Optics & Laser Technology 85 (2016) 14–18

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

1.2 MW peak power, all-solid-state picosecond laser with a microchip laser seed and a high gain single-passing bounce geometry amplifier

Chunhua Wang [a], Lifeng Shen [a], Zhiliang Zhao [b], Bin Liu [a], Hongbo Jiang [a], Jun Chen [a], Chong Liu [a,*]

[a] The State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027, China
[b] Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang 621900, China

ARTICLE INFO

Article history:
Received 20 February 2016
Received in revised form
11 May 2016
Accepted 27 May 2016
Available online 6 June 2016

Keywords:
Diode-pumped
Optical amplifiers
Picosecond pulse
Thermal effects

ABSTRACT

A semiconductor saturable absorber mirror (SESAM) based passively Q-switched microchip Nd:YVO_4 seed laser with pulse duration of 90 ps at repetition rate of 100 kHz is amplified by single-passing a Nd:YVO_4 bounce amplifier with varying seed input power from 20 μW to 10 mW. The liquid pure metal greasy thermally conductive material is used to replace the traditional thin indium foil as the thermal contact material for better heat load transfer of the Nd:YVO_4 bounce amplifier. Temperature distribution at the pump surface is measured by an infrared imager to compare with the numerically simulated results. A highest single-passing output power of 11.3 W is obtained for 10 mW averaged seed power, achieving a pulse peak power of ~1.25 MW and pulse energy of ~113 μJ. The beam quality is well preserved with $M^2 \leq 1.25$. The simple configuration of this bounce laser amplifier made the system flexible, robust and cost-effective, showing attractive potential for further applications.

1. Introduction

Picosecond pulsed lasers at ~1 μm with peak power up to 1 MW and repetition rates between several tens and hundreds of kilohertz have been widely used in industrial and scientific fields, such as laser micromachining process [1], and nonlinear optics [2]. Master oscillator power amplifier (MOPA) is an effective solution to provide considerable pulse energy and average output power for subsequent applications. Generally, the mode-locked fiber laser or crystal-based solid-state laser oscillators are employed as seed lasers, whose typical repetition rates are in the range of several tens of megahertz. Lower repetition rates down to 50–200 kHz can be achieved by introducing a pulse picker, which hence makes the system more complex and expensive. Gain-switched semiconductor laser diodes and microchip lasers are the alternative seed sources. The average power (typically sub-mW) of gain-switched laser diodes is limited by the low duty cycle of the diode. The microchip laser, passively Q-switched (PQS) with SESAM, can offer pulse duration from 16 ps to sub-nanosecond and repetition rates in the demanded range [3]. And, the pulse repetition rates could be tuned accordingly by changing the pump power. The available average power delivered from SESAM based microchip lasers is also low (typically several tens of milliwatt), owning to the unwanted optical and thermal-mechanic stress effects induced by the intense intra-cavity radiation [4].

A power scalable amplifier with high extraction efficiency is required to boost the low power seed source to much higher single pulse energy and average output power. Amplifiers with fiber architecture can offer high gain. However, it is bothered by the unwanted nonlinear effects and the optical damage due to the high peak power during the pulse amplification [5]. Then, fiber/solid-state hybrid amplifier is proposed [6]. At the other extreme, regenerative amplifier can also provide high gain and perform with pulse repetition rate of ~100 kHz. But the system is bulky, in which the high voltage power supply is demanded for the pockel cell. So, less bulky, more costeffective, and straightforward amplifiers are in hunger.

All-solid-state amplifiers with bounce Nd:YVO_4 medium were widely used these years. A pulse picked 2 mW, 6.3 ps 1 MHz mode-locked laser seed was amplified to 26 W output by a Nd:YVO_4 amplifier using a relatively complex setup with a four-passing bounce configuration, achieving a high gain of 41 dB [7]. A high gain bounce geometry amplifier for nanosecond pulses was demonstrated by Teppitaksak et al. [8]. A 8.1 mW gain-switched semiconductor seed laser with 100 ns duration was amplified to 6.5 W by single-passing one bounce amplifier. The limitation of power scaling was attributed to the amplified spontaneous emission (ASE).

