

Article

Diode-Pumped High Energy and High Average Power All-Solid-State Picosecond Amplifier Systems

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Abstract: We present our research on the high energy picosecond laser operating at a repetition rate of 1 kHz and the high average power picosecond laser running at 100 kHz based on bulk Nd-doped crystals. With diode-pumped solid state (DPSS) hybrid amplifiers consisting of a picosecond oscillator, a regenerative amplifier, end-pumped single-pass amplifiers, and a side-pumped amplifier, an output energy of 64.8 mJ at a repetition rate of 1 kHz was achieved. An average power of 37.5 W at a repetition rate of 100 kHz pumped by continuous wave laser diodes was obtained. Compact, stable and high power DPSS laser amplifier systems with good beam qualities are excellent picosecond sources for high power optical parametric chirped pulse amplification (OPCPA) and high-efficiency laser processing.

Keywords: diode-pumped solid state laser; picosecond laser; amplifier

1. Introduction

High power picosecond lasers have attracted widespread attention due to their wide application in nonlinear frequency conversion, precision processing, and bio-medicine. A picosecond laser operating at a repetition rate of a few kHz, with both high peak power and high average power, is an excellent source for optical parametric chirped pulse amplification (OPCPA), an optical parametric oscillator (OPO), optical parametric generation (OPG), and UV light generation [1–4]. At ELI-Beamlines, two picosecond lasers with 1 kHz, >100 mJ, were used to pump an OPCPA system as a part of an X-ray pump laser [5]. A laser operating at a 193 nm wavelength could be also realized by mixing the fourth harmonic of 1064 nm (266 nm) and 708 nm, which was obtained by an OPO pumped with a picosecond 532 nm laser [6]. Recently, ultra-short laser pulses, especially picosecond pulses, have been widely used in the field of material processing. To achieve high processing speed and productivity, high average power picosecond lasers operating at repetition rates of hundreds of kHz are preferred. The demand for compact, stable, and low-cost picosecond lasers has increased rapidly. Laser diodes are preferred pumps for high power lasers. Diode-pumped solid-state lasers (DPSSLs) are smaller, more stable, and have a lower cost, thus making them more practical for more applications [7–9].

In order to achieve high output power, higher power has to be pumped into the gain medium. In this case, excessive heat will be generated in the gain medium due to a finite conversion efficiency. Thus, the key issue in a high power laser system is how to remove the heat from the gain medium effectively. In the past years, several designs of high power picosecond lasers have been studied. Using rod materials, pulses with 1.5 J energy and 110 ps duration at 10 Hz [10], with 130 mJ and 64 ps at 300 Hz [11], with 80 mJ and 50 ps at 1 kHz, and with 145 W average power and 200 ps duration at 3 kHz were demonstrated with Nd-doped YVO₄ and YAG [12,13]; pulses with 1 J and 5 ps at 100 Hz [4], with 115 mJ before compressing at 200 Hz [14], and with 58.5 mJ at 1 kHz were also recently reported with cryogenically cooled bulk Yb:YAG [9]. Using thin-disk technology, a 300 W picosecond laser operating at 10 kHz was demonstrated with 1.6 ps in 2013, and a 1.3 kW thin-disk multi-pass amplifier running at 300 kHz with sub-8 ps was reported in 2014 [15,16]. Recently, the team at ELI-Beamlines presented a 110 mJ picosecond thin-disk amplifier with good beam quality. A 1-kHz-repetition-rate thin-disk regenerative amplifier was reported with a pulse energy of 10 mJ and a pulse duration of 1.29 ps after compression [5,17]. With innoslab and fiber materials, an average power of 250 W at 12.5 kHz was obtained, and 97 W average output power at 5.47 MHz picosecond pulses was generated from a fiber master oscillator power amplifier (MOPA) system, respectively [18,19]. Combining some of the different technologies mentioned above, a hybrid CPA laser system was reported recently. The system consisting of fiber pre-amplifiers, a bulk material-based regenerative amplifier, and multi-pass amplifiers provided 70 mJ pulse energy at the repetition rate of 1 kHz and about 6 ps pulse duration after compression [20]. Although thin-disk and innoslab lasers have the advantage of easy heat dissipation, lasers based on bulk materials generally could have higher efficiencies and simpler structures, making them more attractive.

In this paper, the research on high energy and high repetition rate DSPP picosecond amplifier systems with bulk Nd-doped crystals is reported. Nd-doped laser media with large emission cross-sections and long upper level lifetimes are very suitable for laser amplifications. Due to its comparatively short upper state lifetime and broad pumping bandwidth, Nd:YVO₄ is appropriate for efficient oscillators and amplifiers. In addition, the 0.8 nm emission bandwidth of Nd:YVO₄ supports sub-10 or sub-100 ps

