A Joint Mode Permutation Architecture for 10-mode-multiplexed Long-haul Transmissions

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Abstract: For the first time, we propose and experimentally demonstrate a joint mode permutation architecture for 10-mode transmission. Compared with cyclic mode-group permutation, the required equalizer window is further reduced by 30.7%, while the transmission reach is extended to 2000 km. © 2024 The Author(s)

1. Introduction

The exponential growth of global Internet traffic has spurred extensive research efforts in mode-division multiplexing (MDM) technology over the past decade [1]. Achieving ultra-high capacity and ultra-long-distance transmission has been a constant pursuit in MDM systems [2-7]. However, for conventional MDM transmission schemes, the spread of the signal impulse exhibits a linear growth with the increased distance due to the differential mode delay (DMD) [8]. The large DMD-induced signal pulse spread causes unacceptable computational complexity of multiple-input multiple-output digital signal processing (MIMO-DSP). To address the accumulation of DMD and mode-dependent loss (MDL), a cyclic mode permutation (CMP) strategy is initially proposed and applied to high-performance MDM transmissions [9,10], significantly extending the transmission distance. Subsequently, various researches on mode permutation strategies (MPSs) such as cyclic mode-group permutation (CMGP) [11-13] and mirror-flipped mode permutation (MFMP) [14] have emerged to improve the system performance further. However, these existing solutions are all constrained to a straightforward system architecture that carries out only one mode permutation per span. Consequently, the overall number of mode permutation times just equals to the number of spans of the whole link, resulting in insufficient mixing of different signal channels.

Herein, we propose a novel system architecture, where multiple mode permutations can be carried out in each fiber span. This enables more frequent mode mixing for the same transmission distance, further suppressing the DMD- and MDL-induced impacts. Based on this, we newly propose a dual-CMGP (DCMGP) strategy referring to CMGP and combine it with our previously proposed MFMP in each span. In this way, the joint mode permutation scheme (MFMP-DCMGP) achieves a further signal spread compression by 30.7% and a Q-improvement by 2.1 dB compared with the CMGP at 1600 km. Furthermore, it is noted that the proposed scheme with two permutations per span can extend the reach to 2000 km, while the conventional CMGP reaches 1600 km.

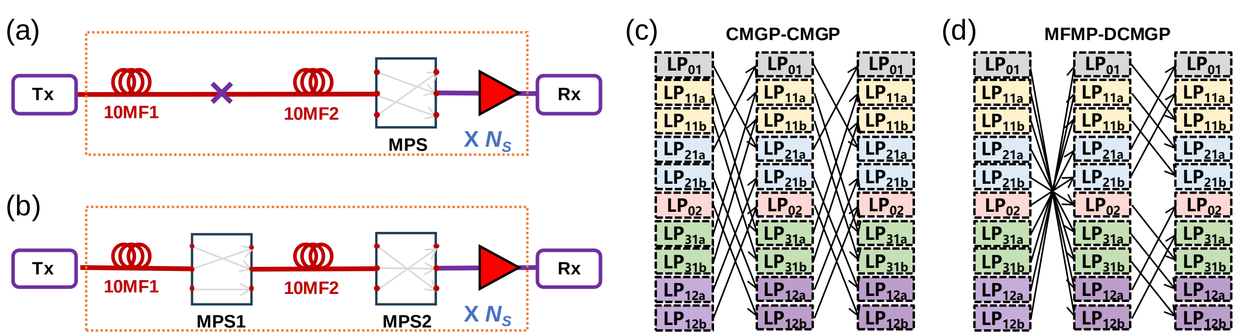

Fig. 1. Schematics of the MDM system architecture containing (a) one mode permutation per span and (b) two mode permutations per span. The two 10-mode fiber spools are directly fusion spliced in (a), while they are connected by a certain MPD in (b) to introduce more frequent mode exchanging and provide the flexibility for combining different MPSs together. Mode permutation configurations for the double CMGPs (or CMGP-CMGP) per span and our optimized joint MPS (called MFMP-DCMGP) for 10-mode systems are shown in Fig. (c)&(d), respectively.

