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Single polarization picosecond fiber MOPA power scaled to beyond 500W

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Abstract
We demonstrate a gain-switched diode-seeded, ytterbium-doped fiber based master oscillator power amplifier (MOPA) system, capable of delivering 2.4 μJ, 35 ps pulses at a repetition frequency of 215 MHz in a single-polarization, close to diffraction limited beam. We are aware that the corresponding average power of > 500 W is a record for such a MOPA system. Further pulse energy scaling was limited primarily by the onset of nonlinear effects such as self-phase modulation and stimulated Raman scattering which led to a compromised pulse quality at higher peak powers (> 70 kW).

Keywords: fiber amplifier, high power laser, picosecond, nonlinear effects

(Some figures may appear in colour only in the online journal)

1. Introduction

Laser systems producing short optical pulses spanning the femtosecond to nanosecond regime are finding their way into an ever increasing range of important applications, including materials processing [1], nonlinear microscopy and laser medicine [2]. Whilst traditional bulk solid state lasers such as titanium sapphire and Nd:YAG lasers offer suitable levels of technical performance, for many of these applications they generally have a large foot print and require periodic maintenance in order to ensure optimum operation. However, with recent advances in fiber laser oscillators and amplifiers, fiber based laser systems are now emerging as an alternative solution in many instances, offering high average powers, high wall plug efficiency, compact devices and robustness in regard to thermal effects due to their fiber geometry which allows efficient heat dissipation [3].

One of the most common approaches for generating high average powers from fiber lasers is to use a master oscillator power amplifier (MOPA) architecture. This configuration allows the output from a relatively low-power, but readily-controlled, seed laser to be boosted to high power levels in a chain of fiber amplifiers. The goal is to preserve the desirable characteristics of the seed signal during the amplification process to provide a highly controlled signal at a high average power at the MOPA output. The key to high average power operation is the application of the cladding-pumping technique in the final stages of amplification together with the use of high brightness diode pump lasers. Using variants of this basic approach, fiber MOPAs with output powers in excess of 20 kW have been achieved in the continuous wave (CW) regime [4].

The MOPA approach is particularly attractive in the pulsed regime, as it allows the development of pulsed laser systems with unprecedented levels of performance and flexibility. For example, the highest average power results to date have been achieved in the femtosecond regime, with the kW-class femtosecond operation demonstrated [5], albeit using an expensive and complicated system configuration incorporating many bulk elements (as is required to manage nonlinear effects). There is however a growing interest in high power ps-systems as it has been shown that many of the benefits of using fs-pulses in materials processing can in fact be achieved using picosecond pulses. These can be generated in a more straightforward, practical and cost-effective manner than fs-pulses: for example, using gain-switched pulses from a semiconductor laser. To this end we recently demonstrated a fully fiberized picosecond fiber MOPA system that produced an average output power of 200 W at variable repetition frequencies with a pulse width of 28 ps and a maximum peak power of 100 kW [6]. Herein, we extend this earlier work up to a maximum average output power of 513 W (35 ps pulses and a corresponding

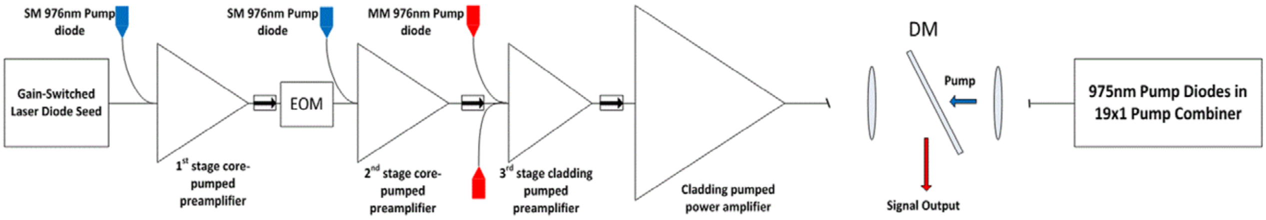

Figure 1. Fully fiberized picosecond seed laser based YDFA MOPA system incorporating the 4 amplifier stages.

maximum peak power of 68 kW). The output beam is close to diffraction-limited and the average power performance exceeds the previous record of 321 W for a picosecond fiber MOPA demonstrated by Dupriez *et al* [7] (which had an M^2 of 2 and also incorporated a significant amount of bulk optics). To the best of our knowledge, this is the highest optical power demonstrated from a picosecond fiber MOPA system to date.

