applied sciences

MDPI

Article

A High-Energy, 100 Hz, Picosecond Laser for OPCPA Pumping

Hongpeng Su [1,2], Yujie Peng [1,*], Junchi Chen [1], Yanyan Li [1], Pengfei Wang [1,2] and Yuxin Leng [1,*]

1 State Key Laboratory of High Field Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, 390# Qinghe Road, Jiading District, Shanghai 201800, China; spamsu@siom.ac.cn (H.S.); chenjunchi01@163.com (J.C.); yyli@siom.ac.cn (Y.L.); wangpengfei@siom.ac.cn (P.W.)

2 University of Chinese Academy of Sciences, Beijing 100190, China

* Correspondence: yjpeng@siom.ac.cn (Y.P.); lengyuxin@mail.siom.ac.cn (Y.L.); Tel.: +86-021-6991-8261 (Y.P.); +86-021-6991-8436 (Y.L.)

Received: 31 August 2017; Accepted: 25 September 2017; Published: 27 September 2017

Abstract: A high-energy diode-pumped picosecond laser system centered at 1064 nm for optical parametric chirped pulse amplifier (OPCPA) pumping was demonstrated. The laser system was based on a master oscillator power amplifier configuration, which contained an Nd:YVO_4 mode-locked seed laser, an LD-pumped Nd:YAG regenerative amplifier, and two double-pass amplifiers. A reflecting volume Bragg grating with a 0.1 nm reflective bandwidth was used in the regenerative amplifier for spectrum narrowing and pulse broadening to suit the pulse duration of the optical parametric amplifier (OPA) process. Laser pulses with an energy of 316.5 mJ and a pulse duration of 50 ps were obtained at a 100 Hz repetition rate. A top-hat beam distribution and a 0.53% energy stability (RMS) were achieved in this system.

Keywords: diode-pumped solid-state laser; picosecond laser; OPCPA pumping

1. Introduction

High energy, ultrafast laser in the mid-infrared (mid-IR) is desirable for applications in strong field physics [1], high-harmonic generation [2], and driving X-ray sources [3]. An optical parametric chirped pulse amplifier (OPCPA) is one of the most promising ways to achieve amplification for mid-IR laser pulses by applying proper nonlinear crystals and a phase matching condition. A kHz, mJ-level OPCPA at 2.1 μm is reported with a high-energy cryogenic Yb:YAG pump laser [4]. The current limitation for a higher OPCPA output depends upon the development of high-energy picosecond pumping sources. Several investigations have been developed for the generation of high-energy OPCPA pump sources. A picosecond pump laser for IR OPCPA delivering 25 mJ at 3 kHz based on a Yb:YAG thin-disk amplifier has been reported [5]. A 100 mJ, 1 kHz laser output has been achieved as a pump for picosecond OPCPA based on Yb:YAG thin disk regenerative amplifier [6]. Additionally, an OPCPA pump laser based on rod-shaped Nd:YAG crystals has been reported, producing 130 mJ, 64 ps pulses with a repetition of 300 Hz [7].

In this paper, we present a diode-pumped solid-state laser (DPSSL) amplification system based on a master oscillator power amplifier (MOPA) configuration, delivering 316.5 mJ, 50 ps pulse energy at a wavelength of 1064 nm and a repetition of 100 Hz. The amplification system works at room temperature. A thermal lens and thermally induced depolarization were studied and compensated. A reflecting volume Bragg grating was utilized in the regenerative amplifier to achieve temporal stretching of the laser pulses to suit the width of the signal laser pulses in the optical parametric amplifier (OPA) process. The output of the amplification system also features an approximately flat-top spatial distribution and a 0.53% energy stability (RMS).

