12-Core Erbium/Ytterbium-Doped Fiber Amplifier for 200G/400G Long-Haul, Metro-Regional, DCI Transmission Applications with ROADM

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Abstract *A 12-core Er/Yb-doped fiber amplifier with 21-dBm output power per core and 5.3-Watts multimode pump is used here to address various transmission applications with ROADM. 1200-km with 200G DP-QPSK and 300-km with 400G DP-16QAM are achieved in serial configuration at 1550-nm. Parallel 12x100-km transport with 400-ZR+ transceiver is also implemented.*

Introduction

Space division multiplexing (SDM) is expected to be one of the solution to deal with the up-coming capacity crunch of single-core (SC) single-mode fiber (SMF) transport networks [1-4]. Beyond passive and active multicore fibers (MCF) [3-10] required in few years to replace legacy SC-SMF infrastructure, MCF amplifiers [3-10] already have a real interest for optical communications. Indeed, they could amplify at once fiber bundle inside currently used optical cables [11], and be inserted in colorless, directionless, contentionless (CDC) ROADM in replacement of EDFA array, while reducing power consumption [12]. Submarine cables that have very stringent energy requirements [13] also constitute a very relevant application domain for MCF amplifiers.

In this paper, we use the 12-core Er/Yb-doped fiber (12c-EYDF) amplifier prototype presented in [8] to address various transmission applications in long-haul (LH), metro-regional, data-center interconnect (DCI) transport networks. More precisely, we successfully insert the MCF amplifier in a 1200-km SC-SMF transmission line with 200G DP-QPSK format, and in a 300-km SC-SMF link with 400G DP-16QAM, both in serial configuration. Parallel 12x100-km transport with 400-ZR+ transceiver is also implemented. MCF amplifier insertion in ROADM is finally shown.

12-core Er/Yb-doped MCF amplifier

The 12c-EYDF [8] was manufactured using the stack-and-draw process. Accordingly, the preform was based on a circular arrangement of doped preforms around a central rod, with all the cores lying on a single circle. The core diameter was fixed to ~6-µm, while the [Er]/[Yb] atomic ratio was ~20 to meet the amplifier gain (20-dB), output power (21-dBm/core) and average noise figure (~7-dB) requirements. Er/Yb-doped preforms were obtained through the MCVD process. Drawing was performed to obtain a 35.0-µm core-to-core spacing, a 187.5-µm silica clad diameter, and a numerical aperture (NA) of 0.48 for the multimode clad. Total rare-earth clad absorptions were estimated to be 3.7 dB/m and 0.53 dB/m, respectively at 914 nm and 1534 nm. The 12c-EYDF cross-section is shown in Fig. 1a).

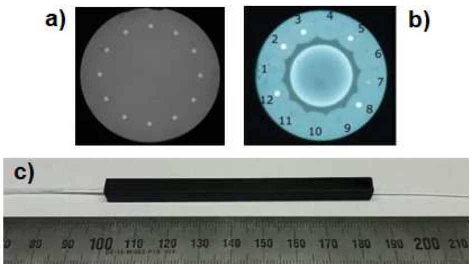

Fig.1: (a) Optical microscopy picture of the 12c-EYDF. (b) Fiber bundle combiner/fan-in. (c) Packaging of the combiner/fan-in spliced to the 12c-EYDF.

Pump and signals were coupled into the 12c-EYDF using a tapered fiber bundle combiner/fan-in. Pump light was launched through a central multimode fiber (core/clad dimension of 195/230-µm and NA of 0.22) and signals through 12 outer single-mode fibers (core/clad size of 15/80-µm and NA of 0.19) designed to match the mode field diameter of active cores after down-tapering. Owing to an optimized fusing/tapering process, reproducible core-to-core spacing of 35±0.5-µm were obtained, leading to a good matching with the 12c-EYDF geometry. The combiner/fan-in cross-section and its compact packaging of 80 x 5 x 5 mm are shown in Fig. 1b) and Fig. 1c), respectively.

