Higher-Order Mode Erbium-Doped Fiber Amplifier with Output Reconversion to the Fundamental Mode

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Abstract: A CW, higher-order mode, Er-doped-fiber amplifier is demonstrated with output reconversion to the fundamental mode for the first time. Amplification takes place in the LP0,14 mode with an effective area of 6000 μm^2.

Nonlinearities in high-power fiber lasers can be mitigated by increasing the mode effective area (A_{eff}). Among the approaches investigated for scaling of large-mode area (LMA) fibers are rod-type fibers [1], chirally coupled fibers [2], leakage channel fibers [3], and helically coiled cores [4]. Fibers operating in the fundamental mode however suffer from bend induced reductions in A_{eff}, and this effect becomes more pronounced as the mode size is increased [5].

Another approach to increasing A_{eff} is to use a fiber specifically designed to operate in a higher-order mode [6]. Large effective-area, higher-order modes are robust to bend-induced area reductions as well as distributed scattering to nearest neighbor modes [7]. Amplification has previously been demonstrated in a cladding-pumped, Yb-doped HOM fiber at 1μm [8]. In addition, core pumping of a CW Er-doped HOM fiber in the $LP_{0,10}$ with an effective area of 2700 μm^2 has been demonstrated [9]. The HOM-Er amplifier is unique in that it is a core-pumped amplifier with both pump (a high power 1480 nm cascaded Raman fiber laser [10]) and signal propagating in the same higher order mode, allowing for maximum pump-signal overlap and thus short lengths of amplifier fiber. Nanosecond pulse amplification in an HOM-Er fiber has been demonstrated in the $LP_{0,9}$ mode with an effective area of 2440 μm^2 and the nonlinear properties of this amplifier compared to a conventional Er-doped LMA fiber with 800 μm^2 A_{eff} [11]. The nonlinearity of the HOM amplifier was found to be significantly lower than a conventional LMA amplifier, decreasing in proportion to the increase in A_{eff}. More recently, the effective area of the HOM-Er fiber was further scaled to 6000 μm^2 in the $LP_{0,14}$ mode, and nanosecond pulses were amplified, generating up to 226 μJ pulses with 226 kW peak power in this fiber [12]. In this work, we demonstrate for the first time an Er-doped fiber amplifier where amplification occurs in the higher-order mode with 6000 μm^2 A_{eff} and an output mode converter re-converts the signal to the fundamental mode.

The system schematic is shown in Fig 1. A seed source at 1560 nm with up to 1 W average power was coupled together with the output from a high power 1480 nm Raman laser into a single mode, fused-fiber WDM and launched into the amplifier fiber. Recently a record output power of greater than 100 W at 1480 nm was demonstrated from a Raman fiber laser [13].

A UV-written, long-period grating (LPG) coupled both 1480nm and 1560 nm light from the LP_{01} into the $LP_{0,14}$ mode, which had an effective area of 6000 μm^2, as calculated from the measured index profile. The fiber absorption was approximately 35 dB/m at 1530 nm. Pump and signal co-propagated in 4m fiber length in the HOM. At the output end of the amplifier a second LPG reconverted the signal back to the fundamental mode. The output end of the fiber was angle cleaved approximately 25 cm after the second LPG. The output beam was collimated, and a portion of the beam picked off using an uncoated glass wedge, filtered using dielectric long pass filters and then imaged using a phosphor coated CCD camera. The main beam was measured with a power meter.

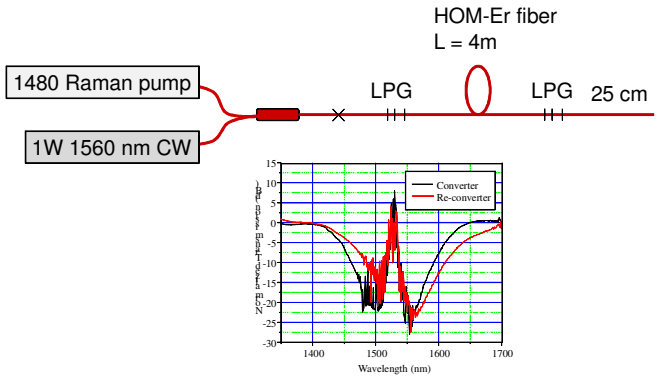

Fig. 1: (a) Schematic of a core-pumped HOM Er-doped fiber amplifier with output mode reconvertor