2. Principle of the Joint Mode Permutation

In fact, an actual long-haul fiber transmission system is composed of many relatively independent spans. Figure 1(a) shows a regular MDM system with a single mode permutation device (MPD) per span, which has a limited times of mode permutations and lacks flexibility. To overcome this disadvantage, we propose an architecture with multiple mode permutations per span. Without loss of generality, we take the case of two mode permutations per span for the following experimental demonstration, whose schematic is shown in Fig. 1(b). On the one hand, benefiting from the more frequent mode exchanging, the configuration of two mode permutations per span can enhance the mode mixing to suppress the DMD- and MDL-induced impacts further. To verify this, we take the CMGP-CMGP strategy illustrated in Fig. 1(c) into consideration, which carries out two identical MPSs per span.

On the other hand, the configuration of two mode permutations per span provides the possibility to flexibly combine different MPSs together. For one type of MPS per span, each signal channel may only go through a limited number of spatial paths within a certain distance. For example, definitely, MFMP only introduces the interaction between a lower-order mode and the corresponding higher-order mode at the end of each span. Thus, it forms five mode-exchanging pairs (MEPs), i.e., $LP_{01} \rightleftarrows LP_{12b}$, $LP_{11a} \rightleftarrows LP_{12a}$, $LP_{11b} \rightleftarrows LP_{31b}$, $LP_{21a} \rightleftarrows LP_{31a}$, $LP_{21b} \rightleftarrows LP_{02}$, that are inadequately coupled and thus relatively independent [14]. Considering an incomplete centrosymmetric fiber DMD distribution, the effect of mode mixing is actually far from perfect. Therefore, to enhance the overall mode mixing, we need to introduce efficient connections between MEPs and make the extra connection work frequently enough. Based on this, a DCMGP is designed specifically here to serve as the second MPS placed after the MFMP. This joint MPS called MFMP-DCMGP is shown in Fig. 1(d), where the DCMGP can disrupt the established MEPs of MFMP during transmission.

3. The 10-mode Transmission System Based on Joint Mode Permutation

The experimental setup for a 10-mode transmission system is illustrated in Fig. 2(a). Light around 1550 nm from 16 external cavity lasers is modulated with a 15-Gbaud QPSK signal by an IQ modulator. After polarization and wavelength multiplexing, 16-λ PM-QPSK signals are generated and then split into ten paths by a 1×10 optical coupler and decorrelated using delay lines with a relative delay of 2 µs between adjacent paths.

In our experiment, we construct a ten-fold recirculating loop system for long-haul transmission. Two trench-assisted graded-index 10-mode fiber (10MF) spools with lengths of 20 km are used for transmission. Figure 2(b) shows the refractive index profile of the fiber and the corresponding guided modes. The maximum DMD of the 10MF is 445 ps/km. The average fiber loss is ~0.25 dB/km and the MDL of one span is estimated to be ~2.5 dB. The optical power launched into the 10MF is set as 4.5 dBm per mode. Compared with the conventional mode-permutation-based systems, we introduce an additional pair of mode multiplexer and mode demultiplexer between the two sections of fibers to carry out another mode permutation. Finally, the ten-output signals are received by two coherent receivers. The electrical signals are digitized in a real-time oscilloscope with 36-GHz electrical bandwidth operating at 80 GSample/s. A time-division multiplexing scheme is applied that enables the reception of all signals by two coherent receivers [15]. The transmitted signals are stored for offline processing.

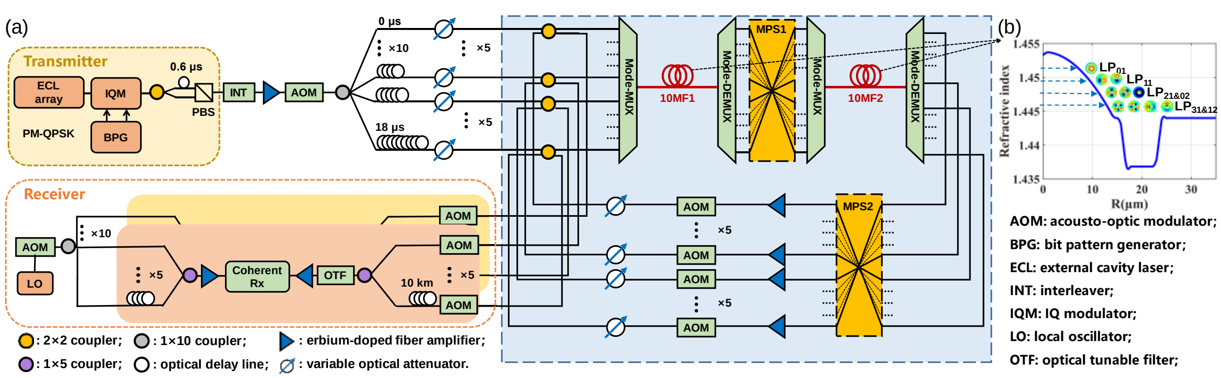

Fig. 2. (a) Experimental setup for the 10-mode joint mode-permutated transmission.
(b) The refractive index profile of the fabricated 10-mode fiber and the corresponding guided modes.

