Method of Estimating Inter-Core Crosstalk for Constructing Uncoupled Multi-Core Fiber Transmission Line

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Abstract: We propose and experimentally demonstrate a method based on optical time domain reflectometry for evaluating splices in terms of ensuring the total end-to-end inter-core crosstalk of transmission lines consisting of uncoupled multi-core fibers.

1. Introduction

Uncoupled multi-core fibers (MCFs) are promising transmission media for achieving long-haul and large-capacity transmissions using space division multiplexing [1,2]. In particular, uncoupled MCFs with a standard cladding diameter have attracted attention because of their optical compatibility with current optical fiber technologies [3,4]. A key requirement for transmission systems using uncoupled MCFs is the total end-to-end inter-core crosstalk (XT) because the XT limits the transmission capacity and distance of the system [5,6]. The end-to-end XT depends on the loss of each core and mode coupling between cores. They occur not only in all system components but also at splice points generated during the construction of MCF transmission lines. The loss and mode coupling inherent in the system components can be guaranteed during their manufacturing. However, those induced by splices depend on the construction work quality, so telecommunications carriers have to evaluate them to suppress the end-to-end XT below an allowable value. If any abnormality in the splice point is found after finishing the construction of the whole transmission line, the cost effectiveness deteriorates because of the need to conduct repairs. Thus, we have to estimate the end-to-end XT during the construction phase to determine whether or not each splice is acceptable.

Optical time domain reflectometers (OTDRs) are widely-used tools for evaluating the construction work quality of splices because they can measure the loss distribution along the fiber by accessing from one end of the fiber. An OTDR-based technique for measuring the XT along MCFs has also been proposed [7,8]. However, this method may not be applicable because the XT is often too low to be measured directly with commercially available general-purpose OTDRs. Although the XT can be measured by introducing optical amplifiers or coherent detection into an OTDR, either leads to an increase in cost. To ensure minimal cost, we require a method for evaluating the effect of splices on the end-to-end XT using existing OTDRs rather than new instruments.

This paper first presents our investigation of how splices affect the end-to-end XT. On the basis of this investigation, we then propose a method to estimate the XT indirectly from the loss difference between cores that general-purpose OTDRs can easily measure. Finally, we describe a proof-of-concept experiment we conducted to demonstrate the feasibility of the method.

2. End-to-End Crosstalk of Spliced Uncoupled MCFs and Its Estimation Method

2.1 Matrix Propagation Model of Spliced MCFs

We consider an uncoupled MCF transmission line composed of N cascaded fiber sections. Also, we consider two adjacent cores and define the input and output vectors of $\mathbf{P}_{\mathrm{in}} = [1,\ 0]^{\mathrm{T}}$ and $\mathbf{P}_{\mathrm{out}} = [P_1,\ P_2]^{\mathrm{T}}$, respectively. The superscript T denotes the matrix transpose. The output vector $\mathbf{P}_{\mathrm{out}}$ can be expressed as

$$\mathbf{P}_{\mathrm{out}} = \mathbf{M}_N \mathbf{C}_{N-1} \mathbf{M}_{N-1} \mathbf{C}_{N-2} \cdots \mathbf{C}_3 \mathbf{M}_3 \mathbf{C}_2 \mathbf{M}_2 \mathbf{C}_1 \mathbf{M}_1 \mathbf{P}_{\mathrm{in}}, \tag{1}$$

$$\text{with} \quad \mathbf{M}_k = \exp\left(-\alpha_k L_k\right)\exp\left(-h_k L_k\right)\begin{bmatrix} \cosh\left(h_k L_k\right) & \sinh\left(h_k L_k\right) \\ \sinh\left(h_k L_k\right) & \cosh\left(h_k L_k\right) \end{bmatrix}, \quad \text{and} \quad \mathbf{C}_k = \begin{bmatrix} \eta_{k11} & \eta_{k12} \\ \eta_{k21} & \eta_{k22} \end{bmatrix}, \tag{2}$$

where $\mathbf{M}_k$, and $\mathbf{C}_k$ represent the transfer matrices of the k-th MCF and splice point, respectively. α_k, h_k, and L_k stand for the attenuation coefficient, power coupling coefficient, and length of the k-th section, respectively. η_{kij} represents the mode coupling efficiency from core j to core i at the k-th splice point. The diagonal and non-diagonal elements correspond to the loss of each core and the mode coupling between different cores, respectively. The end-to-end XT can be obtained as $\mathrm{XT} = 10\log_{10}(P_2/P_1)$ in decibels.

Assuming that splices are created every few kilometers, the non-diagonal elements at splice points are typically negligibly low compared with those in each MCF section. In other words, we can approximate non-diagonal elements at splice points by zero. We must emphasize that the scalar multiplication does not affect the end-to-end

XT, which is obtained from the ratio of transmitted power between two cores, because the scalar components of the matrices are commonly multiplied for each core. Therefore, the difference in splice losses between two cores is more important rather than the losses themselves for each core in terms of estimating the end-to-end XT.

