VILNIUS UNIVERSITY

CENTER FOR PHYSICAL SCIENCES AND TECHNOLOGY

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HIGH AVERAGE POWER PICOSECOND PUMP SOURCE FOR OPTICAL PARAMETRIC CHIRPED PULSE AMPLIFICATION

Summary of doctoral dissertation

Technology sciences, material engineering (08T)

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DIDELĖS VIDUTINĖS GALIOS PIKOSEKUNDINIS KAUPINIMO ŠALTINIS FAZIŠKAI MODULIUOTŲ IMPULSŲ PARAMETRINIAM STIPRINIMUI

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Contents

Introduction

Laser is a great tool for fundamental research. Out of all the technology currently possessed by humanity only the laser radiation can create an electric field of strength comparable to the electric field inside of an atom. This allows deformation of the electric field and reaching relativistic regimes. Using high intensity ultrashort femtosecond (10^{-15} s) laser pulses it is possible, through high harmonic generation, to generate attosecond pulses (10^{-18} s). This allows monitoring of the dynamics of electrons inside molecules.

Traditionally, since 1985, when chirped pulse amplification (CPA) was introduced [1], such femtosecond high energy pulses were generated by using sapphire doped by titanium ions (Ti:sapphire) active medium based laser systems. Currently systems with peak power exceeding 100 TW levels are operating at different laboratories around the word and are also commercially available. However due to limited bandwidth of the Ti:sapphire further improvement of parameters of these systems is complicated. To generate pulses of durations not exceeding 35 fs, spectrum narrowing during amplification needs to be compensated. Best case scenario is to achieve pulses of durations between 15 and 30 fs, depending on the scale of amplification, by using spectral filtering technology. A system was demonstrated producing pulses with output bandwidth of ~78 nm (full width half maximum), compressible to 22 fs duration [2].On the other hand some technologies, such as spectral broadening in a hollow core fiber, allow to generate quasi-single optical cycle pulses out of this radiation. Another factor limiting the performance of such systems is thermal effects. Because of these the average power of such systems is difficult to scale beyond the level of 30-40 W. Possibility of creating systems generating average powers of 26 W with pulse durations of 50 fs has been demonstrated.

Currently one of the main and most promising ways of generating such few optical cycle high energy pulses is a technology presented in 1992 by Lithuanian scientists – optical parametric chirped pulse amplification (OPCPA) [3]. One of its advantages is, that during amplification energy is not accumulated in the amplification medium, meaning, that almost no parasitic thermal phenomena occurs. This allows to create systems of almost unlimited repetition rates and average powers. High average power allows to achieve high electric field strengths, while high repetition rate allows to speed up the collection of experimental data. Big advantage of the OPCPA is its broad amplification bandwidth, allowing to generate pulses with durations shorter than 10 fs and, also, allowing to work at different central wavelengths: 5 fs (1.7 optical cycle) at 880 nm [4], 10.5 fs (1.5 optical cycle) at 2100 nm [5], 67 fs (6.3 optical cycle) at 3200 nm [6], and 83 fs (6.4 optical cycle) at 3900 nm [7]. Theoretically, the output parameters of the OPCPA are only limited by the parameters of the pump laser. However, at some instances, some parasitic phenomena do occur, such as, for example idler wave absorption by the crystal, caused by its insufficiently broad transparency window. Using OPCPA technology both high peak power, for example 16 TW [8], and high average power – 53 W [9] – could be achieved. One of the main challenges of constructing an OPCPA system is creation of a pump laser with suitable parameters. Synchronization of signal and pump pulses is of no lesser importance as well. The most convenience solution for the synchronization problem is optical synchronization, when signal and pump branches of the system both start from the same seed source (optical oscillator). Different approaches to choosing the parameters of the pump laser exist. For large systems generating pulses of very high energy (joule level) pump pulses of nanosecond durations are used, this way amplification bandwidth is sacrificed. Pulse durations of hundreds of femtoseconds are achieved in such systems [10, 11]. Using pump pulses of durations in the range of ~50-100 ps allows reaching millijoule level energies and pulse durations shorter than 10 fs [12, 13]. The third group of OPCPA pump lasers is one generating pulses of around ~1 ps duration [5]. High peak power of these pulses allows usage of short parametric crystals, thus very broad bandwidth can be achieved and very short pulses can be generated. The negative aspect of using such short pump pulses is the increased sensitivity to pump and signal pulse synchronization: fluctuations of the optical path in the OPCPA system caused by thermal effects and mechanical instabilities could become comparable to the pump pulse duration. Such pulses are usually generated using ytterbium doped active media, such as Yb:YAG, based chirped pulse amplification (CPA) systems, most often in the form of thin disk regenerative amplifiers [14-16]. Thin disk technology is also known as active mirror [17]. Its main idea is to use an active medium with thickness smaller than the laser beam diameter. Heat is removed through the end face of such an active medium. This maximizes the cooling efficiency by reducing the distance from the zone where heat is generated to the cooler. Thus negative impact of thermal effects on the beam profile is mitigated. The small length of the active medium also reduces the non-linear self-action of the beam. Thanks to its small quantum defect Yb:YAG active medium is well suited for this technology [18].

In comparison with neodymium doped active media, ytterbium doped active media are characterized by lower amplification, but broader amplification bandwidth, allowing to achieve ~1 ps pulse durations, while neodymium doped active media support pulse durations of around 10 to 20 ps (8 ps pulse duration was achieved in [19]. Such pump pulse durations (10-20 ps) are interesting for OPCPA pumping, as they provide a compromise between high peak energy achievable by using 1 ps pump pulses and lower sensitivity to synchronization of signal and pump pulses as in the case of ~50-100 ps pump pulses.

It would seem that Ti:sapphire systems should be forgotten and entirely replaced by OPCPA systems, but using a hybrid of both of these technologies allows for very good results. The latest trend in creating high power laser systems is to use an OPCPA system as a seed source for a Ti:sapphire amplifier system, as this allows to generate pulses of high energy and at the same time greater temporal contrast than the ones generated by Ti:sapphire systems. As the biggest part of the amplification performed in the OPCPA part, the amplification in the Ti:sapphire part can only be of the order of tens of times, reducing spectral narrowing due to amplification. Ti:sapphire systems are well suited for this application, as they are characterized by good amplification and large accumulated inversion, as energy is accumulated in the amplification medium. Ti:sapphire amplifiers are pumped by relatively simple and cheap nanosecond lasers, able to produce immense, joule level, pulse energies, while output parameters of OPCPA systems are limited by the complexity and high prices of the pump lasers. This hybrid technology allows to generate very high energy, joule level, short pulses of tens of femtoseconds in duration with good temporal contrast.

