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HIGH AVERAGE POWER EFFECTIVE PUMP SOURCE AT 1 kHz REPETITION RATE FOR OPCPA SYSTEM

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A laser amplifier set-up that can be used as an effective pump source for an optical parametric chirped pulse amplification system is presented in this paper. 1-mJ 48-ps seed pulses were amplified to the energy of 80 mJ. The system operated at 1 kHz repetition rate resulting in an average output power of about 80 W. The results of enhancement of beam focusability by use of deformable mirror are presnted.

Keywords: picosecond pulses amplifier, Nd:YAG, diode pumped, OPCPA

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1. Introduction

The laser radiation with the intensity of petawatt level can be obtained by means of direct chirped pulse amplification (CPA) in large aperture Ti- or Yb-ion doped laser crystals and subsequent compression to tens of femtoseconds [1]. An alternative way to generate ultrashort pulses with petawatt peak powers is to use a technique of optical parametric chirped pulse amplification (OPCPA) [2]. OPCPA systems are usually pumped by fundamental or second harmonic radiation of high-power lasers based on Nd- or Yb-doped laser crystals, namely Nd:YAG, Nd:YLF, or Yb:YAG. Recently OPCPA systems operating either at repetition rates as high as 1 kHz [4] or at output energies beyond 100 mJ [3] while maintaining the pulse duration of 9–10 fs have been demonstrated. In the optical parametric chirped pulse amplifiers [4,5] a femtosecond master oscillator generates seed pulses, which after stretching are parametrically amplified. Pump pulses for the OPCPA are generated in regenerative amplifier (RA)/power amplifier systems based on Nd-doped laser materials. The RA is optically or electronically synchronized with the master oscillator and produces millijoule-level pulses with pulse durations ranging from 50 ps to 100 ps. Those pulses are further amplified in power amplifiers capable of reaching 10 to 1000 mJ energies sufficient for pumping OPCPA stages. Finally, the parametrically amplified broadband seed pulses are compressed to a few-cycle pulse duration [4, 5]. Although the concept of OPCPA is well established, the generation of high energy and high repetition rate pump pulses is still challenging.

As it was mentioned before, the majority of OPCPA pump lasers are based on Yb- and Nd-doped laser crystals. Active media doped with Yb ions have lower quantum defect as compared to Nd-ion based active media. This means that less pump power is converted into heat, and parasitic thermal effects, such as thermal lensing and thermally induced birefringence, are less pronounced. However, as at room temperature Yb-doped materials represent a three-level system, a high-brightness pumping is required for the efficient operation of the amplifiers. This limits the pump scheme to a longitudinal one and puts demand on high-brightness pump laser diodes. Recently by using Yb:YAG slab as an active medium an average power of 15W at the repetition rate of 10 Hz, corresponding to 1.5 J pulse energy, was achieved in a multi-pass amplifier configuration. The amplified pulses duration of 1.8 ps and M^2 value of 1.2 have been reported [6]. With a CPA system using an end-pumped Yb:YAG rod as an active medium, Klingebiel et al. have generated 0.9-ps, 200-mJ pulses at the repetition rate of 10 Hz (2W average power) [7]. By using cryogenic cooling (at cryogenic temperatures Yb-doped laser media represent a four-level system), Hong et al. [8] achieved 20 mJ pulse energy at 1 kHz repetition rate (average power of 20W) in a two-pass Yb:YAG amplifier. Even a higher average power has been demonstrated with the Yb-doped fibre amplifier which generated 470-ps, 1-mJ pulses at the repetition rate of 40 kHz (40W of average power) [9]. The flat-top temporal profile of generated pulses, good beam quality, and compactness of the system reported in [9] are advantageous for pumping OPCPA systems.

Nd:YAG, as compared to Yb:YAG, has a larger emission cross section, which means that large gain can be achieved also in the case of side-pumping. Several groups employed Nd:YAG medium with the side-pumping while constructing efficient pumping sources for OPCPA systems. A pump laser operating at 10 kHz repetition rate with 1 mJ output pulse energy and with pulse duration of 85 ps was demonstrated in [10]. The authors in [10] also discussed a possibility of scaling of the output energy to 20 mJ level.