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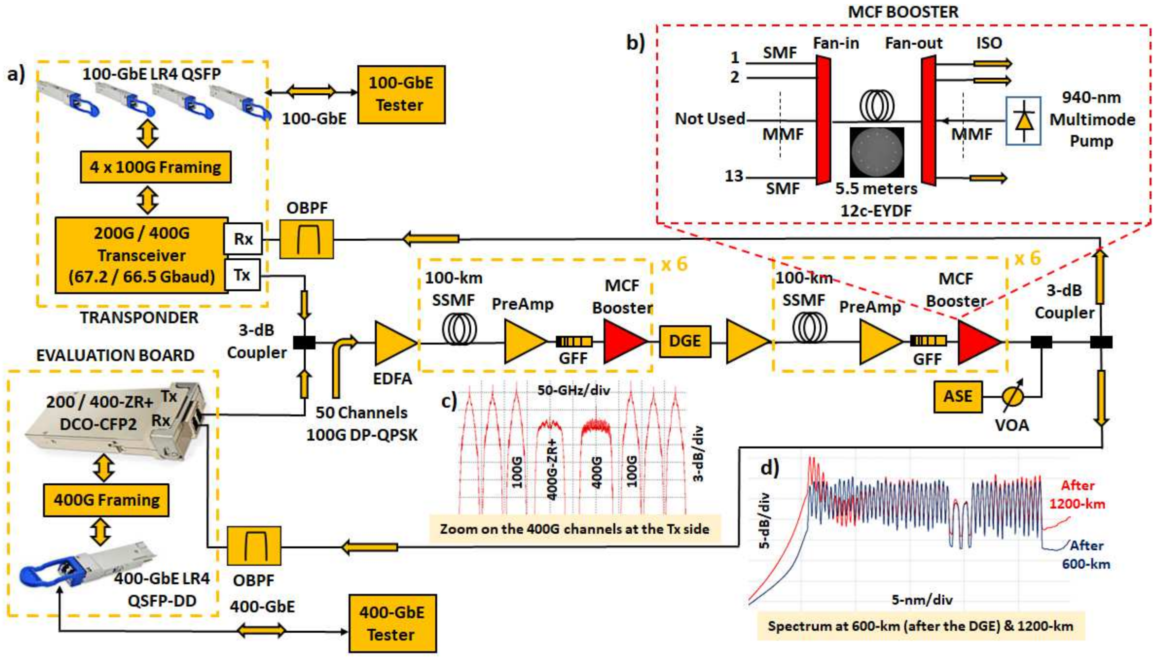

Fig.2: (a) Set-up of the transmission experiment, with the 200/400G-ZR+ DCO-CFP2 transceiver, the proprietary 200G/400G transponder, the 52 DP-QPSK channels at 100 Gbps, and the 12x100-km ITU-T G.652 fiber line including the 12c-EYDF amplifier. (b) 12c-EYDF amplifier architecture. (c) Zoom over the WDM multiplex where are located the 200G/400G signals under test at the transmitter output. (d) Spectrum of the WDM multiplex at 600-km after the DGE (blue curve) and 1200-km (red curve).

Experiment & Results in Serial Configuration

The experimental set-up is depicted in Fig.2a). The WDM transmitter comprises two 200G/400G DP-QPSK/DP-16QAM interfaces at 1549.32-nm and 1550.12-nm, and 50 other 100G DP-QPSK channels ranged from 1535.8 to 1557-nm on the 50-GHz ITU-T grid. The first 200G/400G interface is a ZR+ DCO-CFP2 [14] operating at 60.1 Gbaud with the standardized O-FEC [15-17]. It has a BER threshold of ~2x10^{-2}, 15.3-% overhead and a net coding gain of ~11.6-dB @ BER=10^{-15}. The second interface is a proprietary transponder working with a LDPC FEC. It has a BER threshold at 200G/400G equal to ~3x10^{-2}/2x10^{-2}, 22.6/21.5-% overhead, net coding gain of ~11.8/11.4-dB @ BER=10^{-15}, and a total baud rate of 67.2/66.5-Gbaud. A zoom over the WDM multiplex where are located the 200G/400G signals under test is shown in Fig.2c).

