LP_{11} mode, which was measured with OFDR [7], was about 3000 ps/km. Intra-core mode coupling between LP_{01} and LP_{11} modes will be fully suppressed.

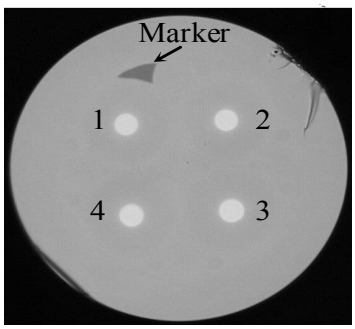

Fig. 3. Crosssection of the Fiber A.

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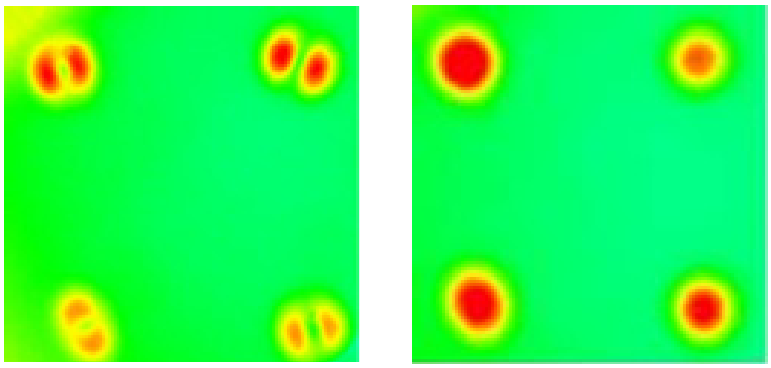
Table 1. Structural parameters of fabricated fibers

Item	Unit	Fiber A	Fiber B	Fiber C
Core pitch	μm	52.3	44.1	47.0
Cladding diameter	μm	175.9	150.5	160.0
a	μm	6.47	6.47	6.89
Δ	%	0.45	0.45	0.45

Table 2. Measurement results of LP_{01} mode

Item	Wavelength	Unit	Fiber A	Fiber B	Fiber C
MFD	1550 nm	μm	11.4	11.2	11.7
	1625 nm	μm	11.6	11.4	11.9
A_{eff}	1550 nm	μm^2	113.7	109.2	119.7
	1625 nm	μm^2	116.9	111.3	122.9
Attenuation	1550 nm	dB/km	0.231	0.229	0.217
	1625 nm	dB/km	0.238	0.236	0.223
Bending Loss (R = 5 mm)	1550 nm	dB/m	0.26	0.64	0.39
	1625 nm	dB/m	0.50	1.2	0.91
Chromatic Dispersion	1550nm	ps/nm/km	20.9	20.7	20.9
Dispersion Slope	1550 nm	$ps/nm^2/km$	0.063	0.063	0.063
PMD	1550nm band	ps/√km	0.075	0.073	0.141



(a) (b)

Fig. 4. The NFP at 1550 nm of Fiber B (a) without bends and (b) with bends.

4. Measurement of inter-core crosstalk

4.1 Measuring higher mode crosstalk

Figure 5 shows a setup for $XT_{11\text{-}11}$ measurement. We reconsidered the measurement system which we use to measure crosstalk in the case of single mode MCF. A single-mode fiber (SMF) connected to light source was offset spliced to a core of a FM-MCF to excite both LP_{01} mode and LP_{11} mode. Output power from cores on another end face was measured with a two-mode fiber (TMF) which has almost the same profile as the FM-MCF.

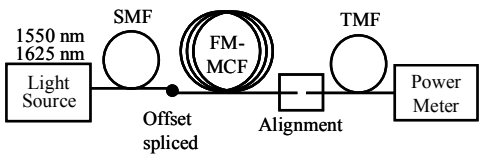


Fig. 5. Measurement system of higher mode crosstalk.