In this work we report on a picosecond pulse amplifier operating at 1 kHz repetition rate with an average output power approaching 100W. The amplifier is based on Nd:YAG modules side pumped with laser diodes (LD). Despite good total efficiency of LD-pumped laser systems, thermal distortions in the laser rod severely affect the beam quality. In the presented work we concentrate on the compensation of thermally induced depolarization, elimination of the beam profile distortions, improvement of the total system efficiency, and compactness of the laser system. The Nd:YVO$_4$ regenerative amplifier operating at 1 kHz repetition rate and producing 50-ps, 1-mJ output pulses was used as a seed source for the multi-stage Nd:YAG amplifier.

2. Experimental layout and results

The design of the amplification system is presented in Fig. 1. When constructing a high average power laser system, thermal effects should be taken into consideration. A strong thermal lensing could cause damage to optical components and should be considered when planning the layout of an amplifier system. Depolarization could be a source of losses of up to 30% and could have a negative effect on the output beam profile.

To find the best solution for depolarization compensation, a series of experiments testing different amplification stage layouts were carried out. The experimental results were in agreement with [11] where it was theoretically proven that the best way to compensate depolarization is the use of the Faraday polarization rotator between identical amplifier modules. To build our system, a two-pass amplifier layout with the relay imaging from the principal plane of the active medium to the retroreflector mirror and back to the principal plane of the active medium was used. This allowed controlling the thermal lensing to some extent and made the optical path difference compensation more precise, also preserving the needed beam intensity distribution throughout the system. To reduce a nonlinear interaction of light in the gain medium or other optical elements, a quarter wave plate before the laser module was used, as the nonlinear interaction is 1.5 times weaker for the circularly polarized light than it is for the linearly polarized one [12].

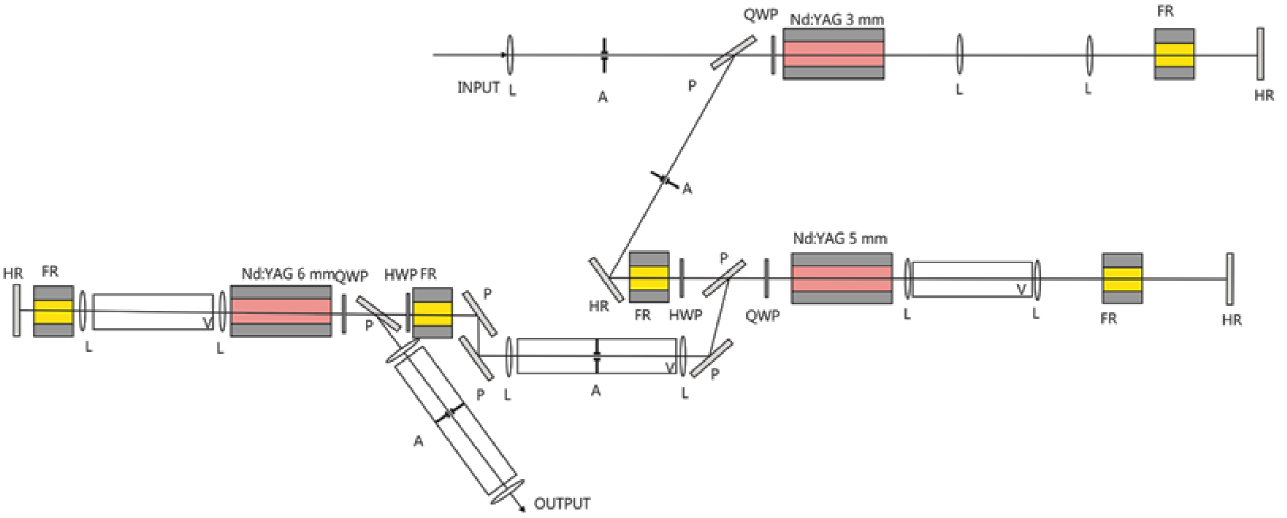

Fig. 1. Amplifier layout: A apperture, P polarizer, L lens, FR Faraday rotator, HR high-reflectivity mirror, V vacuum cell, HWP half wave plate, QWP quarter wave plate.

