Measurement Method for Inter-core Crosstalk and Intrinsic Attenuation in a Weakly Coupled MCF by OTDR Technique

Naoto Norita
Optical Technologies R&D Center,
Fujikura Ltd.
1440, Mutsuzaki, Sakura, Chiba, Japan
naoto.norita@jp.fujikura.com

Mayu Nakagawa
Optical Technologies R&D Center,
Fujikura Ltd.
1440, Mutsuzaki, Sakura, Chiba, Japan
mayu.nakagawa@jp.fujikura.com

Katsuhiro Takenaga
Optical Technologies R&D Center,
Fujikura Ltd.
1440, Mutsuzaki, Sakura, Chiba, Japan
katsuhiro.takenaga@jp.fujikura.com

Kentaro Ichii
Optical Technologies R&D Center,
Fujikura Ltd.
1440, Mutsuzaki, Sakura, Chiba, Japan
kentaro.ichii@jp.fujikura.com

***Abstract*—This study proposes a novel method for inter-core crosstalk (XT) using a standard optical time-domain reflectometer (OTDR) technique. This method can evaluate intrinsic attenuation independent of the XT. XT and attenuation values measured by OTDR are verified by comparing them with those measured by conventional methods.**

Keywords—optical fiber testing, multicore fiber, inter-core crosstalk, attenuation, optical time-domain reflectometer

I. Introduction

Recently, space division multiplexing (SDM) transmission technologies using multicore fibers (MCFs) have attracted attention owing to an increase in communication traffic [1]. Weakly coupled MCFs have been developed since the beginning of research on MCFs because they are compatible with standard single-mode fibers (SMFs) [2]. One of the concerns of MCFs is inter-core crosstalk (XT). Additionally, XT is a phenomenon in which mode coupling occurs between adjacent cores and deteriorates communication quality. Therefore, it is important to measure the amount of XT for the practical use of MCFs. For the measurement of XT, the power meter method has been utilized [3]. Proposed another method is using an optical time-domain reflectometer (OTDR) for the XT measurement. Methods that receive backscattered light and use multiple channel OTDR have also been reported [4, 5]. However, it is necessary to prepare particular devices that can measure XT in MCFs. Therefore, we proposed a method of XT measurement using a standard OTDR for compatibility with the measurement system of standard SMF [6]. Using the method, the XT power was observed as transmitted light. Additionally, XT can affect attenuation. An OTDR is generally used to measure attenuation. However, if a specific core of MCF is excited to evaluate the attenuation by OTDR, the intensity of backscattered light is reduced by XT; and obtaining an accurate measurement of the intrinsic attenuation derived from a waveguide is difficult depending on the amount of XT.

In this study, we propose a novel XT measurement method that uses conventional OTDR to receive backscattered light. In the fiber under test (FUT), XT values should be measured in the longitudinal direction by observing backscattered light. Furthermore, this method can evaluate intrinsic attenuation without the influence of XT attenuation to the adjacent core using a standard OTDR. Additionally, we verified that XT and intrinsic attenuation values measured by the proposed method were in agreement with power meter and cut-back methods, respectively.

II. Experimental Method

We prepared a 2.01 km spool of two-core fiber (2CF) for this experiment. Fig. 1 shows the cross section of the 2CF under test. One of the cores was placed at the center of a cladding (C1), and the other core (C2) was 35 µm away from the center. The cladding diameter was 176 µm. Table I lists the properties of the fiber.

The measurement setup is shown in Fig. 2 (a). The OTDR was connected to a 3 dB coupler. The pulsed light from the OTDR split by the coupler propagates through each 2CF's core using a fan-in fan-out (FIFO) device. Between the coupler and the 2CF, one of the separated pulse lights is incident on a fiber bent to a small diameter, and the other light is incident on an isolator (isolation: 60 dB at 1550 nm, 43 dB

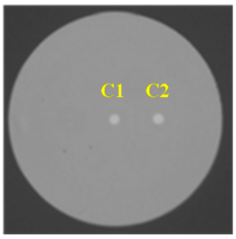

Fig. 1. Cross section of the 2CF.

