First Demonstration of Cladding Pumped Few-moded EDFA for Mode Division Multiplexed Transmission

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Abstract: We report the first experimental demonstration of a cladding pumped FM-EDFA supporting 4 mode groups. The modal gains are measured to be >20dB between 1540nm-1570nm with a modal differential gain of ~4dB among the mode groups.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (060.2330) Fiber optics communications.

1. Introduction

Mode division multiplexing (MDM) for high-speed long-haul transmission is currently under intense investigation as a means to overcome the capacity limit of single-mode systems. 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) [1]. To date, FM-EDFAs that simultaneously amplify 4 linearly polarized (LP) mode groups have been demonstrated based on a core-pumping scheme [2]. However, as the number of modes is scaled-up significantly further then it will be challenging to meet the associated power requirements from single-mode diodes. Moreover, even if this is technically possible, multiplexing a number of single-mode pump diodes together to generate sufficient pump power is an expensive way of pumping such an amplifier. Cladding pumping represents a possible way to address these issues. High power, low cost (in terms of $/W) multimode pump diodes operating in the multi-watt regime are now readily available now given the emergence and success of the high power cladding pumped fiber laser [3]. Cladding pumping has previously been shown as a viable approach to pumping both multi-core [4] and multi-element amplifiers [5] but as of yet has not been demonstrated for a few-mode amplifier. Herein, we address this issue and demonstrate for the first time the feasibility of a cladding pumped FM-EDFA amplifying all the spatial modes of an erbium doped fiber supporting 4 mode groups.

2. Experiment setup

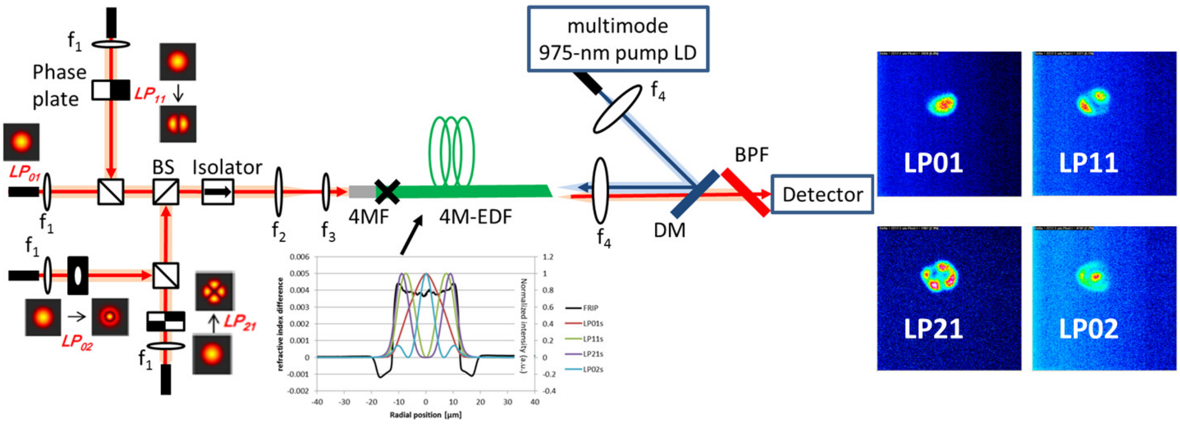

Fig. 1. Schematic diagram of the 4-moded cladding pumped erbium doped fiber amplifier (4M-EDFA). BS: non-polarizing beam splitter, DM: dichroic mirror, 4MF: passive 4-moded fiber, 4M-EDF: 4-moded erbium doped fiber, f1, f2 and f3: lenses with focal lengths of 4.5, 125 and 3.1mm respectively. The CCD camera images show the mode profile after amplification.