The two-pass amplifier with the Faraday rotator and polarization decoupling reduced the depolarization loses to only a couple percent of the output pulse energy, also compensating the effect of bifocality of the thermal lens for the tangential and radial polarization components.

The classic depolarization compensation layout where two identical laser modules are put one after another with polarization rotation and relay imaging between them [13] was not used, because the side-pumped laser modules had quite a low single-pass gain (3–5), so inversion used for amplification would be very small compared to the total inversion accumulated in the active medium.

Based on the aforementioned two-pass amplification stage layout, the three-stage amplifier system was realized with the relay imaging telescopes between the stages with a pinhole in the focal plane of the telescope for spatial filtering (Fig. 1). These telescopes were also used to compensate for the thermal lensing of the laser modules by adjusting the distance between the lenses. The spatial filter between the first and second amplification stages was used to create an intensity distribution with a "dip" in the middle (Fig. 2), which was filled during amplification in the following stages because of amplification being stronger in the centre of the rods. As a result, a flatter super-Gaussian intensity distribution was obtained (Fig. 3). The "depth" of the "dip" can be adjusted by changing the pinhole diameter.

In the first amplification stage, the laser module with a rod of 3 mm in diameter was used. It was experimentally (by measuring the output energy of a short resonator free running laser with two plane mirrors) evaluated to have ~35 mJ of inversion accumulated. The upper safe energy limit at the output of this module was evaluated (B integral <3) to be equal to about 12 mJ for 50 ps pulse duration (for fill factor (ff) of 0.6 of the rod diameter). Actual output pulse energy of this amplifier stage was 6–8 mJ when 1 mJ 50 ps pulse was amplified. In the second stage, the laser module with a rod of 5 mm in diameter was used. The accumulated inversion of it was measured to be ~200 mJ. The safe energy limit was estimated to be ~38 mJ (ff 0.8). Actual output energy of the second amplifier stage was measured to be ~32 mJ before spatial filtering. The last amplifier stage used the module with a rod of 6.3 mm in diameter. The measured inversion was at ~175 mJ for this module, and the safe output pulse energy limit was calculated to be ~60 mJ (ff 0.8). Actual output energy was ~80 mJ, this corresponds to a B integral value that is >3. In the future we plan to use a seed laser with ~100 ps pulse duration, which will put the safe energy limit for this laser module at ~120 mJ.

