European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Measurement of Mode-Coupling Along a Multi-Core Submarine Fiber Cable with a Multi-Channel OTDR

Masato Yoshida(1), Toshihiko Hirooka(1), Nakazawa Masataka(1), Tetsuya Hayashi(2), Takemi Hasegawa(2), Kohei Nakamura(3), and Takanori Inoue(3)

(1) Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, 980-8577, Japan, masato@riec.tohoku.ac.jp
(2) Sumitomo Electric Industries, Ltd., 1 Taya-cho, Sakae-ku, Yokohama, 244-8588, Japan
(3) NEC Corporation, 5-7-10 Shiba, Minato-ku, Tokyo, 108-8001, Japan.

Abstract *We describe the precise distributed measurement of mode-coupling along a cabled 60 km-long 4-core fiber (4CF) for submarine transmission using a multi-channel OTDR. The crosstalk values in the fan-in/out devices and 4CF were evaluated separately with a dynamic range of as high as 85 dB.*

Introduction

Space-division multiplexing (SDM) techniques using multi-core fiber (MCF) and few-mode fiber (FMF) have been attracting a lot of attention as promising approaches with which to greatly increase the transmission capacity of a single optical fiber. Large capacity SDM transmissions exceeding 10 petabit/s have already been reported [1,2]. Recently, long-haul transoceanic-class transmissions using MCFs have also been reported [3-5]. In an SDM transmission, crosstalk between cores in the MCF is a factor limiting the transmission performance. Since mode-coupling occurs locally due to fiber bends or connections, it may be changed after the fiber cable has been installed. Therefore, a technique for measuring the mode-coupling from one end of an installed fiber becomes crucial.

In this paper, we demonstrate the first precise distributed measurement of mode-coupling along a cabled 60 km-long 4-core fiber (4CF) for submarine transmission using a multi-channel optical time-domain reflectometer (OTDR). This technique is advantageous since the crosstalk in the fan-in/out devices and 4CF can be separately evaluated with a dynamic range of as high as 85 dB from one end of the test fiber.

Principle of mode-coupling measurement along an MCF with multi-channel OTDR

The coupled power equations between two adjacent cores can be expressed as

$$\begin{cases} \dfrac{dP_m}{dz} = -\alpha_m P_m + h_{m,n}\left(P_n - P_m\right), \\ \dfrac{dP_n}{dz} = -\alpha_n P_n + h_{m,n}\left(P_m - P_n\right), \end{cases} \tag{1}$$

where P_m and P_n are the transmitted optical powers in each core along the *z*-axis, α_m and α_n are the fiber losses. $h_{m,n}$ is the mode-coupling coefficient from core n to core m, which can be measured by using the OTDR technique [6]. For example, when an optical pulse is coupled into core n of an MCF of length L, Rayleigh backscattering occurs not only in core n itself but also in core m through the mode-coupling. Assuming that the backscattered powers at the incident end of the fiber are P_{bsm} and P_{bsn}, the power ratio $\eta_{m,n}= P_{bsm}/P_{bsn}$ can be expressed as follows by solving the coupled power equations given in eq. (1) [7,8].

$$\eta_{m,n}(L) = \frac{P_{bsm}}{P_{bsn}} = 2h_{m,n}L + K, \tag{2}$$

where we assumed that $h_{m,n}L << 1$. Here, K is a constant at $L = 0$. Since the mode-coupling occurs in the round trip, the amount of mode-coupling is given by $2h_{m,n}L$. From eq. (2), we see that the local mode-coupling $h_{m,n}$ can be measured non-destructively along the MCF [6].

Measurement setup and results

Figure 1 shows a multi-channel OTDR setup for measuring the mode-coupling along an uncoupled 4CF integrated in a submarine cable prototype. We used commercially available SC500 series cable (outer diameter 17 mm) [9] with a length of 15.2 km as shown in the upper photo, in which trench-assisted 4CFs with a cladding diameter of 125 μm and a core pitch of

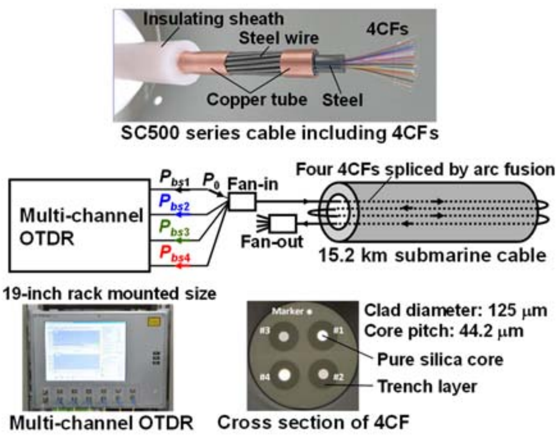

Fig. 1: Measurement setup for mode-coupling along an uncoupled 4CF cable.

