480 km Transmission of MDM 576-Gb/s 8QAM using a Few-Mode Re-circulating Loop

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***Abstract*— We demonstrate successful 3-mode-division-multiplexed × 192-Gb/s dual-polarization 8QAM (total 576 Gb/s) transmission over 480 km of few-mode fiber (FMF). This distance was obtained using an all few-mode re-circulating loop containing a 60 km FMF span.**

I. INTRODUCTION

Space-division multiplexing (SDM) is rapidly emerging as a feasible and powerful means to increase the capacity of optical transmission systems by using the spatial dimension in either multi-core [1-4] or multi-mode [5-8] fibers. After little more than a couple of years impressive progress has been made, including realization of the first Pb/s systems based on multi-core fibers [3,4]. In this paper we focus on few-mode fiber transmission.

Whilst the first steps in SDM research were mainly directed towards proving technological feasibility, an important next step is to demonstrate that the various approaches under investigation are able to support large distance transmission. After all the main reason that this technology is being investigated is to address the foreseen capacity crunch in long-haul transmission systems.

The first research on long-haul transmission using few-mode fiber (FMF) technology consisted of either single-mode (SM) fibers to re-circulate the signal with SM-EDFAs [6, 7], or, in case of an all-FMF re-circulating loop, quadrature phase shift keying (QPSK) as the modulation format [8]. In this paper we show the first all-FMF re-circulating loop using a higher-order modulation format: 8-level quadrature amplitude modulation (8QAM). Using 3-mode fiber, each mode carrying a 192-Gb/s DP-8QAM optical modulated signal (total date rate 576 Gb/s), 480 km transmission is obtained.

II. EXPERIMENTAL SETUP

A. Transmitter setup

At the transmitter side five lasers running at 193.0, 193.1, 193.4 (channel under test (CUT)), 193.8 and 193.9 THz were passively combined using a 1×8 polarization-maintaining coupler, and subsequently modulated using an IQ-modulator, driven by two digital-to-analog converters running at a 32GBaud symbol rate that address the in-phase and quadrature ports of the IQ-modulator (Fig. 1). The electrical driving signal was formed by combining three pseudo-random binary sequences of length 2^{15} which were shifted by 8191 and 16383 symbols with respect to each other before combining them and mapping them onto 8QAM symbols.

After modulation, polarization-multiplexing was emulated by splitting the signal into two equally powered tributaries, delaying one by 700 symbols for de-correlation, and combining them again using a polarization-beam combiner (PBC).

The 192-Gb/s DP-8QAM signal subsequently is split into three signals which are delayed by 2285 and 4415 symbols with respect to the original signal again for emulation of three different signals, and fed to the spot launching spatial

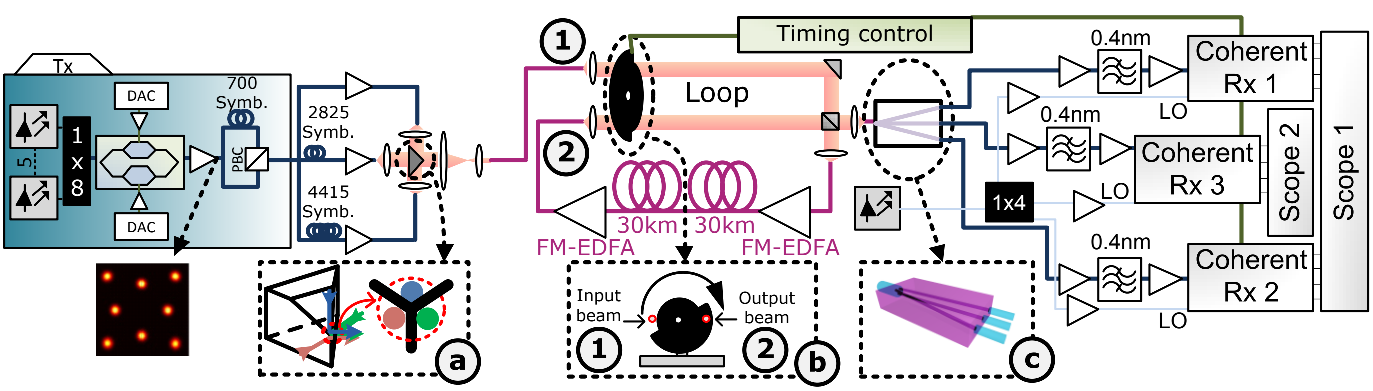

Fig 1. Experimental setup of the 60 km containing all-FMF re-circulating loop. a) 3-spot launching spatial multiplexer [9], b) chopper used as switching mechanism for the re-circulating loop, c) 3D waveguide device with 3 single-mode fiber outputs, used as a spatial de-multiplexer

Tab. 1. 60 km FMF span (@ 1550nm)

	Spool 1	Spool 2
Length [km]	30	30
MPI [dB]	-26	-25
DGD [ps/m]	-0.044	0.053
Disp. LP_{01} [ps/(nm·km)]	19.8	19.8
Disp. LP_{11} [ps/(nm·km)]	20	20

multiplexer (Fig.1a) [9], which launches the signals into a 3-mode supporting FMF pigtail [10].

