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73.7 Tb/s (96 x 3 x 256-Gb/s) mode-division-multiplexed DP-16QAM transmission with inline MM-EDFA

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Abstract: Transmission of a 73.7 Tb/s (96x3x256-Gb/s) DP-16QAM mode-division-multiplexed signal over 119km of few-mode fiber transmission line incorporating an inline multi mode EDFA and a phase plate based mode (de-)multiplexer is demonstrated. Data-aided 6x6 MIMO digital signal processing was used to demodulate the signal. The total demonstrated net capacity, taking into account 20% of FEC-overhead and 7.5% additional overhead (Ethernet and training sequences), is 57.6 Tb/s, corresponding to a spectral efficiency of 12 bits/s/Hz.

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OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications; (060.4080) Modulation; (060.4230) Multiplexing.

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1. Introduction

Space division multiplexing (SDM) has received considerable attention in recent years given the prospects it offers to avoid, or at least delay, a much anticipated future capacity crunch. SDM offers the possibility to scale the capacity of a single fiber by several orders of magnitude. Research groups around the world are focusing on two primary SDM approaches based on two distinct fiber types: multi-core fiber [1,2] and multi mode fiber [3–12]. From an energy perspective, the latter approach has been shown to be more efficient when it comes to amplification [13], and it potentially offers a higher information capacity flow per unit area, which makes it a very interesting proposition.

Using a few-mode fiber (FMF) which supports 3 spatial modes and multiple input multiple output (MIMO) processing, the authors in [5] showed for the first time that mode-division-multiplexed (MDM) transmission over significant distances was feasible, albeit in single wavelength experiments. Since then significant progress has been made through steady improvements in areas such as spatial signal multiplexing and de-multiplexing and the reduction of fiber mode dispersion. Increased transmission distances have been achieved using costly Raman amplification, but only using a single span and single or a low number of wavelengths [6]. A 1200km transmission distance was obtained in recirculating loop experiments but only by splitting the individual modes propagating in the FMF into separate single mode fibers (and back again) to allow amplification in single-mode (SM)-EDFAs after each circulation of the loop [7]. However, this would be impractical for long-haul transmission. In [8] the first wavelength-division-multiplexed (WDM) MDM transmission was shown using 88 wavelengths carrying 112 Gb/s dual-polarization (DP)-QPSK signals

over 50km of FMF. A larger distance of 85km was obtained using a multi mode erbium-doped fiber amplifier (MM-EDFA) mid-span [9], but only using a single wavelength.

In [10] we showed single channel MDM 3x12-Gb/s DP-QPSK transmission over 80km of FMF with a mid-span MM-EDFA and proved the proper working of the system which we used in the experiment presented in [11]. In [11] we upgraded the number of WDM channels to 96 and the modulation format to DP-sixteen-level quadrature amplitude modulation (16QAM). By doing so we showed for the first time MDM DP-16QAM transmission. The actual gross data rate transmitted was 73.7 Tb/s (96x3x256-Gb/s), which was transmitted over 119km of FMF with a mid-span MM-EDFA after 84km. Accounting for 20% of FEC-overhead and 7.5% of additional overhead (Ethernet and training sequences), this translates into a net data rate of 57.6 Tb/s and a spectral efficiency of 12 bits/s/Hz. In this work we extended the results presented in [11] by adding details about the phase plate based mode (de-)multiplexer and the multi mode erbium-doped fiber amplifier used. We also present the impulse response data obtained after 119km of transmission.