2.2 Effect of Splices on End-to-End Crosstalk

We carried out numerical simulations to clarify how the difference in splice loss affects the end-to-end XT. We considered an MCF long-haul transmission line with a length of 80 km. Throughout the following simulations, the power coupling coefficient was set to 1.5×10^{-4} km^{-1}.

First, we investigated how the end-to-end XT changes with the difference in splice loss and its occurrence position. Figure 1(a) shows the contour diagram of XT when the transmission line has single splice point. The horizontal and vertical axes represent the distance at which the loss occurred and the difference in splice loss, respectively. We found from Fig. 1(a) that the higher the loss difference and the further its distance, the higher the XT. Next, we consider the transmission line had a splice point every 2 km, namely it had 39 splice points. Figure 1(b) shows the XT with respect to the transmission distance when all the splice losses of one core were 0.2 dB greater than those of the other. The blue and red lines represent the XT when the splice losses of the input core and adjacent core were higher than those of the other, respectively. The black line shows the XT when the transmission line had no loss difference for comparison. Figure 1(b) shows that the XT value increased when the splice loss of the input core was higher than that of the adjacent core, whereas the XT value decreased in the reverse case. We found from these results that high XT degradation occurred if the splice losses were inclined to one path. Finally, we investigated the statistical properties of the XT variations caused by differences in splice loss. Because analytical expressions are difficult to obtain for the statistical XT variations, we predicted the variations using the Monte Carlo method. Note that we only considered the stochastic variations of XT due to the difference in splice loss between two cores and did not take into account those caused by other factors such as the polarization state and mechanical stress. The loss differences for 39 splice points were randomly generated so that the loss difference was below a given value. Figure 1(c) shows the probability density of the XT for three conditions. The blue, red, and green lines represent the results for the loss differences below ±0.2, ±0.5, and ±1.0 dB, respectively. Figure 1(c) shows that the lower the loss difference, the lower the crosstalk variations. These results indicate that we need to evaluate the splice quality during the construction phase because the end-to-end XT strongly depends on the splice losses.

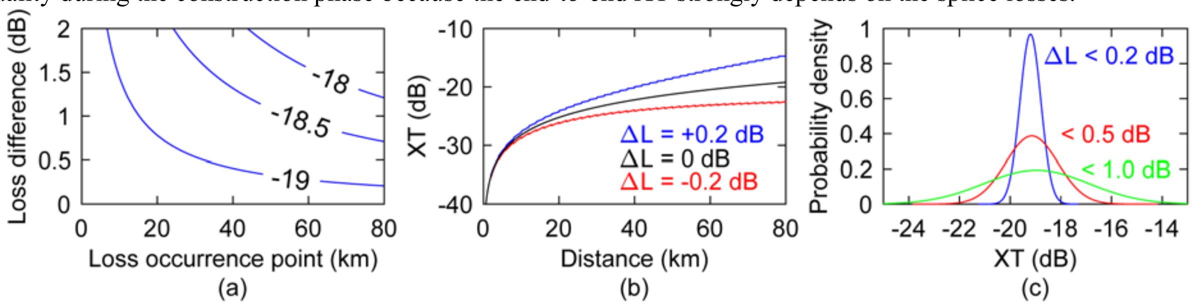

Fig. 1. Numerical results. (a) Contour diagram of XT. (b) XT with respect to transmission distance. (c) Probability density of XT for three differences in splice loss between cores.

2.3 Test Method for Estimating XT Using OTDR

We found from the investigations described in Sections 2.1 and 2.2 that the XT can be estimated using the power coupling coefficient, span length, difference in splice loss between two cores, and Eqs. (1) and (2). Because the power coupling coefficient and span length can be assessed at the manufacturing phase of MCFs, we only need to measure the splice loss difference. Also, the splice losses in each core can be measured using widely-used OTDRs just like in conventional single-mode fibers because the power coupling between cores is usually low in uncoupled MCFs. Moreover, assuming homogeneous MCFs, the splice loss difference between cores can be obtained without depending on the difference in the backscattering coefficients of the two spliced MCFs. Therefore, we propose a method to estimate end-to-end XT using the splice losses measured by using OTDR.

3. Proof-of-Principle Experiment

This section describes an experimental demonstration of the feasibility of the method. We prepared three uncoupled four-fibers with a standard cladding diameter of 125 μm as the fibers under test (FUTs). The FUTs had homogeneous cores with a step-index profile. The core pitch was 40 μm. The mode field diameter at the wavelength of 1310 nm and cable cutoff wavelength were around 8.8 μm and 1250 nm, respectively. The attenuation and power coupling coefficients at the wavelength of 1550 nm were 0.19 dB/km and 1.5×10^{-4} km^{-1}, respectively. The lengths of the two FUTs were 2 km, and that of the other one was 6 km. We composed an MCF transmission line for the entire length of 10 km by connecting the three FUTs using a fusion splicer. We measured the splice losses of each core in the MCF line using an OTDR and estimated the end-to-end XT with the method described in the previous section. We also measured the end-to-end XT by measuring the transmitted power for the sake of comparison.

