Few-mode multi-element fiber amplifier for mode division multiplexing

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Abstract: We experimentally demonstrate a few-moded cladding-pumped multi-element fiber amplifier, comprising 4 Er/Yb co-doped signal fibers and 1 multimode pump-delivery fiber all of which are drawn together in a common polymer coating, providing a total spatial path multiplicity of 12. An average WDM signal gain of 18.3 dB and differential modal gain of 1.1 dB were achieved in the spectral range of 1542-1560 nm.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (060.0060) Fiber optics and optical communications.

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1. Introduction

Space division multiplexing (SDM) [1–3] has generated significant interest within the fiber optics community as the next potential breakthrough technology to address the anticipated telecoms 'capacity crunch'. Various approaches such as multi-mode fiber (MMF) [3], ring-core fiber [4], multicore fiber (MCF) [5–7], hollow-core photonic bandgap fiber [8], and multi-element fiber (MEF) [9–12] have been introduced over the past few years to enable the development of high capacity transmission networks using multiple spatial channels. Recently, fiber technologies combining two or more of the above mentioned approaches have been proposed in order to further increase the transmission capacity. Few-mode multicore fiber is one such example whereby each core in a MCF can accommodate multiple modes, and a spatial multiplicity of 36 was recently demonstrated, employing 3-modes per core in a 12-core MCF [13]. Distributed inter-core crosstalk is a primary concern in any SDM systems based on MCF and, whilst trench assisted and hole assisted core designs offer reduced levels of cross-talk and hence increased core densities [14,15], mechanical reliability issues constrain the maximum outer diameter of the fiber and hence the ultimate achievable spatial multiplicity. The development of complex, high performance multiplexers/demultiplexers, as well as accurate splicing is also essential to ensure low levels of crosstalk between neighboring cores. Moreover, until now, SDM amplifiers supporting few-mode MCFs have not yet been demonstrated. MEF, comprising multiple fiber-elements in a common polymer coating appears an attractive alternative to MCFs in many instances due to the ultralow crosstalk levels (less than −80dB in 9.5km of passive MEF [9]) between individual cores, simple fan-in, fan-out multiplexing (access to individual cores is obtained simply by stripping-off the polymer coating) and practicality in terms of amplifier construction. We have previously fabricated and characterized passive single-mode MEFs for SDM data transmission [9]. Both core-pumped and cladding-pumped MEF amplifiers have also been demonstrated, with up to 7 fibers in a single assembly [10–12]. In order to increase the capacity for future SDM networks, the number of spatial channels needs to be further increased and the introduction of a few-mode core in a MEF structure can help further increase the capacity by taking the benefit of two spatial multiplexing schemes (MMF and MEF). To realize such an SDM system, a few-mode MEF amplifier is an essential subsystem to be developed.

In this paper, we present the first demonstration of a 3-moded cladding-pumped MEF amplifier comprising 5 fiber elements (4 Er/Yb doped signal fiber-elements and 1 central multimode pump-delivery fiber-element) to scale up the spatial multiplicity. Pump couples into the signal fiber-elements via evanescent coupling throughout the length of the fiber if optical contact is maintained [16]. It was verified that the signal fiber-elements maintained optical contact by inspecting the cross-section image at multiple points in 4m of fiber length. Each fiber element can amplify three spatial modes (LP_{01}, LP_{11a}, and LP_{11b}) yielding an overall multiplicity of 12 (3 modes x 4 signal fiber-elements). An average signal gain of 18.3dB and differential modal gain in the range of ~1-6dB were achieved in the wavelength range 1542-1560nm at an input signal power of −12.5dBm per channel. The detailed WDM performance for various pump powers and input signal powers has also been investigated.

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2. Experiment setup of 3M-MEFA

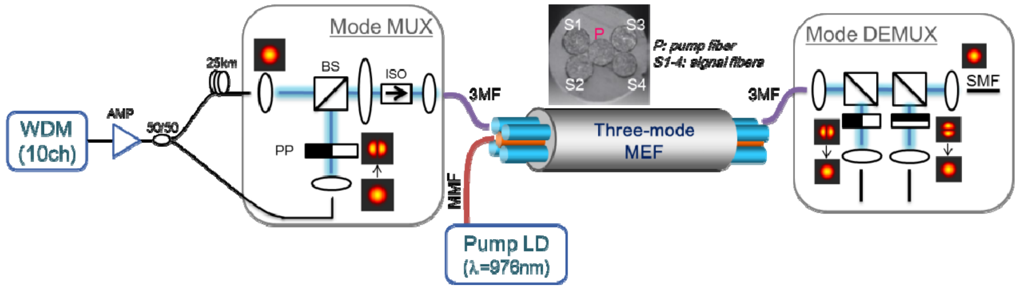

Fig. 1. Schematic diagram of 3-moded cladding pumped multi-element fiber amplifier (3M-MEFA) comprising 4 Er/Yb co-doped signal fibers and 1 multimode pump fiber. (BS: Beam splitter, PP: Phase plate, ISO: isolator, AMP: amplifier, 3MF: 3-moded passive fiber).

