Optimized Cladding-Pumped Few-Mode EDFAs for Space-Division Multiplexed Systems

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Abstract: We report an optimized cladding-pumped 10-modes EDFA with more than 20 dB gain, zero differential modal gain, ~4.5 dB noise figure over the C-band and below 10^{-10} BER for up to 15-spatial modes.
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1. Introduction

Mode-division multiplexing (MDM) transmission over few-mode fibers (FMFs) is a promising space-division multiplexing (SDM) candidate to overcome the capacity limitation of existing single-mode fiber [1]. The design of energy efficient few-mode erbium doped fiber amplifiers (FM-EDFAs) for MDM long-haul systems is very crucial [2]. FM-EDFAs amplifying up to 4 mode groups has been already demonstrated using a core-pumped scheme [3]. Recently, we have reported a core-pumped FM-EDFA supporting up to 10-spatial modes with zero differential modal gain (DMG) and bit error rate (BER) below 10^{-10} at 10 Gb/s bit rate per mode by using an optimized erbium ring-doped profile [4]. However, increasing the number of modes beyond 10-modes requires high pump power. Multiplexing several single-mode pumps to generate a sufficient pump power is also an expensive way of pumping such amplifiers, even if it is technically possible [5]. High power (up to 10 W), low cost multimode pump diodes to be used with cladding pumping is the solution. In that regard, cladding-pumped 6-modes EDFA achieving a modal gain of > 20 dB, DMG of ~3 dB and 6-7 dB noise figure (NF) has been experimentally demonstrated [5]. We have recently validated the results in [5] via simulations, and reported a cladding-pumped 10-modes EDFA with modal gain of more than 20 dB, zero DMG and noise figure of ~9 dB [6].

In this paper, we report an enhanced cladding-pumped 10-modes EDFA by optimizing the core-to-clad area ratio which improved the gain and NF. Moreover, we test the BER performance of the SDM system with the proposed FM-EDFA at 40 Gb/s bit rate per mode.

2. SDM System with the Proposed Cladding-Pumped FM-EDFA

Fig. 1 shows a generic intensity modulation with direct detection (IM/DD) SDM system with the proposed cladding-pumped FM-EDFA over a back-to-back configuration. Transceivers similar to [6] are used in this study. An ideal *N*-mode multiplexer (NM-Mux) emulated using a power combiner is used at the transmitter side. The output signal modes from the NM-Mux are then launched to a double clad few-mode erbium doped fiber (FM-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 double clad fiber is designed with the parameters listed in Fig. 1. The erbium doped fiber (EDF) is pumped with a 980 nm counter-directional multimode pump as in [5].

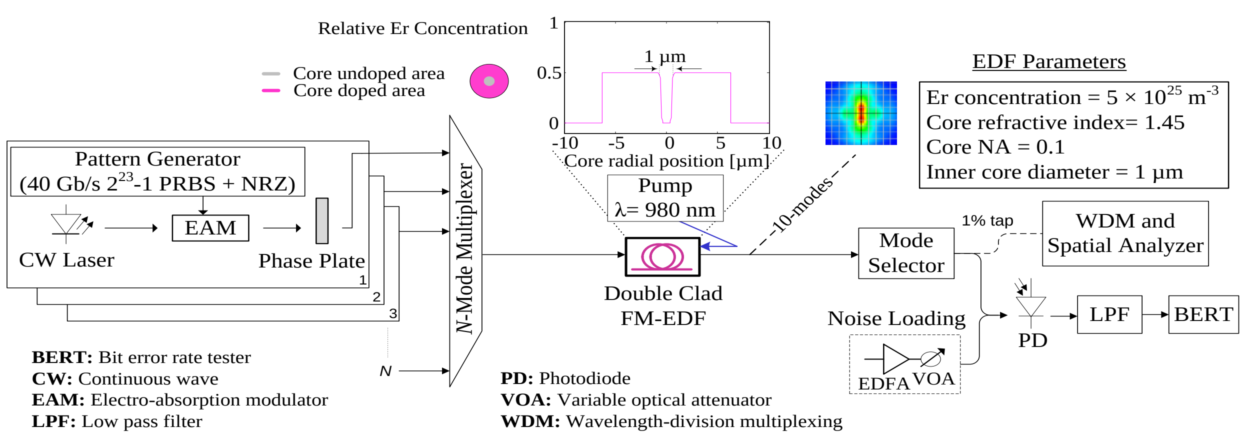

Fig. 1. SDM system architecture with the proposed cladding-pumped FM-EDFA over a back-to-back configuration.

