1.28 Tb/s Single Wavelength Star-16-QAM Transmission over up to 800 m of Graded-Index Multimode Fibre

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Abstract
For the first time, up to 160 Gbaud 16-QAM and 8-PSK transmission over graded-index multimode fibre is demonstrated using optical time division multiplexing and de-multiplexing in combination with coherent detection.

Introduction

Graded-index multimode (GI-MMF) fibre is typically used in local area and storage area networks with a transmission length of usually ≤ 300 m (OM3 fibre class) for 10GbE transmission at a wavelength of 850 nm. The larger core diameter (50 µm) of the GI-MMF in contrast to the standard single mode fibre (10 µm) results in higher coupling tolerances and directly translates into lower transceiver costs.

In GI-MMF transmission systems, the maximum bit rate per wavelength as well as the maximum achievable transmission distance are mainly limited by modal and chromatic dispersion of the fibre.

To increase the capacity times distance product, different techniques have been proposed in the past to overcome these limitations. These techniques include reduction of modal dispersion due to an improved manufacturing process [1], mode-field matched (MFM) centre launching (CL) [2], wavelength division multiplexing (WDM) [3,4], sub-carrier multiplexing (SCM) [3], orthogonal frequency division multiplexing (OFDM) [5], mode-group division multiplexing (MGDM) [7], electronic pre-distortion [6], electronic equalisation at the receiver side [8] or a combination of them. To reduce modal dispersion, excitation of the fundamental mode can be applied by using single mode fibre (SMF) centre launching or the more appropriate MFM-CL. At the receiver side, the fundamental mode can be spatially filtered out by a MMF-to-SMF coupling. In this paper we investigate this technique with respect to the achievable transmission distance and bit rate for 16-QAM and 8-PSK transmission over GI-MMF with high modal bandwidth (BOFL = 5.3 GHz·km @ 1300 nm [1]).

Experimental setup

The experimental setup is shown in Fig. 1. The transmitter consisted of a 10 GHz mode-locked solid state 1550 nm laser (ERGO) which allows to generate Gaussian shaped pulses with a FWHM of 2.1 ps.

The ERGO - pulses were DQPSK modulated to 20 Gb/s by an IQ-modulator and afterwards 8-PSK and 16-QAM modulated to 30 Gb/s and 40 Gb/s using additional phase and Intensity modulators (IM), respectively. The four driving signals are derived from de-correlated 2^7-1 and 2^9-1 pseudo random bit sequences. To generate high bit rates at a single wavelength, the 30 Gb/s 8-PSK or 40 Gb/s 16-QAM signals were multiplexed by a de-correlated optical fibre delay MUX stage with a variable multiplexing factor for the generation of up to 480 Gb/s 8-PSK and 640 Gb/s 16-QAM, respectively. An additional bit-interleaved polarisation multiplexing stage was used to further increase the bit rate by a factor of two, to a maximum of 1.28 Tb/s for 16-QAM.

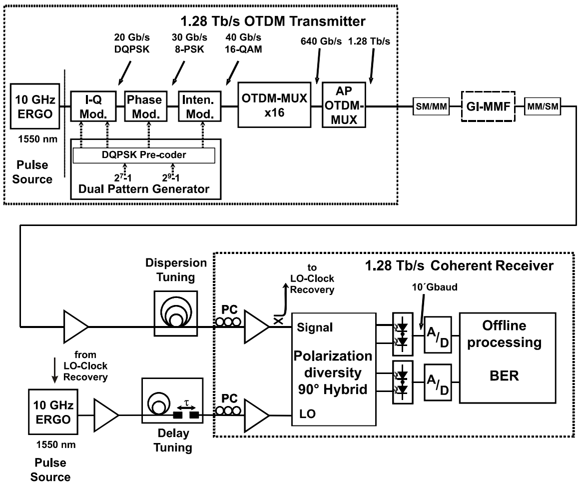

Fig. 1: Experimental setup

The coherent optical receiver consisted of a commercial polarisation diversity optical 90°-hybrid, high-speed balanced photo detectors, a 4-channel 50 GSa/s sampling oscilloscope and a PC for offline processing and BER calculation.

To achieve coherent de-multiplexing and homodyne detection, the pulse train of a second free running ERGO laser, the local oscillator (LO), was adjusted in time to overlap with one of the tributaries of the OTDM signal. In front of the receiver, dispersion compensation was applied to minimize the pulse width of the received signal before optical de-multiplexing. For simplicity one polarization channel of the multiplexed signal was mapped to the upper half of the optical hybrid for data processing, while the lower half was used for monitoring. The off-line processing included sampling of the acquired IQ-data to an integer number of 5 samples per symbol, clock recovery to find and select samples from the centre of the bit slot, frequency offset correction, phase estimation and correction based on the m-th power block scheme (block size 8) and finally error counting. The intensity decision threshold for 16-QAM signals was set to the mean amplitude of all samples. Finally, the bit error ratio (BER) was calculated from sequences containing about 1M symbols using the sum of errors in all of the 3 and 4 bits per symbol for 8-PSK and 16-QAM, respectively.

