Ultra-Low DMG Multimode EDFA

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Abstract: We demonstrate amplification in a multimode cladding-pumped fiber amplifier supporting 36 spatial modes. Using a large core EDF, we obtain <0.5dB differential modal gain, 16dB gain, and 25dBm output power across the C-band.

OCIS codes: (060.2310) Fiber optics; (060.2320) Fiber optics amplifiers and oscillators

1. Introduction

Space-division multiplexing (SDM) in multicore fibers (MCFs) or few-mode fibers (FMFs) are currently under intense investigations to overcome the limitations of current transmission systems based on single mode fibers [1-5]. Regarding FMF amplifiers, the main challenge is achieving high gain with low differential modal gain (DMG) between all the guided spatial modes over the full C-band. Current approaches employed to minimize DMG in erbium doped fiber amplifiers (EDFAs), include tailoring the spatial distribution of the erbium concentration in the doped core [5] and controlling spatial modal of the pump light content [6,7]. While exploiting these techniques can effectively reduce DMG, further scaling of the number of modes requires complex fiber fabrication strategies and/or system implementations in order to achieve low DMG values between the multiple spatial channels [3].

Here, we present a simple and effective scheme of an ultra-low DMG EDFA with negligible mode mixing. By intentionally increasing the fiber doped-core diameter to support a much larger number of spatial modes than required, strong overlap of the signal modes with the pump light is obtained. Our amplifier fiber is a 1.5 m long, cladding pumped multimode EDF supporting 36 spatial modes with 24 μm core diameter and 73 μm outer diameter. The oversized core ensures all desired spatial modes are well confined inside the core, hence, guarantees the maximum overlap of each mode with the gain medium. Besides, the cladding pumping configuration is a promising approach to further assure a uniform pumping of the gain medium.

2. Demonstration of an ultra-low DMG multimode EDFA

The EDF presented here has a core diameter of 24 μm, refractive index difference of 2.3×10^{-3} with respect to the cladding, an erbium ion concentration of 4.5×10^{25} m^{-3} [8]. The fiber supports ~36 spatial modes, however, due to complexity of generating some higher order spatial modes, only 8 modes are used for amplification (LP_{01}, LP_{11}, LP_{21}, LP_{31}, LP_{41}, LP_{51}, LP_{61}, and LP_{71}). The highest order guided modes are not amplified in order to reduce the impact of the cladding and thus obtain low DMG. The highest order modes groups contain the modes that have the largest fractions of their fields in the cladding (smallest overlap with the pump light) and are thus responsible for the largest DMG. Furthermore, by employing a short section of EDF it is possible to achieve negligible mixing between modes.

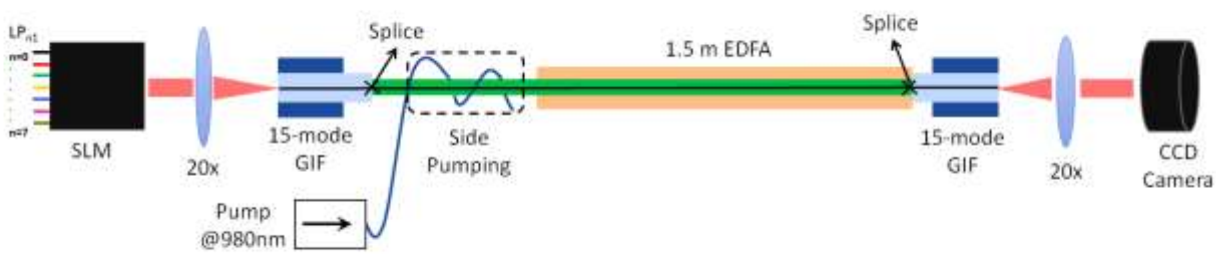

Fig. 1. (a) Schematic diagram of the cladding pumped multimode EDFA. SMM, spatial mode modulator; GIF, graded index fiber; EDFA, Erbium doped fiber amplifier; OSA, optical spectrum analyzer.

Figure 1 shows a schematic of the set up used to characterize the performance of MMF amplifier. A spatial light modulator (SLM) is employed to generate spatial modes up to the 7 order. The output beam of the SLM is coupled to a 0.5 m long 15 mode graded index (GI) fiber which is then spliced to a 1.5 m long EDF. Typical insertion losses were <1 dB for all modes. A CCD camera is used to record the amplifier output mode profiles. A wavelength-stabilized, multimode pump module which is able to deliver an optical power of up to ~25W at 976 nm, was used as the amplifier pump source. We implement side pumping scheme to couple the multi-mode pump light into the amplifier cladding modes with 60% coupling efficiency. In order to do this a tapered core-less fiber was winded around the EDF 2 - 3 times. To enhance the pump intensity, the EDF cladding diameter is designed to be 73 μm and the polymer coating has a numerical aperture (NA) of 0.46 with respect to the glass cladding.

Figure 2 shows the transverse mode images obtained at the output of a 1.5 m long EDF for the supported LP modes before (a) and after (b) amplification. As it is clear, amplification of all spatial modes is successfully achieved without any evident mode mixing. In addition, Fig. 2 confirms spatial mode profiles are well preserved after amplification.

