Impact of Splice Loss on Inter-Core Crosstalk in Bidirectional Multi-Core Fibre Transmission and Its Estimation Method

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Abstract *We clarify how splices affect inter-core crosstalk in bidirectional transmission systems using uncoupled multi-core fibres. We also propose a method based on optical time domain reflectometry for estimating the impact of splices on the crosstalk in bidirectional systems. ©2022 The Author(s)*

Introduction

Uncoupled multi-core fibres (MCFs) are being intensively studied as next-generation optical fibres for achieving long-haul and large-capacity transmissions [1-3]. Low inter-core crosstalk (XT) is a key requirement for transmission systems using MCFs [4,5]. In unidirectional transmission systems, the capacity is limited by forward XT. An attractive approach for suppressing XT is bidirectional transmission [6-8], in which data signals in adjacent cores in an MCF are transmitted in opposite directions. In such bidirectional transmission systems, the capacity is often limited by backward XT.

The XT level is determined by the loss and mode coupling between the cores. A recent study clarified that the forward XT strongly depends on the splice losses [9]. To maintain the XT below an acceptable level, telecommunications carriers have to evaluate the splice losses when constructing MCF transmission lines using, for example an optical time domain reflectometer (OTDR) that can measure the loss distribution along the lines. However, it had not yet been clarified how splices affect backward XT and how the impact of splices on backward XT can be evaluated.

In this paper, we investigated how splices affect backward XT. We also developed a method using a widely used OTDR for estimating the impact of splices on backward XT. We describe a proof-of-concept experiment we conducted to evaluate the feasibility of the method.

Impact of splice loss on backward XT and its estimation method

Let us consider a pair of two adjacent cores in an MCF transmission line composed of N cascaded fibre sections. Cores 1 and 2 respectively transmit data signals from right to left and vice versa, as shown in Fig. 1. Backward XT is defined as the ratio of an undesired noise power, which is generated through Rayleigh scattering and mode coupling between the cores, to the desired signal power.

We define input vector $\mathbf{P}_{\text{in}2}$ as $[0, P_0]^{\text{T}}$, which corresponds to the input signal for core 2. The superscript T indicates the matrix transpose. The backscattered power of $\mathbf{P}_{\text{bs}} = [P_{\text{bs}1}(z), P_{\text{bs}2}(z)]^{\text{T}}$ returning from the distance z to the left side can then be given by

$$\mathbf{P}_{\text{bs}}(z) = \begin{bmatrix} P_{bs1}(z) \\ P_{bs2}(z) \end{bmatrix} = \mathbf{H}_{\text{b}}\mathbf{M}_{N'}\mathbf{K}_{\text{bs}}\mathbf{M}_{N'}\mathbf{H}_{\text{f}}\mathbf{P}_{\text{in}2}, \quad (1)$$

with

$$\mathbf{H}_{\text{b}} = \prod_{i=1}^{N'-1}\mathbf{M}_i\mathbf{C}_i \quad \text{and} \quad \mathbf{H}_{\text{f}} = \prod_{j=1}^{N'-1}\mathbf{C}_j\mathbf{M}_j, \quad (2)$$

where N' stands for the number of splices that exist from the left side to z. $\mathbf{M}_j$ and $\mathbf{C}_j$ represent the transfer matrices of the j-th MCF and splice point counting from the left side, respectively. Assuming that the splices are created every few kilometres, the mode coupling between different cores at splice points are often negligibly low compared with that in each MCF section. Therefore, we can express the transfer matrix at a splice point as $\mathbf{C}_k = \text{diag}[\eta_{1j}, \eta_{2j}]$, where η_{1j} and η_{2j} correspond to the splice losses at the j-th splice point for cores 1 and 2, respectively. The notation $\mathbf{K}_{\text{bs}}$ denotes the matrix of Rayleigh backscattering, which can be regarded as a constant in uncoupled MCFs with homogeneous cores. The undesired noise power can be expressed as

$$P_{\text{noise}} = \sum_{z=0}^{L} P_{bs1}(z), \quad (3)$$

where L represents the entire length of the MCF transmission line. Next, we define the input vector $\mathbf{P}_{\text{in}1} = [P_0, 0]^{\text{T}}$, which corresponds to the input signal for core 1. Then, the output vector $\mathbf{P}_{\text{out}}$ can be given by

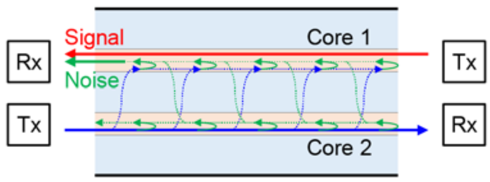

Fig. 1: Diagram of bidirectional MCF transmission.

$$\mathbf{P}_{\text{out}} = \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} = \mathbf{M}_N \left(\prod_{k=1}^{N-1} \mathbf{C}_k \mathbf{M}_k \right) \mathbf{P}_{\text{in}1}. \qquad (4)$$

The desired signal power can be expressed as $P_{\text{signal}} = P_1$. The forward and backward XT can be obtained as $\text{XT}_\text{f} = 10\log_{10}(P_2/P_1)$ and $\text{XT}_\text{b} = 10\log_{10}(P_{\text{noise}}/P_{\text{singal}})$, respectively, in decibels.

