On the Performance of Few-Mode EDFAs with Bidirectional Pumping

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Abstract: A few mode erbium doped fiber amplifier (FM-EDFA) is designed using 980 nm forward pump and 1480 nm backward pump with unequal pump power, we achieve a high gain with low NF and low BER.

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1. Introduction

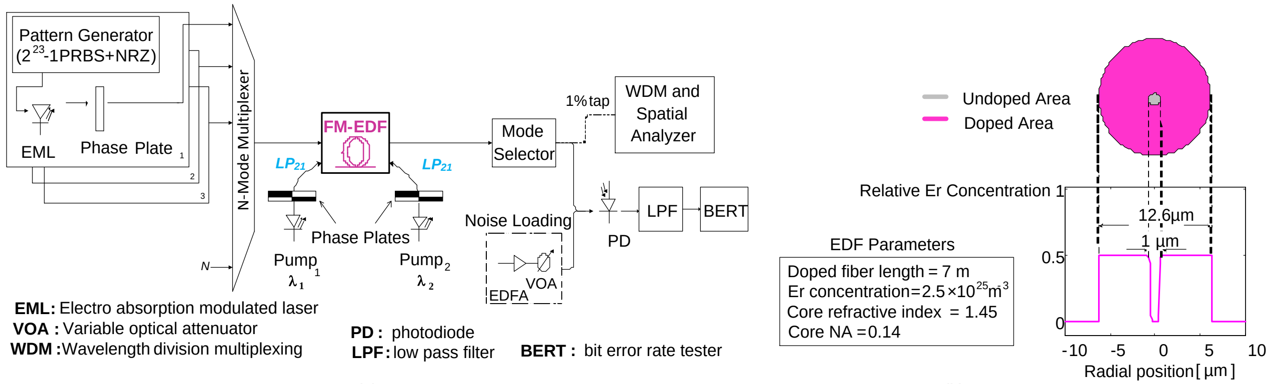
Space-division multiplexing (SDM) has attracted considerable attention in high-capacity fiber-optic communication systems as a radical approach to increase the capacity-per-fiber [1]. Mode-division multiplexing (MDM) is currently under intense investigation as the most efficient technique to overcome the current capacity limitations (100 Tb/s per fiber) of high-speed long-haul transmission systems based on single mode optical fibers [2]. In such systems, each transverse mode can be used as an individual pathway able to carry the total data transmission capacity of a current single mode fiber (SMF). On the other hand, a high performance few-mode fiber amplifier is essential for long-haul systems [2]. One specific requirement that is expected from a few-mode optical amplifier is its ability to provide equal gain and noise figure across the various optical spatial modes. To realize the energy and cost savings offered by MDM systems, the individual guided modes should be simultaneously amplified within a few-mode erbium doped fiber amplifier (FM-EDFA). Recently, bidirectional pumping with equal pump wavelength at 980 nm and equal pump power of 170 mW has been used to obtain a signal gain greater than 20 dB for the guided modes (LP_{01}, LP_{11} and LP_{21}) with zero differential modal gain (DMG) and good gain flatness across the C-band [3]. From the other side, 8 channels wavelength-division multiplexed (WDM) transmission system with a conventional in-line EDFA using both co-propagation (980 nm) and counter propagation (1480 nm) pumping configuration was reported in [4].

In this paper, we examine a few-mode EDFA using unequal pump power with pump wavelengths 980 nm and 1480 nm for forward and backward pumping, respectively. A gain greater than 20 dB is achieved with low noise figure (NF) over the C-band. Moreover, we study the bidirectional pumping FM-EDFA in case of equal pumping wavelength at 980 nm and different pump powers.

2. System Architecture

The generic SDM system with a FM-EDFA over a back-to-back configuration in Fig. 1a illustrates an example of a FM-EDFA supporting 4 mode groups (LP_{01}, LP_{11}, LP21 and LP_{02}). A phase plate is used after the electro absorption modulated laser (EML) to selectively excite the tested mode similar to the procedure explained in [3]. To allow effective modal gain and NF measurements, a wavelength division multiplexing (WDM) signal over C-band is sent over the different spatial modes. A 40 Gb/s 2^{23}-1 pseudo random binary sequence (PRBS) non-return-to-zero (NRZ) signal from a pattern generator is applied to an EML. The output modes from an ideal mode multiplexer are then launched to a ring-doped erbium doped fiber (EDF), in which the erbium ions are substantially confined within the ring inside the fiber core to help mitigate the DMG as shown in Fig. 1b [5]. The EDF is designed with an inner core diameter of 1 µm and the rest of EDF parameters are listed in the same figure. The FM-EDF is bidirectionally pumped using both co-propagation (980 nm) and counter propagation (980 nm or 1480 nm) and is adjusted to the LP_{21} mode by using LP_{21} phase plates and then is coupled into the two ends of the FM-EDF.

