Multi-mode Optical Fiber Amplifier Supporting over 10 Spatial Modes

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Abstract: We demonstrate a multimode cladding-pumped fiber amplifier that supports 10 modes with 2-dB mode-dependent gain, 20-dB gain, and 25-dBm output power. The mode-dependent gain is minimized using an oversized core supporting additional modes.

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1. Introduction

Multi-mode and multi-core erbium doped fiber (EDF) optical amplifiers can amplify many spatial channels in a single optical fiber. This simplicity enables space-division multiplexed (SDM) communication systems to scale to a large number of spatial-channels while reducing the complexity and costs per spatial-channel. Some notable amplifiers include a 19 core amplifier with core pumping [1], a 7 core amplifier with cladding pumping [2], and a six mode amplifier with cladding pumping [3].

The simplest multi-spatial channel amplifier is a uniform doped core that supports multiple modes and recent SDM transmission experiments using 10 and 15 spatial modes [4, 5] indicate the need for amplifiers supporting at least 10 spatial modes. However, a uniform doped amplifying core has large mode-dependent gain (MDG) because the signal and pump modes have different transverse profiles and therefore non-uniform overlaps with the gain medium. Researches have employed complex MDG minimizing schemes such as tailoring the pumping spatial mode content

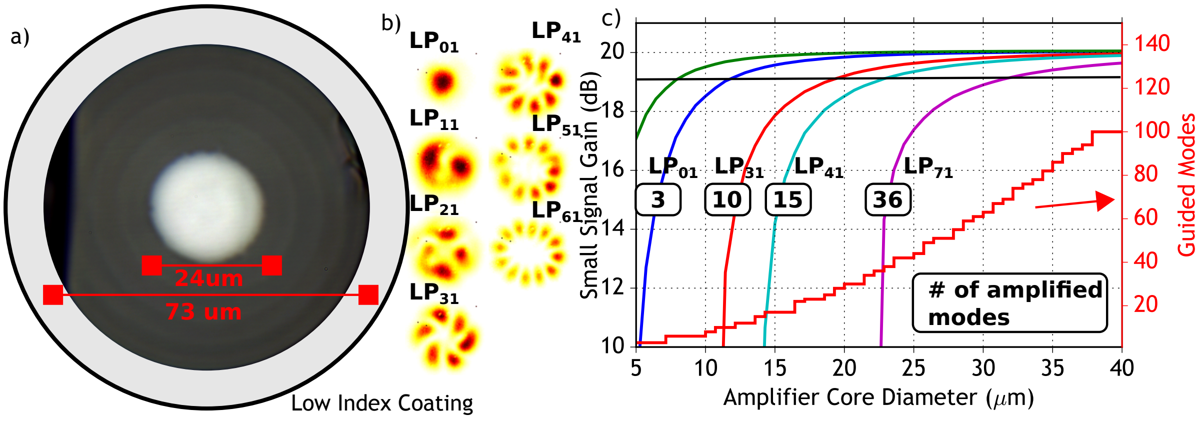

Fig. 1: a) Er-doped fiber facet image. b) Modes from each mode group. c) Mode dependent small signal gain vs. amplifier core diameter for different mode groups. The refractive index step is 2.3×10^{-3}.

