Peak Power Scaling of a Multi-kHz, Picosecond, DPSS MOPA System for OPCPA Pumping

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Abstract: We address the peak power scaling of our DPSS MOPA system from 10 MW to >100 MW (anticipated) at multi-kHz for OPCPA pumping. We discuss the challenges in scaling this Nd-based picosecond amplifier system.

OCIS codes: (140.0140) Laser and laser optics; (140.3280) Laser amplifiers

1. Introduction

Optical parametric chirped-pulse amplification (OPCPA) is an extremely powerful ultrafast amplification technique for the direct generation of high intensity quasi single-cycle laser pulses. Absence of gain narrowing [1] as well as high intensity [2] and high power scalability are just a few characteristics that offer OPCPA advantages over the traditional Ti:sapphire-based chirped pulse amplification (CPA). The performances of these systems are currently limited in terms of average and peak power by the picosecond pump lasers. Thus, there is currently a demand for the development of next generation highly stable picosecond pump lasers providing MW to GW peak powers and multi-10-W average powers. Here, we present that our approach based on DPSSL (diode-pumped solid-state laser) MOPA (master oscillator power amplifier) technology satisfies these performance criteria.

Several approaches have been pursued in the past decade. Flash-lamp-pumped, Nd:YAG amplifiers have been used to generate over 1.5 J pulse energy at 79 ps with 15 W average power [2]. Pump lasers utilizing CPA in Yb:YAG were introduced in recent years, such as a Yb:YAG slab producing 20 mJ at 830 ps and 250 W average power [3]. The use of chirped-pulse amplification (CPA) greatly increases the peak power of the pump, but also increases the complexity of the system. By comparison, the amplification of transform-limited pulses in DPSS systems is capable of producing high average power and high peak power simultaneously with a simpler system architecture. One such DPSS system has been recently presented with 40 mJ pulse energy at 1 kHz [4].

We present the key aspects of power scaling our current ps amplifier system, operating at 10 MW peak power, to the anticipated 200 MW-level at few kHz repetition rate. We will present the design challenges and solutions to achieve multi-10 mJ pulse energy output, corresponding to >100 MW peak power.

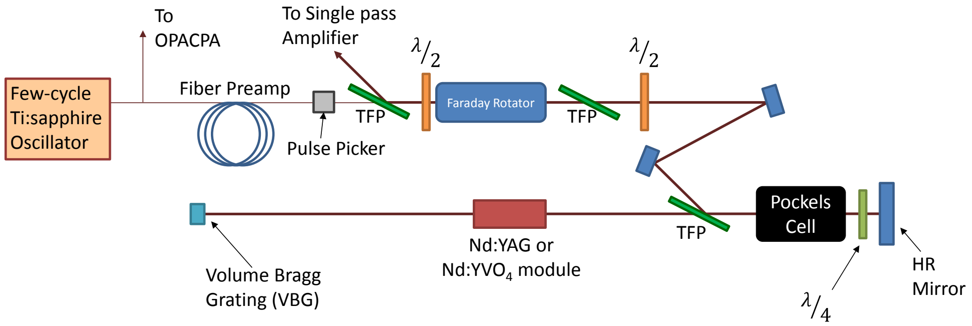

Fig.1. Schematic of the high energy, picosecond amplifier system.

2. Hybrid Amplifier Chain for High Peak Power

The amplifier system is based on a hybrid MOPA configuration [5] with several amplifier stages as shown in Fig. 1. The seed pulses are derived from an ultra-broadband, few-cycle, Ti:sapphire oscillator (MenloSystem, Inc.) and amplified in 5 m Yb-doped fiber. The output pulses are centered at 1064 nm with 25 pJ and ~25 ps duration due to the reduced bandwidth (3 nm FWHM) and material dispersion. Next, the repetition rate is reduced from 85 MHz to several kHz using an electro-optic pulse picker (Quantum Technology, Inc.) before seeding a regenerative amplifier.

Our previous reported output from this amplifier system was 0.88 mJ pulse energy at 1 kHz repetition rate with a Nd:YVO$_4$ amplifier module. The gain material in the regenerative amplifier was replaced with a 2 mm diameter, 5 cm long Nd:YAG amplifier module. Due to the extended length of the crystal, this allowed higher pumping of the material and higher stored energy in the system. The measured output from this system was over 1.5 mJ output at 3 kHz. With the reduced gain of Nd:YAG, the regenerative amplifier required more round trips to reach saturation, which was associated with an increase in pulse duration from 85 ps to ~170 ps as shown in the next section.

