Recent Progress in the Development of Few Mode Fiber Amplifiers

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Abstract: We review the performances of both core and cladding pumped few-mode erbium doped fiber amplifiers supporting 6 spatial modes (4 mode groups) which incidentally the highest mode count demonstrated to date.
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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 by employing multiple distinguishable spatial information channels through the same fiber [1,2]. Such an approach is now needed since all other dimensions i.e. wavelength, polarization, phase and amplitude are already close to fully exploited in Single-Mode Fiber (SMF) based systems. One form of SDM uses Few Mode Fibers (FMFs) which guide a restricted number of modes that are used to define the independent spatial channels. Mode division multiplexing (MDM) [2] is currently under intense investigation as the most efficient approach to overcome the current capacity limitations (~100Tbit/s per fiber) of high-speed long-haul transmission systems based on single mode optical fiber. 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). In FM-EDFAs, differential modal gain (DMG) directly affects the system outage probability and minimizing the gain difference between the guided spatial modes is essential to guarantee robust performance of the overall MDM system. DMG fundamentally arises from the difference in the overlap between pump, signal and rare earth dopants between modes. Two main strategies have been used to equalize the DMG: i) tailoring the radial erbium-doping concentration profile of the erbium doped fiber [3] and ii) controlling the pump field intensity distribution [3]. In practice, a combination of both strategies is required for higher mode count amplifiers. To date, FM-EDFAs that simultaneously amplify up to 4 linearly polarized (LP) mode groups (i.e. 6 spatial modes) [3-4] have been demonstrated and a DMG of less than 2dB has been achieved using a ring-shaped erbium doped fiber combined with bi-directional higher-order mode (LP_{21}) pumping [3]. A comprehensive theoretical study shows that it may be possible to achieve low DMG over the full C-band of EDFAs supporting 4 and 6 mode groups by using a simple step index core but a rather complex erbium dopant distributions [5].

Here we review the recent progress made towards the development of few mode erbium doped fiber amplifiers supporting a maximum of 4 mode groups using both core and cladding pumped approaches.

2. Few Mode EDFA

Since the first demonstration of a FM-EDFA supporting 3 spatial modes (namely LP_{01}, LP_{11a} and LP_{11b}) in 2011 [6,7], significant progress has been made in scaling up the number of guided modes and minimizing the mode dependent gain through the use of various methods including spatial control of the Er-ion distribution within the core region and/or controlling the pump field distribution [3]. Figure 1 shows an example of a FM-EDFA supporting 4 mode groups (LP_{01}, LP_{11a}, LP_{11b}, LP_{02}, LP_{21a} and LP_{21b}). A phase plate based mode multiplexer was used to selectively excite the pure LP_{01}, LP_{11}, LP_{21} and LP_{02} signal modes in a passive 6-moded fiber (6MF) with four tunable external cavity lasers. No attempts were made to excite the orthogonal modes of the LP_{11} and LP_{21} mode groups (namely, LP_{11a} and LP_{11b}, LP_{21a} and LP_{21b}) as our earlier experiment [3] led us to believe that they behave similarly. The passive 6MF was then spliced directly to a 5m long ring-doped EDF in which the erbium ions are substantially confined within a ring inside the fiber core to help mitigate the DMG. The single mode outputs from two 976nm pump laser diodes were first converted to the LP_{21} modes using 980nm borosilicate phase plates and then free-space coupled into the two ends of the 6M-EDF.

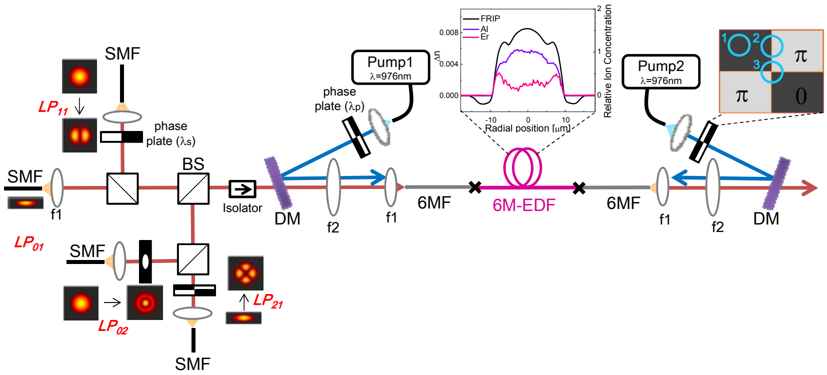

Fig. 1. Schematic diagram of the 6-moded erbium doped fiber amplifier (6M-EDFA) gain tailored by bi-directional pumping configuration. BS: non-polarizing beam splitter, DM: dichroic mirror, 6MF: passive 6-moded fiber, 6M-EDF: 6-moded erbium doped fiber, f1 and f2: lens with focal length of 4.5 and 125mm [3].