pulses [21]. In 2010, an output power of 53 W with a peak power of 40 kW from a hybrid amplifier laser system using Nd:YVO₄ was reported, corresponding to an optical efficiency of 42.4% [22]. In 2012, using gratings to stretch and compress the pulses, a multi-pulse picosecond laser with 14 mJ and a pulse duration of 28 ps operating at a repetition rate of 1 kHz from a Nd:YVO₄ regenerative amplifier was reported [23]. In 2013, a laser beam with an average power of 4.7 W running at the repetition rate from 1 kHz to 10 kHz was delivered from a diode dual-end-pumped Nd:YVO₄ regenerative amplifier [24]. Most recently, 10.5 W, 14.2 ps pulses at 1064 nm with a repetition rate of 10 kHz from a Nd:YVO₄ amplifier system was obtained [25] and an average power of 44.5 W, a pulse duration of 8.8 ps at 100 MHz with an optical efficiency of 56% was achieved from a sapphire face-cooled Nd:YVO₄ slab amplifier [26]. However, Nd:YVO₄ has low mechanical fracture so the pump intensity must be kept under a threshold. Considering the characteristics of the Nd:YVO₄ crystal, we employed quasi-continuous wave laser diodes as end-pumping sources for Nd:YVO₄ crystals and a side-pumped Nd:YAG module as a power amplifier. At a repetition rate of 1 kHz, an output energy of 64.8 mJ centered at 1064.4 nm was achieved. An average power of 37.5 W at a repetition rate of 100 kHz pumped by continuous wave (CW) laser diodes was obtained. Compact, stable, and high power DPSS laser amplifier systems with good beam qualities are excellent picosecond sources for high power OPCPA and high-efficiency laser processing.

2. Experiments and Results

2.1. Picosecond Amplifier System at 1 kHz

The picosecond laser system consisted of a picosecond oscillator, a regenerative amplifier, four stages of end-pumped single-pass amplifiers, and a side-pumped amplifier. The whole system was water-cooled and the timing was controlled by a homemade delay generator for synchronization. The generator had seven output channels and each channel provided a control signal at a repetition rate of 1 kHz with delay adjustable from 0.25 ns to 1 ms for the pump lasers and Pockels cells.

2.1.1. Picosecond Oscillator

The seed pulse was provided by a diode-pumped picosecond oscillator designed as shown in Figure 1. The laser crystal was an a-cut, 0.5 at. % Nd-doped YVO₄ crystal with a size of $3 \times 3 \times 5$ mm³. The surfaces of the crystal were antireflection-coated at 808 nm and around 1 μ m ($T > 99\%$). For heat dissipation, the crystal was wrapped with indium foil and mounted tightly in a water-cooled copper heat sink, where the water temperature was maintained at 18 °C. The pump was a fiber-coupled diode laser with a 50 μ m core diameter (BWT, Beijing, China) and 2 W output power at 808 nm. With a semiconductor saturable absorption mirror (SESAM), the oscillator ran in a CW mode-locking state and provided about 400 mW average power at a repetition rate of 80 MHz as shown in Figure 2a. The stability of the output power was measured to be $<0.7\%$ rms as shown in Figure 2b. By controlling the dispersion of the cavity with Gires-Tournois interferometer (GTI) mirrors, the pulse duration could be changed from 10 ps to 15 ps. Figure 3 shows the intensity autocorrelation traces and spectra (AQ6315A, Ando Inc., Tokyo, Japan) of the mode-locked pulses with 10 ps and 15 ps, if sech^2 -pulse shapes were assumed, measured by a commercial intensity autocorrelator (Femtochrome, FR-103MN). Considering the amplification efficiency and to avoid damaging optics, a 15 ps pulse was used as the seed for the

regenerative amplifier. The oscillator worked at room temperature without cooling for its high efficiency and low pump power.

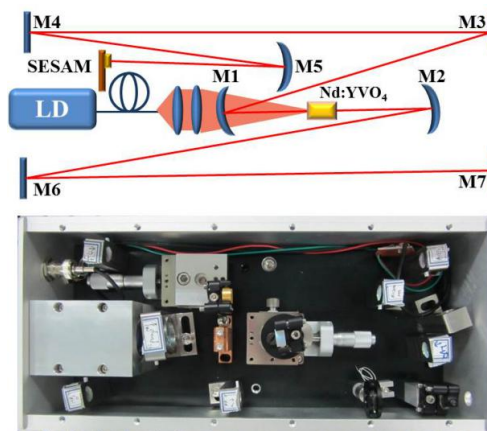


Figure 1. Set-up diagram and photograph of the picosecond oscillator. M1, M2: plane-concave pump mirrors, $R = 75$ mm; M3, M4, M6: high-reflection plane mirrors; M5: concave mirror, $R = 200$ mm; M7: output coupler, $T = 10\%$.

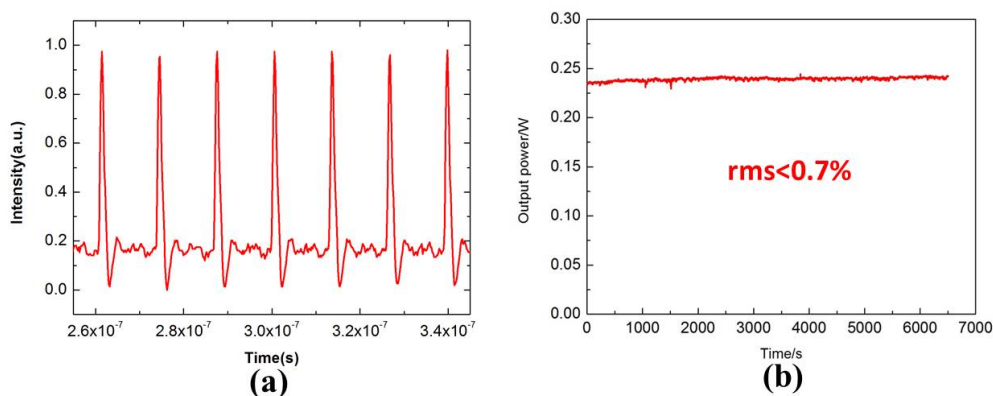


Figure 2. (a) Mode-locked pulse trains; and (b) power stability curve of the picosecond oscillator.