TABLE I. Properties of the 2CF under Test

Items	Unit	Values	
		C1	*C2*
Fiber length	km	2.01	
Cladding diameter	µm	176	
Core distance	µm	35	
Mode field diameter (at 1550 nm / 1625 nm)	µm	9.2 / 9.5	9.1 / 9.4
Fiber cut-off wavelength	nm	1578	1584
Attenuation[a] (at 1550 nm / 1625 nm / 1650 nm)	dB/km	0.268 / 0.275 / 0.294	0.261 / 0.268 / 0.278
XT value[b] (at 1550 nm / 1625 nm / 1650 nm)	dB/km	−35 / −28 / −23	

a. Measured by the cut-back method.

b. Measured by the power meter method.

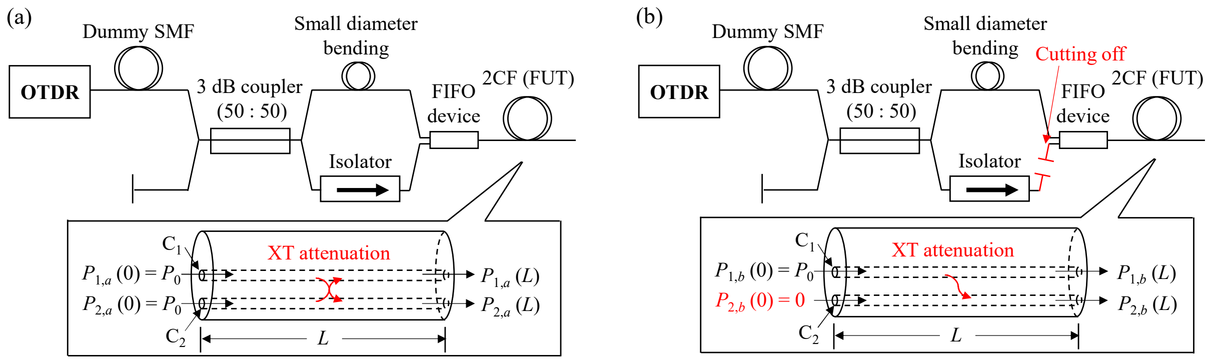

Fig. 2. Schematics of XT measurement setups with an OTDR: (a) Before and (b) after cutting the fiber between the isolator and FIFO device off.

at 1625 nm, 33 dB at 1650 nm). In this setup, the pulsed light from the OTDR was divided into two cores, and the backscattered light from C1 propagates and is measured by an OTDR. Moreover, by adjusting the bending diameter to equalize the light intensities incident on 2CF, the XT from C1 to C2 was equal to that from C2 to C1. In this setup, the optical power transmitted along C1 after propagation over a fiber length L ($P_{1,a}(L)$) is given as the solution of the power-coupling equation for the two-core model with the conditions $P_{1,a}(0) = P_0$ and $P_{2,a}(0) = P_0$ [5] as

$$P_{1,a}(L) = P_0 \exp(-\alpha L), \tag{1}$$

where the attenuation coefficient of each core is assumed to be α. In this study, the incident light intensities were optimized by adjusting the bending diameter and referring to a power meter so that the difference is <0.3 dB. Backscattered light passing through C1 was detected in the OTDR without the influence of XT attenuation.

Furthermore, the setup shown in Fig. 2 (b) was prepared. The setup is practically the same as that shown in Fig. 2 (a). However, the optical fiber between the isolator and the FIFO device is cut off to block the excitation of C2. In this system, the light propagating through C1 is affected by the attenuation due to the waveguide and XT. In this condition, by solving the power-coupling equation with the conditions $P_{1,b}(0) = P_0$ and $P_{2,b}(0) = 0$, the optical power $P_{1,b}(L)$ is

$$P_{1,b}(L) = \frac{P_0}{2}\exp(-\alpha L)\,[1 + \exp(-2hL)], \tag{2}$$

where h is the power coupling coefficient.

Then the optical power $P_{2,b}(L)$ is rewritten as

$$\begin{aligned} P_{2,b}(L) &= \frac{P_0}{2}\exp(-\alpha L)\,[1 - \exp(-2hL)] \\ &= P_{1,a}(L) - P_{1,b}(L)\,. \end{aligned} \tag{3}$$

Therefore, the amount of XT ($X(L)$) is expressed as [7]

$$\begin{aligned} X(L) &= \frac{P_{2,b}(L)}{P_{1,b}(L)} = \frac{P_{1,a}(L) - P_{1,b}(L)}{P_{1,b}(L)} \\ &= \frac{1 - [P_{1,b}(L)/P_{1,a}(L)]}{[P_{1,b}(L)/P_{1,a}(L)]}\,. \end{aligned} \tag{4}$$

The ratio of $P_{1,b}(L)$ to $P_{1,a}(L)$ ($P_{1,b}(L)/P_{1,a}(L)$) can be obtained by OTDR measurement as the waveform difference between $P_{1,a}$ and $P_{1,b}$.