An effective pump source for an OPCPA system should generate pulses with highest possible energy. The spatial intensity distribution should be as homogeneous as possible. High repetition rate is important for main OPCPA applications, as higher repetition rate allow for higher experimental data collection rate, but in reality a compromise is chosen between the repetition rate and pulse energy. To achieve maximum possible efficiency, apart from the spatial homogeneity of the beam, a rectangular temporal pulse profile is beneficial [20, 21]. Precision and stability of synchronization of the pump laser and the radiation amplified in the OPCPA plays an important role.

Creating an effective pump source for an OPCPA system is a non-trivial task. The main goal of the experiments described in this thesis was to solve this problem. While Yb:YAG thin disk technology is the most popular solution for creating OPCPA pump sources at the moment, we chose to use traditional rod shaped Nd:YAG active media. We think this is the most optimal way of creating a laser system with parameters suitable for OPCPA pumping. There are several other groups working with similar technology. A system generating 10 mJ pulses of 207 ps in duration, operating at 3 kHz repetition rate is presented in [22]. While [23] describes a system generating output pulses with higher energy, 130 mJ, and shorter duration – 64 ps, however the system operated at a repetition rate of only 300 Hz. Comparing to these results UAB “EKSPLA” has demonstrated laser systems with exclusive parameters.

Relevance

The subject of this work is very relevant as one of the most efficient ways of generating high energy ultrashort optical cycles of several optical cycles in duration to date is optical parametric chirped pulse amplification (OPCPA). One of the main parts of such OPCPA systems is the pump laser. The main aim of the presented work is creation of an effective pump source of an OPCPA system. Based on part of the results of research described in this paper UAB “Ekspla” has produced a pump laser for the OPCPA system situated at the open access research center “Naglis” [24]. Later a system generating pulses with energy in excess of 300 mJ at 532 nm wavelength was produced, which was used to pump an OPCPA system created by UAB MGF “Light conversion”, with pulse energy of 53 mJ and sub-9 fs duration at 1 kHz repetition rate. This system will be used at an international research center Extreme Light Infrastructure (ELI) ALPS SYLOS research which is being built in Hungary [25]. The experiments described in the last part of this work are an investigation into ways of upgrading the SYLOS system.

Goals and objectives

- To create a high energy (more than 100 mJ) laser system working at a 1 kHz repetition rate designed for high energy optical parametric chirped pulse amplifier (based on LBO and BBO crystals) pumping.
- To investigate the methods of formation and control of the intensity distribution and apply them to a high energy amplifier system.
- To control the parasitic effects caused by high heat dissipation in a high average power laser system.
- To investigate chirped pulse amplification technology and apply it to a laser amplifier system based on neodymium doped active media, and to reach highest possible energetic efficiency.
- To investigate and realize methods allowing preservation of widest possible spectral bandwidth in a laser amplifier system based on neodymium doped active media.

Novelty and significance

An optimized effective double-pass amplification stage which could be used as a building block for high average power lasers systems using side-pumped amplification modules was presented in this work. Increasing the number of such amplification stages allows for easy system output power scaling. This optical layout is based on well-known solutions and physical effects, however, as far as we know, we were the first to use the specific combination of optical elements that is presented in this work.

A novel beam intensity distribution shaping method, based on an element produced by inscription of nanogratings by femtosecond pulses in fused silica, was also tested in this work.

Also, as far as we know, compression of narrowband pulses amplified in neodymium doped active media by using custom made diffraction gratings with high line density, instead of using hyper-compressor technology, employing grating pairs to increase the dispersion of the compressor, was used in this work for the first time.

A double output fiber oscillator was used for the first time as a seed source for an amplification system, allowing for optical synchronization of seed and pump channels of the OPCPA system.

As far as we know, we were the first to use the combination of fiber stretcher with tunable chirp and diffraction grating compressor for chirped pulse amplification and compression.

Statements to be defended

1. Use of the suggested effective compact optical chain for picosecond pulse amplification, using laser-diode side-pumped amplifier modules, based on Nd:YAG active medium, employing relay imaging between the active medium and the back reflecting mirror, a Faraday polarization rotator, and a quarter wave plate, allows minimization of influence of thermal effects and nonlinear self-action on spatial and spectral properties of the beam of a laser amplifier operating at 1 kHz repetition rate.
2. Use of the super Gaussian beam formation technology based on nanogratings inscription in fused silica using femtosecond light pulses, allows to shape a super Gaussian beam of 14th order with 50% energy losses, which allows to increase the fill factor of the active medium from 29% (for a Gaussian beam) to 84%, while also reducing the B integral value by 4.9 times for the same pulse energy, thus increasing the total efficiency of the amplifier setup.
3. Spectrum width sufficient for compression of pulses to time bandwidth limited durations of ~10 ps could be achieved in a high average power CPA system based on neodymium and ytterbium doped media generating output pulse energies of ~130 mJ by detuning the central wavelength of the seed source in respect of the center of the amplification bandwidth.
4. Pulses of 0.1-0.2 nm bandwidth at 1064 nm central wavelength could be effectively compressed, while preserving good spatial profile of the resulting picosecond pulses, by employing high efficiency multilayer dielectric (MLD) diffraction gratings and relay imaging with beam magnification into the compressor and then relay imaging out of it.

Author’s contributions

The author carried out the designing, assembly and characterization of the amplifier schemes. Also the author processed the results of the experiments, contributed to writing of abstracts for the conferences and preparing the publications. Presented the results at conferences in both poster and oral formats.

Co-authors’ contributions

A. Michailovas was the initiator of the research and the main source of ideas.

A. Zaukevičius created the regenerative amplifiers and was the author of the concept of the compressor.

R. Danilevičius, S. Frankinas and N. Rusteika created the fiber oscillators provided consulting about chirped fiber Bragg grating used as the stretcher.

S. Balickas conducted numerical simulations and designed the high average power OPCPA pump lasers.

A. Aleknavičius and J. Adamonis constructed high average power OPCPA pump lasers.

V. Petrauskienė conducted numerical modelling of chirped pulse amplification.

V. Smilgevičius consulted on the preparation of the doctoral thesis.

A. Baltuška and A. Pugžlys were the creators of the Yb based amplification system.

T. Gertus created the spatially variable wave plate used for beam shaping.

All of the above have had a part in preparing the publications.