2. Experiments and Results

2.1. Front-End and Regenerative Amplifier

The schematic of the laser system is shown in Figure 1. The master oscillator is a home-built Nd:YVO_4 mode-locked laser, providing up to 280 mW, 8.4 ps laser pulses at a wavelength of 1064 nm and a frequency of 80 MHz. The OPCPA system we serve is seeded by a commercial ultrafast laser (Vitara, Coherent Corporation, Santa Clara, CA, United States) centered at 800 nm. The laser is then converted to 4 µm via a three-stage OPA based on $KTiOAsO_4$ (KTA) nonlinear crystals [8]. The 4 µm laser will serve as the signal pulses in the following OPCPA process. OPA is an interactive process between pump pulses and signal pulses, thus the temporal and spatial overlap between two pulses determines actual gain performance. To achieve perfect temporal synchronization, the Nd:YVO_4 mode-locked oscillator is designed to operate at 80 MHz, which is the same with the commercial 800 nm laser. The commercial 800 nm oscillator is equipped with a synchronization accessory, which can synchronize its oscillator to an external Radio Frequency (RF) source. Part of the Nd:YVO_4 mode-locked laser pulses are utilized and converted into a master signal by a photo-diode. The synchronization accessory will accept the trigger and automatically adjust the length of the cavity to achieve precise frequency synchronization with the master Nd:YVO_4 oscillator. At the same time, the trigger signal from the Nd:YVO_4 mode-locked oscillator is transmitted to a synchronizer, which provides all delay signals for latter electrical devices.

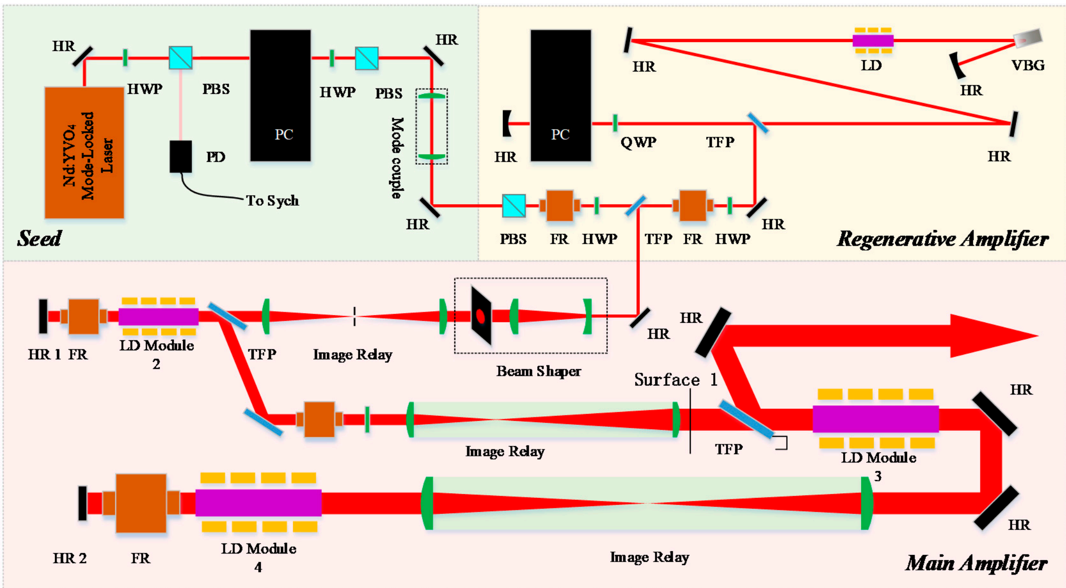
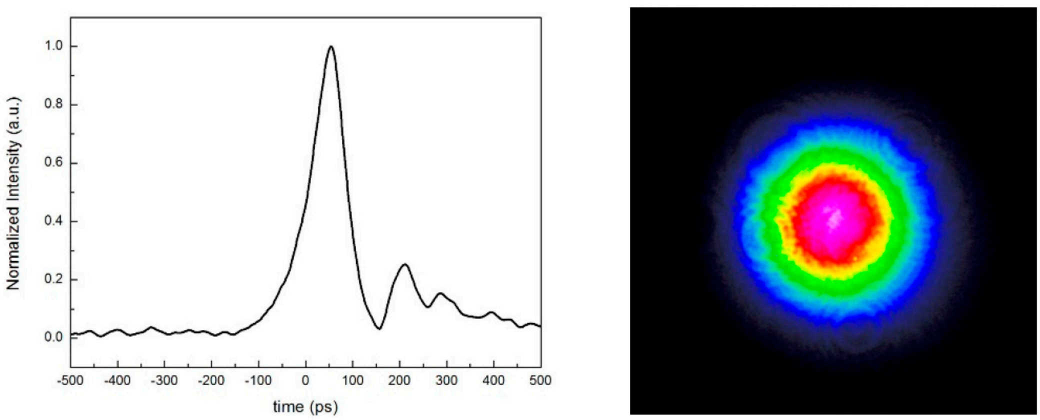


Figure 1. Schematic of the laser system. HR: high reflector; HWP: half-wave plate; PBS: polarization beam splitter; PD: photo diode; PC: Pockels cell; FR: Faraday rotator; TFP: thin-film plate; QWP: quarter-wave plate; LD: laser diode; VBG: volume Bragg grating.