Figure 1 shows the schematic of the setup used for the characterization of the 3-moded cladding pumped MEF amplifier (3M-MEFA). Each signal fiber-element has a cladding diameter of 80µm and a core diameter of ~8µm with a step-index refractive index profile (NA~0.17-0.20), which can guide up to three spatial modes (LP_{01}, LP_{11a}, and LP_{11b}). The fiber-elements were coated with a common low-index polymer coating (n~1.373) to obtain a double-clad fiber design and thereby enabling the possibility to use a low cost, high-power, multimode laser diode as a pump laser operating at a wavelength of 976nm. The cores of the signal fiber-elements were co-doped with Yb to enhance pump absorption. A cladding pump absorption of 2.2-4.1 dB/m was measured at 976nm. The signal source used in the setup consisted of 10 wavelength multiplexed external cavity lasers spread over the range 1536-1560 nm. The wavelength division multiplexed (WDM) channels were pre-amplified, split into two and fed into the mode multiplexer to allow the gain performance of the individual amplifier elements to be measured. A 25km single mode fiber span was inserted along the LP_{01} path to minimize modal beating due to the high degree of coherence between the seed lasers. A phase-plate based mode multiplexer was used to selectively excite the pure LP_{01} and LP_{11} signal modes in a 10m long passive 3-moded fiber (3MF). The passive fiber (a graded index fiber with 16µm core diameter and an NA of 0.14, OFS Denmark) was then spliced directly to one of the Er/Yb-doped elements of the 3M-MEF. The amplified output was fed into the mode demultiplexer to analyze the mode dependent gain quantitatively. The large mode field diameter mismatch between the passive and active fibers resulted in a mode dependent splice loss (~1.1dB for the LP_{01} and ~2.5dB for the LP_{11} mode). The 105/125µm pigtail of the 976nm multimode pump laser was adiabatically tapered down to 80µm and fusion spliced to the central pump fiber element of the 3M-MEF. The pump light gradually coupled from the pump element into the 4 surrounding Er/Yb-doped fiber elements through evanescent field coupling and is steadily absorbed by the rare-earth ions within the FMF cores.

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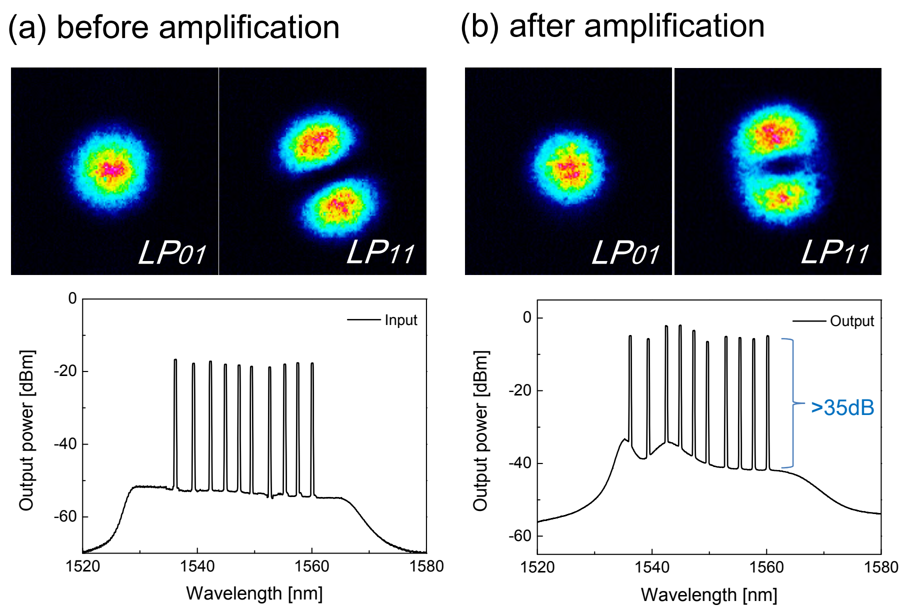

Fig. 2. Measured mode images and optical spectra before (a) and after (b) amplification.

