Mode-division-multiplexed 3x112-Gb/s DP-QPSK transmission over 80-km few-mode fiber with inline MM-EDFA and Blind DSP

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Abstract *We show transmission of a 3x112-Gb/s DP-QPSK mode-multiplexed signal up to 80km, without and with multi-mode EDFA, using blind 6x6 MIMO digital signal processing. We show that the OSNR-penalty induced by mode-mixing in the multi-mode EDFA is negligible.*

Introduction

The capacity of the single-mode fiber (SMF) is rapidly approaching its theoretical limit[1] and a new approach to increase capacity is needed to keep up with the demands of future data-traffic. As recently shown, spatial division multiplexing (SDM) can significantly increase capacity by exploiting the distinct modes as transmission channels in a few-mode fiber (FMF)[2-6], or by increasing the number of cores and therefore transmission channels in a fiber[7-9].

Most of the experiments using SDM up to now show a limited reach, due to the lack of a multi-mode EDFA (MM-EDFA). However, in [5] the authors showed the first re-circulating loop experiment with few-mode fiber over a 1200km distance, but unfortunately the system required mode (de-)multiplexing every loop for amplification by single mode EDFAs. In [6], the authors show transmission with inline MM-EDFA, however with a relative high penalty after transmission and only ~11 dB modal gain. In this paper we show transmission over few mode fiber[10], both with and without inline MM-EDFA[11] with modal gains up to ~20 dB, Although high crosstalk levels were observed, this only induced a 0.9 dB OSNR-penalty at a BER of $1\cdot10^{-3}$ employing blind digital signal processing (DSP).

Experimental Setup

Fig. 1 depicts the experimental setup. At the transmitter side, an ECL laser (linewidth <100 kHz) is tuned to a wavelength of 1550.1 nm. The output is divided into four equally powered signals using a passive coupler. Three of these signals serve as local oscillators (LOs) after amplification to a +14 dBm output power by polarization-maintaining EDFAs. The fourth signal is

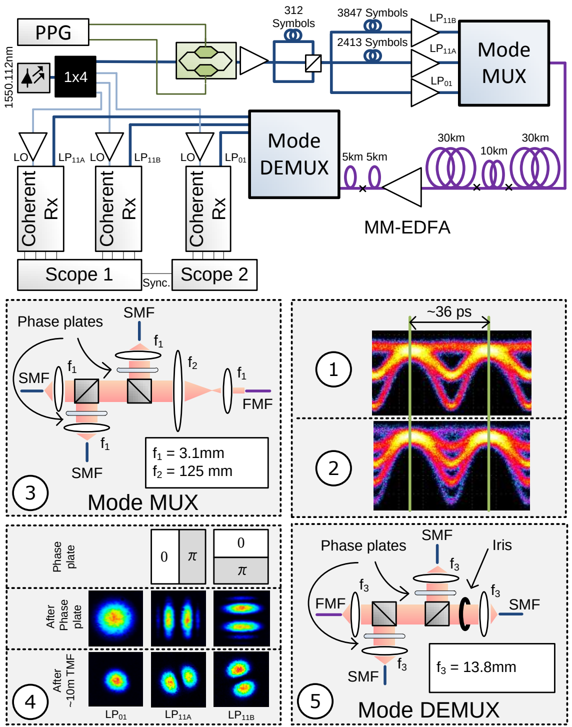

Fig. 1: Experimental Setup. (1) Optical 56-Gb/s QPSK eye, (2) Optical 112-Gb/s DP-QPSK eye, (3) 3-Modes (LP_{01}, LP_{11a} and LP_{11b}) Multiplexer (Mode MUX) (4) Mode intensity profiles after phase plates and ~10m of two-mode fiber (TMF), (5) Mode de-multiplexer (Mode DEMUX)

112-Gb/s QPSK-modulated as described in [12].

This 112-Gb/s DP-QPSK signal is split up into three equally powered signals, which are fed to the mode multiplexer (MUX), making use of the same concept as reported in [4], as shown in Fig. 1 inset 3. The signals going to the LP_{11a} port and LP_{11b} port have delays of 2413 and 3847 symbols, respectively, with respect to the signal going to the LP_{01} port to make sure the three distinct signals after transmission are still separated enough to ensure convergence of the time-domain equalizer (TDE) in the DSP.