44.2 μm were installed. We spliced four 4CFs using arc fusion and measured the mode-coupling along the fiber, which had a total length of 60.8 km. Here, the electrical discharge power in the fusion splicing was reduced since the melting point of the fluorine-doped fiber in the trench layer was low.

In Fig. 1, the Rayleigh backscattered signal from each core was simultaneously detected with a multi-channel synchronous OTDR [6]. A 10 μs optical pulse (corresponding to a spatial resolution of 1 km) was coupled into core n of the 4CF, and the backscattered power from each core was independently detected. Here, a dynamic range of as high as 85 dB was obtained for detecting a weak backscattered signal by setting the pulse width as wide as 10 μs. Finally, the mode-coupling from core n to core m was calculated by using eq. (2).

Figure 2 shows the measurement results when an optical pulse was coupled into core 2 from the forward direction. Figure 2(a) shows the backscattered power in each core. The backscattered signals observed at cores 1, 3, and 4 correspond to the mode-coupling from core 2. In the OTDR measurement, a high dynamic range of 85 dB was obtained, which indicates that we can successfully measure the distributed mode-coupling along the MCF. We observed small Fresnel reflections at each splicing point, which result from the weakly-discharged fusion splicing. This would be removed by optimizing the fusion splicing condition.

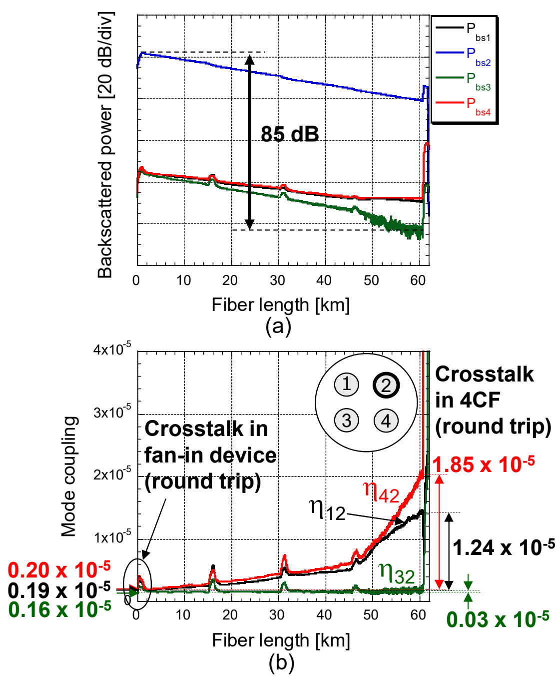

Fig. 2: Measurement result for mode-coupling when an optical pulse was coupled into core 2 from the forward direction. (a) Backscattered power, (b) mode-coupling along the MCF.

Figure 2(b) shows the local mode coupling from core 2 to other cores. The intercept at L=0 corresponds to the crosstalk generated in the fan-in device. The mode-coupling subsequently increases gradually along the 4CF. At the splicing points, although we observed small peaks due to the Fresnel reflection, the amount of mode-coupling remained unchanged after the Fresnel reflection. This indicates that the crosstalk caused by the fusion splicing is negligible. It is also seen that the largest mode-coupling occurs in the 4th stage located in the section from 45.6 to 60.8 km. This is because the MCF preform for the 4th stage is different from those for the other three stages. Here, since the OTDR method measures the mode-coupling that occurs in a round trip, we evaluate the crosstalk in the fan-in device and 4CF by halving the measurement results as shown on the left and right sides in Fig. 2(b), respectively. Thus, we could clarify that the crosstalk values in 4CF were around 1x10^{-5} between adjacent cores and around 1x10^{-7} between crossed cores.

Figure 3 shows the local mode-coupling when an optical pulse was coupled into core 2 from the opposite direction. This change is the same as that when Fig. 2(b) is rotated by 180 degrees, which confirms the reversibility of the mode-coupling characteristics with respect to the measurement direction [6].

