

Characterization of crosstalk in ultra-low-crosstalk multi-core fiber

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Abstract—We describe a newly-developed method to measure inter-core crosstalk of single-mode multi-core fiber (MCF) statistically, and characteristics of the crosstalk of a previously fabricated MCF. To measure the crosstalk lower than -60 dB, we suppressed power floor of the measurement system by employing trench-assisted fiber as launching and receiving fibers. We measured statistical crosstalk distributions by utilizing wavelength dependence of the crosstalk, and the mean crosstalk between the neighboring cores was observed to be about -70 dB after 17.4-km propagation at 1625 nm. The measurement results were in good agreement with the previously proposed model. Based on the measurement results and the model, the crosstalk after 10000-km propagation was estimated to be less than -30 dB. We also confirmed that the crosstalk was varied stochastically depending on polarization state, and on mechanical shock and stress on the MCF.

Index Terms—Optical crosstalk, Optical fiber communication, Optical fiber testing, Optical fibers, Space division multiplexing.

I. INTRODUCTION

DEMAND for transmission capacity is increasing exponentially, and rapidly approaching its fundamental limit [1]. Spatial division multiplexing with multi-core fiber (MCF) is one of the candidate technologies to cope with the increasing traffic [2]. In the last few years, to transmit signals independently on each core, suppression of inter-core crosstalk has been a primary concern in MCF research for high-capacity long-distance transmissions [3]–[10], after the proposal of all-solid heterogeneous MCFs utilizing the phase mismatch between the fiber cores for reducing the crosstalk [3]. The measured crosstalk in fabricated heterogeneous MCF showed discrepancies in calculations based on conventional coupled-mode equations [4]. The crosstalk and its dependence on the fiber length were calculated using the coupled-power theory by assuming random fluctuations on the fiber structure along the longitudinal direction [5].

Recently, theoretical [6], [7] and experimental [7] reports showed that crosstalk significantly varies on the basis of the

bending radius of the MCF and is a stochastic value. Calculations based on the coupled-mode theory considering fiber bend are in good agreement with the experimental measurements [7]. We designed and fabricated an ultra-low-crosstalk homogeneous MCF by utilizing the fiber bend and employing trench-assisted cores based on our proposed model for longitudinal evolution of bend-affected crosstalk [8], and characterized the crosstalk of the MCF statistically [9]. We have already described details of the proposed model [10], but not described the details of the crosstalk characterization yet.

This paper reports methods for measuring the crosstalk statistically and crosstalk characteristics of the fabricated MCF in [8]–[10]. We investigated and eliminated the cause of measurement floor (lower limit) of crosstalk measurement system for measuring ultra-low crosstalk. We developed a novel measurement method that can obtain mean and shape of the statistical crosstalk distribution by utilizing wavelength dependence of the crosstalk. By using the developed measurement method, we confirmed that the crosstalk of the MCF was extremely low, and that the statistical distribution of the crosstalk was in good agreement with the theoretical estimation described in [10]. We also investigated the effect of fiber splice on the crosstalk to evaluate its impact in actual deployment of the MCF, and no significant crosstalk increase caused by misalignment of cores was observed. Stochastic variations of the crosstalk were observed depending on polarization state, and on mechanical shock and stress on the MCF

II. SUPPRESSION OF THE CROSSTALK MEASUREMENT FLOOR

A MCF evaluated in this paper was a homogeneous seven-core MCF that was made with trench-assisted pure-silica cores [8]–[10]. The core pitch, the cladding diameter, and the coating diameter of the MCF were 45 μm , 150 μm , and 256 μm , respectively. A cross section and optical properties of the MCF are shown in Fig. 1 and Table I, respectively. Attenuation of each core was measured to be 0.175–0.181 dB/km at $\lambda = 1550$ nm and 0.192–0.202 dB/km at $\lambda = 1625$ nm. Cable cutoff wavelength (λ_{cc}) of the each core was measured to be 1483–1509 nm. Mode field diameter (MFD), effective area (A_{eff}), chromatic dispersion (CD), dispersion slope (D. Slope) at $\lambda = 1550$ nm were measured to be 9.72–9.88 μm , 78.2–81.3 μm^2 , 22.1–22.2 ps/nm/km, 0.062 ps/nm²/km, respectively.

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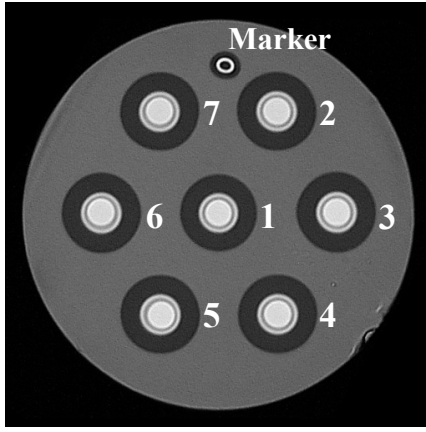


Fig. 1. Cross section of the evaluated MCF [8].

