Novel Inter-core Crosstalk Measurement Method Using Loopback and Bidirectional OTDR Technique

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Abstract *We have proposed a novel inter-core crosstalk* measurement *method using loopback and bidirectional optical time-domain reflectometer (OTDR) technique. In this method, the crosstalk and attenuation can be measured simultaneously. The measured crosstalk using the new and power meter methods has been compared.*

Introduction

With the increase in communication traffic capacity, space division multiplex (SDM) technologies are focusing on expanding the transmission capacity [1]. Particularly, uncoupled multi-core fibres (MCFs) are receiving significant attention owing to their compatibility with standard single-mode fibres (SMFs) [2].

One of the issues in the practical use of MCFs is inter-core crosstalk (XT). XT is a phenomenon in which optical signals interfere with other cores and deteriorate communication quality. Therefore, it is necessary to evaluate the amount of XT when MCFs are used for transmission.

Generally, the power meter method measures XT's amount [3]. It is essential to prepare a measurement system separately from that of the standard SMF so that the measurement system is not compatible with the standard SMF.

Thus, XT measurement methods have been suggested using an optical time-domain reflectometer (OTDR) device. The methods of receiving backscattered light and using a multiple channel OTDR have been reported [4, 5]. In the method using an OTDR, it is difficult to measure the small amount of XT due to minimal backscattered light from XT. In addition, we need to prepare a particular device, and it takes cost.

This paper proposes a novel XT measurement method using loopback and bidirectional OTDR technique. A conventional OTDR can be used for this method, so it is possible to measure XT using the same system for a standard SMF measurement. Moreover, this method can measure a small amount of XT because XT power can be observed as a transmitted light instead of a backscattered light. In addition, it can measure XT between the exciting core and any other core under the test and attenuation of both cores simultaneously. Consequently, the measurement efficiency of MCFs improves using the proposed method. We have also verified that the XT values measured by this method are in agreement with those of the power meter, a standard measurement method of XT.

Measurement Method

Figures 1(a) and 1(b) show schematics of the proposed XT measurement method using an OTDR. The OTDR connects to the excitation core (core 1) at A's end. At the end of B, core 1 and the neighbouring core (core 2) are connected to both ends of a dummy SMF length L_{SMF}. To simplify, we discuss using a two-core fibre (2CF) model whose length is L_{2CF}. In addition, attenuations of dummy SMF and 2CF are ignored. In Figure 1(a), when pulse light P_0 is incident to core 1 from the end of A, the XT pulse $P_{XT}(L_{2CF})$ occurs from core 1 to core 2. $P_{XT}(L_{2CF})$ transmits core 2 at the same speed as P_0 and is output from the connection point between the 2CF and the dummy SMF at the exact timing as P'_0. The output pulsed light P'_0 and $P_{XT}(L_{2CF})$ pass at the midpoint of the dummy SMF, P'_0 enters core 2, and $P_{XT}(L_{2CF})$ enters core 1. The backscattered light $P_{BS}(L_{2CF} + L_{SMF}/2)$ occurs from the midpoint

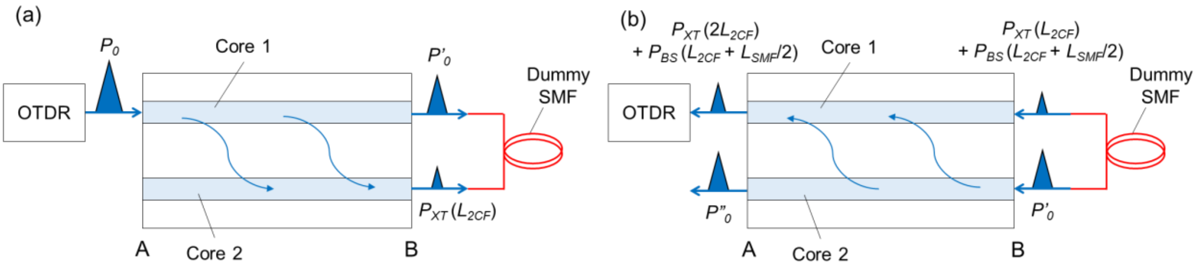

Fig. 1: Schematics of a novel XT measurement method, (a) when a pulse light transmits from end of A to end of B, (b) when a pulse light transmits from B to A.

