50 ch x 250 Gbit/s 32-QAM transmission over a fully integrated 7-core multicore link

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Abstract *A transmitted distance of 180 km over an integrated multicore link is demonstrated for a C-band 32-QAM WDM system, where the complete usable amplification region of the integrated 7-core amplifiers, supporting 50 channels per core, is exploited.*

Introduction

Multicore fibre (MCF) transmission, a type of space division multiplexing (SDM) relying upon encompassing several spatial paths within a single cladding structure, represents a promising technology for accommodating the increasing data rates required for future applications[1]. Over the past few years, MCF-systems have been shown to be capable of exhibiting sufficiently low crosstalk to support transoceanic transmission distances[2,3], have transmitted high-order modulation formats[4] and achieved high-data rates while promising to be cost-efficient[5]. Nevertheless, to truly demonstrate the potential of MCF-systems, it is important to investigate their performance on realistic transmission links with integrated components in order to illustrate the practical challenges and the possible economical advantages of SDM. The integration of multicore components has allowed for fully spliced repeatered systems to be constructed[6,7], however the focus has been on the multicore components or the transmission characteristics in a reduced area of the C-band. In this paper, we transmit a signal with 50 WDM channels, fully occupying the usable amplification region of our current 7-core cladding-pumped erbium-ytterbium-doped fibre amplifiers (MC-EYDFAs). A high-order modulation format is used to demonstrate high capacity transmission through an integrated multicore link (IML) in a recirculating loop.

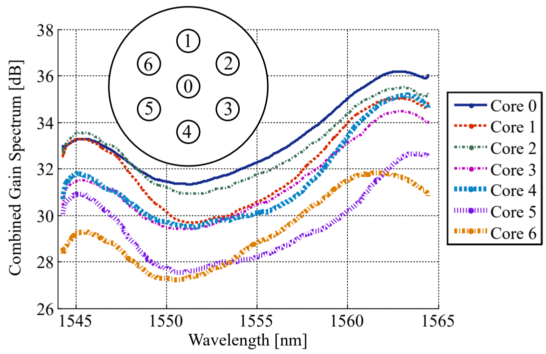

Fig. 1: Structure of the MCF and cascaded gain spectrum of both MC-EYDFAs for one loop iteration corresponding to pump currents of 3.0 A and 2.2 A (loss caused by the fiber and fan-in/fan-out couplers is neglected).

Integrated 7-core repeatered link

The multicore link[7] consists of a homogenous trench-assisted 7-core MCF with a hexagonal core layout (Fig. 1), spliced together with two MC-EYDFAs in order to compensate for fibre attenuation and the loss caused by the elements in the recirculating loop, and integrated fan-in/fan-out couplers based on free-space optics. Because the adopted setup does not allow us to measure the launch power of the cores directly at the input of the MCF, we have to optimize our system by sweeping the pump current levels and evaluating the BER performance for a 16-QAM channel after 240 km. Taking into account that different cores might have different optimal pump currents, we compared the best performing settings for the centre core (core 0) and two of the outer cores (core 5 and core 6), and proceeded to obtain an

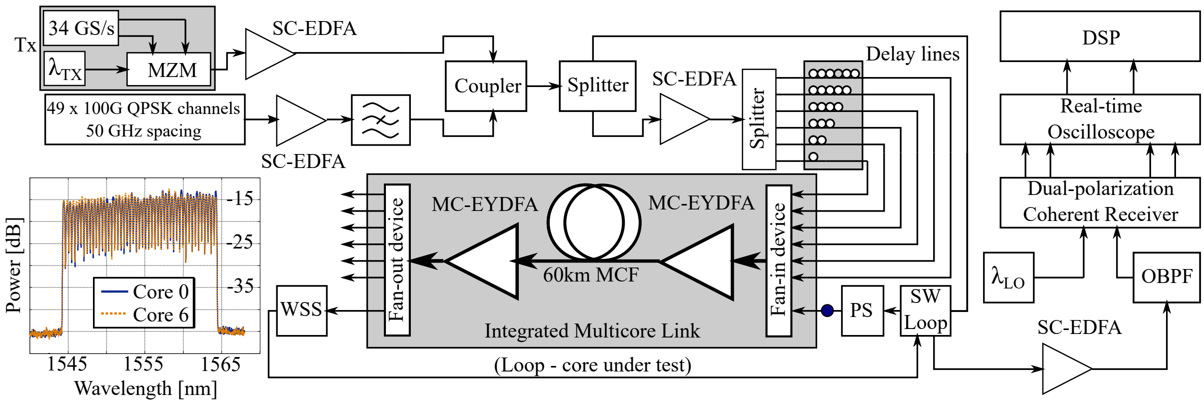

Fig. 2: Experimental setup and spectra of the inner core and one outer core before the integrated multicore link. (λ_{TX}: transmitted wavelength for the channel under test, λ_{LO}: wavelength for the local oscillator)

average value. This optimization method yielded pump currents for the first and second MC-EYDFA of 3.0 A and 2.2 A, respectively, for a channel at 1550.116 nm, which lies in the worst performing region of the usable amplification spectrum[7]. Figure 1 displays the overall combined gain spectrum of the cascaded MC-EYDFAs. The variation between the centre core, which is the best-amplified channel, and core 6 is 5-6 dB, arising from different losses in the passive components of the IML.