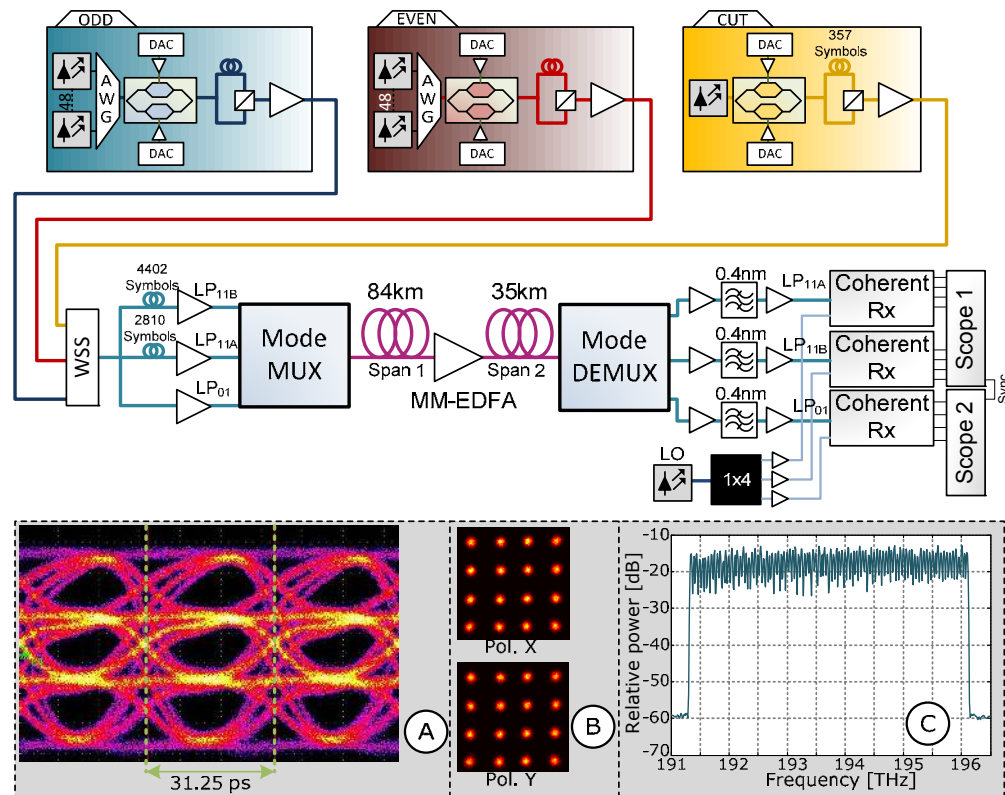


Fig. 1. Experimental setup. (a) Electrical 4-PAM generated by the DAC. (b) 256-Gb/s DP-16QAM constellations in back-to-back single-mode configuration. (c) Spectrum at transmitter side (96 channels).

2. Experimental setup

2.1 Transmitter side

Figure 1 depicts the experimental setup. At the transmitter side, 96 channels carrying a 256-Gb/s DP-16QAM modulated signal were created. The channels are composed of 48 even and 48 odd channels, of which one is dropped and a channel under test (CUT) is inserted. The even and odd channels were generated by multiplexing 48 ECL lasers running on the 50-GHz extended C-band (191.35 THz – 196.1 THz) ITU grid using arrayed waveguide gratings

(AWGs). Subsequently the signals containing 48 wavelengths each were 128-Gb/s 16QAM modulated using IQ-modulators. The modulators were driven with electrical four-level pulse amplitude modulated (4-PAM) signals (Fig. 1(a)) generated by separate digital-to-analog converters (DACs) for the in-phase (I) and quadrature (Q) port. These 4-PAM signals were created in the digital domain by adding two PRBS13 sequences together, shifted by 383 symbols for de correlation. The 4-PAMs feeding I and Q were shifted with respect to each other by 767 symbols. The outputs of the DACs were electrically amplified before feeding them to the IQ-modulators. The output swing was set such that the IQ-modulators were operated in the linear regime with no applied pre-distortion. After modulation the 256-Gb/s DP-16QAM signals were emulated by polarization-multiplexing (POLMUX) the outputs of the IQ-modulators. This was achieved by splitting the signal into two equal power tributaries, delaying one by ~ 200 symbols, and combining them again using a polarization beam combiner. The CUT was generated the same way as the even and odd channels, with the exception that only one laser was modulated and different sequences and delays were used. The 4-PAM signals were generated using PRBS15 sequences, shifted by 8191 symbols. The 4-PAM signals fed to I and Q were shifted by 16383 symbols. In the POLMUX stage of the CUT one of the tributaries was delayed by 357 symbols with respect to the other. Finally, the three setups were wavelength-division-multiplexed (WDM) using a wavelength-selective switch (WSS), and equalized. One of the even or odd channels was dropped and the CUT was inserted on that wavelength instead. The constellations obtained for the CUT in a single-mode back-to-back configuration and the WDM spectrum at the transmitter side are depicted in Fig. 1(b) and Fig. 1(c), respectively.