B. *Re-circulating loop*

The FMF pigtail was connected to a free-space 3dB coupler. The input signal was coupled into the loop containing two few-mode (FM) EDFAs [11], and 60 km of FMF with the parameters listed in Tab. 1. The 60 km FMF span has a differential group delay between the LP_{01} and LP_{11} modes of around 9 symbols. At the input and output of the loop a FM-EDFA was placed to compensate for the span and coupling loss of the 3dB coupler.

In SM re-circulating loops acousto-optic modulators (AOM) are used for switching, i.e. filling, re-circulating and emptying the loop. However, FM-AOMs do not exist. Therefore a chopper (Fig. 1b) was used inside the free-space 3dB coupler which provides the same functionality, although careful control of timing is required. The free-space optics is tuned such that the output of the loop is blocked when the input is open, and vice versa. The chopper provides a signal which was used to control the timing to trigger the scopes at the receiver side after determining the loop time and hold off time.

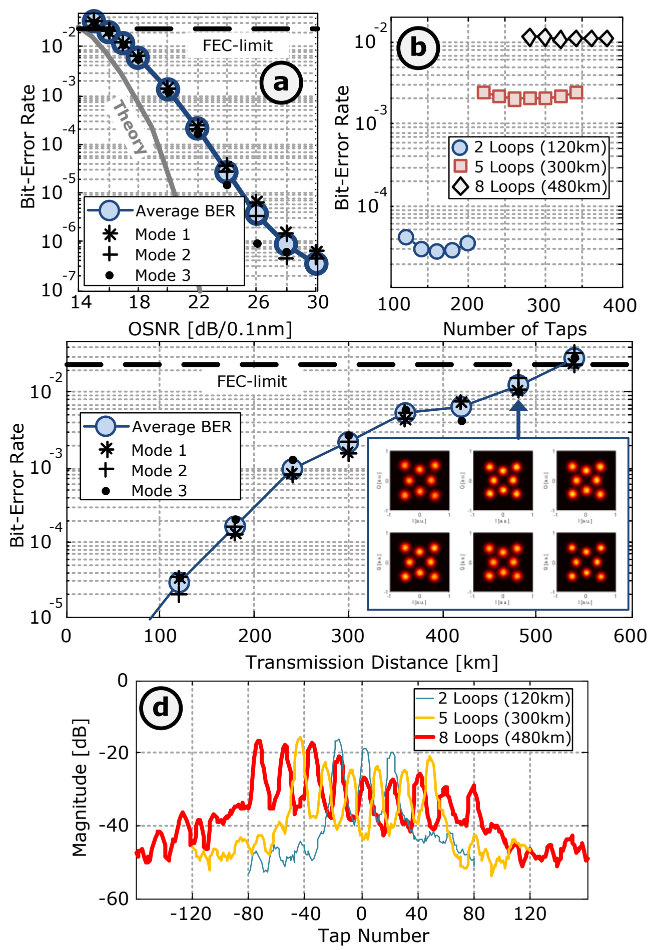

Fig. 2.a) Back-to-back curve, b) Tap sweep for 120, 300 and 480 km, c) Distance sweep, d) Impulse response after 120, 300 and 480 km

C. *Receiver*

At the output of the re-circulating loop a 3D waveguide device (Fig.1c) was used to spatial de-multiplex the three signals. The 193.4 THz CUT was filtered out using 50-GHz tunable filters and afterwards fed to three coherent receivers connected to two digital sampling scopes: an 8 port 40-Gsamples/s scope (20 GHz electrical bandwidth) and a 4 port 50-Gsamples/s scope (16 GHz electrical bandwidth). Both digital sampling scopes were carefully synchronized beforehand to assure all signals are received time-aligned. Afterwards, offline 6x6 MIMO-DSP was employed to reconstruct the sent signals [12].

III. Results

Fig. 2a shows the back-to-back performance of the 192-Gb/s DP-8QAM signal when mode multiplexed and de-multiplexed. The performance shows a ~1.5dB penalty with respect to theory at the FEC-limit.

Fig. 2c shows the transmission distance versus bit-error rate. After 480 km an average BER over all modes of $\sim 1.3 \cdot 10^{-2}$ is reached. After 540 km this BER increased to $3 \cdot 10^{-2}$, which is above the assumed FEC-limit at $2.4 \cdot 10^{-2}$ [13]. The inset shows the recovered constellations after 480 km.

Fig. 2b shows the optimization of the tap number after 2, 5 and 8 loops. As observed in Fig. 2d, from the impulse responses after 120, 300 and 480 km transmission, the DGD between the LP_{01} and LP_{11} mode in the 60km span is not fully averaged out. This causes the number of peaks to grow in each loop as well as the number of taps needed to compensate this (Fig. 2b). For 480 km the optimum number of taps is ~321.

IV. Conclusion

We showed successful transmission of MDM 576-Gb/s 8QAM over 480 km of FMF using an all-FMF component re-circulating loop. As best we are aware this is the first demonstration of a higher-order modulation format signal being transmitted over an all-FMF re-circulating loop.

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