Mode-Multiplexed 6×20-GBd QPSK Transmission over 1200-km DGD-Compensated Few-Mode Fiber

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Abstract: Low differential group delay (DGD) between the modes of a graded-index few-mode fiber is obtained by combining segments with DGD of opposite sign. Transmission of mode-multiplexed 6×20-GBd QPSK over a record distance of 1200 km is demonstrated.

1. Introduction

The quest for a new optical fiber, capable of scaling the capacity of next generation long-haul links, has just begun [1–6]. In particular, space-division multiplexing (SDM) over a single fiber has gained considerable interest and two main approaches are currently being pursued. The first approach tries to minimize crosstalk between individual fiber cores [1, 2] or modes [3] along the complete link which requires a careful design of the involved optical components. The second approach for realizing SDM over a single fiber allows for substantial mixing between the modes and multiple-input-multiple-output (MIMO) digital signal processing (DSP) is used to recover the transmitted signals [4–6]. In this case, the challenge for the fiber design and manufacturing consists in controlling the differential group delay (DGD) between the modes in order to minimize the required DSP complexity. In this paper, we demonstrate for the first time a way to compensate for DGD in a few-mode fiber (FMF) that supports six spatial- and polarization modes by concatenating multiple fiber segments with DGDs of opposite sign, resulting in a 30-km long fiber span with a DGD of less than 50 ps. The composite fiber is used in a recirculating loop experiment, demonstrating transmission of six 20-GBd quadrature phase-shift keyed (QPSK) signals over a record distance of 1200 km. This exceeds the longest previously demonstrated FMF-transmission distance [5] by almost one order of magnitude.

2. Composite Graded-Index Few-Mode Fiber

The FMF used in this work has a graded-index profile supporting propagation of six spatial- and polarization modes that can, under the weakly guiding approximation, be expressed as the linearly polarized (LP) LP_{01} mode and the twofold degenerate LP_{11} mode, each with two orthogonal polarization modes. In the following, we refer to the horizontally and vertically oriented realizations of the LP_{11} mode as LP_{11h} and LP_{11v}, respectively. The fiber design is optimized to minimize the DGD between the LP_{01} mode and the LP_{11} mode. However, initial prototypes of the design yield a variation of the DGD on the order of ±300 ps/km along the length of the fiber. The fiber loss, measured by optical time-domain reflectometry, is 0.24 dB/km; the chromatic dispersion, calculated from the preform profile, is around 18.5 ps/nm/km for both LP modes; and the effective areas are 64 μm^2 for the LP_{01} and 67 μm^2 for the LP_{11} mode. We characterized the DGD of multiple FMFs of different lengths by launching an intensity modulated pulse as described in [7] and selected two fibers of lengths 25 km and 5 km, respectively. Both fibers have a DGD of about 1.5 ns. However, while in the first fiber the LP_{01} mode propagates faster, the LP_{11} mode propagates faster in the second fiber. We connected the two FMFs using a commercial fusion splicer where we took special care to minimize the modal crosstalk introduced by splice imperfections. The overall DGD of the 30-km long fiber span is <50 ps at 1550 nm and <100 ps across the full C-band.