TABLE I
OPTICAL PROPERTIES OF THE EACH CORE OF THE EVALUATED MCF

	Attenuation (dB/km)	λ_{cc} (nm)	MFD (μm)	A_{eff} (μm^2)	CD (ps/nm/km)	D. Slope (ps/nm ² /km)
λ [nm]	1550	1625	1550	1550	1550	1550
Core 1	0.176	0.196	1509	9.83	80.2	22.2
Core 2	0.179	0.197	1500	9.76	80.2	22.2
Core 3	0.181	0.202	1504	9.88	81.3	22.2
Core 4	0.177	0.199	1498	9.85	80.8	22.2
Core 5	0.175	0.192	1485	9.74	79.0	22.2
Core 6	0.179	0.200	1483	9.80	79.9	22.1
Core 7	0.177	0.197	1498	9.72	78.2	22.2

In [8], we reported that the values of the crosstalk between neighboring cores of the MCF after 17.6-km propagation were measured to be about -60 dB for both $\lambda = 1550$ nm and $\lambda = 1625$ nm. Each of those values was obtained from one measured value without any statistic treatments. Furthermore, they are largely discrepant from the mean values of the crosstalk distribution (XT_μ) calculated from the theoretical approximation model described in [10], as shown in Fig. 2. The crosstalk discrepancy can be explained to be due to unexpected crosstalk that occurred at a butt joint between the MCF and a receiving single-core fiber, as following. Fig. 3 shows relationships between misalignment and normalized power coupled at a butt joint of two single-core single-mode fiber (SMF) for $\lambda = 1550$ nm. SSMF and TA-SMF denote standard SMF and trench-assisted SMF, respectively. Solid and dashed lines represent measured and theoretical profiles, respectively. The latter were calculated by the overlap integral between fundamental modes of the two SMFs by using following equation:

$$|c_{pq}|^2 = \frac{\left| \iint E_p E_q dx dy \right|^2}{\iint |E_p|^2 dx dy \iint |E_q|^2 dx dy}, \quad (1)$$

where E_p and c_{pq} represent amplitude the fundamental mode of Core p , and coupling coefficient of a butt joint between Core p and Core q , respectively. x and y denote local coordinates in a fiber cross section. The measured profiles were observed to have power floors. The floor for SSMFs was about -60 dB, and that for TA-SMFs was less than -90 dB. The floor for SSMFs was assumed to be caused by coupling from cladding modes to a core mode during propagation in the receiving SMF, which can be the cause of the crosstalk discrepancy and can be sup-

pressed by a trench layer. According to these results, we employed TA-SMFs, which have almost the same core profile with cores of the MCF, as a launching fiber and a receiving fiber in measurements reported in this paper.

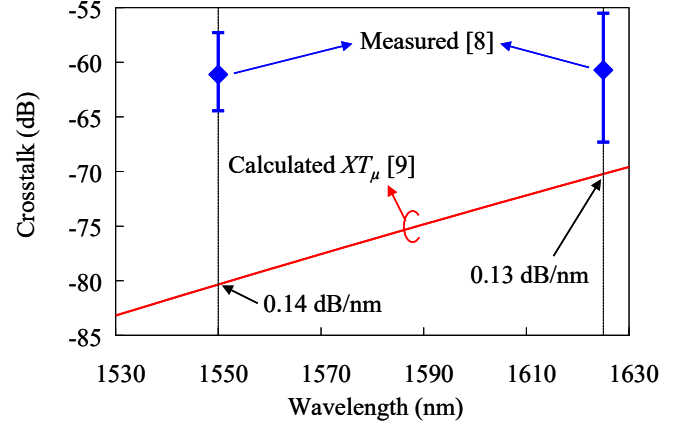


Fig. 2. Difference between the measured and the theoretically calculated crosstalk. Diamonds represent averages of the measured values. Errorbars represent the maximum and the minimum of the measured values. Solid line represents calculated mean value of statistical crosstalk distribution (XT_μ).

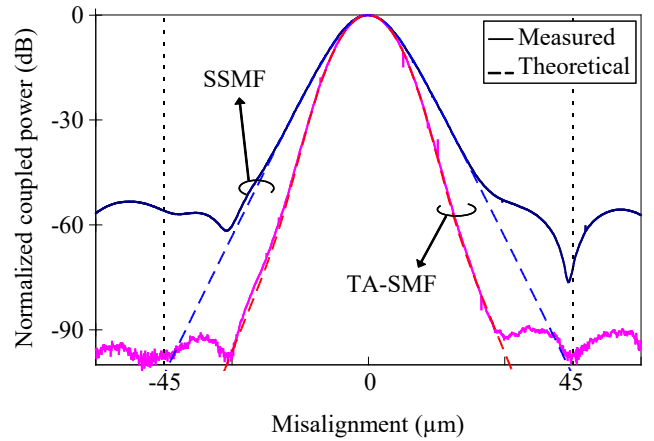


Fig. 3. Normalized power coupled at a butt joint between two single-core SMFs [9].