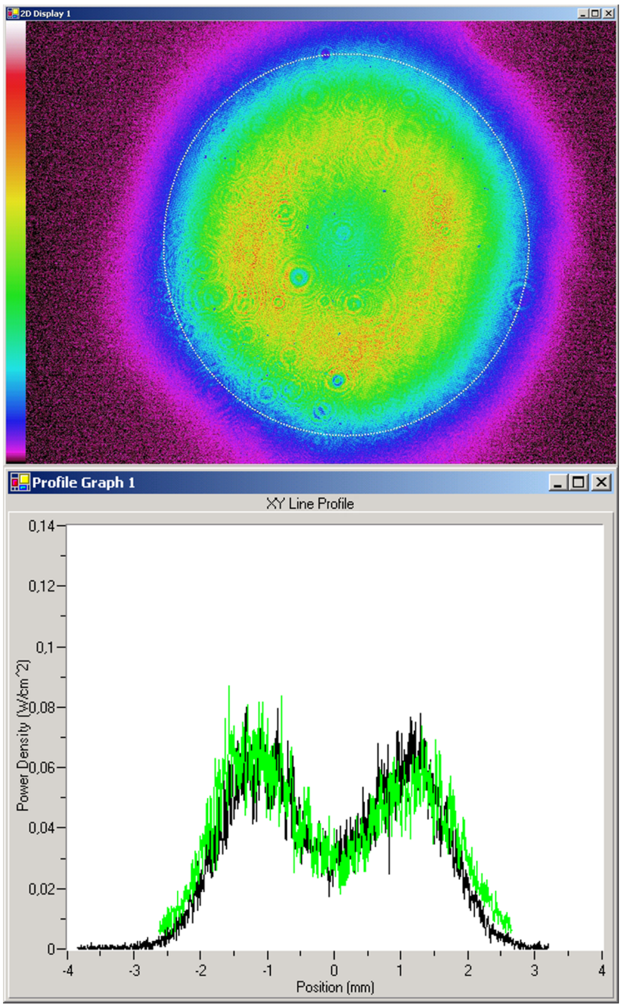

Fig. 2. Intensity distribution with a "dip" formed by the spatial filtering. Profiles look noisy due to interference effects in neutral density filters and in the camera.

The output pulse energies of ~80 mJ were achieved at repetition rate of 1 kHz when amplifying 1 mJ ~50 ps pulses. The output beam intensity distribution (Fig. 3) was similar to a third-order super-Gaussian intensity distribution:

$$I(r) = I_0 e^{-2(r/r_0)^{2n}}, \text{ where } n = 3.$$

It was proven using a second-type LBO crystal that over 50% of the output energy can be converted to the second harmonic radiation needed for OPCPA pumping. This was done by the relay imaging the output intensity distribution onto the second harmonic crystal and collimating the beam.

The output beam quality was evaluated by measuring the M^2 value of the output beam: for horizontal axis it was 6.25; for vertical axis it was 6.18. The beam pointing stability was also evaluated for both axes: 27.3 μrad for horizontal, 49.3 μrad for vertical.

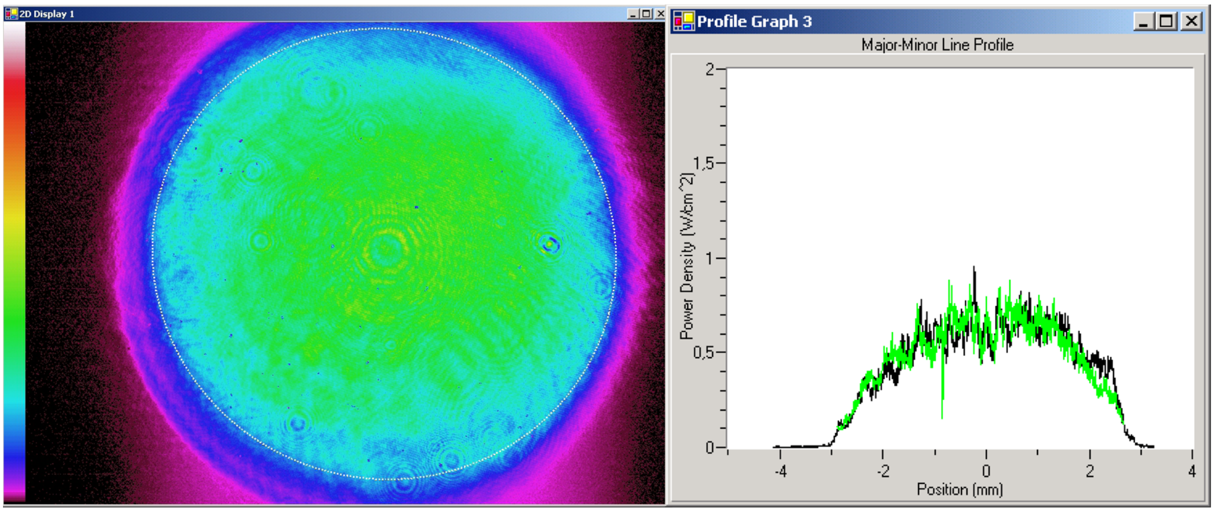

Fig. 3. Output intensity distribution.