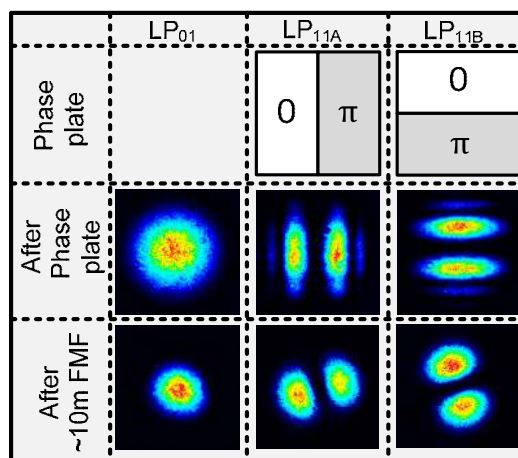


Fig. 2. Mode intensity profiles after phase plates (middle row) and after ~ 10 m of FMF (bottom row).

2.2 Mode (de-)multiplexer

After WDM, the signal containing 96x256-Gb/s DP-16QAM was split up into three equally powered signals, which were fed to a mode multiplexer with respective delays of 0, 2810 and 4402 symbols for de-correlation. For this experiment a phase plate based mode multiplexer (MUX) and de-multiplexer (DEMUX) [12] were used. The three modes used were the linearly polarized (LP) mode LP_{01} , and the twofold degenerate LP_{11} mode: LP_{11A} and LP_{11B} . The LP_{11} modes were created by using phase plates to match the phase profile inside the few-mode fiber (FMF) [12]. This method was verified by looking at the intensity profiles after ~ 10 m of FMF (Fig. 2) and through extinction ratio (ER) measurements.

2.3 Extinction ratio optimization

To realize a mode (de-)multiplexer able to (de-)multiplex three modes together with a high enough ER between the modes to assure orthogonality of the signals, basic measurements were done to select the best phase plates, lens combinations and launch technique. These basic measurements are depicted in Fig. 3.

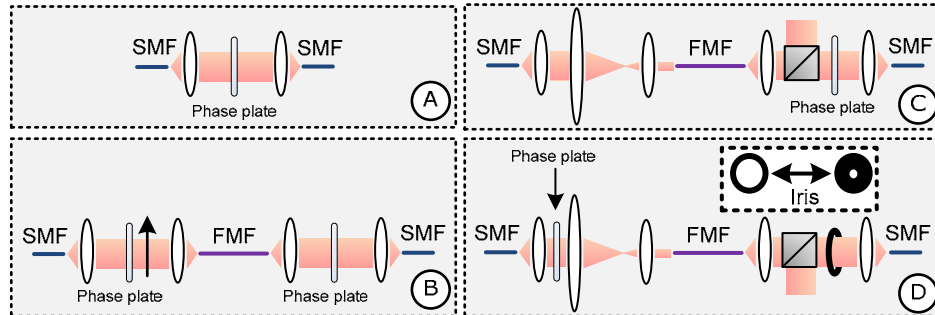


Fig. 3. Basic measurements for ER between LP₀₁ and LP₁₁ modes. (a) Coupling of a LP₁₁ mode into a single-mode fiber (SMF) to select the best phase plates (b) Exciting the LP₀₁ / LP₁₁ mode and checking the ER and back-conversion from LP₁₁ to LP₀₁ (c) Using tele-centric launching to obtain a cleaner LP₀₁ excitation in the FMF (d) Increased LP₁₁ to LP₀₁ ER.

Polymethylmethacrylate (PMMA) phase plates were used for the mode conversion. By optimizing free-space coupling from a single-mode fiber (SMF) to SMF and sliding in the phase plate, an ER of better than 30 dB was obtained (Fig. 3(a)). This confirmed that the phase shift in the phase plate was close to π . After selecting the best phase plates, the simplest launching method, i.e. using one lens to collimate the beam and another one to focus it (Fig. 3(b)), was tested for ER. The ER for LP₀₁ was measured to be ~ 12 dB at most and was considered insufficient for the launching of higher-order modulation format signals like 256-Gb/s DP-16QAM. The back-conversion from LP₁₁ to LP₀₁ was confirmed, i.e. the setup in Fig. 3(b) could provide a good mode-selectivity for LP₁₁ (ER > 20dB). A much better mode-selectivity (ER > 28 dB) was however obtained for the LP₀₁ mode when using the tele-centric launch technique [12] (Fig. 3(c)). To avoid the need for another lens in the mode demultiplexer, an iris was used in front of the LP₀₁ port as depicted in Fig. 3(d). By doing so, at the cost of just a small power penalty, an ER of >25 dB was achieved launching LP₁₁ by minimizing lens aberration effects.