The uncompensated 1200-km transmission line is constituted of twelve 100-km spans of ITU-T G.652 fiber. The span losses are compensated by double-stage amplifiers. The first stage is constituted by a conventional SC single-mode EDF pre-amplifier followed by a gain flattening filter (GFF) and the 12c-EYDF amplifier used as a second stage or booster. A 940-nm multimode pump laser diode of 5.3-watts is coupled into 5.5-meters of 12c-EYDF via the fan-out in a backward pumping configuration with an efficiency > 99%. The amplifier total power consumption is ~11-Watts [8]. The MCF amplifier architecture is shown in Fig. 2b). Fan-in/out have average insertion loss of ~1.7-dB. Over the [1535-1564]-nm range, the gain flatness is ~7 dB (corrected by the GFF) which is typical of an Er/Yb co-doped fiber amplifier. The total gain of the amplification stage is ~30-dB (with ~20 dB for the 12c-EYDF booster) to compensate for the span, GFF and fan-in/out losses. A dynamic gain equalizer (DGE) is inserted in the middle of the link. The WDM multiplex spectrum measured at 600-km (after the DGE) and 1200-km is shown in Fig.2d).

At the receiver side, the 200G/400G channels are extracted by two ~80-GHz square flat-top optical band-pass filters (OBPF) and sent into the DCO-CFP2 receiver and the proprietary transponder. As shown in Fig.2a), the evaluation board that embeds the DCO-CFP2 module, and the proprietary transponder are equipped to host respectively one client 400-GbE LR4 QSFP-DD interface and four client 100-GbE LR4 QSFPs (directly connected to 400-GbE and 100-GbE testers). The post-FEC errors can thus be measured and error-free operation of the configurations under test identified.

Fig. 3 below presents the results obtained in this serial configuration at 200G and 400G.

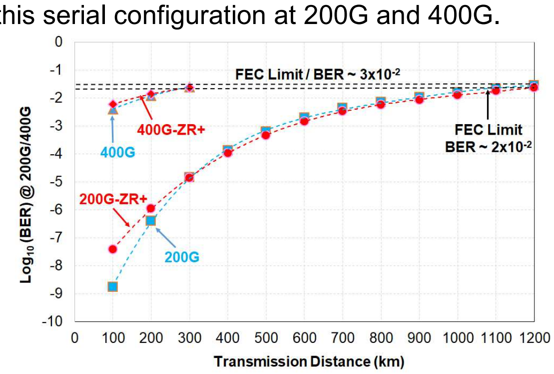

Fig.3: BER vs. transmission distance at ~1550-nm for the 200G/400G interfaces under test in the serial configuration.

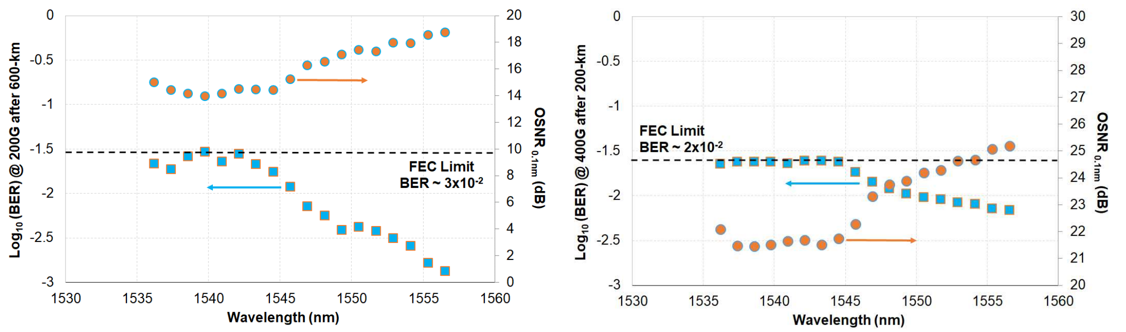

Fig.4: BER & OSNR (in 0.1-nm) vs. wavelength (by step of 150-GHz) for the 200G channel after 600-km (left) and for the 400G channel after 200-km (right) with the proprietary transponder in the serial configuration.

It appears that the FEC limit (BER~2x10^{-2}) at ~1550-nm is reached after only 300-km at 400G with a received OSNR~22-dB. Switching to 200G greatly relaxes the transmission constraints and allows achieving 1200-km with a received OSNR~13.5-dB. In Fig. 4, we measure the performance of 200G/400G channels for the proprietary transponder when wavelengths are varied from 1535.8 to 1557-nm by step of 150-GHz. BERs and OSNRs are plotted as a function of wavelengths. It appears that the distance has to be reduced to 600-km at 200G and 200-km at 400G to have an error-free behavior for all the bandwidth. In particular, the lowest wavelengths show an OSNR worse of 5-dB at 200G and 3.5-dB at 400G compared to the highest wavelengths.