Fig.1 shows the schematic diagram of our cladding pumped 4-moded EDFA (CP 4M-EDFA) that simultaneously amplifies the LP_{01}, LP_{11}, LP_{21} and LP_{02} mode groups. A mode multiplexer based on a collection of phase plates and beam splitters was used to selectively excite the individual mode group in a 4 mode group passive fiber (4MF) using four tunable external cavity lasers. The 4MF was then spliced directly to a cladding pumped 4 mode group erbium doped fiber (4M-EDF). The splice losses between the 4MF and 4M-EDF for the different modes were measured as 0.5±0.3dB. The refractive index and the erbium doping profile of the EDF are similar to that of ref [1]. The primary difference between this fiber and that of [1] is that the current fiber has a low-index polymer coating to define the pump waveguide (NA~0.44). The 4M-EDF has an outer cladding diameter of 97µm and a core diameter of ~26µm. The estimated effective NA of the core is ~0.10. The estimated cladding absorption is ~1.08dB/m at 975 nm. The fiber was counter-directional pumped via a dichroic mirror which was highly reflective (>99%) at the pump wavelength and highly transmissive (~98%) at the signal wavelength. The multimode pump module can deliver an output power of up to ~10W and was wavelength-stabilized with a volume Bragg grating (VBG) at 975nm. Even though, the pump wavelength is 3nm shorter than the peak absorption wavelength of ~978nm, our simulation predicts that this will only have a slight impact on the total pump absorption and hence the signal gain. The output end of the 4M-EDF was angled-cleaved at ~8° to suppress any back-reflections. The coupling efficiency of the pump power into the inner cladding was measured to be ~80 %. The modal gain was measured by choosing a unique wavelength for the mode under test (MUT). At the output of the 4M-EDFA, the MUT was de-multiplexed via a tunable narrow bandpass filter (full width at half maximum=2nm). The wavelength allocation of the individual modes is discussed below. We estimate a measurement error of ±0.5dB in to all of our gain measurements. The right hand side of Fig.1 shows the measured mode profiles when the individual modes are amplified separately by the 4M-EDFA.

3. Experimental results

We first investigated the CP FM-EDFA with a 9-m long 4M-EDF. Fig. 2(a) shows the modal gain measured by setting the MUT at 1555nm while other modes were fixed at 1560 nm. Since the EDF predominantly experiences homogenous broadening, we assume that the effect due to spectral hole burning caused by the 1560nm signal to be minimal. We therefore believe that in this way the modal gain of the individual modes at 1555nm can be measured with low uncertainty originating from the spectral gain dependence. The DMG at 1555nm was measured to be ~4dB for >20dB modal gains. The optical power efficiency (i.e. the ratio of total output signal power to launched pump power) was ~8.5% at launched pump power of ~2.07W. At the launched pump power of ~1.7W, Fig. 2(b) shows the measured modal gain as a function of input MUT signal power with the wavelength assignment the same as that of Fig. 2(a). The signal gains decrease linearly with an increase in signal power for all modes due to the amplifier being operated in the unsaturated gain regime. The DMG did not show much dependence on the input signal power and remains at ~3dB for all the input signal powers investigated.

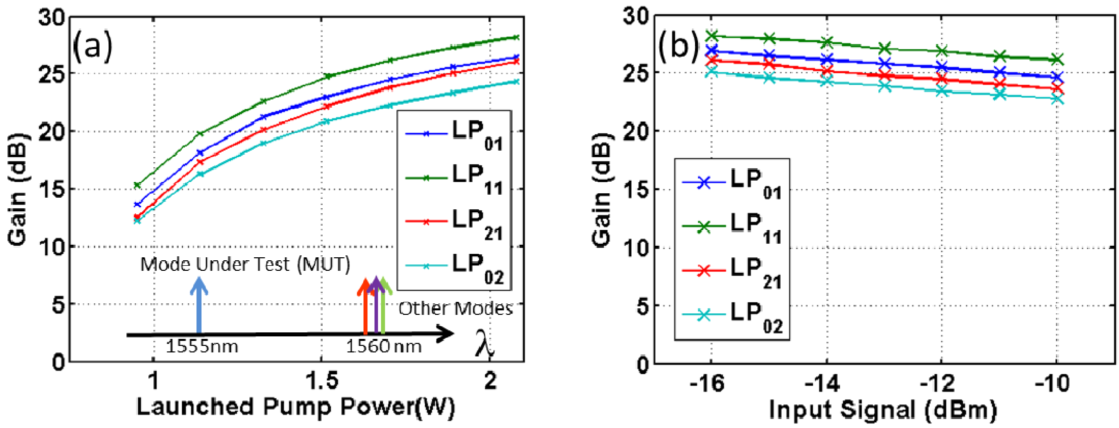

Fig.2. (a) Mode dependent gain as a function of input pump power for the four individual modes centered with the wavelength placement shown in the illustration. The input signal is -10 dBm for all modes (b) Measured modal gain as a function of input signal power per mode at launched pump power of ~1.7W.

