Progress and Challenges of Coupled Core MCF Transmission

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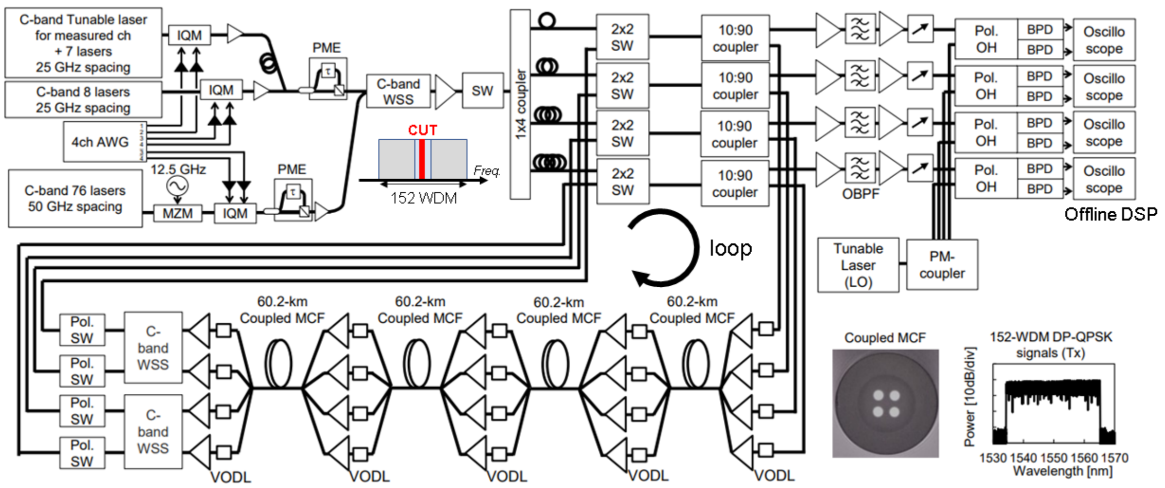
Abstract *We review recent reports of long-haul coupled-core multicore fibre transmission experiments. Challenges for real-time multiple-input multiple-output digital signal processing and real-time transmission experiments are also reviewed. We also discuss the requirements for mode-dependent loss and spatial mode dispersion. ©2023 The Author(s)*

Introduction

Space-division-multiplexed (SDM) transmission systems using multicore fibres (MCFs) are promising candidates for future high-capacity long-haul optical transmission systems [1]. MCFs have two or more cores in a fibre, and the cores are used as different spatial paths. Coupled-core multicore fibres (CC-MCFs) [2-5] have a higher core count than uncoupled-core MCFs [6-8] in the same cladding diameter because the core pitch can be reduced by introducing multiple-input multiple-output digital signal processing (MIMO DSP) to compensate for intercore crosstalk. A record 19-core CC-MCF with a standard cladding diameter has been recently reported [5]. High-capacity long-haul transmission experiments using CC-MCFs have been reported [9-11]. Moreover, real-time CC-MCF transmission experiments using real-time MIMO DSP have been studied [12-15].

However, CC-MCF transmission systems suffer from mode-dependent loss (MDL) and spatial mode dispersion (SMD). MDL breaks the orthogonality between spatial paths (i.e., cores and polarizations) in a fibre and causes residual crosstalk that cannot be compensated for by MIMO DSP [16-19]. Since MDL accumulates as the transmission distance increases, it limits the maximum capacity and transmission distance of long-haul CC-MCF transmission systems [10,18,20]. SMD causes delay spread of crosstalk and an increase in the required finite impulse response (FIR) tap count in MIMO equalization [2]. Although an FIR tap count greater than 1,000 is feasible in offline MIMO DSP [21], the maximum FIR tap count in the case of real-time MIMO DSP is strongly limited by available DSP resources [12-15]. To date, the maximum FIR tap counts in real-time DSP have been 27 and 32 taps in time and frequency domain equalization, respectively [12,22]. When the SMD exceeds the FIR tap count, part of the crosstalk spread over time cannot be compensated for [23]. Since SMD accumulates as the transmission distance increases, it limits the transmission distance of long-haul transmission systems.

In this paper, we show our recent long-haul CC-MCF transmission experiments using offline and real-time MIMO DSP. We also discuss the requirements for MDL and SMD, which are limiting factors of the transmission performance



IQM: IQ modulator, AWG: Arbitrary waveform generator, PME: Polarization multiplexing emulator, SW: Optical switch, VODL: Variable optical delay line, WSS: Wavelength selective switch, Pol. SW: Polarization switch, OBPF: Optical bandpass filter, Pol. OH: Polarization-diversity optical hybrid, BPD: Balanced photodetector, LO: Local oscillator

