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Fakulta jaderná a fyzikálně inženýrská
Katedra fyzikální elektroniky

REGENERATIVE THIN-DISK AMPLIFIER FOR HIGH-POWER kW-CLASS LASER

TEZE K DISERTAČNÍ PRÁCI

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Fakulta jaderná a fyzikálně inženýrská
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Contents

1. INTRODUCTION AND STATE OF THE ART

Laser-matter interaction research using ultrashort optical pulse has been producing rich scientific knowledge, as the background for novel short wavelength sources from EUV (Extreme Ultra Violet) to hard X-ray region, in the last two decades by using Ti:sapphire laser technology. MID-IR pulse generation and precise EUV micro-machining are also emerging from the same field. It is important to realize a practical laser technology, to replace Ti:sapphire laser by a robust, compact and low-cost alternative. Thin-disk laser is best suited for this candidate with its feature of high pulse energy in sub-picosecond region.

Nowadays in the Czech Republic, there are two ongoing projects involved in development of laser technologies and their applications. High-average power pulsed lasers project (HiLASE) and Extreme Light Infrastructure Beamlines (ELI-Beamlines) are both co-financed by the European Union and the Czech Ministry of Education, Youth and Sports. They are also supported by the Institute of Physics of the Academy of Sciences of the Czech Republic. The HiLASE project focuses on development of high-repetition lasers and laser systems that will find use in science and hi-tech industrial applications. For this purpose it will offer several laser systems with different output parameters ranging from a few picosecond pulses with energies of 5 mJ – 0.5 J and repetition rates of 1-100 kHz (based on thin-disk technology) to systems with 100 J output energy in nanosecond pulses and repetition rate of 10 Hz (based on multi-slab technology). The research program 1 (RP1) in the HiLASE project is focusing on the development of thin-disk-based kW-laser systems which are separated into beamlines aiming at different parameters, namely Beamline A (0.75 J, 1.73 kHz, 1-2 ps), Beamline B (0.5 J, 1 kHz, 1-2 ps), and Beamline C (5 mJ, 100 kHz, 1-2 ps). Figure 1 shows the block diagram of each thin-disk-based beamlines [1].

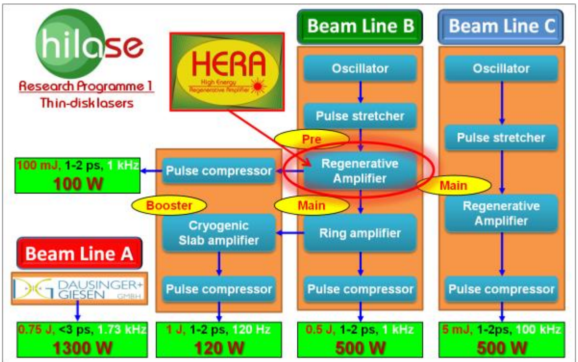

Figure 1 Block diagram of Yb:YAG thin-disk-based beamlines in the Hilase project.

This dissertation is devoted to the development of a thin-disk regenerative amplifier that will be used in Hilase beamline B as a preamplifier for the thin-disk ring power amplifier. The compressed output of the regenerative amplifier itself will be used for small scale experiments. One of them is investigation of the conversion efficiency improvement of soft X-ray source, emitting in the ‘water window’ spectral range at the wavelength of 2.88 nm, for transmission microscopy. Another direct application of the compressed output from the elaborated regenerative amplifier is to pump the optical parametric amplifier developed within HiLASE [2].

Thin-disk lasers operated in pulsed mode are able of delivering ultrashort pulses with high average and peak powers. Thin-disk based mode-locked oscillators became a convenient approach for generation of ultrashort pulses. They were obtained for the first time from a diode-pumped Yb:YAG thin-disk laser oscillator in year 2000. Mode-locking was obtained by utilizing a semiconductor saturable absorber mirror (SESAM). Achieved pulses were as short as 730 fs with pulse energy of almost half micro joule [3]. But even shorter pulses are possible to obtain from Yb:YAG disks, in 2013, 350 fs pulses were presented from a Kerr-lens mode-locked oscillator with pulse energies of 4 µJ at 30 MHz repetition rate resulting in outstanding 120 W of average power [4]. By using other host for Yb^{3+} like $LuScO_3$, which belongs to the sesquioxides group of materials, it was possible to obtain 96 fs pulses from a SESAM-based mode-locked thin-disk oscillator [5]. When it comes to the most powerful oscillator in case of the delivered average power, 275 W of average power from an Yb:YAG SESAM mode-locked oscillator was demonstrated. At 25.6 MHz repetition rate 16.9 µJ pulses were delivered with pulse duration of 583 fs [6]. The most energetic pulses were delivered also by an Yb:YAG SESAM mode-locked oscillator with pulse energies of 80 µJ at 3 MHz (242 W of average power) and 1 ps pulse duration [7].

Regenerative amplification is a well suited amplification approach allowing overall gain in the range of 10^6. Once applied to a thin-disk gain medium it can well compensate its relatively low gain per pass via increased number of passes within a very short time, hence it can produce average powers over 300 W, pulse energies exceeding 100 mJ, high peak powers in range of tens of GW with pulse duration in the region of 1 ps [

Table 1]. First Yb:YAG thin-disk regenerative amplifier was presented in 1997 by Dr. Clemens Hönninger. The laser delivered 2.3 ps pulses amplified from 140 pJ up to 180 µJ, providing amplification of 10^6. The amplifier was seeded with 750 fs pulses; nevertheless, due to the gain narrowing effect during amplification process, the resulting pulse duration was elongated to 2.3 ps. The repetition rate of the amplifier was dedicated by the switching speed of the Pockels cell and it was limited to 1 kHz repetition rate due to technological limitations [8]. With the improvement of the Pockels cells, progress in the regenerative amplifiers performance could be observed. In 2009, a 15 GW peak power regenerative amplifier was demonstrated. At 3 kHz repetition rate, 25 mJ pulses with pulse duration of 1.6 ps were demonstrated. The Pockels cell contained a BBO crystal with 12x12 mm^2 aperture and 20 mm length, resulting in high quarter-wave voltage of 16 kV [9]. In case of high-repetition rate operation, 180 W of average power and 870 fs pulses were demonstrated at 1 MHz repetition rate (180 µJ). In this case the BBO crystal in the Pockels cell was much smaller, since switching of high voltage with MHz repetition rate causes serious issues in the electronics circuit of the high voltage switch as well as the high voltage power supply. The dimensions of the crystal were 5x5x25 mm^3 resulting in high voltage of 6 kV [10]. So far, the highest average power delivered by a thin-disk regenerative amplifier equals to 300 W. Pulses with the energy of 30 mJ were delivered at repetition rate of 10 kHz and 1.6 ps pulse duration. It was possible thanks to the implementation of the state-of-the-art Yb:YAG thin-disk mounted on a diamond heat sink and pumped at zero-phonon line providing direct pumping of the upper-laser level [11].

Reaching even higher power levels is possible by applying second amplification stage in a form of a multipass amplifier, realizing usually from 4 to 12 passes through the thin-disk. In this way it was possible to obtain 1.1 kW of average power at 800 kHz repetition rate with extraordinary beam quality of M^2=1.25 and short 7 ps pulses [12]. At repetition rate of 300 kHz, output power of 1.3 kW was presented with pulses below 8 ps [13]. Highest output power of 14 kW was obtained from a 2-stage cascaded Yb:YAG thin-disk multipass amplifier system at 100 kHz repetition rate and 140 mJ pulses [14]. At low repetition rates high pulse energies are also possible and this was shown in 2009 at Max Born Institute in Germany. Maximum output energy of 320 mJ at 100 Hz repetition rate was obtained from a multipass amplifier realizing 12 passes after being seeded with 165 mJ from a thin-disk regenerative amplifier. Even though the output was not compressed (2 ns stretched pulse duration) based on the amplified spectrum, pulses could be recompressed below 5 ps [15].

Overview of the pulsed thin-disk oscillators and amplifiers using a diamond-based thin-disk is given in Table 1.

Table 1 Overview of Yb^{3+} doped ultrafast thin-disk lasers.