Tab. 1: Span 1 (spool 1,2,3) (total length 70km) and span 2 (spool 4,5) (total length 10km)

	Spool 1	Spool 2	Spool 3	Spool 4	Spool 5
Length [m]	30000	9930	30000	4850	5030
MPI [dB]	-26	unknown	-26	-30	unknown
DMD [ps/m]	0.060	0.0044	-0.047	0.18	-0.006
Dispersion LP_{01} [ps/(nm·km)]	19.9	19.9	19.9	19.9	19.8
Dispersion LP_{11} [ps/(nm·km)]	20.0	20.0	20.0	20.1	19.9

Polymethyl methacrylate (PMMA) phase plates are used to convert the LP_{01} to the LP_{11a} and LP_{11b} modes. We measured a better than 30 dB extinction ratio after mode conversion for all the four phase plates used. As can be seen in Fig. 1, the focal lengths used for the telecentric imaging are f_1=3.1mm and f_2=125mm for the lens combination. We also used lenses with f_1=3.1mm to collimate the beams. The highest insertion loss, 8.5 dB, was measured for the LP_{01} port.

The transmission link consisted of few-mode fiber[10] and a multi-mode EDFA (MM-EDFA)[11]. The first span consisted of three few-mode fiber spools of length 30km, 10km and 30km. The second span consisted of two times 5km of fiber. Fiber details are given in Tab. 1. The spools in the first span were combined such that the average differential mode delay (DMD) over the span was low (433.7 ps ≈ 12 symbols). The average measured loss of all spools was ~0.2 dB/km for both LP modes. After the first span a MM-EDFA is placed, which is able to deliver >20 dB gain per mode. The gain was tunable by changing the pump power.

After the transmission link the signal was sent into a mode de-multiplexer (DEMUX) which had a slightly different design than the MUX. The design DEMUX is shown in inset 5 of Fig 1. In the DEMUX no telecentric imaging was used and the focal length of the lenses were different (f_3 = 13.8mm). To reduce the crosstalk from LP_{11} to LP_{01} an iris was used at the cost of some power loss. A crosstalk of less than 26 dB was achieved for all ports from MUX and DEMUX combined (Tab. 2). The highest insertion loss for the DEMUX, 8.9 dB, was measured for the LP_{01} port.

The outputs of the DEMUX were sent into commercial coherent receivers using single-ended detection with trans-impedance amplifiers. The optimal signal input power into the coherent receivers is about -10 dBm. Because of the high gain of the MM-EDFA and the relatively short length of the second FMF span, no EDFA's were needed in the single-mode regime after the DEMUX. The LP_{11a} and LP_{11b} receiver were connected to the same 40 GSamples/s digital sampling scope (scope 1 in Fig. 1), whereas the LP_{01} was connected to a 50 GSamples/s digital sampling scope (scope 2). The delays between the scopes and signals were carefully determined and compensated for to assure synchronization of all channels. The samples obtained from the scopes were processed offline. The DSP was based on the proven blind single mode approach of 2x2 multiple input multiple output (MIMO), extended to a 6x6 equalizer[13]. 800,000 from scope 1 and 1,000,000 samples from scope 2 were captured, resulting in 560,000 DP-QPSK symbols per mode. First the chromatic dispersion was blindly estimated on the LP_{01} received signal and compensated for subsequently on all received modes. In the next stage, time-domain 6x6 MIMO equalizer (TDE), containing 121 taps, 100,000 symbols are used for CMA followed by 100,000 symbols used for decision-directed LMS for convergence. This leaves 720,000 bits per spatial-polarization mode to evaluate the BER. Per evaluated BER point two shots at different time instances are processed and averaged.

Results

Fig. 2 depicts the OSNR vs. BER curves measured back-to-back (A), after 30km (Spool 1) (B), 70km + MM-EDFA (C), 70km + MM-EDFA + 5km (Spool 5) and 70km + MM-EDFA + 10km (D). First proper MUX and DEMUX working was confirmed by comparing the back-to-back penalty with MUX and DEMUX compared to single mode performance at a BER of $1 \cdot 10^{-3}$. A small OSNR-penalty of ~0.4 dB was obtained. Afterwards fiber was added. The measured highest crosstalk levels and delays between the LP_{01} and LP_{11} modes are given in Tab.3.

