200 Gbit/s 16QAM WDM Transmission over a Fully Integrated Cladding Pumped 7-Core MCF System

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Abstract: A complete, realistic integrated system is investigated, consisting of directly spliced 7-core MCF, cladding-pumped 7-core amplifiers, isolators, and couplers. The system is demonstrated in a 16QAM C-band WDM scenario over 720 km.

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1. Introduction

Multicore fiber (MCF) technology has received a lot of attention in the last few years, positioning itself as a promising candidate for the next step in optical communications due to its ability to transmit high capacity [1], achieve long-haul transmission [2], and potentially reduce manufacturing and operational costs by sharing components [3]. Until recently, single-core and isolated components were the only alternative for MCF systems [4, 5], but developments in multicore technologies such as amplifiers [3], isolators [6], and bundled fiber couplers have permitted integrated in-line multicore repeatered systems [7] to be implemented and the potential economic benefits offered by space-division multiplexing (SDM) to be demonstrated. In this paper, we investigate for the first time a fully integrated, spliced-in-line 7-core repeatered recirculating transmission system using side-coupled cladding-pumped amplifiers operating in the C-band. A transmission distance of over 700 km is achieved using a 200 Gbit/s 16QAM signal, demonstrating the applicability of this technology to realistic system scenarios.

2. Integrated multicore link

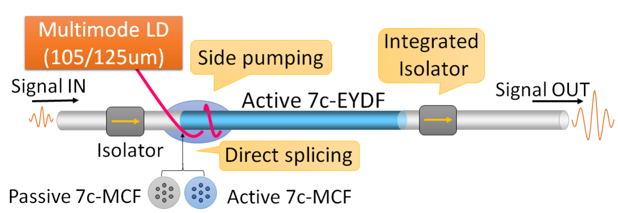

Fig. 1: Schematic of the internal structure of the MC-EYDFA.

We constructed an integrated multicore link consisting of multicore amplifiers and MCF spliced together in order to produce an in-line repeatered system. In our experiment, the system consists of fiberized fan-in (FI)/fan-out (FO) devices, multicore cladding-pumped erbium-ytterbium-doped fiber amplifiers (MC-EYDFAs), and 60 km of 7-core homogeneous trench-assisted fiber [5]. The fiberized FI/FO devices couple signals coming from different SSMFs into one MCF by free-space optics methods. Figure 1 presents the schematic of the MC-EYDFAs used. The setup consists of a fiber coupled (NA=0.22, core/cladding 105/125 µm) multimode pump laser diode operating at 975 nm. The pump fiber was tapered down to 15 µm and coiled around the fiber near the point at which the passive MCF is spliced to the active fiber. It is recoated with low index polymer to enable efficient guiding of the pump light. Additionally, multicore isolators were spliced between the FI/FO couplers and active 7c-EYDF. The 7-core MCF incorporates the cores at the vertices of a hexagonal structure with one core in the middle. The differences between the refractive indices in the

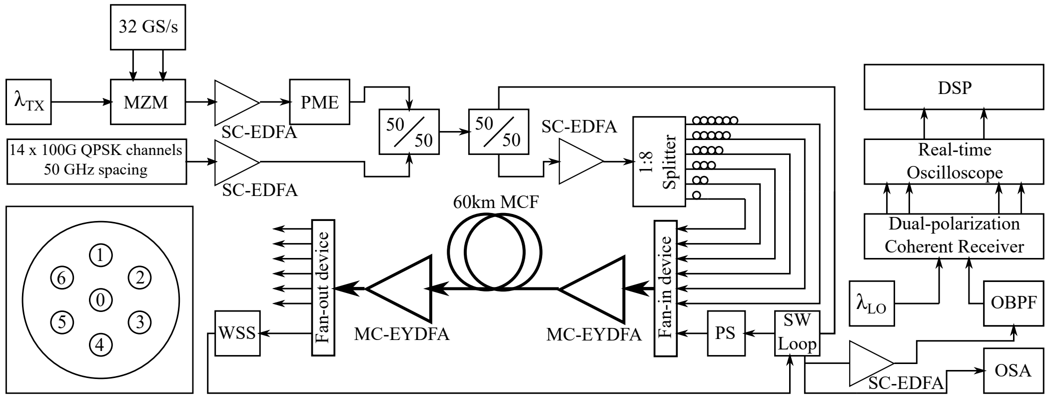

Fig. 2: System setup and core identifiers for the MCF.

cladding and trenches, and cores and cladding are -0.7% and 0.23%, respectively. The fiber has an average core-to-core pitch of 49.3 µm and a cladding diameter of 195 µm, which leads to a worst-case crosstalk value of -58.5 dB (in the central core) after 60 km.