In this paper, a single-passing Nd:YVO_4 bounce configuration is used to amplify a SESAM based PQS microchip seed laser with

* Corresponding author.
E-mail address: chongliu@zju.edu.cn (C. Liu).

http://dx.doi.org/10.1016/j.optlastec.2016.05.016
0030-3992/

pulse duration of 90 ps and repetition of 100 kHz. The thermal managements in the gain medium are discussed. Temperature distribution at the pump surface of the slab is measured and compared with the simulation results. Gain saturation effects are also measured by tuning the input seed laser power. A highest output power of 11.3 W is obtained for 10 mW seed laser power, corresponding to a pulse peak power of ~1.25 MW and pulse energy of ~113 μJ. The beam quality is well preserved with $M^2 \leq 1.25$. The all-solid laser system is simple and robust, showing attractive potential in the further applications.

2. Expermental setups

The experimental setup of the $Nd:YVO_4$ bounce amplifier is shown in Fig. 1. A passively Q-switched microchip $Nd:YVO_4$ seed laser with a SESAM is built as the seed source. The average power and repetition rates of the seed source can be tuned linearly with the pump power. For the pump power of 250 mW, a 10 mW output at 100 kHz with pulse duration of 90 ps is obtained. The beam quality factor of M^2 is measured to be 1.2. An optical isolator (OI), consisted of a half-wave plate (HWP_3), a polarization beam splitter (PBS) and a Faraday rotator (FR), is used to prevent the unwanted feedback or even optical damage to the microchip seed laser. Besides, the OI is used to tune the seed output power from 20 μW to 10 mW by rotating the optic axis of the HWP_2 placed before the PBS.

An 1 at% doped a-cut $Nd:YVO_4$ slab with dimensions of $20 \times 5 \times 0.8$ mm^3 is used as the gain medium. The two 5×0.8 mm^2 end laser faces are anti-reflection coated at 1064 nm for an incident angle of 24° and wedged at the angle of 13° to suppress the parasitic oscillation effect in the slab medium [9]. The slab is pumped from one of the 20×0.8 mm^2 faces while the other 20×0.8 mm^2 face is roughed for parasitic oscillation suppressing. The top and bottom 20×5 mm^2 faces of the slab are gold coated for better contacting with the thermally conductive contact. The slab is sandwiched with two cooper blocks, which are cooled by circulating water with temperature of 18 °C.

A 55 W TE-polarized 808 nm single bar laser diode (LD) collimated along the fast axis is used as the pump source. An 808 nm HWP is used to rotate the pumping laser polarization to parallel to the *c*-axis of the $Nd:YVO_4$ slab for high absorption coefficient. The pump absorption depth in the 808 nm laser propagating direction is ~0.5 mm. The pump laser is focused on the 20×0.8 mm^2 surface of the slab with the dimension of 15×0.12 mm^2 by a vertical cylindrical lens with focal length of 40 mm (VCL_2). The seed laser is collimated by a spherical lens (SL_1) with focal length of 500 mm and reshaped to an elliptical spot size 0.7×0.1 mm^2 by a horizontal cylindrical lens (HCL_1) with focal length of 1000 mm and a vertical cylindrical lens (VCL_1) with focal length of 100 mm. The seed beam size matches the pumping region of the amplifier well. The output laser beam from the amplifier is collimated by two cylindrical lenses of VCL_3 and HCL_2.