III. CROSSTALK CHARACTERISTICS OF THE MCF

A. Statistical measurement by sweeping wavelength

If a MCF is bent and twisted, and if there are phase-matching points where equivalent effective indices of the cores along the MCF, the crosstalk in the MCF changes dominantly at the phase-matching points [7]. The crosstalk after fiber propagation is a statistic value, because how much the crosstalk increases or decreases at the phase-matching points is varied by variations of the phase offsets between coupled cores at the phase-matching points, and because the phase offset can be easily varied by slight difference of fiber conditions such as fiber bend, twist, and so on. Accordingly, randomization of the phase offsets between the cores along MCFs is needed to obtain statistical distributions of the crosstalk of the MCFs. In [7], we had rewound MCFs for perturbing slightly their twist and bending, but this method is unpractical to obtain the distribution with a large number of sample values, which requires many

times of rewinding. However, the phase offsets can be varied not only by the variations of fiber bend and twist but also by variations of propagation constants that are dependent on the wavelength. Therefore, we developed a method for randomizing the phase offsets utilizing wavelength dependences of the phase offsets.

Wavelength dependences of the coupling coefficient κ must be cared in this method, because they affect how the crosstalk is distributed.

According to [10], the crosstalk (XT) is distributed with chi-square distribution with four degrees of freedom scaled by $1/\sigma^2$, whose probability distribution is represented as

$$f(XT) = \frac{XT}{4\sigma^4} \exp\left(-\frac{XT}{2\sigma^2}\right). \quad (2)$$

where, in case of a homogeneous MCF, σ^2 is represented as

$$\sigma^2 = \frac{1}{2} \frac{\kappa^2}{\beta} \frac{R}{\Lambda} L, \quad (3)$$

with mode coupling coefficient κ , propagation constant β , fiber bending radius R , core pitch Λ , and fiber length L . This is because in-phase (I) and quadrature (Q) components of two polarization modes of the crosstalk are normally distributed with the variance σ^2 . Mean value of the crosstalk distribution, i.e., mean crosstalk XT_μ , is represented as

$$XT_\mu = 4\sigma^2 = 2 \frac{\kappa^2}{\beta} \frac{R}{\Lambda} L = XT_{\text{coeff}} RL, \quad (4)$$

where XT_{coeff} represents the crosstalk coefficient on R and L .

Assuming that the mean crosstalk XT_μ can be approximated to be exponentially—linearly in the decibel scale—proportional to the wavelength as shown in Fig. 4 based on Fig. 2, the wavelength dependence of XT_μ can be represented as

$$XT_{\mu,0}(\delta\lambda) = XT_\mu(\lambda_0) 10^{\frac{XT_s \delta\lambda}{10}}, \quad (5)$$

where $XT_{\mu,0}(\delta\lambda)$ and XT_s denote XT_μ at $\lambda_0 + \delta\lambda$, and slope of XT_μ against the wavelength in the decibel scale, respectively. The mean value $XT_{\mu,\text{meas}}$ of the crosstalk distribution measured over the wavelength range from $\lambda_0 - \lambda_{\text{dev}}$ to $\lambda_0 + \lambda_{\text{dev}}$ can be represented as

$$\begin{aligned} XT_{\mu,\text{meas}} &= \frac{1}{2\lambda_{\text{dev}}} \int_{-\lambda_{\text{dev}}}^{\lambda_{\text{dev}}} XT_{\mu,0}(\delta\lambda) d\delta\lambda \\ &= XT_\mu(\lambda_0) \text{sinhc}\left(\frac{\ln 10}{10} XT_{\mu,\text{dev}}\right), \end{aligned} \quad (6)$$

where XT_{dev} equals to $XT_s \lambda_{\text{dev}}$, and

$$\text{sinhc}(z) \equiv \begin{cases} \frac{\sinh z}{z} & (z \neq 0) \\ 1 & (z = 0). \end{cases} \quad (7)$$

Since σ^2 is linearly proportional to XT_μ , the crosstalk distribution at $\lambda_0 + \delta\lambda$ can be represented as

$$f_0(XT, \delta\lambda) = \frac{XT}{4\sigma^4 10^{\frac{XT_s \delta\lambda}{5}}} \exp\left(-\frac{XT}{2\sigma^2 10^{\frac{XT_s \delta\lambda}{10}}}\right). \quad (8)$$