3. Temporal Control Through VBG

In this MOPA system, a volume Bragg grating (VBG) is used as one of the cavity mirrors in the regenerative amplifier as elegant method to prevent the buildup of ASE and to narrow the bandwidth of the pulse [5] [6]. The second effect of the narrow-band VBG is to reduce the linewidth of the optical pulses from 3 nm to sub-50-pm. A numerical investigation on the effect of an intra-cavity VBG on the pulse duration of the amplified pulse was performed. Simulations show that as the number of round trips increase the bandwidth continues to decrease. Therefore, the pulse duration continuously increases with each round trip. In the case of a VBG reflectivity of 50 pm, the output pulse duration increases to 110 ps after 10 round trips. After 25 round trips the pulse duration was ~170 ps and after 50 round trips it was ~230 ps. A similar trend is presented for the cases of 300, 150, 100, and 70 pm FWHM VBG reflectivity.

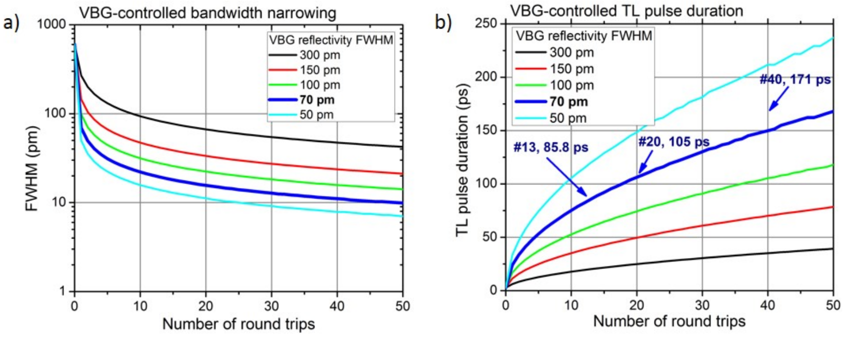

Fig. 2: Linewidth (a) and transform-limited pulse duration (b) for several number of round trips in a regenerative amplifier with a VBG as cavity mirror.

Experimentally, the utilized VBG (OptiGrate, Corp.) had 70% reflectivity, reflectivity FWHM of 50 pm and an aperture of 5 mm x 5 mm with 1 cm length. The number of round trips in the regenerative amplifier was always chosen to provide optimal energy extraction from the gain material and thus, highest output pulse energy. Three operational points are indicated in Fig. 2 (b) which are obtained with this VBG configuration: 85 ps with the ND:YVO_4 at 13 passes [7], 106 ps with Nd:YVO_4 at 20 passes and 171 ps with Nd:YAG at 40 passes. These observations indicate that the chosen reflectivity bandwidth of the VBG and the number of passes in the regenerative amplifier allow tuning of the pulse duration for the entire MOPA system. With this method, we anticipate to maintain a pulse duration of below 100 ps effectively increasing the peak power of the system by almost factor 2.

4. Single Pass Amplifier

Subsequent amplification is achieved using additional modules. The first is a single pass amplifier consisting of a Nd:YVO_4 module with a small signal gain of ~4.5. Fig. 3 (a) shows the output energy produced with different pumping currents of the single pass module. With a seed energy of 0.93 mJ, the maximum output energy was >2.9 mJ. A second harmonic autocorrelator is used to verify the output pulse duration. The pulse duration was measured to be 171 ps with an intensity autocorrelator as shown in Fig. 3 (b).