Resulting from these experiments a mode MUX and DEMUX were built as depicted in Fig. 4. The lens combinations used in the mode MUX were a focal length of $f_1 = 3.1$ mm for the collimators and $f_2 = 125$ mm for the other lens, leading to a beam diameter of around 12 μ m, which matched well the core diameter of the FMF. For the DEMUX lenses with a bigger focal length of $f_3 = 13.8$ mm were used for ease of tuning.

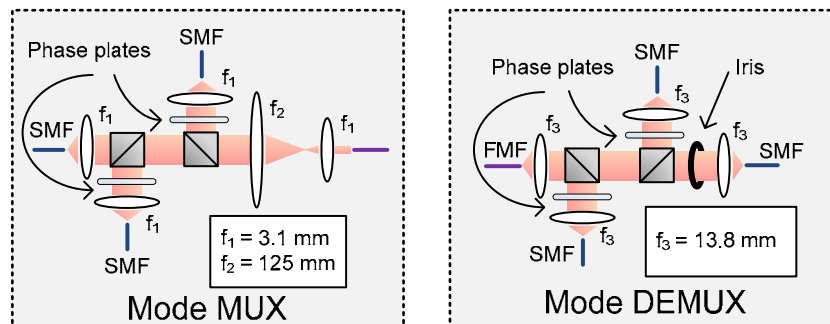


Fig. 4. Mode multiplexer and de-multiplexer as used in the transmission experiment

We define the crosstalk levels referred to in Table 1 as the ER between LP_{01} and the sum of the degenerate LP_{11} modes when one of the three modes is launched. The crosstalk levels obtained in the back-to-back configuration, where the mode MUX and DEMUX are connected together by means of $\sim 15\text{m}$ of FMF, are listed in Table 1. As can be observed, the crosstalk from launching LP_{01} to LP_{11} is still the highest even when a tele-centric launch system is used.

Table 1. Crosstalk levels back-to-back [dB]

	LP_{01} in	LP_{11A} in	LP_{11B} in
LP_{01} out	0	30.1	29
LP_{11A} out	31.5	0	0
LP_{11B} out	30.6	1.8	1.6
Crosstalk $LP_{01} \leftrightarrow LP_{11}$	28	32.3	31.3

The highest loss in both the MUX and DEMUX was observed for both LP_{01} ports. For these ports the light has to cross two beam-splitters for which the “through-loss” was slightly higher than the “reflective-loss”. At the DEMUX a small additional loss penalty was paid for use of the iris. The loss for these ports was 8.5 dB and 8.9 dB, for the MUX and DEMUX respectively, in the optimal case. This means that ~ 18 dB of power was already lost just from multiplexing and de-multiplexing the modes.

2.4 Multi mode erbium-doped fiber amplifier (MM-EDFA)

Figure 5(a) depicts the MM-EDFA used in the experiment. The MM-EDFA was designed to simultaneously amplify the LP_{01} , LP_{11A} and LP_{11B} mode. A 980nm fiber pigtailed diode laser was used to pump the active fiber in a backward pumping scheme. The 980nm pump radiation was free-space, offset-launched into the MM-EDFA using two dichroic mirrors. A length of the FMF [14] was spliced directly to a 6m length of the few-mode Er^{3+} -doped active fiber and the amplified output was coupled into the output FMF. The free-end of the 980nm pump laser fiber-pigtail was angle-cleaved to suppress Fresnel reflection and a polarization-insensitive isolator was used to suppress any signal light propagating in the backward direction. Figure 5(b) shows the signal gain for LP_{01} , LP_{11A} and LP_{11B} as a function of frequency when pumped with a coupled power of 22dBm.