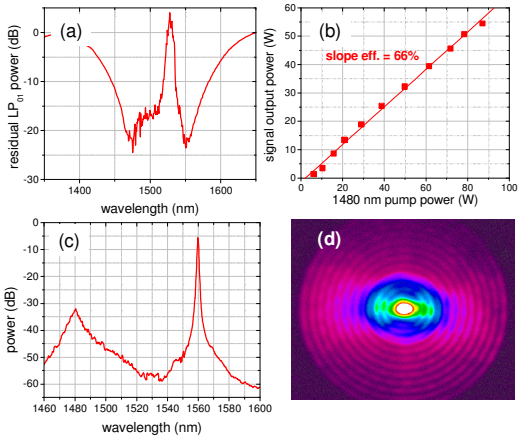

Fig. 2: (a) Conversion efficiency of the LPG showing residual LP_{01} power after the grating. (b) CW amplifier performance. (c) Output spectrum (d) Beam profile at maximum power.

Transmission spectra for the input mode converter and output mode re-converter are shown in Fig. 1. Strong mode conversion was measured at both 1480 nm and 1550 nm for the input mode converter. The output mode reconverter also showed strong mode conversion at 1550 nm.

CW amplifier performance for an amplifier without an output mode converter is shown in Figure. 2. 1 W of signal power was input to a 4.5 m long HOM. Output signal power vs. pump power is shown in Fig. 2b. A slope efficiency of 66% was measured, compared to 44% for the previous CW, HOM-Er amplifier. The beam profile at maximum pump power is shown in Fig. 2d, showing a high quality $L_{P0,14}$ mode. Note that the beam profile was measured using a phosphor coated CCD, and as such, the camera cannot fully resolve the inner rings of the mode.

In comparison, amplifier performance for a 4 m long HOM amplifier with output mode converter is shown in Fig. 3. Output power vs. pump power and output spectrum for different pump power are shown. Performance was very similar to the amplifier without output mode converter that is shown in Fig. 2. However the output mode converter reconverted the $LP_{0,14}$ mode back to the $LP_{0,1}$ mode, and output beam profiles in Fig. 3 show clean fundamental mode output at all power levels.

In conclusion we have demonstrated CW amplification in a higher-order mode Er-doped fiber with effective area of 6000μm^2 and for the first time demonstrated reconversion to the fundamental mode using a second, matched long period grating. Both LPGs showed high conversion efficiency at 1560 nm, and the broad bandwidth LPGs used make the system suitable for femtosecond pulse amplification. Finally, the mode properties were stable, the fiber was coilable, and no competing gain effects were observed. The large effective area of the higher order modes makes the Er-doped HOM fiber amplifier suitable for high energy pulse amplification at eye-safe wavelengths.

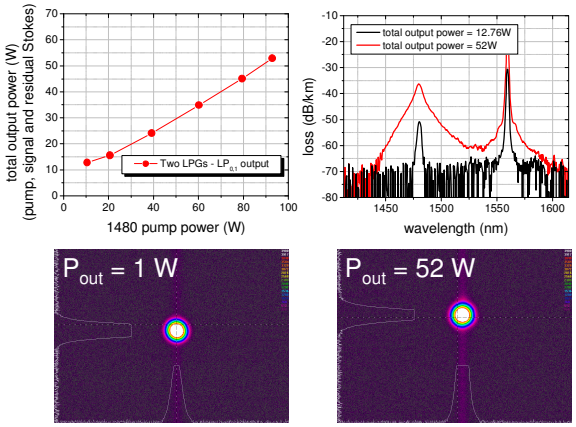

Fig. 3: Performance of an Er-doped HOM amplifier with an output mode reconverter.

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