At the receiver side, a mode selector is used to select the mode under test. WDM and spatial analyzers are used to display the output signal mode and determine the output signal and noise power, and hence the gain and NF of individual channels. A conventional EDFA followed by a variable attenuator is added at the receiver to control the optical signal-to-noise ratio (OSNR) for the BER calculations [3], [5]. Finally, the selected signal mode is then passed to a photodiode (PD) followed by a 30 GHz Gaussian low pass filter (LPF) to remove out the band noise. A bit error rate tester (BERT) then estimates the BER for each signal separately. Erbium doping concentration is chosen to be obtained 2.5×10^{25} m^{-3}, where a high modal gain and accepted NF are obtained. It may be possible to reduce that lateral dopant diffusion by depositing a thin layer of pure silicon dioxide (SiO_2) as a diffusion barrier between the inner and outer regions [6].

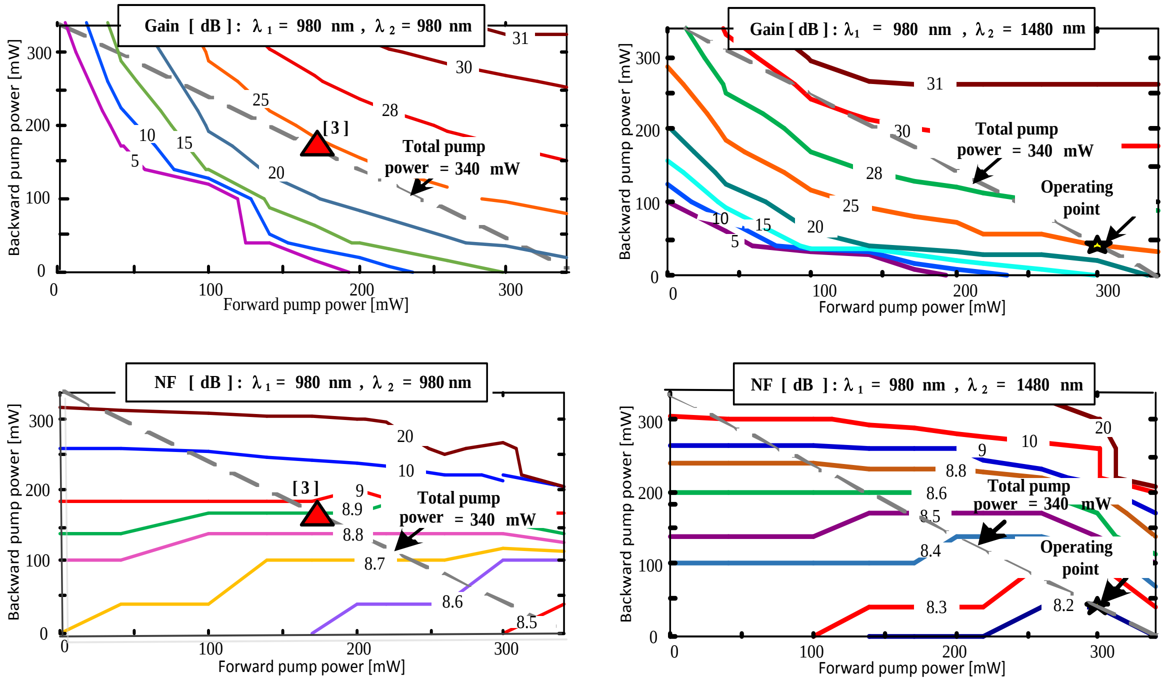


(a) (b)

Fig. 1. (a) Architecture of SDM system with the proposed FM-EDFA and (b) Erbium (Er) profile inside the fiber core and EDF parameters.

3. Performance of the Proposed FM-EDFA

We test the gain, NF and BER performance of the FM-EDFA supporting 4 mode groups (LP_{01}, LP_{11}, and $LP_{21}$and LP_{02}). A 1550 nm signal is chosen for the different modes with input signal power of -10 dBm per mode. Figure 2a shows contour plots of the 6M-EDFA gain (top) and average NF (bottom) as a function of both forward and backward pumping power with equal wavelength at 980 nm and different pump powers. As shown, the equal pump power proves the achieved gain (> 20 dB) in [3] and reports an average NF of ~8.9 dB.