3. Coherent MIMO Transmission Experiment

In order to study the transmission performance of the DGD-compensated fiber over long distances we built a recirculating loop as shown in Fig. 1. The optical field emitted from an external cavity laser (ECL) at 1555 nm with a linewidth of <100 kHz is modulated using a double-nested Mach-Zehnder modulator (DMZM) producing a 20-GBd QPSK signal from the two outputs of a programmable pattern generator (PPG). The PPG is programmed to generate two independent De Bruijn binary sequences (DBBSs) of length 2^{12} for the in-phase (I) and quadrature (Q) components. After the polarization multiplexing stage, which produces two orthogonally polarized copies with a relative delay of 25 ns, the signal is again split into three copies with relative delays of 49 ns and 97 ns. These signals are then
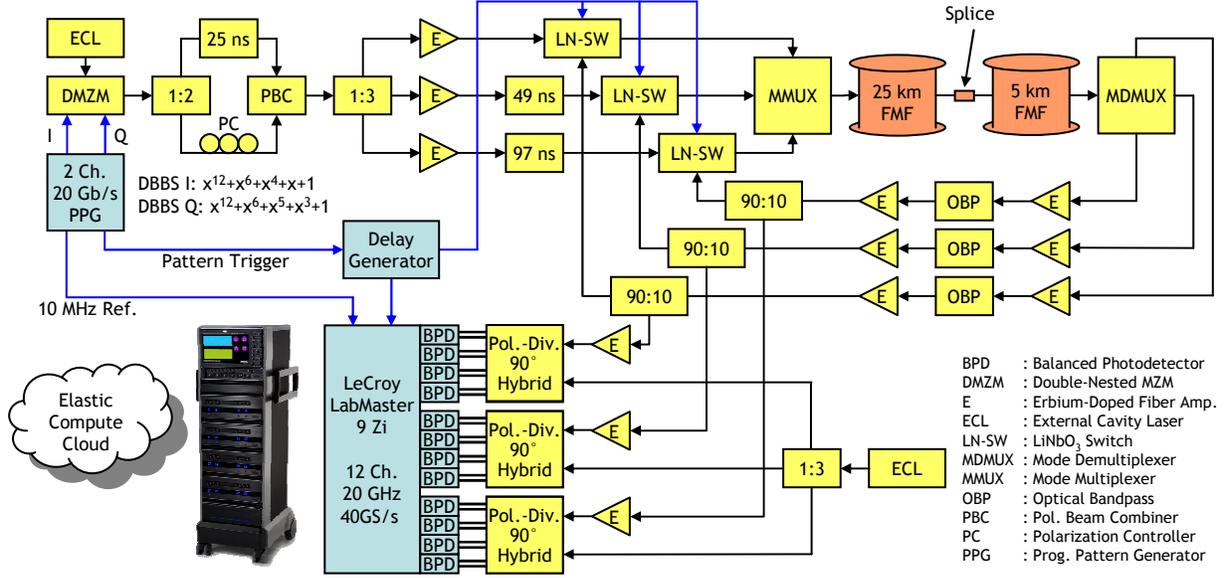
Fig. 1. Experimental setup.

fed into a triple recirculating loop using three LiNbO$_3$ switches (LN-SWs) to load and close the loop. The switches are controlled by a delay generator which also generates the trigger for data acquisition, and the path lengths of the three loops are accurately tuned to a relative time delay of less than 50 ps. A mode-multiplexer (MMUX) and a mode-demultiplexer (MDMUX), both based on phase plates [7], are used to couple into and out of the FMF. The span loss, defined as the loss of the fiber plus the loss of the MDMUX, is between 15 dB and 18 dB and is compensated by three two-stage Erbium-doped fiber amplifiers. Optical bandpass filters (OBPs) are placed between the two amplifier stages in order to reject out-of-band noise. The launch power into the FMF is equalized between the spatial modes. Three 90:10 couplers are utilized to extract the signal from the loop and to feed three polarization-diverse coherent receivers, which are operated in intradyne configuration using a second ECL as local oscillator. The electrical signals from the 12 balanced photodiodes (BPDs) are captured by a modular multichannel digital oscilloscope (LeCroy LabMaster 9 Zi) at a sampling rate of 40 GS/s with a bandwidth of 20 GHz. Finally, the measured waveforms are processed off-line, where, in a first step, the frequency offset and the chromatic dispersion are compensated and then, a channel estimation and adaptive 6×6 MIMO equalization are performed as described below.