Experimental investigations and results

Figure 2 shows the three investigated transmission sections, which differ with respect to length of the GI-MMFs and the number of FC/PC connectors.

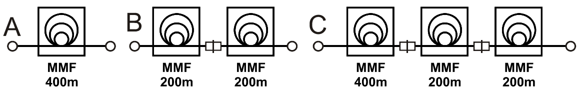

Fig. 2: Investigated transmission sections

For the first transmission experiment, 400 m of the high bandwidth GI-MMF was used as fibre under test (section A in Fig. 2). The spooled fibre was assembled with standard FC/PC connectors. Transmitter and receiver were directly connected to the GI-MMF via SMF patch cords with standard FC/PC connectors. The launch power into the GI-MMF was chosen to 0 dBm. The transmission over 400 m GI-MMF and the mode filtering by the MMF-to-SMF coupling resulted in an overall attenuation of 3 dB. Figure 3 shows the measured BER versus bit rate for transmission of 16-QAM and 8-PSK through section A. For transmission of 160 Gbaud 16-QAM and 8-PSK through section A, BERs of $1.3 \cdot 10^{-3}$ and $2.5 \cdot 10^{-5}$ were measured, respectively.

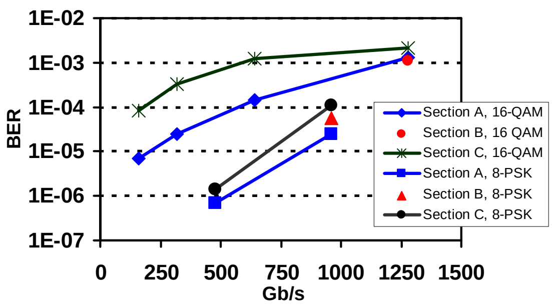

Fig. 3: BER versus bit rate for 16-QAM and 8-PSK transmission through sections A, B and C

In a second experiment, the influence of connectors within the transmission path was investigated. Therefore, the 400 m GI-MMF was replaced by two pieces of 200 m GI-MMF (section B in Fig. 2), which were connected by standard FC/PC connectors. The BER measurements for this section resulted in no significant BER degradation (s. Fig. 3). In addition, transmission over 800 m GI-MMF (section C) that consisted of 3 pieces of GI-MMF, with lengths of 400 m, 200 m and 200 m, was investigated. BER versus bit rate after transmission through section C is also shown in Fig. 3. The additional two connectors and 400 m GI-MMF in comparison to section A resulted in a BER degradation of approximately one order of magnitude for 16-QAM for bit rates of up to 640 Gb/s. For 8-PSK, the measured BER penalties, in comparison to section A, were less than half an order of magnitude. In Fig. 4, the received constellation diagrams are shown for 1.28 Tb/s and 640 Gb/s 16-QAM transmission through section C. Figure 5 shows constellation diagrams for 960 Gb/s and 480 Gb/s 8-PSK after transmission through section C.

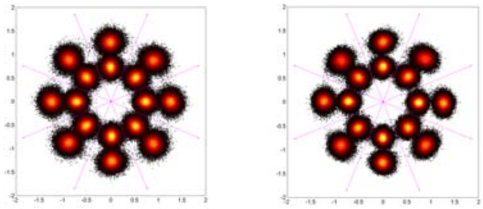

Fig. 4: IQ-plots of 1.28 Tb/s (left) and 640 Gb/s (right) 16-QAM after transmission through section C

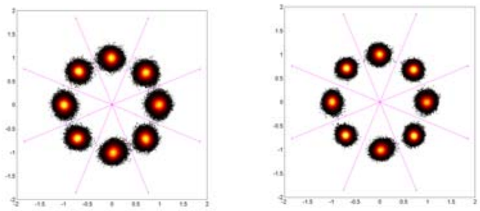

Fig. 5: IQ-plots of 960 Gb/s (left) and 480 Gb/s (right) 8-PSK after transmission through section C

Conclusions

Considering an UFEC limit of BER $\leq 2 \cdot 10^{-3}$, we demonstrated error free transmission of 1.28 Tb/s Star-16-QAM and 960 Gb/s 8-PSK (including UFEC overhead) over 400 m and 800 m of spooled GI-MMF, respectively, using optical time division multiplexing and de-multiplexing, coherent detection and offline BER estimation. Further improvement with respect to transmission distance and bit rate could be achieved by applying mode-field matched centre launching as well as improved signal processing algorithms. For practical application, further investigations have to be carried out on already installed high bandwidth GI-MMF.

Acknowledgement

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