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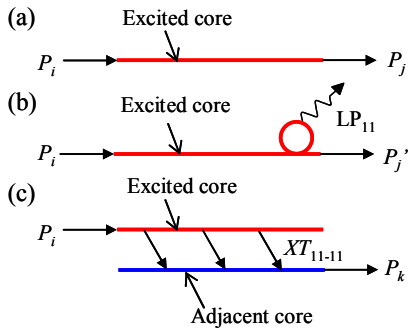

Fig. 6. Measurement procedure of $XT_{11\text{-}11}$.

Figure 6 explains the measurement procedure of $XT_{11\text{-}11}$. At first, we measure P_j which is an output power of an offset excited core (core j) without bend as shown in Fig. 6(a). The P_j is the sum of the power of LP_{01} and LP_{11} modes: $P_j = P_{j\text{-}LP01} + P_{j\text{-}LP11}$. Then, P_j' is measured with bends of 20 turns whose diameter was 10 mm to eliminate LP_{11} mode as shown in Fig. 6(b): $P_j' = P_{j\text{-}LP01}$. The difference of the power ($P_j - P_j'$) indicates $P_{j\text{-}LP11}$. Finally, the output power of core k P_k, which core is not the excited core, is measured without bend condition as shown in Fig. 6(c). The most of P_k is comprised of the power of LP_{11} mode because the crosstalk between few-mode cores is dominated by LP_{11}-LP_{11} crosstalk as shown in Fig. 2: $P_k = P_{k\text{-}LP11}$. Accordingly, we obtain:

$$\begin{aligned} XT_{11-11} &= 10\log(P_{k-LP11} / P_{j-LP11}) \\ &= 10\log(P_k / (P_j - P_j')). \end{aligned} \quad (1)$$

4.2 Results of measured crosstalk and comparison with simulated results

Figure 7 shows results of measured $XT_{11\text{-}11}$ of Fiber A, Fiber B and Fiber C, respectively. The lengths of Fiber A, Fiber B and Fiber C were 3709 m, 2730 m and 4403 m, respectively. The fibers were wound on spools with a diameter of 210 mm. The horizontal axis denotes the excited core number and the graph legends denote the measured core number as shown in Fig. 3. The left side is measured crosstalk at 1550 nm and the right side is at 1625 nm. In the case of Fiber A, the crosstalk of the cores that located at the diagonal positions from the excited cores were about −80 dB, which were the lower limit of the measurement setup. On the other hand, in the case of Fiber B and Fiber C, crosstalk was detected even for the diagonal cores. The direct crosstalk between the diagonal cores is estimated to be very small compared to the measured crosstalk because of the large diagonal core pitch of 62 μm. The measured crosstalk of the diagonal cores may originate from the repeat of the crosstalk between adjacent cores.

Figure 8 shows the 100-km inter-core crosstalk estimated from the measured crosstalk with the coupled-power theory [8] and simulated $XT_{11\text{-}11}$ for comparison as a function of core pitch. Lines are simulated results. Deep blue and red lines correspond to Fiber A and Fiber B. The pale blue and red lines correspond to Fiber C. The parameters used in the simulations are also shown. The symbols indicate the averaged crosstalk and the error bars indicate the maximum and the minimum values. The blue ones are at 1550 nm and red ones are at 1625 nm. In the case of Fiber B and Fiber C, estimations match well with simulated results. In the case of Fiber A, there were discrepancies between estimations and simulated results. We think there are two reasons. The first is the simulations were based on the worst case where the overlap of fields of LP_{11} mode between adjacent cores gets to be maximum. The second is these simulations did not take into account of crosstalk dependence on bending diameter [9]. Although, the averaged 100-km crosstalk of Fiber A was −42 dB at 1550 nm and −32 dB at 1625 nm, which means Fiber A realized 100-km crosstalk of smaller than −30 dB over C-band and L-band as we had expected.

