10-spatial-mode 1300-km Transmission over 6-LP Graded Index Few-Mode Fiber with 36-ns Modal Dispersion

Kohki Shibahara[1], Megumi Hoshi[1], and Yutaka Miyamoto[1]
[1]*NTT Network Innovation Laboratories, 1-1 Hikari-no-oka, Yokosuka, Kanagawa, Japan*
kouki.shibahara.nv@hco.ntt.co.jp

Abstract: We demonstrate record-long 10-mode-multiplexed transmission over 1300 km with 6-LP few-mode-fiber with modal dispersion coefficient of 157 ps/km. Modal-dispersion-unmanaged link was built by cyclic mode-group permutation, achieving reduction in modal dispersion accumulation by 82 %.

1. Introduction

Towards future ultra-high-capacity optical transport systems, significant research efforts for enhancing per-fiber-capacity have been devoted to spatial division multiplexing (SDM) technology. Recent studies based on mode-division-multiplexing (MDM) have revealed a high potential of multi-mode fibers/ few-mode fibers (MMFs/FMFs) realizing extremely-high capacity over 1 Pbps with standard cladding fibers supporting 15 modes [1] and 55 modes [2]. Another important aspect in developing MDM technology is achievable reach extension of MDM transmission. To date, long-haul MDM transmission experiments have been reported up to 6300 km for 3 modes [3], 3250 km for 6 modes [4], and 115 km for 10 modes [5]. In long-haul MDM transmissions with several mode-groups (MGs) that exhibit dissimilar propagating properties depending on each MG, technical challenge lies in how we handle these differences within acceptable performance deterioration. In particular, pulse broadening effect induced by differential mode delay (DMD) is one major and fundamental performance-limiting factor that enhances computational cost required in MIMO-DSP for digitally undoing mode mixing effects. As an approach for extending MDM transmission reach without managing profiles of DMD along link, we previously proposed cyclic mode permutation (CMP) for 2-LP-mode FMF [3] and cyclic mode-group permutation (CMGP) for 4-LP-mode FMF [4] that mutually switches each mode in every span. Understanding a capability of handling higher-order modes in distances over 1000 km is essential for clarifying a feasibility of those higher-order modes in future optical MDM transport systems.

In this paper, we demonstrate a world's-longest long-haul 10-spatial-mode 11-WDM transmission over 6-LP graded-index (GI) FMF. Through an adaptation of CMGP with respect to 4-MG transmission, we achieve a reduction in memory length required for MIMO-DSP by 82 % at 1300 km. This enabled us to perform 10-mode DMD-unmanaged transmission over 1300 km only with low modal dispersion of 36 ns, corresponding to a reach extension compared with previously-reported works by an order of magnitude (Figure 1). To the best of our knowledge, this is the first demonstration of inline amplified fully-loaded 10-mode transmission using 6-LP FMFs.

2. Experimental Setup

We start with discussion of a design for CMGP adaptation with respect to four-MG MDM transmission. Obviously, a realization number of mode interchange would be massive up to the factorial of ten. Based on the results obtained in [4] that mode-to-mode averaging effect in MDM transmission performance was enhanced with interchange of spatial modes between dissimilar MGs, we focused here on two representative CMGP configurations illustrated in Figure 2. A first option is designed on the basis of "symmetric" mode interchange, referred to as CMGP-I (Fig. 2(a)). Denoting k as the number of MG hops via CMGP, mode interchange with a largest k of 3 between LP_{01} and LP_{12b} is obtained in CMGP-I, which, in turn, produces connections within the same MG (i.e., $k = 0$) between LP_{21b} and LP_{02}. Another option is a "forced" mode interchange satisfying $k \geq 1$ for all spatial modes, referred to as CMGP-II (Fig. 2(b)). Transmission performance with both CMGP configurations will be clarified in Section 3.

