Submitted

Low Computational Complexity Mode Division Multiplexed OFDM Transmission over 130 km of Few Mode Fiber

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Abstract: We demonstrate 337.5-Gb/s MDM-8QAM-OFDM transmission over 130 km of FMF. This confirms that OFDM can significantly reduce the required DSP complexity to compensate for differential mode delay, a key step towards real-time MDM transmission.

1. Introduction

Space division multiplexing (SDM) has attracted attention over the last few years as a potential solution to further increase capacity in optical communications [1-3]. Transmission over few mode fiber (FMF) is one of the most vividly investigated SDM approaches. FMF increases capacity by allowing transmission of more than one mode per fiber core. However, due to the differential modal delay (DMD) between the propagating modes in a FMF, the equalizer complexity is significantly higher compared to SMF. In [4], the effective modal delay was reduced to 50 ps for 30km fiber with the aid of DMD compensation, but still the time domain equalizer required 400 taps for 6x6 multiple input multiple output (MIMO) transmission over 1200 km FMF. In [3] again 400 taps were needed for 120 km FMF transmission. This poses a momentous challenge towards realizing real-time mode-division-multiplexed (MDM) transmission.

In [5, 6] we analyzed some of the most common blind and training symbol (TS) based equalizers, time domain, hybrid time/frequency domain (FDE/TDE), TS based frequency domain equalizer (FDE), orthogonal frequency division multiplexing (OFDM) and hybrid FDE/OFDM. Among these different equalization structures, OFDM gives the least complexity. In [7] MDM OFDM transmission has previously been demonstrated over 7 meter FMF at 102 Gb/s. In this paper, we show transmission over 130 km FMF with OFDM, with an inline multi mode (MM) EDFA in between, realizing a total data rate of 337.5 Gb/s. The equalizer needs only one tap and 7.7 complex multiplications per bit whereas a FDE/TDE for the same link requires 122 complex multiplications per bit when FDE is used for chromatic dispersion compensation.

2. Experimental Setup

Fig. 1 depicts the block diagram of the experimental setup. At the transmitter side, two synchronized digital to analog converters (DAC) drive the IQ modulator. The laser used for the IQ modulator has 1 kHz linewidth in order minimize the effects of the laser phase noise. In the middle, an RF-pilot is sent along with the signal in order to compensate for the laser phase noise at the receiver. After IQ modulation, the signal is polarization-multiplexed with a one symbol delay.

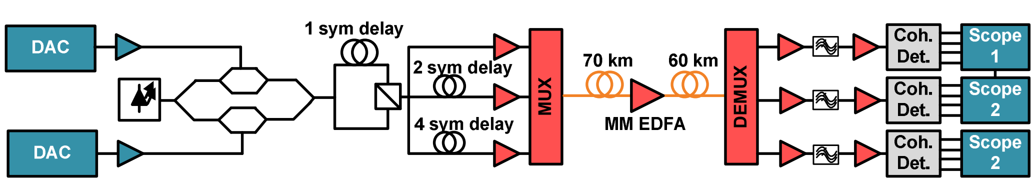

Fig. 1 Block diagram of the experimental setup used for OFDM over FMF transmission.

Tab. 1 Characteristics of the fiber spools used in the experiment

	Span 1 Spools			Span 2 Spools	
Length [m]	30000	9930	30000	29980	29980
DGD [ps/m]	0.060	0.0044	-0.047	0.039	-0.034
Distributed mode coupling LP01 to LP11 [dB]	-26	unknown	-26	-26	-26

The output is divided into three branches for the LP01, LP11a and LP11b inputs of the free space mode-multiplexer (MUX) based on phase plates. The training symbols of LP01, LP11a and LP11b have to be de-correlated. To properly implement de-correlation for the different tributaries we use the following training symbol configuration. In total 11 symbols are used for training, a two symbol delay is used for LP11a and a four symbol delay for LP11b. As a result, the training symbol of each tributary is properly de-correlated, as shown in Fig. 2. Note that, if six DAC pairs were used instead, only one training symbol could be used instead of eleven. For example, orthogonal training symbols can be generated with subcarrier multiplexing [8], which would decrease the training symbol overhead significantly. In this experiment, training symbols are sent every 30 symbols.