We measured attenuation from OTDR under the setups shown in Figs. 2 (a) and (b) and evaluate XT by taking the difference between the waveforms before and after cutting the fiber. Additionally, the intrinsic attenuation can be obtained by the setup shown in Fig. 2 (a) is compared with the attenuation measured by the 2m-cut-back method. In this method, the 2CF is connected to a receiving section to receive directly the light of both cores and exclude the influence of XT attenuation.

III. Results

Fig. 3 (a) shows two waveforms obtained using the proposed XT measurement method shown in Figs. 2(a) and (b). We performed the measurement using a standard OTDR under the conditions that the measured wavelength was 1625

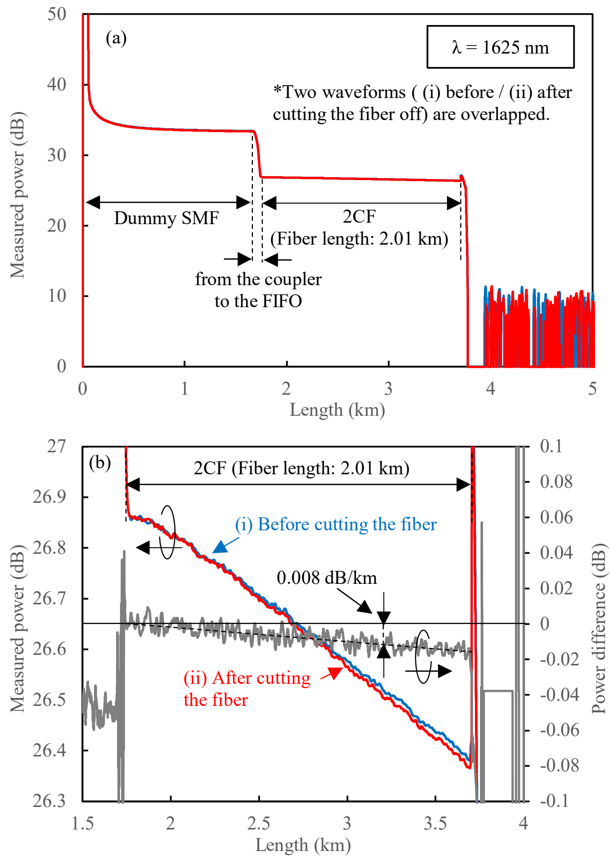

Fig. 3. Measured power of the (i) before (blue line) and (ii) after (red line) cutting the fiber obtained by OTDR. (Measured wavelength was 1625 nm, pulse width was 500 ns, and average time was 60 sec.) (a) Entire image and (b) Enlarged view of 2CF section. Power difference between (i) and (ii) is plotted as the right axis in (b) (gray line).

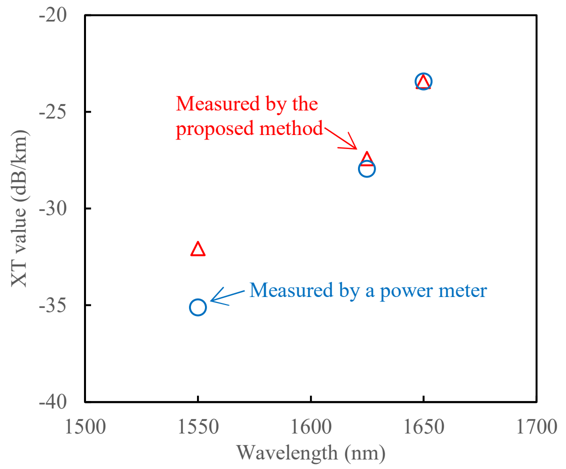

Fig. 4. Wavelength and measurement method dependence on XT. Triangle symbols (red color) indicate wavelengths measured by the proposed method and Circle symbols (blue color) measured by a power meter.