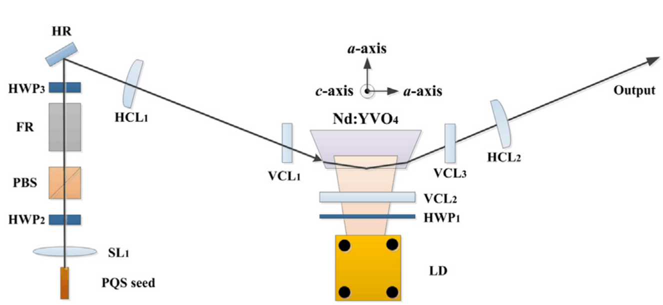

Fig. 1. Setup of the $Nd:YVO_4$ slab amplifier. SL: spherical lens; PBS: polarization beam splitter, 1064 nm; HWP_2, HWP_3: half-wave plates, 1064 nm; FR: faraday rotator; HCL: horizontal cylindrical lens; VCL: vertical cylindrical lens; HWP_2: half-wave plate, 808 nm; HR: high reflectivity mirror; LD: single bar laser diode.

3. Thermal managements of the slab medium

Thermal managements are very important in solid-state laser amplifiers. The thermally induced aberrations in the medium degrade the beam quality. Moreover, researches show that the gain of the $Nd:YVO_4$ medium decays rapidly with the increasing temperature by the heat loading from both quantum defect and several non-radiative decay process such as cross relaxation and fluorescence quenching, due to the emission section decrease [10]. $Nd:YVO_4$ mediums are usually highly doped in slab amplifiers, which show strong absorption of the pumped laser. This has the advantage of high inversion density for high optical gain [11]. It also shows the disadvantage of high temperature in the medium center. Therefore, highly-doped side-pumped $Nd:YVO_4$ slab amplifiers in bounce configuration with very small pump volume have the potential to improve the laser performance, given the good managements of thermal effects [12].

The heat transfer is dependent on how well the slab top and bottom faces contact with the water cooled copper. Thin indium foil was used typically as the cooling contact material in previous works for its soft property [4]. However, the contact is dependent on the applied pressure, and an "effective" heat transfer coefficient of 0.9 W/cm^2/K is measured with indium foil contact for an applied pressure of 22 kg/cm^2. And, it is not easy to realize a heavy and uniform pressure on such a thin slab (as thin as 0.8 mm with large surface area to volume ratio), which, otherwise, will give rise to the potential risk of fragile. Better "effective" heat transfer coefficient was obtained with traditional heat sink grease and the heat contact is independent of the applied pressure [13]. However, the possible pollution from long term operation caused by the grease diffusion to the working faces of the crystal is challenging. The pure metal greasy thermally conductive material, whose volatilization rate is lower than 0.001% and thermal conductivity is as high as 25 W/m/K, contains no silicone oil and other volatile substances. These characteristics make it be a suitable substitution of the heat sink grease [14].

In our setups, the liquid pure metal greasy thermally conductive material is used to replace the traditional thin indium foil as the thermal contact material for better heat load transfer. Temperature of the pump surface of the slab is measured by an infrared thermal imager (Ti27 from Fluke Corporation), operating in the range of 8–14 μm. The highest temperature, corresponding to the center of the pump surface, is recorded at different pump power without seed laser, shown in Fig. 2. It is 43 °C with a 20 W pump power. The maximum temperature of 90.1 °C is measured with a 55 W pump power, corresponding to a 6.7 K temperature rise with every 5 W pump power.

Temperature distribution of the pump surface is also measured in the case of using the 0.1 mm thickness thin indium foil as the thermal contact material. A higher temperature of 120.4 °C is observed at the pump power of 55 W, as shown in Fig. 2. This would lead to a considerable gain reduction of the 1 at% doped $Nd:YVO_4$ slab according to the investigation results in [15].

The temperature distributions are estimated by numerical simulation to compare with the measured values. The ideal contact cooling condition is supposed in simulations, that means, temperature of the top and bottom faces of the slab is set as the same as the circulating water. The four side faces of the slab are surrounded by air with convective heat transfer coefficient of 5 W/m^2/K and the air temperature of 25 °C. The fractional heat load without lasing in the amplifier is given by [16]: