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Spectrally Wide and High-Power Er-Yb fiber Amplifier for 40 Gb/s Telecommunications Applications

Raja Ahmad, Martin Rochette, and Stephane Chatigny*
Department of Electrical and Computer Engineering, McGill University, Montreal, QC H3A 2A7, Canada.
**Coractive High-Tech inc., 2700 Jean-Perrin suite 121, QC G2C 1S9, Canada.*
martin.rochette@mcgill.ca

Abstract: A multimode Erbium-Ytterbium doped fiber can be advantageously used for DWDM channel amplification over an extended spectral band with respect to conventional designs. Bit error ratio at 40 Gb/s, gain and noise figure are provided.

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Optical amplifiers aimed for dense wavelength division multiplexed (DWDM) system require high power throughput to support the large number of channels spread throughout the conventional 1530 nm to 1565 nm (C) band. In particular, the use of amplifiers with an output in excess of 30 dBm are economically justified in sub-Mm fiber links where the amplifier spacing can be advantageously increased to reduce the total number of required amplifiers. Conventional Erbium-doped fiber amplifiers (EDFAs) are of limited use for this purpose due to their design complexity that increases abruptly as they reach the maximum output power of a few hundred mW even with double clad fiber [1]. In contrast, basic designs of Yb-codoped EDFAs (EYDFAs) can provide significantly higher output powers than EDFAs. This results from the relatively high solubility and absorption coefficient of Yb ions followed by an efficient energy transfer to Er ions via cross-relaxation in the gain medium [2]. One of the limitations of the high-power EYDFAs is their gain bandwidth that spreads in the 1545-1565 nm band [3,4] and that thus leave the available 1530-1545 nm band with insufficient gain. A straightforward way to increase the gain in the 1530-1545 nm band is to increase the population inversion of Er ions throughout the Er/Yb doped fiber (EYDF) [5]. For a constant multimode pump power, increasing the population inversion can be achieved by increasing the cross-sectional area of the EYDF core [6].

In this paper, we present an EYDFA which provides a high output power of 30.2 dBm and an extended gain spectrum covering the 1535-1560 nm band and report the first bit error ratio (BER) performance measurement of an EYDFA in a WDM context. The wide gain bandwidth of the EYDF is based on an improved population inversion of the gain medium from a multimode core geometry. We show that although the EYDFA uses a multimode fiber, the amplified eye-diagram has no trace of modal dispersion and the signal degradation is less than 0.4 dB.

Fig. 1a shows the structure of the EYDF. The fiber has a circular core diameter of 10 µm, NA=0.22, V-number=4.46 and an Er/Yb ion concentration ratio of l/10. The numerical aperture allows splicing compatibility with standard G.652 fiber whereas the V-number indicates that the fiber is slightly multimode with four guided LP modes (LP_{01}, LP_{02}, LP_{11}, LP_{21}). Making the EYDF multimode is beneficial to increase the population inversion through a 244 % increased pump absorption with respect to a single mode fiber (with V-number=2.40). The fiber also has a double-cladding geometry with NA=0.46 compatible with standard multimode pumps and confines the propagation of pump light in an inner octagonal of 125 µm diameter. Since the fundamental mode of the EYDF matches closely the mode of a G.652 fiber, patchcords of G.652 fiber were spliced directly at the input and output of the EYDF using standard splicing procedures.

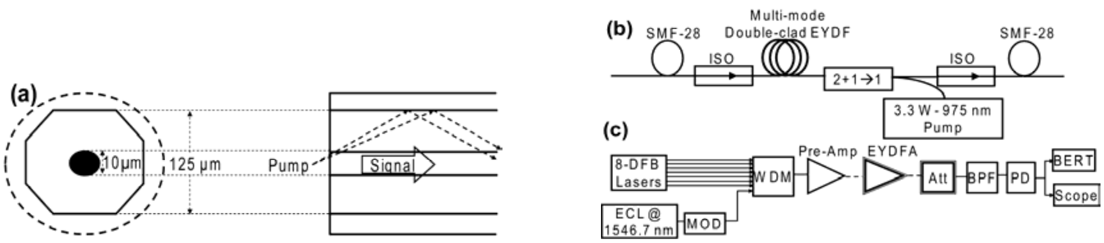

Fig. 1. Schematics of (a) the EYDF, (b) the EYDFA, and (c) the bit error ratio measurement setup. Mod: modulator, WDM: wavelength division multiplexer, BPF: bandpass filter@1546.7 nm, Att: variable attenuator, PD: Photodiode, BERT: BER tester.