Accordingly, the crosstalk distribution to be measured over the wavelength range from $\lambda_0 - \lambda_{\text{dev}}$ to $\lambda_0 + \lambda_{\text{dev}}$ can be obtained as

(see Appendix):

$$\begin{aligned} f_{\text{meas}}(XT) &= \frac{1}{2\lambda_{\text{dev}}} \int_{-\lambda_{\text{dev}}}^{\lambda_{\text{dev}}} f_0(XT, \delta\lambda) d\delta\lambda \\ &= \frac{10}{\ln 10} \frac{1}{2XT_{\text{dev}}} \left[\left(\frac{1}{XT} + \frac{1}{2\sigma^2 10^{\frac{XT_{\text{dev}}}{10}}} \right) \exp\left(-\frac{XT}{2\sigma^2 10^{\frac{XT_{\text{dev}}}{10}}}\right) \right. \\ &\quad \left. - \left(\frac{1}{XT} + \frac{1}{2\sigma^2 10^{-\frac{XT_{\text{dev}}}{10}}} \right) \exp\left(-\frac{XT}{2\sigma^2 10^{-\frac{XT_{\text{dev}}}{10}}}\right) \right]. \end{aligned} \quad (9)$$

Estimated error of XT_μ caused by XT_μ variation, i.e., $XT_{\mu,\text{meas}}/XT_\mu$, against the variation width $2XT_{\text{dev}}$, and the crosstalk distributions estimated to be measured for several $2XT_{\text{dev}}$ are shown in Fig. 5 and Fig. 6, respectively. $2XT_{\text{dev}}$ of a few decibels induces the measurement error less than 0.1 dB and negligible change in the shape of the crosstalk distribution. Therefore, we determined the wavelength sweeping range for the MCF shown in Fig. 1 as 10 nm so that $2XT_{\text{dev}}$ can be less than 1.4 dB based on Fig. 2.

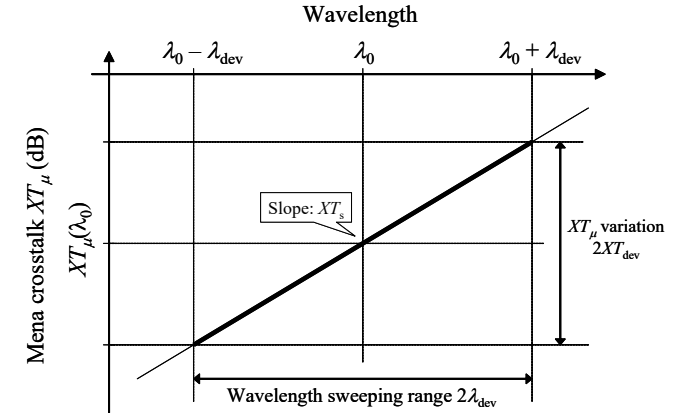


Fig. 4. A schematic of the wavelength dependence of mean crosstalk.

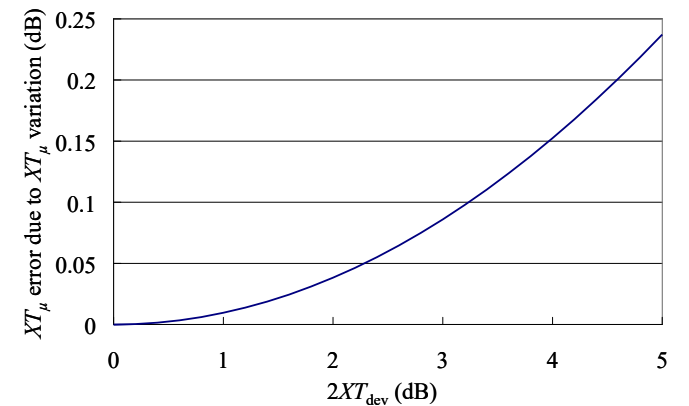


Fig. 5. Estimated error of the mean crosstalk XT_μ due to the variation of XT_μ in the wavelength sweeping range against the variation width $2XT_{\text{dev}}$.

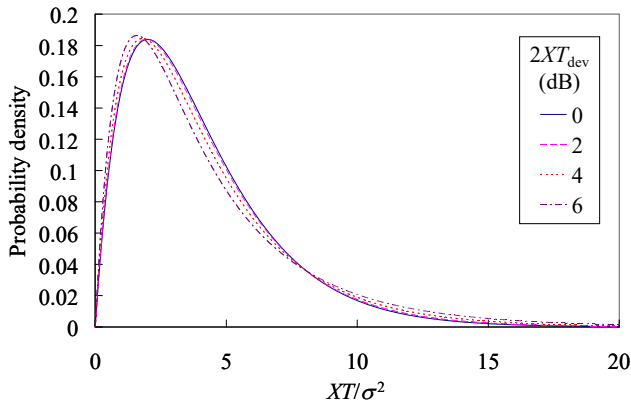


Fig. 6. Crosstalk distributions estimated to be measured over the wavelength sweeping range for several XT_μ variation widths $2XT_{dev}$.

