Long-Haul DMD-Unmanaged 6-Mode-Multiplexed Transmission Employing Cyclic Mode-Group Permutation

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Abstract: We demonstrate a long-haul 6-mode-multiplexed WDM transmission with a record reach of 3250 km. Newly-developed mode-group permutation technique mitigated modal-dispersion-impact by > 70%. We also show diversity-enhanced MIMO transmission extending the achievable reach over 9000 km. © 2020 The Author(s)

1. Introduction

Rapidly increasing traffic growth has made research efforts in space division multiplexing (SDM) transmission as a promising candidate technology for application in future fiber optic communication systems [1]. Mode division multiplexing (MDM) technology that simultaneously transmits multiple data streams over multi-mode fibers or few-mode fibers (FMFs) is appealing because it can perform spatially efficient optical transmissions over a single fiber. MDM transmission technology that enhances the reach achievable over FMF transmission links needs to be developed to realize future deployable SDM systems. The first long-haul MDM WDM transmission that used 3 spatial modes with a distance up to 1000 km was reported in [2]. Recent studies reported longer 3-mode transmission experiments with a distance of 3500 km [3]. By focusing on higher-order modes, long-haul MDM transmission experiments with 6 spatial modes have been demonstrated over 708 km [4] and 1475 km [5]. One dominant performance-limiting factor commonly faced in long-haul MDM transmission is the accumulation of differential mode delay (DMD). MDM transmission over longer distances and/or higher-order propagation modes generally causes wider pulse spreading, thereby enhancing computational cost required in MIMO-DSP. We previously proposed a novel cyclic mode permutation (CMP) technique as a key enabling technique for the DMD-unmanaged long-haul 3-mode-multiplexed transmission over 6300 km [6,7].

In this work, we develop a new scheme based on the CMP technique for application in MDM transmission guiding higher-order modes. By introducing a modal interchange with mode-group granularity, we demonstrate a record-long 6-mode-multiplexed transmission over 3250 km using 10-WDM PDM-QPSK signals with a net rate of 37.56 Gb/s/λ/mode (Figure 1). To the best of our knowledge, this work is the world's first demonstration of a long-haul MDM transmission that does not manage DMD profiles along a 6-mode FMF. Moreover, with decreased system throughput, we present a longer MDM transmission with variable distances up to 9000 km by exploiting spatial diversity in conjunction with the proposed mode-group permutation technique.

2. Cyclic Mode-Group Permutation

In regular MDM transmission over weakly-coupled FMFs, DMD is piled up in almost linear fashion with increasing transmission reach. To overcome this negative feature of DMD, one popular way is introducing DMD management technique in which an DMD profile along a FMF link is designed to minimize the total DMD [3-5,8,9]. As an alternative approach, we have previously proposed the CMP scheme in 2LP-mode transmission where mutual mode switching is cyclically performed in every span [6]. Applying the CMP scheme into weakly-coupled MDM transmission was found to equivalently have strong inter-mode coupling effects because modal mixing is effectively stimulated when signal pulses propagate as mutually degenerated spatial modes.

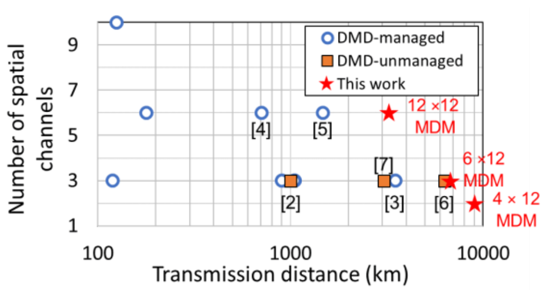

Fig.1. Recent MDM transmission experiments over 100 km.

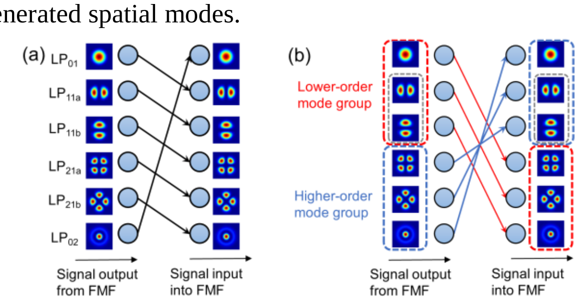

Fig. 2. Schematics of (a) cyclic mode permutation (CMP) [6] and (b) cyclic mode-group permutation (CMGP).