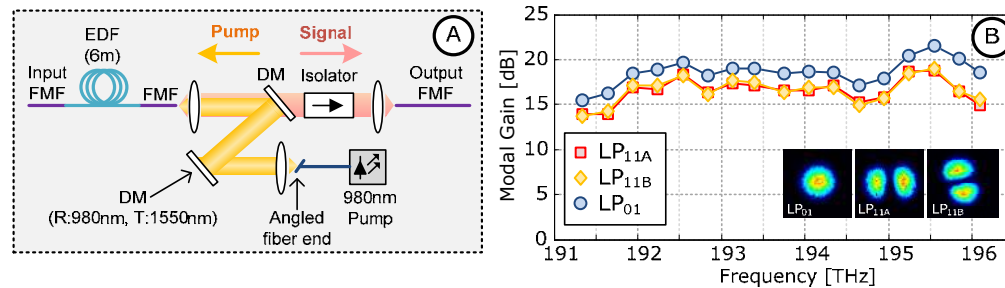


Fig. 5. DM = Dichroic mirror. (a) Schematic of the MM-EDFA. (b) The measured modal gain spectrum versus frequency at a coupled 980nm pump power of 22dBm and a signal power of -5 dBm per mode.

The shape of the gain spectrum of the MM-EDFA is similar to that of conventional single mode EDFA, which has a gain peak around 195.5 THz and a flat region centered at 194 THz. For an input signal power of -5 dBm per mode at the input of the MM-EDFA, the average gain across the full C-band was 18.5dB for the LP_{01} and 16.5dB for the LP_{11} modes. The

CCD images of the amplified output beam confirm that the modal integrity of the signals is well preserved through the amplification process.

2.5 Transmission link

After multiplexing the modes, the MDM signal was sent into the transmission link. The transmission link consisted of graded-index FMF [14] and the MM-EDFA [15] briefly described above. For the 119km transmission experiment the first span was built up out of three FMF spools with lengths of 30km, 30km and 24km. The second span was created by combining a 30km and a 5km spool. Two more 30km spools were available to achieve a longer distance, but these were not used in the final experiment for reasons explained later on. The fiber characteristics are listed in Table 2. The attenuation for LP₀₁ is around 0.198 dB/km, whereas this is slightly lower for the LP₁₁ modes, 0.191 dB/km. The mode field diameter of both modes is around 11μm. The spools in the first span were combined such that the average differential mode delay (DMD) and distributed mode-coupling over the span was low to try to reduce the spread of the impulse response. The MM-EDFA after the first span provided more than 16 dB of gain per mode.

Table 2. Span 1 (spool 1,2,3) (total length 84km) and span 2 (spool 4,5) (total length 35km)

	Spool 1	Spool 2	Spool 3	Spool 4	Spool 5
Length [m]	30000	29980	23809	29980	5030
Dist. Mode-coupling [dB]	-26	-26	-28	-26	Unknown
DMD [ps/m]	0.060	-0.034	-0.052	0.039	-0.006
Dispersion LP ₀₁ [ps/(nm·km)]	19.9	19.8	19.8	20.1	19.8
Dispersion LP ₁₁ [ps/(nm·km)]	20.0	20.0	19.9	20.0	19.9

After the transmission link the signal was sent into the mode de-multiplexer as discussed before. The outputs of the DEMUX were amplified using SM-EDFAs. After amplification the CUT was filtered out using a 50-GHz tunable optical filter. After another amplification stage, the signal was sent into commercial coherent receivers using single-ended detection with trans-impedance amplifiers. The LP_{11A} and LP_{11B} receivers were connected to the same 40 GSamples/s digital sampling scope (scope 1 in Fig. 1), whereas the LP₀₁ receiver was connected to a 50 GSamples/s digital sampling scope (scope 2). The delays between the scopes and signals were carefully compensated before measuring to assure proper synchronization. The samples obtained from the scopes were processed offline using data-aided digital signal processing (DSP). 800,000 samples from scope 1 and 1,000,000 samples from scope 2 were captured, resulting in 640,000 DP-16QAM symbols per mode. First the chromatic dispersion was blind estimated on the received LP₀₁ signal and then compensated for on all modes. Subsequently feed-forward timing recovery was applied. The next step was a time-domain 6x6 MIMO equalizer (TDE) with 401 taps (200 symbols). Here ~260,000 symbols were used for training using decision-directed LMS. A digital phase-locked loop (PLL) was used to remove the frequency offset between the local oscillator and signal and for phase recovery. Afterwards ~1.5 million bits per spatial polarization mode were obtained for bit error rate (BER) evaluation. Three shots per measured BER point were processed and averaged for the back-to-back curves and two shots at different time instances were used for the other measurements.

