Gain-controlled erbium-doped fiber amplifier using mode-selective photonic lantern

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ABSTRACT

For the first time, we demonstrate the implementation of a core pumped few mode erbium amplifier utilizing a mode selective photonic lantern for spatial modal control of the pump light. This device is able to individually amplify the first six fiber modes with low differential modal gain. In addition, we obtained differential modal gain lower than 1 dB and signal gain of approximately 16.17 dB at λ_s = 1550 nm through forward pumping the LP21 modes at λ_p = 976 nm.

Keywords: Photonic lantern, mode division multiplexing, amplifier.

1. INTRODUCTION

Current exponential growth in data transmission demands new technologies to efficiently and cost-effectively increase the capacity of single mode fiber based transmission systems [1-3]. New fiber architectures have been proposed to address these problems by utilizing the spatial domain - space division multiplexing (SDM) in few mode fibers (FMFs), multimode fibers (MMFs) and multicores fibers (MCF). In mode division multiplexing (MDM), several spatial modes are propagated simultaneously in the optical fiber, enabling parallel data traffic within a single fiber.

Future SDM transmission systems require new components such as: mode multiplexers and demultiplexers, routing, switching and active elements such as FM Raman amplifiers or few modes Er^{3+} doped fiber amplifiers (FM-EDFAs) [4]. Mode selective photonic lanterns (MSPL) are promising compact all-fiber mode multiplexers for SDM applications [5-7]. Considerable research effort has been focused on improving their fabrication process in order to achieve low-loss devices with minimal mode dependent loss (MDL) and large number of modes. Recently, multiplexing 6, 10 and 15 modes using PL has been demonstrated [7-11].

Furthermore, fiber amplifiers capable of individually amplify several spatial modes are required for long haul SDM transmission systems. For FM-EDFAs, a key challenge is achieving relatively adequate gain with low differential modal gain (DMG) between all the supported spatial modes [12]. Gain equalization is critical to the overall performance of the SDM transmission system as high DMG results in system outrage. However, the signal mode that possesses the strongest overlap with the pump light experiences the highest gain. Tailoring the modal content of the pump has been used to achieve equal gain for all signal modes [12, 13]. While this approach is promising, previous implementations have relied on free space optics, which comes with drawbacks when highly efficiency and robust optical systems are required.

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MSPLs can be straightforwardly integrated into a FM-EDFA system to achieve the required spatial control of the pump light. This approach offers several advantages over previously reported bulk optics based demonstrations. In addition, PLs are nearly lossless, can support a large number of modes [5, 7, 14], and can be directly spliced to the active fiber [11].

Here, we demonstrate the use of a MSPL for mode selective excitation and pump profile control in a core pumped FM-EDFA. The proposed scheme replaces all free space components, allowing the implementation of a novel few mode amplifier systems with reconfigurable gain. We present a six mode EDFA with low differential modal gain through mode selective pumping using the MSPL.

2. EXPERIMENT

2.1 Mode Selective Photonic Lantern Multiplexer

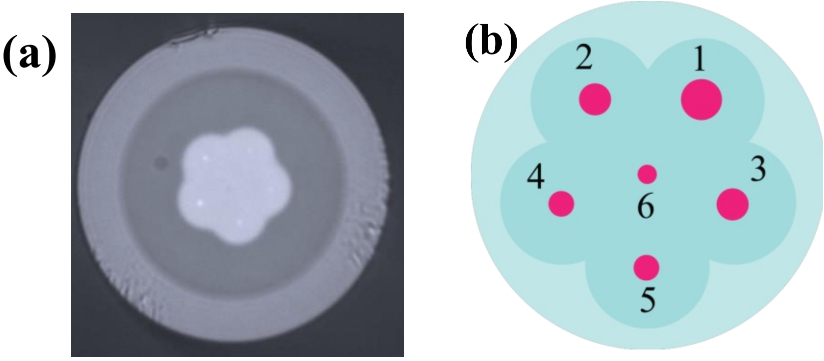

Figure 1. – (a) Fabricated and (b) designed cross section of a six mode MSPL, indicating the core position of the 6 fibers.

The structure of a MSPL that supports the first four spatial LP modes (LP_{01a}, LP_{11a}, LP_{11b}, LP_{21b} or LP_{02}) is shown in Fig. 1(b). The device was fabricated following the geometrical configuration and engineering process summarized in [6]. The devices were optimized in order to reduce mode dependent losses.