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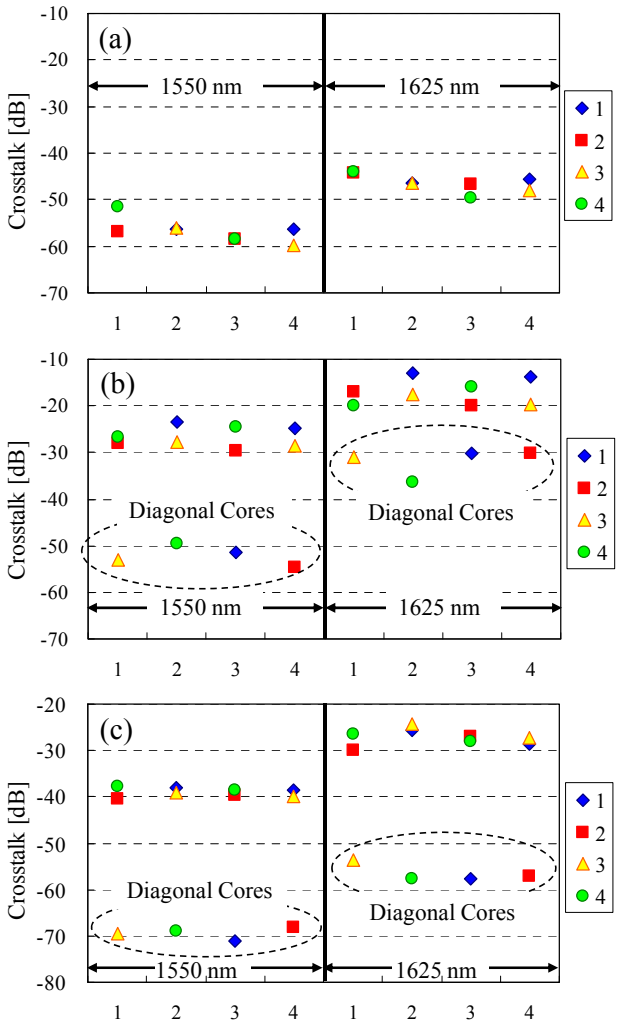
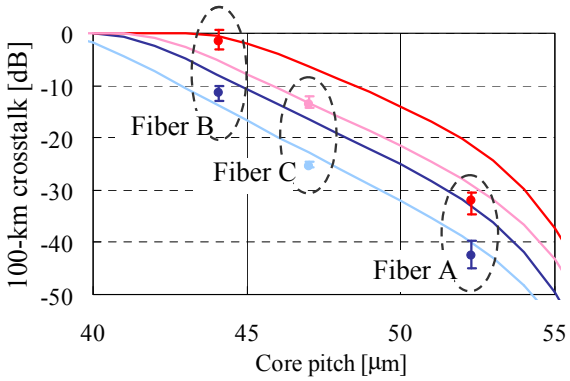


Fig. 7. Results of measured $XT_{11\text{-}11}$ of (a) Fiber A, (b) Fiber B and (c) Fiber C.



Δ [%]	a [μm]	A_{eff} at 1550 nm [μm^2]	Wavelength	
			1550 nm	1625 nm
0.45	6.47	110		
0.45	6.89	120		

Fig. 8. The comparison of 100-km crosstalk estimation from measured results and simulation results as a function of core pitch.

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4.3 Wavelength dependence of crosstalk

Figure 9(a) and 9(b) shows the wavelength dependence of crosstalk from core 1 to core 2 and core 1 to core 4 of Fiber B. We measured the wavelength dependence, which is denoted as a black line in Fig. 9, by using supercontinuum wideband light source and spectrum analyzer as shown in Fig. 10. The fiber length was 22 m and a bending diameter was 280 mm. In Fig. 9, solid symbols indicate the estimated 22-m crosstalk from measured crosstalk, which is already shown in Fig. 7(b), with the conventional measurement setup shown in Fig. 5. A blue line and a red line indicate simulated results of $XT_{11\text{-}11}$ and $XT_{01\text{-}01}$ as a function of wavelength. Simulated inter-core crosstalk is dominated by $XT_{11\text{-}11}$ over the wavelength from LP_{21} cutoff wavelength of about 1530 nm to LP_{11} cutoff wavelength of about 2000 nm because $XT_{11\text{-}11}$ is much larger than $XT_{01\text{-}01}$ by 40 dB. In this area, the measured wavelength dependence of crosstalk matched with the simulated wavelength dependence of $XT_{11\text{-}11}$. The measured crosstalk gradually converged to the simulated $XT_{01\text{-}01}$ over the wavelength longer than LP_{11} cutoff wavelength of about 2000 nm. The change of the measured crosstalk around 1400 nm originates from the crosstalk that relates to the next higher modes such as LP_{21} mode. The results indicate that FM-MCF should be designed with the careful consideration of crosstalk of higher-modes.

