2 mJ pulse energy, 420kW peak power, all-fiber amplifier with diffraction-limited beam quality

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ABSTRACT

We demonstrate record high energy of 2 mJ, with 4 nanosecond pulses a peak power of >420 kW and average power of 660 W, in a fiber amplifier using a novel 26 μm mode-field diameter Yb-doped gain fiber. The TMI threshold for this fiber was measured to be 1kW. This is achieved at a diffraction limited beam quality of M^2=1.14.

Keywords: Pulse fiber laser, high pulse energy, diffraction limited, high average power, high peak power, high HOM loss

1. INTRODUCTION

High average-power, diffraction limited (DL) fiber lasers and amplifiers have been demonstrated with powers of up to a few kW, where they are typically limited by transverse modal instabilities (TMI) [1]. However, when trying to achieve high average power with nanosecond pulses, the limit is much lower, due to nonlinear effects, such as spontaneous Raman scattering (SRS) and self-phase modulation (SPM), which are generated due to the high intensities and the long interaction lengths typical of fiber lasers. Increasing the mode-field diameter (MFD) will decrease nonlinearities, but higher MFD typically decreases higher-order mode (HOM) bend-loss, causing a lower TMI threshold and deterioration of the beam quality.

Last year [2], we reported 5 kW CW amplifier results based on a Yb doped fiber with a 19.8 um MFD and an increased HOM loss (a factor of x3 higher than conventional fiber) allowing for high TMI threshold. This fiber design strategy was applied to even larger mode-field fibers, resulting in a 24.5 μm MFD fiber [3]. We used this fiber and presented 1.2 mJ pulse energy with 620 W average power [3], enabled by the combination of large MFD and high HOM losses. Using this same fiber, we recently achieved [4] 1.6 mJ and 1.2 kW average power. In the present work, we report pulse amplification results from a new fiber with increased MFD of 26 μm and higher cladding absorption, enabling 2 mJ pulse energy. The highest previous reports of all-fiber DL at high-power levels with nanosecond pulse that we are aware of are Zhang [5], who reported pulse energies of 0.63 mJ with an average power of 570 W. Su [6] reported an average power of 913 W with ns pulses, however the pulse energy was only ~0.09 mJ, while 466 W with 0.046 mJ energy was reported in [7].

2. RESULTS AND DISCUSSION

In the present work, using a 40/400 fiber with a MFD of 26 μm, we demonstrate further increase in pulse energy up to 2mJ, at a rep-rate of 333kHz, with an average power of 660 W and a peak power of >420 kW. The three 976 nm, wavelength locked diode pumps were coupled into the gain fiber together with the seed laser through a 6+1x1 combiner in a co-pumping configuration. A seed laser was first preamplified to a level of 3W, and then power amplified in the 26 μm MFD fiber, with a 7 dB/m clad absorption at 976 nm. The amplifier was first run with a CW seed. The higher absorption of this fiber resulted in a lower TMI threshold than the previously reported 24.5 μm MFD fiber, but we were still able to achieve 1000 W signal power before TMI prevented from further increasing the power. The high average power obtained in such a large MFD, high absorption fiber confirms that the HOM losses helped increase the TMI threshold.

Next, a pulsed seed laser (333 kHz) with 8 nsec pulse was preamplified to 3 W and amplified in the power amplifier. The optimum length of the fiber was determined using a cutback method. The fiber was tested at lengths from 3.8 to 2.5 m. For a given fiber length, we stopped increasing the pump power when the extinction ratio between the fundamental wavelength peak (1064 nm) and the Raman wavelength peak (~1115 nm) was ~10 dB. Fig. 1 shows the power out and efficiency vs. pump power (L=2.5 m), in the pulsed mode. Each of the three pump diodes, which were not fully wavelength locked below 200 W, produced lower efficiency, when operated below that level. This can be observed in the lower efficiency obtained at below~600 W pump power. Fig. 2 shows our achieved results here, and in our previous publications [3-4], in comparison to previous reports in the literature [5-11]. This figure demonstrates that the strategy for increasing HOM losses in the LMA fiber, results in an unprecedented combination of pulse energy and average power.

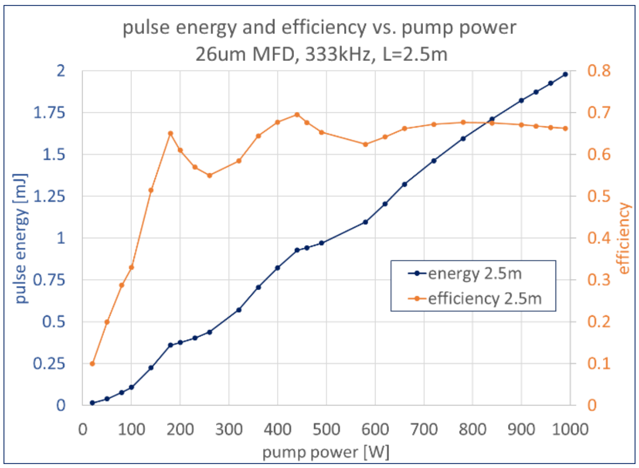

Fig. 1. Power out and efficiency vs. pump power.