4. Experimental Results and Discussion

We experimentally demonstrate the 10-mode transmissions based on the single CMGP, CMGP-CMGP and MFMP-DCMGP schemes with an identical system setup, for a comparative analysis of signal pulse spread and Q-factor at different transmission distances. Figure 3(a) shows the impulse responses averaged over all mode channels at 320 km and 1600 km. When the transmission distance remains as short as 320 km, the impulse response still represents many spikes (meaning insufficient mode mixing) for CMGP. In contrast, it becomes bell-shaped for CMGP-CMGP and MFMP-DCMGP, meaning that they work well already. When the distance comes to 1600 km, the MFMP-DCMGP still keeps the signal pulse spread at a lower level, while the effect of CMGP-CMGP is not efficient enough. Figure 3(b) shows the required equalizer time windows covering 99% impulse energy. It proves that the proposed architecture has a great effect on signal pulse spread compression. CMGP-CMGP and MFMP-DCMGP reduce the required equalizer window by 9.4% and 30.7% at 1600 km compared with the single CMGP, respectively. The detailed impulse compression ratios are shown in Table 1. Compared with the case without permutation, MFMP-DCMGP can get a compression ratio of 86.7%, which is very friendly to MIMO-DSP. It is also confirmed that the proposed architecture can mitigate MDL impact with 2.1-dB Q-factor improvement, which can be extracted from Fig. 3(c). Referring to the BER threshold of 3.8×10^{-2}, the proposed scheme with two permutations per span significantly extends the reach to 2000 km, while the conventional CMGP reaches 1600 km.

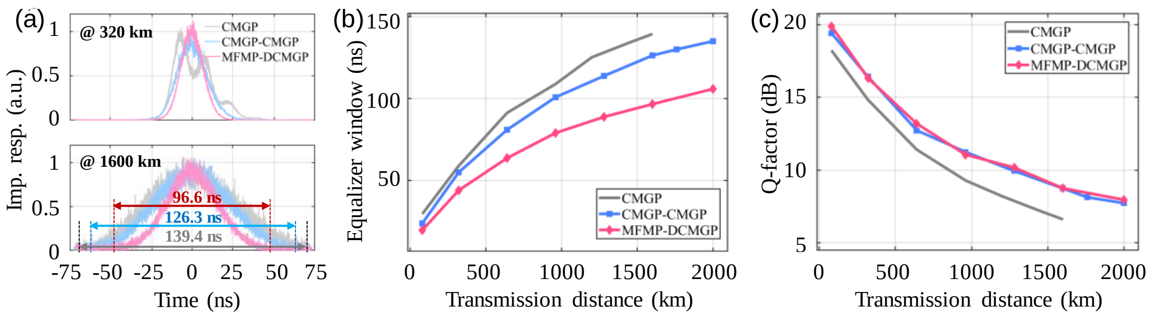

Fig. 3. (a) Impulse responses for different mode permutation schemes observed at 320 km and 1600 km, respectively. The required equalizer windows (b) and Q-factors (c) as functions of transmission distance for different mode permutation schemes. Compared with the conventional CMGP, the required equalizer window is further reduced by 30.7%, while the transmission reach is extended to 2000 km, increased by 400 km.

Table 1. The compression ratio for the signal pulse spread at 1600 km

Permutation Scheme	Impulse Compression Ratio	
	Compared with **non-permutation**	Compared with **CMGP**
CMGP	80.8%	0
CMGP-CMGP	82.6%	9.4%
MFMP-DCMGP	86.7%	30.7%

5. Conclusion

A novel MDM system architecture with multiple MPSs per span is proposed and experimentally demonstrated for the first time. Compared with the conventional CMGP strategy, the proposed MFMP-DCMGP is more suitable for long-haul MDM transmission with greater mitigation of DMD accumulation. As a result, the required equalizer window is decreased by 30.7%, while the transmission reach is finally extended to 2000 km, increased by 400 km.

6. Acknowledgements

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7. Reference

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