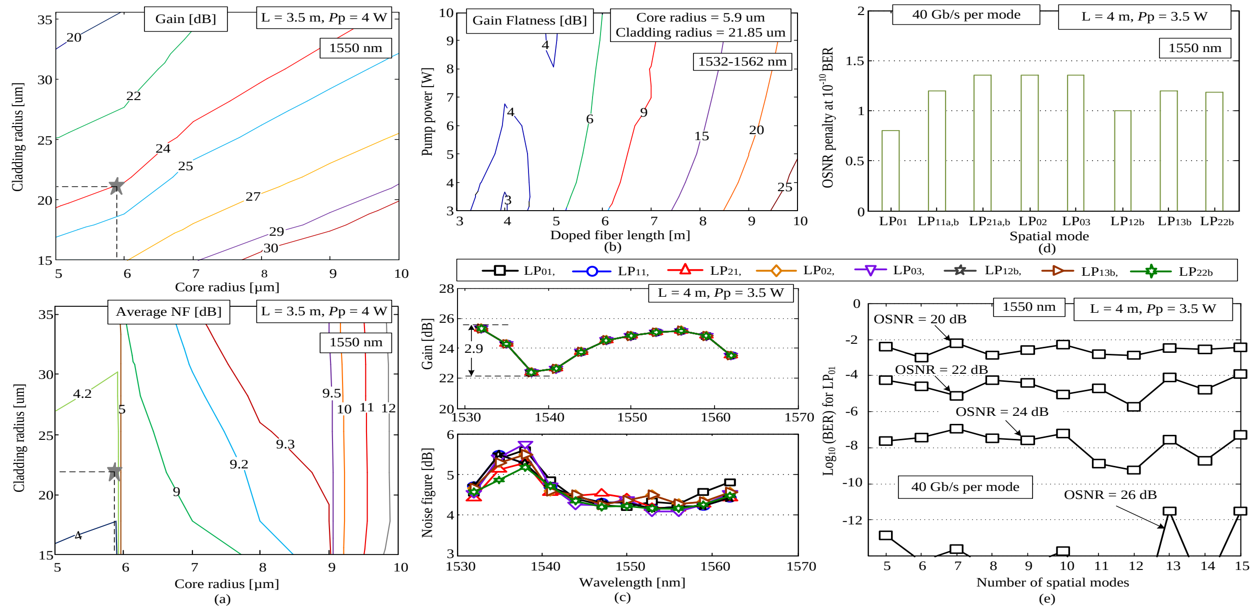

Fig. 2. (a) Gain (top) and average NF (bottom) contours versus the core and cladding radii, (b) Gain flatness of the 10M-EDFA as a function of EDF length and pump power (*P*p), (c) Gain and NF for the 10-modes across the entire C-band, (d) OSNR penalty at 10^{-10} BER for the different spatial modes, and (e) BER for LP_{01} versus number of spatial modes at different OSNR levels. The input signal power per mode is -7.5 dBm.

3. Performance of the Proposed FM-EDFA

We test the gain, NF and BER performance of the FM-EDFA supporting 10-spatial modes with the 8-spatial mode groups (LP_{01}, LP_{11}, LP_{21}, LP_{02}, LP_{03}, LP_{12b}, LP_{13b}, and LP_{22b}). A 1550 nm signal is chosen for the different modes and with input signal power of -7.5 dBm per mode. Fig. 2a shows contour plots of the 10M-EDFA gain (top) and average NF (bottom) as a function of core and cladding radii of a 3.5 m double clad fiber length at pump power of 4 W (DMG is equal to zero at all points). For the core radius ≤ 5.9 µm; signal gain of > 25 dB and < 4 dB NF is observed at small cladding radius. However, the gain decreases with a bit increase in NF at large cladding radius for the reason that the pump power becomes insufficient when the cladding radius increases.

A point of 24 dB gain and ~4.1 NF at core and cladding radii of 5.9 µm and 21.85 µm respectively is chosen from Fig. 2a to study the gain flatness of the 10M-EDFA under WDM configuration across the C-band for the different EDF length and pump power as shown in Fig. 2b. A gain flatness of < 3 dB is observed at EDF length of 4 m and pump power of 3.5 W. Then, the gain and NF performance of the 10M-EDFA is evaluated across the C-band as shown in Fig. 2c. A gain of > 20 dB with zero DMG and NF of ~4.5 dB is reported across the C-band.

We also evaluate the BER performance of the system for the different number of modes and up to 15 modes at the optimized EDF length of 4 m and pump power of 3.5 W. Fig. 2d shows the OSNR penalty at BER of 10^{-10} for the different spatial modes in 10M-EDFA compared to a conventional EDFA with 20 dB gain and 4 dB NF. As shown, the OSNR penalty is ~1 dB for all modes which verifies that all channels behave similarly and confirms the zero DMG and same NF in Fig. 2c. Furthermore, the BER for LP_{01} mode is calculated for different number of modes up to 15-spatial modes at different OSNR levels. The BER is below 10^{-10} for the different number of modes at an OSNR of 26 dB as shown in Fig. 2e.

4. Conclusions

We reported an enhanced performance of cladding-pumped 10-modes EDFA by optimizing the core-to-clad area ratio. A signal gain of > 20 dB, zero DMG and NF of ~4.5 dB has been achieved. Moreover, OSNR penalty of ~1 dB has been reported at the BER of 10^{-10} compared to a conventional EDFA. BER below 10^{-10} for LP_{01} signal mode was also demonstrated for the different number of modes up to 15-spatial modes (600 Gb/s aggregate bit rate).

References

[1] D. J. Richardson, et al., "Space-division multiplexing in optical fibers," *Nat. Photonics*, vol. 7, no. 5, pp. 354-362, (2013).
[2] P. Genevaux, et al., "Amplification of 5 modes carrying each 100 Gb/s with a few-mode EDFA," in *Proc. OFC*, paper Tu3C.5 (2015).
[3] Y. Jung, et al., "Reconfigurable modal gain control…," *IEEE Photon. Technol. Lett.*, vol. 26, no. 11, pp. 1100–1103 (2014).
[4] H. A. Youssef, et al., "Performance of few-mode EDFAs…," in *Proc. ACP*, paper ATh3A.81, (2014).
[5] Y. Jung, et al., "Cladding pumped few-mode EDFA…,'' *Opt. Express*, vol. 22, no. 23, pp. 29008-29013, (2014).
[6] H. A. Youssef, et al., "Performance of cladding-pumped few-mode EDFAs…," in *proc. IPC*, paper WG2.2, (2015).