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# Single-stage Yb:YAG booster amplifier producing 2.3 mJ, 520 fs pulses at 10 kHz

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520fs, 2.3-mJ pulses are demonstrated in a Yb:YAG booster amplifier delivering peak powers up to 4.4GW. To avoid damage and nonlinear-effect issues, passive divided pulse amplification is studied for the first time for bulk-amplifier.

**Keywords :** Laser ytterbium, bulk amplifiers, Ultrafast lasers

Great efforts have been deployed in the development of laser systems delivering femtosecond pulses for industrial and scientific applications. Among all available technologies, fiber lasers came out as one of the best choice due to their capability to deliver short pulse duration (typically 300 to 500 fs) together with high average power within very reliable and robust systems. Nevertheless, one of the main drawbacks remains the limited output energy available for such laser due to the strong confinement of the light. Standard femtosecond fiber lasers can deliver typically up to 10s  $\mu$ J energy pulses; and lasers based on rod type technology allow to reach up to the mJ level for laboratory systems [1-2] and 200  $\mu$ J for industrial systems.

We propose here to enhance the energy from fiber sources by implementing a very simple, but optimized, Yb doped YAG booster stage. This booster consists in using a cm-long crystal to have a simple high gain booster together with a rather-modest length to prevent from deleterious nonlinear effects like self-phase modulation and critical self-focusing. Secondly, the use of a simple and passive divided pulse amplification (DPA) setup [3] is also investigated, in order to exceed the energy limitation. We investigate how the DPA permits to overcome the laser threshold limits from 2.9 mJ to 4.1 mJ. This simple and straightforward amplifier geometry allows to deliver, in a nominal and safe regime, ultrashort pulses below 520fs for energy of 3mJ (before compression) 2.3 mJ after. We demonstrated then pulses up to 4.4 GW of peak power.

The fiber laser source used is a standard industrial laser -developed by Amplitude Systems- that delivers pulse energy 180 $\mu$ J up to 100 kHz repetition rate with duration of 350 fs. By limiting output energy below 200 $\mu$ J, nonlinear effects and damages threshold in the laser are safely avoid. The Yb:YAG booster is implemented between the fiber amplifier and the compressor (Fig.1).

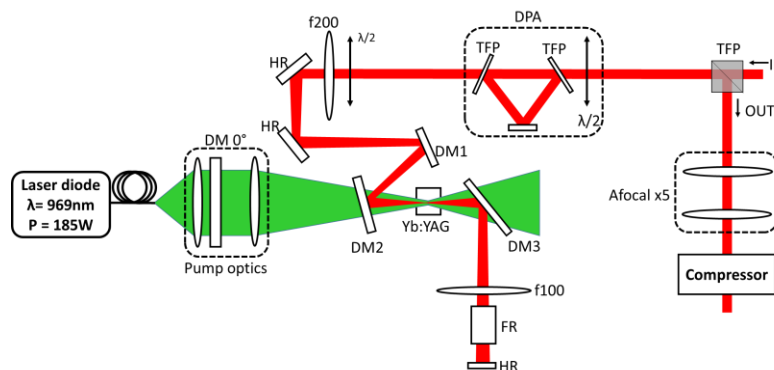


Figure 1: Experimental setup – HR: High reflective Mirror, DM: Dichroic mirror, FR: Faraday rotator; TFP: thin film polarizer.

The gain medium is a 15-mm-long, AR-coated, 3%-Yb-doped YAG which is cooled on both top and bottom faces. The 200- $\mu$ m-diameter 0.22-N.A. fiber-coupled pump laser diode provides up to 170W incident on the crystal at 969 nm (wavelength stabilized). The pump and the laser beam diameters in the crystal are 500 $\mu$ m and 440 $\mu$ m respectively. In double pass configuration (fig. 1), the beam is sent back in the crystal with a 100 mm focal lens; and a Faraday rotator rotates the polarization minimizing thermal induced depolarization issues. The amplified beam is extracted on the s-polarization. To compress the 500-ps chirped output amplified pulse, we used a transmission grating-based compressor. To avoid any damages on the grating's components, we enlarged the beam up to 5mm of diameter. The overall efficiency of the compressor is 80%.