The crosstalk between LP01 and LP11 resulting from the MUX and DEMUX (mode de-multiplexer) is approximately -27 dB [9]. The spools are combined into span 1 and 2 as shown in Tab. 1 [10]. The first 70 km span has a total of 826.9 ps DMD and the second 60 km span has a DMD of 149.9 ps. The chromatic dispersion (CD) is around 20 ps/km/nm for all FMF spools and is nearly identical for LP01 and LP11. The loss was approximately 0.2 dB/km. The MM-EDFA has approximately 17 dB gain for both LP01 and LP11 [11]. After the mode DEMUX, an amplifier followed by a 50 GHz filter and another amplifier is used in front of the coherent receiver front-end. Two real-time scopes are used in synchronization. Scope 1 is used to receive LP01, using 4 parallel channels and running at 50 GS/s, whereas scope 2 receives LP11a and LP11b on 8 parallel channels and runs at 40 GS/s. For each OSNR measurement, 5 million samples are collected from scope 1 and 4 million from scope 2.

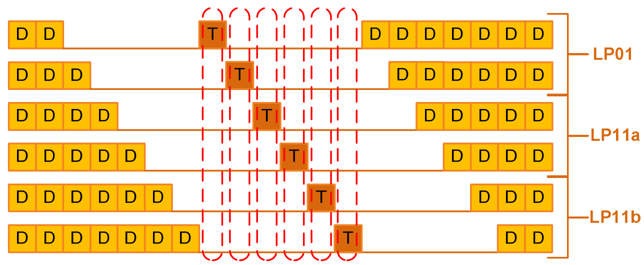

Fig. 2 Training symbols for each mode. D stands for data and T for training symbol.

3. Verification of Mode Division Multiplexed OFDM Setup

Fig. 3(a) shows the measured BER curves averaged for the LP01, LP11a, LP11b tributaries. An arbitrary waveform generator is used as DACs with 8 bit resolution running at 10 GS/s. A 512 FFT size is used, of which 440 subcarriers are modulated. There are 64 samples used for cyclic prefix (CP), resulting in a 6.4 ns guard band. This guard band is already longer than what is required to compensate for all linear effects. For 130 km the CD adds up to 2.6 ns and the DMD to close to 1 ns, whereas the polarization mode dispersion (PMD) is negligible. The CP overhead can be further lowered by using a frequency domain equalizer for block CD compensation at the receiver. Dual polarization (DP) QPSK is used, which is 34.4 Gb/s on each mode adding up to 103 Gb/s. A set of measurements are taken; MUX and DEMUX connected back to back, followed by transmission over the 70 km span , followed by the MM-amplifier together with the 70 km span, and finally both spans and MM-EFDA combined. The FEC limit is set to $2.4 \cdot 10^{-2}$, which is possible with soft decision FEC and 20% of FEC overhead [12]. As Fig. 3(a) shows, the penalties between the abovementioned cases are negligible. An error floor is observed at $\sim 2 \cdot 10^{-6}$ for the MUX-DEMUX, 70 km, and 70 km with MM-EDFA scenarios, it increases to 10^{-5} for 130 km with the MM-EDFA scenario. Fig. 3(b) illustrates the constellation diagrams at high OSNR.

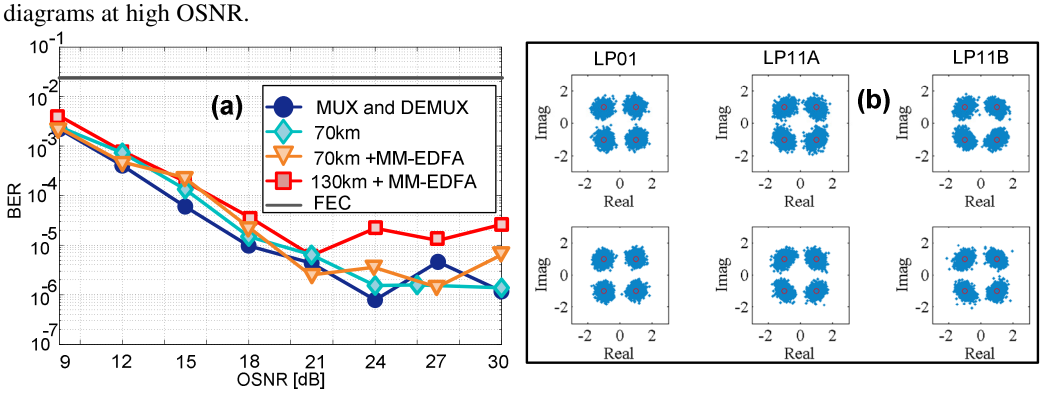

Fig. 3 (a) BER curves for 3 x 34.4Gb/s with DP-QPSK, in total 103 Gb/s. (b) Constellation diagrams at 30 dB OSNR.

