Detailed study of modal gain in a multimode EDFA supporting LP_{01} and LP_{11} mode group amplification

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Abstract: We demonstrate simultaneous modal gains of ~20dB for different pair-wise combinations of spatial and polarization modes in a MM-EDFA. The differential modal gains are reduced by fiber design and control of the pump field distribution.

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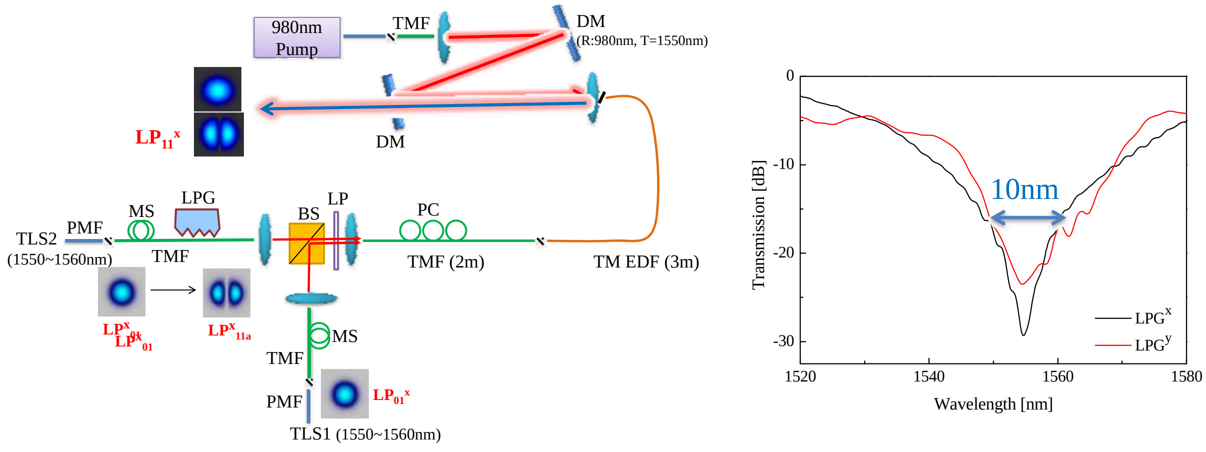
1. Introduction

There are concerns that radically new fiber designs and network architectures will soon be required in order to keep up with exponential growth of internet traffic in the backbone network in a cost effective manner [1]. Spatial division multiplexing (SDM) schemes employing either multi core fibers (MCFs) or multi-mode fibers (MMFs) have been recently proposed and successfully demonstrated [2,3]. SDM in principle allows upscaling of the capacity per fiber by a factor proportional to the number of cores or modes. However suitable in-line optical amplifiers will clearly need to be developed if SDM is ever to be used in long haul networks. We very recently reported the demonstration of a multimode fibre amplifier for use in SDM systems. In these first experiments we demonstrated the simultaneous amplification of two signals propagating on two separate modes of different order and with orthogonal polarization (namely the LP^x_{01} and LP^y_{11a} modes). Gains of > 22dB were obtained for both modes using a fibre with an optimized refractive index/erbium ion distribution profile and suitable pump profile [4].

Clearly, in order to exploit the full potential of such an amplifier it is essential to be able to simultaneously amplify signals in all spatial and polarization modes supported by the amplifier i.e. 6 modes altogether in our particular fiber (which supported two transverse mode groups). Here we extend our previous work to demonstrate the simultaneous amplification of LP^x_{11a} and LP^y_{11b} (different polarization, different high-order transverse mode) as well as LP^x_{01} and LP^x_{11} (same polarization, different transverse mode group), achieving similar gains and differential modal gains to those achieved for the mode combinations investigated previously. Our results highlight the potential for simultaneously achieving well matched gains for all 6 guided modes through fiber design and suitable pump excitation.

2. Experimental results



(a) (b)

Fig. 1 (a) Experimental setup to characterize TM-EDFA. LD: Laser Diode, PMF: Polarization Maintaining Fiber, MS: Mode Stripper (LP_{11}), TMF: Two Moded Fiber, LPG: Long Period Grating, HWP: Half Wave Plate, PBS: Polarization Beam Splitter, PC: Polarization Controller, DM: Dichroic Mirror, TM-EDF: Two Mode-Group Erbium Doped Fiber; (b) Typical transmission curve of the mechanical LPGs.