P_{avg}	P_{peak}	E_{pulse}	τ_{pulse}	f_{rep}	M^2	Reference
Mode locked thin-disk oscillators						
5.1 W	677 kW	65 nJ	96 fs	77.5 MHz	-	[5]
7 W	767 kW	109 nJ	142 fs	64 MHz	-	[5]
16.2 W	560 kW	470 nJ	730 fs	34.6 MHz	<1.5	[3]
120 W	11.4 MW	4 µJ	350 fs	30 MHz	-	[4]
275 W	25.6 MW	16.9 µJ	583 fs	16.3 MHz	<1.05	[6]
76 W	27.9 MW	25.9 µJ	928 fs	2.93 MHz	-	[16]
242 W	66 MW	80 µJ	1.07 ps	3 MHz	1.05	[7]
Thin-disk regenerative amplifiers						
4.6 W	464 MW	116 µJ	250 fs	40 kHz	1.9	[17]
0.1 W	78 MW	180 µJ	2.3 ps	750 Hz	-	[8]
180 W	207 MW	180 µJ	870 fs	1 MHz	-	[10, 18]
167 W	277 MW	208 µJ	750 fs	800 kHz	1.2	[19]
100 W	412 MW	330 µJ	800 fs	300 kHz	1.35	[20]
85 W	1.3 GW	850 µJ	650 fs	100 kHz	1.2	[19]
182 W	3 GW	2.6 mJ	870 fs	70 kHz	-	[10, 18]
45 W	662 MW	4.5 mJ	6.8 ps	10 kHz	-	[21]
75 W	15 GW	25 mJ	1.6 ps	3 kHz	<1.1	[9]
300 W	18.7 GW	30 mJ	1.6 ps	10 kHz	-	[11]
150 W	17.6 GW	30 mJ	1.7 ps	5 kHz	1.1	[22]
120 W	23.5 GW	40 mJ	1.7 ps	3 kHz	-	[22]
100 W	29 GW	50 mJ	1.7 ps	2 kHz	-	[22]
120 W	40 GW	120 mJ	3 ps	1 kHz	<1.3	[23]
16.5 W	82 MW	165 mJ	2 ns [a]	100 Hz	1.1	[15]
Thin-disk multipass amplifiers						
32 W	160 MW	320 mJ	2 ns [b]	100 Hz	-	[15]
1.1 kW	189 MW	1.38 mJ	7.3 ps	800 kHz	1.25	[12, 24]
1.3 kW	550 MW	4.4 mJ	<8 ps	300 kHz	-	[13]
14 kW	-	140 mJ	-	100 kHz	-	[14]

[a] uncompressed output for seeding of multipass amplifier, if compressed to 5 ps, 33 GW peak power would be possible, [b] uncompressed output, after compression to envisioned 5 ps peak pulse power would be 64 GW

2. GOALS OF THE DISSERTATION

In order to provide a state-of-the-art thin-disk laser system for the Beamline B of Hilase project, developed laser has to utilize smart solutions unraveling any obstacles.

The *first goal* is to elaborate a method that would reduce the amount of the thin-disk deformations caused by highly intensive pumping, that lead to degradation of the beam quality and drop in the efficiency. Since a soldered thin-disk is more susceptible to deformations than a diamond-based one, a way to decrease the thermal loading of a thin-disk should be presented. Thanks to the advances in the semiconductor industry and to the improvement of the capabilities of laser optics manufacturing several solutions that were not available few years ago could be applied.

Second goal is to develop an experimental setup for the measurement of the thin-disk deformations. Due to the manual manufacturing part in the soldering process of the thin-disks, produced thin-disks can slightly differ from each other. In order to provide a reliable solution of a thin-disk laser, in case of damage, thin-disk should be replaced with a disk having similar radius of curvature in order to provide stable operation of the resonator.

The third goal- main part of dissertation work is concentrated on development of Yb^{3+}:YAG thin-disk regenerative amplifier for high-power kW-class laser system. The goal parameters of the regenerative amplifier are:

- high pulse energy- over 30 mJ at 1 kHz repetition rate;
- few picosecond pulse duration- below 5 ps;
- economical approach- soldered thin-disk, operational at room temperature, compact design.

For this purpose, it is firstly necessary to develop a prototype laser to evaluate the potential of the soldered thin-disks and to optimize the pumping methods. Afterwards, basing on the thin-disk deformations study and extensive cavity modeling, *the final goal*, the large aperture regenerative amplifier has to be constructed for obtaining high pulse energy. Output of the high energy regenerative amplifier (H.E.R.A.) should be compressed below 3 ps pulse duration. The developed laser would be used for a practical application in Hilase beamline B thin-disk laser system as well as in a smaller scale experiments mentioned earlier, such as microscopy, optical parametric amplification or industrial applications.

3. METHODS USED

3.1. Theoretical modelling methods

In order to design a laser cavity of the regenerative amplifier numerous ABCD-matrix calculations had to be conducted to precisely determine the laser mode size in the resonator. For this purpose the WinLase^{TM} software was used which allows analysis of the Gaussian beam propagation in complex optical systems by means of ABCD-matrix algorithms used for its calculations. A standing-wave resonator package was used for the calculations which allowed the observation of the laser mode size throughout the laser cavity as well as monitoring of the cavity stability zones.

3.2. Experimental methods

In this section, methods used in the experimental part of the dissertation will be listed. The experimental part is concentrated on the construction of the regenerative amplifier with a thin-disk gain medium and measurement of the output parameters. The following physical quantities were measured in the experiments.

Laser pulse average power

Measurement of the laser pulse average power is one of the most common tasks in laser development. The average powers generated during experiments which are described in this dissertation were in the range of several milliwatts (mW) to few hundred of watts (W). Such wide power range required using of different types of power meters depending on the laser power level. For the measurement and alignment of the seed beam from the oscillator a photodiode-based sensor PD300-3W from Ophir Company was used with the measurement range from 5 nW up to 3 W.

Thermal sensors have a long response time of approximately 2 s, but they allow measurement of power level from mW up several tens of kW. This type of the power sensors was used for the measurement of high power levels. For monitoring of regenerative amplifier output a thermal power sensor L50(150)A-PF-35 from Ophir Company was used with the measurement range up to 150 W. For the measurement of the pumping laser diodes two other sensors were used, the FL500A from Ophir Company with a measurement range up to 500 W and the PM5K from Coherent Company with a measurement range up to 5 kW.

Laser pulse average power

-<u>Measurement of nanosecond pulses</u>

For the observation of temporal development of laser radiation pulses in the nanosecond pulse duration range, ultrafast photodetectors can be used. For the experimental part of this dissertation an InGaAs ultrafast photodiodes UPD-40-IR2-P from Alphalas Company were chosen since they characterize with a very short rise time below 40 ps. The electrical signals from the photodetectors were observed and recorded using a DPO4104B Tektronix oscilloscope with bandwidth of 1 GHz and sample rate of 5 GS/s.

-<u>Measurement of picosecond pulses</u>

Duration of picosecond laser pulses was measured using a laboratory-made non-collinear intensity autocorrelator as shown in Figure 2.

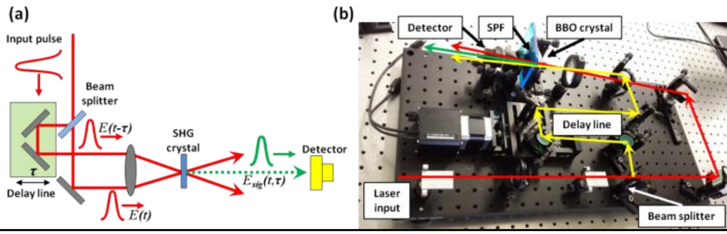

Figure 2 Autocorrelator setup (a) and its laboratory realization (b) (SPF-short-pass filter, SHG second harmonic generation).

Laser radiation spectrum

In the experiments, for the measurement of the radiation spectrum, a USB2000+ miniature fiber optic spectrometer from Oceanoptics Company was used. It incorporates a 2 MHz analog-to-digital (A/D) converter, programmable electronics, a 2048-element CCD-array detector and a high-speed USB 2.0 port. The utilized grating with 1200 lines blazed at 750 nm provides detection range from 840 nm up to 1100 nm with resolution of 0.1 nm.

Laser beam spatial profile

In the experiments for the beam profile measurement, a silicon CCD camera SP620U from Spiricon Company was used. The spectral range of the beam profiler was 190-1100 nm. The active area of the sensor was 7.1 mm x 5.4 mm with the pixel size of 4.4 µm x 4.4 µm giving the number of effective pixels 1600 x 1200. The minimum system dynamic range is 62 dB. The beam profiler is operated by the BeamGage® software for the laser beam measurement.

Laser beam quality

The beam quality of a laser beam can be defined in many ways but usually it is understood as a measure of how tightly a laser beam can be focused under certain conditions. In other words it determines the focusability property of the laser beam. For the measurement of beam quality the M^2 meter from Laser-Laboratorium Göttingen e.V. was used consisting of a CCD camera and a translation stage that were controlled by MrBeam software.

4. OVERVIEW OF THE RESULTS

4.1. Experimental setup

Layout of the regenerative amplifier together with front-end, stretcher and compressor is presented in Figure 3. The system consists of the Yb-doped fiber oscillator operating at 50 MHz repetition rate, delivering the output power of 2 W at the center wavelength of 1030 nm with 20 nm bandwidth. Pulses with duration of 6 ps from the fiber laser are stretched by a Martinez-type stretcher up to 500 ps. The gold-coated grating which has the grove number of 1740 l/mm was employed so that providing the group delay dispersion of $1.8 \cdot 10^7$ fs^2. After the pulse stretching, pulses are coupled into the regenerative amplifier cavity, which contains an Yb:YAG thin-disk, a thin-film polarizer (TFP), a BBO Pockels cell, and a quarter-wave plate (λ\4). When the quarter-wave voltage is applied on the Pockels cell, the pulses are captured inside the resonator, and travel in the cavity as long as the high-voltage is applied. After the amplification, the amplified pulse is ejected through the TFP and diverted by polarized beam-splitter (PBS) to a Treacy-type compressor utilizing two gold-coated gratings and providing exact opposite group delay dispersion than the stretcher. The size of BBO crystal at the Pockels cell is 10x10x24 mm^3 and its quarter-wave voltage is 9 kV. Yb:YAG thin-disk has the free aperture of 8 mm and the thickness of 220 µm, and is soldered on a CuW heatsink.