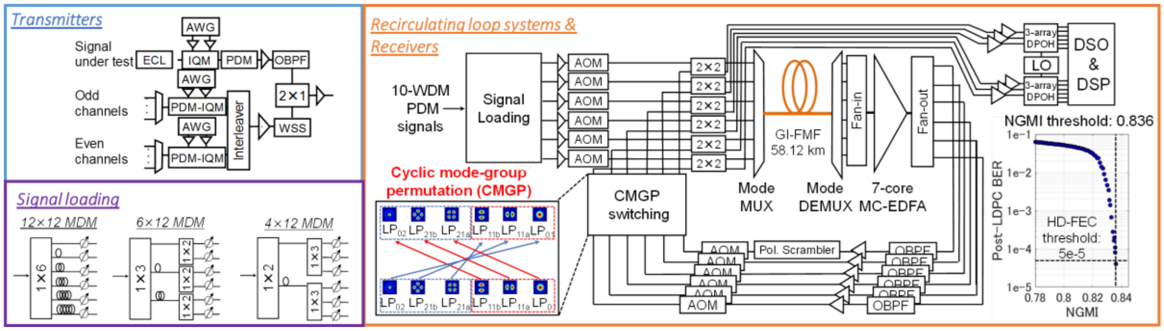

Fig. 3. Experimental setup.

We consider its implementation in MDM transmission supporting several mode groups. Figure 2(a) shows a configuration example of a *straightforward* application of the CMP scheme for 4LP-mode transmission that simply connects single-mode ends between neighboring spatial modes. Mode-to-mode averaged performance in this configuration might be ineffective because of the similarity in propagation constants between mode permutation pairs. In this work, we propose a novel scheme that introduces mode-group granularity, termed cyclic mode-group permutation (CMGP). Figure 2(b) explains the CMGP scheme for a 4LP-mode case. We first categorize 6 spatial modes into 2 mode groups—namely a lower-order mode group with $LP_{01}/LP_{11a}/LP_{11b}$ modes, and a higher-order mode group with $LP_{21a}/LP_{21b}/LP_{02}$ modes—although the former group contains non-degenerate modes. Then mode permutation is performed with respect to these mode groups. In addition, clockwise and anti-clockwise mode permutations are respectively adopted to lower- and higher-order mode groups to keep cyclic transition properties.

3. Experimental Setup

The setup for a long-haul 6-mode MDM transmission is shown in Figure 3. Binary patterns for 2×6-GBaud dual-subcarrier QPSK modulation was coded with an LDPC code with a code rate of 4/5 defined in the DVB-S2 standard. We also assumed a BCH (30832, 30592) code with the HD-FEC threshold BER of 5×10^{-5} [10] for the error floor removal after LDPC decoding to achieve post-FEC BER of 1×10^{-15}. An NGMI threshold was estimated to be 0.836 through Monte Carlo simulations of an LDPC decoding performance with 50 iterations (Fig. 3). The transmission frame comprised a 33360 symbol-length QPSK-pattern containing 1.4%-OH for the training sequence. The test channel was generated by a 24-GSa/s AWG, an IQ-modulator, and a PDM emulator with a 295-ns delay for decorrelation. This setup yields 37.56-Gb/s/λ/mode PDM-QPSK signals with a spectral efficiency (SE) of 3.00 b/s/Hz/mode. The even/odd channels with the same signal format located from 1549.627 nm to 1550.529 nm with 12.5-GHz channel spacing were also created. These signals were combined through a 2×1 optical coupler to yield 10 WDM PDM signals, and then split into six and decorrelated with delays of 566, 1151, 1768, 2359, and 3524 ns for LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, and LP_{02} inputs, respectively.