3. Experimental setup

We experimented with a system comprising 15 WDM channels, where the test channel (TC) is a 200 Gbit/s 16QAM signal and the remaining channels are 100 Gbit/s QPSK signals. Such arrangement is simultaneously used for all the cores. Figure 2 illustrates the experimental setup of our system. At the transmitter, a dedicated DAC generates the data for the TC with periodically spaced pilot symbols and constant amplitude zero auto-correlation (CAZAC) training sequences. The multilevel signal at 32 GBaud is fed to the optical modulator to produce an optical signal, which, after a polarization-multiplexing emulation (PME) stage, corresponds to a channel with a gross data rate of 256 Gbit/s. The 14 neighboring 100 Gbit/s channels are generated between 1558.578 and 1564.71 nm according to a 50 GHz channel grid. The system setup allows us to analyze the transmission characteristics of any given core, while keeping the rest of the cores as potential sources of spatial channel interference. The signals fed into the interfering cores are de-correlated versions of the original signal, which are obtained by first splitting the signal via a 3 dB coupler to produce one copy for the core-under-test (CUT) and one for the rest of the cores. For the second copy, further splitting is required; realized using a 1:8 coupler to produce enough signal duplicates. They are subsequently de-correlated by optical delay lines of different lengths and then connected to the remaining 6 cores. Additional single-core EDFAs (SC-EDFAs) are used to equalize the powers of the optical signals. As a result, the power variation of the WDM signals are within 1 dB and the total power of the cores, within 2 dB. The signal from the CUT goes into the recirculating loop structure consisting of a low-speed polarization scrambler (PS), the integrated multicore link (IML), and a WSS for gain-flattening purposes. After the recirculating loop, we boost the signal with a SC-EDFA at the receiver, set an optical bandpass filter (OBPF) to extract the TC, and deliver the signal to a dual-polarization coherent receiver. A 40 GSamples/s oscilloscope captures the electric signals and then digital signal processing is performed offline as follows: the signals are resampled to 2 samples per symbol, chromatic dispersion is compensated by a frequency-domain equalizer, the carrier frequency offset and coefficients for the 2-by-2 multiple-input multiple-output equalizer are estimated with help from the training sequences inserted in the transmitted data and, after clock recovery, phase estimation is carried out using the Viterbi-Viterbi algorithm for m-QAM data sets. Assuming a soft-decision FEC with 15% overhead and considering the training information used in the data, we end up with a net data rate of 206.62 Gbit/s.

3.1. Results and discussion

The BER measurements for the 200 Gbit/s 16QAM TC after 720 km in all 15 channel positions using the IML in a recirculating loop is illustrated in Fig. 3 (a). We observe that all channels perform below the assumed FEC threshold of $2.4 \cdot 10^{-2}$. There is a slight variation in the BER performance between cores arising mainly from the different overall losses experienced by the cores in the multicore components (FI/FO devices, isolators in the EYDFAs, and attenuation in the MCF). Some channels reached a maximum distance of 780 km, but the majority reached a slightly lower maximum distance of 720 km. From Fig. 3 (a) we conclude that the limiting factor in our system is a combination of noise and inter-core crosstalk. Core 0, which should have around 3 dB more crosstalk than its neighbors, shows the same performance as the rest of the cores due to lower amplification gain in the MC-EYDFAs and higher insertion loss for the outer cores in the isolators. Since the performance is similar between channels and cores, we chose a TC in

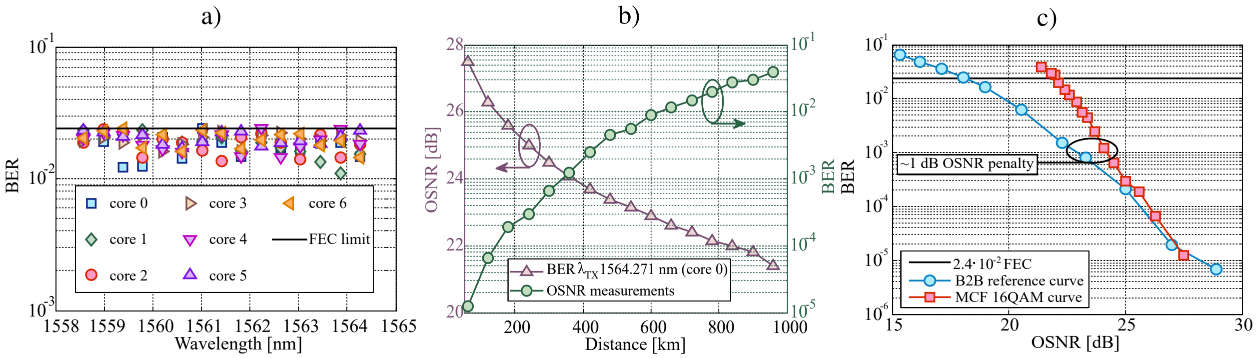

Fig. 3: a)BER measurements for the 200 Gbit/s 16QAM channel with 14 x 100 Gbit/s QPSK neighboring channels after 720 km. b)OSNR (left y-axis) and BER (right y-axis) measurements for the TC at a wavelength of 1564.271 nm for different transmission distances. c)BER vs. OSNR comparison between optical B2B and the corresponding BER-OSNR points presented in Fig. 3 (b).

core 0 at a wavelength of 1564.271 nm to characterize the BER performance of the MCF system. Figure 3 (b) shows in detail the BER performance as a function of the transmitted distance (green line and markers) and the available OSNR given at a resolution bandwidth of 0.1 nm (purple line and markers). Taking the pairs of values at each distance from Fig. 3 (b) and plotting them in a 1-to-1 correspondence, we produce a BER vs. OSNR curve for the transmission of the TC and compare it against the optical back-to-back (B2B) performance. The result is shown in Fig. 3 (c), where at high OSNR values corresponding to short transmission distances the data curves seem to be within an OSNR penalty of approximately 1 dB for BER values below $1 \cdot 10^{-3}$. At low OSNR and long distances, the inter-core crosstalk and the additional impairments acquired within the loop setup accumulate faster than the noise and affect the transmission performance. We observe that the crosstalk in the integrated link could be inferred but not directly measured, because the active fiber in the MC-EYDFAs is highly absorbing within the operating transmission band.

4. Conclusions

We demonstrated a realistic integrated 7-core MCF system comprising directly spliced cladding-pumped multicore amplifiers, MCF, MC-isolators and FI/FO couplers. In a WDM scenario with recirculating loop setup, we transmitted one 200 Gbit/s 16QAM channel alongside 14 x 100 Gbit/s QPSK neighboring channels in the C-band on a 50 GHz grid, achieving transmission distances of up to 780 km. The performance of all 7 cores was compared, and the viability of this system for communication over at least 720 km was proven.

5. Acknowledgements

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