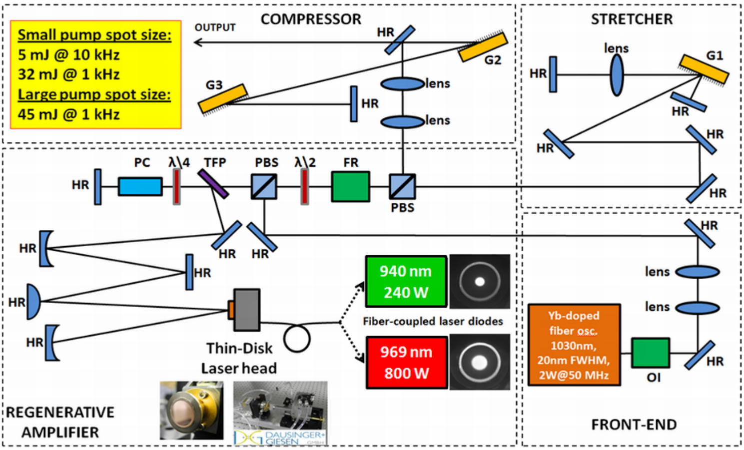

Figure 3 Layout of the laser (OI-isolator, HR-high reflector, PBS-polarized beam splitter, TFP-thin-film polarizer, FR-Faraday rotator, PC-Pockels cell, G-grating, λ\2-half wave-plate, λ\4-quarter wave-plate).

The thin-disk was pumped by the fiber-coupled laser diodes emitting at 940 nm with 240 W output power for the case of the prototype laser with small pump spot size. For the large mode size operation laser diodes emitting at 969 nm with 800 W output power were chosen. At the wavelength of 969 nm with line width is smaller than 0.9 nm and the wavelength is stabilized by volume Bragg grating. The laser diode is driven by pulsed diode driver supporting fast rise time of the current pulse, which is below 9 µs, as well as fast fall time, below 3 µs. We measured the laser diode spectra under the CW and the pulsed operation with various pulse durations and currents and found that the spectra of laser diode were well stabilized in both CW and pulsed operation.

Bearing in mind the need for compactness of the developed laser system, all supporting devices like power supplies, high current switches, chillers and laser diodes were installed in a 19 inch rack cabinet. Pump light was delivered from the rack to the thin-disk via 5 m long fiber with 1 mm core diameter. High-voltage for the Pockels cell switch was delivered via special high-voltage-cable, also 5 m long. Thanks to this approach the regenerative amplifier can be fitted on a small optical breadboard and the rack cabinet can be placed nearby.

The used thin-disk laser head was delivered by the Dausinger&Giesen Company. The 'TDM 1.0 Lab' laser head consist of a water cooled fiber connector, collimation optics and pump chamber inside of which the thin-disk is installed on a cooling nozzle with a separate water cooling circuit. Figure 4 shows a photograph of the used thin-disk laser module.

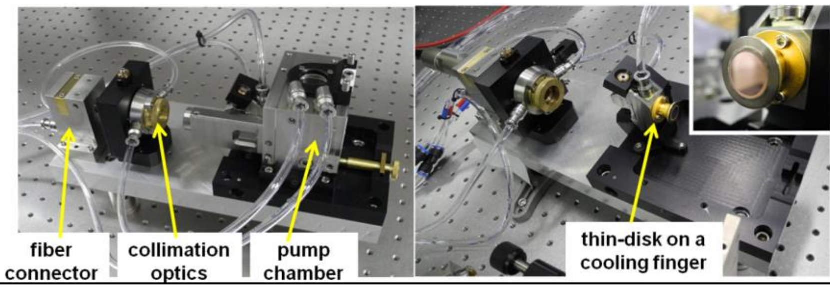

Figure 4 TDM 1.0 Lab thin-disk laser module used in the regenerative amplifier.

Thin-disks themselves were also delivered by the Dausinger&Giesen Company. In every case the thin-disk thickness was 220 µm, with the free aperture of 8 mm. The Yb:YAG crystal was doped at the level of 7 at.%. Maximum pump spot diameter was 5 mm and the maximum pump power density equals to 5 kW/cm^2. Even though the Yb:YAG crystal was soldered to a CuW heatsink using a tin-gold solder, the radius of curvature was around 4 m for most of the thin-disks.

One of the most important elements for the regenerative amplifier operation is the fast electro-optical switch which is used for coupling the pulses in and out the resonator. The Pockels cell utilizes the BBO crystal with 10 and 24 mm in thickness and length, respectively. For these parameters the quarter-wave voltage of 8.8 kV is required for proper coupling of the pulses in and out of the resonator. In order to deliver such high-voltage pulses, the driver and high-voltage switch were ordered from the company Bergmann Messgeräte Entwicklung KG (BME). Maximum operational voltage of the driver is 20 kV up to 5 kHz repetition rate and 11 kV at 10 kHz. The typical rise-time of high-voltage pulse at 18 kV and 1 kHz repetition rate is 12 ns, which means that for a cavity length of 2 m and the round trip time of 13.3 ns, the switching time of the Pockels cell would be enough to properly couple the pulses. In order to properly apply the high-voltage to the BBO crystal a special holder was designed as in Figure 5. Gold-coated copper electrodes with rounded edges are mounted by the special plastic screws to the aluminium nitride (AlN) ceramic, with a very high electrical insulation, which is mounted on a water-cooled heatsink installed on a 5-axis stage for precise alignment.

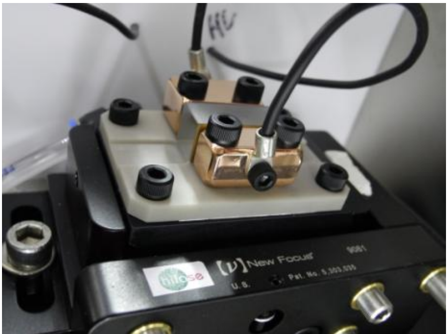

Figure 5 Designed BBO holder with electrodes on a ceramic, water-cooled plate and 5-axis translation stage.

Oscillator provides necessary pulses for the amplification in the regenerative amplifier. To allow its stable operation the oscillator should be stable as well. Because of that an Yb-doped fiber laser was chosen for seeding the regenerative amplifier since it is stable, reliable and does not require any realignment. Among many fiber oscillators, Fianium FP series was chosen based on its remarkable set of parameters and attractive price. Table 2 presents parameters of the Fianium oscillator. In this version of the oscillator there is no compressor after fiber amplifier, therefore the output pulses are approximately 6 ps long, nevertheless, the output is compressible below 100 fs.

Table 2 Parameters of the Fianium oscillator.

Fianium FP-1030-2-01 fiber oscillator	
Central wavelength	1030.4 nm
Repetition rate	49.5 MHz
Output power	2.1 W
Pulse energy	42.5 nJ
Spectral bandwidth (FWHM)	20.5 nm
Pulse duration	6 ps (<100fs)
Horizontal M^2	1.05
Vertical M^2	1.04

Amplification of pulses up to high energies with ultra-short pulse durations results in a high value of peak power. This limit the obtainable output energies to few mJ at several kHz repetition rate because of two fundamental constrains. High peak power leads to intensification of the non-linear effects like self-phase modulation SPM responsible for distortion of temporal pulse shape and can also cause catastrophic damage of the optical components. Amplification of a picosecond pulses in Yb:YAG, at the level of saturation fluence, without Chirped Pulse Amplification would lead to the intensity in the amplifier of 9.2 TW/cm^2. Such high intensity is 1000 times higher than the ~GW/cm^2 level for nonlinear effects, B-integral and optical damage threshold of optical components. In order to significantly decrease the intensity but not to change the input pulse fluence, which is responsible for the energy extraction, one should stretch the input pulse width. Since input pulse fluence is independent of a pulse width, the energy extraction would not be influenced. Once the intensity inside the amplifier has been decreased the B-integral level can be kept at a reasonable level. After pulse is amplified from nJ to the mJ-kJ level the stretched pulse can be recompressed by the same stretching ratio. Thanks to the possibility of using gain materials with a small cross-section, therefore with higher stored energy, together with CPA technique results in making the high power laser systems extremely compact.