3. Results

3.1 Back-to-back performance

Figure 6(a) depicts the BER versus optical signal-to-noise ratio (OSNR) curves measured back-to-back in the single-mode regime only and back-to-back for MDM with the mode MUX and DEMUX in between. An FEC-overhead of 20% was assumed with an FEC-limit at a BER of $2.4 \cdot 10^{-2}$ [16]. The single mode results show a 2.2 dB OSNR-penalty at the FEC-

limit with respect to theory. An error-floor of $2 \cdot 10^{-5}$ is observed. The OSNR-penalty and error-floor are expected to improve when pre-distortion is used. However for this experiment the DAC was running at 1 sample per symbol, limiting the possibilities to pre-distort to simply optimizing the output levels of the 4-PAM signals in order to obtain the most equal spacing between the points in the constellations. For the MDM setup there is practically no additional penalty at the FEC-limit compared to the single-mode setup. However, for the MDM setup an error-floor at $1 \cdot 10^{-4}$ is observed when averaging the BER over the three modes. As can be observed this was mainly limited by the LP₀₁ performance.

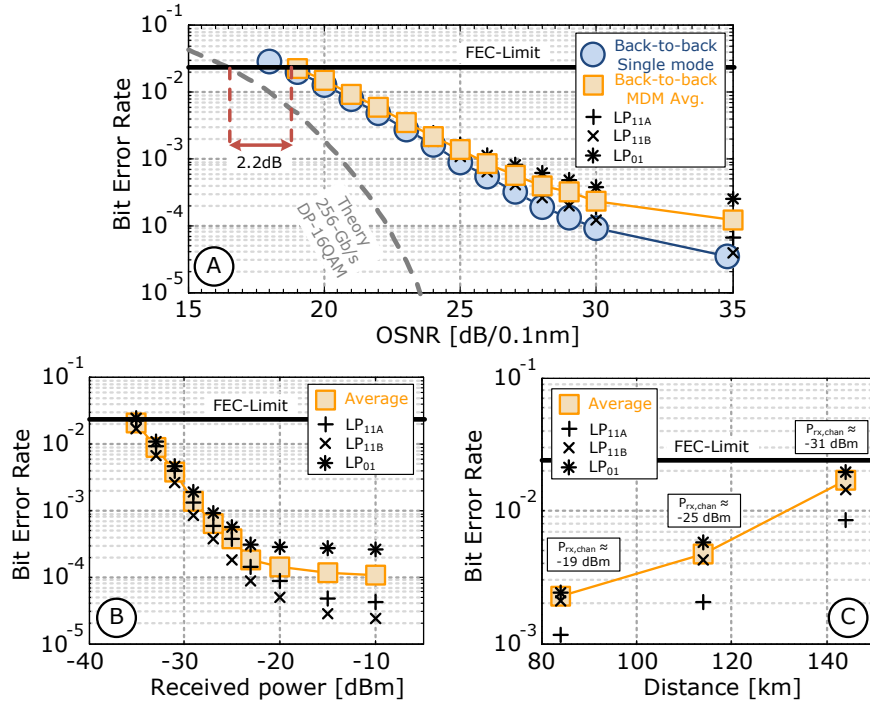


Fig. 6. (a) Back-to-back curves. (b) Bit error rate versus received power per channel in MDM back-to-back configuration. (c) Bit error rate versus distance for the 193.40 THz channel

3.2 Output power limitation and transmission distance

Figure 6(b) shows the BER versus the output power out of the DEMUX per spatial mode per wavelength channel in a back-to-back configuration. This plot shows that amplified spontaneous emission (ASE) produced in the SM-EDFAs at the receiver side limits the performance as soon as the received power gets lower than -20 dBm per channel. This is confirmed in Fig. 6(c), which shows the BER versus transmission distance. As the distance grows, the received power reduces and becomes a major source of penalty. This proves that a lower loss from coupling the modes in the multiplexer and de-multiplexer should substantially increase the transmission distance. It was decided to transmit over 119km of fiber such that a decent margin with respect to the FEC-limit was assured.

