10-mode PM-QPSK Transmission over 2320 km Enabled by Optimized Mode Permutation Strategies

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Abstract: For the first time, we demonstrate a 15-Gbaud PM-QPSK 10-mode transmission, extending the record reach by 1000 km, to 2320 km now. We develop the rules for identifying superior mode-permutation strategies (MPSs) among a huge number of MPSs. 24 MPSs are verified in experiments to greatly mitigate the differential mode delay and mode-dependent loss. © 2024 The Author(s)

1. Introduction

Rapid growth of global Internet traffic has driven significant research efforts for the development of mode-division multiplexing (MDM) technology in the past decade [1]. Ultra-high capacity and ultra-long distance have always been pursued for an MDM transmission system. However, in most cases, transmission distance is traded off with system capacity, associated with the number of spatial modes in an MDM link, as shown in Fig. 1(a). It should be noted that 10-mode-multiplexed transmission, representing a capacity increase by one order of magnitude, has long been studied in a relatively short reach [2-5], and until very recently it has been reported for a long-haul transmission over 1300 km [6]. The tradeoff between system capacity and distance also holds for 10-mode MDM links as shown in Fig. 1(b), and thus pushing the capacity-distance product to a higher level would be of great interest.

In fact, this is very difficult, requiring multifold innovations in both transmission media and system architecture. The signal pulse spread, induced by differential mode delay (DMD), and mode-dependent loss (MDL) are the fundamental limiting factors for reach extension. Except for DMD management, which suffers from the imperfection in fiber drawing [7,8], cyclic mode group permutation [6,9,10] and mirror-flipped mode permutation [11,12] are promising approaches to achieve an MDM system over 1000 km. However, these works for >10-mode transmission provided few mode permutation strategies (MPSs) to be verified in experiments due to the huge number of possible MPSs, e.g., ~35 million for 10 modes.

Here, we develop the rules to identify the most superior MPSs for 10-mode systems, showing only 24 noteworthy strategies as 5 series. In experiments, we show a 15-Gbaud PM-QPSK 10-mode transmission, extending the record reach by 1000 km, to 2320 km here, which greatly enriches the application scenarios of 10-mode transmission. A 28-Gbaud 1760-km transmission is also achieved with higher system capacity.

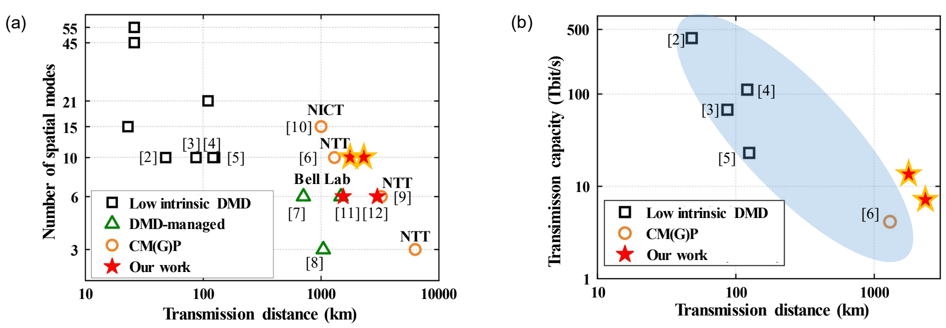


Fig. 1. (a) Recent MDM transmission experiments show a trade-off between spatial mode count and transmission distance. This work shows the largest mode-count-distance product so far for 10-mode transmission. (b) Mapping the 10-mode WDM transmissions in terms of capacity and distance, we show the largest capacity in >1000-km cases.