Publications on the topic of the doctoral thesis

Publications in ISI WEB of Science periodicals:

1. **K. Michailovas**, V. Smilgevičius, and A. Michailovas, High Average Power Effective Pump Source at 1 kHz Repetition Rate for OPCPA System, Lithuanian Journal of Physics **54**(3), 150–154 (2014).
2. **K. Michailovas**, A. Baltuska, A. Pugzlys, V. Smilgevicius, A. Michailovas, A. Zaukevicius, R. Danilevicius, S. Frankinas, and N. Rusteika, Combined Yb/Nd driver for optical parametric chirped pulse amplifiers, Optics Express **24**(19), 22261-22271 (2016).
3. J. Adamonis, A. Aleknavičius, **K. Michailovas**, S. Balickas, V. Petrauskienė, T. Gertus, and A. Michailovas, Implementation of a SVWP-based laser beam shaping technique for generation of 100-mJ-level picosecond pulses, Applied Optics **55**(28), 8007-8015 (2016).
4. **K. Michailovas**, A. Zaukevičius, V. Petrauskienė, V. Smilgevičius, S. Balickas, and A. Michailovas, Sub-20 ps high energy pulses from 1kHz neodymium-based CPA, accepted to Lithuanian Journal of Physics.
5. A. Marcinkevičiūtė**, K. Michailovas,** R. Butkus, Generation and parametric amplification of broadband chirped pulses in the near-infrared, accepted to Optics Communications.

Publications in ISI WEB of Science proceedings periodicals:

1. T. Gertus, A. Michailovas, **K. Michailovas**, V. Petrauskienė, Laser beam shape converter using spatially variable waveplate made by nanogratings inscription in fused silica, Proceedings SPIE **9343**, Laser Resonators, Microresonators, and Beam Control XVII, 93431S (2015)

Presentations at scientific conferences:

1. **K. Michailovas** , V. Smilgevicius, A. Michailovas High average power high repetition rate picosecond pulses amplifier for efficient OPCPA pumping, XXth Lithuania-

Belarus Seminar „Lasers and Optical Nonlinearity“, P1, Vilnius, Lithuania, November 21-22, 2013, (poster)

2. **K. Michailovas**, A. Michailovas , A. Zaukevicius , V. Smilgevicius, High average power high repetition rate chirped pulse amplifier for OPCPA pumping, 16th International Conference "Laser Optics 2014", TuR1-12, St. Petersburg, Russia, June 30 - July 04, 2014 (oral)
3. **K. Michailovas**, A. Michailovas, A. Zaukevicius, V. Smilgevicius, High average power high repetition rate chirped pulse amplifier for OPCPA pumping, ThP-T1-P-28 , 6th EPS-QEOD Europhoton Conference, 24 - 29 August 2014, Neuchâtel, Switzerland (poster)
4. **K**. **Michailovas**, A. Michailovas, A. Zaukevicius, V. Smilgevicius, Tens of Picoseconds Pulse Duration High Average Power 1kHz Repetition Rate Chirped Pulse Amplifier for OPCPA Pumping, T - P35, International Conference on Ultrahigh Intensity Lasers ICUIL2014, October 12 -17, Goa, India, 2014 (poster)
5. **K. Michailovas**, V. Smilgevicius, A. Michailovas, A. Zaukevicius, Neodymium Doped Active Medium Based High Power High Energy 10-20ps Pulse Amplification System Using Chirped Pulse Amplification Technique, Advanced Solid State Lasers Conference, 16 - 21 November 2014, Hilton Shanghai Hongqiao, Shanghai, China ATh2A.27 (poster)
6. T. Gertus, A. Michailovas, **K. Michailovas**, V. Petrauskiene, Laser beam shape converter using spatially variable wave plate made by nanogratings inscription in fused silica, Photonics West 2015, SPIE Paper Number 9343-64, San Francisco, USA, 7-12 February, 2015 (poster)
7. **K. Michailovas**, A. Michailovas, A. Zaukevicius, and V. Smilgevicius, Feasibility study on application of chirped pulse amplification technique in Nd:YAG picosecond pulses amplifier, P15, Northern Optics & Photonics 2015 (NOP 2015), 2-4 June 2015, Lappeenranta, Finland (poster)
8. T. Gertus, **K. Michailovas**, V. Petrauskiene, and A. Michailovas, Flexible laser beam shaping technique employing a fused silica spatially variable waveplate, P38, Northern Optics & Photonics 2015 (NOP 2015), 2-4 June 2015, Lappeenranta, Finland (poster)
9. A.Michailovas, A. Zaukevicius, **K. Michailovas**, and V. Smilgevicius, Neodymium Doped Active Medium Based CPA Laser System for OPCPA Pumping With Average

Output Power of 100W and 20ps Output Pulse Duration Operating at 1 kHz repetition rate, CA-11.2 (1359), CLEO®/Europe-EQEC 2015 June, 21 - 25, 2015, Munich, Germany (oral)

10. J. Adamonis, A. Michailovas, A. Aleknavičius, J. Kolenda, S. Balickas, **K. Michailovas**, L. Jacinavičius, A. Šniukšta, G. Masian, High Power Picosecond Pump Laser for OPCPA System of ELI-ALPS SYLOS-1 Beamline, Abstract ID : 8, International Conference on Extreme Light (ICEL 2015) 23-27 November 2015, Bucharest, Romania (poster)
11. A. Michailovas; J. Adamonis; A. Aleknavicius; S. Balickas; T. Gertus; A. Zaukevičius; **K. Michailovas**; V. Petrauskiene, A New Beam Shaping Technique Implemented In 150 W, 1kHz Repetition Rate Picosecond Pulse Amplifier, JTu5A.40, CLEO:2016, June 05 - 10, 2016, San Jose, California, USA (poster)
12. J. Adamonis, A. Aleknavicius, S. Balickas, T. Gertus, A. Michailovas, A.Zaukevicius, **K. Michailovas**, V. Petrauskiene, A New Beam Shaping Technique Implemented in 260 Wat Kilohertz Repetition Rate Picosecond pulse amplifier, ThR1-27, Laser Optics 2016, 27 June – 1 July 2016 in St. Petersburg, Russia (oral)
13. J. Adamonis, A. Aleknavicius, S. Balickas, T. Gertus, A. Michailovas, A.Zaukevicius, **K. Michailovas**, V. Petrauskiene, Building block of picosecond pump laser for large femtosecond OPCPA infrastructure projects , PO-1.16, Europohoton-2016, August 21-26, Viennna, Austria (poster)

14. K. Michailovas, V. Petrauskiene, S. Balickas, A. Michailovas, 85mJ Sub-20 ps Pulses from 1 kHz Chirped Pulse Amplifier based on Nd-doped Laser Crystals, Advanced Solid State Lasers Conference, 1-6 October 2017, Nagoya, Japan, JTu2A.28 (poster)

Thesis summary

Thesis consists of introduction, 5 chapters, and a list of references. Every chapter is ended with conclusions. Thesis consists of 122 pages and contains 94 figures and 5 tables. There are 72 listed references.