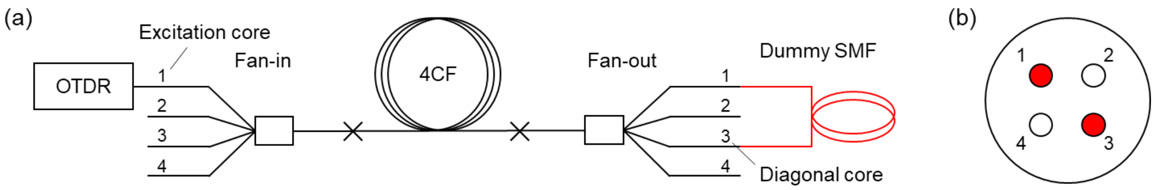

Fig. 2: (a) Measurement setup of XT, (b) cross section model of fibre under test.

of the dummy SMF and transmits with $P_{XT}(L_{2CF})$.

Figure 1(b) shows that the pulse light P'_0 transmits through core 2 and outputs as P''_0 from the end of core 2. The XT pulse from core 2 to core 1 occurs in core 1 from P'_0. This XT transmits with $P_{XT}(L_{2CF})$ and $P_{BS}(L_{2CF} + L_{SMF}/2)$, so we can observe the amount of XT at $2L_{2CF}$ as the transmitted light $P_{XT}(2L_{2CF})$. Thereby, a small amount of XT can be measured by the OTDR.

Next, we consider the calculation method of XT. The powers P''_0, $P_{BS}(L_{2CF} + L_{SMF}/2)$, and $P_{XT}(2L_{2CF})$ are expressed as the following equations:

$$P''_0 = P_0 \times \left\{\frac{1 + \exp(-2h \times 2L_{2CF})}{2}\right\} \quad (1)$$

$$\begin{aligned} &P_{BS}(L_{2CF} + L_{SMF}/2) \\ &= P_0 \times \alpha_S B \times \left\{\frac{1 + \exp(-2h \times 2L_{2CF})}{2}\right\} \\ &= \alpha_S B \times P''_0 \end{aligned} \quad (2)$$

$$\begin{aligned} &P_{XT}(2L_{2CF}) \\ &= P_0 \times \left\{\frac{1 - \exp(-2h \times 2L_{2CF})}{2}\right\} \end{aligned} \quad (3)$$

where h is the power coupling coefficient between core 1 to core 2 [6], α_S is the local scattering coefficient, and B is the backscattered capture fraction [4]. The calculated equation of XT value is expressed as follows:

$$\frac{P_{XT}(2L_{2CF})}{P''_0} = \alpha_S B \times \frac{P_{XT}(2L_{2CF})}{P_{BS}(L_{2CF} + L_{SMF}/2)} \quad (4)$$

equation (4) indicates that the XT can be calculated by the ratio of $P_{XT}(2L_{2CF})$ and $P_{BS}(L_{2CF} + L_{SMF}/2)$. $P_{XT}(2L_{2CF})/P_{BS}(L_{2CF} + L_{SMF}/2)$ in the right side of equation (4) can be measured from the proposed method, so the XT can be calculated if $\alpha_S B$ is known value. It is possible to calculate the value of $\alpha_S B$ by comparing the measured value by the proposed method with the XT value measured another method (for example, the power meter method).

Measurement Results

Figure 2(a) shows the measurement setup of the proposed method. We used an uncoupled four-core fibre (4CF) for this measurement test. A pair of fan-in/fan-out (FIFO) devices must be used at both ends of the 4CF to connect an OTDR and a dummy SMF. To verify the possibility of smaller XT measurement, the XT between diagonal cores (between core 1 and core 3) was measured, as shown in Figure 2(b).

Figure 3(a) shows an image of the measured power of the proposed XT measurement method. The length of the 4CF and a dummy SMF were 21 km and 10 km, respectively. The waveform shows attenuation properties of the excitation core (core 1) in 4CF, the looped dummy SMF, and the diagonal core (core 3) in 4CF. The waveform of core 1 and core 3 is the same as a standard OTDR measurement, and it is possible to measure the attenuation coefficient of each core. In the waveform of dummy SMF, the peak of XT appears at the midpoint.