A deformable mirror at the output of the amplification system was used in order to enhance the beam quality parameter M^2. The flexible 15 mm diameter metallic MMDM37 mirror with additional dielectric coating, using 37 electrostatic actuators produced by *Flexible Optical B.V.* was chosen as the adaptive component for the experiments. The optimization process was performed by a computer algorithm alternating the voltages of the actuators finding the brightest and smallest image possible at the focal plane of a lens. As a result, reduction of M^2 value to 4.31 for the horizontal axis and 4.15 for the vertical axis was achieved. Visual improvement of the intensity distribution in the far field was observed too (Fig. 4).

The improvement in the beam quality was not as big as expected. Further improvement of the output beam quality of the amplifier system can be achieved by the use of laser modules with a more homogenous pump light distribution across the rod.

3. Conclusion

The three-stage amplifier set-up was realized reaching the average output power of ~80 W at the repetition rate of 1 kHz with the homogenous output beam intensity distribution. The output pulses were ~50 ps long. Using an adaptive mirror, M^2 value of ~4.3 was achieved. It is thought that this kind of a system can be a good effective pump source of an OPCPA set-up.

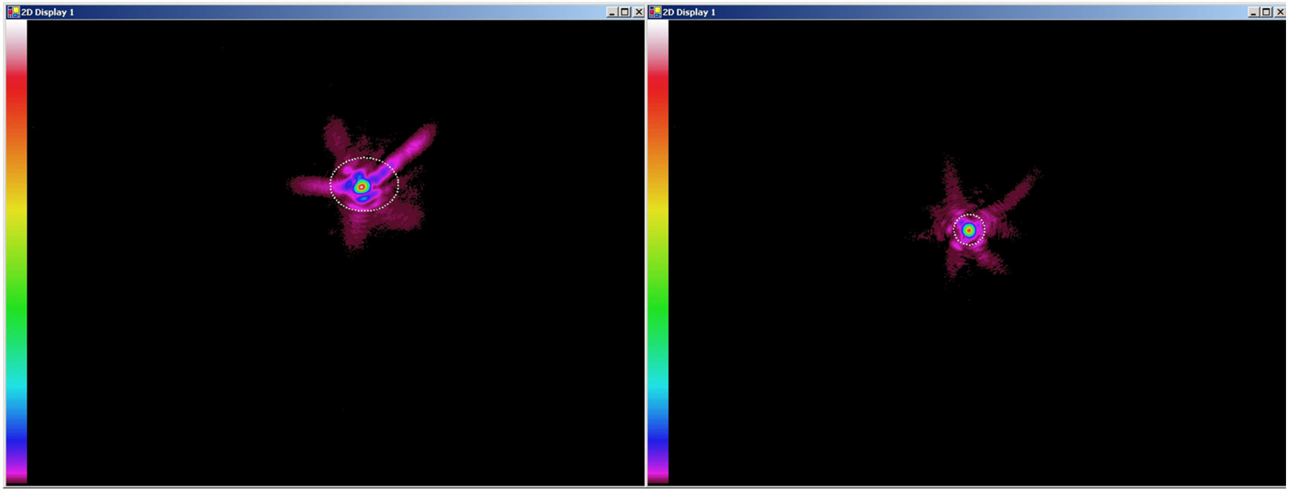

Fig. 4. Far-field intensity distribution before optimization using the adaptive mirror (left) and after the optimization process (right).

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EFEKTYVUS DIDELĖS VIDUTINĖS GALIOS 1 kHz PASIKARTOJIMO DAŽNIO KAUPINIMO ŠALTINIS OPCPA SISTEMAI

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Santrauka

Pristatoma lazerinė stiprinimo sistema, kuri gali būti efektyviu kaupinimo šaltiniu optiniam parametriniam fazişkai moduliuotų („čirpuotų“) šviesos impulsų stiprintuvui. Sistemos vidutinė išėjimo galia buvo apie 80 W, jai veikiant 1 kHz pasikartojimo dažniu ir stiprinant 1 mJ 48 ps trukmės impulsus. Pateikiami pluošto fokusuojamumo pagerinimo deformuojamo veidrodžio pagalba rezultatai.