Novel Mirror-flipped Mode Permutation Technique for Long-haul Mode-division Multiplexing Transmissions

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Abstract: We propose a mirror-flipped mode permutation scheme based on newly developed differential-mode-delay-symmetric fibers, which further suppresses modal-dispersion impact by 30% and mitigates mode-dependent-loss impact with 3.8-dB Q-factor improvement compared with the traditional permutation method in 1028-km 6-mode transmission. © 2022

1. Introduction

Rapid global Internet traffic growth has driven significant research efforts for the development of space-division multiplexing (SDM) technology in the past decade. The capacity of optical fiber communication will soon approach the nonlinear Shannon limit of single-mode fibers. As one of the most important branches of SDM, mode-division multiplexing (MDM) transmission experiments have shown extremely high capacity by using few-mode fibers (FMFs). Recently, a 64-quadrature amplitude modulated transmission spanning 82-nm bandwidth over a 23-km-long 15-mode fiber has been demonstrated, in which the total data rate exceeded 1 Pb/s [1]. In the traditional MDM transmission scheme, the spread of the signal impulse exhibits a linear growth with the increased distance because of the presence of differential mode delay (DMD). This large spread causes increased the computational complexity of multiple-input multiple-output digital signal processing (MIMO-DSP) which is responsible for undoing modal crosstalk and DMD-induced effects in the electrical domain.

One way to mitigate the DMD-induced impact is to build a DMD-compensated link by managing the refractive index profiles of FMFs. For example, an over 1000-km MDM transmission has been achieved based on this technique [2, 3]. However, due to the limitation of fiber drawing process, the deviation between the designed and actual refractive index profile could lead to insufficient DMD compensation. Therefore, as an alternative and promising approach, a discrete strongly coupled (or called quasi-strongly coupled) regime was proposed to achieve long-haul MDM transmission, in which spatial channels are cyclically permutated at each span. Cyclic mode permutation (CMP) strategy was firstly proposed and applied to high-performance MDM transmission [4, 5], with suppressed DMD-induced impact and mitigated mode-dependent-loss (MDL) effect.

In this work, we propose a new type of mode exchanging scheme based on DMD-symmetric FMFs for MDM transmission, called mirror-flipped mode permutation (MFMP). Compared with conventional CMP scheme, the MFMP scheme takes 2 spans as a period of permutation so that modes exchange more frequently and alleviate DMD effect notably. By specially designing the refractive index profile, the newly developed 6-mode fiber's mode group delays distribute symmetrically. After 1000-km 6-mode MFMP transmission using this fiber, modal dispersion's impact is further suppressed by 30%, and MDL impact is mitigated with 3.8-dB Q-factor improvement, compared with the traditional CMP method.

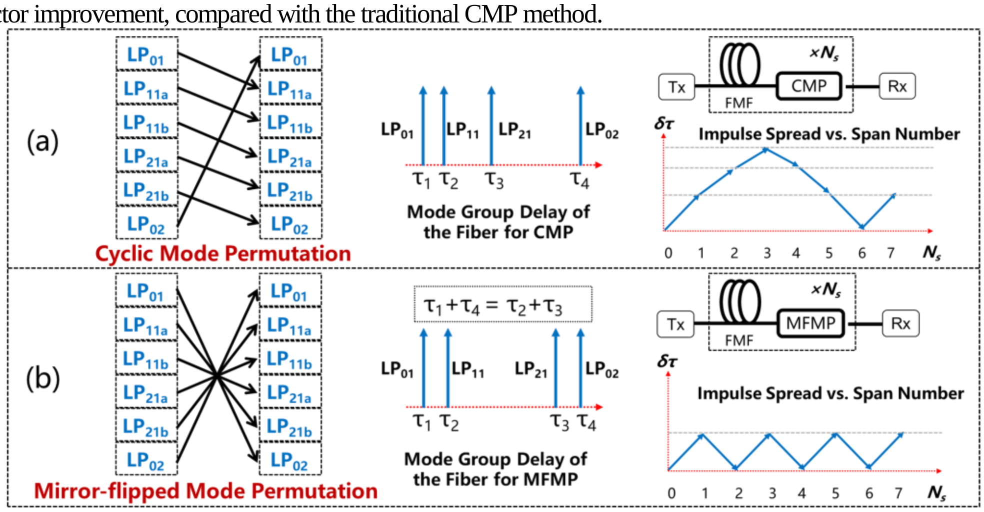

Fig. 1. Schematics and the transmission strategies of (a) CMP and (b) MFMP.

