Behavior of Inter-core Crosstalk of Two-core Fiber in Submarine Cable

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Abstract: We study inter-core crosstalk of two-core fiber in a submarine cable and show the crosstalk in cable is improved by 12 dB compared with that on fiber spool thanks to the heterogeneous core configuration.

1. Introduction

Spatial division multiplexing (SDM) is now the most promising way to increase the capacity and to improve the power efficiency of submarine cables. Two-core fiber (2CF) is going to be introduced to the next generation of spatial division multiplexing in submarine cables [1], and the 2CF was also successfully developed for mass-production [2]. One of the most important optical characteristics of uncoupled multi-core fibers (MCFs), including 2CFs, is inter-core crosstalk (XT) because high XT causes additional noise and consequently degrades the system SNR. Therefore, XT should be managed for applying uncoupled MCFs to the submarine cables. One of the complexities in managing the XT might be its dependence on bending and twisting of the MCF, resulting in possible variation in XT during cable production. For preventing XT degradation in cable production, heterogeneous core MCF is anticipated to be effective because it causes the XT to decrease as the bending radius increases [3,4], and the fiber bending radius generally increases in cabling process. However, the effectiveness of heterogeneous core MCF in reducing the XT in a submarine cable has not been reported.

In this paper, 2CF with heterogeneous core and submarine cable was manufactured and the XT was evaluated before and after cabling. We show that the XT in the cabled fiber was improved by 12 dB from that of the spooled fiber wound on a bobbin. These results show that the submarine cable using the 2CF should be effective to prevent the XT affecting the SNR performance.

2. XT in spooled heterogeneous 2CF

It is known that the XT has bending radius dependence due to the effective refractive index variation induced by bending. In the homogeneous-core configuration, bending promotes the difference between the effective indexes of the cores resulting in the reduction of the XT. Therefore, the XT increases as the bending radius increases because the effective index difference due to bending decreases. On the other hand, in the heterogeneous configuration, the XT is theoretically predicted to have a maximum value at the critical bending radius R_{pk} where the effective indexes of the cores match. Then the XT decreases as the bending radius increases beyond R_{pk}. Therefore, a heterogeneous-core configuration whose R_{pk} becomes smaller than the bending radii that occur in submarine cables would be effective to realize a low XT in the actual cables.

We fabricated a heterogeneous-core 2CF, which characteristics are summarized in Tab. 1. A 20-km length section of the 2CF was wounded on a spool with an inner diameter of 168 mm. The effective index difference between the cores was designed to be on the order of 10^{-4}. The XT was measured by wavelength scanning method with continuous-wave (CW) tunable light source (TLS) as shown in fig. 1(a). To compensate the difference of insertion loss of FIFO (Fan-in, Fan-out), we also measured XTs in case that the FIFOs were connected to the other end of fiber each other as shown in fig. 1(b) and these measured values were averaged in dB scale separately at each end. The measured co-propagating XT (XT_{co}) and counter-propagating XT ($XT_{counter}$) were -35 dB and -66 dB, respectively. They correspond to -28 dB/100 km (XT_{co}) and -50 dB at 100 km ($XT_{counter}$), respectively. The longitudinal dependence of XT_{co} was also evaluated using a single channel OTDR with optical switches as shown in fig. 1(c) [5]. When the pulse signal from a laser diode (LD) was launched into a core of the 2CF, the backscattered power from the cores were detected corresponding to the selected path with the optical switches. Because the XT signal was small, a relatively wide pulse width of 20 μs was used for enhancing the SNR. Figure 2 shows the longitudinal dependence of XT_{co} of the 2CF. There is a dead-zone from 0 to ~4 km because the long pulse width of OTDR caused a large reflection at the input end. Here we define End A and End B as the beginning and end of the winding, respectively. The bending diameter becomes larger from End A towards End B. We can see that the XT_{co} is accumulated along with the propagation and that there is a difference how the XT accumulates depending on the test signal input end. This is because the bending radius changes along the fiber length and the power coupling coefficient also changes [6].

Table 1. Characteristics of fabricated 2CF at 1550 nm.

Length [km]	Aeff [μm²]	Loss [dB/km]	XT_{co} [dB]	$XT_{counter}$ [dB]
20	114	0.154	-35	-66

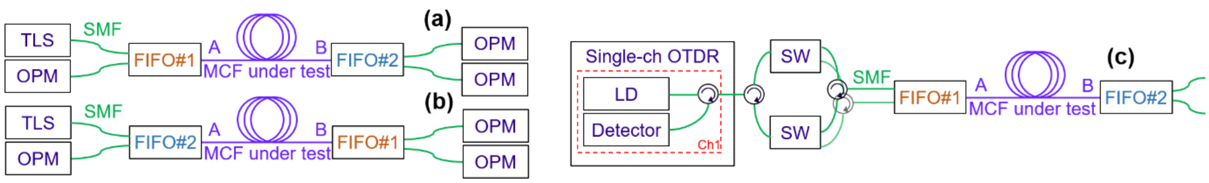

Fig.1 Experimental setup for (a) direct power measurement using CW light source, (b) the same method as (a) with the FIFOs connected to the other end each other and (c) distributed XT measurement using single-channel OTDR. LD: laser diode, TLS: tunable light source, OPM: optical power meter and SW: optical switch.