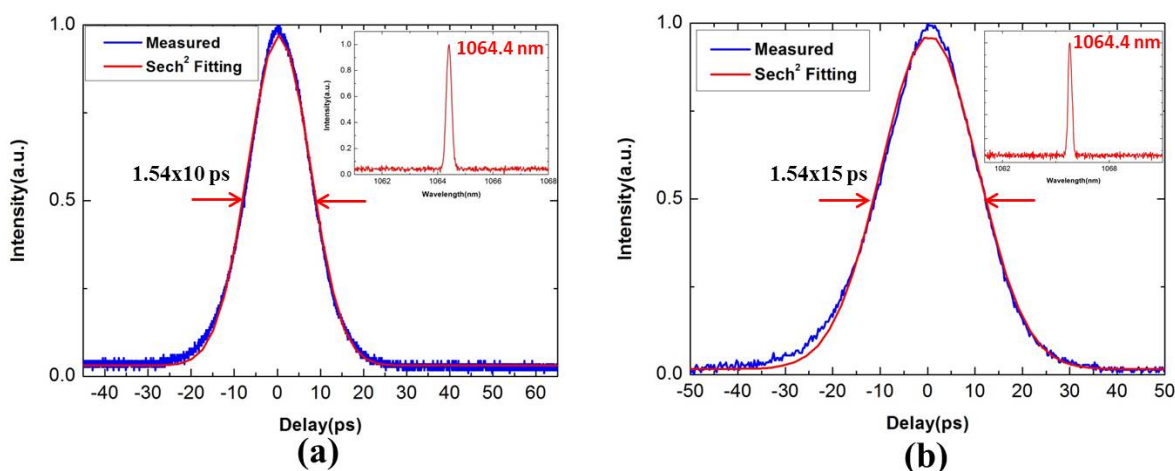


Figure 3. Intensity autocorrelation traces and spectra (insets) of the mode-locked pulses; (a) with dispersion compensation, pulse duration was 10 ps; (b) without dispersion compensation, pulse duration was 15 ps if sech^2 -pulse shapes were assumed.

2.1.2. Regenerative Amplifier

The seed pulse was first amplified by the Nd:YVO₄ regenerative amplifier shown in Figure 4. The laser medium was a $4 \times 4 \times 10 \text{ mm}^3$, a-cut, 0.3 at. % Nd:YVO₄ crystal, which was wrapped with indium foil and mounted tightly on a water-cooled copper heat sink at 14 °C. The surfaces of the crystal were antireflection-coated at 808 nm and around 1 μm ($T > 99\%$). Measures were taken in the regenerative amplifier to reduce the thermal effect. Firstly, the crystal is of low doping concentration and long length. It had high absorption for the pump laser (more than 85%) and good cooling capacity. Besides, the pump laser was a fiber-coupled quasi-CW laser diode with a 400 μm core diameter centered at 808 nm (DILAS, Germany), which produced less heat in the crystal than a CW laser diode. The pump laser was controlled by a trigger signal with a gate width of 120 μs at 1 kHz and focused into the crystal by an imaging system with a magnification of two. Finally, a thermal compensation cavity was constructed as shown in Figure 4. Since pulse energy in the cavity was very high, laser beams in the crystal and Pockels cell were relatively large to avoid damage. The beam diameters in the crystal and Pockels cell were about 1.2 mm and 1.4 mm. The intra-cavity transverse mode between the convex mirrors did not change when the focal length of the thermal lens changed from 1000 mm to infinity, which was caused by the increasing pump power, for ensuring the stability of the laser cavity. The stretcher and compressor were not used since the pulse duration of 15 ps was long enough in our laser system. In order to improve the contrast of the amplified pulses, the seed pulses passed through a Pockels cell to reduce the repetition rate from 80 MHz to 1 kHz before being injected into the amplifier. The seed pulse with about 1 nJ energy centered at 1064.4 nm was then amplified to 1.5 mJ at 1 kHz under the pump energy of 8 mJ in the regenerative amplifier. Figure 5 shows the pulse building process in the regenerative amplifier. Figure 6 shows the beam quality of the output pulses measured by a commercial instrument (M2-200S-FW, Ophir-Spiricon Inc., North Logan, UT, USA). The result ($M^2 < 1.15$) proved a good quality of the laser beam from the regenerative amplifier.

