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To cite this article: G V Kuptsov et al 2018 J. Phys.: Conf. Ser. 999 012008

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The Multidisk Diode-Pumped High Power Yb:YAG Laser Amplifier of High-Intensity Laser System with 1 kHz Repetition Rate

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Abstract. The source of instabilities in the multidisk diode-pumped high power Yb:YAG laser amplifier with cryogenic closed-loop cooling in the laser amplification channel of the high-intensity laser system with 1 kHz repetition rate was determined. Dissected copper mounts were designed and used to suppress instabilities and to achieve repeatability of the system. The equilibrium temperature dependency of the active elements on average power was measured. The seed laser for the multidisk amplifier was numerically simulated and designed to allow one to increase pulses output energy after the amplifier up to 500 mJ.

1. Introduction

In recent years, high power laser systems and their applications made a prominent progress. In spite of such laser systems are broadly used, at the present time, there are many studies targeted at the development and advancement of simultaneously high average and high peak power laser systems. Remarkable attention is attracted owing to the fact that fundamental and applied science require simultaneously high average and high peak power laser systems. Remarkable attention is attracted owing to the fact that fundamental and applied science require simultaneously high average and high peak power laser systems. For instance, to generate high flux attosecond pulses [1], to create novel and effective sources of charged particle beams, to produce ultra-bright X and γ-rays [2] and high XUV flux [3] and other applications. Besides the development the principles and methods of creation, it is highly important to increase the laser system effectiveness [4]. To solve this problem, one can use modern high efficient diode laser sources as a pump and cryogenic cooling of active elements. Moreover, cryogenic cooling allows one to obtain high average and high peak power radiation while keeping beam quality [5]. In addition, there are extensive researches aimed at discovery and development of new optical media, laser and nonlinear as well, to fulfill continuous demands in the field of high-power laser systems [6].

Presently, at the Institute of Laser Physics of the Siberian Branch of the RAS an all diode-pumped all solid state high-intensity laser system with 1 kHz repetition rate is developed. The layout of the system is shown in Fig. 1.
Figure 1. The layout of the high-intensity laser system with 1 kHz repetition rate

The first stage of our system consists of master oscillator, stretcher and regenerative preamplifier. The master oscillator is based on Yb:Y_2O_3 ceramic cooled with liquid nitrogen. It produces $\sim 1$ nJ, $\sim 1$ ps pulses with spectral width of $\sim 1.7$ nm FWHM (full width at half maximum) centered at 1030 nm with $\sim 80$ MHz repetition rate. In fibre stretcher (not shown in Fig. 1) the pulses are at the same time spectrally widened to 6 nm FWHM and temporally stretched to 500 ps [7]. These pulses are picked and amplified at 1 kHz repetition rate in the Yb:KYW regenerative preamplifier to 0.5 mJ. After the regenerative preamplifier, the beam is split to two optically synchronized parallel channels: laser amplification channel and parametric amplification channel.

The parametric amplification channel has highly nonlinear photonic crystal fibre[8] and optical parametric amplifier [9]. The input signal is broadened to $\sim 150$ nm FWHM in photonic-crystal fibre what allows one to obtain $\sim 10$ fs pulses after compression. After broadening, the pulses are to be amplified to 10 mJ, which corresponds to 1 TW of peak power at the output of the system. The parametric amplification channel takes the radiation from the laser amplification channel as the pump. This method keeps synchronization between pump and seed pulses effortlessly, thus, provides reliable stability while retaining high output intensity and high repetition rate [10].

Two serial all-diode pumped multipass laser amplifiers and a frequency doubling unit form the laser amplification channel. It is elaborated to provide 150 mJ pulses with central wavelength 515 nm and 1 kHz repetition rate. The first amplifier is water cooled 6-pass Yb:YAG amplifier which takes a 0.5 mJ pulse and amplifies it to 10 mJ. The second amplifier, multistik diode-pumped high power Yb:YAG laser amplifier, is closed-loop cryogenically cooled and designed to boost pulses energy up to 300 mJ.