1. Solid-state laser amplifiers

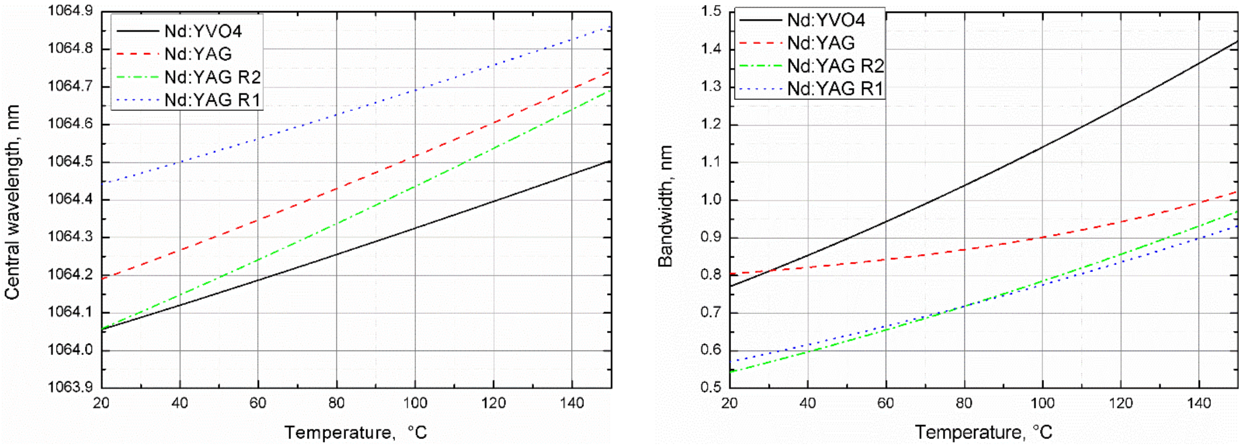

Fig. 1. (Left) central wavelength and (right) bandwidth dependencies on temperature of the active medium for Nd:YVO_4 and Nd:YAG

The first part of this chapter contains a simplified explanation of the lasing process based on the three-level and four-level models. It also includes an overview of solid-state materials used as gain media for lasers. Special emphasis is placed on active media used in experiments described in the work, such as Nd:YAG and Nd:YVO_4. Properties of these materials are compared to properties of Yb:YAG, as it is the main competing technology when it comes to OPCPA pump laser creation. This part also contains discussion of dependence of the spectral properties of Nd:YAG and Nd:YVO_4 on the temperature of the

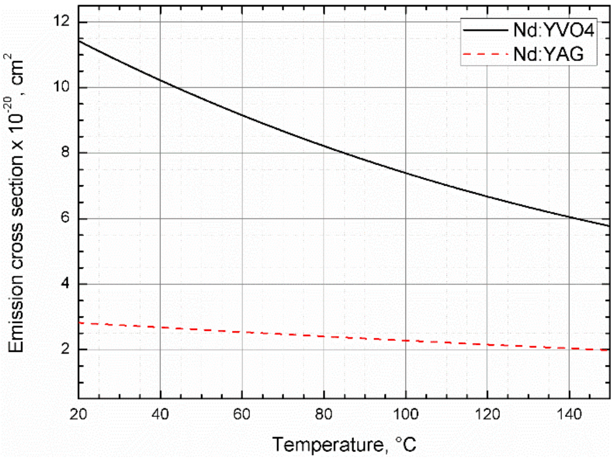

Fig. 2 Emission cross section of Nd:YVO4 and Nd:YAG dependencies on active medium temperature

active medium. Dependence of central wavelength (Fig. 1 left), spectral bandwidth (Fig. 1 right), spectral shape and emission cross section (Fig. 2) on the temperature of the active medium is shown graphically. These properties of the materials are important for projecting the performance of the system and estimating the possibilities of tuning the spectrum by temperature control in a chirped pulse amplification based (CPA) laser system.

Next, pulse amplification is discussed based on the Frantz-Nodvik formula (1). Dependence of the efficiency of amplification on the amplified pulse duration is mentioned.

$$E_{out} = E_s \ln\left\{1 + \left[exp\left(\frac{E_{in}}{E_s}\right) - 1\right] exp(g_0 l)\right\} \tag{1}$$

Radiation self-action and methods of its reduction are discussed. B-integral parameter is introduced as a measure of evaluating the self-action of the radiation (2).

$$B = \frac{2\pi}{\lambda\tau}\int n_2\, I(z)dz \tag{2}$$

Thermal effects, such as thermal lensing and depolarization, in a rod shaped Nd:YAG active medium are described.

Lastly, concept of chirped pulse amplification (Fig. 3) is discussed.

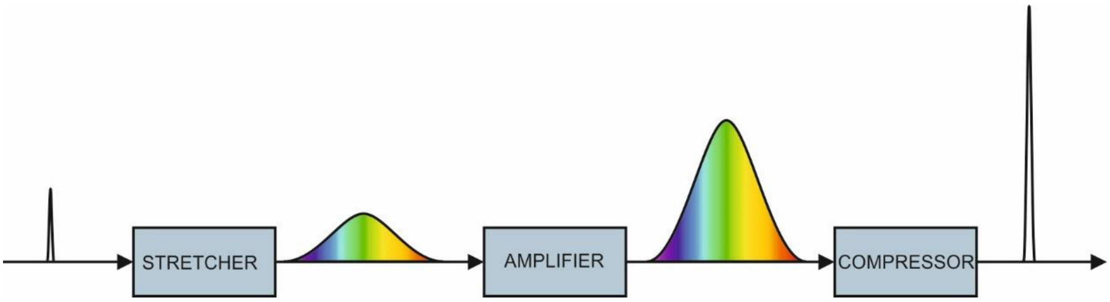

Fig. 3. The concept of chirped pulse amplification

2. Depolarization compensation and choosing the amplifier layout

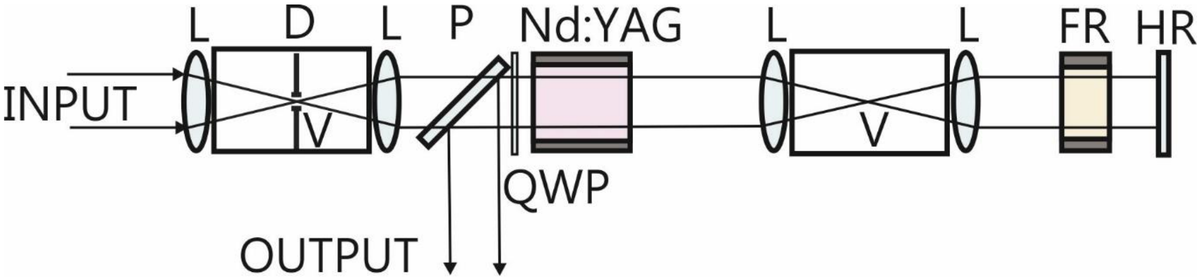

Fig. 4. Layout of an effective compact double-pass amplification stage. L – lens, D – aperture, V – vacuum cell, P – polarizer, QWP – quarter wave plate, FR – Faraday polarization rotator, HR – high reflectivity mirror.