Fig. 1: Experimental setup

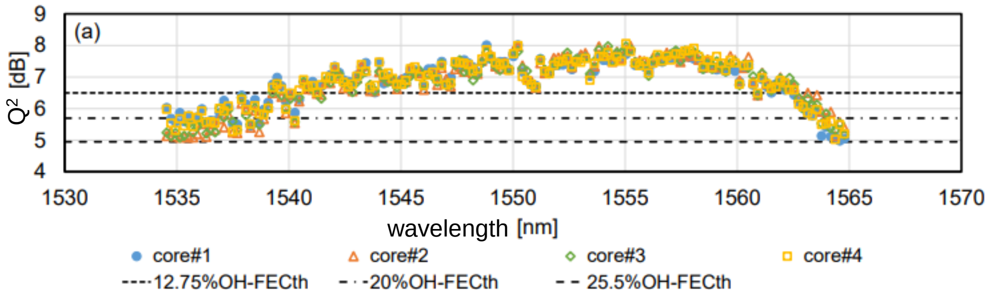


Fig. 2: Q^2 versus wavelength after 9,150-km CC-4CF transmission using offline DSP.

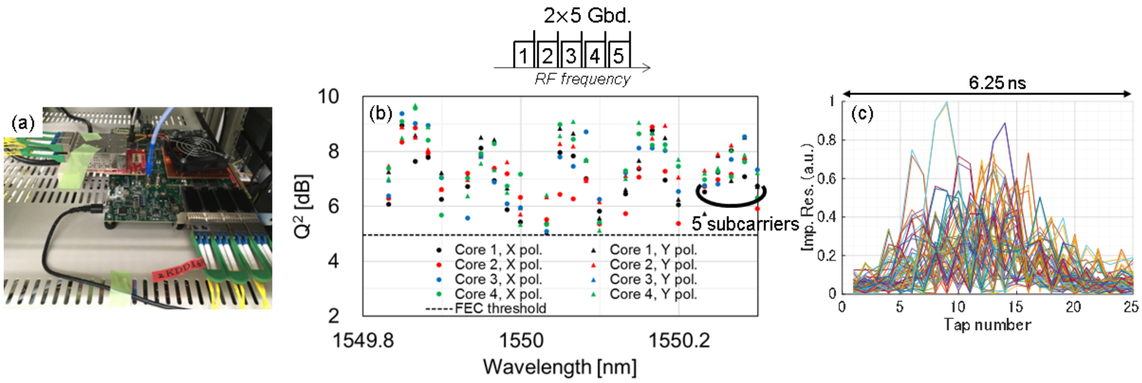


Fig. 3: (a) Real-time DSP for MIMO equalization. (b) Q^2 versus wavelength after 7,200-km real-time CC-4CF transmission. (c) MIMO impulse response measured by the real-time MIMO DSP.

of long-haul CC-MCF transmission systems.

Long-haul CC-4CF transmission experiments

Figure 1 shows the experimental setup using offline MIMO DSP [10]. In a transmitter, 152-WDM 25-GBd DP-QPSK signals covering the C-band were generated. The signals were copied to four signals, followed by optical delay lines for decorrelation. The signals were fed into a recirculating loop system consisting of four spans of a 60-km CC-4CF, fan-in (FI) devices, EDFAs, variable optical delay lines (VODLs) and wavelength-selective switches (WSSs) for gain equalization. The VODLs were adjusted to mitigate excess skew due to the path length difference between single mode fibres (SMFs). After transmission, one of 152 WDM channels was extracted by optical bandpass filters. The signals were received by coherent receivers and digitized by 80 GSa/s oscilloscopes. The samples were processed via offline MIMO DSP. The FIR tap count was 250, and the tap coefficients were updated by the modified least mean square (LMS) algorithm. Figure 2 shows the Q^2 after 9,150-km transmission. The Q^2 of all measured SDM and WDM tributaries exceeded the assumed multirate FEC thresholds. The aggregated capacity was 50.47 Tb/s. Thus, the feasibility of high-capacity long-haul CC-4CF transmission was confirmed.

We also conducted real-time transmission experiments by developing real-time MIMO DSP [13]. The experimental setup is similar to that of the offline experiment. The transmitted signals were 16-WDM 5-subcarrier-multiplexed (SCM) 2 GBd DP-QPSK signals, where the signal baudrate was limited by the sampling rate of analogue-to-digital converters (4 GSa/s). Fig. 3 (a) shows the real-time MIMO DSP for 4-mode MIMO equalization using a field programable gate array (FPGA) board. In the FPGA board, 4-mode-division multiplexed 2 GBd DP-QPSK signals were equalized with 25-tap MIMO-FIR filters using a modified LMS algorithm, and one desired spatial mode tributary was demodulated. The DSP function except for MIMO equalization, such as chromatic dispersion compensation, frequency offset estimation and timing synchronization, were performed using other FPGA boards. Board-to-board communication to transfer time-domain waveforms was implemented using 100 G QSFP transceivers. Fig. 3(b) shows the Q^2 in five of 16 WDM channels after 7,200-km real-time CC-4CF transmission. The Q^2 in all measured SDM, WDM and SCM tributaries exceeded the assumed FEC threshold. Figure 3(c) shows a measured MIMO impulse response after 7,200-km transmission. The crosstalk spread over time was sufficiently covered by 25-tap MIMO-FIR filters. Thus, the feasibility of long-haul real-time CC-MCF transmission was confirmed.