First spool 1 with a length of 30km was added. A small penalty of ~0.3 dB is observed compared to back-to-back. Afterwards span 1 was created. The delay between the LP_{01} and

Tab. 2: Crosstalk levels back-to-back [dBm]

	LP_{01} in	LP_{11a} in	LP_{11b} in
LP_{01} out	0	-23.7	-24.8
LP_{11a} out	-31.5	0	-0.5
LP_{11b} out	-28.6	+1.9	0
Crosstalk LP_{01} <->LP_{11}	-26.8	-27.8	-27.5

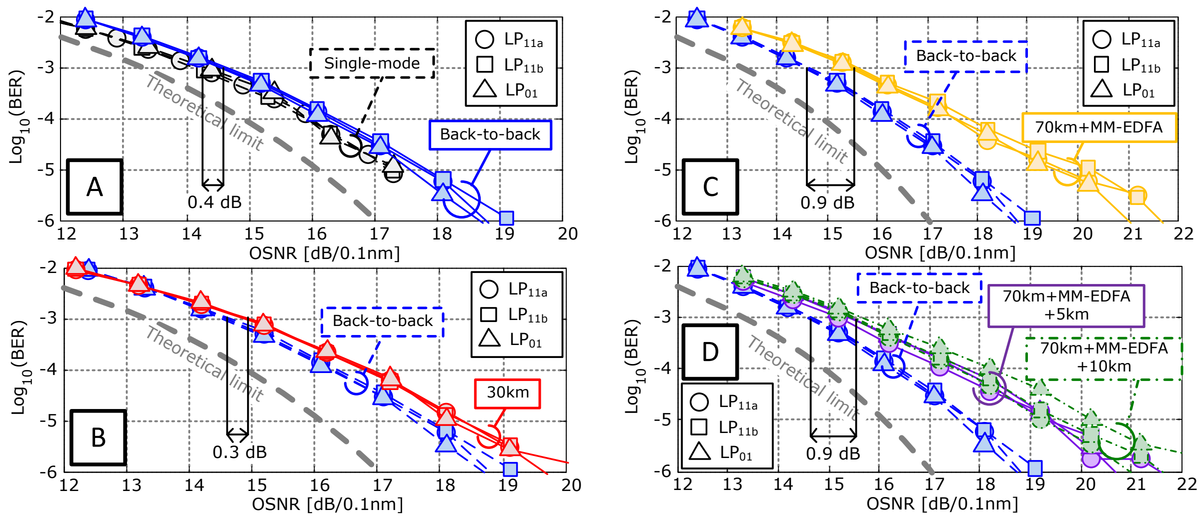

Fig. 2: OSNR vs. BER curves for a) Single mode back-to-back (3 receivers) vs. (multi-mode) back-to-back, b) back-to-back vs. 30km, c) back-to-back vs. 70km + MM-EDFA, d) back-to-back vs. 70km + MM-EDFA + 5km and 10km

LP_{11} modes was 17 symbols, confirming that the combination of positive and negative DMD spools averaged out the accumulate DMD successfully. The increase in crosstalk going from 30km to 70km (see Tab. 3) is mainly attributed to imperfections in the FMF splicing. The automatic alignment function of our splicing device did not properly align the fiber ends and as a result active core alignment was needed to obtain the lowest crosstalk levels. Because the received power after 70km was too low for measurements, the MM-EDFA was added. After the amplifier very high levels of crosstalk were observed (in the range -5 to -0.4dB) which we believe to result again from the difficulties we encountered in making and monitoring MM fiber splices. The difficulty exacerbated at this point in the system due to a significant mode-mismatch between this particular transmission fiber and the MM-EDF. We fully envisage reducing this crosstalk significantly in due course. Nevertheless, the blind DSP was able to handle this level of crosstalk, with an OSNR-penalty of only 0.9 dB compared to back-to-back at a BER of $1{\cdot}10^{-3}$. From Fig. 2 can be seen that the OSNR-penalty did not increase by adding spool 5 and 4, the measured OSNR-penalty was still 0.9 dB. This shows that the transmission performance was not directly affected by the high crosstalk.

Tab. 3: Delays between LP_{01} and LP_{11} in symbols calculated (Calc.) and measured (Meas.), and Crosstalk (X-talk) level [dB]

	Calc.	Meas.	X-talk
30km	50	52	-19.2
70km	12	17	-15.4
70km+EDFA	12	17	-0.4
70km+EDFA+5km	11	18	-
70km+EDFA+10km	36	42	-

Conclusions

Using blind 6x6 MIMO DSP, we have shown successful transmission of 3x112-Gb/s DP-QPSK mode-multiplexed signal over different distances without and with MM-EDFA. Although we observed strong mode-mixing and therefore high crosstalk levels after the MM-EDFA, transmission performance was not directly affected. We measured for transmission over 80km with in-line MM-EDFA an OSNR-penalty of 0.9 dB compared to back-to-back performance.

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