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High power picosecond MOPA with anisotropic ytterbium-doped tapered double-clad fiber

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ABSTRACT

Generation of ultrashort pulses with high average power and moderately high pulse energy generally requires a mode-locked laser followed by several fiber amplifiers in a master-oscillator power-amplifier configuration. Recently, gain-switched diode lasers have emerged as a viable replacement to mode-locked oscillators as sources of sub-100 ps pulses in these systems, but the low output power available from the diodes necessitates the use of multiple costly amplifier stages. Here, we demonstrate the generation of 1.7 µJ pulses at 1030 nm, and 11.7 µJ pulses at 1064 nm from a gain-switched diode seeded compact MOPA with only two amplification stages. The final stage is a tapered fiber amplifier, whose geometry efficiently suppresses amplified spontaneous emission and allows reaching a gain of ~40 dB. This research work is still in progress, and further increase in pulse energy should be possible by optimizing the setup.

Keywords: Fiber laser, active fiber, fiber amplifier

1. INTRODUCTION

The technology of ultrafast (pico- and femtosecond) fiber lasers for industrial and medical applications is progressing rapidly over the last decade. Powerful ultrafast fiber lasers are in high demand for applications in micromachining, nonlinear microscopy and biomedical research [1, 2].

Typically, the ultrafast fiber laser is a master oscillator – power amplifier (MOPA) system, which combines a mode-locked fiber laser and concatenated chain of fiber amplifiers. The serious drawback of master oscillator based on ultrafast fiber laser is a fixed frequency to their fundamental repetition rate. To control repetition rate, an additional element such as a pulse picker is introduces. It increases the system cost and complexity. In contrary, gain-switched diode lasers (GSLD) offer a compact and simple solution for the generation of sub-100 ps pulses with a tunable repetition rate. Moreover, the pulse emission can also be synchronized to an external source. This flexibility makes GSLD an attractive seed source for the industrial application. However, the pulse energies achievable with gain-switched diode lasers are limited by pJ level due to the small volume of the active medium; so an external amplifier is essential to reach the desired level of output power. Yb-doped fiber amplifiers have become the go-to solution optical amplification at the 1 µm spectral region owing to high efficiency, robustness and ease of thermal management.

In the recent years, several authors have reported MOPA systems consisting of a gain-switched diode laser as the seed source and a multi-stage Yb-doped fiber amplifier [3-7]. The group of researchers from the University of Southampton have performed series of works [3-6] with high average power (up to 300 W) and rather modest pulse energies (3µJ). Kanzelmeyer et al. demonstrated the amplification of 20 pJ pulses to 13.1 µJ using broadband (20 nm) diode laser with a pulse duration of 40 ps and 1 MHz repetition rate [7]. The onset of stimulated Raman scattering limited further scaling of the pulse energy in this work.

All MOPA schemes, described earlier [3-7], contains several amplification stages (minimum four). It makes overall MOPA scheme very long and this, in turn, caused nonlinear effects (primarily SPM and SRS), which finally limits the energy and peak power of the pulse. Another reason that defines the energy scaling it is a relatively small core diameter. In [3], single

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trench fiber (STF) with a core diameter of 30 µm is used, and in [4], [5,7] and [6] double clad large mode area (LMA) fibers with diameters of 25, 30 and 43 µm are exploited, respectively.

In this paper, we demonstrate the all-fiber short MOPA system containing a birefringent tapered double-clad Yb-doped fiber amplifier with 100 µm core seeded by 60-ps gain-switched diode lasers at both 1030 and 1064 nm wavelengths. This MOPA delivered up to 20 W of output power (more than 40 dB gain) with ~12 µJ at 60-ps pulse energy with 160 kW of the peak power.

2. EXPERIMENTAL SETUP

The schematic of the compact MOPA system is shown in Fig. 1. The system relies on the direct amplification of the GSLD pulses without any additional pulse stretching elements. The fiber components of the system are polarization maintaining to ensure linearly-polarized operation.

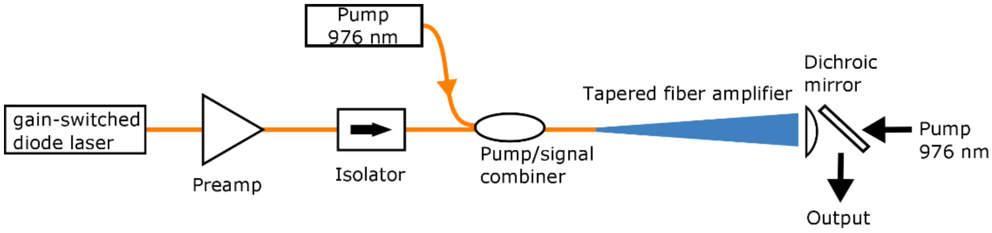

Fig. 1: A schematic of the MOPA system.