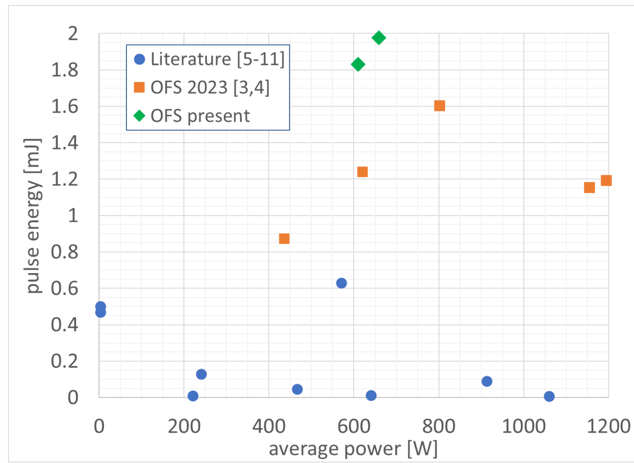

Fig. 2. Comparison to previous results in literature

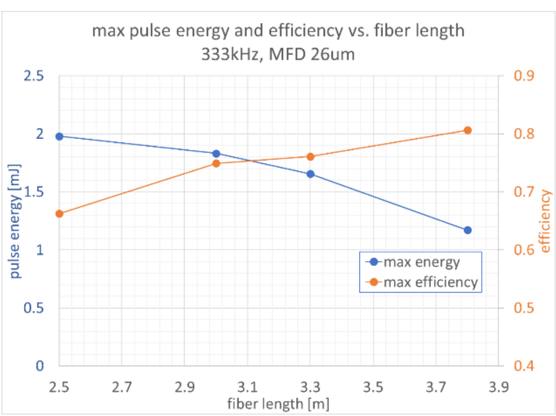

Fig. 3. Max. power/efficiency vs. fiber length.

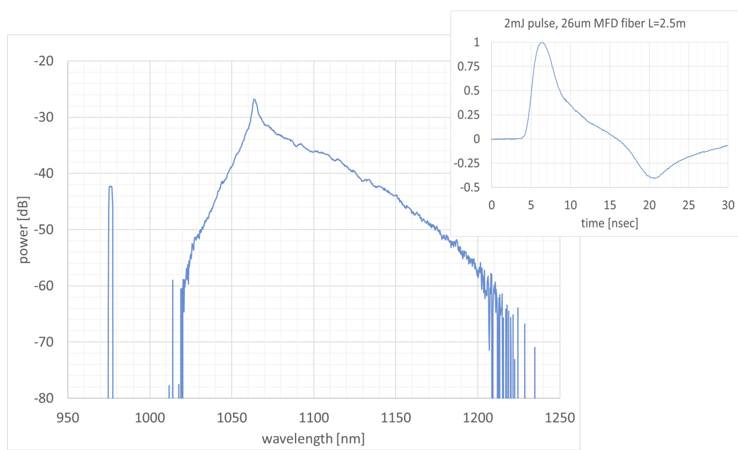

Fig. 4. Output spectrum at max. pulse energy. Inset: pulse shape

Fig. 3 shows the maximum power and efficiency at the maximum power, obtained as a function of fiber length. Shortening the fiber lowers the efficiency, since less pump is absorbed, but enables to increase the maximum output power, since the nonlinearity is lower. 1.2 mJ was achieved with an efficiency of 81% with a fiber length of 3.8 m. 2 mJ with an efficiency of 66% was achieved at a fiber length of 2.5 m. Fig. 4 shows the spectrum at the maximum energy of 2 mJ. A widening of the pulse spectra due to SPM is visible. The Raman peak at 1115 nm can barely be seen buried under the SPM. The inset in Fig. 4, shows the pulse shape, which had shortened to ~4 nsec at the maximum energy of 2 mJ, as sampled with a Thorlabs FPD310-FC-NIR photodetector with a 1 GHz bandwidth. The beam quality was measured at pulsed average powers of up to 660 W, and had an M^2 of 1.14.

3. CONCLUSIONS

In conclusion, these results show that this new fiber design with increased HOM loss and a large mode-field diameter provides high TMI thresholds and enables all-fiber, mJ pulse energy, kilowatt average power systems, with hundreds of kW peak power, nanosecond pulselengths with diffraction limited beam quality.

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