Investigation of MDL Accumulation in Recirculating Loop Systems Using Coupled-Core Multicore Fibres with a Quasi Mode Scrambler

Shohei Beppu, Daiki Soma, Yuta Wakayama, Noboru Yoshikane

KDDI Research, Inc., sh-beppu@kddi.com

Abstract *We propose a quasi mode scrambler to mitigate exaggerated MDL accumulation specific to recirculating loop systems. We measured accumulated MDL in a recirculating loop system using coupled-core multicore fibres and mode scrambler. Unlike PDL in uncoupled-core multicore fibres, accumulated MDL was not reduced by scrambling.*

Introduction

Space-division-multiplexed transmission systems using multicore fibres (MCFs) are garnering much attention for future high-capacity long-haul optical transmission systems [x]. MCFs have two or more cores in a fibre, and cores are used as different spatial paths. There are two kinds of MCFs. One is uncoupled-core (UC-) MCF [2-4], and the other is coupled-core (CC-) MCF [5,8]. UC-MCFs do not require advanced multiple-input multiple-output digital signal processing (MIMO-DSP) as long as inter-core crosstalk is negligibly small, although the number of cores that can be accommodated in a fibre is smaller than in CC-MCFs. Recently, high-capacity long-haul transmission experiments using UC or CC-MCFs have been reported [8-14].

To demonstrate the feasibility of long-haul transmission systems in the laboratory, recirculating loop systems are often used [9-14]. However, since an optical signal passes through the same optical devices (e.g., optical amplifiers) many times, imperfections in the devices accumulate faster than those in straight-line transmission systems as the transmission distance increases [15]. The accumulation of polarization-dependent loss (PDL) affects the transmission performance of single-mode fibres (SMFs) and UC-MCFs since it cannot be fully compensated for by DSP [16]. To avoid exaggerated PDL accumulation specific to recirculating loop systems, a polarization scrambler (PS) is often introduced in a recirculating loop system [17,18]. The PS makes states of polarization (SOPs) between the *k*-th and *k*+1-th loops uncorrelated, resulting in the avoidance of exaggerated PDL accumulation.

In CC-MCFs, the concept of PDL is generalized as mode-dependent loss (MDL) [19,20]. The SOP is also generalized as the state of mode (SOM). It has been reported that long-haul transmission performance in CC-MCFs is dominated by MDL because the MDL per device is much higher than the PDL per device so far [9,10,12,21]. Moreover, by analogy with PDL in SMFs and UC-MCFs, exaggerated MDL accumulation can occur in recirculating loop systems. However, it is unclear whether exaggerated MDL accumulation will occur in recirculating loop systems. If this occurs, spatial mode (i.e., core and polarization) scramblers can stop the exaggerated MDL accumulation and improve the transmission performance of recirculating loop systems using CC-MCFs. However, recirculating loop transmission experiments using mode scramblers have not been reported thus far.

In this paper, we propose a quasi mode scrambling method using a conventional PS in cooperation with a CC-MCF. To clarify whether exaggerated MDL accumulation will occur, we compared accumulated MDLs after recirculating loop transmission over CC-4CFs with or without mode scrambling. The experimental results showed that exaggerated MDL accumulation does not occur even if scrambling is not applied, as opposed to PDL accumulation in UC-MCFs.

Principle of quasi mode scrambler

The proposed quasi mode scrambler relies on the fact that the distinction between cores and polarizations is meaningless once optical signals pass through a CC-MCF because a CC-MCF mixes optical signals carried over cores and polarizations thoroughly. Figure 1(a) shows a configuration of the quasi mode scrambler. The quasi mode scrambler is a concatenation of a conventional PS and a CC-MCF. To understand the principle of the quasi mode scrambler, consider a unitary matrix model of the physical configuration. $\boldsymbol{E}$ is an input eight-dimensional generalized Jones vector to the PS. T and H are generalized 8×8 Jones matrices of PS and CC-4CF, respectively. The matrix product of H and T, namely, $H' = HT$,

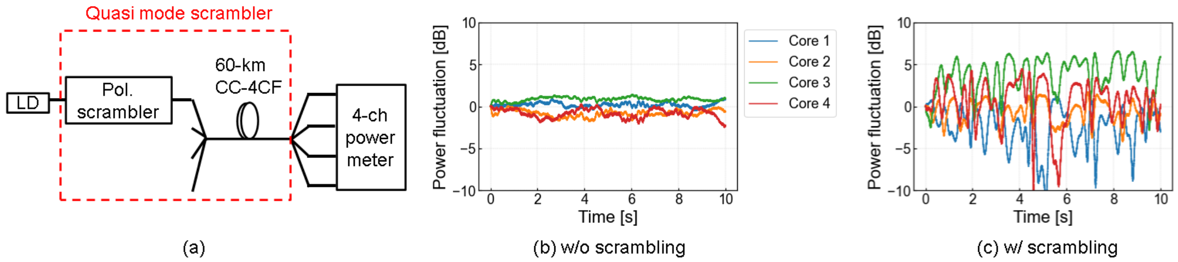

Fig. 1: (a) Experimental setup includes a quasi mode scrambler. Output power fluctuation after a 60-km CC-4CF transmission (b) without and (c) with 1-Hz scrambling.