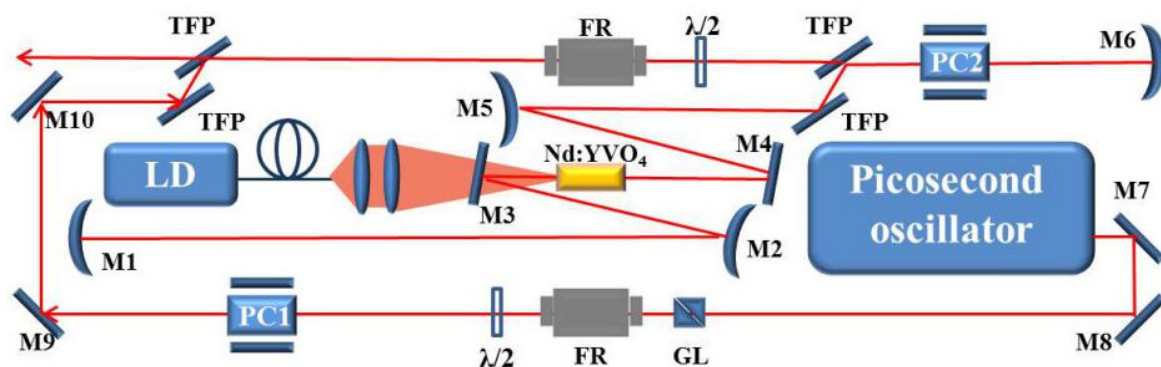


Figure 4. The scheme of the regenerative amplifier operating at a repetition rate of 1 kHz. M1, M6: Concave mirrors, $R = 900 \text{ mm}$; M2, M5: Convex mirrors, $R = -1000 \text{ mm}$; M3, M4, M7–M10: Plane high-reflection mirrors; PC: Pockels cell; TFP: Thin-film polarizer; FR: Faraday rotator; GL: Glan prism.

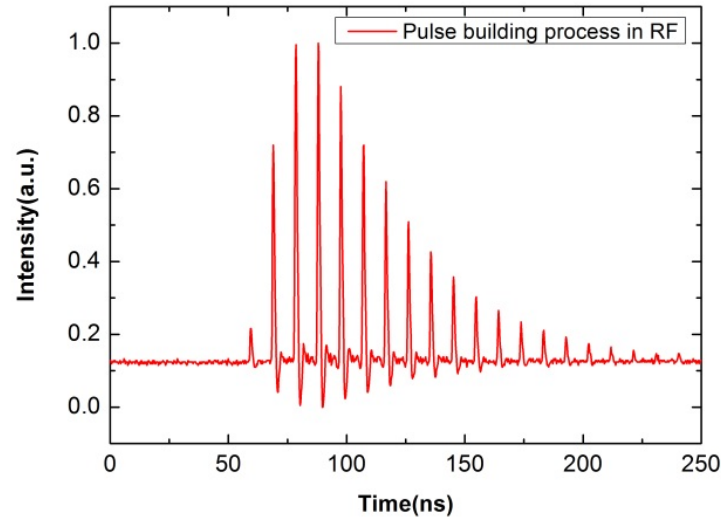


Figure 5. Pulse building process in the regenerative amplifier.

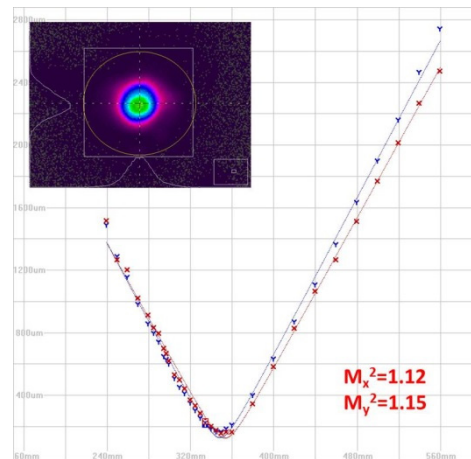


Figure 6. The beam quality of the output pulses from the regenerative amplifier.

2.1.3. End-Pumped Single-Pass Amplifiers

A 1.5 mJ, 1064.4 nm, 1 kHz pulse with high contrast and good beam quality was obtained by the regenerative amplifier as described in the previous section. Higher pulse energies are required for many applications [4–6]. As previously reported [12], multiple stages of side-pumped amplifiers were used to obtain 80 mJ picosecond laser pulses. However, due to the inhomogeneity in the directions of the side-pumped modules, the beam quality ($M^2 > 4$) was not good enough for some applications. To obtain a high pulse energy picosecond laser with good beam quality, we implemented a hybrid power amplifier consisting of four stages of end-pumped single-pass Nd:YVO₄ amplifiers and a side-pumped Nd:YAG amplifier as shown in Figure 7. In end-pumped amplifiers, 0.3 at. % Nd:YVO₄ crystals with a dimension of $4 \times 4 \times 10 \text{ mm}^3$ were used as gain media and also wrapped with indium foil and mounted on water-cooled copper heat sinks at 14 °C. The fiber-coupled quasi-CW laser diodes with an 800 μm core diameter centered at 808 nm (DILAS, Mainz-Hechtsheim, Germany) were used as pump sources, and each of them produced a 120 μs pulse at 1 kHz and focused into the crystal by an imaging system with a magnification of two. For time synchronization of the whole system, a homemade delay generator provided trigger signals at the repetition rate of 1 kHz to drive the Pockels cells and quasi-CW pumps.