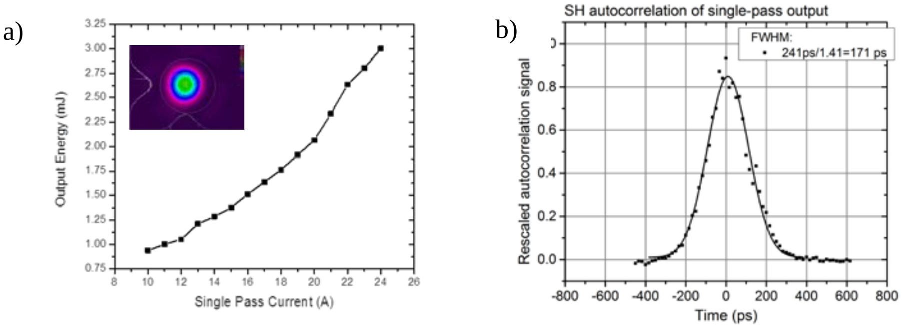

Fig. 3: (a) Output energy for given pumping current in Nd:YVO_4 single pass amplifier and (b) intensity autocorrelation trace of the output pulses.

5. Energy Scaling Booster

Two major barriers need to be addressed for building a high energy Nd:YAG-based DPSS amplifier: thermal lensing and efficient energy extraction. Without proper care additional loses due to thermally induced depolarization can be as high as 35%. Through use of depolarization compensation schemes, as shown in Fig. 4 (a), the depolarization effect can be reduced to below 5%. Additionally, thermal lensing is significant at such levels, so compensation methods are necessary to assure optimal beam quality.

Curved amplifier rod facets and negative lenses are incorporated into the system for thermal lens compensation. It should be noted, this approach gives a good approximate compensation but it does not include higher order aberration terms. For maximum energy extraction, the combination of beam input size and thermal lens power are crucial (given by the pump current), as shown in Fig. 4 (b). For efficient extraction, the fill factor in the amplifier must be high while avoiding hard-aperture clipping and maintain excellent Gaussian beam profile.

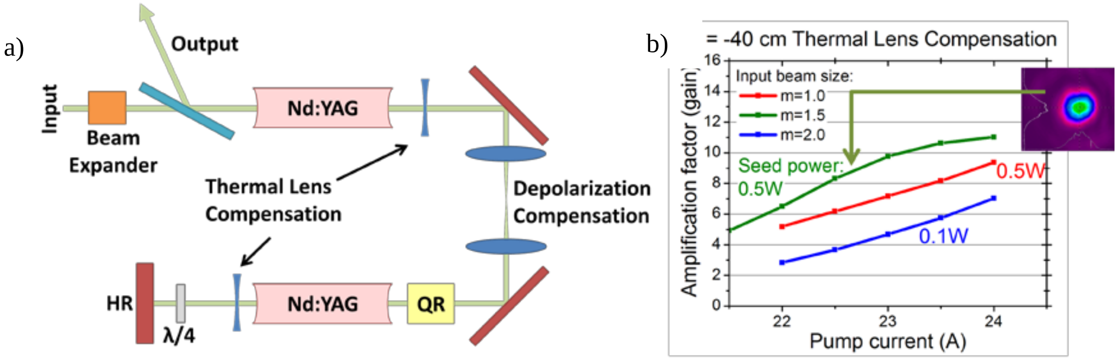

Fig. 4: Amplifier stage with thermal lens and depolarization compensation scheme (a) and the experimental optimization of the stage (b).

This approach based on amplifiers with 3 mm aperture is anticipated to reach up to 20 mJ pulse energy with sub-100-ps duration corresponding to more than 200 MW peak power. Currently, due to the longer pulse duration (factor 2) and lower extraction efficiency, the system operates at the 50 MW peak power level. The experimental and fundamental challenges with this DPSS MOPA approach, during implementation from the 10 MW to the anticipated >100-MW-level, are discussed in detail.

Since the output of the system is synchronized to a sub-5-fs oscillator, the here discussed MOPA system is well-suited as pump beam generation for OPCPA. The anticipated OPCPA output at kHz repetition rates, is designed to have high average power as well as high pulse energy enabling a variety of novel experiments employing these CEP-stabilized few-cycle pulses.

6. Conclusion

Peak power scaling of DPSS picosecond amplifiers imposes several challenges on laser technology. Here, we discuss in detail our high energy picosecond laser development approach, including the design of the amplifier stage and challenges for OPCPA pumping. The key aspects for further energy and power scaling of DPSS amplifiers will be presented with the anticipation to reach the multi-10-mJ and >100 MW peak power level in the immediate future. The fundamental and experimental challenges of this DPSS MOPA system are discussed. This system is specially designed for the OPCPA application, which enables the generation of few-cycle pulses with several mJ pulse energy at high repetition rates.

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