The MSPL consist of six fibers adiabatically tapered inside a fluorine-doped capillary, creating a few mode fiber at the taper waist. Table 1 summarized the fibers used for the MSPL fabrication, fibers with four dissimilar core sized are used. The adiabatic transition constrains can be considerable relaxed by using optical fibers with graded index profiles [6, 14]. For this reason, fibers with graded index cores were used. The refractive index contrast of the cores and the fluorine-doped silica capillary are $\Delta n = 16X10^{-3}$ and $\Delta nF = -9X10^{-3}$, respectively. The taper ratio was 1:8.

Table 1. Core diameter and fiber position of the six fibers used for PL fabrication and the corresponding mode generated.

Mode	**LP_{01}**	**LP_{11a}**	**LP_{11b}**	**LP_{21a}**	**LP_{21b}**	**LP_{02}**
Core diameter (µm)	22	18	18	15	15	06
Position	1	2	3	4	5	6

Previously to the amplification experiment, light at λ_s = 1550 nm and λ_p = 760 nm was coupled into each branch of the MSPL to characterize the generated spatial field profiles. Fig. 2 shows the near field profile at the output facet of the MSPL captured using an infrared camera (Xeniths Xeva 5191). Clear excitation of each mode was observed at both wavelengths.

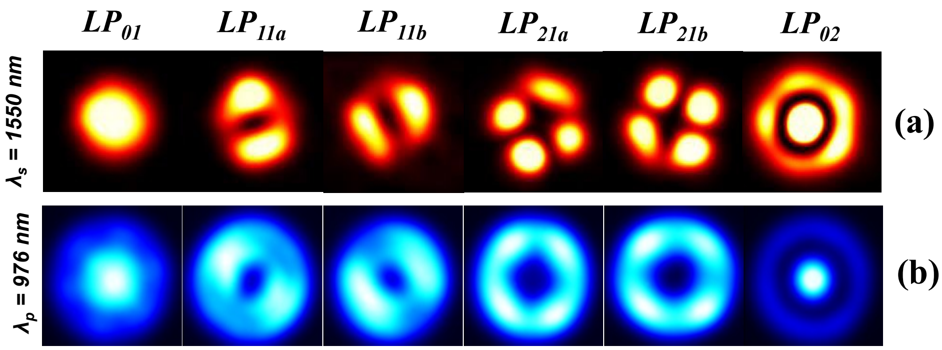

Figure 2. – Near field of the excited mode at the output of the fabricated MSPL at (a) λ_s = 1550 nm and (b) λ_p = 9760 nm.

2.2 FM-EDFA Experimental Setup

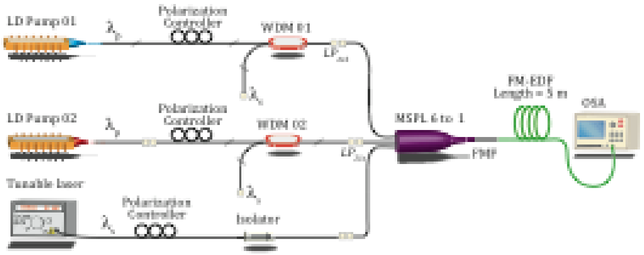

Figure 3. – Schematic diagram of six mode EDFA pumped by the LP21 modes. The MSPL 6 to 1 generates the pump and signal modes.

The schematic diagram of the MSPL integrated with the FM-EDFA is shown in Fig. 3. Two laser diodes (LDs) at λ_p = 976 nm are connected to the MSPL through a polarization controller and a WDM (976 / 1550 nm). Each LD excites, with the fundamental mode, the corresponding LP_{21} mode of the MSPL that are used to co-directionally core pump the FM-EDFA.

A tunable semiconductor laser (Santec TSL-210) was used to provide the signal. An optical isolator was placed in the signal path to avoid spurious optical reflections that could destabilize the laser. In a similar configuration, the delivered signal was coupled into one MSPL input branch to selectively transform and amplify each of the six supported modes (LP_{01a}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b} or LP_{02}). The output end of the MSPL was spliced to 1 m of a FMF with core / cladding diameter of 16 / 125 µm with the finally of reduced the coupled losses. Finally, the FMF was spliced to a 5 m FM-EDF. For the modal gain measurements, the pump and signal were separated using a band pass filter and the output power was determined using an OSA.

2.3 Results and Discussion

The measured modal gain as a function of the pump power launched in LP_{21a} and LP_{21b} modes is presented in Fig. 4. Each mode was individually amplified at λ_s = 1550 nm. The signal input power was 0.1 mW for all modes measured at the input of the MSPL.