2. Rules for Choosing Superior MPSs

In traditional MDM transmissions with 6 or 10 modes, it is not feasible to experimentally verify the performance of all the possible MPSs. Thus, it's necessary to make reasonable rules to pick out the superior MPSs, for which purpose we propose the following 4 criteria for the first time: (1) MPS with more frequent exchanging cycle has better transmission performance, which has been verified in previous works [6,11]. Namely, we prefer MPSs with 2 spans as one period. (2) When one mode is exchanged to either one inside the degenerate modes, the permutation effect is considered to be equivalent, e.g., LP_{01}↔LP_{11a} and LP_{01}↔LP_{11b} are the same. (3) Each mode could not exchange within its corresponding degenerate mode, ensuring the interaction between degenerate modes is maximized, e.g., LP_{11a} LP_{11b} is useless. (4) LP_{31} and LP_{12} modes belong to one mode group, so exchanges between them are considered to be invalid. As shown in Fig. 2(a), we divide the selected MPSs to be 5 series, inside each series the LP_{01} mode would be exchanged to the same high-order degenerate modes. Based on the above 4 criteria, we carefully select 24 MPSs, i.e., 3 for LP_{01}↔LP_{11}, 4 for LP_{01}↔LP_{21}, 3 for LP_{01}↔LP_{02}, 7 for LP_{01}↔LP_{31}, and 7 for LP_{01}↔LP_{12}. Examples for each series can be seen in Fig. 2(b-f).

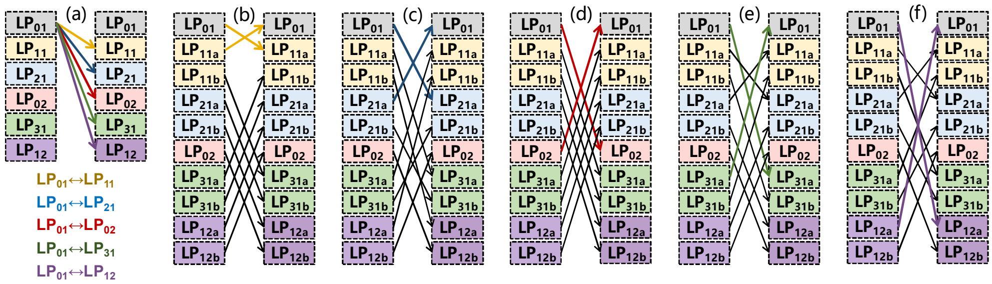
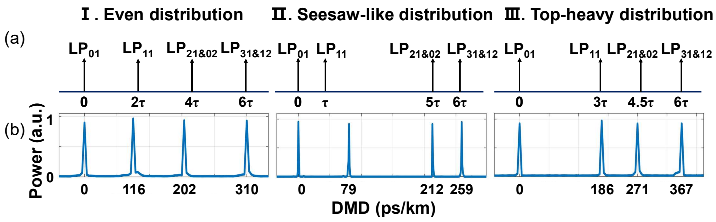


Fig. 2. (a) We divide the MPSs to be 5 series, i.e., LP_{01}↔LP_{11}, LP_{01}↔LP_{21}, LP_{01}↔LP_{02}, LP_{01}↔LP_{31}, and LP_{01}↔LP_{12}. In each series, the LP_{01} mode would be exchanged to the same high-order degenerate modes. Examples for each series are shown in (b-f), respectively.

To achieve ultra-long transmission distance, we have ever fabricated several pieces of 10-mode fibers (10MFs), which usually show 3 types of DMD distribution illustrated in Fig. 3(a). The corresponding measured DMD values are shown in Fig. 3(b). Note that the II-type fiber has the lowest DMD and is therefore chosen for the subsequent transmission. The standard variance, σ, of the fiber DMD after mode exchanges is strongly correlated with the compression effect on pulse spreading for a specific MPS. The larger the σ is, the weaker the compression effect would be. Considering that all the selected 24 MPSs take 2 spans as a period, we take the group delay after 2-span transmission for performance evaluation on DMD compression, and the σ of all channels for the 5 MPS series are calculated in Fig. 3(c). It can be found that the σ of LP_{01}↔LP_{21} and LP_{01}↔LP_{02} are the same while LP_{01}↔LP_{31} and LP_{01}↔LP_{12} are the same. Note that 10 strategies of LP_{01}↔$LP_{31\&12}$ are different from the other 4, which can be explained by the fact that there is no exchange between LP_{11} and $LP_{21\&02}$ in the other 4 strategies. According to Fig. 3(c), the compression on pulse spreading can be ranked from poor to excellent, i.e., LP_{01}↔LP_{11} < LP_{01}↔$LP_{02\&21}$ < LP_{01}↔$LP_{31\&12}$-1~5 < LP_{01}↔$LP_{31\&12}$-6~7, and the ranking is same for all the 3 fiber types mentioned above.



