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Dependence of Q^2 on inter-core skew and mode-dependent loss in long-haul coupled-core multicore fibre transmission

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Abstract *We experimentally evaluate the dependence of the Q^2 on inter-core skew and mode-dependent loss in long-haul coupled-core four-core fibre transmission. A skew within less than 200 ps per span is required for 6,020-km transmission. Large Q^2 degradation and fluctuation and are observed due to MDL. ©2022 The Author(s)*

Introduction

Coupled-core multicore fibre (CC-MCF) has attracted attention as a future high-capacity long-haul transmission medium [1-4]. In CC-MCFs, the inter-core crosstalk (XT) can be compensated by receiver-side multiple-input multiple-output digital signal processing (MIMO DSP), and the distance between the cores can be reduced. Therefore, CC-MCFs can accommodate more cores than uncoupled MCFs with the same cladding diameter.

However, mode-dependent loss (MDL) and inter-spatial channel skew are problems specific to MIMO transmission systems [3]. The inter-core skew occurs in a repeater when conventional erbium-doped fibre amplifiers (EDFAs) for single core fibre are employed with a fan-in fan-out (FIFO) device. The skew as well as the spatial mode dispersion (SMD) of the fibre itself increases the impulse response width. When the impulse response width exceeds the time window for the finite impulse response (FIR) filters implemented in MIMO DSP, Q^2 degradation will occur. Because the time window for FIR filters is limited by hardware resources, the skew should be mitigated span by span as much as possible. However, the requirement of skew has not been studied in detail yet.

One way to avoid the skew is to use MCF devices such as MC-EDFA in a transmission link and remove FIFOs [4,5]. However, reported MCF devices have a nonnegligible MDL of ~1 dB. Because MDL results in degradation of orthogonality between spatial channels, Q^2 degradation will occur [4-8]. In addition, the Q^2 in CC-MCFs can vary with time due to the drift of the MIMO channel, which is much faster than that in conventional single mode fibres [9]. However, the stochastic behaviour of the Q^2 due to MDL has not been studied in detail.

In this work, we experimentally investigate the effect of skew and MDL on the Q^2 in long-haul CC-MCF transmission systems. The Q^2 were measured with varying skew and MDL. The skew requirement of 200 ps/span is confirmed for 6,020-km transmission assuming 100 spans and 6.25-ns time window for FIR filters. MDL not only degrades the average value of the Q^2 but also leads to significant deviations, especially in long-haul transmission systems.

Experimental Setup

The experimental setup is shown in Fig. 1. The

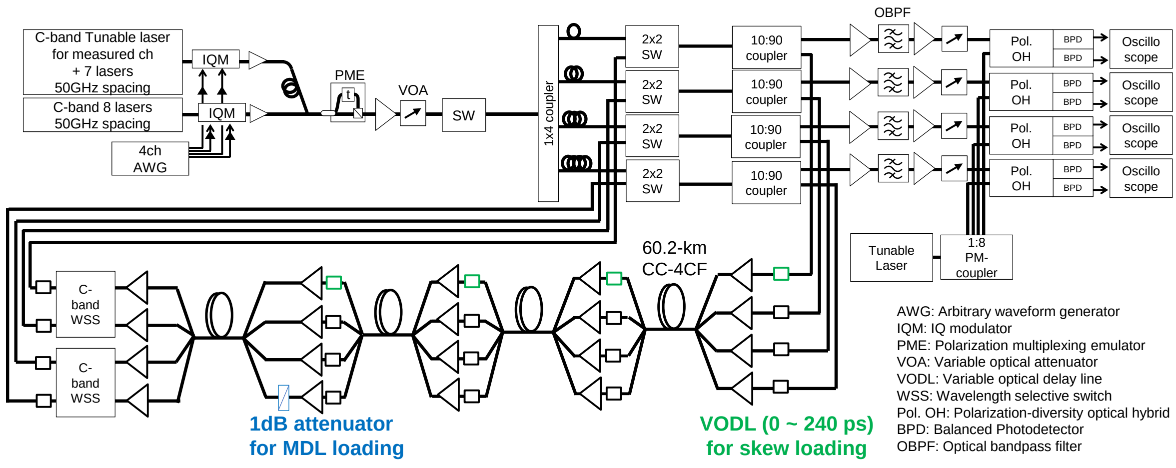

Fig. 1: Experimental setup.