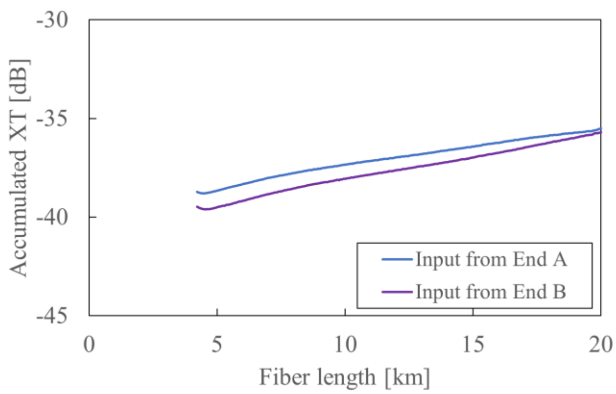

Fig.2 Longitudinal dependence of XT_{co} for spooled 2CF

3. XT in submarine-cabled 2CF

Following, we manufactured submarine cable with the 2CF described in the previous section. We selected standard 17 mm submarine cable as shown in fig.3 that can support up to 32 fibers with 250 μm diameter. Notably, the 3-divided steel segments design has proved to not affect fiber attenuation caused by the cabling process [8]. We evaluated the XT of the cabled fiber in the same way as for the spooled fiber. The measured results are summarized in Table 2. The XTs of the cable were improved about 12 dB in comparison with the spooled fiber. This is because the 2CF has the heterogeneous configuration as explained in the previous section. Figure 4 shows the longitudinal dependence of XT_{co} of the cabled fiber measured by OTDR method. The XT_{co} of the spooled fiber is also plotted for comparison. As can be seen from the figure, the accumulated XT_{co} of the 20 km cable is lower by more than 13 dB compared with that of the fiber. We can also see a slight difference of 3×10^{-6} between the input ends, which is considered to be caused by limited dynamic range of the measurement setup. The measured $XT_{counter}$ was close to the lower limit. Therefore, we estimated $XT_{conuter}$ from the measured XT_{co}. XT_{conter} can be expressed as [7],

$$XT_{counter} = XT_{co}\frac{S\alpha_R}{\alpha}\left[\frac{\sinh(\alpha L)}{\alpha L} - \exp(-\alpha L)\right]$$

where S is the proportion of the Rayleigh scattering component recaptured into the backward direction, α_R is the Rayleigh scattering loss coefficient, α is the transmission loss, and L is the length of the fiber. S can be expressed as,

$$S \simeq \frac{3\lambda^2}{8\pi n^2 A_{eff}}$$

where λ, n, and Aeff are the wavelength, refractive index, and effective area, respectively. Using these equations, $XT_{counter}$ of the cable is calculated as -79 dB. In order to confirm the accuracy of this estimation, the $XT_{counter}$ of the spooled fiber in the previous section was also evaluated. The calculated $XT_{counter}$ was -67 dB, which was good agreement with the measured result. Therefore, the calculated $XT_{counter}$ of the cable would be estimated with good accuracy. $XT_{counter}$ of -79 dB at 20 km corresponds to -62 dB at 100 km.

In this work we measured the XTs with wavelength scanning method and OTDR method. OTDR is a widely used method for measuring a transmission loss and finding failures such as fiber breaks in the optical fibers. Generally, all fibers are tested using OTDR, therefore, it is preferable to be measured XTs and transmission loss or position of fiber failure simultaneously. However, it is difficult to measure XTs using of the shelf commercially available OTDR instruments, especially fibers with low XTs and long distance, due to the limited dynamic range. In addition, multi-channel OTDR would be also preferable in order to simplify the configuration of the measurement. Therefore, multi-channel OTDR with large dynamic range would be desirable for testing large amount of MCFs.

Table 2. Comparison of XTs of the 20 km-long 2CF before and after cabling.

	Bending diameter [mm]	XT_{co} [dB]	$XT_{counter}$ [dB]
Spooled fiber	168	-35	-66
Cabled fiber	2700	-47	-79 (calculated)

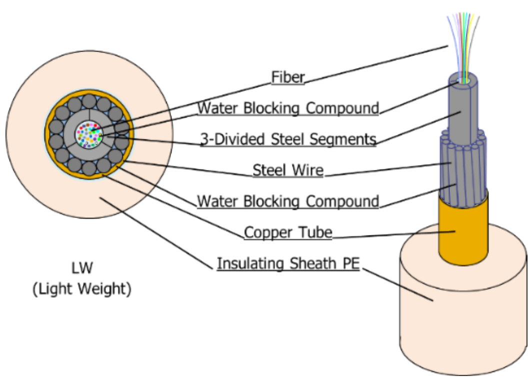

Fig.3 Schematic of manufactured submarine cable

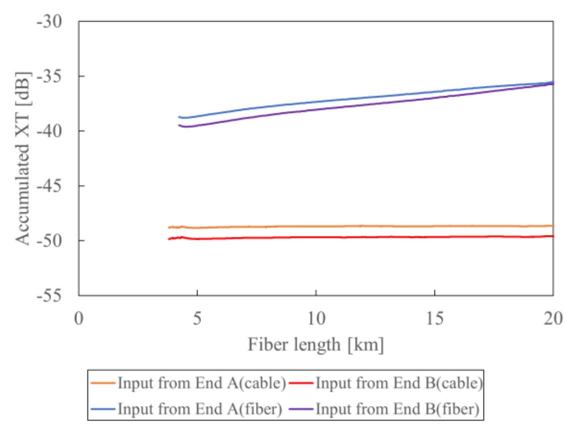

Fig.4 Longitudinal dependence of XT_{co} of spooled and cabled 2CF

4. Conclusions

We have manufactured a LW submarine cable with 2CF having heterogeneous core and evaluated the XT characteristic before and after cabling. We show that the XT in the cabled fiber was improved by 12 dB from that of the fiber wound on a bobbin. These results show that the submarine cable using the 2CF with heterogeneous core configuration should be effective to prevent the XT affecting the SNR performance.

5. References

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