We obtained crosstalk distributions of the MCF, whose length was 17.4 km and bending radius was 140 mm, at $\lambda = 1550$ nm and $\lambda = 1625$ nm by sweeping the laser wavelength in ranges of $\lambda \pm 5$ nm with 5 pm step. An averaging time for each wavelength step was one millisecond. The typical linewidth of the laser was specified to be 100 kHz. Spectra of measured crosstalk from Core 1 to Core 5 of the MCF around $\lambda = 1625$ nm are shown in Fig. 7, as examples. Fig. 7(a) shows the spectrum for 10 nm range and Fig. 7(b) for one nanometer range from the same data. The crosstalk was measured to be heavily dependent on the wavelength, so that the phase offsets were considered to be adequately randomized. As shown in Fig. 7(b), there was no specific cycle length in the crosstalk spectrum, but the crosstalk oscillated with wavelength pitches much less than one nanometer in this case. The crosstalk distribution obtained from the same data of Fig. 7(a) is shown in Fig. 8. The measured crosstalk distribution was well fitted with a scaled chi-square distribution with four degrees of freedom expressed in (2).

Measured values of the mean crosstalk between neighboring cores of the MCF are plotted in Fig. 9, which were obtained by fitting measured crosstalk distributions with (2) and using (4). The values between non-neighboring cores were too low to measure. Average and maximum values of the measured mean crosstalk were -79.5 dB and -77.6 dB respectively at $\lambda = 1550$ nm, and -69.8 dB and -67.7 dB respectively at $\lambda = 1625$ nm. The averages were in good agreement with the calculated XT_μ of -80.3 dB at $\lambda = 1550$ nm and of -70.2 dB at $\lambda = 1625$ nm. Even the mean crosstalk from six outer cores to one center core was calculated to be -72.3 dB at $\lambda = 1550$ nm and -62.1 dB at $\lambda = 1625$ nm from sums of the measured values. Variations of the measured values can be considered to be due to slight variations of core pitches and index profiles among the cores. By using the wavelength sweeping method, the crosstalk of the MCF was statistically confirmed to be extremely low, and XT_μ of the center core of the MCF can be estimated to be less than -30 dB even after 10000-km propagation at $\lambda = 1625$ nm if the bending radius R is less than ~ 39 cm, based on the linear dependence of XT_μ on the bending radius and fiber length.

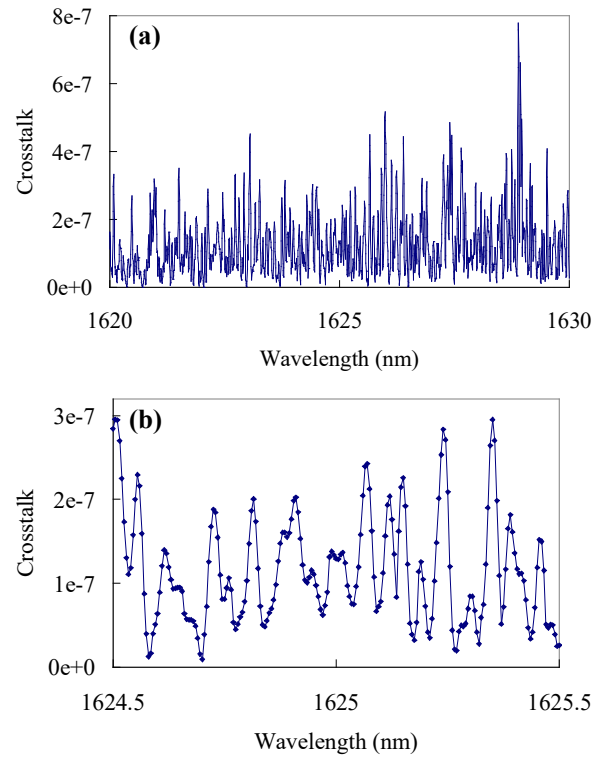


Fig. 7. An example of a spectrum of the crosstalk from Core 1 to Core 5 of the evaluated MCF around $\lambda = 1625$ nm for $L = 17.4$ km and $R = 140$ mm. Crosstalk spectra, (a) for 10 nm range [9], and (b) for one nanometer range, are plotted from the same measurement data.