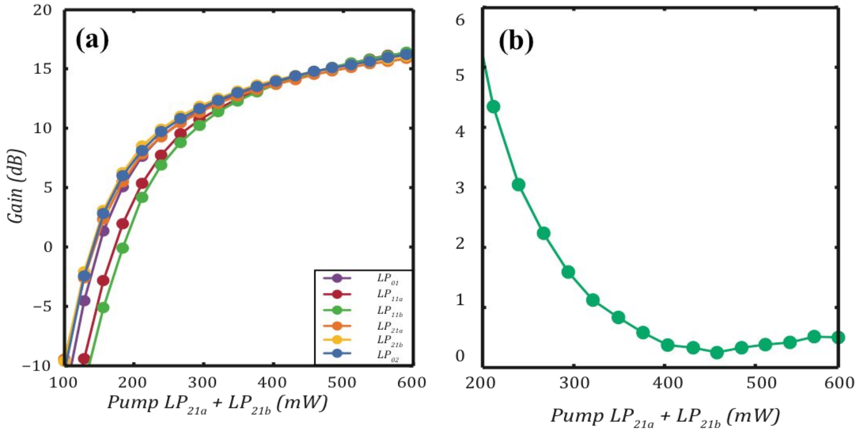

Figure 4. – (a) Measured individual modal gain and (b) DMG as a function of the input pump power at λ_s = 1550 nm.

As observed in Fig. 4 (a) every mode reached around 16.17 dB gain for pumping powers higher than 570 mW. It is clearly observed that the LP_{01}, LP_{21b} and LP_{02} modes reached higher gain than the rest of the modes at low pump powers. For pump power higher than 350 mW we can observe that DMG between the modes is decreasing as the pump power is increasing, see the Fig. 4 (b). The obtained DMG laid between 0.25 to 0.83 dB for pumping powers larger than 350 mW, as seen in Fig. 4(b). Furthermore, for a pump power of 570 mW, the measured DMG was 0.51 dB.

The amplified signal and pump modes were characterized by capturing their transverse mode profiles using an infrared camera (Xeniths Xeva 5191). Figure 5 shows the measured signal after and before amplification at the output of the 5 m long FM-EDFA. As compared from Fig. 2(a) and Fig. 5(a), the amplified spatial modes are well preserved after their propagation in the FM-EDFA. Additionally, same mode preservation is observed after amplification, as observed in Fig. 5.

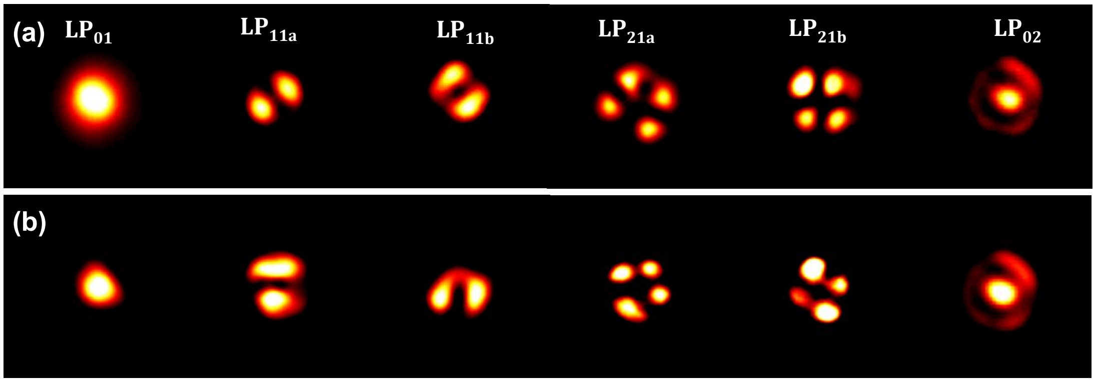

Figure 5. (a) Signal modes (a) previous to the amplification, (b) after the amplification working at λ_s = 1550 nm at the output of 5 m of EDFA.

3. SUMMARY

We demonstrate for the first time, the use of MSPL as a multiplexer element in a six mode EDFA. The proposed PL-EDFA is a scalable and simple all-fiber system with the possibility of providing reconfigurable modal gain control. We obtained individual modal gain values ~ 16.17 dB with relatively low DMG at 1550 nm. It is expected that the DMG values can be minimized by optimizing the modal content of the pump or using a superposition of modes, such as pumping using ($LP_{21} + LP_{02}$).

4. ACKNOWLEDGMENTS

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