Pulses from the Nd:YVO_4 mode-locked oscillator first pass through a half-wave plate (HWP), which works with a polarization beam splitter (PBS), to control the pulse energy injected into the amplification system by rotating the HWP. A Pockels cell (PC) is operated at half-wave voltage with a repetition of 100 Hz, working together with two PBSs and an HWP to achieve pulse picking and isolation from the damage of returning pulses. When the half-wave voltage is applied to the Pockels cell, pulses will maintain p-polarization after passing through the Pockels cell and the HWP. When the voltage is off, laser pulses will change their polarization after passing through the HWP and exit from either PBS. Before they are injected into the regenerative amplifier, laser pulses of 100 Hz are aligned and expanded to 1.8 mm with a pair of plano-convex lenses, which suit the cavity mode of the regenerative amplifier.

Before seeding the regenerative amplifier, laser pulses pass through an optical isolator composed of a PBS, an HWP, and a Faraday rotator (FR) to ensure extra protection for the oscillator. The regenerative amplifier has a linear cavity with a stable cavity mode. The diode-pumped amplification module (Cutting Edge Optronics, RBAT30-1P, St. Charles, MO, USA) has a rod-shaped Nd:YAG crystal with a diameter of 3 mm and a length of 60 mm. When operated at 180 A and 300 Hz with a pulse width of 250 µs, this module has a stored energy of 197.7 mJ. In this system, the operating parameters are set at 75 A and 100 Hz with a duration of 250 µs, which matches the upper state lifetime of the Nd:YAG gain material. A Pockels cell is operated at quarter-wave voltage with an operation frequency of 100 Hz, whose time delay is precisely controlled by the synchronizer to achieve correct build-up of the pulse energy in the cavity before exiting.

To achieve better temporal overlap between pump pulses and signal pulses in the OPA process, pump pulses should also be stretched to tens of picoseconds to suit the temporal width of signal pulses. In this work, a reflecting volume Bragg grating (VBG) is inserted as one of the mirrors to achieve the temporal stretching. The VBG we utilize (OptiGrate, RBG-1064-99, Oviedo, FL, USA) has an aperture of 8.0 mm $\times$ 5.0 mm and a thickness of 12 mm. The VBG has a bandwidth of 0.1 nm centered at 1064 nm with a reflection efficiency as high as 99.7%. Narrower reflected bandwidth will result in stretching in the time-domain. To obtain a maximum, saturated output with a fixed round-trip time, the input pulse energy needs to be maintained constant. If we want to change the duration of the output pulse, we need to vary the energy of the injected pulse and make the regenerative amplifier at the saturated state with different round-trips. We precisely control the input pulse energy, and after 20 round trips in the regenerative cavity, laser pulses are stretched to 115 ps, which is shown in Figure 2a. Using stretched pulses has two advantages: on the one hand, it will match the width of the signal pulses in the OPA process; on the other hand, stretched pulses lower the peak power of laser pulses and promise a higher energy gain without bringing about damage to optical devices. After 20 round trips, a total 2.2 mJ of pulse energy is achieved via the regenerative amplifier. The beam distribution is shown in Figure 2b.



(a) (b)

Figure 2. (**a**) Temporal profile and (**b**) beam distribution of amplified pulses from the regenerative amplifier.

The laser pulses of the regenerative amplifier are then expanded to 6.5 mm and aligned with a pair of plano-convex and plano-concave lenses. In the OPA process, a top-hat distribution of pump pulses is preferred due to its uniform amplification gain. To achieve a top-hat distribution of the laser beam, a serrated aperture with a diameter of 6 mm is inserted behind the regenerative amplifier to select the uniform part of the laser beam, which also reduces the pulse energy from 2.2 to 1.6 mJ. The beam at the serrated aperture is then relay-imaged to the high-reflection mirror 1 (HR1) with a pair of plano-convex lenses. A pinhole is set at the focal point in the relay-imaging setup to achieve spatial filtering.

