Performance of Few-mode EDFAs in Optical Space-Division Multiplexed Communication Systems

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Abstract: We report a novel tailored ring-doped few-mode erbium doped fiber amplifier with mode-selective bidirectional pumping. We successfully demonstrate up to 10-spatial modes with zero differential modal gain, and a BER below 10^{-10} at 100 Gb/s.
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1. Introduction

The design of energy efficient optical amplifiers for space-division multiplexed (SDM) long haul systems is very crucial. Calculations indicate that SDM amplifiers offer power savings compared to the use of multiple parallel single-mode fiber (SMF) systems. In that regard, few-mode fiber (FMF) appears to be more energy efficient than multi-core fiber (MCF)-based systems [1]. It is however well known that the high order modes (HOMs) generally experience higher propagation, bending and coupling losses and thus require higher gain for transmission over multiple fiber spans [2]. Mode selective pumping was proposed to offer higher gains for the HOMs in a few-mode erbium doped fiber (FM-EDFA) supporting two mode groups [3], however in this implementation the differential modal gain (DMG) could not be accurately controlled over the full C-band with a gain flatness of better than 5 dB and changes by as much as 2.5 dB depending on the pump power and operating wavelength. Recently a FM-EDFA supporting 5-spatial modes with adjustable DMG was achieved using a mode-selective bidirectional pumping scheme and an erbium-doped fiber (EDF) with a tailored Er-doping profile [4]. A signal gain of >20 dB was obtained for all the guided modes (LP_{01}, LP_{11}, and LP_{21}) with low DMG and a gain flatness of <2.5 dB across the C-band. The same authors extended their work by adding LP_{02} signal mode; a signal gain of >20 dB was reported for all the guided modes with a differential modal gain <2 dB and a gain flatness of <4 dB across the full C-band [5].

In this paper, we design a FM-EDFA supporting up to 10-spatial modes by using a mode-selective bidirectional pumping scheme in conjunction with an EDF with a specially tailored Er-doping profile to achieve high gain while maintaining a low DMG. We also assess the BER performance of an intensity modulation/direct detected (IM/DD) system with the proposed FM-EDFA.

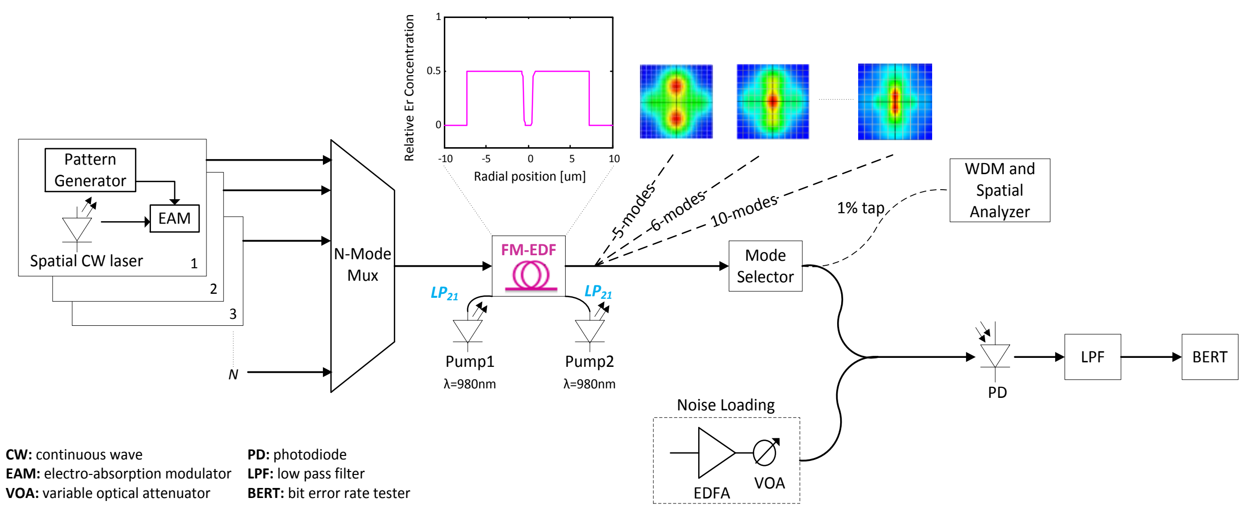

Fig. 1. Simulation setup of few-mode erbium doped fiber amplifier (FM-EDFA) in an intensity modulation/direct detected (IM/DD) system in a back-to-back configuration.