To confirm clean mode amplification of the input signals, mode images were taken using a charge coupled device (CCD) camera before and after amplification at 1550nm. The top row of Fig. 2 shows that two clean spatial modes (LP_{01} and LP_{11}) were excited in the passive 3MF and that the mode quality was well preserved during amplification. The bottom row of Fig. 2 shows the optical spectra of the WDM signals (LP_{01}) before and after the 3M-MEFA demonstrating more than 35 dB optical signal to noise ratio (OSNR) after amplification. The length of the amplifier was chosen to be 3.25 m in order to maximize the signal gain whilst maintaining near full C-band operation. The gain peak of the amplifier was located at 1545 nm.

3. Gain performance of 3M-MEFA

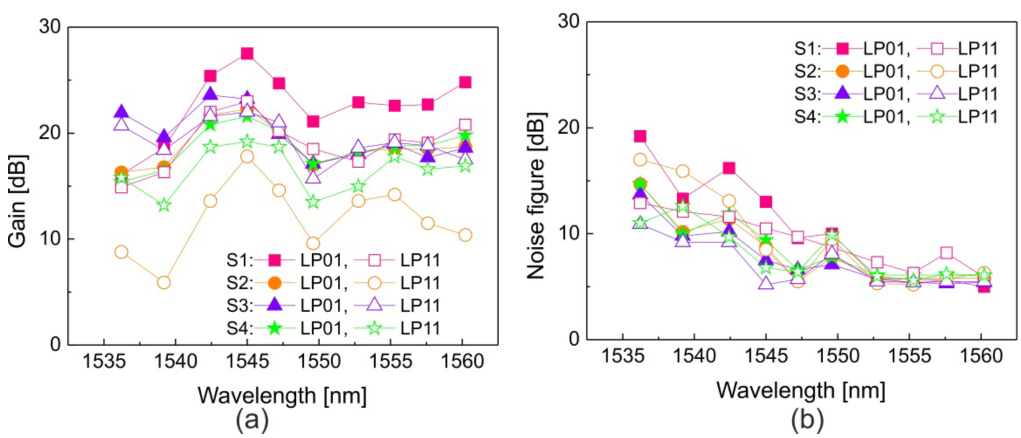

Fig. 3. (a) Gain and (b) noise figure spectra for 4 different signal fiber elements of the 3M-MEFA for an input signal power of −12.5dBm/ch and pump power of ~7.6W.

Figure 3(a) and 3(b) shows the WDM gain and noise figure (NF) spectra for all 4 different signal fiber elements of the 3M-MEFA, referred as S1 to S4, measured consecutively over all

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active fiber elements. A maximum pump power of 7.6W and an input signal power of −2.5dBm per mode (total signal input power of 0.5dBm) were used. An average WDM signal gain of 18.3dB was measured in the spectral range of 1542-1560nm. The NF was found to increase sharply for wavelengths shorter than 1542nm while it tends to decrease at longer wavelengths. The high NF at short wavelengths is mainly due to insufficient population inversion within the active medium and which is clearly evident from the sharp drop in signal gain. We observed large gain variation amongst the different elements, which is mainly due to the variation in core refractive index profiles and rare-earth doping concentrations of the non-identical preform elements used. This could certainly be improved through further optimization of the preform fabrication process. The LP_{01} signal mode experienced higher gain than the LP_{11} mode and the differential modal gain (DMG) between the two guided modes varied by 1-6dB over all 4 active fiber elements. Note that we used a simple step-index core design in the current fibres so this level of DMG is not unexpected, however careful tailoring of the doping profile within the individual elements (as illustrated in [17]) could certainly help in reducing the DMG in few-mode cladding-pumped MEFAs. Also there was no measurable inter-core crosstalk above the ASE levels observed between the neighboring fiber elements which is in agreement with our earlier observations [9,10]. It was not possible to measure the crosstalk below the ASE level due to the high loss in the unpumped cores at the signal wavelengths. As shown in Fig. 3, fiber element-3 (S3) shows the best performance in terms of differential modal gain (average DMG ~1.1dB, maximum DMG ~3dB) and spectral gain flatness across the C-band and as such the detailed gain profiles for various pump power and input signal power levels were investigated for this element.