As shown in Fig. 2(a), maximum modal gains of 22, 23.3, 22.8 and 22.3dB were measured for the LP_{01}, LP_{11}, LP_{21} and LP_{02} signal modes, respectively. In Fig. 2(b) we plot the signal gain as a function of input signal power per spatial mode for a fixed total launched pump power of 25.3dBm. All guided modes experienced gain reduction with an increase in input signal power. A maximum aggregate saturated output power of 18.7dBm was obtained, corresponding to a power conversion efficiency of 21.9%. Figure 2(c) shows the measured gain across the C-band for an input signal power of -10dBm per mode, where the mode under test was spectrally tuned while other modes were fixed at the assigned wavelength and a superposition of the four spatial modes successively made was presented. The amplifier provides >20dB gain for all four spatial modes with low DMG and a gain flatness of <4.0dB across the full C-band.

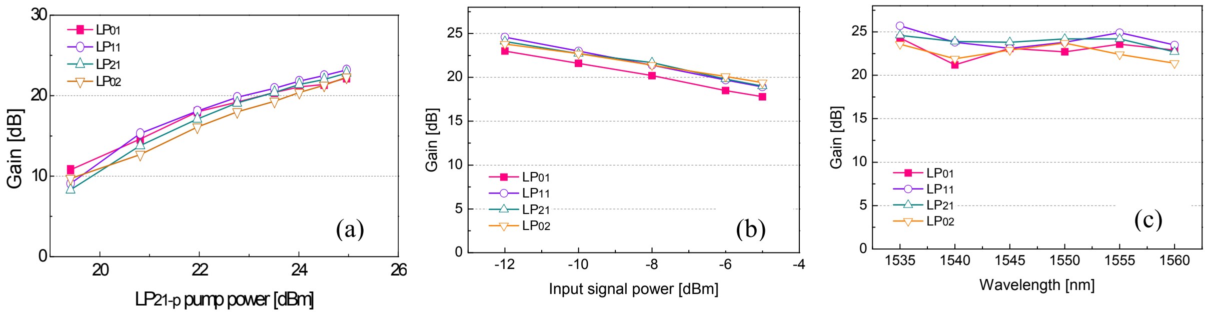

Fig. 2. Mode dependent gain as a function of (a) bi-directional LP_{21} pump power for an input signal power of -10dBm, (b) input signal power for a fixed pump power of 25.3dBm and (c) operating wavelength for a fixed input signal power of -10dBm pump power of 25.3dBm [3].

However, as the number of modes is scaled up to 10 and beyond, it will be challenging to meet the associated pump power requirements with single-mode pump diodes. Even if this is technically possible, multiplexing a number of single-mode pump diodes to generate sufficient pump power is an expensive way of pumping such an amplifier. Reduction in the cost per transmitted bit is essential for SDM to be seriously considered for commercial deployment and cladding-pumping using high-power multimode pump diodes (which has already been demonstrated for multi-core EDFAs [8]) provides a more practical and potentially much cheaper way in terms of $/W to generate and deliver the pump radiation. Figure 3a shows a schematic of a cladding pumped FM-EDFA [9]. The setup is similar to that shown in Fig. 1, except the Er-doped active fiber has a step index core which is counter-directionally pumped by a single multimode pump diode and employed a full de-mux system to enable noise figure (NF) measurement. Left hand plots of Fig. 3 show the measured gain spectra of the guided modes for three different fiber lengths of 6M-EDF, i.e. 6m, 3.5m and 2m respectively, at a constant input signal power of -7.5dBm per mode. For 6m of EDF length (Fig. 3b), the gain peaked at ~1565 nm and exhibited a narrow 3dB gain compression bandwidth of ~10nm spanning from 1560nm to 1570nm. In order to shift the gain peak towards 1550nm to better align with traditional C-band operation, we reduced the EDF length to 3.5m. As shown in Fig. 3c, this resulted in a flatter gain spectra with a 3dB gain compression bandwidth increased to ~20nm spanning from 1545nm to 1565nm.