This part describes the experiments aimed at finding the most efficient layout of an amplification stage, which would allow to control and compensate the thermal effects, such as thermal lensing and thermally induced birefringence, while also reducing the radiation self-action due to nonlinear effects. The result is an effective compact double pass amplification stage (Fig. 4), which could be used as a building block for a high average power amplification system working at 1 kHz repetition rate and allows easy power scaling. Thanks to a combination of relay imaging telescope and 45° Faraday polarization rotator after double pass through the amplification module the optical path difference experienced by tangential and radial polarization components, caused by thermally induced birefringence, is compensated. This minimizes the energy losses and modulation of output intensity distribution caused by depolarization (Fig. 5). Use of a quarter wave plate before the amplification module reduces the nonlinear self-action experienced by the radiation during amplification 1.5 times, as its polarization is circular when passing through the active medium [27].

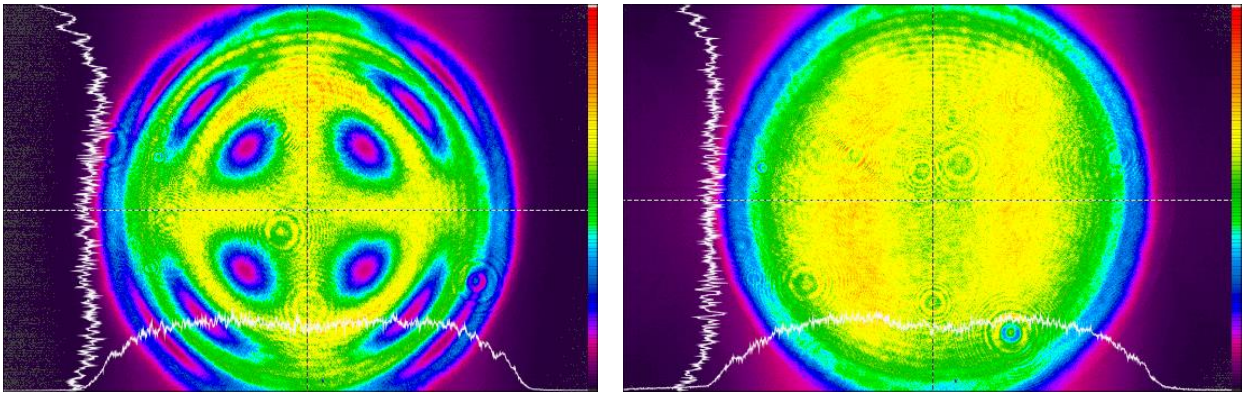

Fig. 5. Comparison of beam profiles at the output of a double pass amplification stage (left) without depolarization compensation and (right) with depolarization compensation by a Faraday polarization rotator and relay imaging telescope.

A variation of the mentioned double pass amplification stage allowing the reduction of heat load on a Faraday polarization rotator is also presented (Fig. 6). In this layout two amplification modules are placed consequently in a double pass amplification stage, with additional relay imaging and a 90° polarization rotator between the modules. This provides similar output power to the one that could be achieved with two separate amplification stages, but with lower average power going through the Faraday rotator. This also reduces the non-linear phase shift accumulated in the system.

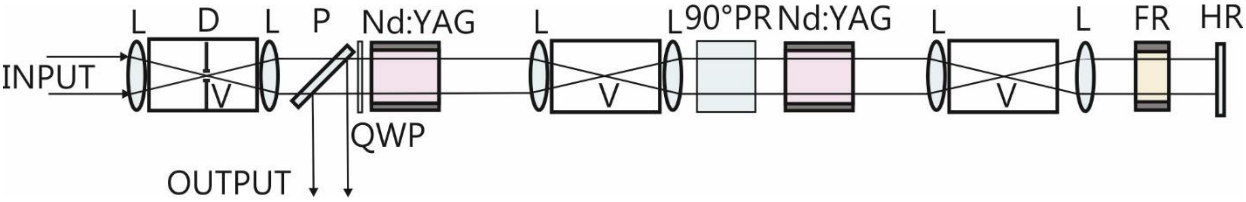

Fig. 6 Variation of the layout of an effective compact double-pass amplification stage aimed to reduce the heat load on the Faraday rotator. L – lens, D – aperture, V – vacuum cell, P – polarizer, QWP – quarter wave plate, 90°PR – 90 degree polarization rotator, FR – Faraday polarization rotator, HR – high reflectivity mirror.

3. Beam formation for amplifiers

The importance of the beam spatial intensity distribution is discussed in this chapter of the thesis: increase of the fill factor is shown for use of super Gaussian intensity distribution (3), where N is an even number starting from 2 (N=2 gives Gaussian intensity distribution).

$$I(r,w) = I_0 exp\left[-2\left(\frac{r}{w}\right)^N\right] \tag{3}$$

Modelled spatial distribution of nonlinear phase shift is presented (Fig. 7). It is shown how the peak nonlinear phase shift accumulated by a beam with intensity distribution described by a 14th order super Gaussian function is 1.7 times smaller than for a Gaussian beam with the same 1/e^2 diameter. Taking into account the fact that a beam with intensity distribution described by a 14th order super Gaussian function could be used with an active medium of the same diameter, a total reduction of 4.9 times in accumulated phase shift is achieved comparing to a beam with a Gaussian intensity distribution. Also this is an illustration of how, due to a more homogeneous distribution of nonlinear phase shift over the cross-section of the beam, a super Gaussian beam is less prone to large scale self-focusing.