describes the quasi mode scrambler. When the PS is turned on, $T_{(i,j)\in\{1,2\}^2}$, which is a partial element of T, changes over time. According to a formula of $H_{ij}' = \sum_k H_{ik}T_{kj}$, partial elements of H', $H'_{(i,j)\in\{1,2,..,8\}\times\{1,2\}}$, should change over time. All elements of the output generalized Jones vector from the CC-4CF, $\boldsymbol{E}' = H'\boldsymbol{E}$, should change synchronously with the PS. Thus, a polarization scrambler followed by a CC-4CF can emulate a mode scrambler. It should be noted that the quasi mode scrambler can not generate an arbitrary eight-dimensional generalized Jones vector due to a lack of degrees of freedom.

To evaluate the quasi mode scrambler, we conducted the experiment shown in Fig. 1(a). Continuous-wave (CW) light from a laser diode (LD) with a linewidth of 5 kHz was fed to the quasi mode scrambler with a launch power of 0 dBm. The quasi mode scrambler was a concatenation of an endless PS (Novoptel GmbH, EPS-1000) and a 60-km CC-4CF [6,10]. The speed of the PS was 1 Hz, and the output SOP followed the Rayleigh distribution. The output power of all cores was measured simultaneously by optical power meters with a 10 μs sampling period. Figures 1(b) and 1(c) show the output power fluctuation of all cores without and with scrambling, respectively. As shown in Fig. 1(b), the output power per core changed over time due to environmental perturbations even if the scrambler was turned off. When the scrambler turned on (Fig. 1(c)), not only output power per polarization but also output power per core changed synchronously with the polarization scrambling as we expected. Thus, the principle of quasi mode scrambler was confirmed experimentally.

Recirculating loop transmission over multicore fibres with a quasi mode scrambler

To investigate whether the quasi mode scrambler can reduce exaggerated MDL accumulation, we performed a long-haul recirculating loop transmission experiment using CC-MCFs and the quasi mode scrambler. Figure 2 shows the experimental setup [14]. At a transmitter, a 16-WDM 25 GBd. DP-QPSK signal was generated. The signal was copied to make four signals and decorrelated by delay lines. The relative delays were 0, 200, 400, and 800 ns. The signals were launched into a recirculating loop system consisting of variable optical delay lines (VODLs), erbium-doped fibre amplifiers, 60-km UC or CC-4CFs, C-band WSSs for gain equalization, PSs, and optical switches. The VODLs for skew adjustment were inserted only for CC-MCF transmission. The PSs followed by the 1st span of CC-4CF work as

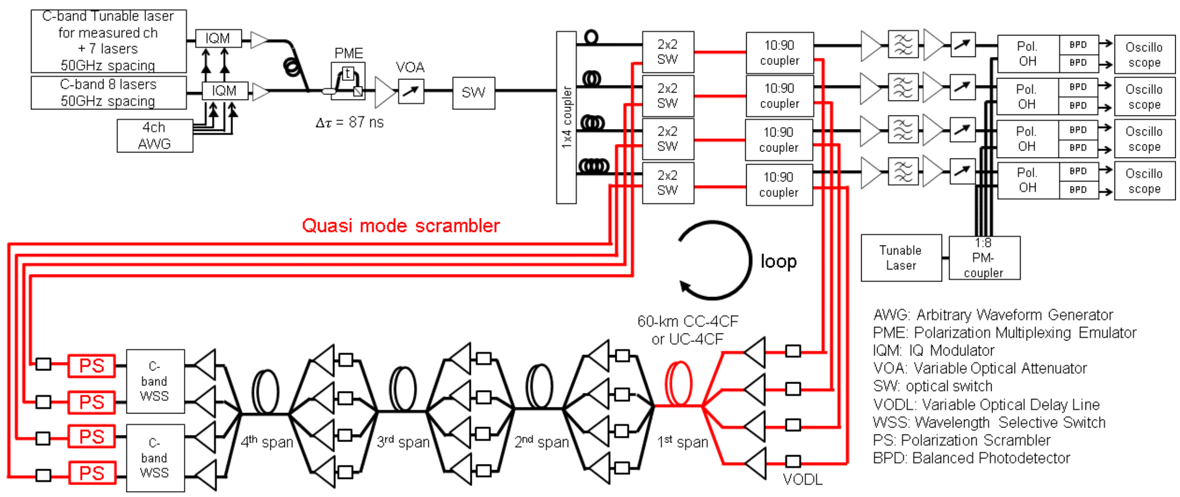

Fig. 2: Experimental setup of recirculating loop system using multicore fibres.

