Reconfigurable Modal Gain Control of a Few-Mode EDFA Supporting Six Spatial Modes

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***Abstract*— We experimentally demonstrate an inline few-mode erbium doped fiber amplifier supporting six spatial modes with reconfigurable differential gain control and excellent gain flatness obtained through mode-selective bidirectional pumping of a custom fiber with a radially profiled erbium dopant distribution. A signal gain of >20 dB was obtained for all the guided modes with a differential modal gain <2 dB and good gain flatness across the C-band.**

***Index Terms*— Mode division multiplexing (MDM), erbium doped fiber amplifier (EDFA), optical fiber communication.**

I. Introduction

MODE Division Multiplexing (MDM) [1]–[5] in which selective mode excitation and detection schemes are used to define multiple distinguishable information channels within a few-mode fiber (FMF) is gathering increasing interest as a cost effective means to accommodate the anticipated future (exponential) growth in internet traffic. Rapid progress has been made in the development of FM transmission fibers and optical amplifiers and a record data transmission capacity of 73.7 Tb/s has recently been demonstrated over a 110km length link of three-mode fiber (3MF) incorporating an inline 3M-EDFA [6]. A longer transmission distance of 500km has been reached at an aggregate line-rate of 16.6 Tb/s in 3MF recirculating loop experiments [7]. The maximum reach in this instance was limited by the differential mode-group delay and the propagation of spurious higher order modes (HOMs) within the loop. Although these preliminary demonstrations are encouraging, for MDM to be seriously considered as an alternative to the use of multiple parallel systems based on single-mode, single-core fiber technology, a further increase in the number of parallel transmitted and amplified channels will be necessary.

To this end work has started on higher mode count fibers and a maximum transmission distance of 177km (3x59km) at a line-rate of 24.6Tb/s over a bandwidth of 800GHz at 25GHz channel spacing has been demonstrated using a 6MF [8]. However amplification in this instance was obtained using 6 single mode EDFAs in conjunction with suitable mode demultiplexers due to the lack of a suitable 6M-EDFA. Recently a FM-EDFA supporting 6-spatial modes was reported using two cascaded lengths of FM-EDF with different erbium dopant distributions, resulting in a differential modal gain (DMG) in the region of 4dB and with the LP_{01} mode experiencing the highest gain [9], [10]. It is however to be expected (and recently demonstrated in Ref [7]) that the HOMs generally experience slightly higher transmission losses (particularly due to bending and coupling losses) and thus the ability to generate slightly higher gains (typically between 0.5 to 1dB) is beneficial to help compensate for mode dependent loss for transmission over multiple fiber spans. Mode selective pumping has previously been shown to offer higher gains for the HOMs in a FM-EDFA supporting two mode groups [11], [12], however in this implementation the DMG could not be accurately controlled over the full C-band with a gain flatness of better than 5dB and changed by as much as 2.5dB depending on the pump power and operating wavelength. Here we report a 6M-EDFA providing adjustable DMG obtained by using a mode-selective bi-directional pumping scheme in conjunction with an EDF with a specially tailored Er-doping profile. A signal gain of >20dB was obtained for all the guided modes with a DMG <2dB and improved gain flatness across the C-band.

II. Gain Performance of 6M-EDFA

Figure 1 shows a schematic diagram of our 6M-EDFA for simultaneous amplification of the four lowest spatial mode groups namely LP_{01}, LP_{11}, LP_{21} and LP_{02}. A mode multiplexer based on phase plates was first 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. Since the current free-space mode multiplexer scheme suffers a minimum 3dB excess loss resulting from the use of non-polarizing beam splitters (BS) for each mode added to the system, the number of simultaneously injected spatial modes was limited to four to keep the signal insertion loss within an acceptable level to allow the amplifier to be characterized over a wide range of signal input powers. Moreover based on our previous experimental results on a 3-moded EDFA [13], we believe that the orthogonal modes of the LP_{11} and LP_{21}