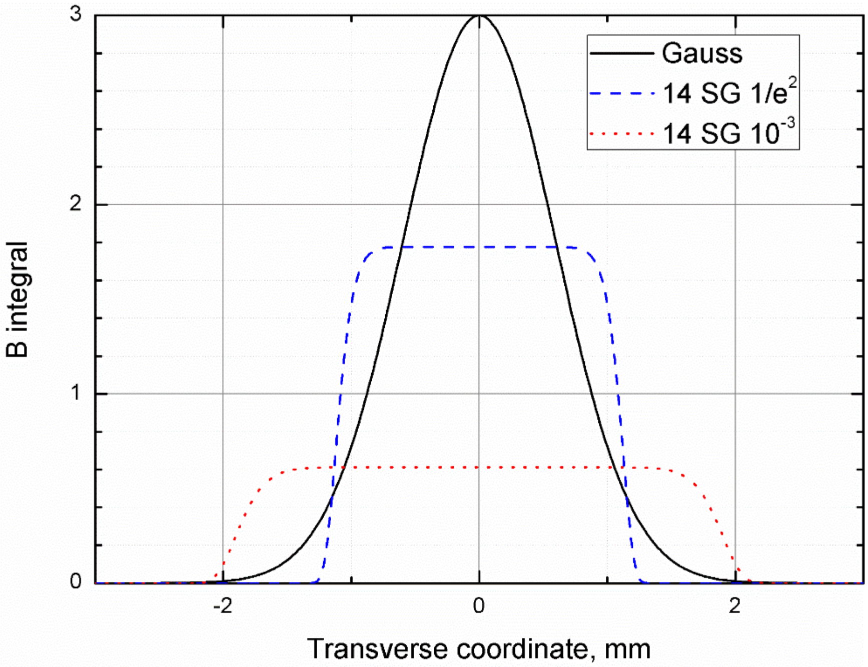

Fig. 7. Modelled axial non-linear phase shift distribution over the cross-section of the beam for several different beam intensity distributions: Gaussian intensity distribution, 14th order super Gaussian intensity distribution of the same 1/e^2 diameter as the Gaussian, and 14th order super Gaussian of the same diameter at 10^{-3} intensity level as the Gaussian.

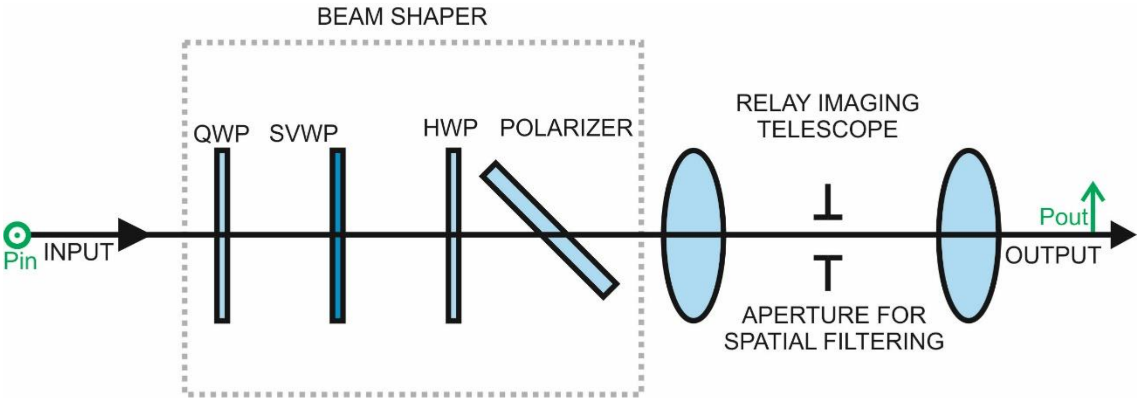

Fig. 8. Layout of beam shaper based on spatially variable wave plate. QWP – quarter wave plate, SVWP – spatially variable wave plate, HWP – half wave plate.

A short overview of beam formation methods is given afterwards. Then, a novel formation method using spatially variable wave plate (SVWP) produced by nanogratings inscription in fused silica by femtosecond light pulses is presented. The layout of such beam shaper is shown in Fig. 8. Together with the polarizer the combination of SVWP and a quarter wave plate acts as a spatially variable attenuator providing a needed transmission function (Fig. 9).

An overview of theoretical parameters achievable using this formation technique follows. Flexibility of the formation method is demonstrated. A concept of using the residual radiation for a separate channel with a Gaussian intensity distribution, thus increasing the total efficiency of the system is presented.

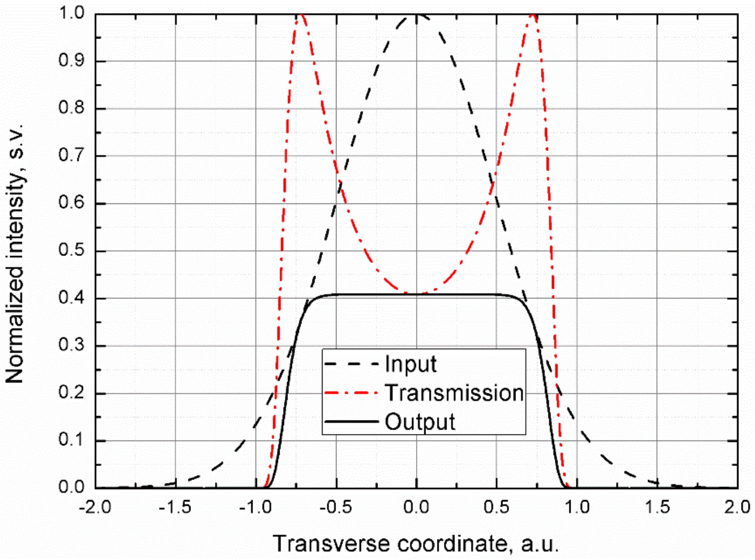

Fig. 9. Theoretical demonstration of the beam shaping process in a spatially variable wave plate based beam shaper. This example is based on an output beam with intensity distribution described by a super Gaussian function of a 14th order.

Fig. 10 demonstrates a beam profile achieved at the output of a high average power amplification system operating at 1 kHz repetition rate producing output power of over 150 W in a single channel. The intensity distribution of the fundamental radiation (Fig.10, a) was transferred almost ideally to the second harmonic radiation (Fig. 10, b) during nonlinear combining of two channels of fundamental radiation. The pulse energy of the second harmonic radiation at 532 nm was ~130 mJ.

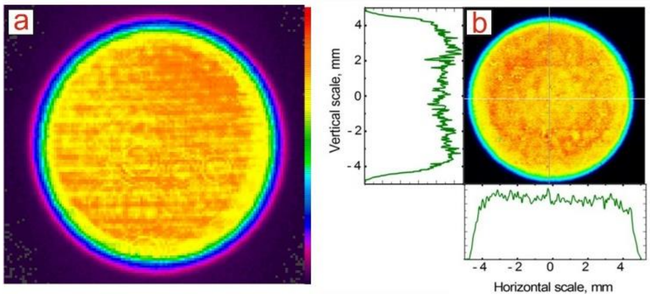

Fig. 10. Demonstration of a super Gaussian beam intensity distribution achieved using the SVWP-based beam shaper: (left) before spatial filtering, showing signs of point-to-point production technology and (right) at the output of a amplification system after 2nd harmonic generation

4. Picosecond pulses amplifier (non-chirped pulses)

This chapter presents the results of experiments aimed at creating an OPCPA pump source with pulse duration in the region of ~50 – 100 ps.

“Foxtrot” laser manufactured by “EKSPLA”, producing 1 mJ 50 ps pulses at 1 kHz repetition rate was used as the seed for the amplification system.