Once considering chirped pulse amplification, at first one should decide how far the seed pulses should be stretched. In order to do so, we should consider avoiding damage of optical components in the laser and efficient extraction efficiency. When it comes to the damage threshold of optical components usually producers characterize this parameter for 10 ns pulses but since we are amplifying picosecond pulses the damage threshold should be rescaled by the 'square root of the pulse width' law which can give quite accurate estimation. For stated damage threshold of 50 J/cm^2 and 10 ns pulses

(5 GW/cm^2), once we assume to have 500 ps pulses in the amplifier, the damage threshold of optical components after rescaling is 11.2 J/cm^2 for 500 ps pulses (22.4 GW/cm^2). This would imply that we could safely operate the amplifier at saturation fluence of 9.19 J/cm^2 and therefore, obtain good energy extraction efficiency. In this case the required chirped pulse width could be estimated from

$$\tau_{stretched} \sim \frac{I_{sat}}{I_{damage\,thr.}} \quad (1)$$

which gives a value of 410 ps. Even though the damage threshold of optical components like mirrors, thin-film polarizer and BBO crystal is high, the main limiting factor is the damage threshold of the thin-disk which is 5 J/cm^2. When we consider limited allowed fluence the estimated stretched pulse duration is 220 ps. In order to safely operate the laser to avoid the damage on all optical components I decided to set the stretched pulse duration to 500 ps. In order to achieve such pulse duration, one should introduce enough dispersion in the stretcher. Required group delay dispersion GDD can be calculated from

$$GDD = \frac{T_{in}}{4ln2}\sqrt{T_{out}^2 - T_{in}^2} \quad (2)$$

where T_{in} and T_{out} are the input and output pulse duration, respectively. For stretching seed pulses from 100 fs to 500 ps the required GDD is $1.8{\cdot}10^7$ fs^2. Because of that the grating pair has been chosen since it can introduce such high dispersion in comparison to coatings or prisms which can generate up to 5000 fs^2 of GDD in 1 m spacing.

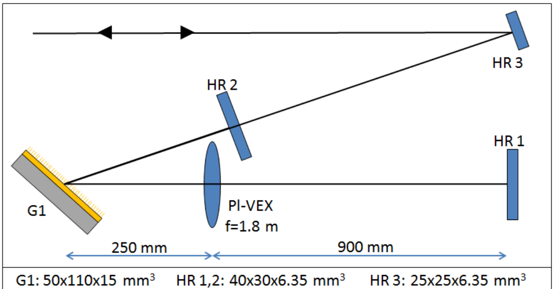

Figure 6 Schematic pulse assembly introducing positive dispersion.

Because of the economical reason and fast delivery time, gold-coated reflection gratings with 1740 l/mm groove density and >90% efficiency, were ordered. Figure 6 presents schematic layout of stretcher.

Stretcher has been designed as a folded Martinez type stretcher utilizing one reflection grating and 4 passes through the grating. Focal length of the used lens is 1.8 m and spacing between gratings 115 cm. Stretcher supports minimally 2 nm FWHM bandwidth which corresponds to 4.8 nm at $1/e^4$ level.

Seed spectrum was measured before and after stretching using Ocean Optics USB2000+ spectrometer. Before stretching the full width at half maximum (FWHM) was 20.5 nm and after stretching 3.2 nm which supports pulses well below 1 ps.

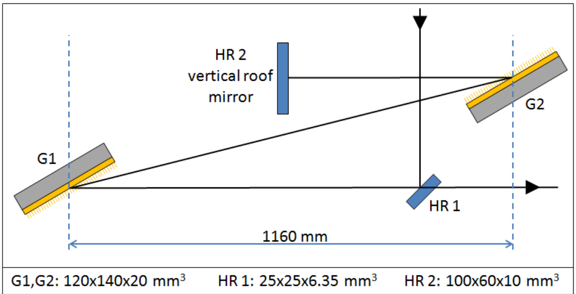

Figure 7 Schematic pulse compressor assembly introducing negative dispersion.

Compressor has been designed as a Treacy type compressor incorporating two parallel refelection gratings and a roof-end-mirror for shifting the beam height instead of standard tilted mirror. It delivers exactly oposite dispersion as the stretcher. Spacing between the gratings is approximately 1 cm longer due to compensation of the additional second order of dispersion introduced by the bulk components like Faraday rotator, thin-film polarizer and BBO Pockels cell. Figure 7 presents schematic layout of the Treacy-type compressor.

For the development of a prototype laser the 240 W laser diodes from DILAS Company were used with a center wavelength of 940 nm which is the standard pump wavelength for Yb:YAG. The prototype laser used small pump spot size of 2.7 mm, therefore those laser diodes were fully sufficient to provide pumping intensity up to 5 kW/cm^2. In case of high-energy regenerative amplifier the 800 W laser diodes, also from DILAS Company, were used with a stabilized central wavelength by volume Bragg gratings providing narrow linewidth for pumping at the zero-phonon line wavelength (969 nm). Such powerful laser diodes were sufficient for providing over 4.4 kW/cm2 pumping intensity with a pump spot size of 4.8 mm. Combination of high-intensity pumping at large mode diameter causes large thermal loading of the thin-disk and may result in the thin-disk deformations leading to increased optical phase distortion (OPD) causing poor mode matching and increased both temperature and amplified spontaneous emission (ASE) causing degeneration of amplification. Fortunately by utilizing wavelength-stabilized laser diodes at zero-phonon-line pumping source resulting in suppression of thermal loading it was possible to diminish these problems. By applying the pulsed pumping technique the thermal loading could be further reduced in case of both pump wavelengths.

Laser diodes were operated in continuous-wave (CW) operation as well as in pulsed mode with pulse duration ranging from 200 µs up to 990 µs, corresponding to a duty cycle at 1 kHz operation of 20% and 99%, respectively. High current switch providing short pulses of electrical current as high as 60 A was able to generate such pulses with a rise time of 8.3-9.3 µs and fall time of 0.7-2.3 µs, depending on the duty cycle.

4.2. Cavity design process

4.2.1. Wave-front sensor setup for thin-disk ROC estimation

Achieving high-energy output at high-repetition rate requires a careful design to prevent any optically induced damage. Simple power scalability is the well known property of the thin-disk lasers. By increasing the pump spot size and keeping the pumping intensity constant one can easily achieve higher output power. The limitation is the thermally induced damage threshold of the thin-disk, which in our case is 5 kW/cm^2. For this reason I decided on a large mode size on the thin-disk, which is pumped by high-intensity laser diodes providing sufficient gain since Yb:YAG is a quasi-three state laser. Increasing of the pump spot also requires redesigning of the resonator in order to realize single mode operation with larger mode size; otherwise the cavity starts to lase in multimode regime. Therefore, it is important to maintain the mode-matching condition, which is the relation between the mode size and the pump spot size with the typical filling factor of around 70-80%. Another aspect that can influence the single mode operation is exceeding the stability range of the resonator that takes place when the radius of curvature (ROC) of the thin-disk changes due to high pumping power. Intense pumping of the thin-disk causes optical path differences (OPDs) which are caused by many different thermal and electronic effects. Stresses leads to expansion of the material in the form of swelling, which in case of the thin-disks induces the curvature difference between the front and back surface, since the backside of disk is bonded on a heatsink. Such bending mainly results in spherical OPD, so larger mode size results in defocusing and influencing stability zones of the resonator. Aspherical part of the OPD's is responsible for mode mismatching and multimode operation. Therefore, analyzing the thin-disk ROC and its variation range is absolutely essential for designing of a stable thin-disk resonator. Special care needs to be taken into account when designing a laser cavity to make it resistant to changes of the thin-disk radius of curvature. For this purpose an extensive investigation of the thin-disk deformations was conducted to determine the behaviour of a thin-disk under high pumping power.

The OPD of the thin-disk can be measured by an interferometric measurement, which is precise enough to measure the surface deviations of the thin-disk, but it is a very sophisticated measurement and is usually impossible to realize inside the resonator. Thanks to a recent progress of Hartmann-Shack wavefront cameras in measuring the wavefront with the displacement sensitivity of 100 picometers, we decided to apply such sensor for the investigation of the thin-disk's radius of curvature and any OPDs induced by pump light. In contrast to a conventional interferometric measurement, this measurement is compact, easy to align and tolerate mechanical vibrations.

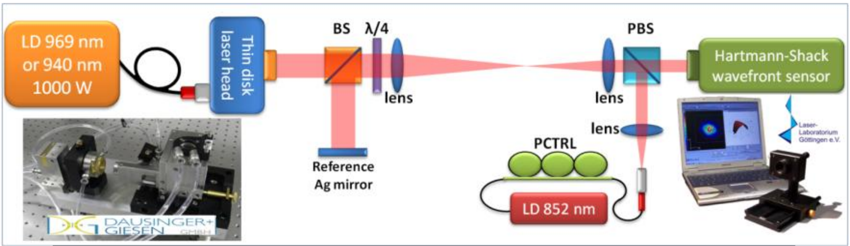

Figure 8 Layout of the experimental setup (BS- beam splitter, PBS- polarized beam splitter, PCTRL- polarization control module).