3.3 Equalizer impulse response after 119km

To understand better the limitations and what is happening in the transmission system, an analysis can be done on the equalizer impulse response. From this one can observe where light from one mode leaked into another, or where a bad splice is [17].

Figure 7 depicts the 36 plots of the magnitude of the impulse response versus taps of the 6x6 MIMO-equalizer as obtained after 119km of transmission. Two taps correspond to one symbol, i.e. 31.25 ps. The LP_{01} mode (bottom right 2x2 square) is used as a reference and therefore the main peak is always at 0. For this particular case, it can be observed that after 119km of transmission the sequences sent on LP_{01} and LP_{11} (upper left 4x4 square) were received almost at the same time (LP_{11} leads by ~ 4 symbols). This shows that the combination of spans used successfully minimized the impulse response.

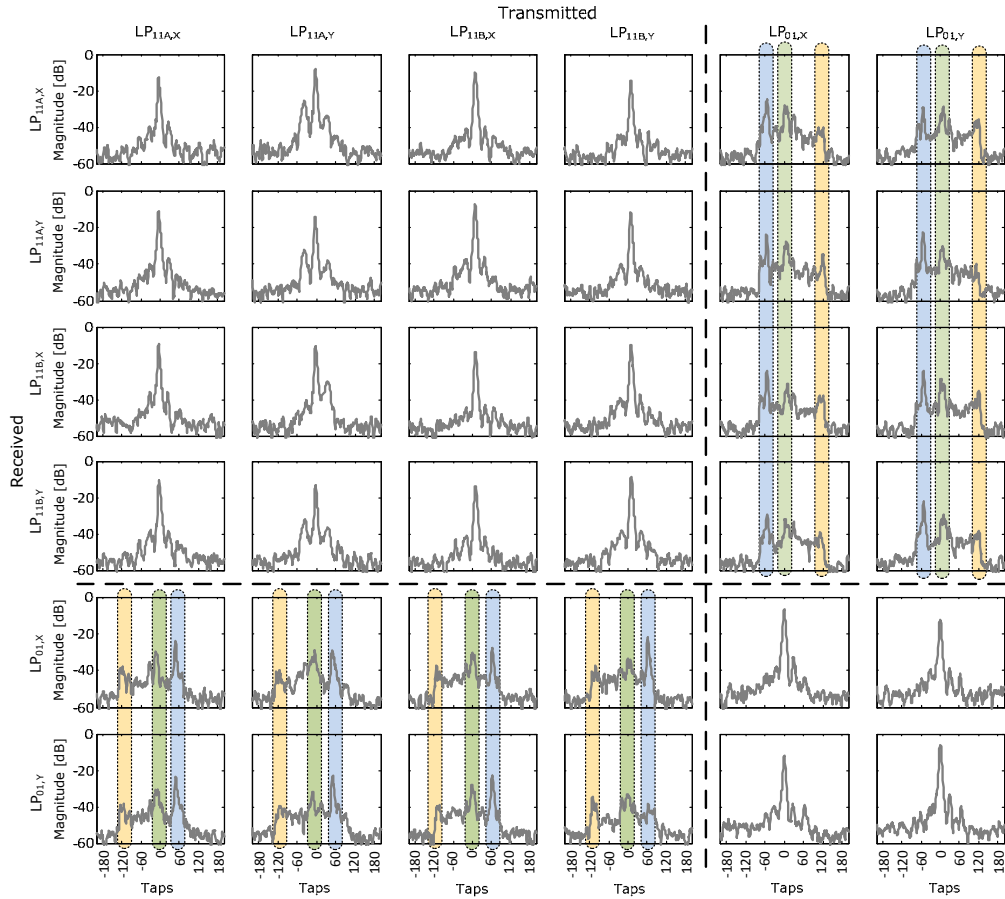


Fig. 7. Magnitude of impulse response versus number of taps of the 6x6 MIMO-equalizer obtained after 119km of transmission for the channel at 193.4 THz.