2. Experimental setup and results

A schematic of the experimental setup is shown in figure 1. A commercial Fabry–Perot laser diode with a polarization-maintaining (PM) fiber pigtail was gain-switched using a stable train of sinusoidal electrical current pulses superimposed upon a dc bias. The pigtail of the SLD was spliced to a PM fiber Bragg grating (FBG) at 1040 nm with a 3 dB bandwidth of 0.24 nm and a reflectivity of 7.2%. The repetition frequency was tuned to 860 MHz to achieve synchronization between the emitted pulses from the diode and the reflected pulses from the FBG. Stable, pedestal-free optical pulses with a duration of 35 ps (see figure 3(*a*)) and a 3 dB spectral bandwidth of 0.12 nm were generated at this frequency (at an average optical power of 6 mW). The corresponding time bandwidth product of the optical pulses was calculated to be ~ 1.07 (assuming a Gaussian profile). The polarization extinction ratio achieved from the seed laser was 25 dB. The optical pulse was then amplified in a four-stage PM ytterbium-doped fiber amplifier (YDFA) MOPA chain.

The first stage amplifier consisted of a 50 cm long core-pumped PM YDFA (5 μm core and 130 μm cladding diameter) pumped by a 180 mW single-mode 976 nm pigtailed laser diode. A total optical power of 50 mW was obtained from this amplifier. The output from this amplification stage was coupled to an in-line electro-optic modulator (EOM), which acted as a pulse picker for reducing the pulse repetition frequency to 215 MHz. A total loss of 11 dB was measured resulting from the 5 dB insertion loss of the EOM and the 6 dB incurred from the four-fold reduction in the operating frequency from the fundamental frequency of 860 MHz. The EOM has a high extinction ratio (over 40 dB) ensuring effective suppression of unwanted additional optical pulses when operating at 215 MHz. The relatively high loss due to the EOM dictated use of an additional preamplifier. This is once again a core-pumped PM YDFA, this time with an active fiber length of 1 m. This second preamplifier ensures adequate seeding of the cladding-pumped third-stage preamplifier. An average optical power of 23 mW was obtained from this stage which operated at a modest gain of 10 dB.

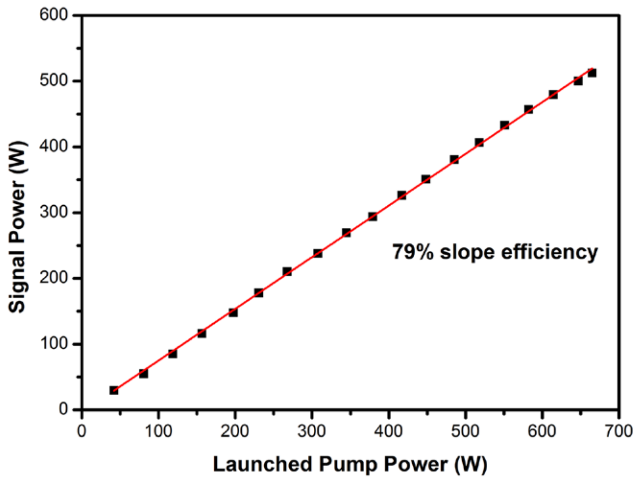

Figure 2. Average signal output power versus the launched pump power of the power stage amplifier.