We did two experiments with two different seed sources and tapered amplifiers. Both seed sources were gain-switched diode laser modules supplied by PicoQuant GmbH, and we refer to them in the text as seed 1 and seed 2. The seed laser used in the first experiment (seed 1) generated pulses at the central wavelength of 1029.8 nm with a repetition rate tunable between 31 kHz and 80 MHz. We chose to use a constant repetition rate of 5 MHz. The initial pulse duration was 50-60 ps, according to the specification by the manufacturer. The seed module included a core-pumped fiber amplifier capable of boosting the pulse energy to 0.19 nJ.

The seed laser in the second experiment (seed 2) had a central wavelength of 1064 nm, and the repetition rate was tunable between 31 kHz – 1 MHz, but we chose to use a repetition rate of 1 MHz. The initial pulse was 68 ps long according to the manufacturer of the seed module. This module also had a built-in fiber amplifier, which raised the pulse energy to 0.30 nJ. The output pulse energies of both seed lasers were calculated by taking into account the fact that a part of the output power was ASE generated in the built-in fiber amplifier. The repetition rates were chosen as a compromise between obtaining high pulse energy and the efficient suppression of ASE level. In the first experiment, higher repetition rate was required to limit the amount of ASE and stimulated Raman scattering (SRS) generated in the narrow part of the tapered amplifier stage.

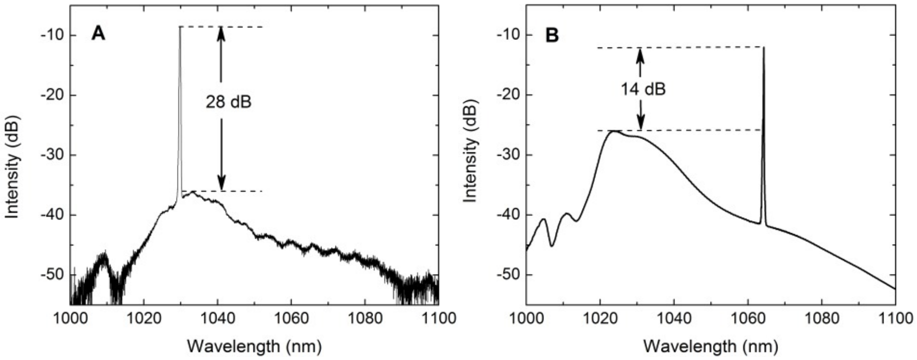

Figure 2: a - The spectrum of the 1030 nm seed module (seed 1). The total output power was 1.03 mW, and the repetition rate was 5 MHz. The signal to ASE contrast was equled to 28 dB. b - The spectrum of the 1064 nm seed module (seed 2). The total output power was 1.93 mW, and the repetition rate was 1 MHz.

Figures 2 a, b show the spectra of the seed modules. In seed 1, ASE is reasonably well suppressed with the spectral peak of the laser being 28 dB above the ASE background and > 90 % of the output power lying within the signal band. In seed 2, however, most of the output power is ASE with only ~15% of the power located within the signal band.

The power amplifier stage was separated from the seed module with a high-power isolator and consisted of a tapered double-clad Yb-doped fiber pumped with two wavelength-stabilized diode lasers at 976 nm from both sides. As the narrow side pump laser, we used a 27 W multi-mode diode laser coupled into the amplifier through a fiber-pigtailed pump/signal combiner, and as the wide side pump laser, a 180 W diode with free space coupling through a dichroic mirror. The output power of the pump lasers was optimized to obtain high pulse energy while keeping ASE and SRS at a low level. A few tapered fibers were tested in the power amplifier. All of them had axial thickness profiles similar to those published earlier [8], a core diameter of ~15 µm at the narrow end and 100 µm at the wide end.

3. RESULTS

3.1 Experiment 1 (1030 nm)

In the experiment 1, the 27 W laser was run at the power of 11.6 W, which resulted in the best possible pulse contrast and minimal SRS. The pump power at the wide side was varied from 17 W to 111 W and the output power, spectrum and pulse form were recorded for each pump power. Fig. 4 shows the output spectra at three different output powers. The spectra were measured using an optical spectrum analyzer (Ando AQ6317B) with a 0.1 nm resolution bandwidth.