For MDM signal transmission, a six-fold recirculating loop system was constructed, each containing EDFAs, optical bandpass filters (OBPFs), and AOMs. We used a multiplexer/demultiplexer pair that exclusively separated each mode with averaged mode crosstalk of -28.7 dB. The transmission fiber was a trench-assisted graded-index FM supporting 6 modes with a length of 58.12 km, measured DMD of 70.5 ps/km, and calculated A_{eff} of 80 μm^2 for LP_{01} mode at 1550 nm. The fiber attenuations were 0.29 dB/km and 0.30 dB/km for $LP_{01/11}$ and $LP_{21/02}$ modes, respectively. To fully compensate the span loss, both discrete EDFAs and integrated core-pumped 7-core multicore EDFA were employed [11]. Considering cyclic propagation over all recirculating loops, a loop-synchronous polarization scrambler was introduced only in one loop. The optical power launched into the FMF was set to -7 dBm/λ/mode. A switching block was introduced at the end of loops to apply the CMP/CMGP schemes. We labelled each data stream by integer numbers from mode 1 to mode 6, corresponding to those launched as LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, and LP_{02} mode at the initial span, respectively.

At the receiver, the transmitted signals were detected and stored for an off-line processing that successively performed front-end error correction, chromatic dispersion compensation, and frequency-domain MIMO equalization. The combined use of a dual-subcarrier transmission and the mode-permutation techniques greatly suppressed the equalizer length to less than 500 half-symbol-spaced taps per mode for a transmission up to 4000 km.

4. Experimental Results

Figures 4(a) to (c) show impulse responses averaged over each mode group at 1162 km when MDM signals were transmitted in a weakly-coupled regime, with the CMP scheme, or with the CMGP scheme. Figure 4(a) indicates that signal pulses drift faster in $LP_{01/11}$ modes, and slower in $LP_{21/02}$ modes at the wavelength used. For a conventional transmission, signal broadening was significant with increased reach because of small inter-group modal mixing. When we applied the CMP scheme, impulse response magnitude became bell-shaped, allowing

DMD-impact mitigation. Further pulse width reduction was obtained by the CMGP scheme at the same distance. We then calculated an equalizer window required in MIMO-DSP, defined as a window range in impulse responses where a pulse magnitude decays by 20 dB. The result is depicted in Fig. 4(d). While a linear growth of equalizer window was observed in conventional transmission, pulse broadening was suppressed by the use of the CMP/CMGP schemes. In particular, the pulse was well suppressed after 1000 km for the CMP scheme, and after several hundreds of km for the CMGP scheme, indicating very efficient mode mixing. Applying the CMGP scheme reduced the required equalizer window at 1162 km decreased by 70%. Next we performed a 12×12 MDM WDM transmission using the CMGP scheme. Figure 5(a) shows the signal performance of all wavelength/spatial channels in a 12×12 MDM transmission over 3250 km. We confirmed that NGMI for all the channels exceeded the NGMI threshold of 0.836, achieving the total capacity of 2.25 Tb/s and the record net SE-distance product of 58677 b/s/Hz×km.

We also exploited the spatial degree of freedom of the 6-mode transmission link with the aim of increasing transmission reliability (diversity gain) rather than system throughput (multiplexing gain), commonly known as a diversity-multiplexing tradeoff in wireless MIMO systems [12,13]. To this end, we investigate three transmission scenarios where the number of data streams loaded into the 6-mode link was varied in the range of six, three, and two ("signal loading" block in Fig. 3). We term the first "fully-multiplexed" MDM transmission, and the latter two "diversity-enhanced" MDM transmission, characterized by a MIMO system size of N×M, where N and M denote a number of transmitters and receivers, respectively. Pulse spreading in transmission with the CMGP scheme at 4068 km and 9008 km is compared in Figure 6(a). Most pulse energy was confined within the window of 50 ns at 4068 km and 75 ns even at 9008 km. Figure 6(b) shows singular values in 4×12 MDM transmission at 9008 km, allowing us to calculate mode dependent loss (MDL) of 7.4 dB. Results in Fig. 6(a) and (b) (namely, low DMD and MDL) indicate the feasibility of the CMGP scheme in performing diversity-enhanced long-haul MDM transmission. Figure 6(c) represents transmission results of mode-averaged Q-factors in 12×12, 6×12, and 4×12 MDM transmission. The achievable reach increased significantly to 6625 km with a net capacity of 1.13 Tb/s in the 6×12 MDM scenario, and 9008 km with a net capacity of 0.75 Tb/s in the 4×12 MDM scenario.