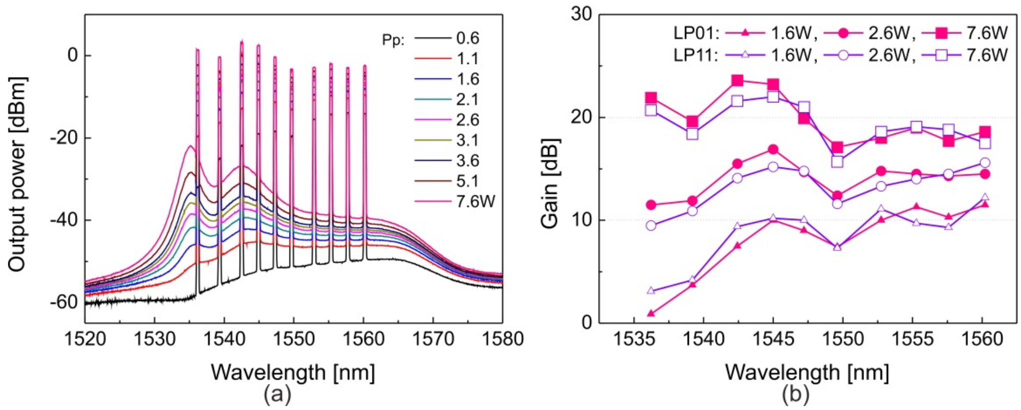

Fig. 4. (a) Output spectra of the LP_{01} mode after the mode demultiplexer and (b) mode-dependent gain for different pump powers with an input signal power of −2.5dBm/mode (or −12.5dBm/ch).

Figure 4(a) and 4(b) shows the output spectra and the mode dependent gain as a function of pump power at a fixed input signal power of −2.5 dBm/mode. As shown in Fig. 4(a), for low pump power (~0.6 W) the amplified spontaneous emission (ASE) peak is located at ~1565 nm and it shifts towards the shorter wavelength side with increasing pump power. A similar trend can be observed in the measured modal gain of the amplifier shown in Fig. 4(b). At low pump power the gain at the short wavelength edge was measured to be very low due to an insufficient inversion level. As the pump power was increased from 0.6 W to 7.6 W, the gain of each of the guided modes increased due to the increased level of population inversion. It should be noted that the gain increment at the shorter wavelengths is higher compared to longer wavelengths resulting in a shift of gain peak from 1560 nm to 1545 nm.

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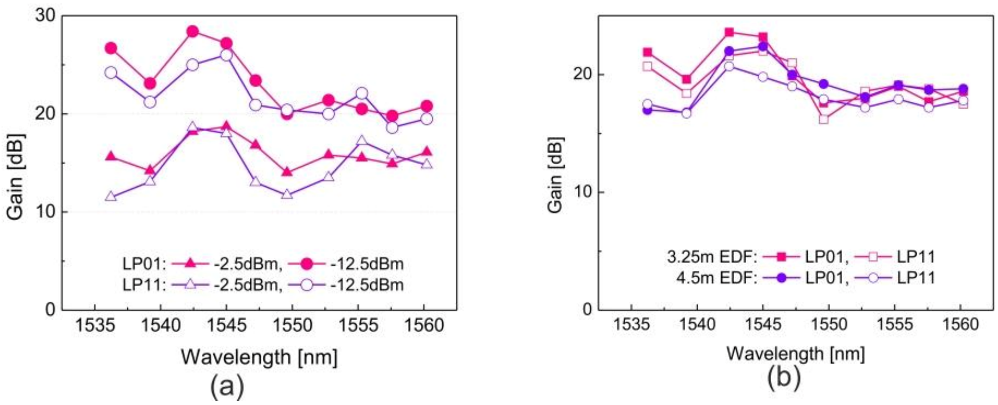

Fig. 5. (a) Mode-dependent gain for different input signal powers per mode at a fixed pump power of 3.6W for 3.25m of fiber, and (b) gain comparison between two different fiber lengths (3.25m and 4.5m) at a fixed pump power of 5.1W.

Figure 5(a) shows the amplifier gain variation for −2.5dBm and −12.5dBm input signal powers per mode at a fixed pump power of 3.6W. Both spatial modes experienced gain reduction with an increase in input signal power due to amplifier gain saturation. The DMG did not show much dependence on the input signal power and the maximum DMG remains at ~3dB for all the input signal powers investigated. We also investigated the length dependence of our 3M-MEFA. Figure 5(b) compares the gain spectra for two different fiber lengths (3.25m and 4.5m), for similar input signal powers (−2.5dBm and −3.3dBm per mode for 3.25m and 4.5m respectively) but at a fixed pump power of 5.1W. It can be seen that 3.25m fiber exhibited about 5dB higher gain in the shorter wavelength region as compared to that of the 4.5m fiber indicating that the gain at shorter wavelength can be increased by optimizing the fiber length.

4. Conclusions

We have successfully demonstrated for the first time a few-mode multi-element fiber amplifier for space division multiplexed systems. An overall spatial multiplicity of 12 (3 spatial modes × 4 signal fiber-elements) was obtained. An average signal gain of 18.3dB and differential modal gain of ~1-6dB were achieved in the wavelength range of 1542-1560nm. This architecture can be further scaled both in terms of the number of elements and number of modes per-element. Improvements in gain differential between elements and modes can also be envisaged by tailoring the rare-earth doping profiles of the optical fiber. Improvements in NF should also be achieved by optimizing the element diameter/length and increasing the pump brightness.

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