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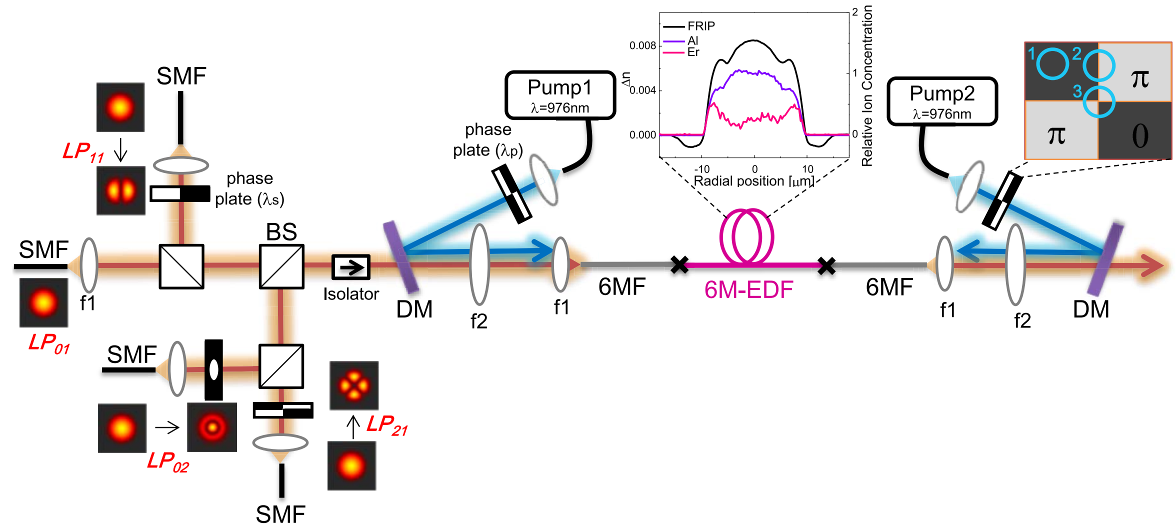

Fig. 1. Schematic diagram of the 6-moded erbium doped fiber amplifier (6M-EDFA) gain tailored by bi-directional pumping configuration. BS: non-polarizing beam splitter, DM: dichroic mirror, 6MF: passive 6-moded fiber, 6M-EDF: 6-moded erbium doped fiber, f1 and f2: lens with focal length of 4.5 and 125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

mode groups (namely, LP_{11a} and LP_{11b}, LP_{21a} and LP_{21b}) will behave similarly. The passive 6MF was then spliced directly to a 5m long ring-doped EDF [14]–[16], in which the erbium ions are substantially confined within a ring inside the fiber core to help mitigate the DMG. The fiber was drawn from the same preform as in Ref. [14] but with a larger core diameter so as to support six spatial modes. The 6M-EDF has an outer cladding diameter of 163μm and a core diameter of 18.7μm. The estimated effective NA of the core is ~0.14. A white light source based on a tungsten-halogen lamp was used to measure the absorption of the Er-doped fiber without any selective excitation of the guided modes. Using the cut-back method the absorption at 980nm was measured to be 8.9dB/m. A bi-directional pumping configuration was adopted to provide DMG control. The single mode outputs from two 976nm pump laser diodes were first converted to the desired pump modes using 980nm borosilicate phase plates and then free-space coupled into the two ends of the 6M-EDF. To allow simple but effective modal gain measurement, different wavelengths were chosen for the four different signal channels (for example 1546nm for LP_{01}, 1550nm for LP_{11}, 1554nm for LP_{21} and 1558nm for LP_{02} respectively) and a tunable narrow bandpass filter (full width at half maximum=2nm) and a power meter were used to determine the output power and hence gain of the individual channels, similar to the setup described in Ref. [13] and [14]. Splice losses of 0.6dB for the LP_{01}, 1.0dB for the LP_{11}, 1.2dB for the LP_{21} and 1.3dB for the LP_{02} modes were measured: the variation being due primarily to mode mismatch between the passive 6MF and active 6M-EDF.

An LP_{21} pump phase plate was inserted in the optical path of the pump beam to provide reconfigurable pump mode control. Fig. 2(a) shows the measured charge coupled device (CCD) images of the spatial profile of the pump mode after the phase plate, when the latter was made to intersect the Gaussian pump beam at different positions, as illustrated by the magnified view of the phase plate in Fig. 1: uniform sector for LP_{01} excitation (region 1), half-sector for LP_{11} (region 2) and quadrant-sector for LP_{21} (region 3). The spatial profiles after propagation through a 10m-long section of the passive 6MF are also presented, showing that a clean spatial pump mode (i.e. single lobe of LP_{01}, double lobe of LP_{11} and quadruple lobe distribution of LP_{21} mode) was generated by the binary pump phase plate and which was well-preserved along the fiber in all instances, which is essential in establishing the role of the pump mode profile in mitigation of the DMG of the amplifier. The coupling losses to the 6MF, however, depend on the particular pump mode and were measured to be 1.1, 2.4 and 3.5dB for LP_{01-p}, LP_{11-p}, and LP_{21-p} pump modes respectively. These relatively large coupling losses