More interesting information can however be deduced from the plots that are outside of the squares. These plots show the leaking of power from LP_{01} to LP_{11} and vice versa. To show the taps that correspond to each other, certain parts in these plots are highlighted using the same colors. The green highlighted part is at the center of the impulse response, which corresponds to the signal received at the DEMUX and for this particular case, because the modes are received at the same time, also the MUX. These peaks therefore correspond to crosstalk induced by the MUX and DEMUX. The peaks in the blue highlighted part correspond to the crosstalk induced by the MM-EDFA after the first span, which was substantially higher in our first experiment due to the un-optimized splicing recipe used at that time [10]. The blue and orange shaded areas show the beginning and end of the plateau

built up by distributed mode-coupling during transmission. This plateau is formed within the DMD window of the two spans together.

3.4 WDM transmission results

Figure 8 shows the transmission results for all the 96 3x256-Gb/s DP-16QAM modulated channels over 119km of few-mode fiber as well as the received spectrum after transmission. All WDM channels performed well below the FEC-limit for each separate mode. The received spectrum turned out to be relatively flat over the full transmitted frequency range.

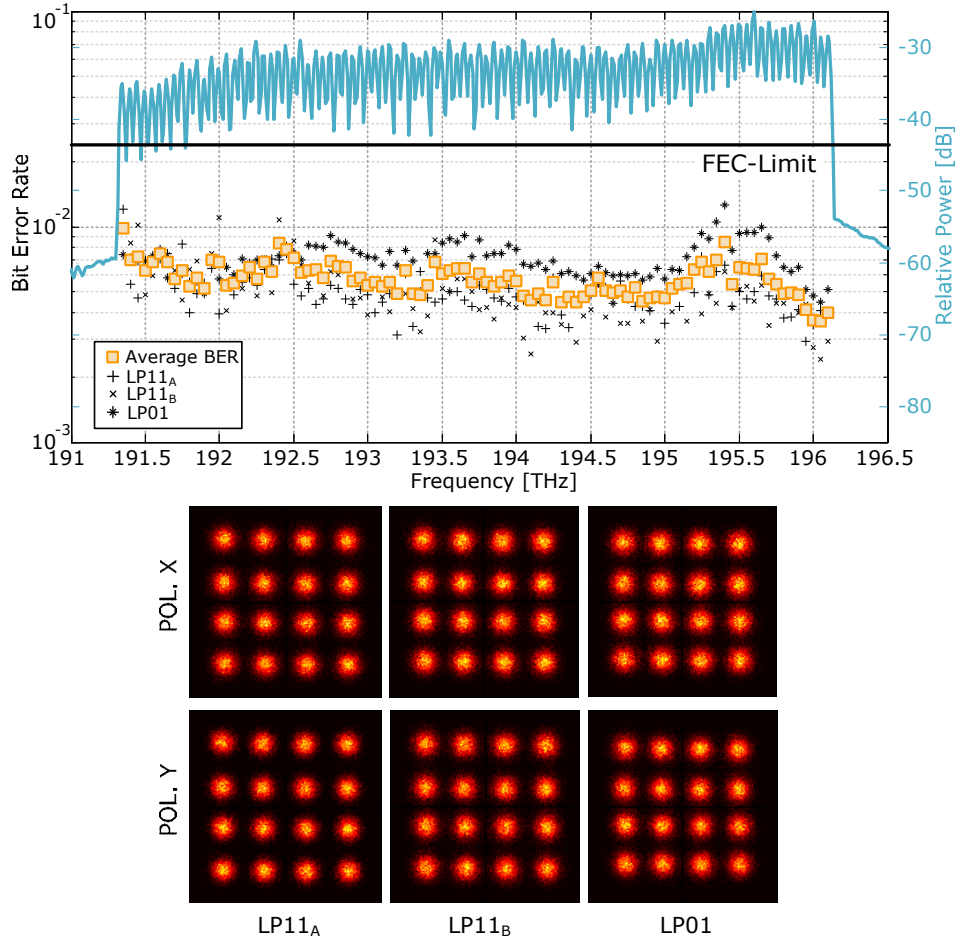


Fig. 8. Bit error rate for all 96 WDM channels after 119km transmission distance with the received spectrum after mode DEMUX. Bottom: constellations after transmission.

4. Conclusions

The successful transmission of 73.7 Tb/s (96x3x256-Gb/s) mode-division-multiplexed DP-16QAM over 119km of few-mode fiber has been demonstrated providing a net total system capacity of 57.6 Tb/s. By reducing the mode coupling losses resulting from the phase plate based mode (de-)multiplexer a substantial further increase in transmission distance should be possible.

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