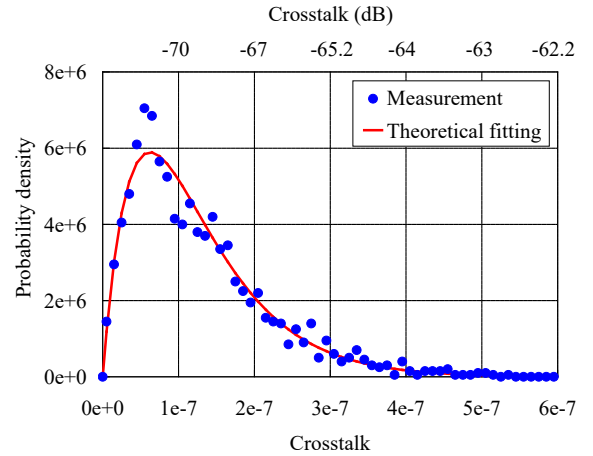


Fig. 8. An example of the crosstalk distribution that was obtained from the data plotted in Fig. 7(a) [9].

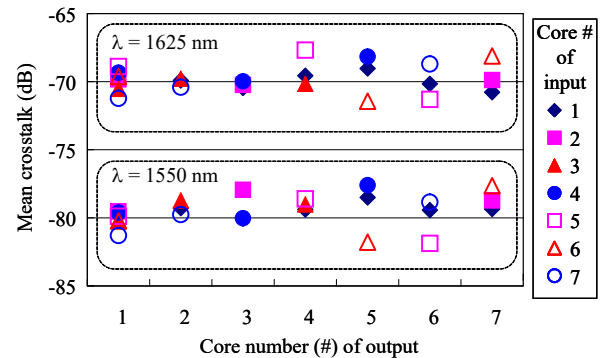


Fig. 9. Measured values of the mean crosstalk of the evaluated MCF after 17.4-km propagation for $R = 140$ mm [9].

B. Mean crosstalk stability against a misalignment

In a practical view, crosstalk at butt joints must be also considered. Therefore, we evaluated crosstalk variation of the MCF due to a misalignment. The mean crosstalk from Core 1 to Core 5 was measured for $\lambda = 1625$ nm, and the core of the launching SMF was traversed on a line connecting Core 2, Core 1, and Core 5 on the input end of the MCF (see Fig. 10). Measurement results are shown in Fig. 11. Positive and negative directions represent directions for Core 5 and Core 2, respectively. Marks, a dashed line, and error bars represent values of the mean crosstalk, average of the values, and measurement error of our measurement system, respectively. Since no significant crosstalk variation was observed for the misalignment of several micrometers, allowable misalignment for the crosstalk at butt joints was much larger than that for splice loss, as for the evaluated MCF. Accordingly, crosstalk increases at butt joints are considered to be negligible for this MCF.

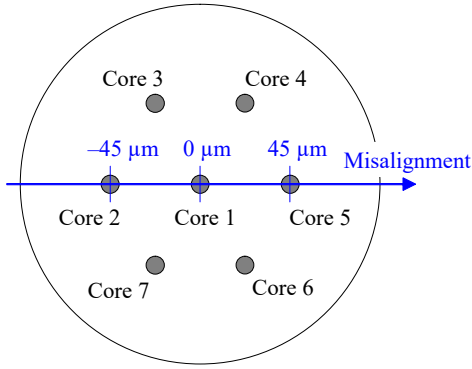


Fig. 10. A schematic of the misalignment on the input end of the MCF.

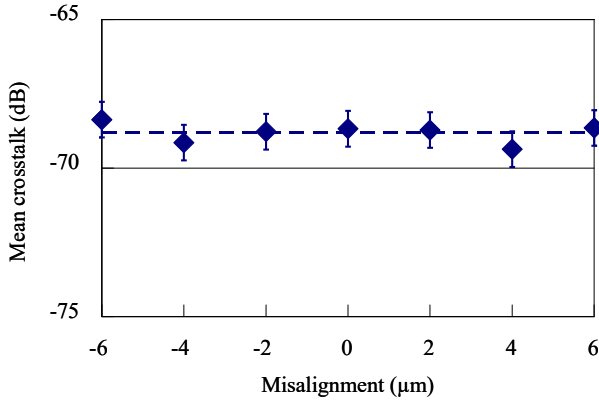


Fig. 11. Stability of mean crosstalk of the MCF against misalignment [9].

IV. STOCHASTIC CROSSTALK VARIATION CAUSED BY POLARIZATION CHANGE AND MECHANICAL DISTURBANCE

Whereas we observed the stochastic behavior of the crosstalk induced by the wavelength sweeping in the process of the statistical measurement as shown in Fig. 7, we also investigated stochastic behaviors caused by polarization change and mechanical disturbance.

A change of the polarization states can induces the variations of the phase offsets, so that the crosstalk can be varied. We investigated the effects of the polarization change on the

crosstalk. Fig. 12 shows time evolutions of the crosstalk (not the mean crosstalk) at $\lambda = 1624.742$ nm and $\lambda = 1625.000$ nm, while the polarization state of the input light was scrambled discretely and uniformly on the Poincaré sphere, and while not scrambled. Values of the crosstalk without the polarization scrambling (PS) were stable for the both wavelength, and those with the PS were heavily varied along the time. Ranges of the crosstalk variations due to the PS were different for the different wavelengths, which implies that the PS can not adequately randomize the phase offsets.