When the fiber length was further reduced to 2m (Fig. 3d) the gain flatness was increased to over 30nm. Although the reduction in the EDF length reduced the overall pump absorption to ~2dB, the FM-EDFA still exhibited respectable modal gains of ≥20dB between 1535 nm to 1565 nm. The variation of noise figure (NF) as a function of fiber length is also shown in the Fig. 3 right hand plots. Figure 3b shows that the NF rises sharply for wavelengths shorter than 1565nm while it tends to decrease at longer wavelengths when 6m long fiber was used. The high NF at short wavelengths is mainly due to insufficient population inversion within the active medium. Situation improves dramatically when EDF length was shortened to 2m. The NF was improved from 13-14dB to 6-7dB for all guided modes due to the gain enhancement at the short wavelengths.

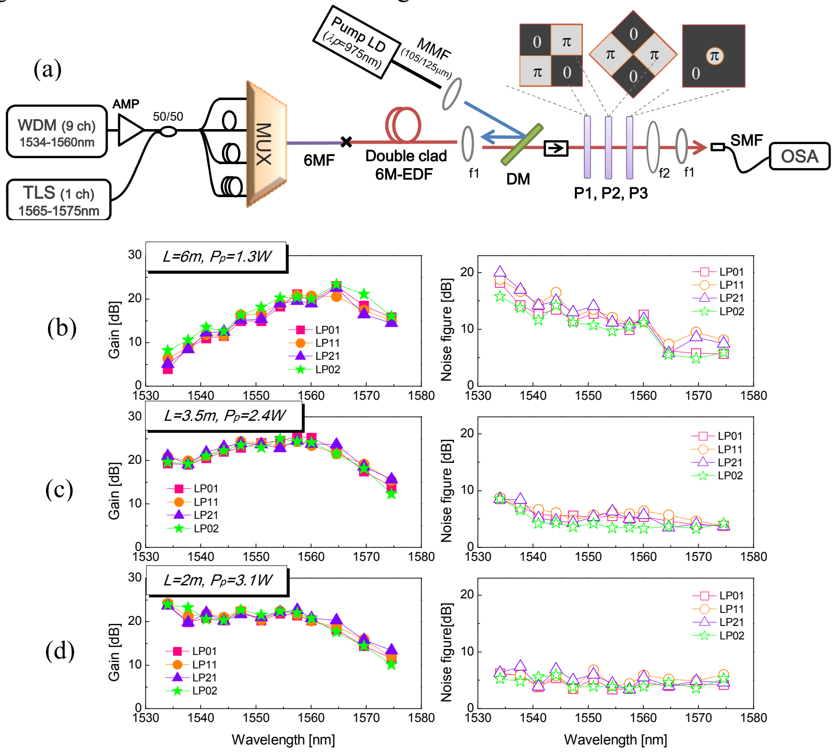

Fig. 3. (a) Schematic diagram of the cladding pumped 6-moded erbium doped fiber amplifier (6M-EDFA); Measured gain (left) and NF (right) of the individual guided modes for 6M-EDF lengths of (b) 6m, (c) 3.5m and (d) 2m [9].

3. Conclusion

We have shown examples of core and cladding pumped FM-EDFAs supporting 4 mode groups which incidentally is the highest mode count EDFAs demonstrated to date. The experimental results clearly highlighted that significant progress has been made over the past few years to reduce DMG whilst increasing the number of guided modes. Very recently a ring core FM-EDFA supporting 6 mode groups has been proposed showing great potential with low DMG amongst the guided modes even with a simple graded-index ring doped core [10] design. To further increase the number of spatial channels a few moded multi-element EDFA has been demonstrated experimentally with an overall multiplicity of 12 (3 modes x 4 signal fiber-elements) [11]. However, it is anticipated that a much improved fiber fabrication techniques will be essential to scale up the mode counts whilst maintaining a low DMG amongst the guided modes.

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