Modal Gain Equalization of Few-mode Erbium-doped Fiber Amplifiers Enabled by Mirrored Mode Exchanges

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Abstract: We propose a six-mode erbium-doped fiber amplifier with significantly reduced differential modal gain (DMG) by mirrored exchanging of the spatial modes for the first time. A DMG of <1.8 dB across the whole C-band is experimentally achieved. © 2023 The Author(s)

1. Introduction

Space-division multiplexing (SDM), utilizing multiple spatial channels in few-mode and multi-core fibers, has been widely studied as an effective approach to overcome the capacity limitations of high-speed long-haul transmission systems based on single-mode fibers [1, 2]. To simplify system configuration and reduce energy consumption, few-mode EDFAs (FM-EDFAs) and multi-core EDFAs to simultaneously amplify all spatial modes are highly desired [3, 4], sometimes assisted by fiber-based optical parametric amplification and distributed Raman amplification in few-mode fibers [5, 6]. The DMG of FM-EDFAs depends on the spatial overlaps between mode profiles and erbium-doping profile, which directly affects the system outage probability. Thus, minimizing the DMG is essential for robust mode-division multiplexing (MDM) systems. Three main strategies have been proposed to minimize the DMG: i) tailoring the erbium-dopant distribution of the FM-EDF [7], ii) controlling the mode content of the pump [8] and iii) forming a ring-core index prolife for the FM-EDF [9]. However, as the number of modes increases, FM-EDFAs using above optimization strategies would suffer from the complexity of design and fabrication.

Another way to reduce the DMG of FM-EDFAs can be realized by intentionally introducing mode coupling in FM-EDFs. A DMG of ~4 dB was achieved by inserting a mode scrambler into a FM-EDFA [10], which is not low enough. Besides, a DMG of 0.5 dB was also show in simulations by introducing strong mode coupling into a FM-EDFA [11]. This scheme is realized with hundreds of coupling events, increasing the complexity. Thus, a FM-EDFA with a low DMG realized by one single device introducing sufficient mode exchanges is highly desired. Stemming from the mode flipping concept recently proposed for reach extension in MDM transmission systems [12], its application to a FM-EDFA is worthy to be explored.

In this paper, we demonstrate significantly reduced DMG in a FM-EDFA with six modes (LP_{01}, $LP_{11a/b}$, $LP_{21a/b}$, LP_{02}) by inserting a pair of mode Mux and deMux devices in the middle of the two-stage FM-EDFs. Here, the FM-EDF in use shows anti-symmetrically distributed modal gains. The equalized gains are realized by efficiently exchanging all modes once inside the amplifier, with DMGs as low as 0.6 dB in design and 1.8 dB in experiment across the full C-band, respectively. To the best of our knowledge, a DMG of <1.8 dB for six-mode EDFAs (6M-EDFAs) represents the lowest DMG, when six modes at multiple wavelengths are simultaneously launched. Moreover, it is noted that the DMG of our FM-EDF is 6 dB due to fabrication imperfections, which confirms the effectiveness of mode exchanging in gain equalization.

2. Design of the proposed FM-EDFA

The gain distribution and mode exchanging strategy for the proposed two-stage FM-EDF are shown in Fig. 1(a). The 1st and 2nd EDFs are designed to have anti-symmetrically distributed modal gains. In this way the sum of modal gains of the highest and lowest order modes is equal to that of the second highest and second lowest order modes, i.e., $Gain_{01}+Gain_{02} = Gain_{11a(b)}+Gain_{21b(a)}$. In the middle of the two-stage amplifier, multi-plane light conversion (MPLC) devices are used to exchange modes. The LP_{02} mode exchanges with LP_{01} mode, and $LP_{11a/b}$ modes exchange with $LP_{21b/a}$ modes. Although the above relation could not be fully satisfied, signals loaded on different spatial modes could experience almost equalized gains through the proposed two-stage FM-EDF. Figure 1(b) shows the configuration of the two-stage FM-EDFA, which is pumped by two 980-nm LP_{01}-mode pumping lasers. Pump lights are combined with signal lights via two 6-mode wavelength-division multiplexed (6M-WDM) couplers. Six-mode isolators (6M-ISO) are inserted to prevent the backward-travelling amplified spontaneous emission (ASE). The core and cladding radius of the FM-EDF are 8 μm and 62.5 μm, respectively. Besides, the numerical aperture of the EDF is 0.15 and erbium-doped region is tailored into two layers. The outer radius of the inner layer and the inner radius of the outer layer are 2.9 μm and 3.4 μm, respectively. The erbium doping concentration of the two layers are 2.9×10^{24} ion/m^3 and 3.4×10^{24} ion/m^3.