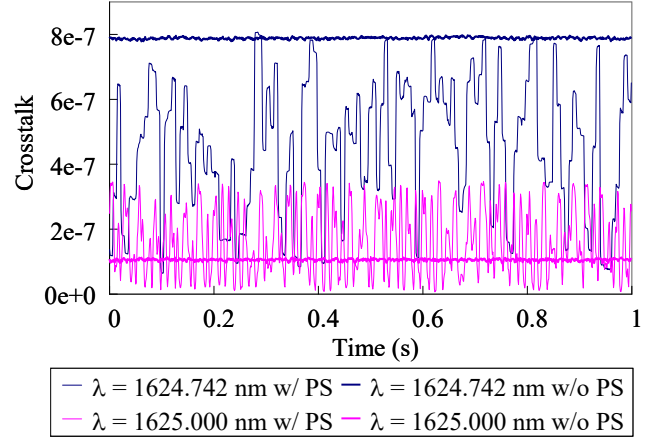


Fig. 12. Time evolutions of the crosstalk from Core 1 to Core 5 of the MCF around $\lambda = 1625$ nm for $L = 16.8$ km and $R = 140$ mm, with and without the polarization scrambling (PS). Each evolution was measured individually.

Mechanical shock and stress can also induce the phase-offset variations, since they can cause variations of the propagation constants and slight changes of fiber bend and twist.

Fig. 13 shows a time evolution of the crosstalk at $\lambda = 1625$ nm, before and after a mechanical shock was applied to the MCF by dropping a steel ball on a flange of the bobbin. The ball was 110 g and dropped from a height of about 10 cm. A rapid variation of the crosstalk was observed just after the shock.

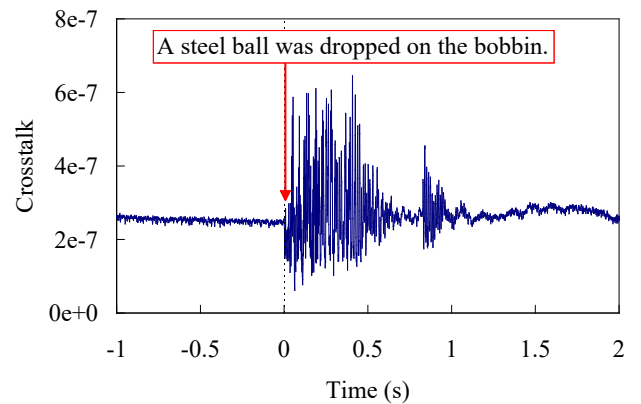


Fig. 13. A time evolution of the crosstalk from Core 1 to Core 5 of the MCF at $\lambda = 1625$ nm for $L = 16.8$ km and $R = 140$ mm, before and after the shock.

Fig. 14 shows a time evolution of the crosstalk at $\lambda = 1625$ nm, and Fig. 15 shows a spectrogram of the crosstalk for the wavelength between 1625 nm and 1626 nm, before and after mechanical stress was applied to the MCF. Results in Fig. 14 and those in Fig. 15 were measured individually. The stress was

applied by pressing the surface of the MCF wound on the bobbin with hands between the measurements, so the MCF was not touched after the stress was applied. The crosstalk was varied in a scale more than several tens of seconds before the stress was applied, and in a scale less than several seconds after the stress. This can be considered as follows: Little residual stress was remained in the MCF and the MCF was mechanically stable before the stress was applied; but much residual stress was remained and gradually relieved from the MCF after the stress was applied; the gradual relief of the stress induced relatively-rapid variations of the phase offsets.

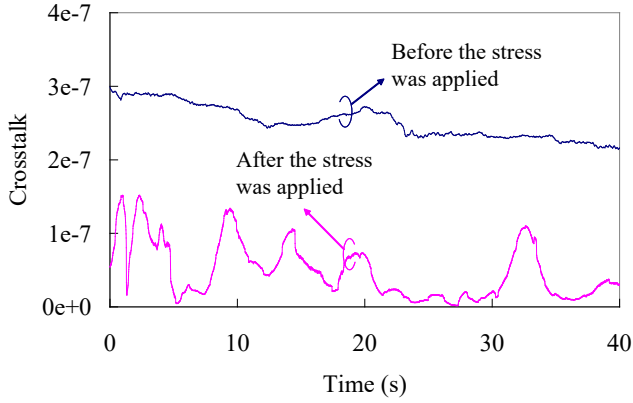


Fig. 14. Time evolutions of the crosstalk from Core 1 to Core 5 of the MCF at $\lambda = 1625$ nm for $L = 16.8$ km and $R = 140$ mm, before and after the stress was applied to the MCF.