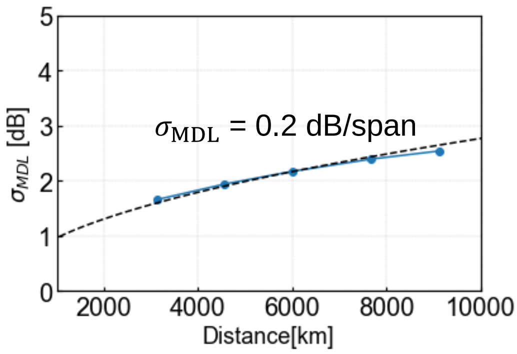


Fig. 4: rms MDL versus transmission distance. The dotted line shows the square root fitting with the 0.2-dB/span rms MDL.

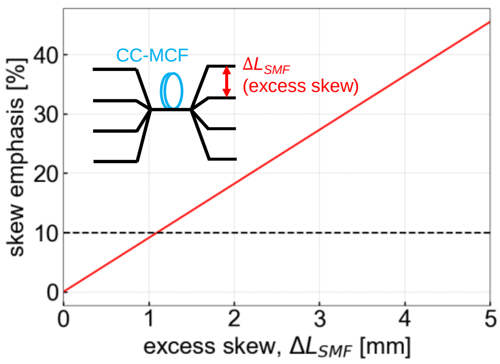


Fig. 5: Skew emphasis versus excess skew. The dotted line shows the 10% threshold of skew emphasis.

Requirements for MDL and SMD in long-haul CC-MCF transmission

We discuss the requirement for MDL in long-haul CC-MCF transmission systems. According to numerical simulations based on the GN model considering MDL [18], the rms MDL (σ_{MDL}) should be lower than 0.2 dB to avoid 1 dB effective SNR degradation after 9,000-km transmission. To date, the reported σ_{MDL} values have been 0.3, 0.35 and 0.7 dB/span depending on the CC-MCF and configuration of the recirculating loop system [10,11,20]. We measured the σ_{MDL} of our recirculating loop system as a function of distance, as shown in Fig. 4. The σ_{MDL} per span obtained by square root fitting [17] was 0.2 dB/span. This value was comparable to the MDL requirement of 0.2 dB/span. However, further MDL reduction is desired to extend the transmission distance beyond 9,000 km. Advanced MIMO DSP techniques such as maximum log likelihood detection (MLD) [24] and successive interference cancellation (SIC) [19] are alternative approaches to relax the requirement for MDL. However, advanced MIMO DSP in real time is challenging because these algorithms introduce additional computational complexity and calculation delay.

We also investigated the requirement for SMD in long-haul CC-MCF transmission systems. When the SMD exceeds a given FIR tap count, part of the crosstalk spread over time cannot be compensated for, resulting in effective SNR degradation. To avoid effective SNR degradation, the time window of FIR filters should cover $\pm 3\sigma$ of a MIMO impulse response [23]. Assuming a 6.25-ns time window implemented in our real-time MIMO DSP [13], the required SMD is 22 ps$/\sqrt{\mathrm{km}}$ for 9,000-km transmission. An SMD of less than 10 ps/$\sqrt{\mathrm{km}}$ has been achieved thus far [2,3,9]. However, considering that in transmission systems, the path length difference of SMF patch codes between fan-in and fan-out (FIFO) devices introduces excess SMD [10,23,25], the path lengths should be precisely matched by VODLs. To investigate the required accuracy of skew matching, we performed a numerical calculation. Figure 5 shows the degree of skew emphasis as a function of the path length difference, ΔL_{SMF}. The skew emphasis is defined as $\left(\frac{\mathrm{SMD}_{\mathrm{CC-4CF}}+c\Delta L_{\mathrm{SMF}}}{\mathrm{SMD}_{\mathrm{CC-4CF}}}\right) - 1$. To suppress the skew emphasis to less than 10%, the required accuracy of skew matching by VODLs is 1.1 mm. However, it is difficult to maintain this accuracy over 25 or more years in practical submarine cable systems. Moreover, VODLs increase span loss [10]. Therefore, FIFO-less multicore (MC-) EDFAs [27] with low mode-dependent gain (MDG) are strongly desired to eliminate excess skew and MDL at the same time.

Conclusion

We reviewed recent long-haul coupled-core multicore fibre transmission experiments. Real-time multiple-input multiple-output digital signal processing is challenging but an essential element to deploy coupled-core multicore fibre transmission systems. From the perspective of transmission performance, the requirements for mode-dependent loss and spatial mode dispersion were discussed.

Acknowledgements

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