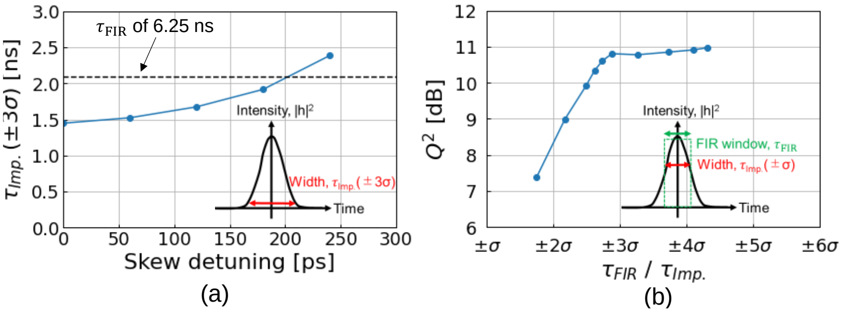

Fig. 2: (a) Skew detuning versus impulse response width $\tau_{Imp.}$. (b) FIR time window τ_{FIR} normalized by $\tau_{Imp.}$ versus Q^2.

details are shown in [10]. A 16-wavelength division multiplexed (WDM) 24-GBd QPSK signals were generated with an even and odd decorrelation method with a channel spacing of 25 GHz. The signal was polarization multiplexed and launched into a recirculating loop system consisting of variable optical delay lines (VODLs), EDFAs, four 60.2-km CC-4CFs, wavelength selective switches for gain equalisation, and optical switches. The skew was first adjusted in each span by tuning the VODLs, and we defined the optimized skew value as 0 ps. In the skew loading experiment, one of the four VODLs in each span was detuned in the range of 0-240 ps to investigate the tolerance. The skew was set to the same value for all spans. In the MDL loading experiment, a few 1 dB optical attenuators were inserted at the FI of the 4th span and generate 1-dB excess MDL per 4-spans to observe MDL-dependent Q^2 degradation. After transmission, the signal at the centre WDM channel was received by four coherent receivers and demodulated by an offline 8x8 MIMO DSP. Impulse response width [11] and MDL [3,6] was calculated from the MIMO impulse response. Finally, bit error rates were counted and converted to Q^2.

Results

First, we evaluated the dependence of the Q^2 on skew. Figure 2(a) shows the skew detuning and impulse response width after 6,020-km transmission. The impulse response width $\tau_{Imp.}$ was evaluated as the ±3σ interval of the Gaussian fitted average intensity MIMO impulse response $|h|^2$ [11]. As the skew detuning is increased, the $\tau_{Imp.}$ also increases. Even a skew of only 60 ps/span affects the $\tau_{Imp.}$. Q^2 degradation occurs when the $\tau_{Imp.}$ exceeds the time window for the FIR filters τ_{FIR} in the MIMO DSP. To determine the required τ_{FIR}, we measured the relationship between τ_{FIR} and the Q^2, as shown in Fig. 2(b). Here, τ_{FIR} is normalized by the ±σ interval of the impulse response. The Q^2 was averaged over cores and polarisations. To avoid Q^2 degradation, the τ_{FIR} should cover a ±3σ interval of the impulse response, as shown in Fig. 2(b). To date, the maximum number of FIR taps implemented in a real-time MIMO DSP is 25 taps for 2 GBd signals, which corresponds to a τ_{FIR} of 6.25 ns [12]. Because it is possible to process a 24 GBd signal as 12-subcarrier multiplexed 2 GBd signals [11], we consider the τ_{FIR} of 6.25 ns as a reference, as shown by the dotted line in Fig. 2(a). The skew should be less than 200 ps/span for 6,020-km transmission with 100 spans. Figure 3 shows the Q^2 versus transmission distance with a τ_{FIR} of 6.25 ns and skew of 0, 120, and 240 ps. The Q^2 penalty due to the shortage of the FIR tap is clearly observed when the skew was larger than 200 ps/span. A skew of 200 ps/span corresponds to a fibre length of 4 cm/span. Considering field-deployed optical transmission systems, it will be difficult to maintain this skew accuracy because repeater failures and repair are inevitable. Therefore, it will be important to use MCF devices such as MC-EDFAs in a transmission link and remove FIFOs, although this may introduce an increase in the MDL [4,5].

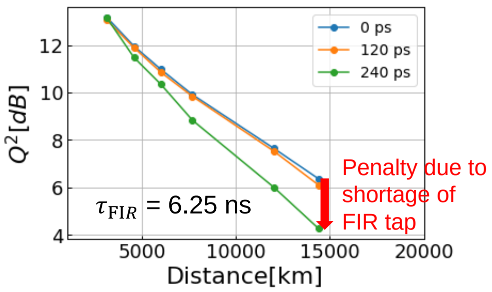

Fig. 3: Q^2 versus distance with a τ_{FIR} of 6.25 ns and a skew of 0, 120, 240 ps/span.