In this setup, laser emission from a single-mode fiber-pigtailed laser diode at 852 nm wavelength is precisely collimated to a 5 mm beam by an achromatic doublet with a focal length of 25 mm as a probe beam for wavefront measurement. The planar wavefront of the probe beam is modulated along the thin-disk surface, and the modulated wavefront is imaged on the Hartmann-Shack sensor by use of 6-f telescope of which enlargement factor is 2:1 to cover the whole area of the thin-disk. The wavefront sensor consists of 14-bit digital camera and 10x10 mm^2 micro-lens array with each element size of 150x150 μm^2. To cut the scattered lights of the pump beam and laser beam, a short-pass filter is inserted in front of the detector. The thin-disk is mounted inside the thin-disk laser head allowing pumping with high power laser diodes. Although the probe beam is well collimated, a flat silver-coated mirror is placed as a reference at the equivalent distance of the thin disk from the imaging lens to obtain the absolute value of thin disk ROC accurately.

This setup allowed measurement of thin-disk ROC under pumping with different pump spot sizes, pump wavelengths (940 nm, 969 nm) and operating conditions- lasing, non-lasing. Basing on the measured ROC changes, the stable cavity for the regenerative amplifier could have been designed.

4.2.2. WinLase calculations

The most elementary step in the design process of a resonator is done by performing ABCD-matrix calculations which allows determining precisely the laser mode size. For this reason necessary calculations have been performed using WinLase™ software package which is dedicated for designing laser cavities and for analyzing the propagation of Gaussian beams in complex optical systems by means of ABCD-matrix algorithms used for its calculations.

In order to evaluate the feasibility of achieving 100-mJ output from the regenerative amplifier with large beam spot diameter and two thin-disk laser heads, I have designed a prototype regenerative amplifier with a single laser head and small pump spot size. The resonator was designed to have a large, constant 2 mm mode size in the BBO Pockels cell, >1 mm diameter on the cavity mirrors and to have constant mode size of 2 mm on the thin-disk, regardless of the thin-disk radius of curvature (ROC) changes. The mode diameter was chosen to be the 70% of the pump spot's, which is 2.8 mm, in order to support single mode TEM_{00} operation. Thin-disk used for the prototype laser was a Dausinger-Giesen thin-disk with specified curvature of 4.6 m which corresponds to the focal length of 2300 mm. Even if the focal length increased due to deformation of the thin-disk caused by strong pumping, the mode size kept its value in range of approximately 1000 mm which corresponds to the increase of the thin-disk ROC of 2 m. Even though the thin-disk will be intensively pumped the cavity should sustain single mode operation.

For the high-energy regenerative amplifier the resonator with large mode size was designed. Laser cavity had a constant mode diameter of 4 mm in the Pockels cell and on the thin-disk. Beam size on the resonator mirrors was always larger than 2 mm which assured safe operation without optical damage. Laser mode on the thin-disk was set to the 80% of the 4.8 mm pump spot size. Large mode size cavity is approximately 1 m longer than the prototype cavity in order to provide large enough beam size on the thin-disk. Again, as in the case of the prototype resonator, the mode size on the thin-disk is kept at the same size regardless of the changes in ROC. Resonator was estimated to be stable from 2300 to ~3100 mm of the thin-disk focal length. This means that the ROC could be changed from 4.6 m up to 6 m without influencing the resonator stability.

4.3. Results of the regenerative amplifier

Here I would like to present the results of the regenerative amplification done with the prototype laser and the high-energy regenerative amplifier. In case of the prototype laser the disk was pumped by 940 nm laser diodes using pump spot size of 2.7 mm. For the operation of high-energy regenerative amplifier, 969 nm laser diodes were used with a pump spot size of 4.8 mm. In both cases pulsed pumping was applied and showed the improvement of the beam quality and the O-O efficiency.

4.3.1. The prototype laser

Laser action obtained in continuous wave (CW) regime allowed reaching the output power of 102 W with the pump power of 280 W at 940 nm corresponding to the pump intensity of 4.5 kW/cm^2. The optical-to-optical (O-O) efficiency was 36% with TEM_{00} mode output as shown in Figure 9.

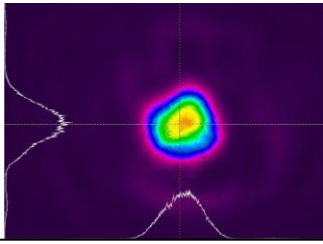

Figure 9 Beam profile of a 102 W laser output in CW operation from an Yb:YAG thin-disk.

At the 10 kHz regenerative amplification, we achieved the output power of 50 W with 250 W pump power corresponding to the O-O efficiency of 20%. We obtained the nearly diffraction limited output beam shown in Figure 10.

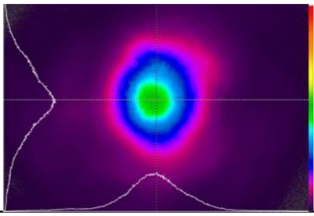

Figure 10 Beam profile of 50 W regenerative amplification at 10 kHz repetition rate with 250 W pump power.

The slope efficiencies in the CW and 10 kHz operation were 32% and 33%, respectively. In 10 kHz amplification we set the Pockels cell timing (the number of roundtrips) to obtain the stable operation just before bifurcation occurred, therefore the maximum output power and O-O efficiency of 10 kHz amplification were relatively lower than in CW operation.

Although, the spectral bandwidth of laser pulse was reduced from 3.1 nm to 1.6 nm caused by the gain narrowing, it could be enough to obtain less than 1 ps pulse after the pulse compression. The Fourier transform limited pulse width is expected to 975 fs.

In order to evaluate beam quality and M^2 parameter, we focused the output beam by a single plano-convex lens with focal length of 100 mm. The

4 mm laser beam was focused down to 40 μm, which implies the M^2 parameter in range of 1.1-1.5 (Figure 12).

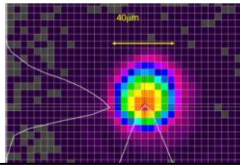

Figure 12 Far-field profile of 10 kHz Yb:YAG regenerative amplifier.

In case of the high energy amplification, we set the repetition rate at 1 kHz to avoid chaotic or bifurcate output [9, 25]. Also, the thin-disk was pumped in pulsed mode with the duty cycle in range of 30-99% under the specified peak power. The duty cycle corresponds to the pump pulse durations from 300 to 990 μs, which is especially advantageous since pumping with pulses shorter than the lifetime of the upper-laser level of Yb:YAG (~1 ms) results in suppression of the ASE. Moreover, thermal loading of the thin-disk can be reduced and fewer distortions of the thin-disk might be introduced. Both of these effects would result in the increased O-O efficiency. In order to evaluate the relationship between the O-O efficiency and the pump pulse duration, we varied the pulse duration and adjusted the average pump power by changing the peak power of each pump pulse so that the output energy of 15 mJ was achieved at the repetition rate of 1 kHz. Figure 11 shows the measured O-O efficiency and the average pump power required as a function of pump pulse duration. Average pump power can be substantially reduced with decreasing pump pulse duration. By decreasing the pump pulse duration from 990 μs, corresponding to the duty cycle of 99%, down to 300 μs, the O-O efficiency increased from 12.4% to 20.4%. Note that even though both peak power and duration of pump pulse can vary the energy of pump pulse, those two parameters affect the output characteristics of regenerative amplifier differently.

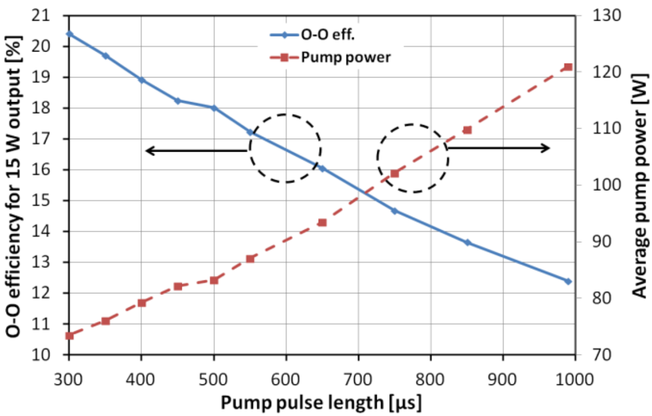

Figure 11 Optical-to-optical efficiency (a) and required pump power to obtain 15 mJ output from Yb:YAG laser at 1 kHz (b) as a function of pump pulse duration. The average pump powers at each settings of pump pulse duration were adjusted so that the output energy was kept to 15 mJ.

We then kept the peak pump power to 265 W and varied the pump pulse duration

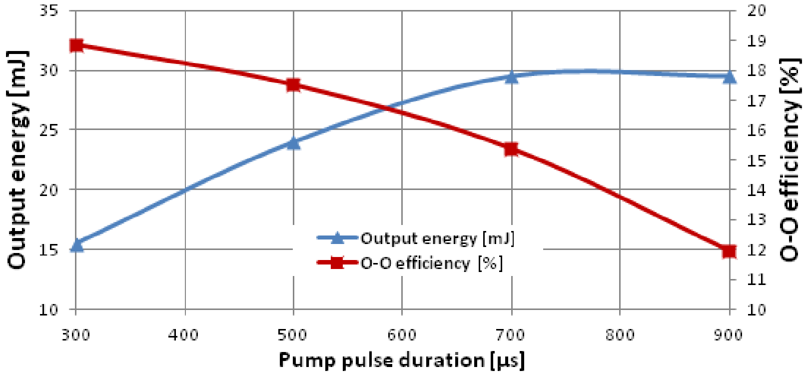

Figure 13 Characteristic of the Yb:YAG regenerative amplifier pumped at 940 nm wavelength.

to determine the maximum output of the regenerative amplifier. The number of round-trips was adjusted at each settings of pump pulse duration by changing the duration of high voltage pulse applied to the Pockels cell to obtain the highest extraction energy. The start timing of the Pockels cell was adjusted so that the amplification began almost immediately after the pump pulse flashed. We obtained output energy of 29.5 mJ at the pump pulse duration of 900 μs. The number of round-trips and the spectral bandwidth of the amplified pulse were 61 and 1.4 nm, respectively. The O-O efficiency was 12% and was increased to 16% at the pump pulse duration of 700 μs with the same output energy. Although the output energy was slightly reduced to 24 mJ, the O-O efficiency was increased to 18% at the pump pulse duration of 500 μs as shown in Figure 13. The amplified spectrum of 24 mJ at 1 kHz repetition rate with 50% duty cycle pulsed pumping had the FWHM bandwidth of 1.4 nm which corresponds to the expected transform limited pulse of 1.1 ps.

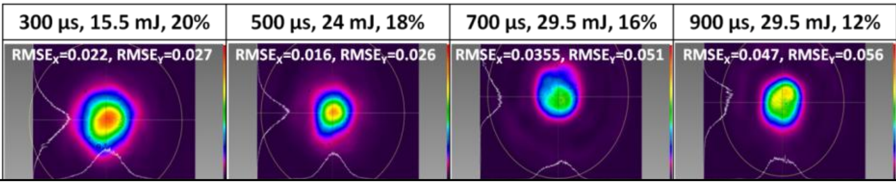

Figure 14 Yb:YAG laser beam quality and O-O improvement for 940 nm pulsed pumping.

Moreover, the beam quality was improved by decreasing pump pulse duration as shown in Figure 14. In order to discuss on the beam quality improvement quantitatively, we approximated the measured beam profiles by Gaussian intensity distribution in vertical and horizontal planes, and calculated the root mean square error (RMSE) of the fitting, which is given in Figure 14. For zero value of the RMSE the beam profile is perfectly matching with the Gaussian distribution. As it can be seen from Figure 14, the lowest RMSE was obtained at the pump pulse duration of 500 µs.

As shown in Figure 11 and Figure 13, the O-O efficiency decreases as the pump pulse duration lengthens. In other words, if the average power is kept the same in different pump pulse durations, the output power decreases as the pump pulse duration lengthens. On the other hand, the amplification period of 1 ms would be much shorter than decay times of typical thermally induced phenomena in solid-state laser media. We measured the surface temperatures of the thin-disk during pulsed and CW pumping by thermal camera and found that the surface temperatures were the same in case of pumping with the same average power. Because of that it is highly possible that the results depicted in Figure 11 and Figure 13 would be caused by the ASE suppression by pulsed pumping and the fast thermally induced effects of the thin-disk which cannot be detected by thermal camera.

4.3.2. High-energy regenerative amplifier

Since the damage threshold of the thin-disk using the 500 ps pulse with a pump spot size of 2.8 mm is approximately 30 mJ, we enlarged the pump spot size from 2.8 mm to 4.8 mm to achieve output energy of up to 60 mJ. Since the pump beam size was enlarged, we had to use more powerful laser diodes in order to provide proper pumping intensity. For this purpose we choose 800 W zero-phonon-line laser diodes operated in pulsed regime. We kept the peak pump power to 285 W and varied the pump pulse durations similarly as in the case of the 940 nm pumping. Figure 15 presents obtained results with 969 nm pulsed pumping.

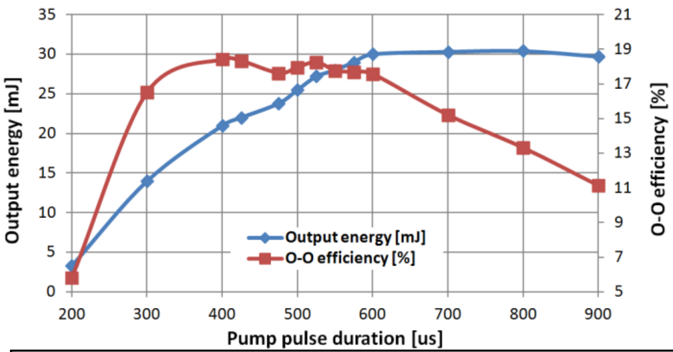

Figure 15 Characteristic of the Yb:YAG regenerative amplifier pumped at 969 nm wavelength.

Using the 969 nm pumping, we obtained output energy of 29.7 mJ with an O-O efficiency of 11% at the pump pulse duration of 900 µs. The number of round-trips and the spectral bandwidth of amplified pulse were 85 and 1.68 nm, respectively. The larger number of round-trips compared to the 940 nm pumping is likely to be caused by the smaller single pass gain due to the larger pump spot size. At the pump pulse duration of 700 µs, the output energy, as well as the O-O efficiency, was increased to 30.3 mJ and 15%, respectively, and the optimum number of round-trips was slightly reduced from 85 to 82. Although the number of round trips was increased to 93 at the pump pulse duration of 600 µs, we still obtained the output energy of 30 mJ with an O-O efficiency as high as 17.6%. The beam profile, in the case of the 600 µs pump, was very similar to that in the case of the 500 µs pump. As the pump pulse duration decreased to less than 500 µs, the output pulse energy decreased significantly as for the 940 nm pumping. However, the O-O efficiency was close to 20 % as shown in Figure 15. At the pump pulse duration below 300 µs, both the output energy and the O-O efficiency decreased. We obtained the symmetric and homogeneous beam profiles, as shown in Figure 16.

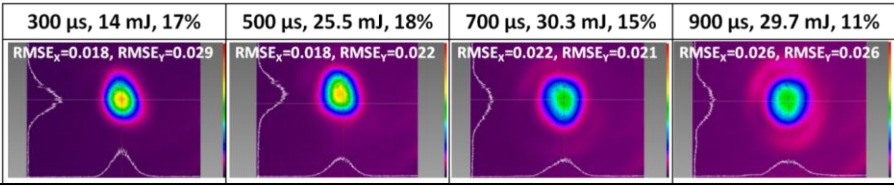

Figure 16 Yb:YAG laser beam quality and O-O improvement for 969 nm pulsed pumping.

As in the case of the 940 nm pumping, the beam quality was improved with the decreasing pump pulse duration. The symmetric and homogeneous intensity profiles are attributed to the significantly smaller thermal load of ZPL pumping. As in the case of 940 nm pumping, the lowest RMSE was obtained at the pump pulse duration of 500 µs. The amplified spectrum of 30 mJ at 1 kHz repetition rate with 50% duty cycle pulsed pumping had the FWHM bandwidth of 1.45 nm which corresponds to the expected transform limited pulse of 1.08 ps.

Since the output energies tended to saturate when the pump pulse durations were exceeded by 600 µs, we set the pump pulse duration of the 969 nm diode to 500 µs and adjusted the peak power of pump pulse to obtain the highest output energy. At the peak pump power of 465 W, corresponding to the average pump power intensity of 1285 W/cm^2, we obtained an output of 45 mJ with an O-O efficiency of 19.3%. The output beam profile was nearly diffraction-limited as shown in Figure 17.

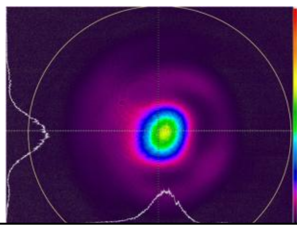

Figure 17 Beam profile of 45 mJ Yb:YAG thin-disk laser output at 1 kHz repetition rate. Pump pulse duration was set to 500 µs at 969 nm wavelength with pump power of 465 W.

Figure 18 shows the signals from the photodiodes measuring the output pulse and pulse build-up time inside the cavity. The pulse build-up was stable and did not fluctuate during a prolonged operation. Photodiode placed close to the output of the laser showed single pulse output without any pre- or post-pulses which implies that the extinction ratio of the water-cooled Pockels cell is very high.

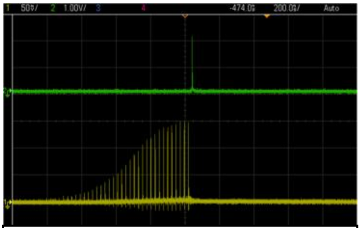

Figure 18 Output pulse (top) and pulse build-up inside the cavity (bottom) of the regenerative amplification with an Yb:YAG thin-disk (time base 200 ns/div).

Output pulses were compressed in a Treacy-type compressor utilizing two gold-coated reflection gratings. Pulse duration after compression was measured by a laboratory-made non-collinear intensity autocorrelator. The measured autocorrelation function in Figure 19 is showing that the pulse duration of compressed pulse is 2.7 ps. Presence of the pedestal in the autocorrelation function implies that the pulses are not fully compressed and further optimization of the compressor’s gratings is necessary. Since the amplified spectrum FWHM bandwidth is around 1.5 nm, the Fourier transform limit of the pulse duration is close to 1 ps, therefore it would be possible to obtain pulses shorter than 2.7 ps after the compression. Unfortunately the experiment was interrupted by the moving of the laboratory to the new location.

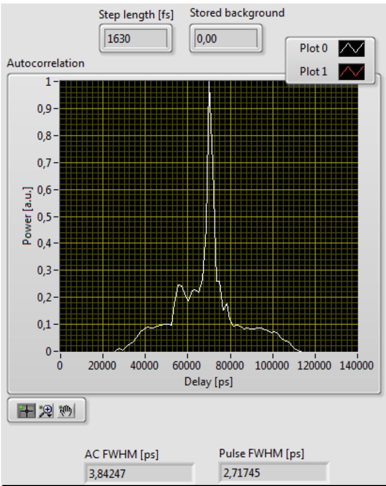

Figure 19 Measured autocorrelation function of the compressed output pulse from a Yb:YAG thin-disk laser.

Since beam pointing stability is one of the important factors for accurate laser applications, we measured the pointing stability of the regenerative amplifier using a focusing lens and a beam profiler. We recorded the position of beam spot per second using the beam profiler for more than 15 and calculated the RMS pointing stability. We found that the RMS pointing stability in horizontal and vertical axis is 3.8 μrad and 3.3 μrad, respectively.

In order to evaluate the beam quality we used a commercial M^2 measurement system from Laser Laboratory Gottingen (LLG) which measures the beam diameters around the beam waist position and calculates the M^2 parameter. We obtained M^2 value of 1.25 and 1.23 for horizontal and vertical axis, respectively. The beam diameter in the waist position focused by f=150 mm lens was 40 µm. Figure 20 shows the measured beam diameters along the beam propagation direction and beam profile at the waist position.

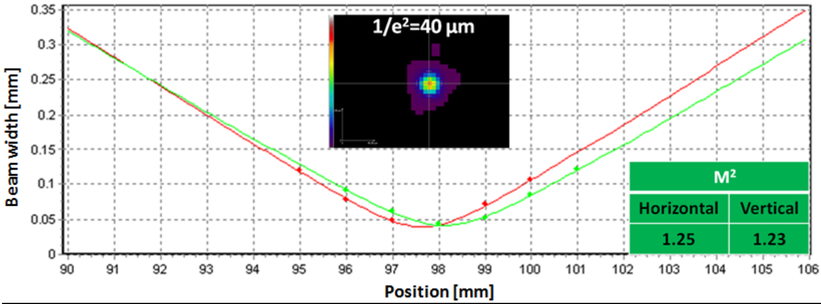

Figure 20 Focusing property of the Yb:YAG thin-disk laser output pulse for the calculation of M^2 value.

When we compare the obtained results for pulsed pumping at 940 and 969 nm, it is clearly visible that the obtained energies and the O-O efficiencies are similar. Such comparison is showed in Figure 21.

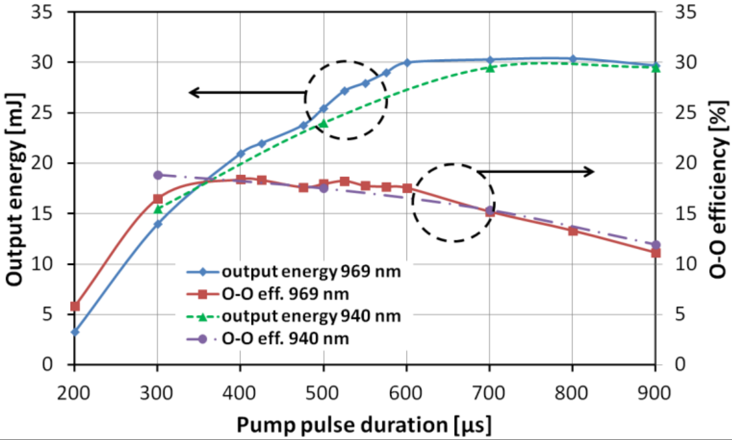

Figure 21 Output characteristics of the Yb:YAG thin-disk regenerative amplifier operated at 1 kHz repetition rate pumped by two different pump wavelengths: 940 nm laser diode with a peak power of 265 W and 969 nm laser diode with a peak power of 285 W.

Even though we obtained similar output energies with similar O-O efficiencies for both pumping wavelengths, there is a very wide gap of average pump power intensity. This difference is very well illustrated in the Figure 22.

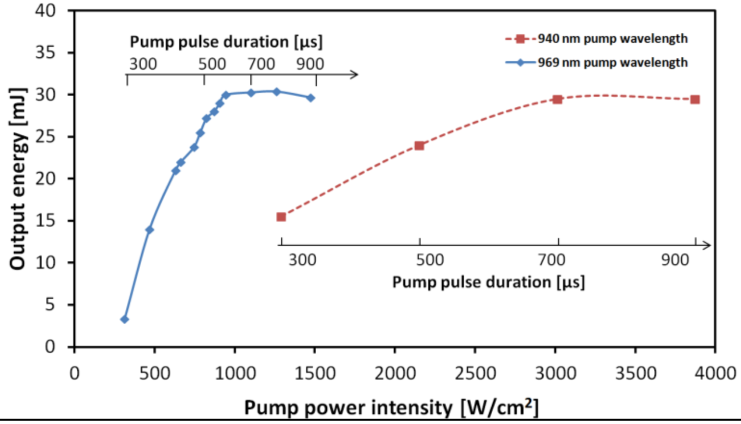

Figure 22 Output characteristics of the Yb:YAG thin-disk regenerative amplifier operating at 1 kHz repetition rate for 940 nm pumping with a pump spot diameter of 2.8 mm and 969 nm pumping with a pump spot diameter of 4.8 mm.

At a pump pulse duration of 700 µs, an output energy of 30 mJ was achieved for the 940 nm pumping as well as for the 969 nm pumping, however, the average pump power intensity of the former was 3013 W/cm^2, while that of the latter was 1101 W/cm^2, as shown in Figure 22. This large difference in required pump power intensity is likely caused by a major suppression of ASE at lower intensity and/or by a reduction of aspheric OPDs in ZPL pumping. The exact physical mechanism could be explained by an extensive numerical modelling of ASE, and by comparing the experimental results pumped by 1 kW laser diode at 940 nm. These results, obtained from both types of pump wavelengths, clearly imply that optimization to achieve the highest pulse energy with the highest O-O efficiency and beam quality is possible by adjusting the peak power and the duration of pump pulse.

5. CONCLUSION

High-energy thin-disk regenerative amplifier for a kW-class laser system was developed within this work and meets all the goals of the dissertation.

Summary of accomplishments

- In order to reduce the thermal loading and the amount of the thin-disk deformations caused by highly intensive pumping, that lead to degeneration of the beam quality and drop in the efficiency, pulsed pumping at zero-phonon-line was applied. Pumping the active medium with pulses shorter than the lifetime of the upper laser level results in reduced thermal loading and helps to reduce the ASE. Further decrease of thermal loading and thin-disk deformations was possible by applying the zero-phonon-line pumping at 969 nm wavelength which thanks to the lower quantum defect allows lowering the amount of heat generated in the gain medium. Since the absorption linewidth at 969 nm is very narrow (<2 nm FWHM) special pump diodes were ordered, utilizing volume Bragg gratings (VBGs) for precise locking and narrowing the emission bandwidth to less than 0.5 nm FWHM. This results in extremely efficient pumping and decreased temperature of the pumped thin-disk. Production of such diodes was possible due to technological progress in material development for the manufacturing of efficient VBGs and in semiconductor industry for the improvement of laser diodes performance.
- Since thin-disks soldered to a CuW heatsink have different ROCs, therefore in order to be able to exchange them in case of a damage an exceptional method for the design of a custom resonator dedicated to a specific thin-disk was presented. It is based on a reliable measurement technique of the thin-disk absolute radius of curvature with a Hartmann-Shack wavefront sensor. The measurement can be done under pumping condition of a thin-disk with various pump spot sizes, which showed a meaningful difference in range of radius of curvature change. Moreover, a single mode cavity was built in the wavefront sensor setup allowing investigation of the thin-disk deformations in lasing and non-lasing conditions. It was also possible to find a proper mode matching condition for the single mode operation. After extensive studies of the thin-disk deformations the regenerative amplifier cavity was designed to specifically support the measured ROC change range. This method can be applied for any thin-disk which makes it very useful.
- The prototype laser was built to evaluate the potential of the soldered thin-disks and to optimize the pumping methods. It was pumped with 940 nm laser diodes and 2.7 mm pump spot size delivering 5 mJ output energy at 10 kHz operation with 20% O-O efficiency. At 1 kHz operation

pulsed pumping technique was applied to reduce the thermal loading. By varying the pump pulse duration it was possible to obtain high pulse energy, high O-O efficiency and good beam quality. It was shown that the pump pulse duration sets the trade-off between high pulse energy, O-O efficiency and beam quality. For optimized parameters the pulse energy of 24 mJ was achieved with 18% O-O efficiency and near Gaussian beam distribution.

- In case of the high energy regenerative amplifier in addition to the pulsed pumping method, zero-phonon-line laser diodes were used which additionally decreased the thermal loading of the thin-disk. Thanks to the volume Bragg gratings stabilizing the laser diodes wavelength at 969 nm it was possible to pump the narrow absorption line of the Yb:YAG. The pump spot size of 4.8 mm was applied. Change of the pump pulse duration resulted in the same trade-off between high pulse energy, O-O efficiency and beam quality as in case of the prototype laser. Nevertheless, after optimization of peak power and duration of pump pulse a nearly diffraction limited output of 45 mJ and O-O efficiency of 19.3% was obtained. The beam quality of the output in horizontal and vertical direction was 1.25 and 1.23, respectively. The measurement of the beam pointing stability showed that RMS stability in horizontal and vertical direction was 3.3 μrad and 3.8 μrad, respectively. Output pulses were compressed down to 2.7 ps and basing on the amplified spectrum, even shorter pulses could be achieved after optimization of the compressor.

Contribution to progress of science

Development of high energy picoseconds sources emitting at 1.03 μm wavelength is one of the main challenges of the solid state lasers physics. The obtained results of the regenerative amplifier clearly imply that optimisation to achieve the highest pulse energy with highest O-O efficiency and beam quality is possible by adjusting the peak power and the duration of pump pulse. The demonstrated advantages of pulsed pumping in the thin-disk regenerative amplifier at 1 kHz repetition rate were obtained although the adopted thin-disk was soldered to a CuW heatsink which presumably has much worse thermal properties compared to a diamond heatsink. The pulsed pumping has shown to be very effective for the improvement of output characteristics pumped by not only the 940 nm wavelength but also the 969 nm. It was shown that lower pump intensity is required for the zero-phonon-line pumping with a larger pump spot size to achieve the same output as in case of the 940 nm pumping with smaller pump spot size. The pulsed pumping method can also be effective for the thin-disk amplifiers with a diamond heatsink, to achieve joule level output at 1 kHz repetition rate.

The results achieved in this dissertation will, in author's opinion, contribute to the development of reliable laser sources for industrial and scientific applications. Moreover, thanks to the applied pulsed pumping method onto a soldered thin-disk, it was shown that an alternative solution to the diamond-based thin-disk lasers is available. This mean an easier access to a highly specific laser sources that are affordable for numerous research groups working in various fields of laser physics and its applications.

The developed thin-disk laser can be suggested for practical use in several applications. The first application area is transmission microscopy. The elaborated laser can be used for the improvement of the conversion efficiency of soft X-ray source, emitting in the 'water window' spectral range at the wavelength of 2.88 nm. Another application for the regenerative amplifier is the optical parametric amplification. High power laser source at 1.03 µm wavelength is required as a pumping source for the OPA system generating wavelengths that are hardly obtainable for typical laser sources. In comparison to the recently obtained output energy of 42 mJ at 1 kHz operation and 17 ps pulse duration from a three-stage cryogenic Yb:YAG amplifier for pumping of an OPCPA system, the developed within this dissertation laser presents more convenient solution in a form of a thin-disk regenerative amplifier, which is compact, operated at room temperature and delivers better output parameters.

During the research work, the new results were published in world class journal and presented at major scientific conferences, making the results accessible to the scientific community all over the world.

Outlook for the future work

High energy regenerative amplifier delivered 45 mJ pulse energy with a pump spot size of 4.8 mm and 465 W of pump power. Nevertheless, the laser diode can provide up to 850 W of output power, hence the pump spot size could be still increased. Therefore, an upgrade of the high energy regenerative amplifier is being prepared. The laser will utilize two thin-disk laser heads in order to reduce the thermal loading of a single disk. Both disks will be pumped by 800 W, 969 nm wavelength laser diodes in pulsed regime and the pump spot size will be increased to 5.8 mm. The compact size of the laser will be maintained as it will be fitted on the 150x190 cm^2 optical breadboard. The laser will be utilized for seeding the second stage amplifier in Hilase beamline B laser system, therefore the developed fiber front-end will provide 1.5 ns pulses. Nevertheless, the free-space stretcher and compressor will be mounted on the 150x60 cm^2 optical breadboard and placed next to the regenerative amplifier. It will be possible to use the regenerative amplifier for the beamline B laser system as well as for a small scale experiments. After lifting the flip mirrors the regenerative amplifier would be operated with 500 ps stretched pulses which could be recompressed below 2 ps. A chirped volume Bragg grating (CVBG) compressor is also considered for future upgrade.

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Summary

In the field of short pulse laser-matter interaction research, a typical requirement of major applications is to keep the beam quality at high average power level. The use of a thin-disk as an amplifying gain medium fulfils those demands taking into account its advantageous geometry allowing efficient backside cooling.

This dissertation is devoted to the development of a Yb:YAG thin-disk regenerative amplifier for seeding the ring amplifier in the HiLASE Beamline B amplifier chain and to use the compressed output of regenerative amplifier itself for small scale experiments. Due to the much lower cost and easy availability of a thin-disk gain media soldered on a copper-tungsten (CuW) heatsink, in comparison to a thin-disk mounted on a diamond substrate, a special care had to be taken to reduce the amount of the thin-disk deformations caused by highly intensive pumping. An analysing technique based on a Hartmann-Shack wavefront sensor was developed for the measurement of such deformations under pumping condition.

Within this dissertation a method reducing the thermal loading of a thin-disk was developed by applying the pulsed pumping technique. It was showed, that even though we adopt the thin-disk mounted on a CuW heatsink which presumably has much worse thermal properties compared to a diamond heatsink, the output beam quality and the optical-to-optical efficiency was significantly improved by optimising the peak power and duration of pump pulses. By applying the zero-phonon-line pumping at 969 nm wavelength the further decrease of the thermal loading and lower required pumping intensity was reached. The developed regenerative amplifier delivers nearly diffraction-limited output of 45 mJ of pulse energy at 1 kHz repetition rate with 19.3% of optical-to-optical efficiency and 2.7 ps pulse duration. The new elaborated pulsed pumping method can also be effective for the thin-disk amplifiers with a diamond heatsink, to achieve joule level output at the frequency of 1 kHz.

Resumé

Častým požadavkem mnoha moderních aplikací ve výzkumu interakce laserového záření s látkou je zesílení optických pulsů na vysokou úroveň středního výkonu při zachování dobré kvality laserového svazku. Aktivní prostředí ve tvaru tenkého disku vzhledem k jeho výhodné geometrii, která umožňuje účinné chlazení ze zadní strany disku, splňuje velmi dobře tyto požadavky.

Předložená disertační práce je věnována vývoji diodově buzeného regenerativního zesilovače na bázi Yb:YAG aktivního prostředí ve tvaru tenkého disku, který bude použit jako první stupeň laserového řetězce s vysokou energií emitovaných pulsů a velkou opakovací frekvencí budovaného v centru Hilase pod interním označením Beamline B. Zároveň by měl tento zesilovač sloužit i v dílčích experimentech průmyslového a vědeckého výzkumu centra Hilase. Vzhledem k nižší ceně a lepší dostupnosti tenkodiskových aktivních médií s chladičem CuW, ve srovnání s tenkými disky s chladičem ze syntetického diamantu, musela být věnována zvýšená péče kompenzaci deformace disku a následné deformaci vlnoplochy laserového svazku, která je způsobena intenzivním buzením laseru. Byla proto vyvinuta měřicí technika, která prostřednictvím Shack-Hartmannova senzoru vlnoplochy umožňuje diagnostiku deformací disku během provozu laseru.

V rámci experimentální práce byla také úspěšně redukována celková tepelná zátěž aktivního prostředí pulsním buzením laseru. I přes použití disků připájených na CuW chladiči (které mají podstatně horší tepelné vlastnosti než disky na diamantovém chladiči) po provedené optimalizaci špičkového výkonu a doby trvání budicího pulsu vedly tyto změny k výraznému zvýšení kvality výstupního laserového svazku a optické účinnosti zesilovače. Přímá excitace elektronů na horní laserovou hladinu Yb:YAG krystalu bez emise fononu (tedy tzv. zero-phonon line buzení na vlnové délce 969 nm) dále snížila množství uvolněného tepla a zvýšila účinnost systému. Vyvinutý regenerativní zesilovač emituje téměř difrakčně limitovaný svazek záření s energií v pulsu 45 mJ, opakovací frekvencí pulsů 1 kHz a dobou trvání pulsu 2.7 ps. Optická účinnost zesilovače dosáhla 19.3%. Navržená technika pulsního buzení zesilovače laserovými diodami může být efektivní i ve spojení s účinněji chlazenými tenkými laserovými disky na diamantovém chladiči, které budou pravděpodobně nezbytné pro zvýšení energie zesíleného pulsu na úroveň 1 J při zachování opakovací frekvence pulsů 1 kHz.