(a) (b)

Fig. 2. (a) Gain [dB] (top) and average NF, dB, (bottom) contours as a function of forward and backward pump powers for conventional pumping with 980 nm forward and backward pumps, (b) Gain, dB, (top) and average NF, dB, (bottom) contours as a function of forward and backward pump powers with 980 nm forward pump and 1480 nm backward pump.

Figure 2b plots the contours of the 6M- EDFA gain (top) and average NF (bottom) using 980 nm forward pump and 1480 nm backward pump where the DMG is equal to zero at all points. A higher gain can be achieved compared to conventional pumping in [3]. The NF is also reduced to 8.2 dB at the operating point chosen of 300 mW forward and 40 mW backward pump power with the same total pump power used in [3].

Figure 3a shows gain (top) across the full C-band at a total pump power of 340 mW. The gain is found to be ≥ 22 dB for all the tested modes with zero DMG and a gain flatness of 4 dB. The estimated NF is ~8.5 dB for the wavelengths longer than 1537 nm with a standard deviation of ±0.13 dB at 1550 nm as shown in Fig. 3a (bottom). Figure 3b plots the BER versus OSNR for the 6 modes. A BER below 10^{-10} is observed for all the tested modes at an OSNR of ~25 dB as shown. It can be noticed that all channels behave similarly which confirms the zero DMG in Fig 3b. The eye diagrams are shown in Fig 3b for all the tested modes.

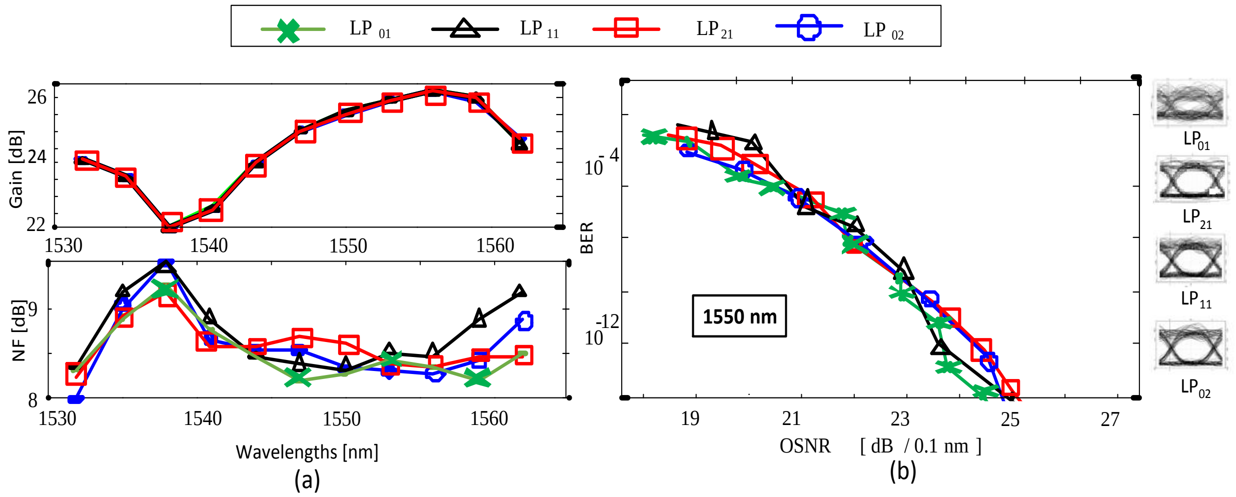


Fig. 3. (a) Gain [dB] (top) and average NF [dB] (bottom) across the C-band for 6M-EDFA (b) BER as a function of OSNR for the 6 modes with 980 nm forward pump and 1480 nm backward pump using 40 Gb/s per mode.

4. Conclusion

The gain and NF characteristics of a 6M-EDFA have been studied in an SDM system for different pumping wavelengths and power levels in the C-band. A gain ≥ 22 dB with zero DMG and NF of ~8.5 dB are achieved across the C-band for all the tested modes using different pumping wavelengths and unequal pump power.

The bit error rate performance of the system is tested with the proposed 6M-EDFA over a back-to-back configuration and a value below 10^{-10} is reported for all modes at OSNR of ~25 dB.

5. References

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