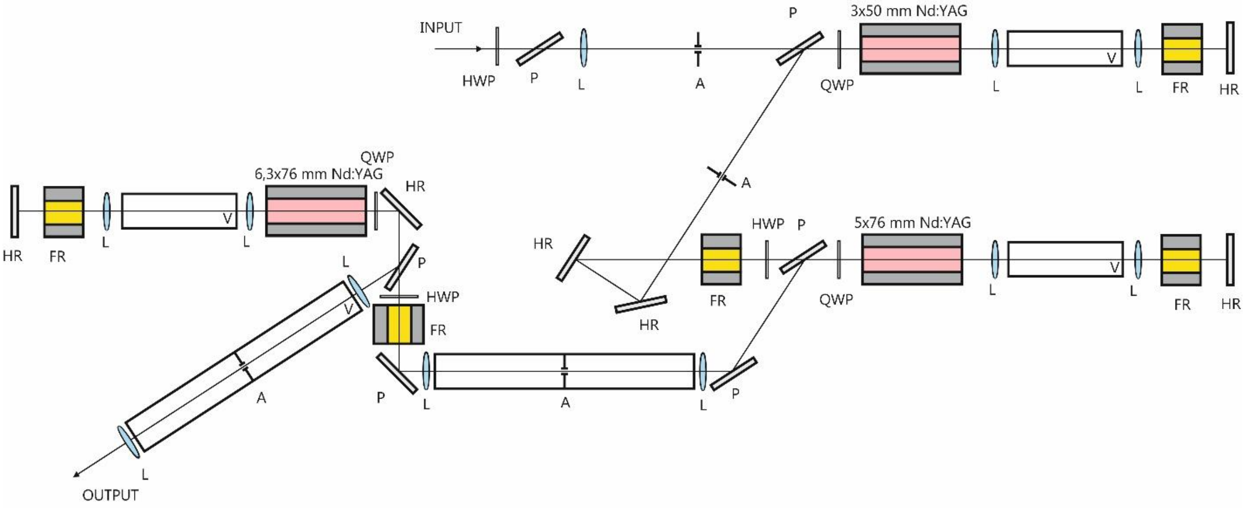

Fig. 11. Amplification system layout. HWP – half wave plate, P – polarizer, L – lens, A – aperture, QWP – quarter wave plate, V – vacuum chamber, FR – Faraday polarization rotator, HR – high reflectivity mirror.

Amplification system consisted of three double-pass stages, employing diode side-pumped amplification modules with active media of 3, 5 and 6.3 mm in diameter (Fig. 11). The 3 mm diameter module was produced my Monocrom (Spain) and generated 0.9 kW of peak pump power. The 5 and 6.3 mm modules were produced by Cutting Edge Optronics (USA) and both produced about 6 kW of peak pump power. Beam formation using radially varying gain of the amplification modules was realized, using spatial

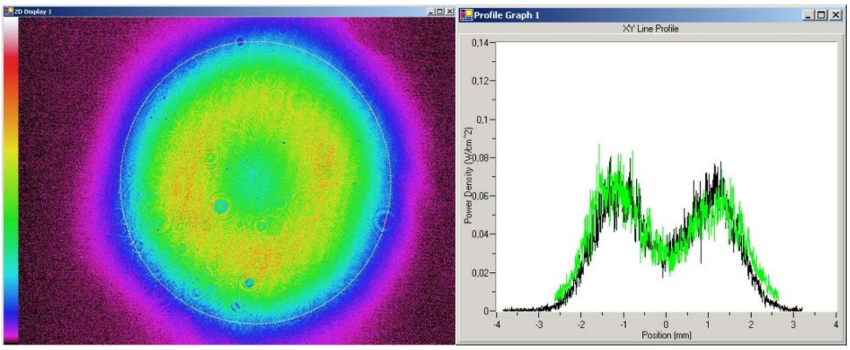

Fig. 12. Beam intensity distribution with a dip in the middle, pre-formed for amplification by spatial filtering

filtering to pre-shape the beam intensity distribution (Fig. 12). The dip in the center of the intensity distribution was compensated by higher gain in the center of the active medium.

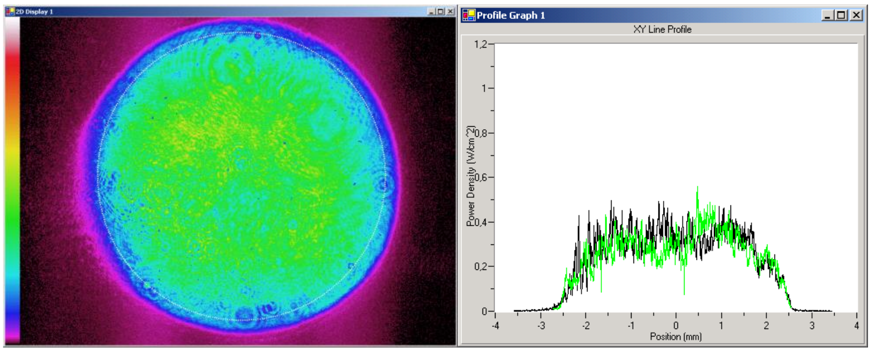

Fig. 13. Intensity distribution at the output of the amplification system.

Intensity distribution at the output of the amplification system was quite homogeneous, resembling a super Gaussian function (3) of the 6th order (Fig. 13). Output pulse energy of 80 mJ was achieved. Beam quality was characterized by measuring the M2 parameter of the beam, its value was ~6.2.

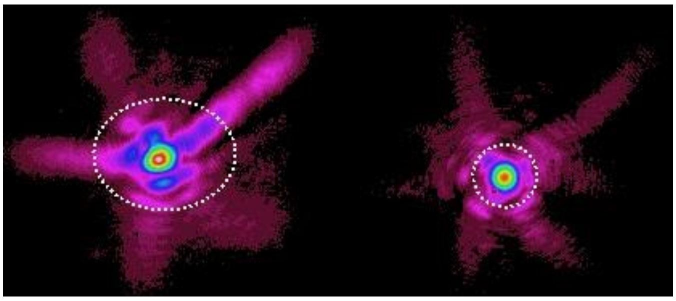

Fig. 14. Far field intensity distributions of the beam with (left) the flexible mirror switched off and (right) with optimum voltages applied to the flexible mirror.

