

Quadratically Suppressed Accumulation of Crosstalk Between Second Neighboring Cores of Multi-Core Fiber Measured by Commercial Single-Channel OTDR

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Abstract—We experimentally confirmed that crosstalk between diagonal cores in 4-core fiber with 2x2-layout are suppressed quadratically compared to the crosstalk between nearest neighboring cores, with the distributed crosstalk measurement using commercial single-channel OTDR.

Keywords—optical fibers; multicore fibers; crosstalk

I. INTRODUCTION

Space division multiplexing has been attracted a lot of attentions to address the transmission capacity limit of single mode fiber and to realize power efficient optical fiber networks. Among various SDM fibers, multi-core fiber (MCF) is the strong candidate for practical transmission media. Crosstalk (XT) suppression is crucial for uncoupled MCF transmissions for using conventional SMF transceivers. Bidirectional MCF transmissions where signals propagate in counter direction between nearest neighboring cores are very effective to reduce XT [1,2]. In bidirectional MCF transmissions, three types of XT have to be taken account of: Rayleigh backscattered and back reflected XT from the counter-propagating signal in nearest neighboring cores, and indirect XT from the co-propagating signals in second neighboring cores via nearest cores (XT_{indir}). XT_{indir} can become a dominant XT source both long-haul and short-reach transmission systems when XT coefficient is high [3]. The XT_{indir} was theoretically predicted to quadratically grow within each span [4]; however, it has not been experimentally confirmed in details.

In this paper, we present the quadratic but suppressed accumulation of the XT_{indir} between the diagonal (second neighboring) cores of a 4-core fiber with square lattice (2x2) layout by using a commercial single-channel OTDR. The XT_{indir} was experimentally confirmed to be suppressed to the square of the direct XT of the co-propagating lights (XT_{dir}) between nearest neighboring cores in linear scale, i.e., twice XT_{dir} in dB scale—for example, XT_{indir} becomes 10^{-4} (−40 dB) when XT_{dir} is 10^{-2} (−20 dB). The experimental result also indicated that the XT_{dir} between the diagonal cores is negligibly low compared to the XT_{indir} .

II. INDIRECT XT IN 2X2-LAYOUT FOUR-CORE FIBER

XT_{indir} can be approximated as [4]:

$$XT_{indir} = \frac{1}{2}(hL)^2, \quad (1)$$

where h is the power coupling coefficient between the co-

propagating modes of nearest neighboring cores, and L is the fiber length. In the case of 2x2 layout MCF, the second neighboring core of a certain core is only one farthest core in diagonal position. However, the number of the indirect coupling paths from the certain core to its farthest core is two because both the certain core and its farthest core have the same two cores for their nearest neighboring cores, as shown in Fig. 1. Therefore, XT_{indir} from a certain core to its farthest core in 2x2 layout can be approximated as $(hL)^2$, i.e., twice the RHS of Eq. (1).

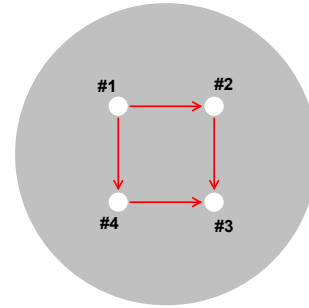


Figure 1. Schematic illustration showing the indirect XT from Core 1 to Core 3 has 2 paths via Core 2 and Core 4.

III. MEASUREMENT METHOD

XT_{dir} between nearest neighboring cores can be evaluated using multi-channel OTDR as [5]:

$$XT_{dir} = \frac{1}{2} \frac{P_{BSj}}{P_{BSi}}, \quad (2)$$

where P_{BSi} and P_{BSj} denote the backscatter powers from the cores that the signal pulses are and are not launched into, respectively. The factor of 1/2 is the correction of the propagation distance because the signal pulses make a round trip, and P_{BSj}/P_{BSi} gives the XT for twice the fiber length.

XT_{indir} between diagonal cores can also be evaluated OTDR signals, but the correction factor has to be modified. Because XT_{indir} grows quadratically with the propagation distance, the correction factor has to be $(1/2)^2$, and XT_{indir} can be evaluated as

$$XT_{indir} = \left(\frac{1}{2}\right)^2 \frac{P_{BSj}}{P_{BSi}}, \quad (3)$$

In this study, instead of multi-channel OTDR, we used a commercially available single-channel OTDR for XT measurements. Fig. 2 shows the experimental setup. The use

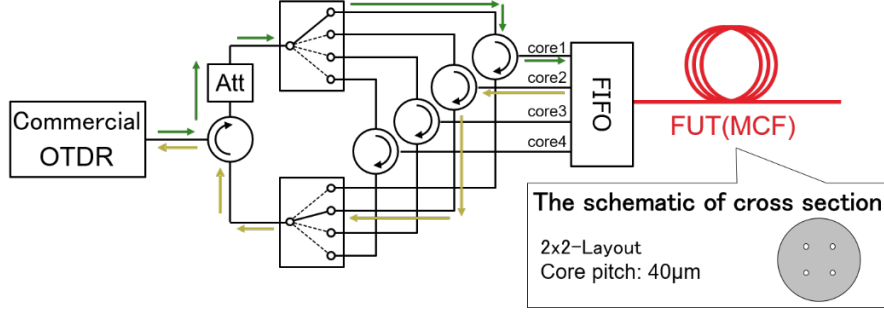


Figure 2. The experimental setup for distributed XT measurement using commercial single-channel OTDR.

of optical switches and circulators realized sequential measurement of multiple OTDR channels. For instance, the channel for the input to Core 1 and output from Core 2 is schematically shown with arrows in Fig. 2. The signals of the individual channels are measured not simultaneously but sequentially by changing the optical switching paths.