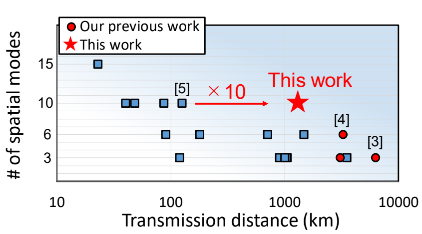

Fig. 1. Recent MDM transmission experiments over FMFs.

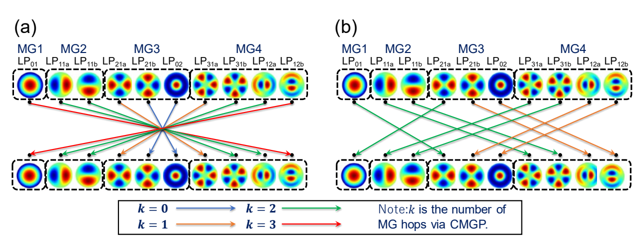

Fig. 2. Inter-connection options in CMGP. (a) CMGP-I (symmetric interchange) and (b): CMGP-II (forced interchange).

An experimental setup was built for an evaluation of 10-spatial-mode-multiplexed signals propagating over long distances, shown in Figure 3. A test channel was created as 2×6-GBaud dual-subcarrier QPSK signals by 24-GSa/s AWG and an IQ-modulator with binary pattern coded by an LDPC code with a code rate of 4/5 defined in the DVB-S2 standard and a BCH (30832, 30592) code with the HD-FEC threshold BER of 5×10^{-5} [6] for avoiding the error floor after LDPC decoding to achieve post-FEC BER of 1×10^{-15}. Each transmission frame contained 1.4%-overhead (OH) for a training sequence. The test channel was then decorrelated via PDM emulator with a 295-ns delay, combined with WSS-shaped ASE sources to yield 11-WDM 12.5-GHz-spaced signals locating from 1549.556 nm to 1550.558 nm, and again decorrelated for producing MDM signal inputs with delays of 567, 1204 1796, 2388, 2965, 3534, 4149, 4751, 5232 ns as inputs of mode 1 through mode 10, respectively. Note that each spatial channel with integer corresponds to those launched at the first span as LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, LP_{02}, LP_{31a}, LP_{31b}, LP_{12a}, and LP_{12b}, respectively. Through this setup, we obtained PDM-QPSK signals with a throughput of 37.56-Gbps/λ/mode, a spectral efficiency (SE) of 3.00 bps/Hz/mode, and normalized general mutual information (NGMI) threshold of 0.836 [4].

Ten-fold recirculating loop systems were also constructed, each containing multi-core/discrete EDFAs, OBPFs, AOMs, and multi-plane light conversion based mode-selective multiplexer/demultiplexer (MUX/DEMUX). Inline optical amplifiers for fully compensating span loss were employed with discrete EDFAs and integrated core-pumped 7-core multicore EDFAs [7]. Transmission fibers were graded-index (GI) 6-LP FMF designed with fiber parameters of a cladding diameter of 125 μm, a core diameter of 25 μm, a fiber attenuations of < 0.25 dB/km for all spatial modes, and calculated A_{eff} larger than 80 μm^2 at 1550 nm. 52-km-long 6LP-GI-FMF line comprising four spools connecting through FM connectors and fusion splicing, yielding measured fiber span loss of 11.9 dB and an DMD coefficient of 157 ps/km. CMGP scheme was introduced to carry out at the ends of recirculating loop systems with two configurations of CMGP-I and CMPG-II. Loop-synchronous polarization scramblers were also introduced in first and seventh loop recirculating loops considering the fact of signal's cyclic excursion over all recirculating loops.