Figure 2 shows the experimental setup for measuring the splice losses and the end-to-end XT. For the splice loss measurements, we used an OTDR and a fan-in device. The insertion losses of the fan-in device were 0.84, 0.89, 0.99, and 0.92 dB for cores #1 to #4, respectively, including the fusion splice losses between the device and MCF. The XT of the fan-in device was less than 50 dB, which is negligibly low compared with what occurs in one span of the MCF. Regarding the end-to-end XT measurements, we used an amplified spontaneous emission light source (ASE) and an optical bandpass filter (OBPF) to generate the test light with the center wavelength of 1550 nm and the 3-dB bandwidth of 3 nm. The test light was launched into one core of the FUT through the aforementioned fan-in device. The optical power from the input core and that from the adjacent core were measured using a multi-channel optical power meter. The insertion losses of the fan-out device were 0.97, 0.86, 0.73, and 0.93 dB for cores #1 to #4, respectively. The end-to-end XT was obtained as the ratio of the power of the adjacent core to that of the input core.

Figure 3(a) shows an example of OTDR waveforms. The blue, red, green, and black lines indicate the results for cores #1 to #4, respectively. The splice losses at the first splice point were 0.30, 0.54, 0.36, and 0.20 for each core. Those at the second splice point were 2.51, 1.42, 1.25, 2.21, respectively. Figure 3(b) shows the end-to-end XT when the splice losses of each core were as shown in Fig. 3(a). The blue circles and red triangles represent the results obtained with the transmission and proposed methods, respectively. The broken line indicates the XT when the transmission line has no difference in splice loss for reference. Figure 3(b) shows that the XT estimated with our method agreed well with that measured using the transmission method. Figure 3(c) shows the XT with respect to the loss difference between cores #1 and #2 at the first splice point. Note that the losses at the second splice point were fixed in the state shown in Fig. 3(a). A positive and negative loss difference indicates that the splice loss of core #1 is higher than that of core #2 and vice versa. The solid lines and open circles represent the estimated and measured XT, respectively. Figure 3(c) shows that the measured and estimated XT were in good agreement. From these results, we conclude that our method is useful for evaluating the quality of splices in their construction phase.

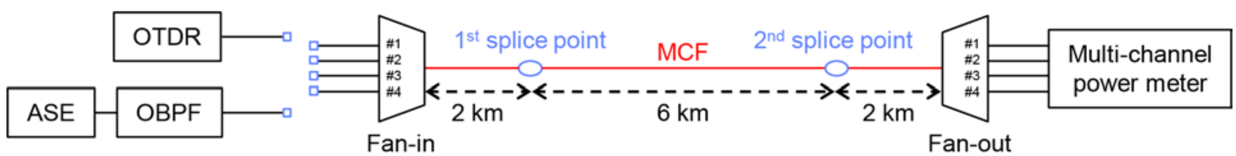

Fig. 2. Experimental setup for measuring splice losses and end-to-end XT.

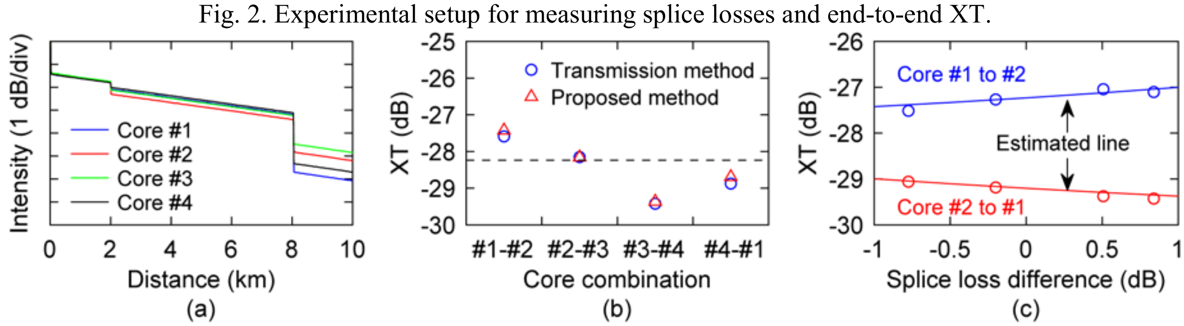

Fig. 3. Experimental results. (a) Example of OTDR waveforms. (b) XT obtained with the transmission and proposed methods. (c) XT with respect to loss difference between cores #1 and #2 at the first splice point.

4. Conclusion

We investigated how splices affect end-to-end XT and then proposed a method for estimating the XT from the loss difference between cores. The feasibility was demonstrated through experiments. The method would be useful for evaluating the quality of splices during the construction phase of MCF transmission lines because it enables us to estimate the XT from the splice losses that widely-used OTDRs can easily measure.

5. References

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