The measured power curves and beam images are shown in Figure 8. The 1.5 mJ, 1064.4 nm, 1 kHz picosecond pulses were amplified to be more than 34 mJ after four stages of end-pumped single-pass amplifiers. The total pump energy was about 125 mJ, corresponding to an optical efficiency of 26%.

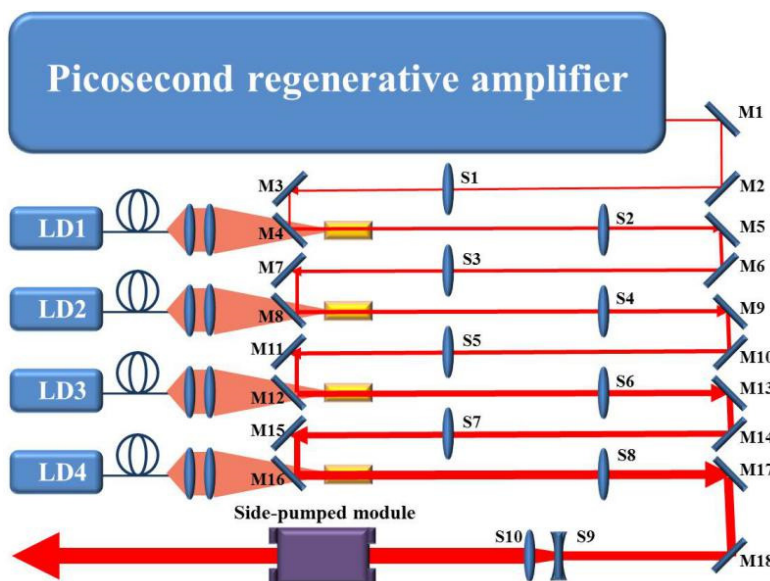


Figure 7. Diagram of the hybrid amplifier. M1–M3, M5–M7, M9–M11, M13–M15, M17–M18: Plane high-reflection mirrors; M4, M8, M12, M16: Plane high-reflection pump mirrors; S1–S8, S10: Plane-convex lens; S9: Plane-concave lens.

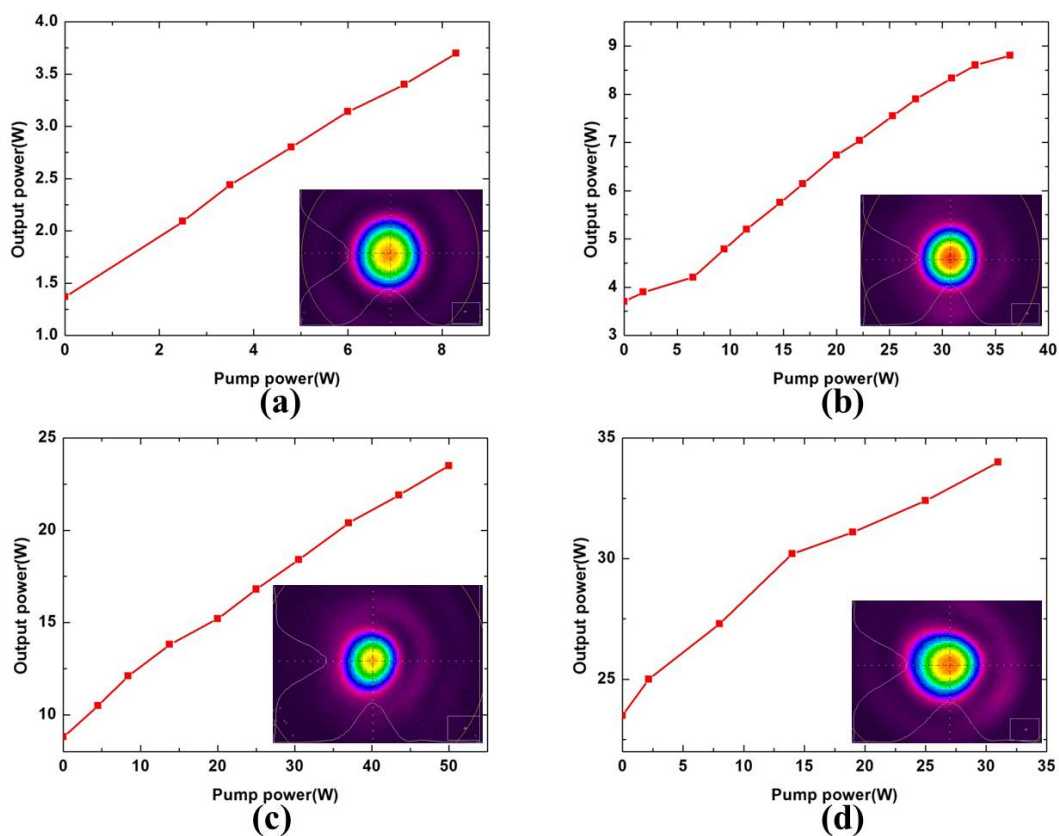


Figure 8. Power curves and beam images of each stage. (a) First stage; (b) second stage; (c) third stage; (d) fourth stage.