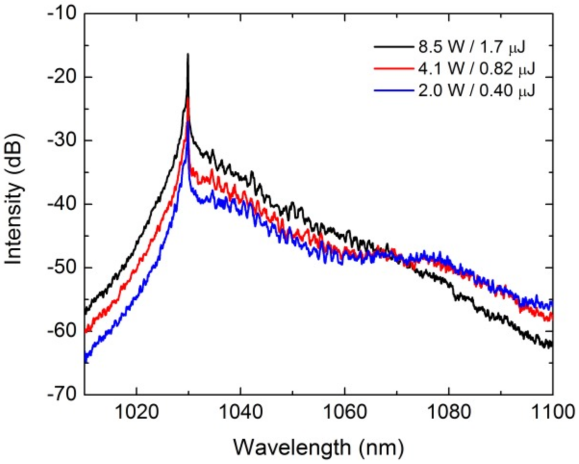

Figure 3: Output spectra at different signal output powers (out-of-band ASE excluded) and corresponding pulse energies in experiment 1.

As is visible from Fig. 3, the output spectrum contained signal and the strong fraction of ASE. The proportion of ASE could be reliably estimated from the spectrum by direct integration because the signal bandwidth was narrow compared to the ASE bandwidth. The effect of in-band ASE was ignored in the calculation. The fraction of ASE was highest at the lowest total pump power of 29 W when the signal power was only 18 % of the total power. At the highest total pump power of 107 W, the average output power of the MOPA was 24 W with ASE included and the actual laser power, confined within a bandwidth of 1 nm, was found to be 8.5 W, corresponding to 34 % of the total output power. The pulse energy, calculated from the repetition rate, was 1.7 µJ, and peak power was equal to 25 kW. The seed signal was scaled up from 1 mW to 8.5 W from one amplifier stage with the total signal gain value was equal to 39.5 dB. Fig. 4 showed the laser power as a function of the pump power. The slight deviations from linear behavior were mostly caused by the changes in the ratio of laser power to ASE power.

Several factors determined the low efficiency of the system: 1) the seed wavelength was at the short wavelength edge of the gain provided by the tapered amplifier. Moreover, due to the geometry of the tapered amplifier, 1030 nm radiation is strongly re-absorbed at the wider part of the taper, where Yb ions concentration is higher per volume. 2) The weak input signal did not fully saturate the tapered fiber amplifier; therefore, a significant part of the output power was in ASE. Even though the signal did not saturated the amplifier, we did not observe CW laser operation, which would be visible as an additional sharp peak in the spectrum.

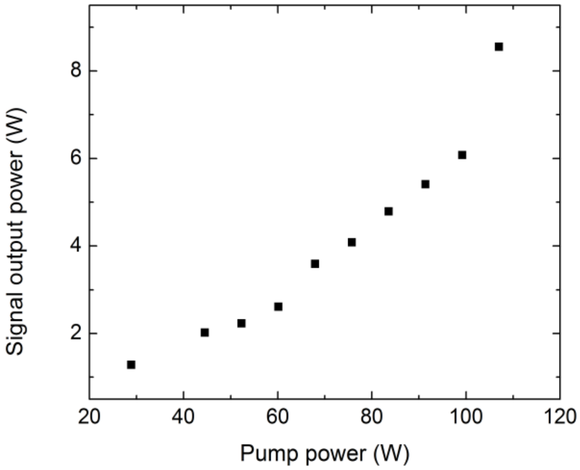

Figure 4: Signal output power (out-of-signal ASE excluded) versus total pump power in experiment 1.

The significant increase in the fraction of the laser power at the last point could be explained by considering the population inversion in different parts of the taper. At low pump powers, only the ends of the taper were adequately pumped and provide gain at 1030 nm, while the middle part of the taper actually absorbs at 1030 nm. Thus, longer wavelength ASE plays a significant role because it did not get absorbed. However, at higher pump powers, the middle part of the taper started also to provide gain at 1030 nm, preserving the signal-to-ASE contrast better.

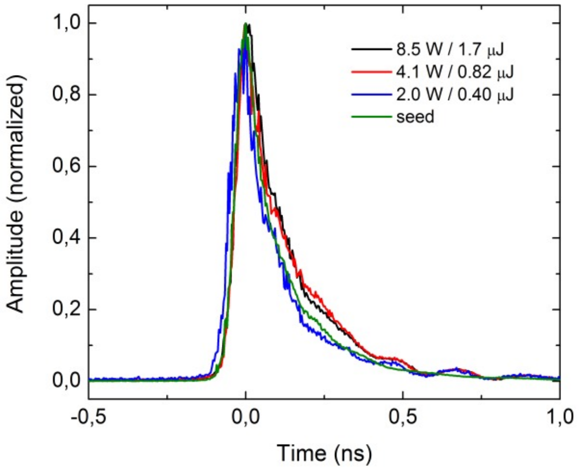

Figure 5: The pulse shapes of the seed and amplified signals in experiment 1. The legend shows the average power of the signal and the calculated pulse energy.