Fig. 1 shows the experimental setup for simultaneous amplification of the orthogonal polarization modes of the LP_{11} mode group. Two external cavity tunable laser sources (TLS) were used as seed sources. The single-mode, single-polarization outputs of the TLSs were spliced to passive two mode fibers (TMFs). The TMF has a core diameter of 19.7μm and a numerical aperture (NA) of 0.12 and effectively guides only two transverse mode groups, namely the LP_{01} and LP_{11} mode groups (comprising 6 distinct modes including all degeneracies and polarizations). Mechanical long period gratings (LPGs) were applied to the TMF to convert light in the LP_{01} mode to the LP_{11} mode. The asymmetrical deformation used can be used to selectively excite one of the spatial modes (LP_{11a}, LP_{11b}) of the second-order mode. The x-polarized fundamental mode (LP^x_{01}) can couple to the second-order LP^x_{11a} mode when the asymmetrical deformation occurs in the vertical direction (LPG^x) and LP^y_{01} can couple to LP^y_{11b} with the deformation applied in the horizontal direction (LPG^y). Typical transmission curves of the two mechanical LPGs are plotted in Fig. 1b showing that an extinction ratio of > 20dB between the LP_{01} and LP_{11} modes could be achieved. (The difference between the two transmission curves was due to differences in the quality of the two mechanical gratings/pressure rigs used). Initially, for ease of demultiplexing at the output of the amplifier, we considered only the x-polarized LP_{11a} mode (LP^x_{11a}) and y-polarized LP_{11b} mode (LP^y_{11b}). The LP^x_{11a} mode from TLS1 and LP^y_{11b} from TLS2 were polarization multiplexed using a polarization beam splitter (PBS) and coupled into a second length of passive TMF. The launch end of the TMF was flat cleaved to enable clean excitation of the fiber modes (this has the slight downside that it leads to an increased buildup of amplified spontaneous emission (ASE) at the amplifier output at low input signal powers). The output of the input length of passive TMF was analyzed to assess the degradation in polarization extinction ratio (PER) between the two orthogonal modes as well as any mode cross-coupling during the free space coupling. A PER in excess of 20dB was measured for both modes which is adequate to allow accurate modal gain measurements. The passive fiber was then spliced directly to a 3m length of mode-matched Er^{3+}-doped active fiber which was designed to have a higher Er^{3+}- density at the edges of the refractive index profile so as to have reduced modal gain sensitivity to the pump field (Fiber #2 in ref [4]). A 980nm fiber pigtailed diode laser was used to pump the active fibers and was free-space coupled into the TM-EDF using dichroic mirrors. The free ends of the active fibers were angle cleaved to suppress Fresnel reflections and a second PBS was used at the output of the amplifier to separate the two orthogonal polarization modes. The amplified output power depends on the pump mode and an offset pump launch scheme was used in our experiment to ensure better spatial overlap between the signal and the pump modes [4]. As shown in the CCD images in Fig. 2(a), two spatial modes of the second-order mode (LP^x_{11a} and LP^y_{11b}) can be cleanly demultiplexed at the output of the TM-EDF. The gains for both LP^x_{11a} and LP^y_{11b} were measured to be ~20dB for an input signal power of -10dBm and a launched pump power of ~200mW. The wavelength tuning was limited to ~10nm due to the limited bandwidth of the mechanical LPGs. Fig. 2(b) shows the amplifier gain as a function of input signal power for offset launch conditions. Both modes experienced gain reduction with an increase in input signal powers as illustrated in Fig. 2b. The CCD images of the two modes are well defined at high signal input powers however the quality of the images degraded with decreasing input signal power due to the increasing dominance of unpolarized ASE light in both the transverse modes and which appears in both arms after the PBS.