nm, pulse width was 500 ns, and average time was 60 s to improve the signal-to-noise ratio. One of the waveforms was obtained before cutting the fiber between the isolator and the FIFO, and the other one was obtained after cutting; the two waveforms almost overlap in Fig. 3 (a). The waveforms show the attenuation properties of the dummy SMF connected to the OTDR, the setup from the coupler to the FIFO, and the 2CF under test. Fig. 3 (b) shows an enlarged view of the 2CF section. The difference in slope between the two waveforms, (i) and (ii), are caused by the presence or absence of XT attenuation, respectively. Additionally, XT attenuation can be evaluated from the waveform difference (gray line, plotted on the right axis in Fig. 3 (b)). The slope of the waveform difference was obtained using the average of the bidirectional data. The slope obtained by the least squares approximation (LSA) was 0.008 dB/km, and the XT obtained by (4) was –27 dB/km.

Furthermore, we measured XT at other wavelengths (1550 nm and 1650 nm) and compared the proposed method with the power meter method. Fig. 4 shows the wavelength and measurement-method dependence of the XT. In contrast to the good agreement between the measured values at 1625 nm and 1650 nm, we observed a discrepancy at 1550 nm. In the proposed method, low XT attenuation degrades measurement accuracy because the waveform difference is practically zero.

TABLE II. ATTENUATION COMPARISON OF C1 OBTAINED BY DIFFERENT MEASUREMENT METHODS

Wavelength (nm)	Attenuation (dB/km)		
	Standard OTDR	***Proposed Method***	***Cut-back Method***
1550	0.261	0.260	0.268
1625	0.279	0.274	0.275
1650	0.308	0.293	0.294

Attenuation values measured by the proposed method were compared with the values obtained by the 2m-cut-back method that receives light from both cores to verify accuracy. Table II summarizes the attenuation values of C1 by a standard OTDR (setup shown in Fig. 2 (b)), the proposed method (shown in Fig. 2 (a)), and the 2m-cut-back method at 1550 nm, 1625 nm, and 1650 nm. For clarity of the waveform, the OTDR measurement was performed under the condition that the pulse width was 1000 ns and average time was 60 s. Although a few inconsistencies occurred because of differences in the measurement methods, the proposed and cut-back methods are generally consistent.

IV. CONCLUSION

In this study, we proposed a novel XT and attenuation measurement method using a standard OTDR. This method was performed using the following steps:

1. Incident light with equal intensity was passed through each core of the FUT, measured the backscattered light of the target core, and derived the attenuation without the influence of XT

2. Observed the backscattered light by exciting only the target core

3. XT was derived by calculating the ratio of the backscattered light intensities of steps 1 and 2.

Using this method, the intrinsic attenuation of the MCF can be measured accurately, which is independent of XT, using OTDR. The amount of XT and intrinsic attenuation obtained by the proposed method were verified using the power meter and cut-back methods, respectively.

REFERENCES

[1] B. J. Puttnam, G. Rademacher, and R. S. Luis, “Space-division multiplexing for optical fiber communications,” Optica, vol. 8, no. 9, pp. 1186–1203, 2021.

[2] T. Matsui, T. Sakamoto, and K. Nakajima, “Step-index profile milticore fibre with standard 125 µm cladding to full-band application,” The 45th European Conference on Optical Communication, Dublin, Ireland, M1.D.3, 2019.

[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.

[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.

[5] M. Nakazawa, M. Yoshida, and T. Hirooka, “Nondestructive measurement of mode couplings along a multicore fiber using a synchronous multi-channerl OTDR,” Optics Express, vol. 20, no. 11, pp. 12530–12540, 2012.

[6] M. Nakagawa, M. Ohzeki, K. Takenaga, and K. Ichii, “Novel Inter-core Crosstalk Measurement Method Using Loopback and Bidirectional OTDR Technique,” European Conference on Optical Communication, Bazel, Switzerland, Tu4A.4, 2022.

[7] K. Takenaga, Y. Arakawa, S. Tanigawa, N. Guan, S. Matsuo, K. Saitoh, M. Koshiba, “An Investigation on Crosstalk in Multi-Core Fibers by Introducing Random Fluctuation along Longitudinal Direction,” IEICE Transmissions on Communications, vol. E94-B, pp. 409–416, 2011.