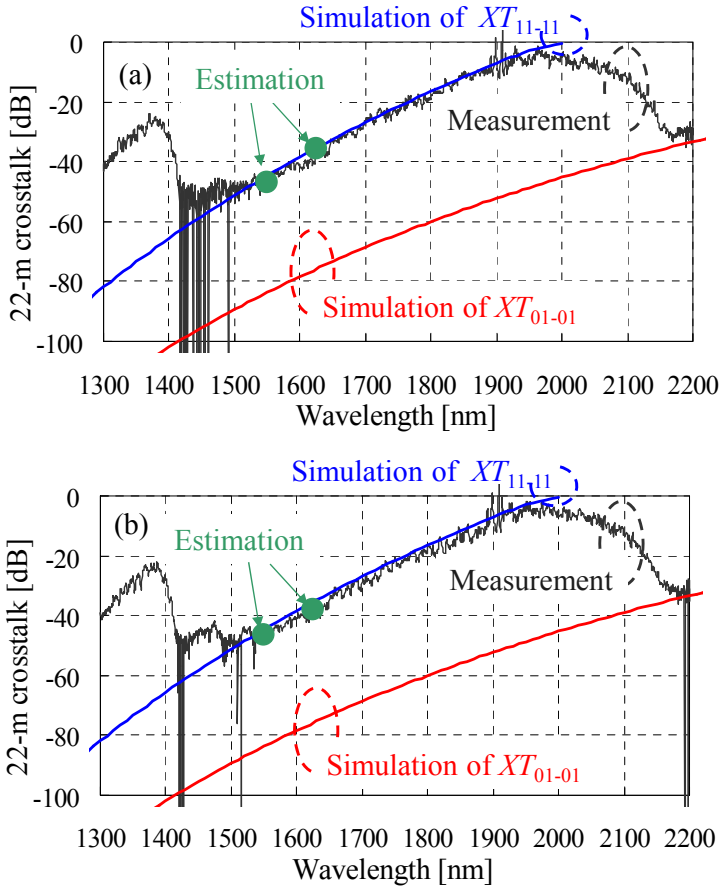

Fig. 9. Wavelength dependence of inter-core crosstalk (a) from core 1 to core 2 and (b) from core 1 to core 4.

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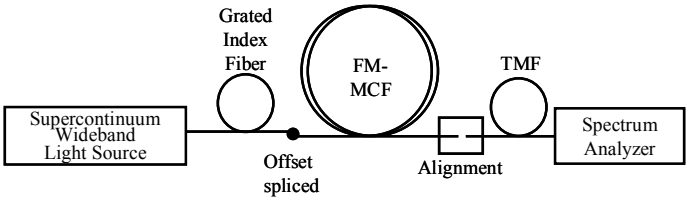

Fig. 10. Measurement setup for measuring wavelength dependence of inter-core crosstalk.

5. Conclusion

We have designed and fabricated few-mode multi-core fibers which support both LP_{01} and LP_{11} modes over C-band and L-band. The fibers had the A_{eff} of LP_{01} mode of about 110 μm^2 at 1550 nm. Inter-core crosstalk characteristics of the fibers were numerically analyzed. Large-effective-area uncoupled few-mode multi-core fiber whose inter-core 100-km crosstalk is smaller than −30 dB at 1550 nm was realized.

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