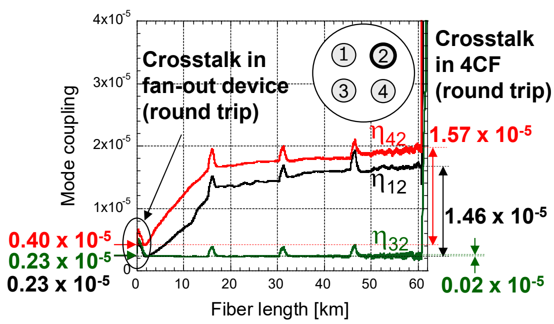

Fig. 3: Mode-coupling along the MCF when an optical pulse was coupled into the core 2 from the opposite direction.

Figure 4 shows the local mode-coupling when an optical pulse was coupled into core 3 from the forward direction. From the intercept at L=0, it can be seen that a relatively large crosstalk occurs between cores 1 and 3 of the fan-in device. On the other hand, the crosstalk in 4CF was around 1x10^{-5} between adjacent cores similar to Fig. 2(b). It is interesting to see that the crosstalk values in the fan-in/out devices and 4CF can be separately evaluated with a high dynamic range of 85 dB.

Table 1 shows the crosstalk values in the fan-in device, 4CF, and fan-out device measured with the OTDR method. The total crosstalk values between adjacent cores and crossed cores were -50.7~-45.8 dB and -55.9~-53.4 dB, respectively.

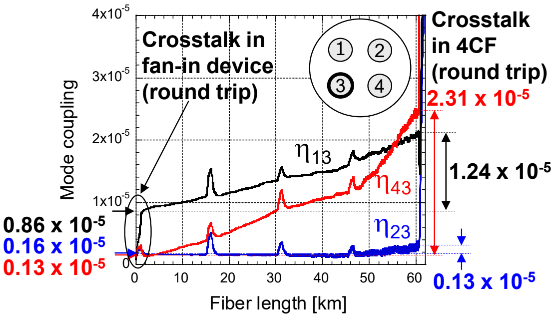

Fig. 4: Mode-coupling along the MCF when an optical pulse was coupled into the core 3 from the forward direction.

A large crosstalk occurred between the crossed cores due to the fan-in/out devices, although the crosstalk along the 4CF was negligible. These clarifications are not possible with the conventional transmission method.

Tab. 1: Comparison of crosstalk values obtained with the OTDR and transmission methods in 4CF cable.

		OTDR method				Transmission method
		Fan-in	4CF	Fan-out	Total	
Adjacent cores	Cores 1↔2	0.09 x 10^{-5}	0.625 x 10^{-5}	0.13 x 10^{-5}	0.845 x 10^{-5} (-50.7 dB)	-50.0 ± 0.3 dB
	Cores 1↔3	0.35 x 10^{-5}	0.535 x 10^{-5}	0.30 x 10^{-5}	1.185 x 10^{-5} (-49.3 dB)	-48.1 ± 0.4 dB
	Cores 2↔4	0.11 x 10^{-5}	1.02 x 10^{-5}	0.24 x 10^{-5}	1.37 x 10^{-5} (-48.6 dB)	-48.3 ± 0.3 dB
	Cores 3↔4	0.09 x 10^{-5}	1.315 x 10^{-5}	1.25 x 10^{-5}	2.655 x 10^{-5} (-45.8 dB)	-46.1 ± 0.3 dB
Crossed cores	Cores 1↔4	0.15 x 10^{-5}	0.012 x 10^{-5}	0.29 x 10^{-5}	0.452 x 10^{-5} (-53.4 dB)	-52.2 ± 0.6 dB
	Cores 2↔3	0.08 x 10^{-5}	0.027 x 10^{-5}	0.15 x 10^{-5}	0.257 x 10^{-5} (-55.9 dB)	-52.6 ± 0.9 dB

Finally, we compare the present crosstalk values with those obtained with the transmission method [10]. Table 1 and Fig. 5 show the crosstalk values obtained with the transmission method in blue, where the measurement error was within 1 dB. The results obtained with the present OTDR method are shown in red. It can be seen that there is good agreement between the OTDR and transmission methods, which indicates that the present OTDR method is highly advantageous since single-end measurement is possible with the same accuracy as with the transmission method. In Fig. 5, the crosstalk values between cores 2 and 3 exhibit a relatively large deviation, where the measurement error appears large on a logarithmic scale since the crosstalk value is very small.