2. Principle of MFMP Scheme

In regular MDM transmissions over FMFs suffering from modal crosstalk, DMD is piled up in almost linear fashion with increasing transmission reach. To overcome this negative feature of DMD, a popular way is to adopt a permutation system architecture [4, 5]. Figure 1(b) shows our proposed novel MFMP scheme and the mode group delays of the fiber. The fiber is designed to have symmetrically distributed group delays for LP_{01}/LP_{11} and LP_{21}/LP_{02} modes as illustrated in the middle of Fig. 1(b). In this way the sum of the mode group delays of lowest and highest order modes, i.e. $LP_{01}+LP_{02}$, is equal to the sum of that of second lowest and second highest order modes, i.e. $LP_{11}+LP_{21}$. Assuming equal span length then after the MFMP operation, we will ideally have the DMD of MDM system fully mitigated to 0 with the amount of residual DMD no more than that of one span as illustrated in the right of Fig. 1(b). In comparison, conventional CMP method will only have the DMD fully compensated at every 6 spans for a 6-mode transmission link and the residual DMD will be accumulated within these spans and become much larger than that of the MFMP case, as illustrated in the right of Fig. 1(a). Note that the MFMP method further applies to MDM systems with more than 6 modes and will be especially in favor of these system due to the aforementioned reason. In this work, the 6-mode fiber fabricated has DMD values of 0 ns/km, 0.11 ns/km, 0.92 ns/km, 0.97ns/km for $LP_{01}/LP_{11}/LP_{21}/LP_{02}$ mode, respectively. Although these values do not fully satisfy the above stated relation ($LP_{01}+LP_{02} = LP_{11}+LP_{21}$) due to manufacture defects, it will be demonstrated later that this still results in a significant amount of improvement for our MFMP system, which on the other hand shows the robustness of our proposed scheme.

3. Transmission System

The setup for a 6-mode transmission is shown in Fig. 2. An external cavity laser with a linewidth of 100 kHz operating at 1550 nm is modulated with a 28-Gbaud QPSK signal by an IQ Mach-Zehnder modulator. Transmitted signal is split into six paths through a 1×6 optical coupler and decorrelated with the length of delay lines of 400, 800, 1200, 1600 and 2000 m for LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, and LP_{02} inputs, respectively.

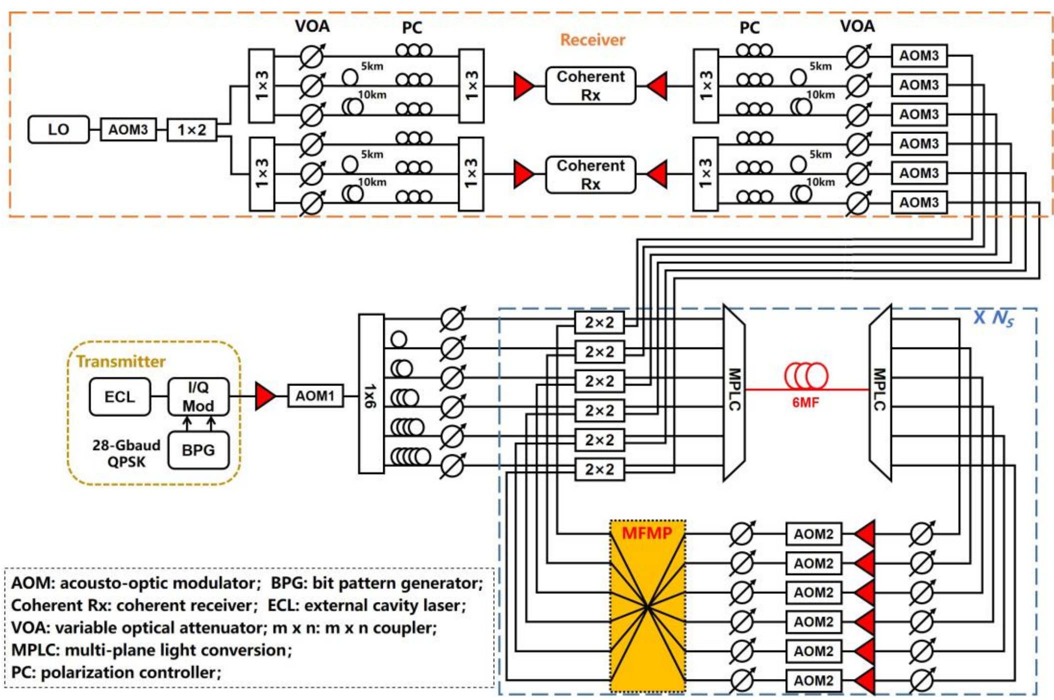

Fig. 2. Experimental setup for 28-Gbaud 6-mode 1028-km transmission.

In our experiment, a six-fold recirculating loop system is constructed for long-haul transmission. We use six EDFAs and multiple VOAs to fully compensate the span loss respectively and alleviate MDL effect in each span. AOM1 and AOM2 switches ensure that light of different periods would not interfere with each other. The transmission fiber is a trench-assisted graded-index 6-mode fiber with a length of 51.4 km, measured DMD of ~1 ns/km. The fiber loss is ~ 0.30 dB/km for all modes and the MDL of one span is estimated to be ~2 dB. The optical power launched into the FMF was set as 4.5 dBm per mode. The channel permutations are realized by exchanging corresponding paths at the end of each loop to apply the MFMP/CMP schemes.