2.2. Power Amplifiers and Compensation of Thermal Effects

The power amplification stage consists of two successive laser gain configurations. The first setup contains a diode-pumped gain module (Cutting Edge Optronics, REA6306-1P), which has a rod-shaped Nd:YAG crystal with a diameter of 6 mm and a length of 120 mm. This module has a maximum operating parameter of 180 A and 300 Hz, a condition under which it has a stored energy of 513.3 mJ. In this system, the module is operated at 100 A and 100 Hz with a small signal gain of 3.49 in consideration of controllable thermal effects and sufficient amplification performance. After exiting from the serrated aperture, laser pulses pass through the gain module and a Faraday rotator, and are reflected back. The laser pulses change their polarization after the double-pass of the Faraday rotator and exit from thin film polarizer (TFP).

In the diode-pumped gain module, unabsorbed pumping light will bring about heat accumulation. A water-cooling circulatory system is used to take away the redundant heat to prevent the fracture of the gain crystal. The pumping system together with a water-cooling system will result in a nonuniform radial temperature distribution in the rod-shaped crystal. The thermal strains in the rod-shaped crystal brought by the nonuniform radial temperature distribution will result in a change in the refractive index via the photoelastic effect, which will lead to a thermally induced birefringence and thermal lensing.

The thermally induced birefringence will bring about depolarization and lead to a loss of laser energy when pulses pass through polarization-related devices. According to Reference [9], thermally induced depolarization will be compensated when laser pulses pass through the same gain module with a 90-degree polarization rotation. Thus, a Faraday rotator is placed between the gain module and HR1 to achieve the polarization rotation and depolarization compensation. With our measurements, the loss of depolarization is below 3%.

After the double-pass of Gain Module 2, laser pulses are relay-imaged from HR1 to Surface 1 and expanded from 6 to 10 mm with an imaging system composed of a pair of plano-convex lenses. Laser pulses will show little convergence due to a thermal lensing effect in Gain Module 2. When operated at 100 Hz and 100 A, the gain module has a measured focal length of 30 m, as shown in Figure 3. Thus, in the imaging setup, the distance between two lenses is precisely adjusted to achieve the compensation of the thermal lensing effect and alignment for the laser beam. In order to avoid air breakdown, a vacuum tube is placed in the imaging setup. An HWP and Faraday rotator are placed inside the imaging setup together with two TFPs to achieve another optical isolation. After the double-pass of Gain Module 2, laser pulses are amplified to 38.5 mJ.

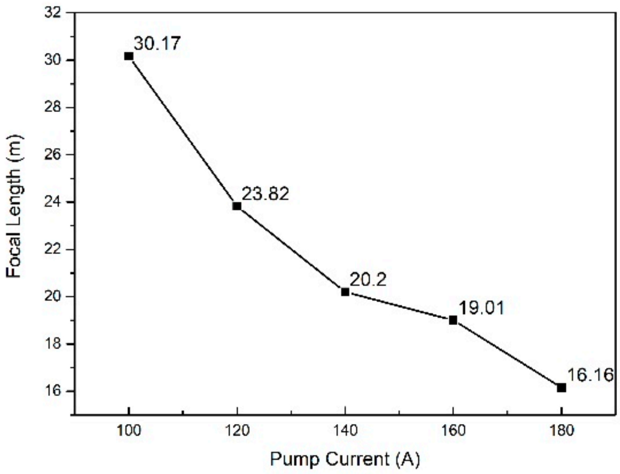
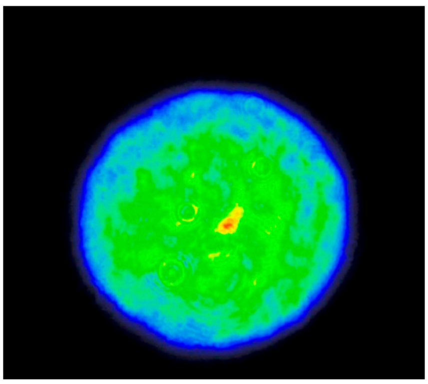