Although the multimode EYDF supports four guided modes, simulations predict that only the LP_{01} mode will significantly benefit of the available EYDF gain. This is achieved through two processes of higher order mode stripping. The first process is the mode coupling from the G.652 fiber to the EYDF fiber and back to the G.652 fiber. Most of the power from the G.652 fiber is coupled in the fundamental mode of the EYDF and back since they have

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identical mode profiles. The second process of higher order mode stripping comes from the high confinement of the fundamental EYDF mode into the gain medium of the EYDF. Calculating the overlap integral and confinement factor of each available mode in the EYDF, we find that the fundamental LP_{01} mode experiences at least 60.5 dB more gain than the next most powerful mode (LP_{02}). As a result, the multimode geometry of the EYDF leads to the benefit of extended gain spectrum without significant modal dispersion.

Fig. 1b shows a schematic structure of the EYDFA. The pump light from only one multimode 3.3 W broad-area laser at 976 nm is coupled in counter-propagation in 2.15 m of EYDF via a commercially available 2+1→1 multimode pump/single mode signal combiner. Fig. 1c shows the setup used to characterize the EYDFA. A WDM signal consisting of 8 channels spreading throughout the C-band was used to measure the gain and noise-figure of the EYDFA. The WDM signal was spectrally equalized at the output of a pre-amplifier and totalizes 15.9 dBm. The pre-amplifier stage saturates the EYDFA and ensures a low noise-figure (NF) of the signal for the pre-amplifier + EYDFA stage. A probe laser with a power level of -10.2 dBm was also used to measure gain and NF at intermediate wavelengths between the saturating tones. A BER measurement was performed at 40 Gb/s with the 1546.7 nm channel to measure signal degradation caused by the high power EYDFA in the communication link. The probe channel was modulated with a return to zero (RZ) format with 50 % duty cycle, following a pseudo random binary sequence of length 2^{15}-1.

Fig. 2 shows the gain and NF of the EYDFA. The natural gain spectrum spreads from 1535.0 nm to 1565.8 nm with a peak value of 18.4 dB and with a 4.9 dB gain variation. The gain could be flattened even further by using an appropriate filter in the mid-stage of the dual-stage amplifier [7]. The total output power is 30.2 dBm after amplification and could be increased by increasing the pump power. The NF of the EYDFA varies between 4.1 dB and 9.7 dB over the same wavelength band. The most important noise contribution in the EYDF is assumed to arise from the amplified spontaneous emission filling the available modes of the EYDF and partially coupled to the output fiber. The use of a low-noise preamplifier and a high-power amplifier in tandem is greatly beneficial in reducing the overall NF of the amplifying system since the NF of the preamplifier dominates in such a system [8]. We also measured the gain and NF of the dual stage amplifier consisting of a pre-amplifier and the EYDFA. The NF was then reduced to 4.9 dB, with a variation of less than 0.5 dB over the spectral range of interest.

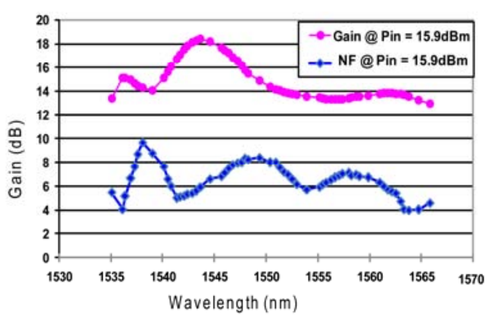

Fig. 2. Gain and Noise Figure (NF) of the EYDFA alone with input power to EYDFA (P_{in}) =15.9dBm

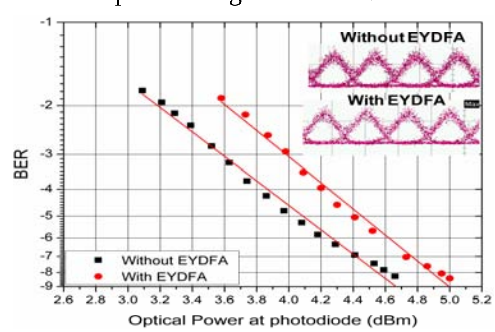

Fig. 3. Bit error ratio and eye diagrams (inset) at 40 Gb/s with and without the EYDFA in the communication link.

Fig. 3 shows the BER curves of the 1546.7 nm channel with and without the EYDFA. The result shows a signal power penalty of 0.4 dB imposed by the EYDFA. The eye diagram in Fig. 3 (inset) shows no sign of pulse broadening and signal degradation, as predicted by the simulations.

To conclude, a high power multimode Er-Yb co-doped fiber amplifier enables the amplification of WDM signals over an extended wavelength span from 1535.0 nm to 1565.8 nm, with an output power of more than 30.2 dBm. This multimode EYDFA provides a negligible amount of power penalty (<0.4 dB) on the BER of 40 Gb/s WDM signals. To the best of our knowledge, this is the first report of WDM BER measurement with an EYDFA. The resulting amplifier configuration simultaneously enables an extended gain bandwidth compatible with high data rate communication, high-power and low cost.

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