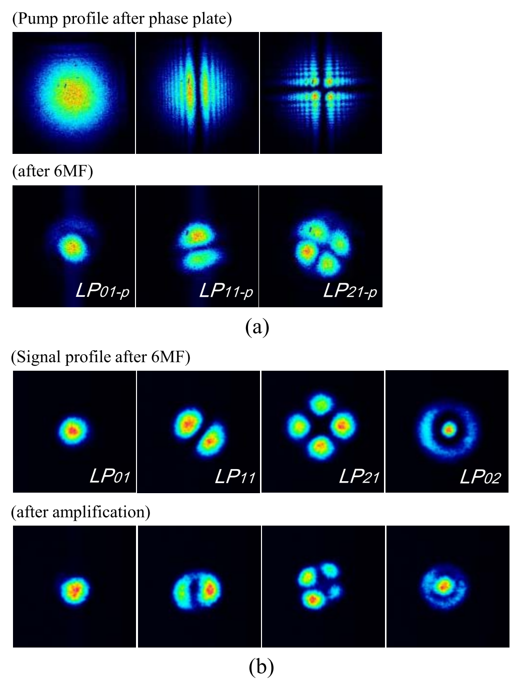

Fig. 2. (a) Pump mode profile after phase plate (top) and after 10m-long 6MF (bottom). (b) Signal mode profile before (top) and after (bottom) amplification.

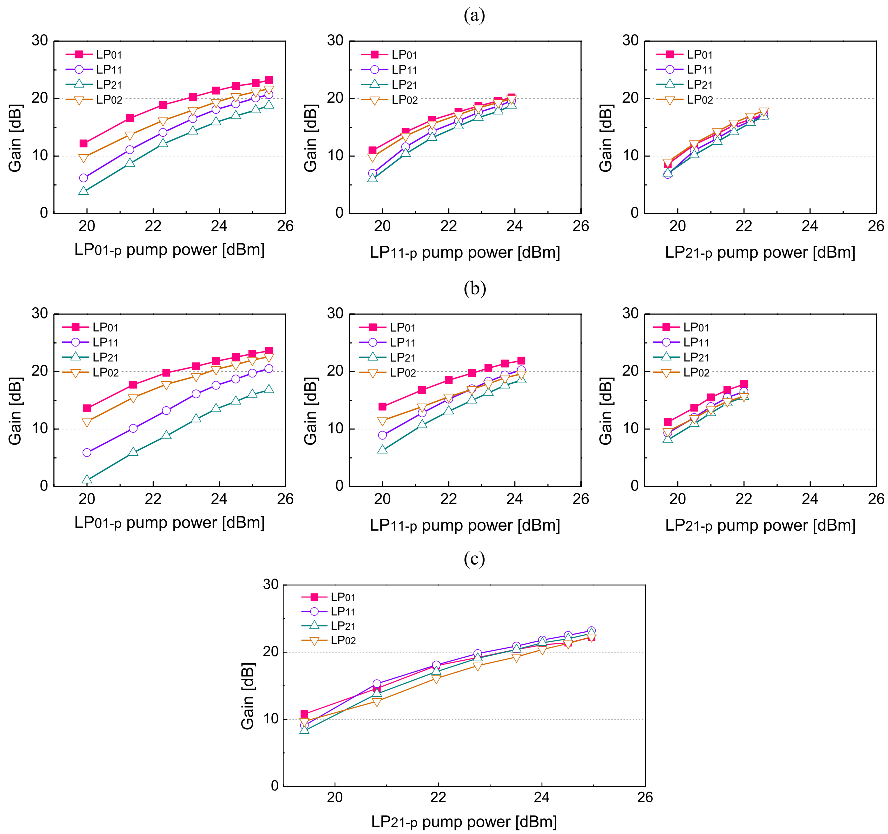

Fig. 3. Mode dependent gain as a function of three different pumping configurations: (a) co-propagating, (b) counter-propagating, and (c) bi-directional.

might ultimately be improved by using a long period fiber grating assisted mode converter [17], [18] written directly into the pump fiber.