2. System architecture and gain performance of FM-EDFA

Fig. 1 shows a generic SDM system with a FM-EDFA in an IM/DD system in a back-to-back configuration through an Optisystem simulation. A spatial laser source is first used to selectively excite the signal modes in the *N*-mode multiplexer (NM-Mux) (ideal power combiner is used for emulation). To allow simple and effective modal gain measurements, 1550 nm wavelength is chosen for the different modes. The output signal from the multiplexer is then launched into an 8 m long ring-doped EDF, in which the erbium ions are substantially confined within the ring inside the fiber core to help mitigate the DMG as per inset. The EDF was designed with an inner core diameter of 1 μm and a corresponding erbium-doped ring thickness of 6.8 μm and the core refractive index is 1.45. The estimated effective numerical aperture (NA) of the core is ~0.14. A bidirectional pumping configuration is adopted to provide DMG control as in [4,5]. The signal mode output from two 980 nm pump lasers is adjusted to the LP_{21} mode and then coupled into the two ends of the FM-EDF. A mode selector is used after the FM-EDF to select the signal mode under test. A WDM and spatial analyzers are used after the mode selector to display the output signal mode and determine the output signal power, and hence the gain of the individual channels.

Erbium doping concentration is chosen to be 1.7×10^{25} m^{-3}, where high modal gain is observed. Diffusion towards the center of the core is to be expected in practical to some degree during the final tube collapse and/or additionally during the fiber drawing process, with the extent dependent on several factors including the composition of the glass host, the detailed nature of the heat treatment during collapse, the duration of the collapse process, and the fiber drawing temperature itself. That undesired diffusion is taken in consideration in our simulation setup, as shown in the Er^{3+} profile in Fig. 1. It may be possible to reduce this lateral dopant diffusion by depositing a thin layer of pure SiO_2 as a diffusion barrier between the inner and outer core regions [6].

We test the gain performance of the FM-EDFA supporting 5-modes with the three lowest spatial mode groups namely (LP_{01}, LP_{11}, and LP_{21}). Based on previous experimental results of a 3-mode EDFA [6,7], we expect that the orthogonal modes of LP_{11} and LP_{21} mode groups will behave similarly. Fig. 2a shows the mode dependent gain as a function of pump power at an input signal of -10 dBm per mode for the proposed 5M-EDFA. No mode dependent gain (zero DMG) is observed for different pump power. The measured gain for 5M-EDFA is 23.3 dB for all signal modes at total pump power of 25.3 dBm, the gain increases to 25.28 dB for all signal modes at 26 dBm of total pump power.

Fig. 2b plots the signal gain as a function of input signal power per spatial mode for a fixed launched pump power of 25.3 dBm. All guided modes experienced gain reduction with an increase in input signal powers. It's shown also in Fig. 2b, an evidence of clean amplification of the input signals. Fig. 2c plots the measured gain across the C-band for an input signal power of -10 dBm per mode and pump power of 25.3 dBm. The amplifier provides >20 dB gain for all 5-spatial modes with zero DMG and a gain flatness of <3.7 dB across the full C-band.

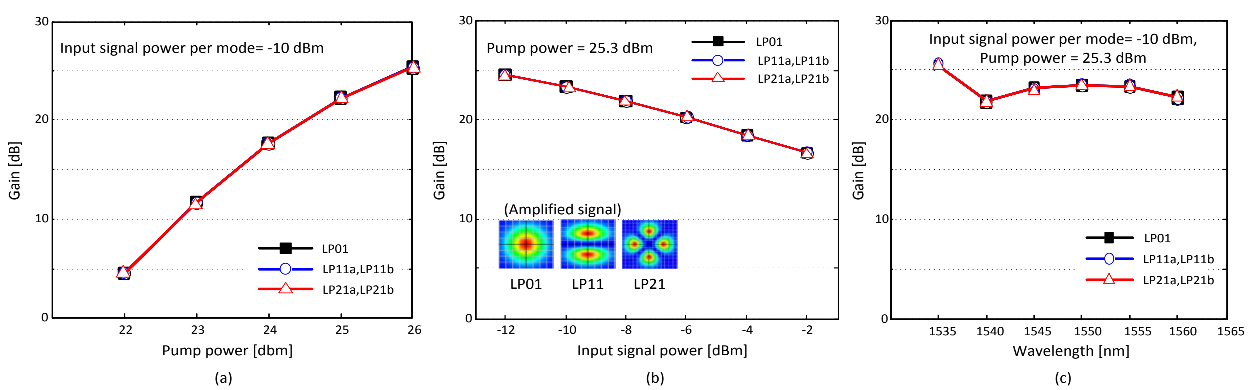

Fig. 2. (a) Mode dependent gain for 5M-EDFA as a function of pump power using bidirectional LP_{21} pumping configuration, (b) modal gain as a function of input signal power per mode and (c) gain spectra across the entire C-band without a gain flattening filter.