(c)

	σ of the supposed DMD distribution			
Type	LP_{01}↔LP_{11}	LP_{01}↔$LP_{21\&02}$	LP_{01}↔$LP_{31\&12}$-1~5	LP_{01}↔$LP_{31\&12}$-6~7
Ⅰ	1.67τ	1.15τ	0.94τ	0.67τ
Ⅱ	2.11τ	1.26τ	1.22τ	1.02τ
Ⅲ	1.55τ	1.16τ	0.92τ	0.77τ
	σ of the measured DMD distribution (ps/km)			
Type	LP_{01}↔LP_{11}	LP_{01}↔$LP_{21\&02}$	LP_{01}↔$LP_{31\&12}$-1~5	LP_{01}↔$LP_{31\&12}$-6~7
Ⅰ	83.28	59.83	46.77	33.99
Ⅱ	81.86	51.28	47.09	39.02
Ⅲ	93.37	71.28	55.65	46.81

Fig. 3. (a) Three types of supposed fibers with different DMD distribution, and (b) their corresponding measured DMD values. (c) The discreteness of the supposed fiber and measured fiber is in the same order for each type.

3. Experimental Setup and Results

In Fig. 4(a), light around 1550 nm from 16 ECLs is modulated with 15/28-Gbaud QPSK signals by an IQ modulator. After polarization and wavelength multiplexing, 16-channel 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. Here, we utilize a 40-km 10MF for transmission, which has been mentioned as the II-type fiber in Fig. 3(b). Figure 4(b) shows the refractive index profile of the fiber. For the four mode groups, the DMDs are 0, 79, 212 and 259 ps/km, respectively, extracted from the impulse response peaks in Fig. 3(b). Besides, the losses and effective mode field areas are 0.22~0.25 dB/km and 133~276 μm^2, respectively. Mode permutations are realized by exchanging corresponding paths at the end of each loop. Finally, the electrical tributaries are digitized by an 8-channel real-time oscilloscope with 36-GHz electrical bandwidth for off-line DSP.

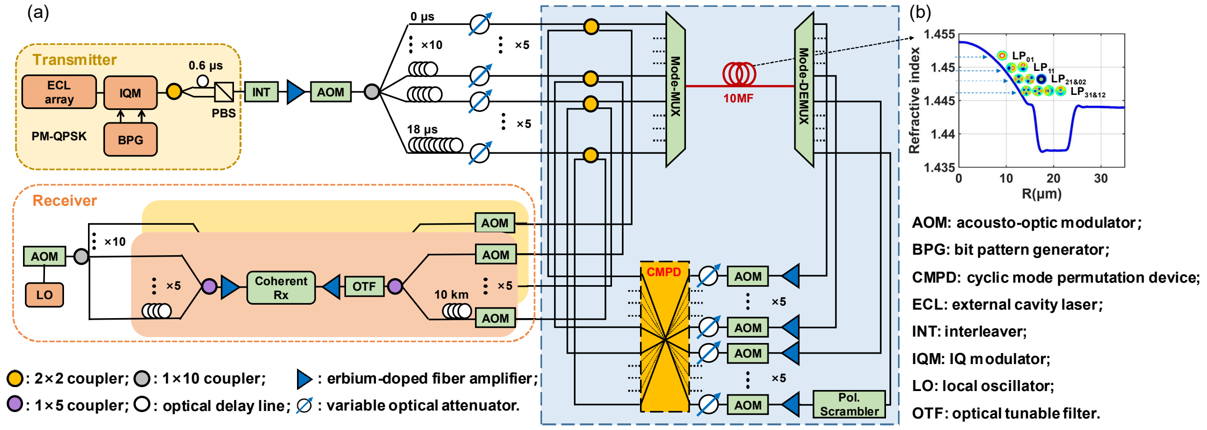


Fig. 4. (a) Experimental setup for 10-mode transmission. (b) The graded-index profile of the fabricated 10-mode fiber.