The third-stage PM YDFA comprised of a 1.5 m long cladding-pumped large-mode-area (LMA) fiber with a core diameter of 10 μm, core numerical aperture (NA) of 0.08 and an inner-cladding diameter of 125 μm and cladding an NA of 0.46. The fiber was co-directionally pumped by two 10 W, 975 nm multi-mode (MM) pump diodes through a fiberized (2+1)x1 MM pump combiner. A total average power of 3.4 W at a pump power of 8.6 W with an optical signal to noise ratio (OSNR) > 35 dB was measured at the output of the amplifier. The output power was carefully chosen to ensure maximum peak power extraction before the onset of SRS while substantially preserving the signal quality.

The output of the third stage preamplifier was then taper-spliced to the final-stage amplifier, comprising a 3 m long LMA fiber with core and cladding diameters/NAs of 25 μm/0.06 and 250 μm/0.46, respectively. The combination of taper-splicing and coiling (80 mm coil diameter) ensured a single-mode operation whilst the use of a fast-axis blocking PM isolator ensured single-polarization seeding into the power amplification stage. A polarization extinction ratio of 27 dB was measured after the PM isolator. The power amplifier was free-space counter-pumped by 16 spatially combined MM laser diodes operating at 974 nm. A 19x1 pump combiner with an output fiber having a diameter of 200 μm and an NA of 0.46 was used to spatially combine the MM pump diodes. A combination of two aspherical lenses with identical focal length (f = 20 mm) was used, resulting in a ~95% pump coupling efficiency into the LMA fiber. A dichroic mirror (DM) was used to separate the pump and signal beams. To avoid damage to the output facet, a short-length end cap

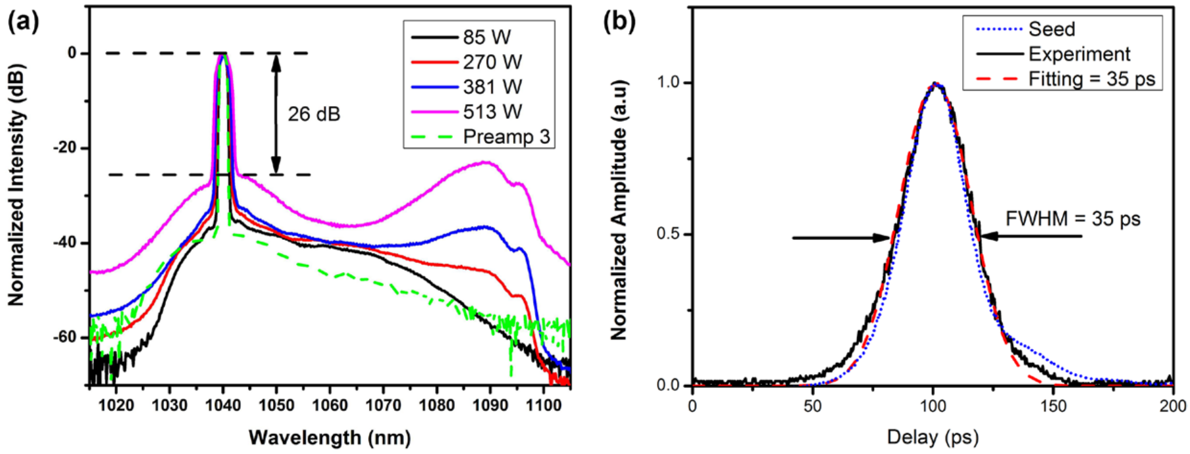

Figure 3. (*a*) Spectra measured at various output powers with an optical spectrum analyzer (OSA) at a resolution setting of 1.0 nm and (*b*) optical pulse width measured directly with a fast photodetector.