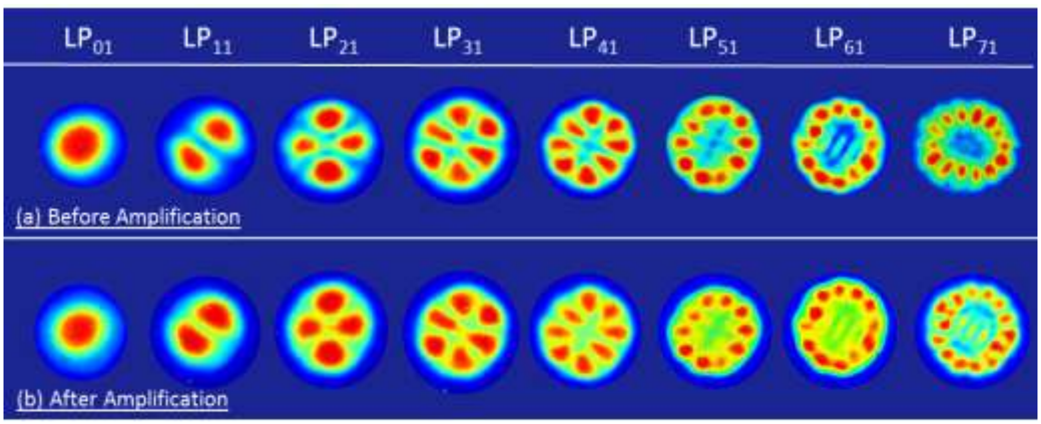

Fig. 2. Signal mode profiles at the output of the EAF before (a) and after (b) amplification.

3. Mode Dependent Gain Measurements of the multimode EDFA

By launching the individual spatial modes into the EDFA and recording the amplified output spectra, we can evaluate the amplifier gain and DMG for all supported modes using an optical spectrum analyzer (OSA). The input signal power was 9 mW, in all our experiments. Figure 3 (a) shows the small signal gain for the different modes at 10 W of input pump power. All plots perfectly overlap, highlighting the remarkably small DMD of our amplifier. Figure 3 (b) shows the average DMG measured across the C-band as the pump power is increased from 1-10 W. We observe a variation in DMG of less than 0.2 dB as the pump power is increased to 10 W. This means that all modes experience the same gain regardless of the inversion of the gain medium.

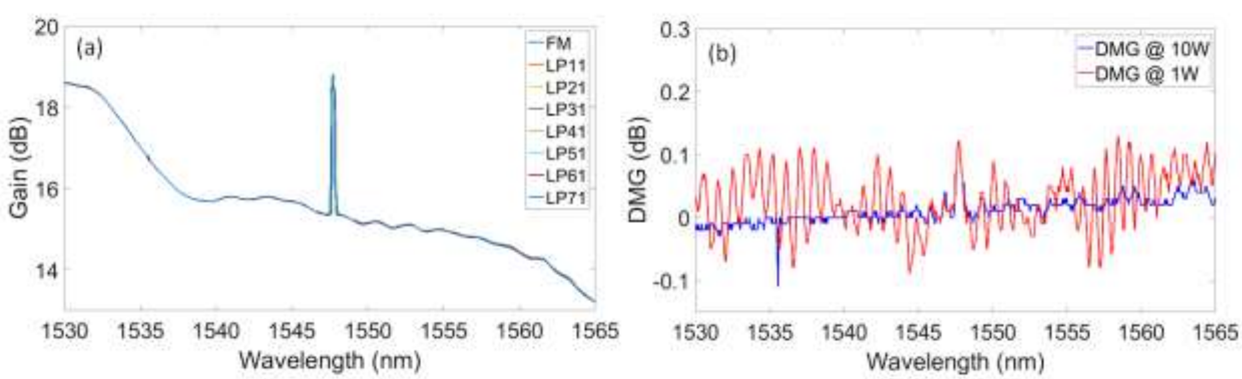

Fig.3. Small signal gain for all modes at 10W of input pump power for 1.5 m EDFA (a). Measured DMG across the C-band under different coupled pump powers (b)

Finally, we studied the modal gain as a function of pump power across the full C-band. Figure 4 shows the small signal gain of the fundamental mode for a 1.5 m long EDFA under different pump powers. This image clearly show that the amplifier is strongly inverted at 10 W of pump power as indicated by the strong gain peak at 1530 nm. The gain measured at 1550 nm is 10 dB at 1 W and increases to 15 dB for a pump power of 10 W.

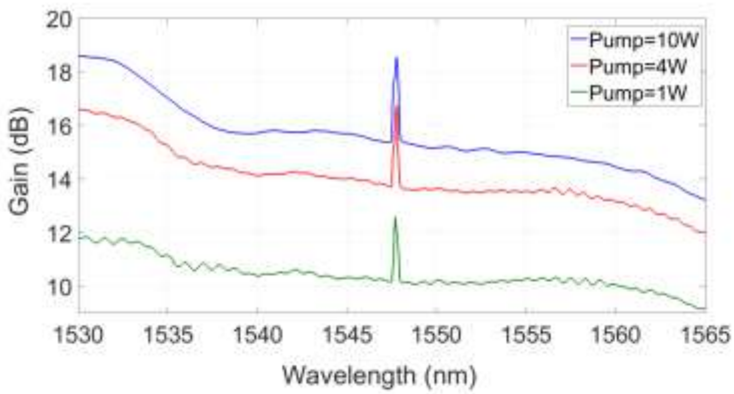

Fig.4. Small signal gain of the fundamental mode at 1.5 m EDFA under different coupled pump powers.

3. Conclusions

We have demonstrated a multimode cladding pumped fiber amplifier supporting 36 spatial modes. By intentionally increasing the fiber core diameter and reducing the outer cladding diameter, an ultra-low mode-dependent gain of <0.5 dB was obtained across the full C-band. All spatial modes are well preserved after amplification without any significant mode mixing. By increasing the pump power from 1 W to 10 W, the differential modal gain changed less than 0.2 dB. The average amplification gain was 16 dB across the C-band. Our approach does not require complex fiber fabrication and/or special pump manipulation schemes.

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