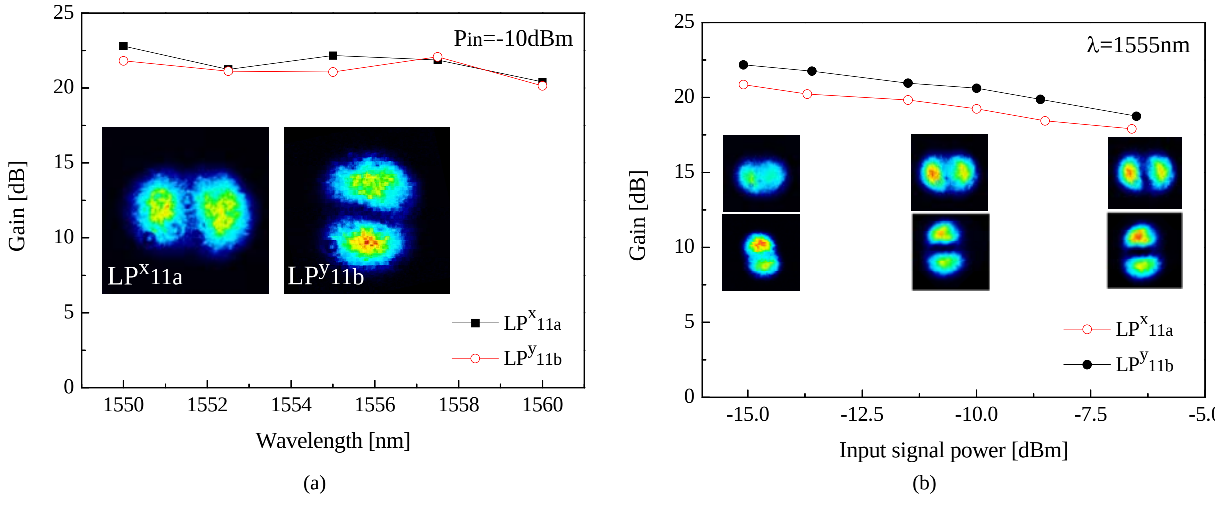
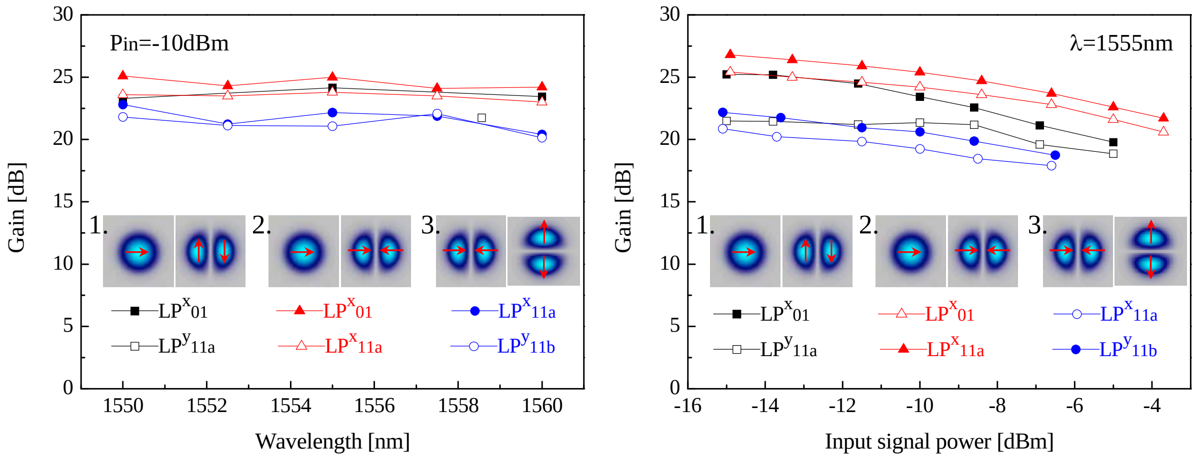


Fig. 2 Gain for LP^x_{11a} and LP^y_{11b} modes as a function of (a) wavelength and (b) input signal power for offset pump launch condition

We have also studied the modal amplification of the two transverse mode groups along the same polarization axis i.e. LP^x_{01} and LP^x_{11a} modes. In this case we replaced the polarization beam splitter (PBS) with a polarization insensitive beam splitter (BS) at the input end of the amplifier. A linear polarizer was added prior to the passive TMF to ensure single polarization excitation. To estimate signal gain, a 2nm bandpass filter was used to measure the amplified output power of the amplified individual modes (set with a wavelength separation of 5nm). Two different pumping schemes (center launch and offset launch) were used to study the effect of pump launch conditions on the modal gains. Typical results from these experiments for offset pump launch conditions are plotted in Fig.3a and b (along with data reported above and previously in reference [4] for other pairwise combinations of modes). In Fig.3a we plot the gain as a function of signal wavelength and in Fig.3b we plot the gain as a function of signal power for fixed pump power. Note that unfortunately there is some variation in launched pump power for the different experiments (launched pump power increased from ~200mW whilst studying the mode groups 1 & 3 to ~275mW for mode group 2 due to variation in launch efficiency) which slightly complicates comparison of the various data sets, however it is clear that gains of order 20dB are possible in two channel experiments for all modal combinations investigated with differential modal gains of order 4-5dB. Our experiments are still in train and it may be possible to reduce the gain differentials by further optimizing the pumping arrangement and we certainly believe that further iterations on the fiber design will bring yet further improvements.



(a) (b)

Fig. 3 Gain for pairwise combinations of modes as a function of (a) wavelength and (b) input signal power for offset pump launch condition

3. Conclusions

We report further characterization work on a MM-EDFA for SDM transmission and show that >20 dB gains can be achieved with modest gain differentials for different pairwise combinations of modes (specifically LP^x_{11a} and LP^y_{11b}, LP^x_{01} and LP^x_{11a} and LP^x_{01} and LP^y_{11a} mode combinations). Our results indicate that it should be possible to simultaneously amplify all 6 guided modes with 20dB or better small signal gain – which we hope to demonstrate in due course once a suitable mode mux/demux set up is available to us).

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4. References

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