Conclusions

We described the precise distributed measurement of mode-coupling along a cabled 60 km-long 4CF for submarine transmission using a multi-channel OTDR. The crosstalk values in the fan-in/out devices and 4CF were evaluated separately with a dynamic range as high as 85 dB. The present OTDR method is expected to constitute a very powerful tool for measuring local mode coupling in detail along an installed MCF from one end of the fiber.

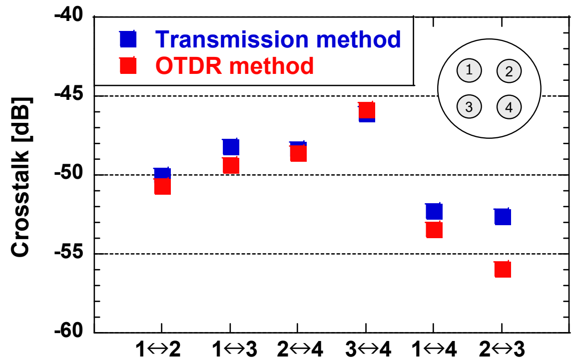

Fig. 5: Comparison of measured crosstalk values in 4CF cable obtained with the OTDR and transmission methods.

Acknowledgements

This work was supported by the Ministry of Internal Affairs and Communications (MIC), OCEANS (JPMI00316).

References

[1] D. Soma, Y. Wakayama, S. Beppu, S. Sumita, T. Tsuritani, T. Hayashi, T. Nagashima, M. Suzuki, M. Yoshida, K. Kasai, M. Nakazawa, H. Takahashi, K. Igarashi, I. Morita, and M. Suzuki,, "10.16-peta-b/s dense SDM/WDM transmission over 6-mode 19-core fiber across the C+L band," J. Lightwave Technol. vol. 36, no. 6, pp. 1362-1368 (2018).

[2] G. Rademacher, B. J. Puttnam, R. S. Luís, J. Sakaguchi, W. Klaus, T. A. Eriksson, Y. Awaji, T. Hayashi, T. Nagashima, T. Nakanishi, T. Taru, T. Takahata, T. Kobayashi, H. Furukawa, and N. Wada, "10.66 Peta-Bit/s Transmission over a 38-Core-Three-Mode Fiber," OFC2020, paper Th3H.1.

[3] R. Ryf, N. K. Fontaine, S. H. Chang, J. C. Alvarado, B. Huang, J. Antonio-Ĺopez, H. Chen, R.-J. Essiambre, E. Burrows, R. W. Tkach, R. Amezcua-Correa, T. Hayashi, Y. Tamura, T. Hasegawa, and T. Taru, "Long-haul transmission over multi-core fibers with coupled cores," ECOC2017, paper M.2.E.1.

[4] D. Soma, S. Beppu, H. Takahashi, N. Yoshikane, I. Morita, and T. Tsuritani, "Performance comparison for standard cladding ultra-low-loss uncoupled and coupled 4-core fibre transmission over 15,000 km," ECOC 2020, paper Mo2E.4.

[5] D. Soma, S. Beppu, S. Sumita, H. Takahashi, N. Yoshikane, I. Morita, and T. Tsuritani, and M. Suzuki, "Trans-Pacific class transmission over a standard cladding ultralow-loss 4-core fiber," Opt. Express, vol. 30, no. 6, pp. 9482-9493 (2022).

[6] M. Nakazawa, M. Yoshida, and T. Hirooka, "Nondestructive measurement of mode couplings along a multi-core fiber using a synchronous multi-channel

OTDR," Opt. Express, vol. 20, no. 11, pp. 12530–12540 (2012).

[7] M. Nakazawa, M. Tokuda, and Y. Negishi, "Measurement of polarization mode coupling along a polarization maintaining optical fiber using a backscattering technique," Opt. Lett., vol. 8, no. 10, pp. 546–548 (1983).

[8] M. Nakazawa, N. Shibata, M. Tokuda, and Y. Negishi, "Measurements of polarization mode couplings along polarization-maintaining single-mode optical fibers," J. Opt. Soc. Am. A, vol. 1, no. 3, pp. 285–292 (1984).

[9] M. Kobiki, H. Hayashi, J. C. Aquino, D. Masuda, S. Fujihara, "Latest high fiber count submarine cable," OECC/PSC2019, paper WC2-2.

[10] T. Hayashi, T. Taru, O. Shimakawa, T. Sasaki, and E. Sasaoka, "Characterization of crosstalk in ultra-low-crosstalk multi-core fiber," J. Lightwave Technol., vol. 30, no. 4, pp. 583-589 (2012).