Figure 3(b) shows an enlarged view of the XT peak. The blue line is the total power of transmitted light by XT and the backscattered light from dummy SMF ($P_{XT\_4CF} + P_{XT\_FIFO} + P_{BS}$), and the black dashed line is P_{BS}. The difference between these lines corresponds to the amount

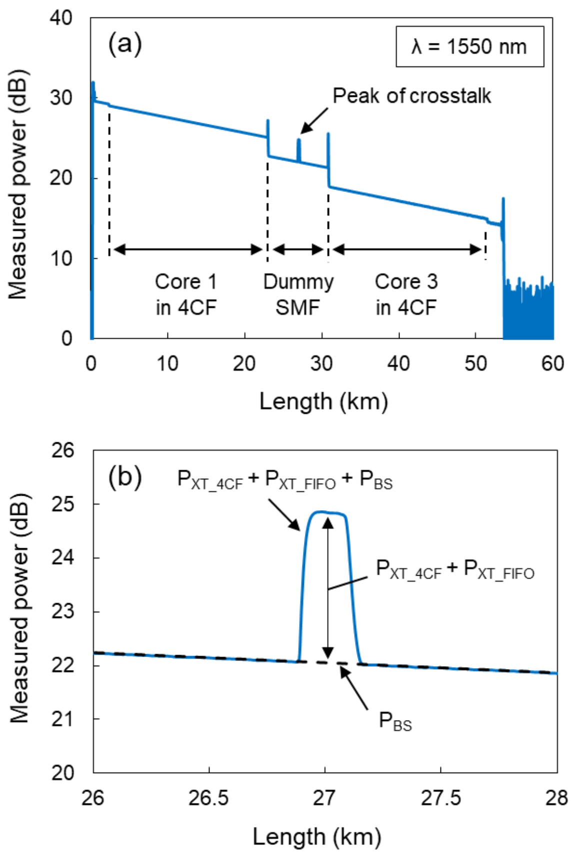

Fig. 3: Measured power of the proposed XT measurement method (pulse width 2 µs, average time 30 sec.) (a) whole image, (b) enlarged view of the XT peak.

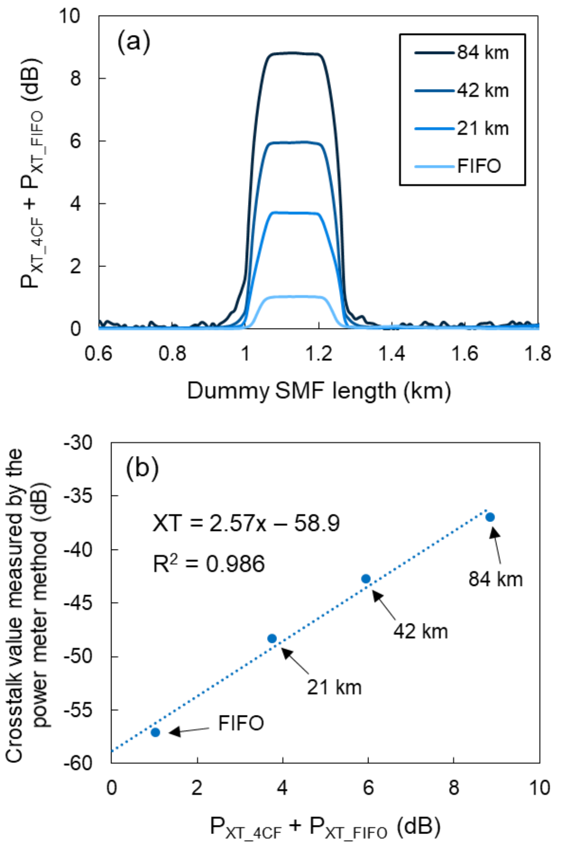

Fig. 4: (a) Peak power of each fibre length, (b) a calibration curve between the values of the peak height and the XT values measured by the power meter method.

of XT (P_{XT_4CF} + P_{XT_FIFO}). The vertical and horizontal axis in the OTDR is half of the actual values. Therefore, the peak of XT shows the amount of XT for 21 km of 4CF instead of 42 km.

Further, we examined the correlation between the proposed method and the power meter method for calculating the amount of XT. Figure 4(a) shows the peak height of XT (P_{XT_4CF} + P_{XT_FIFO}) of fibre length 0 km (only FIFO), 21 km, 42 km, and 84 km. The peak height is calculated as the ratio of (P_{XT_4CF} + P_{XT_FIFO} + P_{BS}) to P_{BS}. All fibres are evaluated with a pulse width of 2 µs and using a 2-km dummy SMF. To cancel the core dependency of insertion loss for FIFO and attenuation for MCF, the average of bidirectional data when pulses are injected from core 1 and core 3 were used. When the pulse width is standardized at the measurement, the peak power increases with fibre length, suggesting that the peak height is proportional to the amount of XT. Therefore, it is possible to create a calibration curve corresponding to the XT value's peak height, and the XT value can be calculated from the calibration curve. Figure 4(b) shows a calibration curve created from the values of the XT peak height measured by the OTDR and the XT values measured by the power meter method. There is a good correlation between the values of peak height and XT ($R^2 > 0.98$).