Fig. 3 shows the gain spectra of the various modes at a constant lauched pump power of 1.7W for two different lengths of 4M-EDF, i.e. 9m and 5m. The input signals of the various modes were fixed at -11dBm for all wavelengths. The wavelength assignment of the various modes was such that, while the MUT was spectrally tuned, the other modes were fixed at 1560nm (with the exception that when the MUT was centered at 1560nm, all other modes were shifted to 1555nm). Fig. 3(a) shows the gain spectra with a 9m of EDF length. The gain peaked at ~1565 nm and exhibited a 3dB gain compression bandwidth of ~15 nm spanning from 1560nm to 1575nm. In order to shift the gain peak towards 1550nm to better align with traditional C-band operation, we reduced the EDF length to 5m. As shown in Fig. 3(b), this resulted in a flatter gain spectra with a 3dB gain compression bandwidth increased to ~30nm spanning from 1540nm to 1570nm. Although the reduction in the EDF length reduced the overall pump absorption to ~5dB, the FM-EDFA still exhibited respectable modal gains of ≥20dB between 1540 nm to 1570 nm. Finally, we note that the noise figure of the 5m FM-EDFA was simulated to be 5-7dB between 1540nm to 1580nm and will be measured in the future.

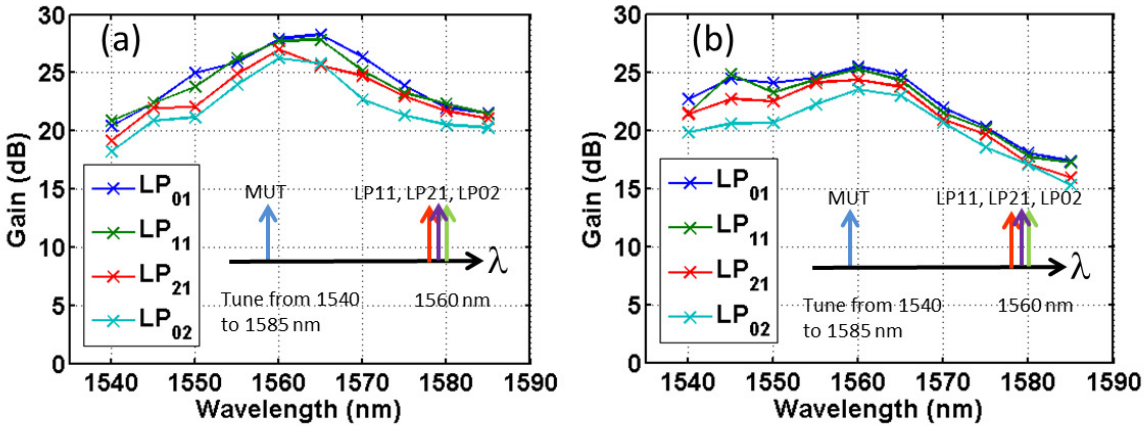

Fig.3. Gain spectra of various modes for a 4M-EDF with length of (a) 9m and (b) 5m at launched pump power of ~1.7W..

4. Conclusion

We have demonstrated for the first time a cladding pumped few moded EDFA supporting 4-mode groups. The modal differential gain was determined to be ~4dB with LP_{11} exhibiting the highest modal gain. Reduction in the EDF length from 9m to 5m widens the operating window of the FM-EDFA from 15 nm to 30 nm and ensures near full C-band operation. We believe that the MDG can be reduced further by optimizing the core design whilst full C-band operation will be possible by optimizing the core-to-clad area ratio of the cladding pumped EDF.

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