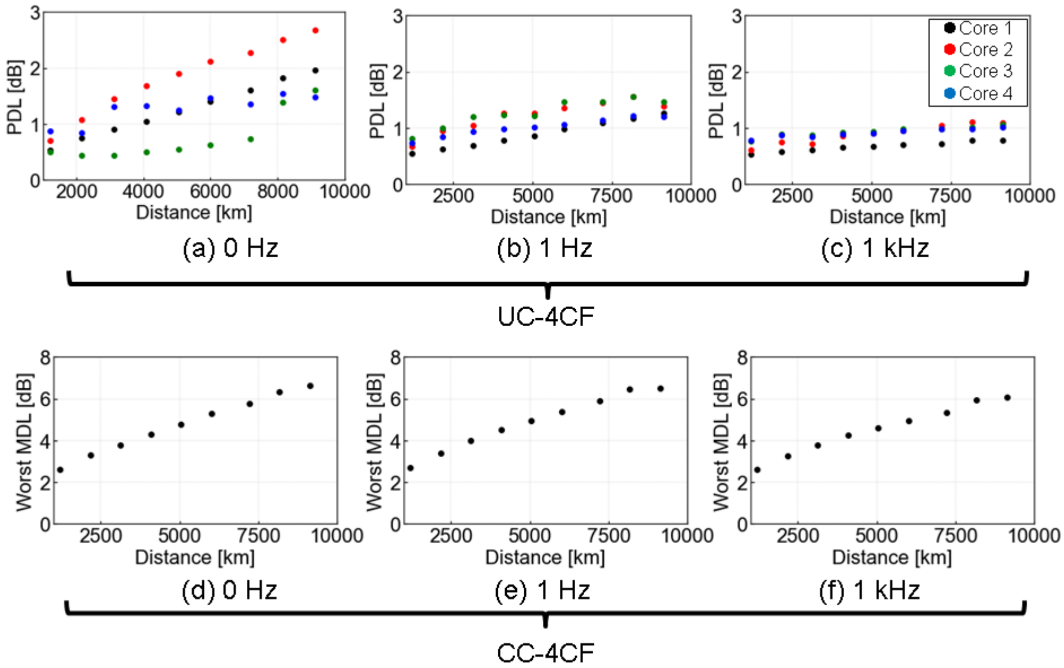

Fig. 3: PDL of UC-4CF in each core versus transmission distance with scrambling, whose speed is (a) 0 Hz (turn off), (b) 1 Hz and (c) 1 kHz. The worst MDL of CC-4CF versus transmission distance with scrambling, whose speed is (d) 0 Hz (turn off), (e) 1 Hz and (f) 1 kHz.

a quasi mode scrambler, which makes the SOMs between the k-th and k+1-th loops uncorrelated. To ensure the decorrelation of SOMs, the speed of scrambling should be higher than that of the recirculating loop (833 Hz). Therefore, the speed of the PSs was varied in the range of 0 Hz (turned off) to 1 kHz. After the recirculating loop transmission, optical signals at a desired wavelength were extracted by optical bandpass filters and detected by coherent receivers. The electrical signals were sampled by 80 GSa/s oscilloscopes and processed by an offline MIMO DSP. Accumulated PDL and MDL were estimated in the DSP for UC and CC-4CF transmissions, respectively. Here, since MDL is not a scalar but an eight-dimensional real-value vector, the *worst MDL*, defined as max(MDL)/min(MDL), was used as a metric [10].

Figure 3 shows the measured PDL and MDL for UC and CC-4CF transmissions, respectively, as a function of transmission distance. The PDL and MDL were measured 100 times and averaged in each measurement condition. As shown in Fig. 3(a-c), the accumulation of PDL decreased as the speed of PS increased. At a speed of 0 Hz (Fig.3(a)), the PDLs became >1.5 dB at 9,000 km and depended on the core. We found that the PDL strongly depends on not the core but rather a realization of SOP, as reported in the literature [15]. At a speed of 1 kHz (Fig.3(c)), all four cores showed similar accumulated PDLs because the PDLs were averaged over random SOPs. Fig. 3(d-f) shows the MDL in CC-4CF transmissions. In contrast to PDL in UC-4CF, MDL did not depend on the speed of scrambling. This would be because the CC-MCFs themselves scrambled the output SOM on the time axis, as shown in Fig. 1(b), which is caused by environmental perturbations. These results suggest that further mitigation of MDL per device is the only way to reduce accumulated MDL in either recirculating loop or straight-line long-haul CC-MCF transmission systems.

Conclusion

We proposed a quasi mode scrambling method using a conventional polarization scrambler and CC-MCF. We investigated the accumulation of PDL and MDL in a recirculating loop using uncoupled and coupled core multicore fibres, respectively, with quasi mode scrambling. Although scrambling was effective in mitigating PDL, it was not effective in mitigating MDL. It would be because the CC-MCFs themselves worked as natural mode scramblers, which is a unique behaviour of CC-MCFs.

Acknowledgements

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