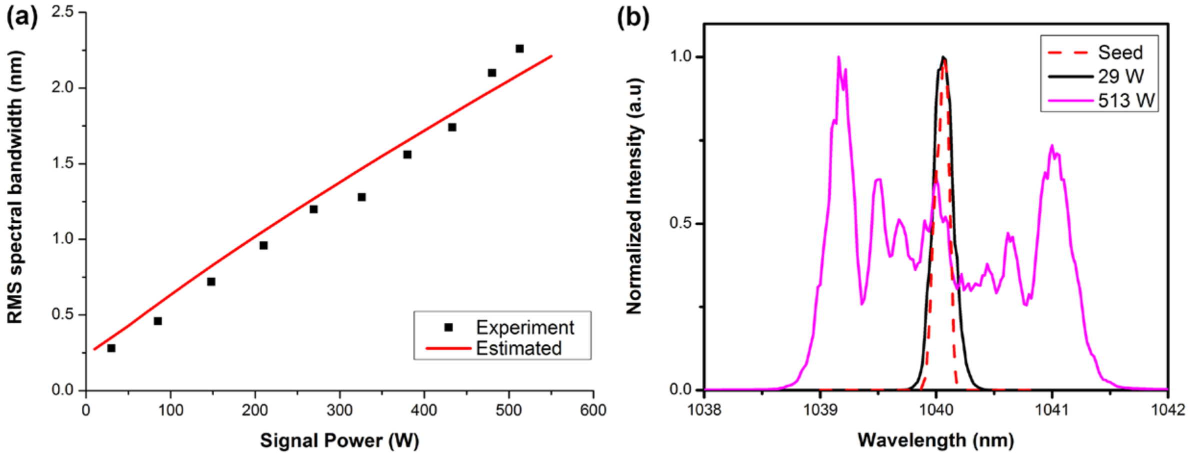

Figure 4. (*a*) Measured spectral linewidth as a function of output signal power and (*b*) the broadening in signal linewidth as a result of SPM. In all cases, the OSA resolution was set at 0.1 nm.

(1.3 mm) was spliced to the output of the LMA fiber and was angle polished to avoid the coupling of the 4% Fresnel reflected signal back into the fiber core.

The resulting amplified output signal versus pump power is plotted in figure 2. A thermal power head (Ophir BDFL500A-BB-50) was used to measure the optical output power. For a total launched power of 670 W, the average signal output power was measured to be 513 W. This corresponds to a total power amplifier signal gain of 21.8 dB assuming that no excess loss was introduced by the tapered splice. The slope efficiency was measured to be 79% with respect to the launched pump power. No roll off in the signal power was observed even at the highest pump power, indicating that further power scaling is still possible. The pulse peak power at the highest operating average power level was estimated to be ~69 kW and the maximum pulse energy was 2.4 μJ. A polarization extinction ratio of 17 dB was measured at the output of the system.

The optical spectra measured at the output of the system with 1.0 nm OSA (ANDO AQ6317B) resolution are shown in figure 3(*a*). At the maximum average output power, the measured OSNR was recorded to be 26 dB, which corresponds to an OSNR degradation of 11 dB as compared to the input signal to the final stage amplifier. Furthermore, a hump with the peak at 1090 nm started to appear for output powers beyond 250 W due to the onset of SRS. However, the power contained in the Raman Stokes line at the maximum operating output power of 513 W is not significant (0.25% of the total optical power) and most of the optical power remained at the signal wavelength. For further power scaling, however, the mitigation of SRS has to be addressed first as the Raman Stokes line grows much faster than the signal at this power level as is evident from figure 3(*a*). The core size of the ytterbium-doped fiber in the power amplifier can be further increased to 40 μm to increase the Raman threshold, but this will have an impact on the preservation of the fundamental mode within the fiber. Another possibility is to use specialty fiber such as micro-structured fiber [8] or chirally-coupled-core fiber [9].