Experiment & Results in Parallel Configuration

In this second experiment, the WDM multiplex generated by the transmitter shown in Fig. 2a) is split in twelve parallel data flows by a coupler and launched into 100-km ITU-T G.652 fiber spans. At the line outputs, signals are amplified by the double-stage amplifiers presented in the previous section (that integrates the 12c-EYDF amplifier as a booster). At the receiver side, an optical switch connects alternatively each of the twelve spans to the 400G receivers to measure the BER performance at ~1550-nm (see Fig. 5).

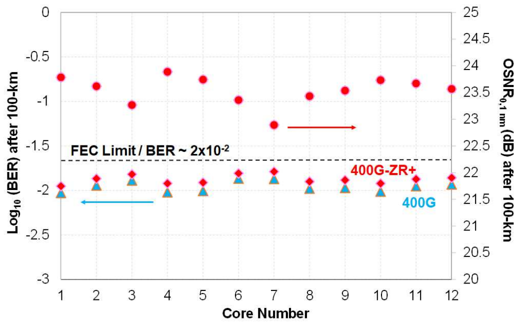

Fig.5: BER & OSNR (in 0.1-nm) vs. core number at 1550-nm for the 400G interfaces under test in the parallel configuration.

It appears that the twelve cores present an homogeneous performance well below the FEC limit with a received OSNR in the [23-24]-dB range. This experiment shows the interest to combine 400G-ZR+ transceivers with MCF amplifiers for such a DCI use case.

Insertion of the MCF amplifier in a ROADM

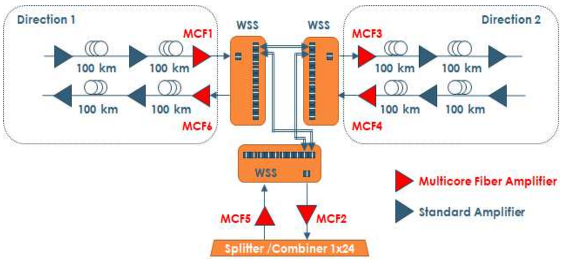

Fig.6: Architecture of a ROADM integrating the MCF amplifier.

Fig. 6 presents the typical architecture of a degree-2 ROADM with the MCF amplifiers. The 100-GHz ROADM is inserted in the middle of a 4x100-km G.652 fiber line. The in-line amplifiers are standard SC-EDFAs with 20-dB gain and 4.5-dB noise figure. Fig. 7 below presents the BER vs. OSNR curves of the proprietary 400G transponder channel in the pass-through, add and drop configurations. The transmission and ROADM penalties do not exceed ~2-dB compared to back-to-back, what is perfectly in line with performance of commercial ROADMs.

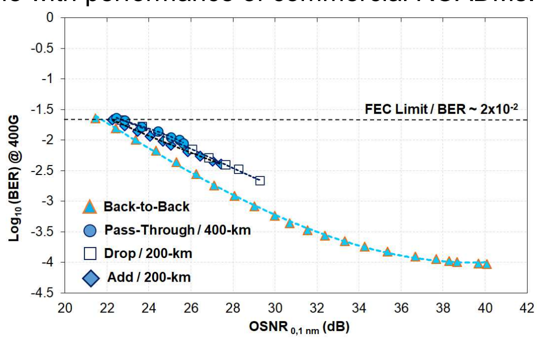

Fig.7: BER vs. OSNR (in 0.1-nm) for the proprietary 400G transponder in the pass-through, add and drop configurations.

Conclusions

We showed here the large application range of a 21-dBm/core 12c-EYDF amplifier for 200G/400G LH, metro/regional and DCI transport networks with ROADM. Even if its bandwidth is reduced compared to a standard EDFA, the 12c-EYDF amplifier presents a total power consumption of ~11 Watts (i.e. ~4-fold less than twelve standard EDFAs). Further developments should allow having two amplification stages based on MCF and a GFF directly printed inside the MCF.

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