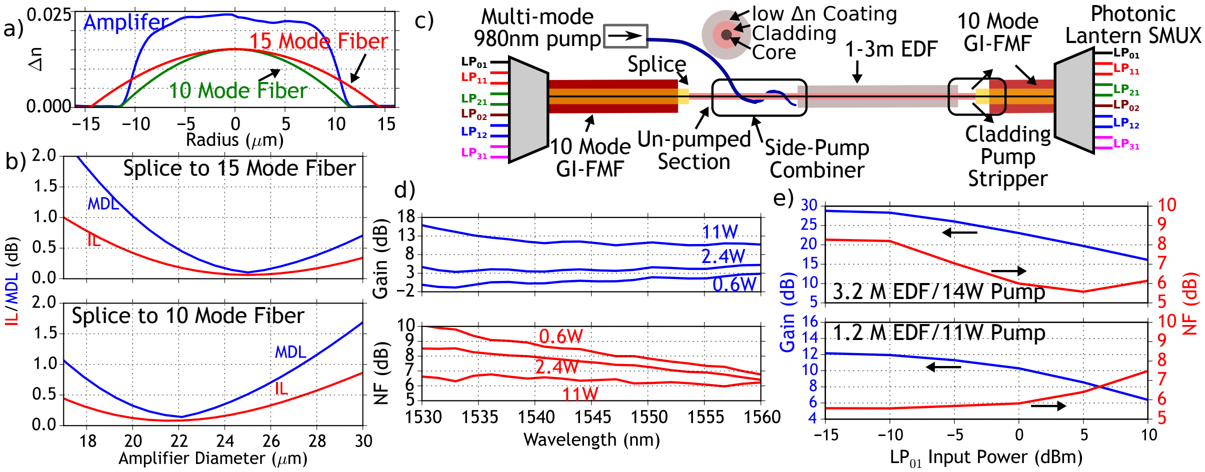

Fig. 2: a) Measured refractive index profiles. b) Simulated splice loss between amplifier and transmission fiber. c) Amplifier characterization. d) Gain and noise figure for 1.2-m EDF under different coupled pump powers. e) Gain and noise figure at 1550 nm vs. signal input power.

using multiple pumps in different modes [6, 7], incorporating complex doping profiles into the fiber design [6], and using external mode equalizers. Here, we present a much simpler scheme to minimize the MDG that is compatible with cladding pumping by intentionally oversizing the core to support many more modes than required. This ensures that the desired amplified modes are well confined inside the core to maximize each modes overlap with the gain, and the cladding pumping ensures that the gain medium is illuminated uniformly. Despite of the fact many more modes are supported, the performance is not degraded because mode mixing is negligible in the short amplifying fiber. We demonstrate amplification of 10 spatial modes with MDG below 2 dB and output power of 25 dBm.

2. Amplifier Fiber Design to Minimize Mode-Dependent Gain and Splice Loss

The amplifier is designed to minimize both MDG for up to 15-spatial modes and mode-dependent loss (MDL) when spliced to the transmission fiber which is typically graded-index (GI) to minimize the differential group delay [8]. Fig. 1a) shows the facet image of the Er-doped fiber. The core has a diameter of 22-24 μm, a refractive index (RI) difference of 2.3×10^{-3} with respect to the cladding and supports approximately 26-28 spatial modes. Fig. 1b) shows measured mode profiles at the output of a 2-m EDF for mode groups 1 through 7. To guide multi-mode pump light in the cladding, the polymer coating has a numerical aperture (NA) of 0.46 with respect to the glass cladding. The cladding diameter is restricted to 73 μm to enhance the pump intensity. The erbium ion concentration is $4.5\times10^{25}\text{m}^{-3}$ and can provide a maximum gain around 10 dB/m at 1550 nm.

Fig. 1c) shows a simulation of the small signal MDG for different modes in a uniform doped core for a target LP_{01} gain of 20 dB assuming uniform illumination of the gain material using cladding pumping. It is calculated as $\exp(2gL\Gamma_{ij})$ where Γ_{ij} is the overlap integral of mode LP_{ij} with the core and gL (gain $\times$ length) is a scaling factor to adjust the LP_{01} gain to 20-dB. When the gain is above 19 dB for the amplified modes, the MDG is less than 1 dB. 1-dB MDG is achieved for 10(15) modes with the amplifying core supporting 20(28) modes, respectively.

Any improvements by minimizing the MDG are undone if it is difficult to eliminate MDL at the splice to the GI transmission fiber. Fig. 2a) shows the refractive index cross section of the amplifier and a 10 and 15 mode transmission fiber [8]. Fig. 2b) shows the simulated MDL and insertion loss (IL) for splices to a 10 and 15 mode GI fiber indicating that an amplifying core of 24 μm will have splice induced IL and MDL well below 1 dB.

3. Gain and Noise Figure Measurements of the Fundamental Mode

The amplifier noise figure (NF), gain, and saturated output power are characterized by launching and receiving the LP_{01} mode. Fig. 2c) shows the setup for testing the amplifier. Mode-selective photonic lanterns spatial multiplexers (SMUXes) spliced to a 5 m piece of 10 mode GI fiber are used at the input and output to couple single-mode fibers (SMF) to all the modes of the amplifier [9]. Side pumping [10] is used to couple the multi-mode pump light into the cladding modes (60% efficient) and eliminates the need for any wavelength dependent components.