To confirm clean amplification of the input signals, mode images of the various input and output signals to the amplifier were taken by a CCD. As shown in Fig. 2(b) (top), the mode images of the four input signals are well defined after propagating through 10m of a passive 6MF. In our experiment, the LP_{02} mode showed a minimum modal extinction ratio (ER) of 15dB (defined as the ratio between the power in desired mode and the power in undesired mode) due to the tight tolerance on the radial dimensions of the phase plate fabrication, nevertheless this is sufficient to analyze the amplifier performance. The ER for all other modes was >20dB. The beam quality of the individual input signals was largely preserved during amplification although some small degradation is noticeable by careful comparison of the images in Fig. 2(b) (top versus bottom). We attribute this to the presence of unpolarized amplified spontaneous emission (ASE) light and modal crosstalk generated at the mode-mismatched splice points (which could potentially be further improved by optimizing the mode field diameters between the passive and active fibers used). Nevertheless the quality is sufficient for our needs.

Figure 3 shows the mode dependent gain as a function of launched pump power for different pump spatial modes (LP_{01-p}, LP_{11-p}, and LP_{21-p}) with (a) co-directional, (b) counter-directional and (c) bi-directional pumping a configurations. For the co-directional pumping (Fig. 3(a)), with an LP_{01-p} pump launch condition the LP_{01} signal experiences much higher gain than the other three modes due to its greater overlap with the erbium ions excited by the LP_{01-p} pump. The measured DMG was 4.5dB for an input signal power of −10dBm and a pump power of 25.5dBm. The DMG decreased to 1.5dB when the LP_{11-p} pump mode was applied; however the gain for the LP_{01} signal mode remained higher than that for the other signal modes. For the LP_{21-p} pump mode however, the DMG not only dropped below 1dB but also the gain for the HOMs became almost equal to that of the fundamental mode. However, as evident from Fig. 3(a), the modal gain was restricted to 17dB for the LP_{21-p} pump mode due to the reduced launched pump power caused by the higher coupling losses. This could be compensated for if necessary by increasing the pump diode drive current.

The amplifier behaved similarly for the counter-directional pumping, as shown in Fig. 3(b), albeit with a slightly larger DMG. It is to be noted here that for the same pump power of 21.5dBm, the measured DMG was larger for the counter pumping configuration, whilst for both pumping configurations there is a clear trend of DMG reduction and relative HOM gain increase relative to the fundamental mode with increasing pump power. Extrapolating these measurements it can be seen that an even higher pump power could lead to gain equalization or even to the potentially desirable condition where HOMs experience a larger gain than the fundamental mode. To prove this point, we also tested a bi-directional pump configuration, where an LP_{21-p} pump mode was injected from both ends with a total coupled pump power of 25.3dBm. As shown in

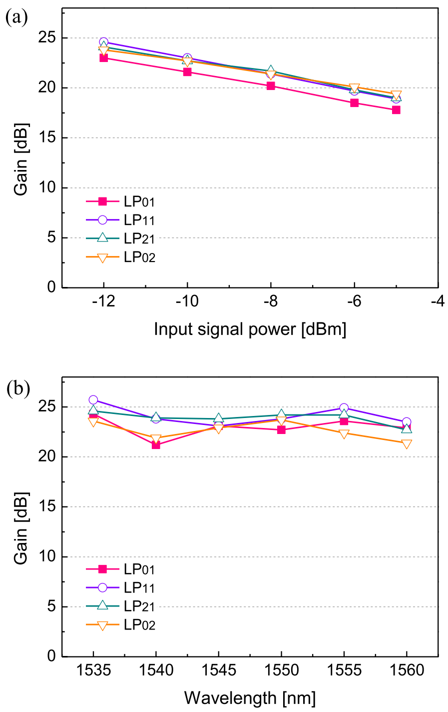

Fig. 4. (a) Measured modal gain as a function of input signal power per mode and (b) gain spectra across the C-band.

Fig. 3(c), 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. The modal gain plots show that a wide range of DMGs can be achieved in the various configurations simply by changing the pump power.

In Fig. 4(a) 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 powers. A maximum aggregate saturated output power of 18.7dBm was obtained, corresponding to a power conversion efficiency of 21.9%. Figure 4(b) 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 all other modes were fixed at the assigned wavelength and a superposition of the four spatial modes measured successively is 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.

III. Conclusion

We have demonstrated a 6M-EDFA providing reconfigurable mode dependent gain by using a bi-directional LP_{21-p} pumping scheme and an Er-doped fiber with a tailored ring-doped profile. We consider this to be an important step in extending MDM transmission both to larger channel numbers and to longer transmission distances and believe the general approach should be further scalable to allow larger number of modes.