2.1.4. Side-Pumped Amplifier

Finally, the 34 mJ picosecond pulses from end-pumped amplifiers were injected into the last amplifier, a module consisting of a $\Phi 8 \times 185 \text{ mm}^3$ Nd:YAG side-pumped by CW laser diodes. The maximum allowed pump power of 1000 W could be obtained at the wavelength of 808 nm. The cooling water system maintained at 14 °C was used for the heat dissipation of the crystal. In this experiment, a pump power of 750 W was used and a 64.8 mJ picosecond laser pulse at 1 kHz was obtained. Figure 9 shows the power curve and beam quality, where a good beam quality of $M^2 < 2$ is illustrated.

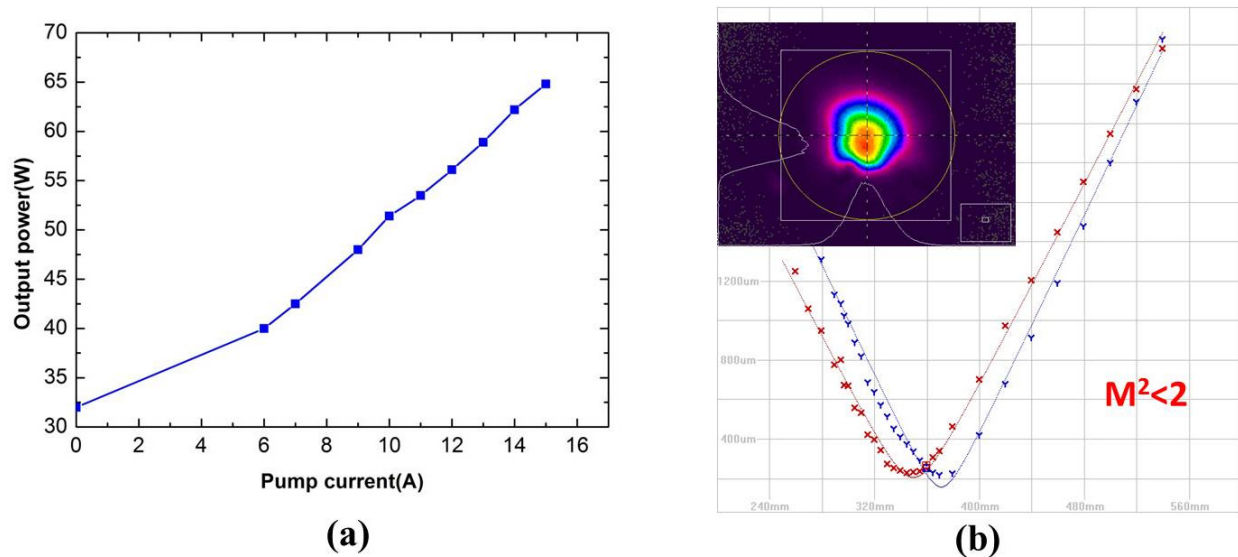


Figure 9. Power curve and beam quality of the side-pumped amplifier. (a) Power curve; (b) Beam quality.

2.2. High Average Power Picosecond Amplifier System at 100 kHz

As mentioned above, while the high energy picosecond laser operating at the repetition rate of 1 kHz is an excellent pump source for OPCPA, OPO, OPG, and UV light generation, a high power picosecond laser running at a higher repetition rate, such as 100 kHz, is preferred in the field of processing. Based on the experience introduced in Section 2.1, we demonstrated a 100 kHz, 37.5 W picosecond DPSS laser system, which was an excellent source for high efficiency laser processing.

At a higher repetition rate, the energy density is lower, but more heat is produced in the crystal. Reducing the diameter of the laser beam in the crystal is a good choice because of the smaller heat generation area and comparatively higher efficiency. Another reason for a smaller beam diameter was that a 3 mm diameter BBO Pockels cell was used as an electro-optic switch and worked at the repetition rate of 100 kHz, and the laser beam in the Pockels cell had to be smaller than that mentioned in Section 2.1.2. Thus, a thermal compensation cavity with a laser beam size smaller than that in Figure 4 was designed and constructed as a regenerative amplifier shown in Figure 10. The convex mirrors were replaced with concave mirrors ($R = 600 \text{ mm}$). The laser beam was about $550 \mu\text{m}$ in the crystal and $730 \mu\text{m}$ in the Pockels cell as the focal length of the thermal lens changed from 300 mm to infinity. This cavity was more suitable for high-repetition-rate amplifier performance. A 0.3 at. %, a-cut, $3 \times 3 \times 10 \text{ mm}^3$ Nd:YVO₄ crystal antireflection-coated at 808 nm and around $1 \mu\text{m}$ ($t > 99\%$) was used for this cavity.

The crystal was wrapped with indium foil and mounted tightly on a water-cooled copper heat sink at 14 °C. The pumping source was a fiber-coupled CW laser diode with a 200 μm core diameter centered at 808 nm (Focuslight, China). Figure 11a shows the power curve of the regenerative amplifier. At the CW pump power of 15.5 W, 2.6 W average output power was obtained at the repetition rate of 100 kHz by injecting a 15 ps seed pulse from a 1064.4 nm, 80 MHz picosecond oscillator. Figure 11b shows the beam quality of the output pulses as good as $M^2 < 1.2$.