Tab. 1: Estimated XT from the calibration curve and XT values measured by the power meter method.

Fibre length (km)	Estimated XT (dB)	XT value (dB)
16	- 47.4	- 47.2
50	- 45.2	- 43.9
62	- 39.7	- 38.9

Table 1 summarizes the XT values for 16 km, 50 km, and 62 km estimated from the created calibration curve and measured by the power meter method. The measurement errors between the values by power meter and the values by OTDR are within 2 dB, these errors are similar to the power meter method. These results show that the proposed method is compatible with the power meter method. It is possible to estimate the XT value at other wavelengths in a similar way.

The advantage of this method is that the XT measurement can be performed simultaneously with the OTDR measurement. In addition, it is possible to measure a small amount of XT because the XT can be observed as a transmitted light instead of backscattered light. In this method, it is preferable to measure the average of bidirectional same as the attenuation measurement using OTDRs to cancel the core dependency of insertion loss for FIFO and attenuation for MCF.

The following conditions must be taken into consideration to measure the correct amount of XT by this method.

- The XT amount of MCF is much more significant than the XT of FIFO.
- The loss of MCF and insertion loss of FIFO and connection point satisfies the dynamic range of the OTDR.
- The length of a dummy SMF should be longer than the length corresponding to the pulse width. If the dummy SMF is extremely short, the peak of XT and the connection point between an MCF and a dummy SMF will overlap, and it is difficult to discriminate the peak of XT.

Conclusions

We proposed the novel XT measurement method using loopback and bidirectional OTDR technique. It measured an XT less than - 50 dB because this method measures the XT as transmitted light simultaneously with the backscattered light of the MCF and dummy SMF. This method is beneficial because the XT can be measured simultaneously as an attenuation measurement. The measurement results have been compared with the XT values measured by the power meter method.

References

[1] B. J. Puttnam, G. Rademacher, and R. S. Luis, "Space-division multiplexing for optical fiber communications," *Optical Society of America*, vol. 8, no. 9, pp. 1186-1203, 2021, DOI: https://doi.org/10.1364/OPTICA.427631

[2] T. Matsui, T. Sakamoto, and K. Nakajima, "Step-index profile multicore fibre with standard 125 μm cladding to full-band application," *The 45th European Conference on Optical Communication,* Dublin, Ireland, M1.D.3, 2019, DOI: https://doi.org/10.1049/cp.2019.0751

[3] T. Hayashi, T. Taru, O. Shimakawa, T, Sasaki, and E. Sasaoka, "Characterization of Crosstalk in Ultra-Low-Crosstalk Multi-Core Fiber," *Journal of Lightwave Technology*, vol. 30, no. 4, pp. 583-589, 2012, DOI: https://doi.org/10.1109/JLT.2011.2177810

[4] M. Ohashi, K. Kawazu, A. Nakamura, and Y. Miyoshi, "Simple Backscattered Power Technique for Measuring Crosstalk of Multicore Fibers," *OptoElectronics and Communications Conference*, Busan, South Korea, P1-25, 2012, DOI: https://doi.org/10.1109/OECC.2012.6276724

[5] M. Nakazawa, M. Yoshida, and T. Hirooka, "Nondestructive measurement of mode couplings along a multicore fiber using a synchronous multi-channel OTDR," *Optics Express*, vol. 20, No. 11, pp. 12530-12540, 2012, DOI: https://doi.org/10.1364/OE.20.012530

[6] K. Takenaga, Y. Arakawa, S. Tanigawa, N. Guan, S. Matsuo, K. Saitoh, and M. Koshiba, "An Investigation on Crosstalk in Multi-Core Fibers by Introducing Random Fluctuation along Longitudinal Direction," *IEICE Transmissions on Communications2011*, vol. E94-B, No. 2, pp. 409-416, 2011, DOI: https://doi.org/10.1587/transcom.E94.B.409