After transmissions, MDM signals were detected through a coherent SDM-TDM receiver setup that shared optics/electronics for coherent reception in the time domain by introducing 5-km SMF-delay spools. One noteworthy point is that an input configuration of local oscillator (LO) laser was simplified such that it does not require additional delay lines for satisfying injection within coherent length, digitally assisted by MIMO carrier phase recovery (CPR)

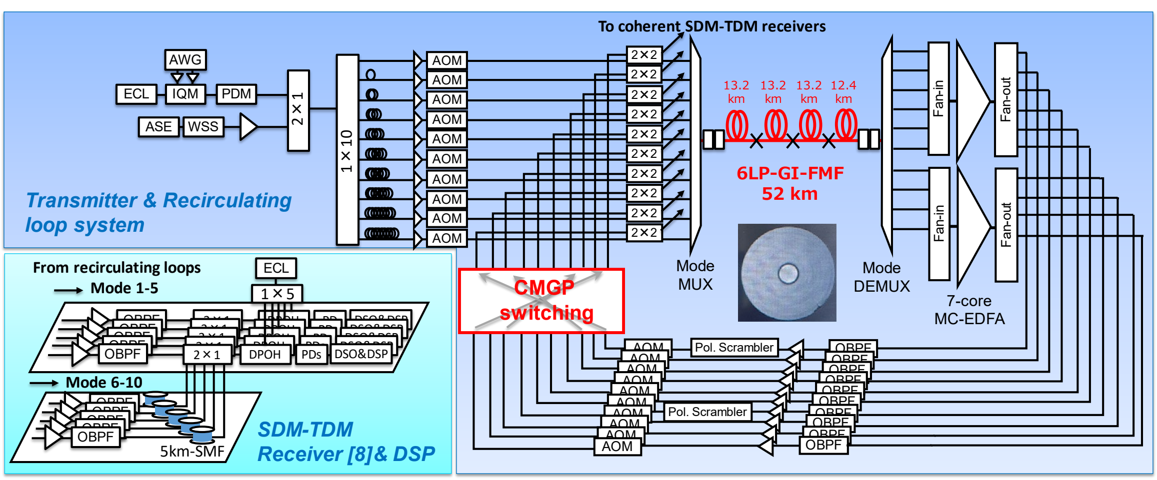

Fig. 3. Experimental setup.

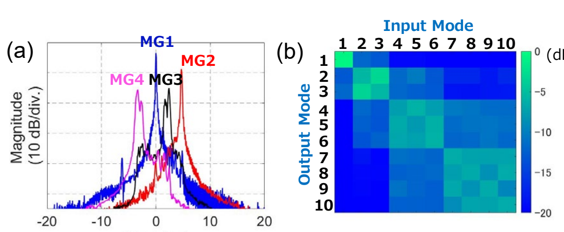

Fig. 4. (a): Impulse response for each MG at 52 km. (b): Intra/inter-mode crosstalk matrix at 52 km.

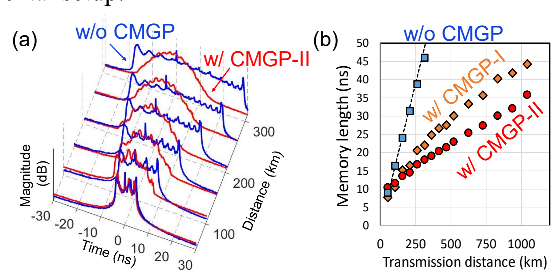

Fig. 5. (a): Evolutions of impulse response in 10-mode transmission. (b): Memory length growth along distance.

technique [8]. Each SDM-TDM receiver was then assigned for receptions of 2 spatial channels, saving receiver setup counts from 10 to 5. The detected signals were then stored for an off-line processing, performing front-end error correction, chromatic dispersion compensation, and MIMO-CPR-embedded frequency-domain MIMO equalization. Equalizer coefficient length was maintained below 430, corresponding to memory length window of 36 ns.