3. BER performance of the proposed IM/DD system with a FM-EDFA

In this section, we report the BER performance of the proposed system shown in Fig. 1 for the guided spatial signal modes. To evaluate the BER performance, pseudo random binary sequence (PRBS) (2^{23}-1 length) non-return to zero (NRZ) signal from a pattern generator is applied with 1550 nm signal mode (10 Gb/s bit rate) to an electro-absorption modulator (EAM) and that's done for all modes separately. The modes are then coupled through an NM-Mux and inserted into the designed FM-EDF. A mode selector is used after the FM-EDF to select the mode under test, and a conventional EDFA followed by a variable attenuator is used at the received side to control the added noise to be able to measure the BER at different optical signal to noise ratio (OSNR) levels. The selected signal mode is then passed to a photodiode (PD) followed by a 7.5 GHz low pass filter (LPF). A bit error rate tester (BERT) is then used to calculate the BER for each mode signal separately.

We test the BER performance of the system with a FM-EDFA for the different number of modes up to 10-spatial modes at -10 dBm of input signal power per spatial mode, and a total pump power of 25.3 dBm. Fig. 3a shows the BER as a function of the OSNR for the 5-modes (LP_{01}, $LP_{11a,b}$, and $LP_{21a,b}$). As shown, BER below 10^{-10} is observed for all the tested modes at an OSNR of 19 dB. The same is observed for the case of 10-modes (100 Gb/s bit rate) as in Fig. 3b. It can be noticed that all channels behave similarly, which confirms the zero DMG in Fig. 2a. The BER for LP_{01} signal mode is calculated for different number of modes up to 10-spatial modes at different OSNR. The calculated BER is below 10^{-10} for the different number of modes at an OSNR of 19 dB as shown in Fig. 3c.

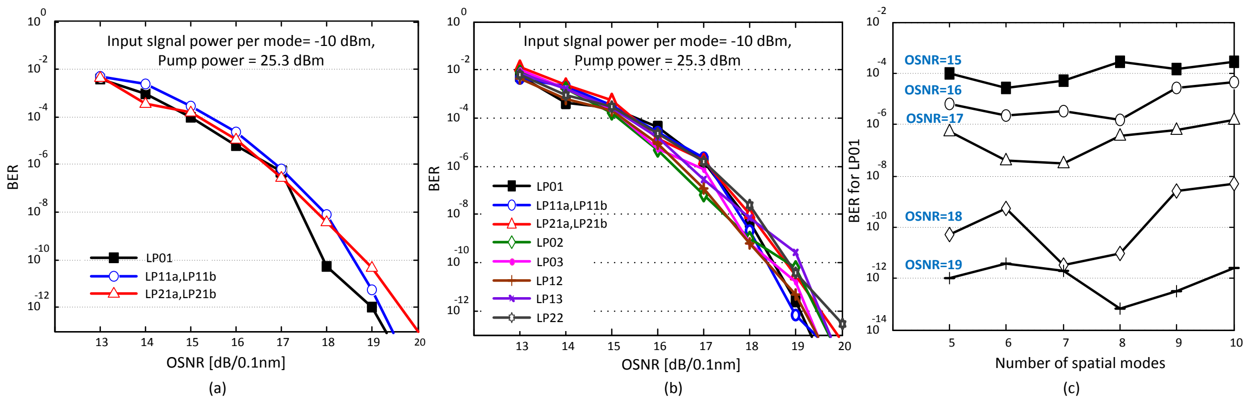

Fig. 3. BER as a function of OSNR for: (a) 5-modes in a 5M-EDFA and (b) 10-modes in a 10M-EDFA. (c) BER for LP_{01} mode versus number of spatial modes at different OSNR.

4. Conclusion

We evaluated an SDM system performance with a FM-EDFA in a back-to-back and IM/DD configuration. 5M-EDFA has been reported with zero DMG controlled over the full C-band, signal gain of >20 dB for all modes, good gain flatness of <3.7 dB, and with excellent BER performance for all the tested modes. That was achieved by using bidirectional LP_{21} pumping scheme and an Er-doped fiber with a tailored designed ring-doped profile. 10M-EDFA has been reported with a BER below 10^{-10} for all the signal modes at 100 Gb/s. BER below 10^{-10} for LP_{01} signal mode has been calculated for the different number of modes up to 10-spatial modes. We consider this an important step in extending SDM transmission to larger channel numbers to achieve high bit rates and to increase the system capacity.

5. References

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