To further improve the average power, a hybrid power amplifier was also used. The hybrid power amplifier consisted of three stages of end-pumped single-pass amplifiers with CW laser diodes and a side-pumped module introduced in Section 2.1. The 2.6 W output pulses from the regenerative amplifier were then amplified by the single-pass amplifiers. The 0.3 at. %, a-cut, $3 \times 3 \times 10 \text{ mm}^3$ Nd:YVO₄ crystals were employed as gain media. At the total pump power of 88.5 W, an output average power of 21 W was obtained at 1064.4 nm, corresponding to a pulse energy of 210 μJ and an optical efficiency of 20.8%. At last, the picosecond pulses were amplified to 37.5 W by the side-pumped module at a pump power of 900 W. The pulse energy was as high as 375 μJ at a repetition rate of 100 kHz. Figure 12 shows the power curves and beam images of the power amplifiers.

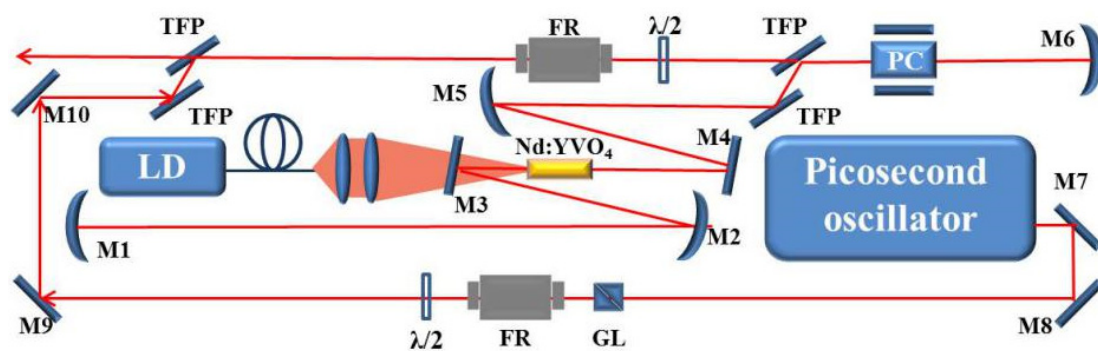


Figure 10. Diagram of the regenerative amplifier running at the repetition rate of 100 kHz. M1, M6: Concave mirrors, $R = 900 \text{ mm}$; M2, M5: Concave mirrors, $R = 600 \text{ mm}$; M3, M4, M7–M10: Plane high-reflection mirrors; PC: Pockels cell; TFP: Thin-film polarizer; FR: Faraday rotator; GL: Glan prism.

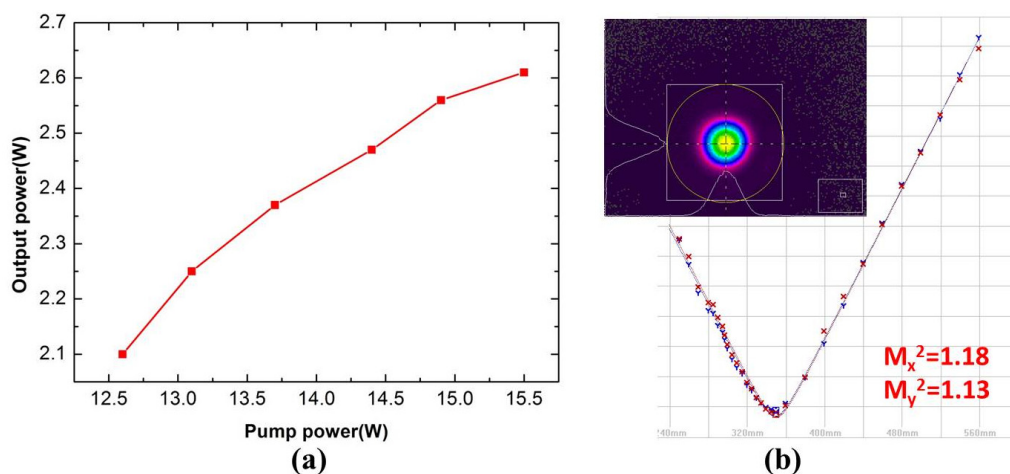


Figure 11. (a) Power curve of regenerative amplification; (b) Beam quality of the output pulses from the regenerative amplifier.