3. Experimental Results

We start an analysis on the experiment with 10-spatial-mode-multiplexed single-span transmission property. Figure 4(a) shows an impulse response of each MG after 52-km transmission. At the used wavelength of 1550 nm, we obtained an DMD coefficient of 157 ps/km that corresponds group velocity difference between MG2 and MG4. Crosstalk matrix at a distance of 52 km is depicted in Fig. 4(b), showing relatively-high inter-mode selectivity was maintained with inter-mode crosstalk below -10 dB. Figure 5(a) visualizes evolutions of sum of impulse response for all MGs with a comparison between cases without and with CMGP. It is clearly understood that a reformation of an impulse response into bell-shaped one is stimulated by an introduction of CMGP with a narrower pulse spread in comparison to CMGP-unintroduced transmission. Memory length, defined as a time window covering a pulse energy of 99%, is summarized in Fig. 5(b) in three transmission scenarios, including CMGP-unintroduced, CMGP-I-adopted, and CMGP-II-adopted transmission. A black broken line in the same figure is drawn as a "linear" prediction calculated based on DMD coefficient of 157 ps/km, showing a good agreement with memory length growth in CMGP-unintroduced transmission. In memory length comparison in two CMGP configurations, we found a considerable narrower memory length was achieved in CMGP-II transmission. This might attribute to occurrence of inter-connection between MGs in CMGP-II enhanced an equalizing effect of DMD.

It is of our next interest of analyzing mode dependent loss (MDL) that fundamentally limits transmission performance of an MDM link. Figure 6(a) shows evolutions of peak-to-peak MDL (MDL_{pp}) and rms MDL (MDL_{rms}) [9,10] with increased distance in CMGP-II transmission under an assumption of quasi strong coupling by an introduction of CMGP scheme. Loss/gain optimization that was performed on the per-mode basis in ten-fold recirculating loop systems well suppressed MDL_{pp} below 13 dB even at 1300 km (Fig. 6(b)), which is comparable to those observed in our-previous MDM transmissions with lower-order MGs [3,4]. Fitting results of MDL_{rms} with respect to the theoretical curve [9] give an estimation of an rms MDL value of each span (σ_g) of 0.8 dB. Finally we performed a 20×20 MDM WDM transmission. With the use of CMGP-II, memory length was suppressed by 82 % at 1300 km based on the linear prediction in Fig. 5(b) (black broken line). NGMI results for all wavelength/spatial channels at 1300 km are summarized in Figure 7. We confirmed that NGMI for all the channels exceeded the NGMI threshold of 0.836, achieving the total capacity of 4.13 Tbps and the net SE-distance product of 39063 bps/Hz×km.

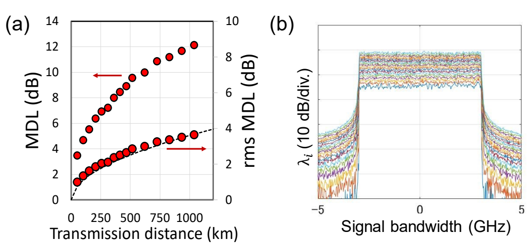

Fig. 6. (a): Accumulation of peak-to-peak MDL and rms MDL along transmission distance. (b): Eigenvalue distribution for all spatial channels at 1300 km.

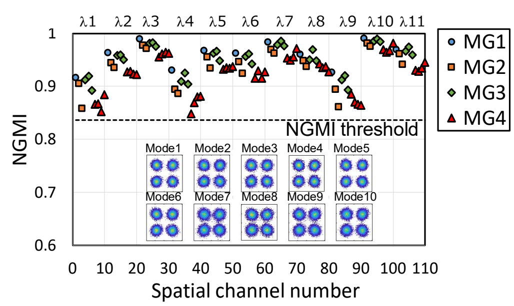

Fig. 7. NGMI for all channels after 10-spatial-mode 1300-km transmission. Inset shows representative constellations of wavelength channel #7.

4. Conclusion

We have demonstrated the world's-longest 10-mode 1300-km transmission over 6-LP graded-index FMF. Cyclic mode interchange over 4 mode groups affected on modal dispersion accumulation to be reduced by 82 % at 1300 km.

5. Acknowledgement

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