We carried out numerical simulations to clarify how splices affect backward XT. Throughout these simulations, the power coupling and attenuation coefficients were set to 1.3×10^{-4} km^{-1} and 0.19 dB/km, respectively.

We first considered a 20-km long MCF transmission line with a splice point every 2 km, namely 9 splice points. Since the values of splice losses are random in practice, we predicted the statistical properties of backward XT variations due to the splices by using the Monte Carlo method. We also predicted forward XT for the sake of comparison. Note that we only considered the stochastic variations of XT due to splice losses and did not take into account those caused by other factors such as the polarization state. The splice losses for each core were generated as uniformly distributed random values from a given range. Figure 2 shows the probability density of XT under three conditions, where (a) and (b) represent the results for forward and backward XT, respectively. The blue, red, and green lines indicate the results when the average splice losses $\bar{\gamma}$ were 0.2, 0.5, and 1.0 dB, respectively. We found that the higher the splice loss, the higher the variations occur both in forward and backward XT. It must be emphasized that although the mean levels of the forward XT were unchanged with the splice loss levels, those of the backward XT worsened with increasing splice loss levels.

Next, we investigated how the mean XT and standard deviation change with the number of splices. In this simulation, we fixed the entire length of the MCF transmission line to 20 km. We assumed that splices are placed at equal intervals. We then predicted the mean XT and standard deviation of the forward and backward XT using the Monte Carlo method. The splice losses were generated as uniformly distributed random values with the average value of 0.5 dB. Figure 3 shows the statistical properties of the forward and backward XT, where (a) and (b) represent the results for the mean XT and standard deviation, respectively. The blue and red lines indicate the results for the forward and backward XT, respectively. We found that the mean value of the forward XT did not change with the number of splices, whereas that of the backward XT increased. Moreover, the standard deviations both for the forward and backward XT increased with the number of splices, and the growth in the backward XT was slightly larger than that in the forward XT. These results indicate that backward XT is more sensitive to splices than forward XT. To construct MCF transmission lines with an acceptable level of backward XT, evaluating the impact of the splice losses on backward XT will be essential.

The aforementioned investigations showed that backward XT can be estimated using the transfer matrices of MCF spans, Rayleigh backscattering, and splices. Since the transfer matrices of each MCF span and Rayleigh backscattering can be assessed at the manufacturing phase of MCFs, all we have to do is measure the splice losses of each core. Thus, our proposed method estimates the backward XT from the splice losses measured using an OTDR.

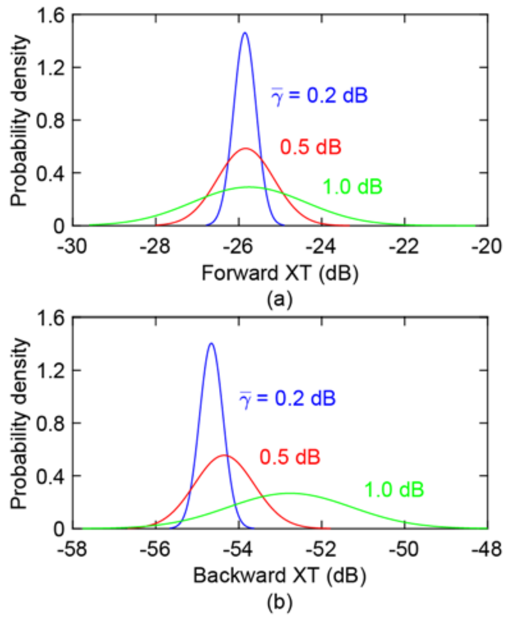

Fig. 2: Probability density of (a) forward XT and (b) backward XT.

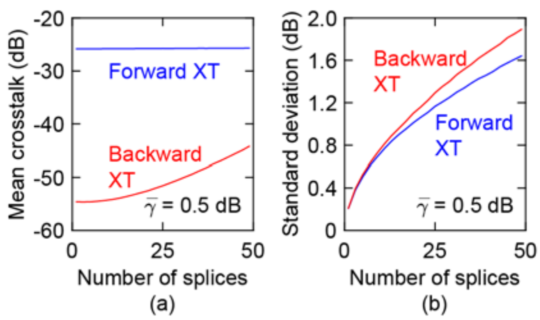

Fig. 3: Statistical properties of forward and backward XT: (a) mean XT and (b) standard deviation.