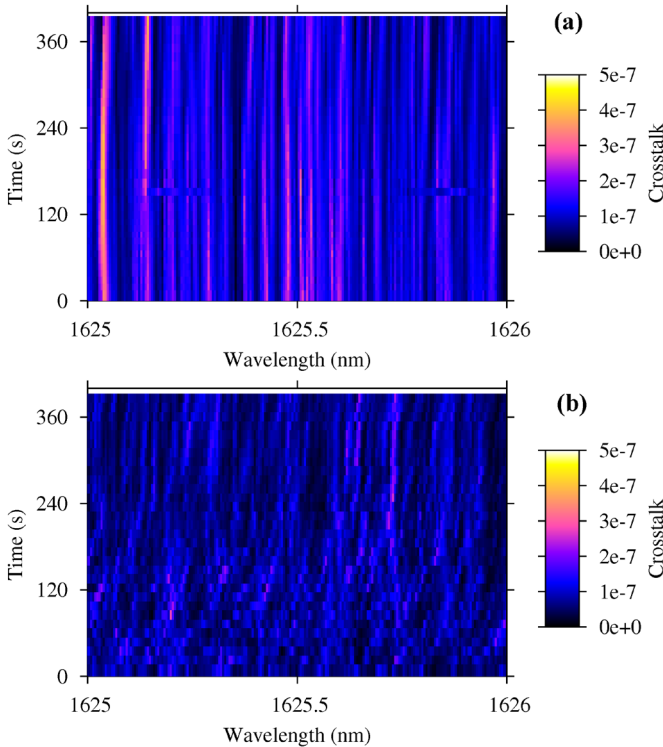


Fig. 15. Spectrograms of the crosstalk from Core 1 to Core 5 of the MCF from 1625 nm to 1626 nm for $L = 16.8$ km and $R = 140$ mm, (a) before and (b) after the stress was applied to the MCF. Time intervals of the spectral measurements were around 12 s. The time evolution in (b) seems to be faster than the measurement intervals, based on Fig. 14.

The stochasticity of the crosstalk can be rather favorable for forward error correction because it can enhance the time decorrelation of the crosstalk, but can be unfavorable and may have to be cared in case of mitigating high crosstalk using digital signal processing.

V. CONCLUSION

We developed a method to measure extremely low crosstalk of MCF statistically, and investigated characteristics of the crosstalk of a previously fabricated MCF. The ultra-low crosstalk of the MCF demonstrated the feasibility of spatial-multiplexed ultra-long-haul transmission without any digital signal processing for the demultiplexing. Stochastic behavior of the crosstalk induced by the variations of the wavelength, polarization states, and mechanical conditions of the MCF may be required to be considered in case of mitigating high crosstalk using digital signal processing.

APPENDIX: DERIVATION OF (9)

Based on (8) and the first line of (9), $f_{\text{meas}}(XT)$ can be derived as

$$\begin{aligned} f_{\text{meas}}(XT) &= \frac{1}{2\lambda_{\text{dev}}} \int_{-\lambda_{\text{dev}}}^{\lambda_{\text{dev}}} \frac{XT}{4\sigma^4 10^{\frac{XT_s \delta \lambda}{5}}} \exp\left(-\frac{XT}{2\sigma^2 10^{\frac{XT_s \delta \lambda}{10}}}\right) d\delta \lambda \\ &= \frac{1}{2XT_s \lambda_{\text{dev}}} \frac{10}{\ln 10} \frac{1}{XT} \int_{\frac{XT}{2\sigma^2 10^{XT_s \lambda_{\text{dev}}/10}}}^{\frac{XT}{2\sigma^2 10^{-XT_s \lambda_{\text{dev}}/10}}} t \exp(-t) dt \\ &= \frac{1}{2XT_{\text{dev}}} \frac{10}{\ln 10} \frac{1}{XT} \left[\Gamma\left(2, \frac{XT}{2\sigma^2 10^{XT_{\text{dev}}/10}}\right) - \Gamma\left(2, \frac{XT}{2\sigma^2 10^{-XT_{\text{dev}}/10}}\right) \right], \quad (10) \end{aligned}$$

by substituting

$$t = \frac{XT}{2\sigma^2 10^{XT_s \delta \lambda / 10}}, \quad (11)$$

and using the incomplete gamma function:

$$\Gamma(a, x) \equiv \int_x^\infty t^{a-1} \exp(-t) dt. \quad (12)$$

When a is an integer n , the incomplete gamma function can be rewritten as [11]:

$$\Gamma(n, x) = (n-1)! \exp(-x) \sum_{k=0}^{n-1} \frac{x^k}{k!}. \quad (13)$$

By using (13), (10) can be rewritten as the last line of (9).

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