To firstly investigate average-power issues, the system is operated at its maximum repetition rate: 100 kHz without divided pulse scheme. The average power of the amplified signal versus the input power is given in Fig. 2. The maximum output power performed is 53 W in single pass and 73 W in double pass configuration, corresponding to energies of 530 and 730  $\mu\text{J}$ , respectively. In single pass, depending on the injection level, the gain ranges from 10 to 3, with output average powers between 10 W and 53W, respectively. In the double pass configuration, the gain increases and ranges from 40 to 4 with corresponding output powers from 33W up to 73W. At high repetition rates, the limiting effect is the heat load that leads to spatial distortions of the output beam. The thermal effects are also maximum because of a stronger pump absorption due to the important depleting of the excited state by the laser with consequences also on the spatial profile.

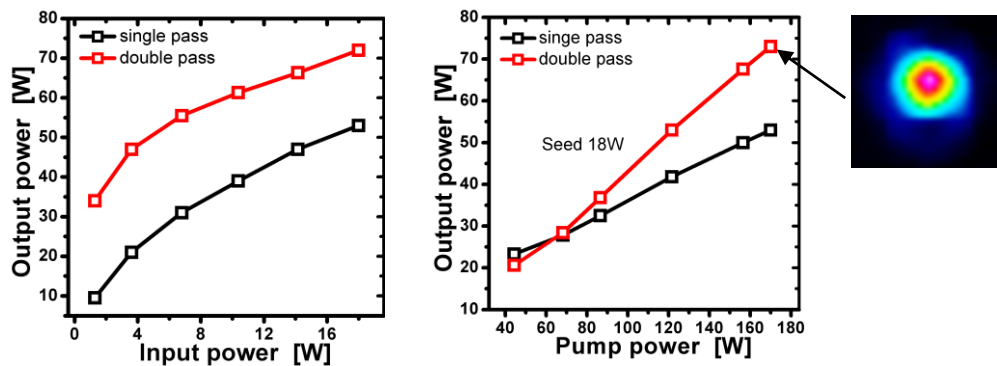


Figure 2: (Left) Average power versus seed power in single (black) and double (red) pass – (Right) Average power versus pump power for a seed of 18W in single (black) and double (red) pass

In a second step, the energy is increased by reducing the repetition rate. Evolution of the output energy versus repetition rate is depicted in Fig. 3. In single pass, amplified pulses energies ranges from 500 $\mu\text{J}$ , at 100 kHz, to 1.5mJ, at 10 kHz. By adding a second pass through the amplifier, we increase the pulse energies up to 700 $\mu\text{J}$  and 2.9 mJ at 100 kHz and 10 kHz, respectively. At this level, stochastic damages on both dichroic mirror and crystal coatings are observed. An ultra-simple DPA scheme using a free space delay line producing 2 replicas separated by 1 ns is then implemented. The laser induced damage threshold (LIDT) is then pushed to more than 4 mJ at 5 kHz which corresponds to an expected improvement of  $\sqrt{2}$  [4] when we assume that the pulse duration is increased by a factor of 2 due to the DPA set-up.

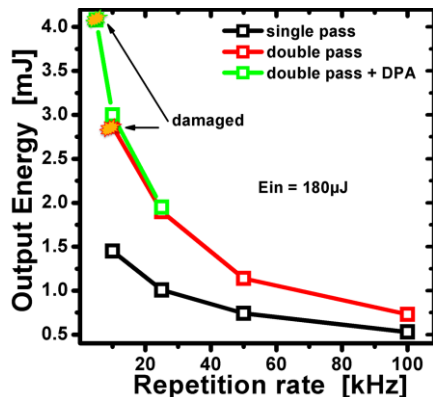


Figure 3: Output energy versus repetition rate for single-pass, double-pass and double-pass with DPA configurations.