Experiments

We prepared ten uncoupled four-core fibres (4CFs) with a standard cladding diameter of 125 μm. The 4CFs were made from the same preform. The core pitch was 40 μm. The optical characteristics of each core complied with ITU-T G.652 [10]. The length of each 4CF was 2 km. We composed an MCF transmission line with the entire length of 20 km as a fibre under test (FUT) by splicing the five FUTs using a fusion splicer. We measured the splice losses of each core in the FUT using an OTDR and estimated the backward XT with the method described in the previous section. We also measured the forward and backward XT by using the conventional transmission method for the sake of comparison.

Figure 4 shows OTDR waveforms, where (a) and (b) represent the results when the FUT had low and high splice losses, respectively. The blue, red, green, and black lines indicate the results for cores 1 to 4, respectively. We confirmed that the average splice losses were about 0.26 and 0.86 dB, as shown in Figs. 4(a) and 4(b), respectively.

Figure 5 shows the forward and backward XT, where (a) and (b) represent the results when the FUT had low and high splice losses, respectively. The horizontal and vertical axes indicate the core pair and XT level, respectively. The blue circles and red triangles represent the forward and backward XT obtained with the transmission method, respectively. The green squares indicate the backward XT estimated with the proposed method. The broken lines show the average XT level over each core pair for reference. As mentioned in Section 2, the average levels of the forward XT in Figs. 5(a) and 5(b) were almost the same regardless of whether the splice losses in the FUT were low or high. The average level of the backward XT in Fig. 5(b), however, was 2.3 dB larger than that in Fig. 5(a). This degradation in the backward XT level is attributed to the higher splice losses. We also confirmed that the backward XT estimated with our method agreed well with that measured using the transmission method.

We conclude from these results that splice losses should be tested to keep backward XT below a desired level, and our method is useful for evaluating whether the quality of splices is acceptable from the perspective of keeping backward XT low.

Conclusions

We investigated how splices affect backward XT in uncoupled MCF transmission lines. On the basis of our investigation, we proposed a method using a widely used OTDR for estimating the impact of splices on the backward XT. We experimentally clarified that high splice losses can degrade backward XT. We also experimentally verified that our method can estimate the impact of splices on backward XT.

The findings of this study will be useful for determining the acceptable splice loss levels before constructing MCF transmission lines. We also believe that our method will be widely used as a test method of splices when constructing MCF transmission lines since it can be easily implemented using the widely used OTDR.

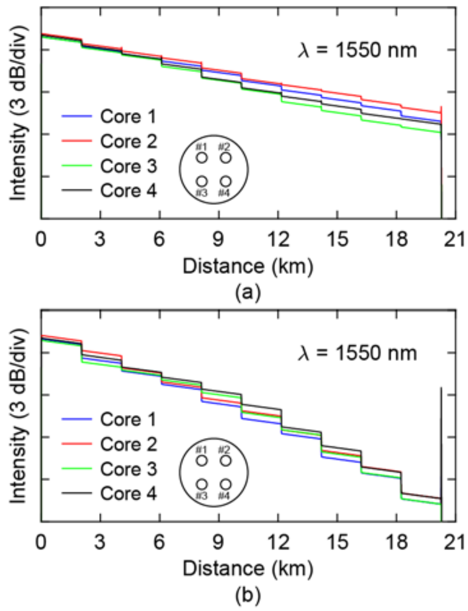

Fig. 4: OTDR waveforms when splice losses in FUT were (a) low and (b) high.

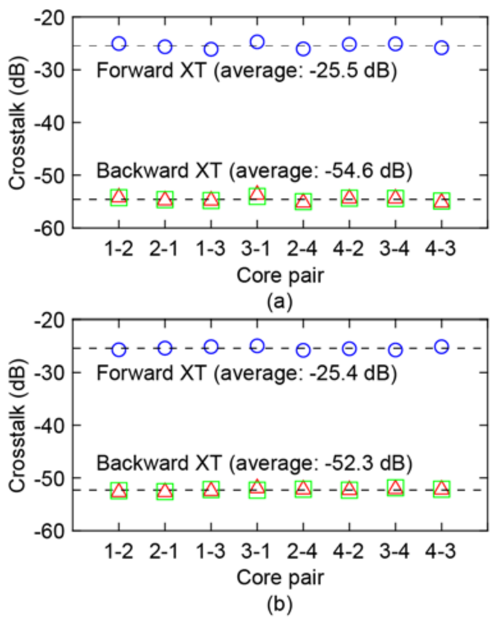

Fig. 5: Forward and backward XT when splice losses in FUT were (a) low and (b) high.

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