Fig. 2d) shows the gain and NF for a 1.2-m EDF under different pump powers. Approximately 11 W of 980-nm pump power can fully invert the gain which is indicated by the large gain at 1530-nm and flat external NF of 6 dB (does not include some unknown coupling losses). Fig. 2e) shows the gain and NF under different signal powers at 1550 nm

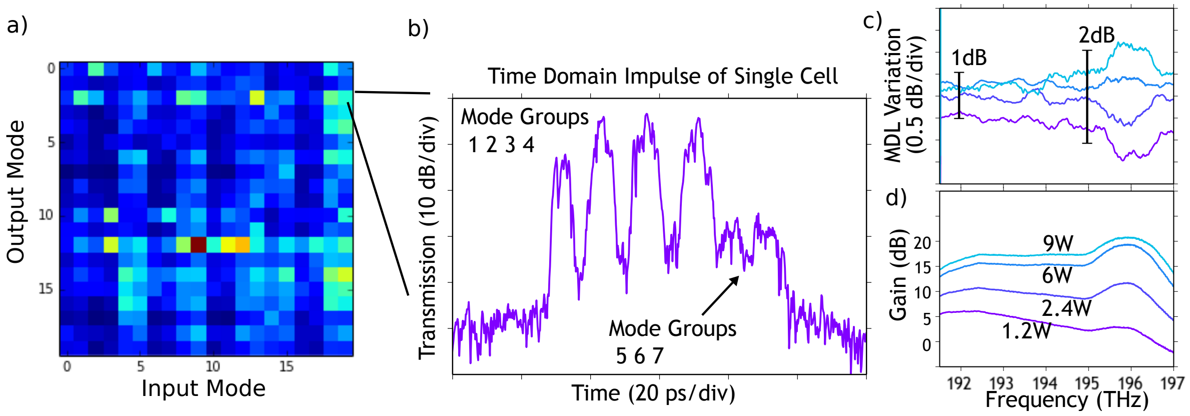

Fig. 3: Mode-dependent gain measurements for 10 spatial modes of a 1.6-m EDF. a) Transfer matrix, b) impulse response, c) mode dependent loss/gain, and mode averaged gain.

for a 1.2-m and 3.2-m EDF. The 3.2-m EDF can achieve over 25 dBm output power with input power between 5 and 10 dBm, however its NF performance suffers due to self-saturation of the input from backwards amplified spontaneous emission (ASE) which improves slightly as the input signal power is increased. From these results, the optimal EDF length for a transmission amplifier (20-dB gain and low NF) is around 2 m.

4. Mode Dependent Gain Measurements from Transfer Matrix Measurements

In a fiber without mode-mixing, MDG can be measured by launching and receiving each mode one-by-one. However, in real fibers the modes mix and scramble in the fibers and at splice points making mode-selective excitation and reception erroneous. In particular, in this setup, the mode-selectivity is limited by the SMUXes, strong intra mode-group mixing in the 10 mode GI fiber, and at the 4 splices between the SMUX, 10 mode fiber, and the amplifier to less than 5-dB. Therefore, the most accurate way to measure MDL/MDG is to characterize the amplitude and phase transfer matrix (TM) of the amplifier between each input and output pair across all wavelengths. From this transfer matrix, the MDL/MDG and mode averaged insertion loss/gain (IL/IG) can be computed by a Eigen-analysis of the TM [11].

We measure the TM using a swept-wavelength interferometer with spatial-diversity [11]. Fig. 3a) shows the intensity of the 20×20 TM (10 modes and 2 polarizations) measured across the entire C-band. The matrix is dense which indicates some mode scrambling from the inputs to the outputs. Each one of the cells contains the full amplitude and phase information across the entire measurement range. Fig. 3b) shows the impulse response computed by taking the Fourier transform of the impulse response of a single cell. The first 4 mode groups are 25 dB stronger than the unused mode groups 5, 6 and 7 indicating good suppression of the additional unused spatial modes.

Fig. 3c) shows the MDG change as the coupled pump power is varied from 1.2W to 9W. The background MDL is around 8.5-dB and is from the MDG inside the two photonic lanterns SMUXes. The important point is the MDG changes less than 2-dB as the pump power is varied. This means that all modes experience the same gain regardless of the inversion of the gain material. Fig. 3d) shows the mode averaged small signal gain for different pump powers. At 9-W coupled pump power, the 1550-nm gain is 16 dB and the amplifier is strongly inverted as indicated by the gain peak at 1530 nm.

In conclusion, we have demonstrated an amplifier with low mode-dependent gain (¡2 dB), supporting 10-15 modes, and with output power over 25 dBm. MDG was minizmied by designing the amplifier core to support many additional modes.

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