We used an optical attenuator for adjusting the optical pulse power such that we can measure the crosstalk signal with high input power and the through signal with low input power to avoid the saturation of the detector. The effect of launch power difference due to attenuation is numerically compensated by adding the values of attenuated power to the measured values. We used an external attenuator instead of the attenuator built in OTDR to achieve better accuracy. The attenuator was put on the common path between the OTDR and the optical switch in the launching side to avoid the channel dependent loss due to attenuators in the separate channels.

In order to precisely measure small signals of XT (especially XT_{indir}), we measured the background noise profile of the OTDR for the measurement distance range by shuttering the optical path in the attenuator, and all measured signal profiles were offset with the measured background noise profile in linear scale (not in log scale).

Table 1 shows the properties of the MCF under test. The length of the MCF was 47 km. The XT measurement was performed with a pulse width of 20 μ s at the wavelength of 1.55 μ m.

TABLE I. THE PROPERTY OF FIBER UNDER TEST

Items	Values
Number of cores	4
Layout of core	2x2 (square)
Core pitch	40 μ m
Clad diameter	125 μ m
MFD (1310 nm)	8.4 μ m
Attenuation coefficient (1550 nm)	0.188-0.190 dB/km
Cable cutoff wavelength	1226-1245 nm

IV. RESULTS AND DISCUSSIONS

Fig. 3 shows the result of the XT measurement with the single-channel OTDR with optical switches. The diamond shape marker indicates the transmission measurement results at the far end of the MCF. The solid lines are the theoretical lines. They are plotted as hL for nearest neighboring cores and $(hL)^2$ for diagonal cores, where h was obtained from the

average of XT_{dir} between nearest neighboring cores measured with transmission method.

The OTDR measurement result of the XT_{dir} between nearest neighboring cores agrees well with the theoretical line (the points are almost overlapped by the theoretical line), and the transmission measurement results. Thus, the XT was successfully measured with the commercial single-channel OTDR and the measurement setup shown in Fig. 2.

The OTDR measurement result of the XT between diagonal cores has larger noise because the measured signal was much lower than XT between nearest neighboring cores. However, the OTDR measurement result agrees both with the transmission measurement and the theoretical line $(hL)^2$. As discussed in Section III, we used the correction factor of $(1/2)^2$, not $1/2$. If we use the correction factor of $1/2$, it just increases the OTDR-measured values of the XT between diagonal cores by ~ 3 dB ($= 10\log_{10} 2$) without any change in its slope. Therefore, the result demonstrated that the XT between the diagonal cores grows quadratically in linear scale with the fiber length, i.e., grows in 20 dB/decade. This fact clearly validated that the XT between the diagonal cores is dominantly induced by XT_{indir} and the XT_{dir} between the diagonal cores has negligible impact in the square lattice layout. The results also confirmed that the XT_{indir} between the diagonal cores $[(hL)^2]$ is suppressed to the square of the XT_{dir} between nearest neighboring cores $[hL]$ in linear scale (twice the XT_{dir} in dB scale). Therefore, the XT_{indir} between the diagonal cores never surpass the XT_{dir} between nearest neighboring cores.

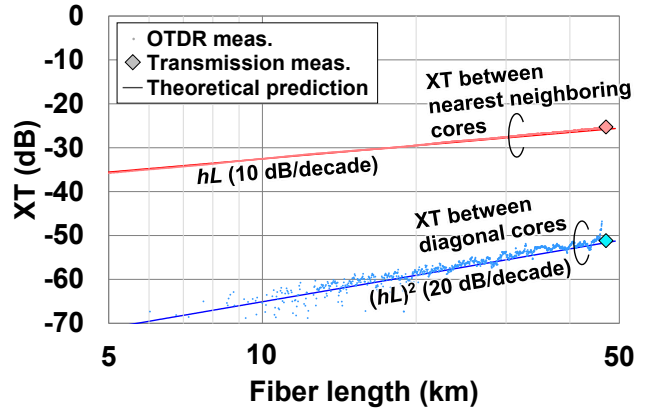


Figure 3. XT versus fiber length in the square-layout 4-core fiber. Note that $(hL)^2$ dependence of XT between diagonal cores is due to two paths as shown in Fig. 1.

V. CONCLUSION

Using the commercial single-channel OTDR, we measured the longitudinal accumulation profiles of the XT of the 4-core fiber with the square lattice layout. The XT between diagonal cores agreed with the square of the direct XT of the co-propagating lights between nearest neighboring cores. From the theoretical prediction [3,4], the experimental result validated that the XT between diagonal cores is dominantly induced by the indirect XT via nearest neighboring cores, and the direct XT between diagonal cores is negligible in the square lattice layout. The indirect XT quadratically accumulates in linear scale, i.e., grows with 20 dB/decade in dB scale, but always lower than the direct XT between nearest neighboring cores. These results strongly support the effectiveness of the XT suppression by the bidirectional MCF transmissions.

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