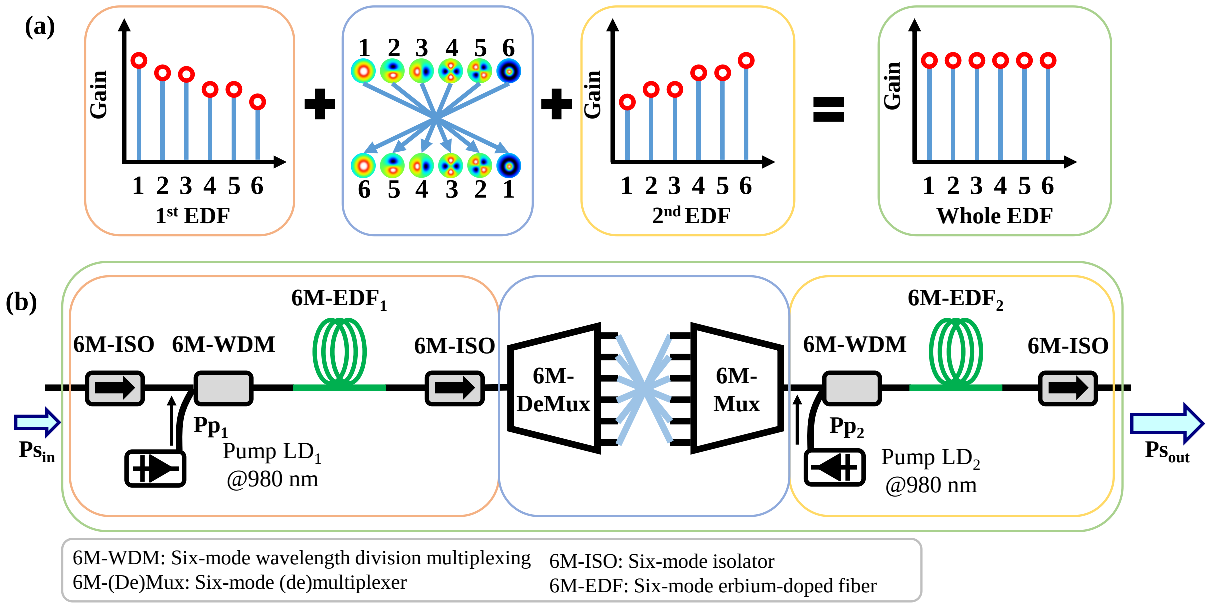

Fig. 1. (a) The EDFs with anti-symmetrically distributed modal gains are used, and mode exchanging enables greatly reduced DMG. (b) The configuration of the proposed two-stage 6M-EDFA, in which a pair of MPLCs is used for mode exchanging.

To realize a wideband low DMG for the proposed FM-EDFA, fiber lengths of the two FM-EDFs and two pump powers are swept. Considering gain competition in the wavelength dimension, nine different wavelength signals with 5-nm interval are simultaneously input to the FM-EDFA. The total input power is -10 dBm/mode. The optimized fiber lengths of two pieces of FM-EDF are 3.8 m and 3.9 m and the pump powers are 500 mW and 600 mW. Figure 2(a) shows the modal gains at 1530 nm along the fiber with/without mode exchanges, considered an insertion loss for each mode of 6 dB induced by MPLC devices. The modal gains are almost anti-symmetrically distributed after the first FM-EDFA and a DMG reduction by >10 dB is realized by mode exchanges. Besides, the FM-EDFA with mode exchanges has a sufficiently low DMG of <0.6 dB across the C-band as illustrated in Fig. 2(b). Figure 2(c) shows the modal gains and DMG at 1550 nm versus different input signal powers. The FM-EDFA has a relatively low DMG of <1 dB within -20 dBm to 0 dBm input signal power range.