4. 337.5-Gb/s Results

In order to further increase the data rate, two FPGA-DAC pairs are used as transmitter. Fig. 4(a) shows the BER curves for 337.5-Gb/s MDM-OFDM. The high-speed DACs have less vertical resolution compared to the previous transmitter, but higher bandwidth allowing an increase of the symbol rate to 20 GS/s. The FFT size is 1024; 960 subcarriers are modulated with 8 QAM. 128 samples are used as CP, which again results in a guard band of 6.4 ns at a 20GS/s symbol rate. In back to back (B2B) configuration single mode fibers at the input of the MUX are directly connected to the single mode fibers at the output of the MUX. Then the MUX and DEMUX are put in between, at the end the two spans and amplifier are also connected. Similar to Fig. 3(a), negligible penalty is observed for the different measured configurations. The optical OFDM spectrum of LP01 after MUX and DEMUX is shown in Fig. 4(b). The roll-off and aliasing effects at both sides are due to the DACs. The error floor increases to ~10^{-3} due to the limited effective resolution of the DACs which is much lower than the nominal 6 bits at high frequencies. Fig. 4(c) illustrates the BER curves of tributaries of transmission over 130 km with MM-EDFA. Fig. 4(d) depicts the constellation diagram at 30 dB OSNR. In both figures it is observed that the LP01 mode has a slightly worse constellation compared to LP11a and LP11b.

The equalizer complexity of this 337.5-Gb/s system can be calculated as described in [5]. The OFDM requires 7.7 complex multiplications per bit and one tap equalization. On the other hand a hybrid FDE/TDE equalizer as used in [1, 3] would require 122 complex multiplications per bit where FDE is for chromatic dispersion compensation and TDE for DMD and PMD compensation.

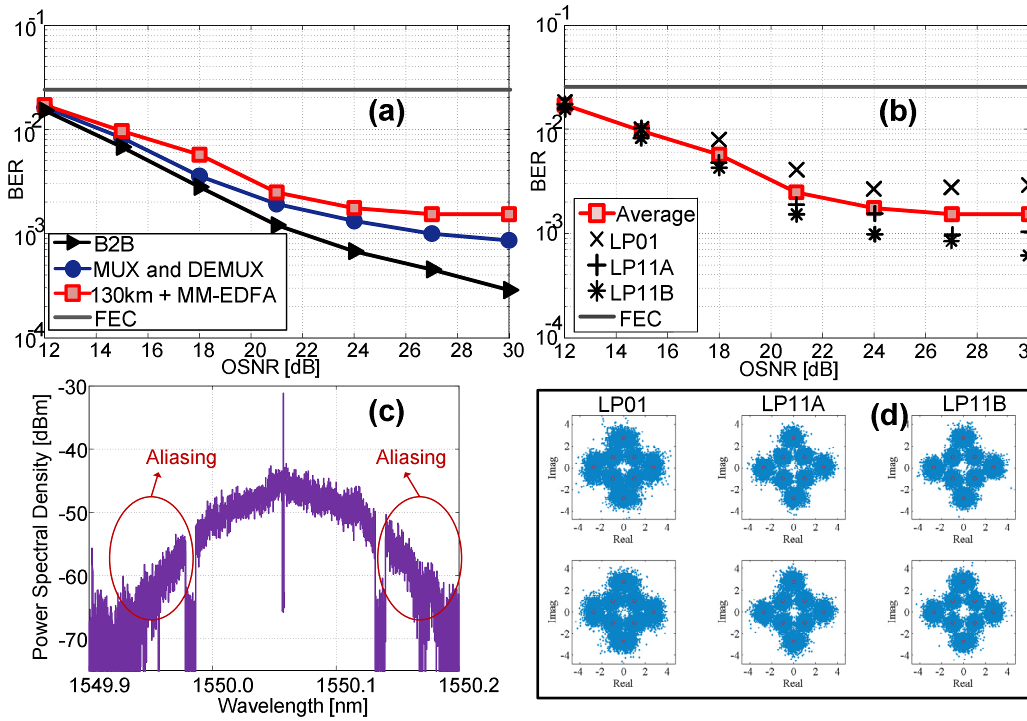

Fig. 4 (a)BER curves for 3 x 112.5 Gb/s with DP-8QAM, in total 337.5 Gb/s. (b) Measurement points for LP01, LP11a and LP11b for 130 km with MM-EDFA case. (c) The optical spectrum of LP01 after MUX and DEMUX. The signal bandwidth is 18.8 GHz. (d) Constellation diagrams at 30 dB OSNR.

5. Conclusion

In this paper, 337.5-Gb/s is achieved over 130 km FMF with inline multi-mode amplifier. OFDM has a one tap equalizer and it requires only 7.7 complex multiplications per bit for this link. The complexity of OFDM is significantly less compared to a time domain approach which is crucial for real time implementation of mode division multiplexed transmission.

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6. References

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