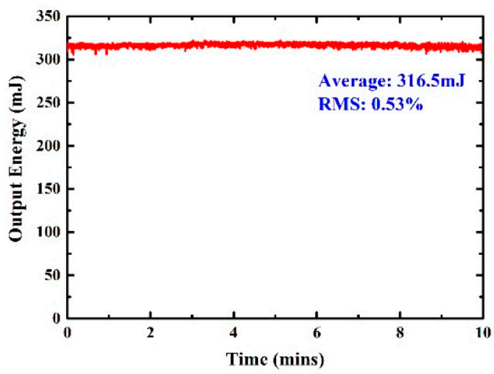
Figure 3. The relationship between pump current and the focal length of the gain module.

The second part of the power amplification setup consists of two identical gain modules (Cutting Edge Optronics, REA12006-3P), which has a rod-shaped Nd:YAG crystal with a diameter of 10 mm and a length of 120 mm. Each has a stored energy of 1.05 J when operated at 125 A and 300 Hz. Both gain modules are operated at 100 A and at 100 Hz with a small signal gain of 2.88 in this system. An equivalent focal length of 3.2 m is measured in such an operating situation. To obtain the best beam distribution in the exit, the laser beam should be relay-imaged from Surface 1 to HR2 and then to the exit. We take advantage of the thermal lensing of the gain module. A plano-convex lens with a focal length of 500 mm is placed behind with a distance of 400 mm to the center of the gain module. After passing through the gain module and the plano-convex lens, laser pulses converge at the focus point. Another identical gain module and a plano-convex lens are placed symmetrically with the focus point. Thermal lenses in two gain modules together with two plano-convex lenses consist of an equivalent imaging system. Due to this equivalent imaging system, laser pulses will pass through the same gain modules with the same optical path in the reflecting round. To overcome thermally induced depolarization, a Faraday rotator is placed behind Module 4 to achieve the polarization rotation and depolarization compensation.

Via the total power amplification system, laser pulses are amplified to 316.5 mJ. An approximate top-hat beam distribution with near-field modulation (peak to mean) of 1.46 is achieved, as shown in Figure 4a. A 10 min energy stability has thus been tested, and 0.53% RMS is achieved, as shown in Figure 4b.



(a)



(b)

Figure 4. (**a**) Beam distribution and (**b**) energy stability of amplified pulses from the whole amplifier.

Due to the gain saturation effect of the Nd:YAG amplifier, after two successive double-pass gain modules, the pulse temporal width shortened from 115 to 50 ps, as shown in Figure 5, which is suitable for the signal laser pulses in the OPA process.

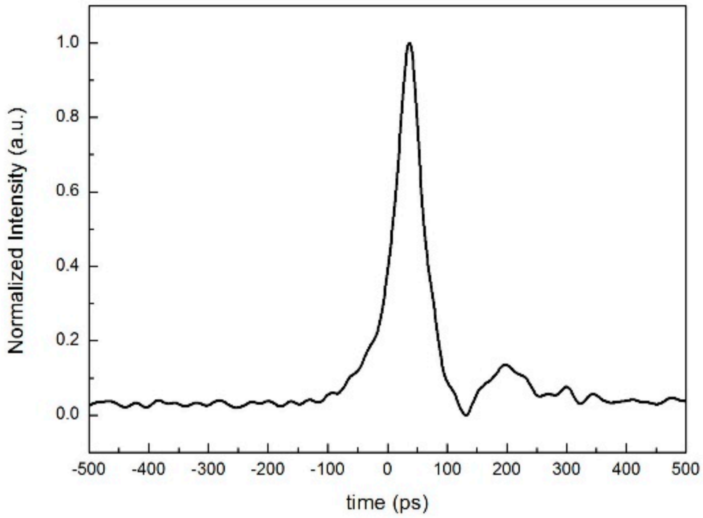


Figure 5. Pulse temporal width via the amplifying system.