4. Channel Estimation

In order to develop a better understanding, we estimate the 36 impulse responses of the 6×6 MIMO channel from the first 32,768 received samples of each waveform using the least squares (LS) algorithm [8]. In Fig. 2(a-f), we compare exemplary impulse responses of the LP$_{11}$ mode for 1, 3, and 5 loops. While the first row (a-c) corresponds to the 25-km long FMF without DGD compensation, the second row (d-f) shows results for the 30-km long DGD-compensated FMF. In all curves, a dominant peak is observed that corresponds to light that is launched into, propagates through, and is received in the LP$_{11}$ mode. In Fig. 2(a-c), we see that one additional smaller peak with a spacing of about 1.5 ns is generated after each loop. This time delay corresponds to the DGD between the LP$_{01}$ and the LP$_{11}$ modes. These side-peaks are due to crosstalk introduced by imperfections of the MMUX and the MDMUX. In each loop, a small fraction of the light is launched into the LP$_{01}$ mode and arrives at the receiver with a DGD of 1.5 ns, where in the MDMUX, another fraction is coupled back into the LP$_{11}$ mode. This effect lets the DGD accumulate linearly with the number of loops. Between the 1.5-ns spaced peaks, we can observe a continuum of lower peaks that are due to random mode coupling in the fiber. After splicing the 5-km long DGD-compensating FMF to the 25-km long FMF we observe the impulse responses shown in Fig. 2(d-f). Now, the impulse responses stay confined around the main peak even after multiple loops. This is due to the fact that the light that propagates in the LP$_{01}$ mode arrives at the MDMUX at the same time as the light that propagates in the LP$_{11}$ mode. However, in Fig. 2(e), we can see another side peak that can be explained by a small imperfection of the splice. If we assume that a fraction of the light is coupled into the LP$_{01}$ mode at launch, and part of this light couples back into the LP$_{11}$ mode at the splice, it arrives with a DGD of 1.5 ns. Accordingly, a 1.5-ns DGD with opposite sign occurs if light couples from the LP$_{11}$ mode into the LP$_{01}$ mode at the splice and part of it is coupled back into the LP$_{11}$ mode due to MDMUX imperfections. For multiple spans, we also see a plateau developing around the main peak that results from random mode coupling in the fiber. In Fig. 2(g-i), we
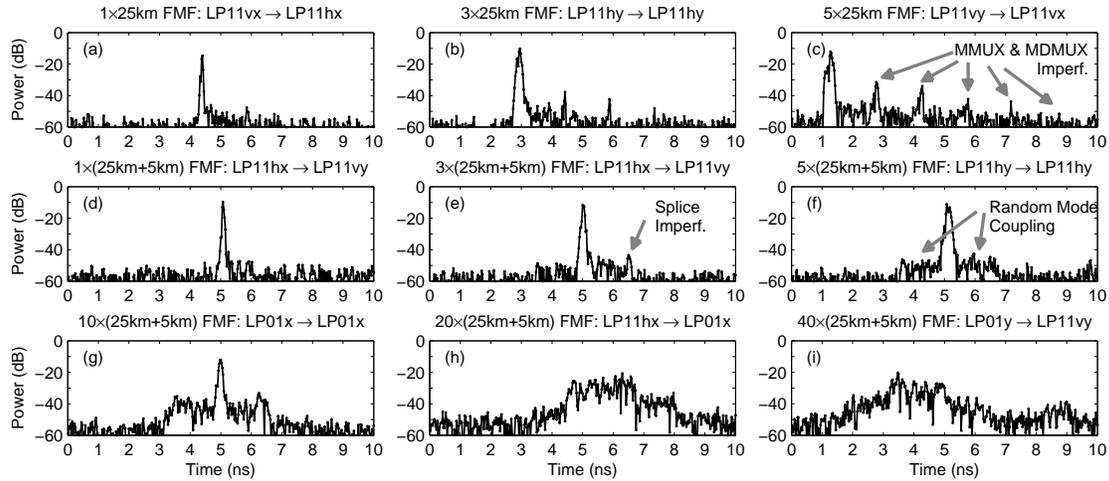
Fig. 2. Exemplary impulse responses estimated from measured waveforms.

show exemplary impulse responses for the LP_{01} mode and for the crosstalk terms at 10, 20, and 40 loops. Even after 40 loops (1200 km) the impulse response is confined to within 10 ns if the DGD-compensated fiber is used.