Experimental setup

We proceed to analyse a fully-spliced MCF-system with cladding pumped-amplifiers, where each core of the system transmits 50 channels in the C-band between the wavelengths of 1544 nm and 1564 nm so as to use the full bandwidth of the multicore amplifiers. The WDM signal for a given core is composed of a 250 Gbit/s 32-QAM test channel and 49 neighbouring 100 Gbit/s QPSK channels aligned to a 50 GHz channel grid. The system setup used in this experiment can be seen in Fig. 2. At Tx, the dual-polarized test channel is generated by a dedicated DAC, inserting uniformly spaced pilot symbols and using constant amplitude zero auto-correlation (CAZAC) training sequences to aid the digital signal processing stage at the receiver. The main principle of the experimental setup is to be able to analyse the characteristics and performance of a particular core by treating the remaining cores as potential sources of inter-core crosstalk. Before using a passive coupler to combine the 32-QAM and the QPSK signals, we have inserted a notch-filter to filter out the noise produced by the single-core erbium-doped fibre amplifier (SC-EDFA) that boosts the 49 neighbouring channels. The complete WDM signal is then split into two copies. The first copy is amplified and further split to provide valid signals for 6 cores of the MCF-system by means of delay lines of various lengths that de-correlate them, whereas the second one is directly connected to the recirculating loop. The analysis of the recirculating loop refers exclusively to the core-under-test; the rest of the cores just pass through the integrated multicore link (IML)[7]. The recirculating loop starts with a low-speed polarization scrambler (PS) before going into the IML. The signals going into the IML have a total power of 1 dBm/core ($\sim$-16 dBm/channel/core), with a variation of about 2 dB between cores. After the IML, the signal passes a wavelength selective switch (WSS) to flatten the spectrum. At the receiver's end, a SC-EDFA boosts the signal before the test channel is extracted by an optical bandpass filter (OBPF) with a 50 GHz bandwidth and fed over to a dual-polarization coherent receiver. Finally, we use a real-time oscilloscope to sample the electrical signals and proceed to perform offline digital signal processing (DSP): resampling to 2 samples per symbol, chromatic dispersion compensation in the frequency domain, carrier frequency offset estimation, 2-by-2 multiple-input multiple-output equalization, and clock recovery. Phase estimation is performed by the Viterbi-Viterbi algorithm for m-QAM data sets.

Results and discussion

The BER values corresponding to the 250 Gbit/s 32-QAM channel after 180 km can be seen in Fig. 3, where all channels are below the assumed FEC threshold of $3.4 \cdot 10^{-2}$. In order to obtain these measurements, the 32-QAM channel was analysed for each wavelength in the WDM spectrum. Looking at the combined gain spectrum of the amplifiers in Fig. 1, we can see that the channels at longer wavelengths perform slightly better compared to channels at the shorter end of the spectrum due to the gain variation between cores.

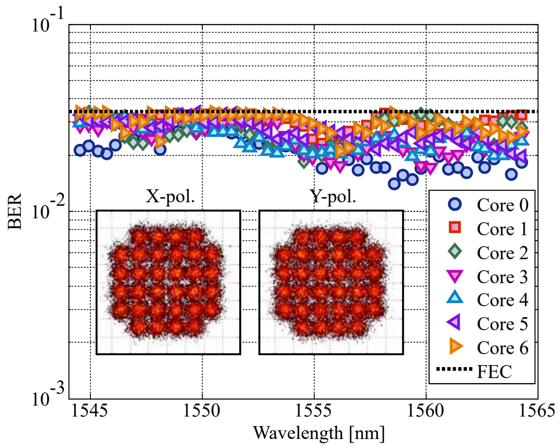

Fig. 3: BER measurements after 180 km using a recirculating loop and an IML for the 32-QAM channel at different wavelengths. As insets, the constellation diagrams for a BER value of $3.4 \cdot 10^{-2}$ are shown.

Although the practical maximum transmitted distance for all 50 channels is 180 km due to some channels being too close to the FEC threshold, it is important to notice that some measurements for channels at longer wavelengths exhibit lower BER values that indicate that they are able to reach larger distances. This leads us to believe that the overall performance of the various cores is dominated by noise instead of crosstalk for a transmission distance of 180 km. This would also support the observation that core 0, corresponding to the middle core, performs slightly better than the outer cores (cores 1-6) despite being exposed to higher cross-talk levels.

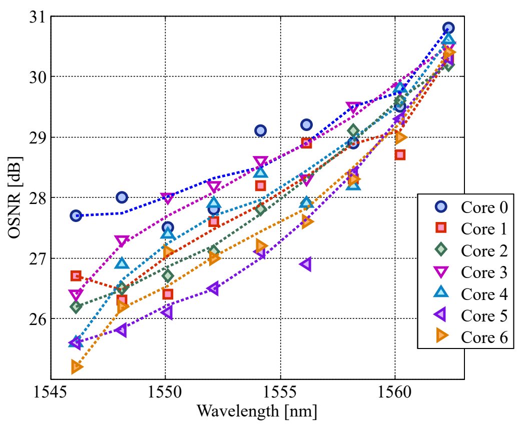

Fig. 4: OSNR measurements for all seven cores of the MCF.

Figure 4 displays the OSNR measurements after 180 km for 9 uniformly spaced channels between 1546 nm and 1562 nm. OSNR readings match the observations extracted from Fig. 3, confirming that the cores with the lowest OSNR readings correspond to the cores with the worst BER performance (core 1, core 5, and core 6); whereas core 0, the best amplified core in the system, consistently displays a better performance than the rest across the analysed wavelength range.

Conclusions

Using a 50 GHz channel grid, we have transmitted 50 channels per core using an integrated 7-core repeated MCF-system, where the 250 Gbit/s 32-QAM test channel reaches distances over 180 km for the entire wavelength range between 1544 nm and 1564 nm. Using the complete usable amplification region of the cladding-pumped amplifiers, we virtually demonstrate a total capacity of 87.5 Tbit/s for the complete MCF-system, corresponding to a spectral efficiency of 35 b/s/Hz.

Acknowledgements

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