3. Conclusions

In conclusion, a laser amplification system combined with an $Nd:YVO_4$ seed, a regenerative amplifier based on an Nd:YAG crystal, and two double-pass Nd:YAG power amplifiers is demonstrated. Thermally induced birefringence and thermal lensing are compensated. A 316.5 mJ, 50 ps laser pulse is achieved with an operating frequency of 100 Hz. The amplification system also features an approximately flat-top distribution and a 0.53% energy stability (RMS). This high-repetition-rate picosecond laser could be used for OPCPA pumping and other applications.

Acknowledgments: This work is supported by the National Science Foundation of China (NSFC) (11127901, 11134010), Shanghai Sailing Program (15YF1413500), the Strategic Priority Research Program of the Chinese Academy of Sciences, rant No. XDB1603, International S&T Cooperation Program of China, Grant No. 2016YFE0119300.

Author Contributions: Yanyan Li conceived and designed the experiments; Hongpeng Su and Yuxin Leng performed the experiments; Hongpeng Su and Yujie Peng analyzed the data; Hongpeng Su, Yujie Peng, Junchi Chen, Yanyan Li, Pengfei Wang and Yuxin Leng contributed reagents/materials/analysis tools; Hongpeng Su wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wolter, B.; Pullen, M.G.; Baudisch, M.; Sclafani, M.; Hemmer, M.; Senftleben, A.; Schröter, C.D.; Ullrich, J.; Moshammer, R.; Biegert, J. Strong-Field Physics with Mid-IR Fields. *Phys. Rev. X* **2015**, *5*, 021034. [CrossRef]
2. Hong, K.-H.; Lai, C.-J.; Siqueira, J.P.; Krogen, P.; Moses, J.; Chang, C.-L.; Stein, G.J.; Zapata, L.E.; Kärtner, F.X. Multi-mJ, kHz, 2.1 µm optical parametric chirped-pulse amplifier and high-flux soft X-ray highharmonic generation. *Opt. Lett.* **2014**, *39*, 3145–3148. [CrossRef] [PubMed]
3. Popmintchev, T.; Chen, M.-C.; Popmintchev, D.; Arpin, P.; Brown, S.; Ališauskas, S.; Andriukaitis, G.; Balčiunas, T.; Mücke, O.D.; Pugzlys, A.; et al. Bright coherent ultrahigh harmonics in the keV X-ray regime from mid-infrared femtosecond lasers. *Science* **2012**, *336*, 1287–1291. [CrossRef] [PubMed]
4. Hong, K.; Huang, S.; Moses, J.; Fu, X.; Lai, C.; Cirmi, G.; Sell, A.; Granados, E.; Keathley, P.; Kärtner, F. High-energy, phase-stable, ultrabroadband kHz OPCPA at 2.1 µm pumped by a picosecond cryogenic Yb:YAG laser. *Opt. Express* **2011**, *19*, 15538–15548. [CrossRef] [PubMed]

5. Metzger, T.; Schwarz, A.; Teisset, C.Y.; Sutter, D.; Killi, A.; Kienberger, R.; Krausz, F. High-repetition-rate picosecond pump laser based on a Yb:YAG disk amplifier for optical parametric amplification. *Opt. Lett.* **2009**, *34*, 2123–2125. [CrossRef] [PubMed]
6. Novák, J.; Bakule, P.; Green, J.T.; Hubka, Z.; Rus, B. 100 mJ thin disk regenerative amplifier at 1 kHz as a pump for picosecond OPCPA. In Proceedings of the 2015 Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, USA, 10–15 May 2015.
7. Noom, D.W.E.; Witte, S.; Eikema, K.S.E. High-energy, high-repetition-rate picosecond pulses from a quasi-CW diode-pumped Nd:YAG system. *Opt. Lett.* **2013**, *38*, 3021–3023. [CrossRef] [PubMed]
8. Chen, Y.; Li, Y.; Li, W.; Guo, X.; Leng, Y. Generation of high beam quality, high-energy and broadband tunable mid-infrared pulse from a KTA optical parametric amplifier. *Opt. Commun.* **2016**, *365*, 7–13. [CrossRef]
9. Lü, Q.; Kugler, N.; Weber, H.; Dong, S.; Müller, N.; Wittrock, U. A novel approach for compensation of birefringence in cylindrical Nd:YAG rods. *Opt. Quantum Electron.* **1996**, *28*, 57–69. [CrossRef]