5. Transmission Results

To compensate for linear mode mixing and delay spread, we use a 6×6 matrix of feed-forward equalizers (FFEs) each with 400 half-symbol-spaced complex-valued taps, corresponding to a memory of 10 ns. We process 1 million symbols using the least-mean square algorithm to adapt the coefficients, and the 4-th power algorithm to recover the carrier phase [4]. We initialize the equalizer over the first 450,000 symbols in data-aided mode, before we switch to decision-directed mode. Then, we evaluate the bit-error ratio (BER) over the last 500,000 symbols. In Fig. 3, corresponding Q-factors for all six modes at launch powers of -3 dBm, 0 dBm, and 2 dBm per spatial mode are plotted vs. transmission distance. The longest reach of up to 1200 km is achieved at -3 dBm if a forward-error-correction limit of 10^{-2} is assumed. For higher launch powers, the transmission distance is limited by fiber nonlinearity.
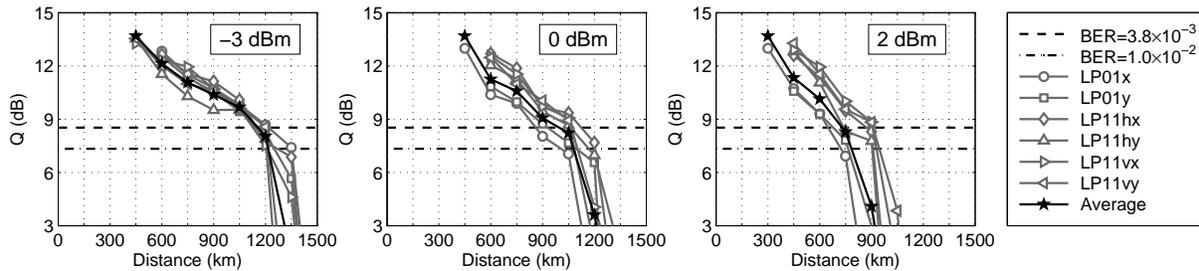

Fig. 3. Q-factor vs. transmission distance for all six modes at 3 different launch powers per spatial mode.

6. Conclusion

We have demonstrated mode-multiplexed transmission over 1200-km DGD-compensated graded-index FMF. The 30-km long composite fiber span has a residual DGD of less than 50 ps and is used to transmit six mode-multiplexed 20-GBd QPSK signals. These results show the feasibility of long-distance MIMO-SDM transmission over FMF.

References

1. S. Chandrasekhar et al., "WDM/SDM transmission of 10 x 128-Gb/s PDM-QPSK over ...," ECOC'11, paper Th.13.C.4.
2. J. Sakaguchi et. al.,"Space division multiplexed transmission of 109-Tb/s data signals ...," JLT **30**(4), pp. 658–665 (2012).
3. M. Salsi et al., "Mode-division multiplexing of 2×100 Gb/s channels ...," JLT **30**(4), pp. 618 - 623 (2012).
4. S. Randel et al., "6×56-Gb/s mode-division multiplexed transmission over 33-km ...," Optics Express **19**(17) (2011).
5. R. Ryf et. al., "Mode-equalized distributed Raman amplification in 137-km few-mode fiber," ECOC'11, paper Th.13.K.5.
6. E. Ip et al., "88×3×112-Gb/s WDM transmission over 50 km of three-mode fiber with ...," ECOC'11, paper Th.13.C.2.
7. R. Ryf et al., "Mode-Division multiplexing over 96 km of few-mode fiber," JLT **30**(4), pp. 521–531 (2012).
8. S. Randel et al., "Adaptive MIMO signal processing for mode-division multiplexing," OFC'12, paper OW3D.5.