The temporal shape of the pulses plotted in Fig. 5 remained unchanged during amplification. We measured the pulse shape with a 12 GHz photoreceiver (rise time 30 ps) connected to a 12 GHz sampling oscilloscope. The pulse exhibited broadening when the output power exceeded 2.0 W level. At the maximum output power of 8.5 W, the pulse duration increased up to 30 %. The pulses were highly chirped (time-bandwidth product was equal to 4.9). Therefore, there is a possibility for the external pulse compression down to sub 10 ps.

3.2 Experiment 2 (1064 nm)

In the second experiment, we used a seed at a longer wavelength to overcome the drawbacks of the system in the first experiment related to low gain, re-absorption and the amount of ASE and SRS in the output signal. The measurement setup and settings were similar as in the experiment 1.

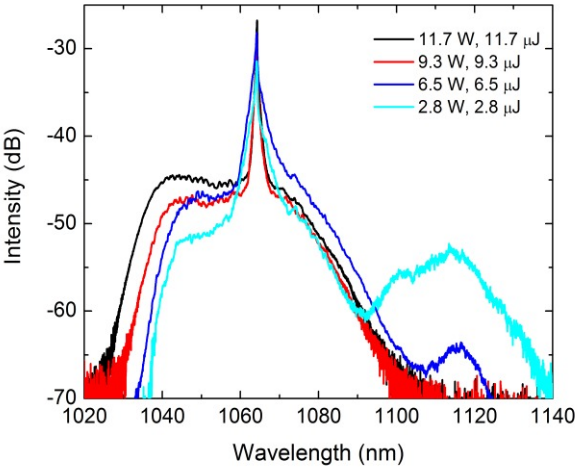

Figure 6: The output spectra at different signal output powers (out-of-band ASE excluded) and corresponding pulse energies in experiment 2.

The spectra measured in experiment 2 are illustrated in Fig. 6. The legend shows both the average power and the pulse energy calculated by excluding out-of-band ASE and SRS radiation. In this experiment, the output consisted roughly 60 % of signal and 40 % of out-of-band noise, which was a definite improvement from the experiment 2. The spectrum with 2.8 W average power was obtained by pumping the power amplifier only from the narrow side with 22.5 W pump power. Because of the clearly visible SRS signal, the pump power at the narrow side of the taper was then decreased to 19 W, and wide side pump power was increased from 0 to 32 W. The SRS signal decreased considerably but was still visible. The last two spectra were measured with the pump power from the narrow side of 18 W, and wide side pump powers of 65 W and 95 W, respectively, and showed no more sign of SRS. The maximum total pump power was 114 W and generated 21.1 W of output power. The signal power was 11.7 W, corresponding to a pulse energy of 11.7 µJ. The peak power was estimated to be as high as 160 kW. The signal gain in the tapered amplifier was 45.9 dB in this case.

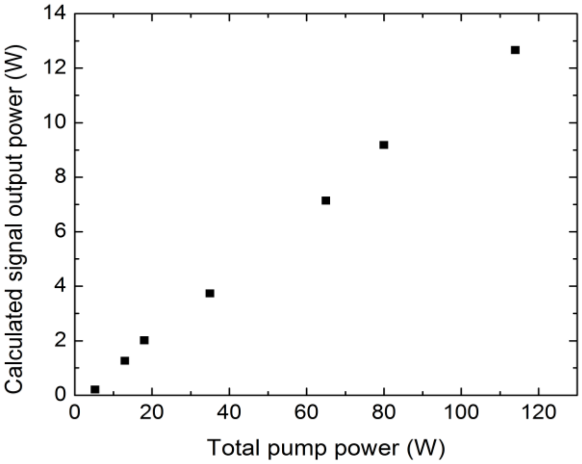

Figure 7: Calculated signal output power (out-of-band ASE excluded using average 40 % ASE fraction) versus total pump power in experiment 2.

The calculated signal output power vs. total pump power in the experiment 2 is shown in Fig. 7. The signal-to-ASE ratio was not measured for each data point in Fig. 8 and, therefore, only an estimation of 40 % ASE fraction is used. However, as mentioned above, the signal was about 60 % of the total power for all the four spectra in Fig. 7 and the ratio should be the same at intermediate pump powers as well.