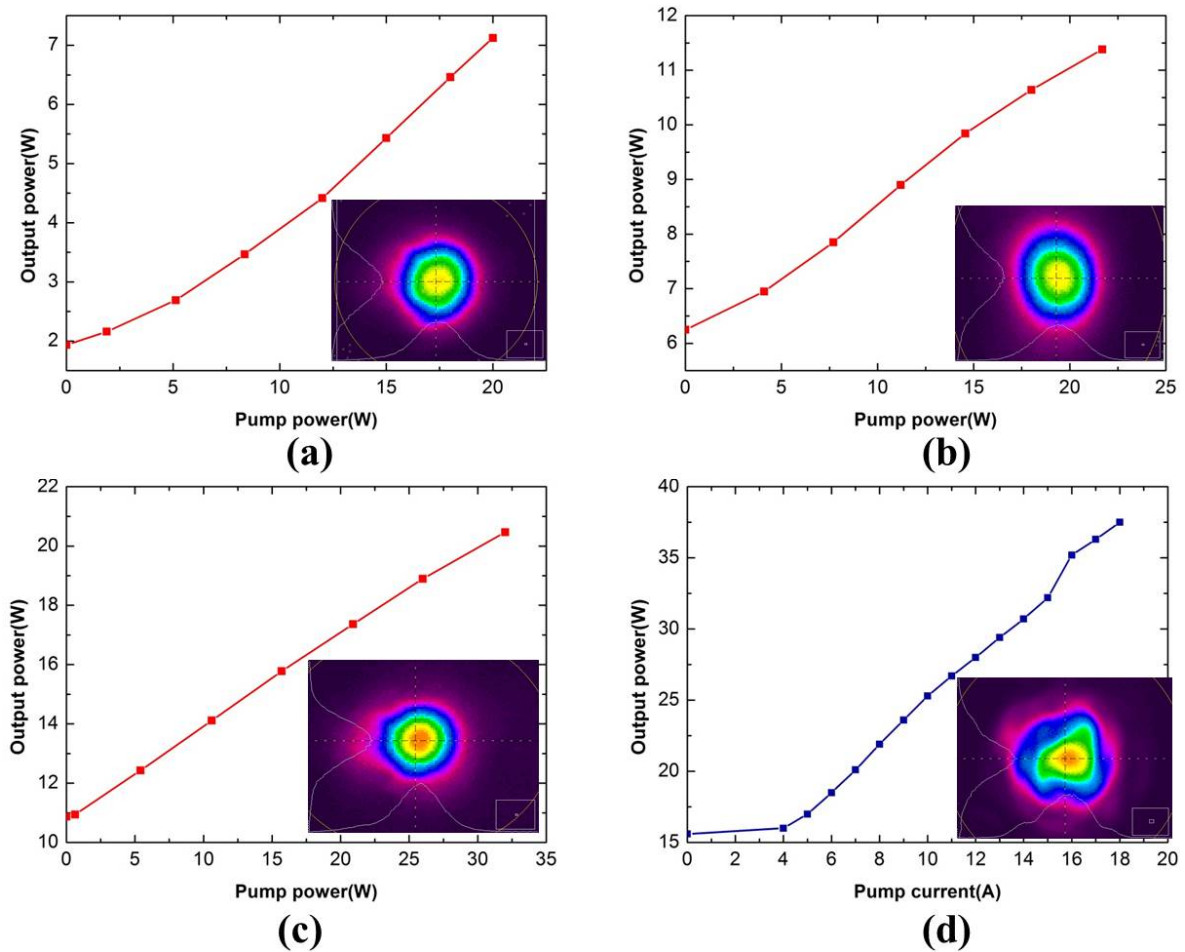


Figure 12. Power curves and beam images of each stage. (a) First stage; (b) second stage; (c) third stage; (d) side-pumped stage.

3. Conclusions and Discussions

In conclusion, we have introduced the latest developments in high power DPSS picosecond lasers. We presented our work on a high energy picosecond laser operating at a repetition rate of 1 kHz. and a high average power picosecond laser running at 100 kHz. With DPSS hybrid amplifiers consisting of a picosecond oscillator, a regenerative amplifier, end-pumped single-pass amplifiers, and a side-pumped amplifier, the output energy of 64.8 mJ at a repetition rate of 1 kHz was achieved. An average power of 37.5 W at a repetition rate of 100 kHz pumped by CW laser diodes was also obtained.

Although without the advantage of heat dissipation, laser systems based on bulk materials generally could have high conversion efficiency and simple structures. These characteristics make bulk materials attractive choices as laser media in high power DPSS picosecond lasers. In this paper, we demonstrated high energy and high average power picosecond laser systems with bulk Nd-doped crystals, proving them as promising candidates to achieve high power DPSS lasers.

To improve the system’s capacity of heat dissipation, we took measures on the crystals, pumps, and cavity design. We used long crystals with low doping concentration and quasi-CW laser diodes as pumps. A thermal compensation cavity was designed and used as a regenerative amplifier. The crystals were water-cooled at 14 °C. In the experiments, we found that the efficiency dropped significantly when

the pump power increased to a certain value beyond the damage threshold of the crystals. The main influence factor, we believed, was the heat accumulated in the crystals. In the next step, we will replace the water-coolers with thermal electronic coolers (TEC) or cryogenic coolers to improve the capacity of heat dissipation to achieve higher power or energy.

By the figures showing the beam qualities of the output pulses in this paper, we noticed that the beam quality deteriorated significantly after including the side-pumped amplifier despite providing a huge pump power. Its inhomogeneity in space had a great influence on the beam quality. However, the beam quality of the picosecond laser is especially important for certain applications. The side-pumped module will have to be replaced by an end-pumped amplifier for better beam quality.

Acknowledgments

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Author Contributions

Zhiyi Wei and Zhaohua Wang designed and supervised the research; Jiaying Liu, Zhiguo Lv and Zhiyuan Zhang performed the research; Jiaying Liu and Wei Wang analyzed the data; and Jiaying Liu wrote the paper with discussions from all authors.

Conflicts of Interest

The authors declare no conflict of interest.

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