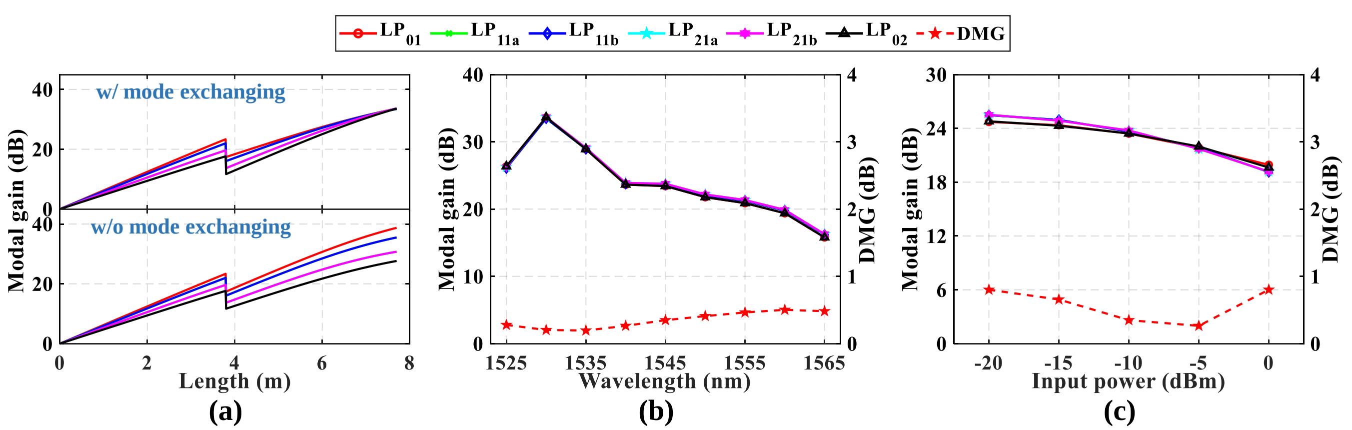

Fig. 2. (a) Modal gains vs. fiber length with/without (above/below) mode exchanges, where the DMG reduction is ~10 dB. (b) The modal gains and DMG across the C-band, where the DMG is <0.6 dB. (c) The modal gains and DMG vs. input power for the proposed FM-EDFA, where the DMG is <1 dB in a large input power range.

3. Experimental verification of the proposed FM-EDFA

Figure 3(a) shows the experimental setup to characterize the proposed 6M-EDFA. A flattened ASE is used as the input signal source. The input signals for 6 modes are equally divided by a 1×6 coupler and then decorrelated by delay lines (DLs) with 40-m interval. The signals are launched into the 6M-EDFA via a 6M-multiplexer (6M-Mux) with an input power of -10 dBm/mode adjusted by the variable optical attenuators (VOA). The amplified signals are demultiplexed by a 6M-demultiplexer (6M-DeMux) and recorded by an optical spectrum analyzer (OSA). The insertion losses and MDL of individual 6-mode passive devices, i.e., 6M-ISOs and 6M-WDMs, both are <1.5 dB and <1 dB, respectively. The insertion losses and MDL of 6M-MPLC devices are <7 dB and <2 dB. The crosstalk of 6M-MPLC devices is <-15 dB, which ensures relatively enough mode exchanges. The lengths of the first and second EDF are 2.5 m and 6.5 m in the integrated 6M-EDFA. The pump powers for the first- and second-stage amplifier are 400 mW and 500 mW. Before characterizing the proposed 6M-EDFA, the first- and second-stage amplifier are characterized separately to match the mode exchanging strategy. The modal gains for the 6 modes after the first-stage amplification are 15.07 dB, 16.59 dB, 16.43 dB, 14.11 dB, 13.85 dB and 9.87 dB, respectively. Similarly, they are 20.10 dB, 20.63 dB, 20.94 dB, 18.01 dB, 18.14 dB and 15.62 dB for the second-stage amplifier. The modal gains for the two amplifiers show a relatively symmetrical distribution. Thus, the mode exchanging strategy is similar to that in Fig. 1(a).