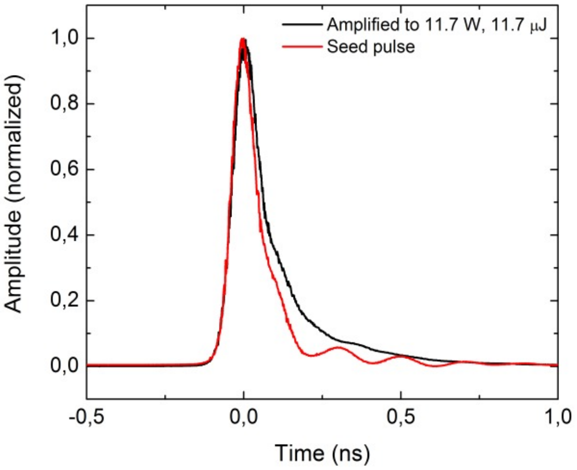

Figure 8: The pulse shapes of the seed and highest power amplified signal in experiment 2. The legend shows the average power of the signal and the calculated pulse energy.

Also in terms of temporal broadening of the pulse, the experiment 2 performed better compared to the experiment 1. The seed pulse duration increased up to only 12 % at the maximum output power. The pulse shapes were shown in Fig. 8. The time bandwidth product of the 11.7 µJ pulses was 7.9, which is larger than in the experiment 1 because of the broader spectrum of the seed 2.

4. DISCUSSION

The main advantage of our setup was that, owing to the high gain in the tapered power amplifier, only two amplifier stages were required to obtain a ten of µJ-level pulse energies and up to hundreds of kW-level of peak power starting from a 1 mW gain-switched picosecond diode laser. It reduced both system complexity and cost. The amplified spontaneous emission limited further increase of signal gain. Backward propagating ASE was effectively suppressed by the geometry of the tapered fiber but forward propagating ASE became significant at the wide end.

The wavelength of the seed had a major impact on the amount of ASE and, consequently, on the achievable pulse energy. In the two experiments, we obtained similar average output powers with both seeds and the tapered amplifiers. However, significantly higher pulse energies were reached in the experiment 2 due to the lower repetition rate and the smaller ASE fraction compared to the experiment 1. As already mentioned, the pumping rates used in the experiments were not high enough to invert the middle part of the tapered amplifier fully. For this reason, gain at 1064 nm was higher than gain at 1030 nm. The significance of this is evident when comparing the output spectra to the seed spectra. In the experiment 1, the output of the seed module contained only a weak ASE component, but ASE was dominant after the power amplifier. The SRS at around 1080 nm also posed a problem since Yb^{3+}-ions also provided gain at that wavelength and seeded the SRS wave through spontaneous emission. In contrast, the seed module in the experiment 2 had a relatively poor quality output with most of the power in ASE. However, the amplifier stage actually improved the signal-to-ASE contrast, as the strong ASE peak at around 1030 nm was reabsorbed in the tapered amplifier.

The output pulses were chirped in both experiments, which suggested the possibility to compress the pulses to a shorter duration down to sub-10-ps level with a grating pair compressor. The signal spectrum was broadened only at the base in the tapered fiber amplifier so the effect of self-phase modulation on the spectral phase should be limited. However, two other effects would likely prevent the compression down to the transform-limited duration. First, the seed pulses were intrinsically nonlinearly chirped because of the transient gain dynamics of the gain-switched semiconductor lasers [9], and second, there was a weak but long pedestal after the pulse containing some fraction of the pulse energy. An additional practical consideration was that the narrow spectrum and long pulse duration together required a large grating separation to provide the amount of dispersion needed for compression. Making a rough estimate using a Gaussian pulse shape and gratings with a typical line density of 1200 lines/mm in a double-pass configuration, the required grating separation would be about 50 m in experiment 1 and about 17 m in the experiment 2.

5. CONCLUSIONS

We obtained 1.7 µJ pulses at 1030 nm and 11.7 µJ pulses at 1064 nm with ~100 ps duration with only two amplifier stages in our MOPA system. This is the first demonstration of amplifying picosecond pulses from a gain-switched diode laser in a tapered fiber amplifier, and thus very much work in progress. There are several possibilities to improve the system. In the current state, the ASE coming from the seed module seeded further ASE generation in the power amplifier leading to weaker gain for the signal. Because of the narrowness of the signal bandwidth, ASE could be efficiently filtered out after the seed with a suitably chosen band pass filter.

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