2. The cooling system of the multistik amplifier

In this paper, the multistik diode-pumped high power Yb:YAG laser amplifier cooling system is discussed. The amplifier has eight diffusion-bonded Yb:YAG (10 at.\% Yb) crystals mounted in pairs to four independent massive copper heatsinks. Copper heatsinks are attached to cryogenic pulse tube refrigerators. The light travels more than 30 m inside the amplifier and undergoes 32 passes through the active elements. This leads to high sensitivity to angular displacements and drifts of the active elements. Closed-loop cryogenic cooling based on pulse tubes provides stable temperature of the crystals and robust operation, however, at the output of the amplifier we observed angular cyclic displacements of beam centroid with magnitude of $\sim 40$ urads. The amplifier self-misaligned itself after each start of cooling. Either displacements and
self-misaligning are proven to be caused by pulse tubes, despite the fact that the pulse tubes have extremely low vibrations in the operation region.

The maximal average pump power used in the experiments for a single heatsink with two active elements attached is 200 W (2x100 W). The heat load therefore is 0-20 W since the quantum defect of Yb ion is ~0.1. The pump pulses have next parameters: power is 0-200 W (peak), repetition rate is 0.1-1 kHz, central wavelength is 936 nm, duration is 500 us long and the temporal pulse shape is rectangular. The minimal achievable temperature in the absence of pump is 40 K. The equilibrium temperature of the non-dissected, solid copper heatsink while pumped with maximum pump power is 120 K. According to simple estimation based on Boltzmann factor for Yb:YAG, one should not let active elements be hotter than ~130 K to preserve amplification efficiency. Also, it is obviously important to remove heat fast in the presence of pump to prevent breakdown of crystals. Based on calculations [11], dissected copper heatsinks were proposed to supress the vibrations while preserving thermal conductivity. The dissected heatsink has two parts: a copper plate matching cryocooler operation region and a massive copper cube. The cube is host to active elements, mounted on the opposite sides of the cube. 12 brazed copper braids connect cube and plate. Each copper braid has cross-section area of 10 mm$^2$.

Thermal properties of the dissected heatsinks were determined. The equilibrium temperature was tested under different pump regimes. With dissected heatsinks, the equilibrium temperature of 120 K is reached when the average pump power equals 100 W (maximal peak pump power but at 500 Hz instead of 1 kHz). This means that the experimental results are not in agreement with calculations approximately by a factor of two, however there is good qualitative agreement. It is supposed that the cause is manufacturing process, notably brazing of contacts.

We have also proven experimentally that the dissected heatsinks have eliminated the self-misaligning problem and reduced cyclic displacements by a factor of 3 down to ~10 urad. The results of measuring the displacements before and after heatsinks modification are given in Fig. 2.

![Figure 2](image_url)

**Figure 2.** The histogram of the vertical angular cyclic displacements of beam centroid:
- a - using solid heatsinks,
- b - using dissected heatsinks.

3. The alternative seed laser of the multidisk amplifier

The estimation shows that one can store more than 500 mJ in the 8 active elements using our diode pumping at 1 kHz. To increase efficiency and simplify the setup, an alternative approach is proposed to amplify the pulse to ~500 mJ instead of 300 mJ at the output of the multidisk amplifier. Therefore, the efficiency of extraction will be almost a unity. Calculations show that a seed laser instead of the first multipass amplifier allows achieving 500 mJ at the output. So, one need a laser that produces pulses having next parameters: energy >30 mJ, duration 2-10 ns, repetition rate 1 kHz and central wavelength 1030 nm.
To determine the best laser design, laser rate equations (1) were solved numerically using Runge-Kutta-Fehlberg algorithm for different laser configurations [12,13]. The laser rate equations system is as follows:

\[
\begin{align*}
\frac{d\phi}{dt} &= \left( V_s B_s N_s - V_s B_s N_s - V_s (1 - N_s) B_{w} - \frac{1}{\tau_c} - Q(t) \right) \phi \\
\frac{dN_s}{dt} &= W_p(t) \left( 1 - N_s \right) - N_s \left( B_s \phi + \frac{1}{\tau_s} \right) \\
\frac{dN_{se}}{dt} &= \frac{1 - N_e}{\tau_s} - B_e N_s \phi
\end{align*}
\]

where \( \phi \) – photon flux; \( N \) – population inversion, \( m^{-1} \); \( W_p \) – pump rate, \( s^{-1} \); \( B \) – emission rate, \( s^{-1} \); \( V \) – mode volume, \( m^3 \); \( \tau_c \) – photon cavity lifetime, \( s \); \( \tau_f \) – fluorescence lifetime, \( s \); \( Q(t) \) – active losses (i.e. gate) switching function, \( s^{-1} \); \( g, s \) and \( se \) indices stand for gain, saturable absorber and saturable absorber excited state, respectively.

All temperature-dependent parameters were taken into account in the modeling. Also, resonator roundtrip losses were considered 15 %, gate reflectivity – 4 %, gate rise/fall times – 5 ns. Considering the numerical data obtained, an actively Q-switched Yb:YAG laser with passive mode-locking in a Cr^3+:YAG saturable absorber was chosen. An electro-optical shutter defines the repetition rate and the saturable absorber forms the pulse duration and shape. Moreover, the laser pulse is not chirped but its duration is few nanoseconds, thus is suitable for parametric amplification pumping, and there is no need to use stretcher-compressor system. Furthermore, it does not collapse in time domain during laser amplification due to spectral narrowing, the well known issue in the cryogenic laser amplifiers.

The best proposed design supposes usage one of the disks of the second multipass laser amplifier as the active element of the alternative seed laser. The huge advantage of this concept is perfect matching of the spectra of the seed laser and the amplifier since their active elements are at the same temperature. The spectral match increases efficiency, eliminates spectral distortion and prevents spectral shape distortions of the amplified pulse. The results of the modeling are shown in Fig.3.

![Figure 3](image-url) (in colour online). The results of modelling of intracavity dynamics. Curves stand for: 1 (green) - the population of inversion (P.I.) of the saturable absorber; 2 (red) - the population of inversion of the active medium; 3 (black) - the intracavity power; 4 (magenta) - the gate losses; 5 (blue) - the output power.
The optimal parameters of the laser, pursuant to modeling, are: cavity length is 3 m, beam diameter at the active element is 1.25 mm, gate pulse duration is 380 ns, the initial transmission of the absorber is 70% and its thickness is 5 mm. The absorber is also cooled with the same closed-loop system, being mounted to the same dissected copper heatsink. The estimated pulse energy is 34 mJ and pulse duration is ~8 ns.

4. Results

The source of mechanical instabilities in the multidisk diode-pumped high power Yb:YAG laser amplifier with cryogenic closed-loop cooling was determined. The experimental and simulation data were used to design dissected copper mounts to suppress instabilities of cryogenic closed-loop cooling. The angular displacements are suppressed by a factor of 3, making the radiation at the output of the multidisk amplifier acceptable for pumping a parametric amplifier. Moreover, the repeatability of the system between room temperature-cryogenic temperature-room temperature cycles is achieved.

The equilibrium temperature dependency of the active elements on average power was measured. The system is able to operate with diode pump pulse repetition rate of 500 Hz. The data is used for further enhancement of the closed-loop cryocooling system to achieve 1 kHz repetition rate.

The seed laser for the multidisk amplifier with cryogenic closed-loop cooling was numerically simulated and designed. The optimal parameters of the designed laser are determined. Calculation shows that it is possible to achieve 500 mJ pulses at the output of the laser amplification channel if one use the alternative seed laser.

All the data, both simulated and experimental, are used in the development of the all diode-pumped high intensity cryogenic laser system working with 1 kHz repetition rate.

Acknowledgements

This work is supported in part by RAS Program “Extreme laser radiation: physics and fundamental applications”, grant 0307-2015-0018 and Government program, 0307-2016-0006.

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