Finally, the six-output signals were received by coherent receivers, where the signals were mixed with the light of a 100-kHz linewidth local oscillator laser. The electrical signals were digitized in a real-time oscilloscope with 36-GHz electrical bandwidth operating at 80 GSample/s. A time-division multiplexing scheme was applied that enabled reception of all signals in two coherent receivers [6]. The transmitted signals were stored for an off-line processing that successively performed front-end error correction, chromatic dispersion compensation, and frequency-domain MIMO equalization.

4. Experimental Results and Discussion

Figure 3(a) compares the transmission results according to MFMP scheme and CMP scheme under the same system architecture. Figure 3(b) shows the constellations of each mode of MFMP scheme after 1028-km transmission. The MFMP scheme takes 2 spans as one cycle, while CMP scheme takes 6 spans as one cycle. Compared with CMP scheme, the modes-exchange of MFMP scheme is more frequent with a low level of overall MDL accumulation, and the Q^2 value of MFMP scheme is much better. As we can see in Fig. 3(a), the Q-factor improvement of MFMP scheme reaches 3.8 dB after 1028-km transmission. Since the DMD effect is completely compensated by a large number of algorithm taps, the greater Q^2 value means the MIMO-enhanced noise caused by MDL has been significantly further mitigated due to the more frequently exchanging through MFMP approach.

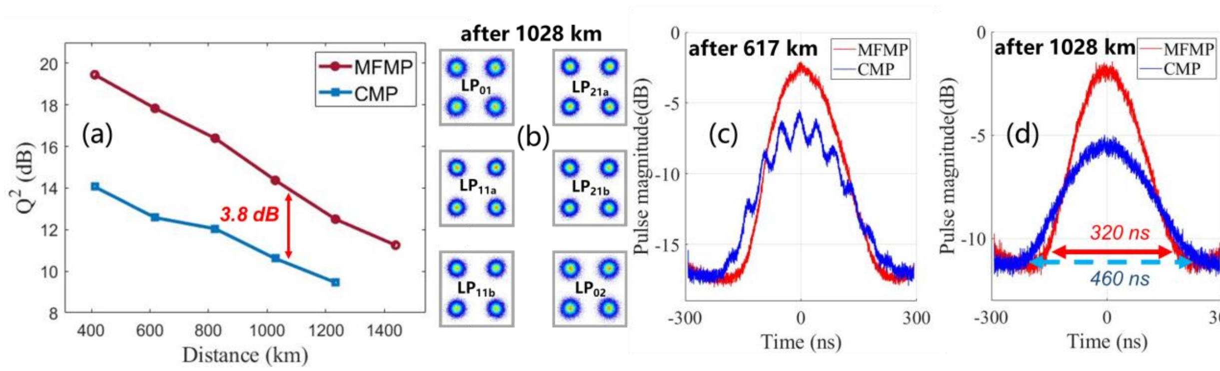

Fig. 3. (a) Averaged Q-factors of each mode vs. transmission distance; (b) Constellations of each mode after 1028-km MFMP transmission; Impulse responses observed at (c) 617 km and (d) 1028 km, respectively.

Figure 3(c-d) show the impulse responses averaged over all the mode groups at 617 km and 1028 km when MDM system was set to be the MFMP type, or to be the CMP type. We calculate a necessary equalizer window for MFMP/CMP schemes required for MIMO-DSP, respectively. For a regular transmission, signal broadening would be significant when the link reach increases due to the slight inter modal mixing. When we applied the MFMP or CMP scheme, the impulse magnitude becomes bell-shaped, allowing DMD-impact mitigation. In contrast, the impulse response of the MFMP strategy takes bell-shaped distribution earlier at 617 km, rather than still existing many spikes (meaning insufficient mode exchange) in the CMP scheme, as seen in Fig. 3(c). Further pulse width reduction was obtained by the MFMP at the same distance compared with traditional permutation method. As shown in Fig. 3(d), applying MFMP scheme reduced the required equalizer window decreased by 30 % at 1028 km.

5. Conclusion

A novel mode permutation scheme cooperating with a new-type symmetric-DMD FMF was firstly introduced and analyzed in experiment. Compared with conventional CMP strategy, our proposed MFMP is more suitable for long-haul MDM transmission with greater mitigation of MDL and DMD accumulation. Especially, the required equalizer window is decreased by 30 % at 1028 km and the Q^2 value is improved by 3.8 dB. The system performance of the proposed MFMP scheme would be further better under more ideal conditions of fabricated fiber.

Acknowledgements

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