On one hand, Figure 5(a) shows the required equalizer time windows covering 99% impulse energy for the 1550.12-nm channel, with a traditional cyclic group permutation (CMP) additionally considered. The results for 24 selected MPSs are averaged within each series. Then the compression performance on pulse broadening can be extracted and ranked from poor to excellent, i.e., $LP_{01}\leftrightarrow LP_{11}$ < CMP < $LP_{01}\leftrightarrow LP_{02}$ < $LP_{01}\leftrightarrow LP_{21}$ < $LP_{01}\leftrightarrow LP_{31\&12}$-1~5 < $LP_{01}\leftrightarrow LP_{31\&12}$-6~7. It is almost consistent with the predicted order derived from the standard deviation of the first two spans' group delays in Fig. 3(c) except for slight separation in $LP_{01}\leftrightarrow LP_{02\&21}$, which in turn confirms the correctness and feasibility of our proposed rules. The rules work for more modes. On the other hand, the Q^2 values for the 1550.12-nm channel at 15 Gbaud in Fig. 5(b) show that series $LP_{01}\leftrightarrow LP_{21}$ is superior among all of the MPSs for its outstanding performance on MDL mitigating, which is preferred for transmission. Based on one of the MPSs in this series, a 16-λ 15-Gbaud PM-QPSK 10-mode transmission has been achieved, extending the record reach to 2320 km. The optical spectrum and the measured bit errors (BERs) of all the 10 spatial channels are shown in Fig. 5(c)&(d) for 15/28 Gbaud. The reach of other series is in the range from 1440 km to 2200 km.

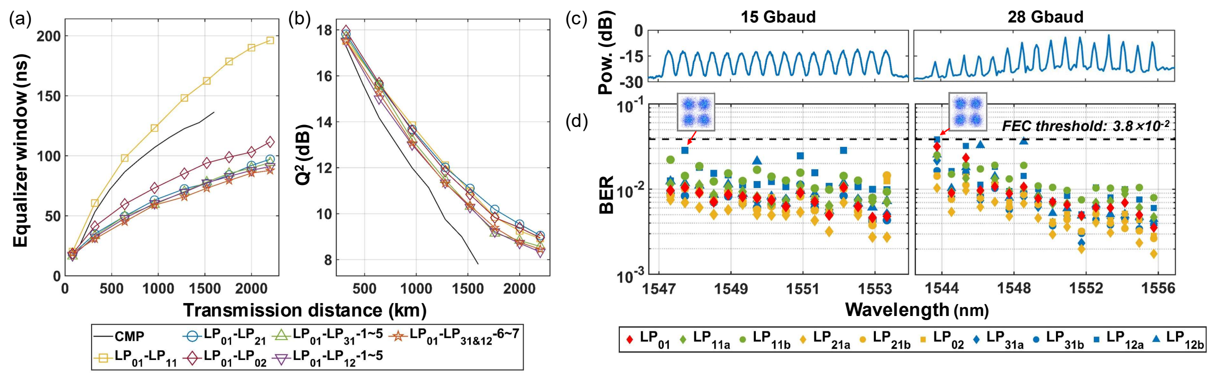


Fig. 5. Based on the results of (a) required equalizer windows and (b) Q^2, it can be concluded that the $LP_{01}\leftrightarrow LP_{21}$ series are relatively preferred. The spectrum (c) and measured BERs of all 10 spatial channels (d) after 2320-km 15-Gbaud transmission and 1760-km 28-Gbaud transmission belong to one of the MPSs in this series for the 16-λ channels.

5. Conclusion

We have proposed 4 rules for superior MPSs for the first time and demonstrated a 10-mode 15-Gbaud 16-λ PM-QPSK transmission over 2320 km, a record reach extension by 1000 km. We also show 1760-km 10-mode transmission at 28 Gbaud, with the highest capacity with 10 modes.

6. Acknowledgements

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