The main goal of HiLASE project (High average power pulsed LASers) is to create a solid platform for development of advanced DPSSLs in the Czech Republic. Two key concepts are being explored within HiLASE: thin-disk laser amplifiers to reach kW average output power, and cryogenically cooled multi-slab laser amplifiers to reach 100 J at 10 Hz output, scalable to kJ regime. There are three separate thin-disk beamlines under construction with different output parameters: Beamline A (750 mJ, 1.75 kHz, 3 ps), Beamline B (500 mJ, 1 kHz, 2 ps), and Beamline C (5 mJ, 100 kHz, 1 ps). In addition, a single-beam 100 J class nanosecond laser system based on a gas-cooled cryogenic, diode-pumped Yb:YAG multi-slab architecture with wall-plug efficiency > 12% and repetition rates up to 10 Hz is now under construction and will be commissioned by August 2015. DPSSL systems deployed in the HiLASE facility shall be at a disposal of external users for testing and prototyping of various laser technologies, and for contract research and development.

Key Words: Thin-disk laser, Multi-slab laser, High average power, Cryogenic cooling, Yb:YAG, Diode pumping

1. Introduction

Diode-pumped, solid state lasers (DPSSL) are very attractive light sources because of their high efficiency and compact size. The main reason is that semiconductor-laser bars have steadily grown in power and decreased in price per watt. In addition, novel beam conditioning techniques have been successfully applied to increase brightness and beam quality of diode-laser bars. As a consequence, several high-energy-class, pulsed DPSSLs are being constructed worldwide (Fig. 1) with the ambitious aim to reach an average power of 1 kW. These devices will have extremely large exploitation potential for various applications in new scientific and high-tech industrial technologies.

2. Thin-disk laser system

We are developing three thin-disk based, kW-class laser beamlines, each delivering different output parameters. Specifications of each beamline were carefully chosen to cover various industrial and scientific applications. Beamline A will deliver 750 mJ of pulse energy at 1.75 kHz repetition rate and is subcontracted to Dausinger+Giesen GmbH (Germany) in order to reduce overall project risk affiliated with high demands. On the other hand, HiLASE research group is independently elaborating Beamline B and Beamline C with output parameters of 500 mJ at 1 kHz repetition rate, and of 5 mJ at 100 kHz repetition rate, respectively. All beamlines will provide pulse duration in the picosecond region. While Beamline B has been described elsewhere, here we present our recent achievements related to Beamline C.

Beamline C is aimed to achieve the pulse energy of 5 mJ at 100 kHz repetition rate. In order to meet these requirements, an intense study has been conducted in developing high-repetition rate regenerative amplifier. The target specifications of Beamline C will be achieved after completing three major milestones determined by the pulse energies, namely 0.5 mJ, 2 mJ, and 5 mJ. Experimental setup for reaching the first milestone is shown in Fig. 2. Regenerative amplifier is seeded by the Yb-doped fiber oscillator while the pulses are stretched by the chirped Volume Bragg grating (CVBG) up to ~160 ps. Dispersion of the CVBG is 60 ps/nm. The FWHM spectral bandwidth and clear aperture are 2.2 ± 0.5 nm and 8 × 8 mm², respectively. The dimension of BBO crystal for Pockels cell
is 5 × 5 × 25 mm$^3$ and its quarter-wave voltage is 5.2 kV. An Yb:YAG thin-disk with the free aperture of 8 mm and the thickness of 220 μm is installed in the laser head. The disk is pumped by 1 kW fiber-coupled laser diodes at 969 nm wavelength with the pump spot diameter of 2.8 mm.

We have achieved the output energy of 450 μJ at 100 kHz repetition rate. The output pulse was compressed to ~1 ps pulse duration and the compression efficiency of CVBG was 88%. The output beam profile is shown in Fig. 3. For reaching milestone 2 (2 mJ at 100 kHz), we are planning to increase the pump spot size while keeping the same level of pump intensity. A pump power of 5-10 kW and improvement of thin disk laser head is required to accomplish the milestone 3 (5 mJ at 100 kHz).

3. Multi-slab laser system

A high repetition rate, single-beam, diode-pumped 100 J class laser system is now under development at the Central Laser Facility (CLF, U.K.) in collaboration with the HiLASE team. This high energy pulsed laser amplification system is based on a gas-cooled cryogenic, diode-pumped Yb:YAG multi-slab architecture. The pre-amplifier and the power amplifier consist of two stacks of quadratic ceramic Yb:YAG slabs. Cold helium gas flowing at initial temperature of about 170 K is forced through the gaps between the slabs for cooling. The amplifiers are end or face-pumped from both sides. Employing slabs with increasing doping level towards the centre of the amplifier reduces the required overall thickness for a given maximum gain coefficient and also equalizes the heat load for all slabs.

The HiLASE multi-slab laser system consists of temporally-shaped fiber front end, regenerative amplifier, 10 J / 10 Hz cryogenically-cooled pre-amplifier, and 100 J / 10 Hz cryogenically-cooled power amplifier. Model predictions developed at HiLASE indicated maximum output energy of 10 J at pump energy of 48 J. Indeed, this is in a very good agreement with the experimental results recently obtained at CLF. The optical layout of the laser system is shown in Fig. 4.

The beam size will be 20 mm × 20 mm in the 10 J pre-amplifier, and 60 mm × 60 mm in the 100 J main amplifier. The details of a cryogenic gas-cooled 100 J / 10 Hz laser system are summarized in Table 1. The pulse shape will be programmable with 150 ps steps.

The baseline power amplifier design consists of 6 slabs with three different doping levels. In order to ensure that the impact of amplified spontaneous emission (ASE) loss in the amplifier is kept to a minimum, the doping levels have been calculated to ensure that the product of the small signal gain coefficient (g0) and the diagonal transverse dimension of the square slabs (D) remains below 3.0 at all positions through the stack of gain slabs.

We have undertaken extensive energetics, thermal and fluid-mechanical modeling in order to optimize the parameters of various amplifier configurations. Figure 5 shows the calculated gas flow into the amplifier head. The inlet flow velocity is 10 m/s, and maximum of 33 m/s is achieved as the gas flows through the amplifier. Figure 6 shows the predicted temperature distribution in the 100 J-class amplifier slab.

The variation of temperature across the pumped area is less than 1.5 Kelvin. The asymmetric temperature profile in the gain medium is due to the fact that the majority of the absorbed pump power is deposited as heat in the cladding. In addition, the heat exchange coefficient decreases along the he-

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**Figure 2** Layout of the Beamline C thin-disk regenerative amplifier.

**Figure 3** Beam profile of 450 μJ output at 100 kHz with 88% compression efficiency.

**Figure 4** Optical layout of the 10 J + 100 J laser system.

**Table 1** Output parameters for 100 J / 10 Hz HiLASE laser system.

| Parameter             | Specification |
|-----------------------|---------------|
| Pulse energy          | > 100 J       |
| Average output power  | > 1 kW        |
| Pulse length (FWHM)   | 2-10 ns       |
| Pulse shape           | Programmable  |
|                       | (150 ps steps)|
| Repetition rate       | 1-10 Hz       |
| Output beam size      | 75 mm × 75 mm |
| RMS modulation        | < 1%          |
| Wavefront quality     | lambda/10     |
| E-o efficiency        | > 12%         |
lum flow direction. Our calculations show that the heat exchange coefficient varies between 3000 W/m²K and 1200 W/m²K with mean value of about 2000 W/m²K. The corresponding optical path difference (OPD) distribution in the gain medium is shown in Fig. 7. In this case the Yb:YAG area was 50 mm × 50 mm and Cr:YAG cladding width was 17.5 mm.

Maximum OPD is on the order of 5.2 waves, i.e. it requires 2.6 waves of displacement of the adaptive optics (AO) surface for correction. This is well within the correction capability of modern AO systems.

Recently, we have set-up an experiment to measure and correct wavefront aberrations in square glass slabs. The layout of the experimental setup is shown in Fig. 8. The generated heat realistically reproduces the wavefront distortions in the 10 J laser amplifier. A laser diode emitting at 970 nm (indicated by yellow color) is used to deform the square-shaped glass slab.

The AO system consists of a square deformable mirror (DM) from Adapta Srl (Italy), wavefront sensor (WFS), and voltage driver (Fig. 9). The DM is a bimorph PZT mirror with clear aperture of 27 mm × 27 mm. It consists of a 6 × 6 actuator array with HR dielectric coating (99.9% at 1030 nm) and high damage threshold (> 20 J/cm²).

The influence functions matrix of the DM is shown in Fig. 10. Closed-loop operation with the DM and Shack Hartmann sensor was easily achieved after 10 iterations, as shown in Fig. 11.

4. Laser application laboratory

The high-tech laser application laboratory established around HiLASE lasers will be focused on the development of
The HiLASE experimental stations are seen as a place for research and development of processes relevant to advanced, high-tech industrial applications. For many of these applications, it is important to investigate the influence of pulse duration as well as to be able to vary pulse overlap. The stations will have access to thin-disk laser beamlines (RP1) and to multi-slab laser (RP2) as shown in Fig. 13.

In order to be one step closer to the possibility of transferring developed processes to real industry, the laser processing station will be equipped with industrial type of a position table as well as with a robot, allowing testing of applications of these technologies in 3-D space. Besides applications related to laser shock peening, this experimental station will be also suitable for other laser applications such as welding, cleaning, drilling and etc.

5. Conclusions

The HiLASE project is aiming to serve as a platform for development of new diode-pumped, picosecond and nanosecond lasers based on thin-disk amplifiers and cryogenically cooled multi-slab amplifiers, as well as to build state-of-the-art application laboratory for high-tech industry.

Acknowledgements

This work benefitted from the support of the Czech Republic’s Ministry of Education, Youth and Sports to the HiLASE (CZ.1.05/2.1.00/01.0027), DPSSLasers (CZ.1.07/2.3.00/20.0143), and Postdok (CZ.1.07/2.3.00/30.0057) projects co-financed from the European Regional Development Fund.

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