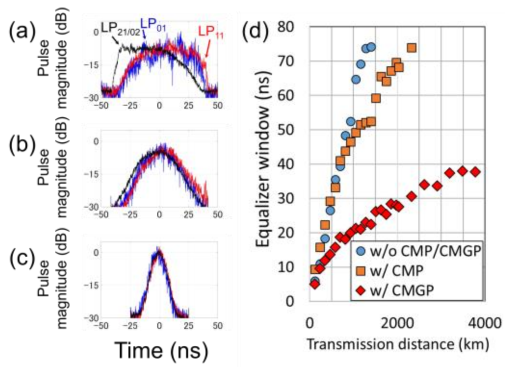

Fig. 4. (a)-(c) Mode-group-averaged impulse responses observed at 1162 km in (a) a conventional transmission, (b) a transmission with CMP, and (c) a transmission with CMGP. (d) Equalizer window required for MIMO-DSP.

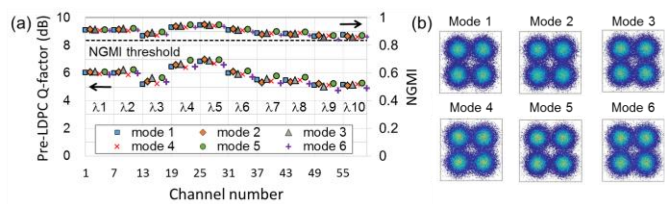

Fig. 5. (a) Q-factors and NGMI for all the channels after 6-mode 3250-km MDM transmission. (b) Received signal constellations for all modes at λ5.

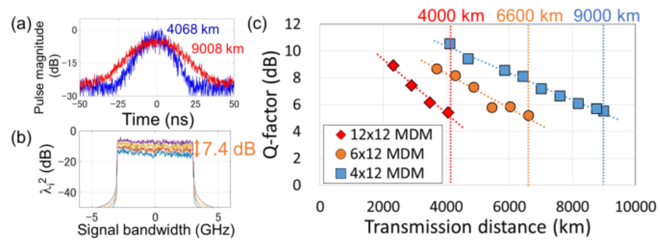

Fig. 6. (a) Impulse response growth at 4068 km (blue) and 9008 km (red), (b) singular value distribution at 9008 km, and (c) mode-averaged Q-factors in fully-multiplexed MDM and diversity-enhanced MDM transmissions.

4. Conclusion

We demonstrated the longest 3250-km 12×12 MDM transmission using 10-WDM 37.56-Gb/s/λ/mode PDM-QPSK signals without managing the DMD of a 6-mode transmission link, achieving a net SE-distance product of 58677 b/s/Hz×km. The newly-developed CMGP technique allowed us to transmit MDM signals with strong inter-mode mixing over a weakly-coupled FMF supporting multiple mode groups. We also showed that the CMGP scheme can achieve longer MDM transmission reach over 9000 km in conjunction with diversity-enhanced MDM transmission.

5. References

[1] T. Morioka et al., OECC2019, FT4 (2019).
[2] E. Ip et al., JLT, **32**(4), pp.790-797 (2014).
[3] G. Rademacher et al., ECOC2017, M.2.E.4 (2017).
[4] R. Ryf et al., ECOC2013, We.2.D.1 (2013).
[5] J. Weerdenburg et al., JLT, **36**(6), pp.1369-1374 (2018).
[6] K. Shibahara et al., OFC2018, Th4C.6 (2018).
[7] K. Shibahara et al., OFC2019, W3F.2 (2019).
[8] V. Sleiffer et al., ECOC2012, Th.3.C.4 (2012).
[9] Y. Wakayama et al., OFC2016, M3E.6 (2016).
[10] D. Millar et al., ECOC2015, Mo.3.3.1 (2015).
[11] K. Takenaga et al., OECC2013, TuS-2 (2013).
[12] L. Zheng et al., IEEE Trans. Inf.Theory, **49**(5), pp.1073-1096 (2003).
[13] S.O.Arik and J.M. Kahn, Opt. Lett. **39**(11), pp.3258-3261 (2014).