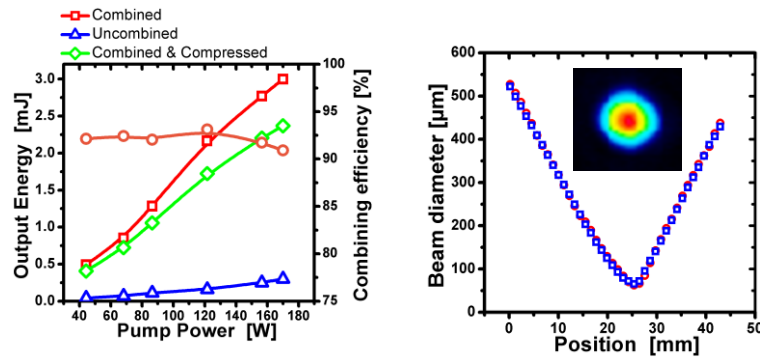


Figure 4: (Left) Uncombined and combined output energy, before and after compression with associated coherent combining efficiency versus pump power at 10 kHz repetition rate. (Right) Caustic of the 3mJ output beam– Insert: associated far field beam profile.

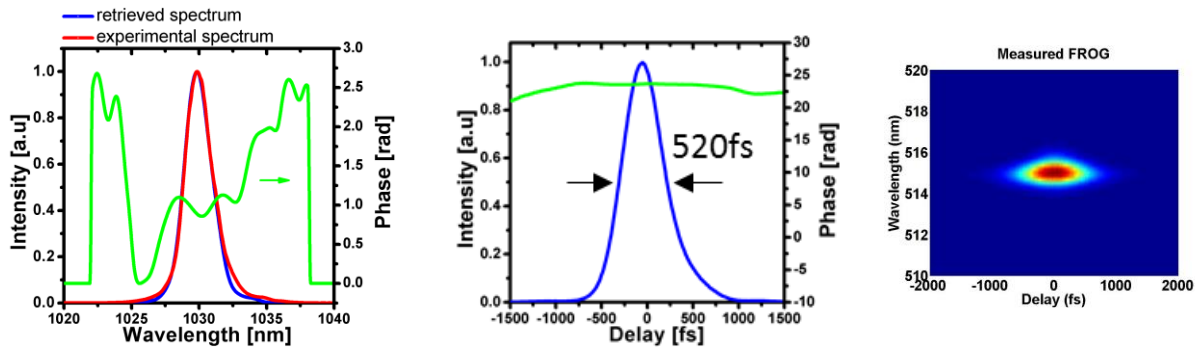


Figure 5: (Left) FROG retrieved spectrum and spectral phase together with directly-measured spectrum - (Right) FROG temporal profile and phase – Insert: FROG trace @ 2.3 mJ, 10 kHz. The FROG grid size is 512x512 and the associated error is 1.2e-3.

In this upgraded system, the nominal energy is chosen at 3 mJ (before compression) with a combining efficiency of more than 91%. The energy is 2.3mJ after compression (23 W of average power). The beam quality of the output pulse is depicted if Figure 4 and is measured close to 1.15. The pulse duration measurement is performed by a SHG FROG. It gives pulse duration of 520 fs which is in good agreement with the experimental spectrum (fig. 5). This leads to a peak power of 4.4 GW.

In conclusion, we demonstrated a simple and powerful single-stage booster amplifier to upscale the pulse energy of a fiber laser system, while preserving short femtosecond pulse duration. The use of a divided-pulse amplification together with crystal length optimized to have both acceptable gain and reduced self-focusing sensitivity allows to demonstrate an output energy up to 3 mJ at 10 kHz (before compression). We demonstrated the interest of the DPA to extend the LIDT from 2.9 mJ to 4.1 mJ, legitimating then its use to obtain 3 mJ in a safe regime. After compression, 2.3 mJ, 520 fs pulses have been measured, with a corresponding peak power of 4.4 GW. The system has also been tested at higher repetition rates. At 100 kHz, we demonstrated in single pass, 360fs, 420 μJ pulses (42 W) and in double pass 440fs, 580 μJ pulses (58 W). Indeed due to the narrow gain cross section of the Yb:YAG, strong gain narrowing is observed for a broad input spectrum. This simple single crystal booster amplifier appears then to be a very interesting scaling-up module, easy to implement in order to extend the performances of high-energy, high-power fiber lasers. The improvements in energy due to DPA -that has been reckoned for the first time for a bulk amplifier- are also very promising. And future prospects to handle both higher power by working on the spatial distortion issues and higher energies by increasing the number of replicas are in progress.

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