References

[1] D. J. Richardson, J. M. Fini, and L. E. Nelson, "Space-division multiplexing in optical fibres," *Nature Photon.*, vol. 7, pp. 354–362, May 2013.

[2] P. J. Winzer, "Energy-efficient optical transport capacity scaling through spatial multiplexing," *IEEE Photon. Technol. Lett.*, vol. 23, no. 13, pp. 851–853, Jul. 1, 2011.

[3] R. Ryf *et al.*, "Mode-division multiplexing over 96 km of few-mode fiber using coherent 6 × 6 MIMO processing," *J. Lightw. Technol.*, vol. 30, no. 4, pp. 521–531, Feb. 15, 2012.

[4] S. Randel *et al.*, "6×56-Gb/s mode-division multiplexed transmission over 33-km few-mode fiber enabled by 6×6 MIMO equalization," *Opt. Express*, vol. 19, pp. 16697–16707, Aug. 2011.

[5] A. Li, X. Chen, A. A. Amin, J. Ye, and W. Shieh, "Space-division multiplexed high-speed superchannel transmission over few-mode fiber," *J. Lightw. Technol.*, vol. 30, no. 24, pp. 3953–3964, Dec. 15, 2012.

[6] V. A. J. M. Sleiffer *et al.*, "73.7 Tb/s (96×3×256-Gb/s) mode-division-multiplexed DP-16QAM transmission with inline MM-EDFA," *Opt. Express*, vol. 20, no. 26, pp. B428–438, 2012.

[7] E. Ip *et al.*, "146λ×6×19-Gbaud wavelength- and mode-division multiplexed transmission over 10×50-km spans of few-mode fiber with a gain-equalized few-mode EDFA," in *Proc. OFC*, 2013, paper PDP5A.2.

[8] R. Ryf *et al.*, "32-bit/s/Hz spectral efficiency WDM transmission over 177-km few-mode fiber," in *Proc. OFC*, 2013, paper PDP5A.1.

[9] G. L. Cocq *et al.*, "Modeling and characterization of a few-mode EDFA supporting four mode groups for mode division multiplexing," *Opt. Express*, vol. 20, pp. 27051–27061, Nov. 2012.

[10] M. Salsi *et al.*, "A six-mode erbium-doped fiber amplifier," in *Proc. ECOC*, 2012, paper Th.3.A.6.

[11] N. Bai, E. Ip, T. Wang, and G. Li, "Multimode fiber amplifier with tunable modal gain using a reconfigurable multimode pump," *Opt. Express*, vol. 19, pp. 16601–16611, Aug. 2011.

[12] N. Bai *et al.*, "Mode-division multiplexed transmission with inline few-mode fiber amplifier," *Opt. Express*, vol. 20, pp. 2668–2680, Jan. 2012.

[13] Y. Jung *et al.*, "First demonstration and detailed characterization of a multimode amplifier for space division multiplexed transmission systems," *Opt. Express*, vol. 19, pp. B952–B957, Dec. 2011.

[14] Y. Jung *et al.*, "Three mode Er^{3+} ring-doped fiber amplifier for mode-division multiplexed transmission," *Opt. Express*, vol. 21, pp. 10383–10392, Apr. 2013.

[15] Q. Kang *et al.*, "Accurate modal gain control in a multimode erbium doped fiber amplifier incorporating ring doping and a simple LP_{01} pump configuration," *Opt. Express*, vol. 20, pp. 20835–20843, Sep. 2012.

[16] Q. Kang, E. L. Lim, Y. Jung, F. Poletti, S. Alam, and D. J. Richardson, "Design of four-mode erbium doped fiber amplifier with low differential modal gain for modal division multiplexed transmissions," in *Proc. OFC*, 2013, paper OTu3G.3.

[17] I. Giles, A. Obeysekara, R. Chen, D. Giles, F. Poletti, and D. Richardson, "Fiber LPG mode converters and mode selection technique for multimode SDM," *IEEE Photon. Technol. Lett.*, vol. 24, no. 21, pp. 1922–1925, Nov. 1, 2012.

[18] L. Grüner-Nielsen and J. W. Nicholson, "Stable mode converter for conversion between LP_{01} and LP_{11} using a thermally induced long period grating," in *Proc. IEEE Summer Topical Meeting*, Jul. 2012, pp. 214–215, paper WC1.2.