Next, we evaluated the dependence of the Q^2 on the MDL. In CC-MCFs, because the Q^2 can change with time due to the drift of the MIMO channel [9], statistical evaluation is important. Figure 4 shows histograms for the Q^2-values for all 4 cores x 2 polarizations after 6,020-km transmission, which was calculated from data acquired 100 times at intervals of approximately 5 seconds. The mean $\overline{Q^2}$ and standard deviation σ_{Q^2} are also shown. Cases (a)-(d) correspond to the insertion of no, one, two and four 1-dB attenuators for excitation of 1-dB excess MDL per 4-spans, respectively. As shown in Figure 4(d), where attenuators are inserted in all paths, a slight $\overline{Q^2}$ degradation of 0.2 dB and σ_{Q^2} degradation of 0.02 dB is observed, compared to Fig. 4(a), where no attenuator is inserted. The Q² degradation arises from OSNR degradation due to the insertion of attenuators. In contrast, as shown in Figs. 4(b) and (c), where attenuators are inserted in only some paths, large $\bar{Q}$ degradations of 1.7 and 2.1 dB are observed compared to Fig. 4(a). Large σ_Q degradations of 0.07 and 0.09 dB are also observed. This degradation cannot be explained by only OSNR degradation because the Q² is lower than that in Fig. 4(d), which has the worst OSNR among cases (a)-(d). Therefore, this degradation mainly arises from the degradation of orthogonality between spatial channels [7], which is a specific issue for MIMO transmission systems. From Fig. 4, it can also be seen that the Q² histogram is almost independent of the core and polarisation. This suggests that core and polarisation coupling occurs sufficiently uniformly in the CC-MCF. Figure 5(a) shows the transmission distance versus MDL with and without an attenuator, which correspond to the setup of Figs. 4(a) and (b), respectively. The worst MDL and standard deviation of MDL σ_{MDL} [6] are plotted. The insertion of a 1-dB attenuator significantly increases the MDL. Figure 5(b) shows the transmission distance versus the Q². Because the distribution of the Q² is independent of the core and polarisation, as shown in Fig. 4, a scatterplot of the Q² for 4 cores x 2 polarisations x 100 data is plotted without distinguishing between 8 spatial channels. As shown in Fig. 5(b), the longer the transmission distance, the greater the degradation of the average and deviation of the Q² because the MDL accumulates as the transmission distance increases. For instance, the average Q² degradation due to the insertion of an attenuator (Fig. 4(b)) is 0.9 dB at 3,120 km, while it is 2.7 dB at 9,120 km. The experiments confirm that MDL leads to large degradation of the average value and deviation of the Q², especially for long-haul CC-MCF transmission.

Conclusions

Q² for long-haul CC-MCF transmission were measured with varying skew and MDL. A skew requirement of 200 ps/span is confirmed for 6,020-km transmission. Large Q² degradation more than 2dB and Q² fluctuation are observed in the presence of 1-dB excess MDL per 4-spans after 9,120km transmission.

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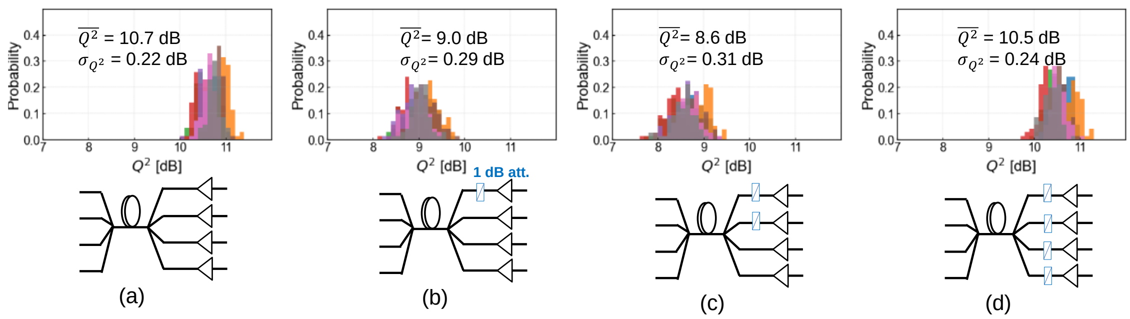

Fig. 4: Histograms for the Q² of all cores and polarizations, which all suffer from MDL after 6,020km transmission. The cases (a)-(d) correspond to the insertion of no, one, two, and four 1-dB attenuators.

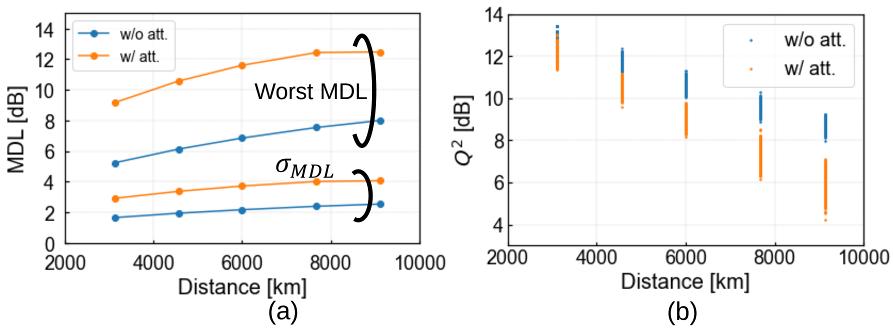

Fig. 5: (a) MDL versus transmission distance with or without the insertion of a 1-dB attenuator. (b) Q² versus transmission distance with or without the insertion of a 1-dB attenuator.

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