We then tested the broadband modal gains and DMG characteristics of the proposed 6M-EDFA and the results are shown in Fig. 3(b-d). Figure 3(b) shows the modal gains across the C-band, all >20 dB. The gain fluctuation in wavelength is <6 dB. Figure 3(c) shows that the DMG is reduced from ~6 dB to <1.8 dB with mode exchanges. The DMGs have slight fluctuations in the wavelength domain, which are caused by the modal crosstalk at splicing points of the FM-EDFA. Figure 3(d) shows the DMG with mode exchanges versus the input signal power. We could find that the DMG is still <2 dB for three different input powers, illustrating the stability of our proposed FM-EDFA.

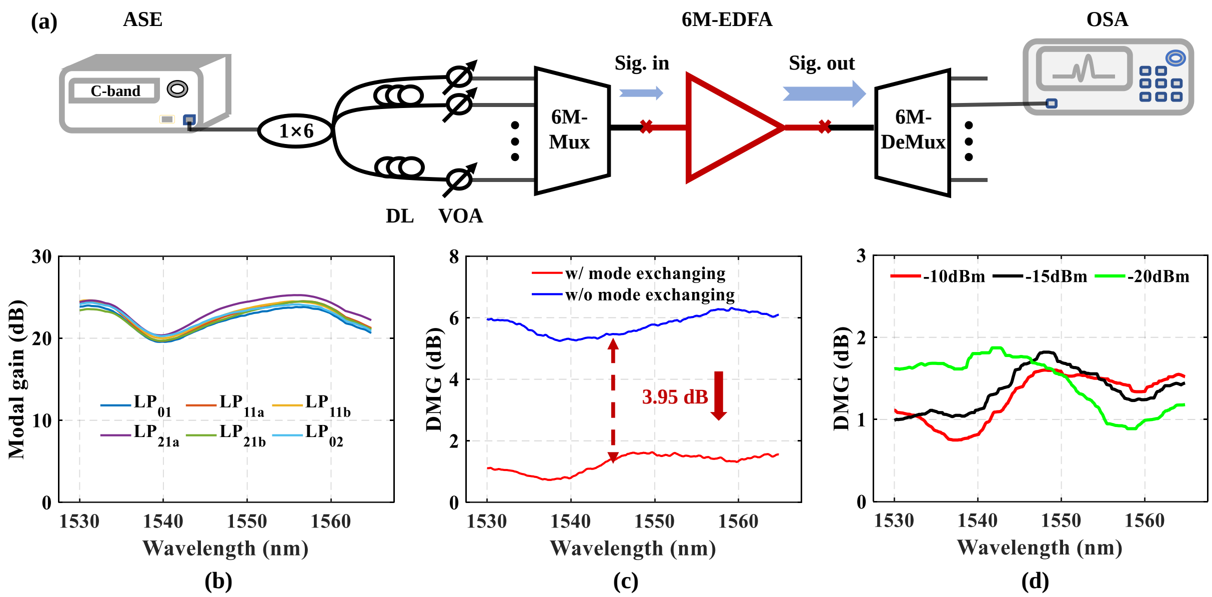

Fig. 3. (a) Experimental setup for characterizing the proposed 6M-EDFA. (b) Modal gains of the 6M-EDFA with mode exchanges, where the all gains are >20 dB. (c) DMG is found to be as low as 1.8 dB after mode exchanging. With mode exchanges, the DMG reduction is more than 3.95 dB. (d) DMG vs. the input power across the C-band, where the DMG is still <2 dB for three input powers.

4. Conclusion

A novel technique is proposed to reduce the DMG based on mode exchanges in the middle of a two-stage FM-EDFA. Simulation results show that a DMG of <0.6 dB is realized by this technique. The experimental results confirmed that the proposed 6M-EDFA can reduce the DMG by 3.95 dB compared to that without mode exchanges. Besides, modal gains of >20 dB and DMG of <1.8 dB across C-band are realized in a large input signal power range. It should be noted that the proposed 6M-EDFA has the potential to realize a lower DMG if the single-stage amplifier has better anti-symmetrically distributed modal gains.

5. Acknowledgements

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