The optical pulse measured at the maximum output power is shown by the solid black line in figure 3(*b*). The optical pulse was measured directly with a fast, wide-band photo-detector and a 50 GHz sampling oscilloscope. A clean optical pulse with no pedestal was observed. By using a Gaussian fit (red dashed line), the full width half

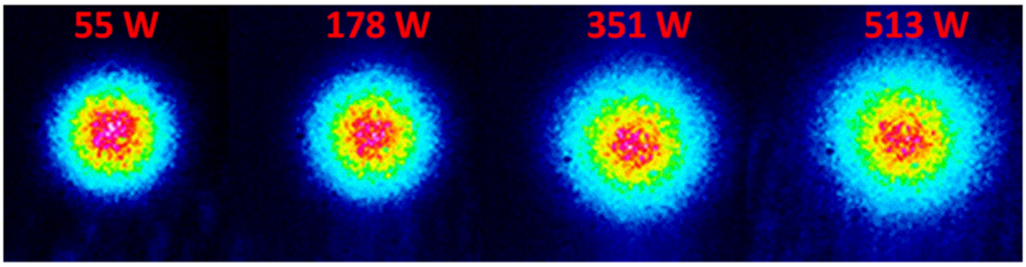

Figure 5. Output beams captured with a CCD camera at various output power levels.

maximum of the optical pulse was estimated to be 35 ps which is similar to the width of the seed pulses. Moreover, no significant temporal distortion was observed even at the maximum output power.

Figure 4 (*a*) shows the rms 3 dB spectral bandwidth obtained both through numerical modeling and experimental measurement. The spectral broadening is primarily caused by SPM along the amplifier chain. The measurement results agree very well with the numerical estimation. The linewidth of the seed source broadened from 0.12 nm to 2.4 nm at the output of the MOPA chain at 513 W of the average output power. The high resolution (0.01 nm) output signal spectra for two different output powers are shown in figure 4(*b*) plotted on a linear scale to emphasize the detailed features resulting from SPM. At a low average output power (29 W), the effect of SPM is not that significant due to the low pulse peak intensity and the spectrum here is measured to be only slightly broader than the seed spectrum. However, at the maximum output power, the effect of SPM becomes significant, creating characteristic sidebands on either side of the central wavelength, resulting in an increased spectral bandwidth. Such spectral broadening, which induces a near linear chirp across the pulse profile, can be beneficial as it can be exploited to compress the pulses using an external grating pair, thereby increasing the pulse peak power [10].

In order to assess the output beam quality, a fraction of the output beam at various output powers was imaged with a silicon based CCD camera. Figure 5 shows the captured beam profiles at four different power levels. As the signal output power was progressively increased, a Gaussian shaped intensity profile was maintained. Furthermore, we did not observe any distortion on the captured mode profile even at the maximum output power. The quality of the output beam was also measured using a commercial M^2 measurement instrument. The M^2 measurement was based on the D4σ method yielding an estimated M^2 of 1.1 at 200 W of output power.

3. Conclusions

A gain-switched diode-seeded all-fiber ytterbium-doped MOPA with 35 ps optical pulses and up to 513 W of average output power at 1040 nm is demonstrated. The system operates at a repetition frequency of 215 MHz corresponding to an estimated pulse energy of 2.4 μJ and a peak power of ~ 69 kW. At the maximum operating output power, an OSNR of 26 dB was recorded, indicating that the ASE was well controlled throughout the MOPA chain. A polarization extinction ratio of 17 dB was measured signifying that the amplified output signal is singularly polarized. Output beam quality measurements using a CCD and a commercial M^2 measurement system indicate that the output mode is essentially Gaussian in nature and close to the diffraction limit. The effect of SPM within the fiber amplifier chain, which causes the signal linewidth to broaden, is in good agreement with the numerical estimation. Furthermore, the amount of energy effectively transferred to the Raman Stokes (peak at 1090 nm) was small. However the experimental results suggest that further power scaling will inevitably be limited by the energy transfer to SRS. Such a high power all-fiber, picosecond MOPA system may find applications in laser machining, surface structuring and laser cutting.

Acknowledgments

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