Experiments were carried out that proved that beam intensity distribution was not the source for beam deterioration, rather the pump geometry was the culprit. One of the ways to improve beam profile is spatial filtering. Experiments showed that while spatial filtering could be used to improve the quality of the beam in our setup, it was far too inefficient,

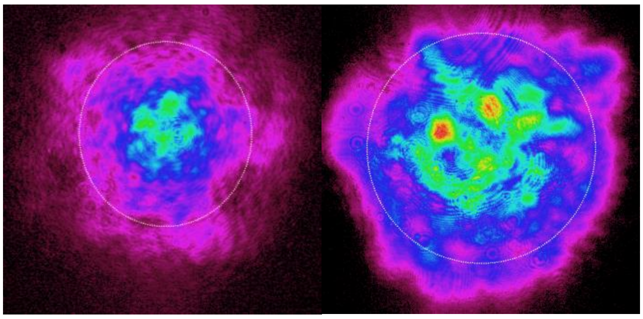

Fig. 15. Beam intensity distribution at different planes between the near field and the far field of the beam.

with losses of over 50%, due to the complex intensity distribution in the focal plane of the beam (Fig. 14, left)

Use of adaptive optics has potential for enhancing the focusability of the beam. Flexible mirror of 15 mm in diameter produced by Flexible Optical B.V. was tested as a tool for improving the quality of the beam. The results were not as good as expected. The value of M^2 was only improved to about 4.2. While there was noticeable improvement of the intensity distribution in the focal plane (Fig. 14), beam profile was distorted in the planes between the near field and the far field of the beam (Fig. 15). A conclusion, that it is not practical to compensate beam distortions by correcting wave front by adaptive optics in the middle of the amplifier chain has been made. If a tightly focused beam is required, it is more practical to correct the wave front of the beam right before focusing the beam on the specimen.

5. Chirped pulse amplification

This chapter of the dissertation starts with some theoretical justification for using chirped pulse amplification technology. Results of some simple calculations on safe energy limits for some actual real laser modules are presented in the form of a table (Table 1). It can be seen, that with longer pulse durations higher output pulse energies could be achieved from active media of a given diameter, thus, a larger part of the accumulated population inversion could be used, increasing the efficiency of the amplification system. One can also see that to extract accumulated inversion efficiently, the input pulse energy has to be comparable to the value of the accumulated inversion.

Table 1. Theoretical efficiency of extraction of accumulated population inversion during double-pass amplification in some laser modules used in our experiments. D – diameter of the active medium, L – length of the active medium, τ – pulse duration, E_{lim} – safe output pulse energy limit in respect of radiation self-action, E_{in} – input pulse energy required to reach the safe output pulse energy, E_{inv} –population inversion accumulated in the active medium, η – ratio of used population inversion to total population inversion accumulated in the active medium.

D x L, mm	**τ, ps**	**E_{lim}, mJ**	**E_{in}, mJ**	**E_{inv}, mJ**	**η**
x50	20	13	2.42	45	0.235
3x50	150	59	27.76	45	0.383
3x50	300	103	69.56	45	0.743
5x76	20	37	2.98	181	0.188
5x76	150	157	39.18	181	0.651
5x76	300	245	111.68	181	0.737
6,3x76	20	42	8.78	181	0.183
6,3x76	150	212	93.5	181	0.655
6,3x76	300	364	230	181	0.740

The next part of the chapter describes the experiments employing CPA technology. Initial experiments were devoted to proving the feasibility of using CPA technology for ps pulses amplification in an Nd:YAG amplifier. In the experiments we used an Yb doped fiber based mode-locked fiber seed laser. Its pulses were stretched to ~600 ps using a 2000 ps/nm chirped fiber Bragg grating (CFBG) stretcher, The oscillator used as the seed source for these experiments had two outputs at two different wavelengths: one broadband at

1030 nm, and another narrowband at 1064 nm. The 1030 nm output pulses were compressible down to 300 fs pulse duration. This would allow for full optical synchronization of seed and pump pulses of an OPCPA system.

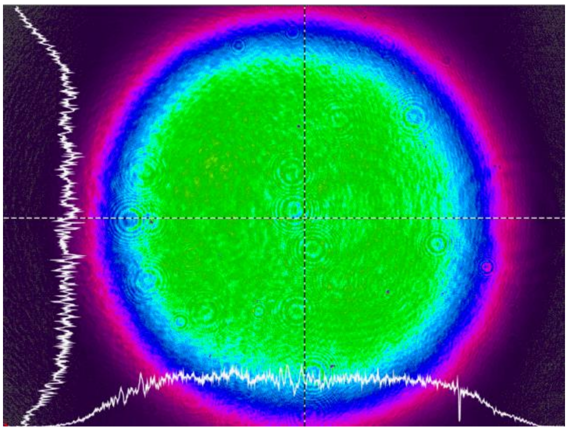

Fig. 16. Beam profile after SVWP based beam shaper. 6th order super Gaussian function.

The 1064 nm pulses stretched by the CFBG were then amplified by an $Nd:YVO_4$ active medium based regenerative amplifier (RA) to ~3 mJ energy. The neodymium doped yttrium orthovanadate active medium was used intentionally in the RA, to achieve broader spectrum of the amplified pulses, than it would be possible using Nd:YAG. The spatial intensity distribution of the beam was then shaped to a super Gaussian function of the 6th order (Fig. 16) by spatially variable wave plate (SVWP) based beam shaper with efficiency of over 50%.

Further amplification after beam shaping was carried out in two double-pass amplification stages (Fig. 17).

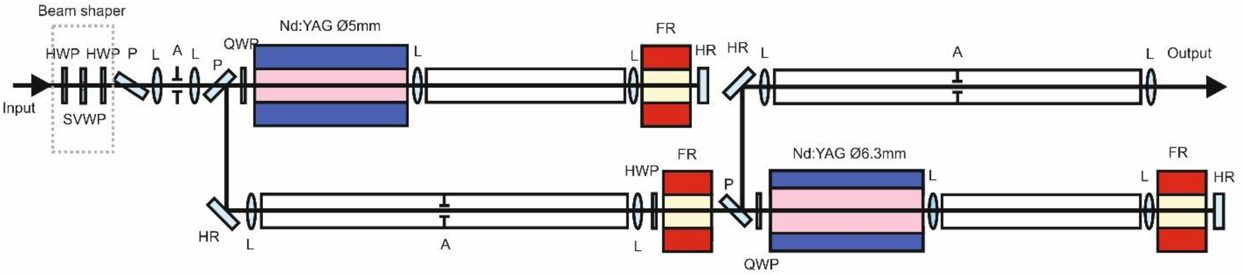

Fig. 17. Layout of the two double-pass stages of the amplification system. SVWP – spatially variable wave plate, HWP – half wave plate, P – polarizer, L – lens, A - aperture, QWP – quarter wave plate, FR – Faraday polarization rotator, HR – high reflectivity mirror.

Output energy of 125 mJ was achieved with quite a homogeneous intensity distribution, but after the 2nd amplification stage the beam didn't propagate through free space well enough for it to travel the distance of the compressor, so compression was only tested after

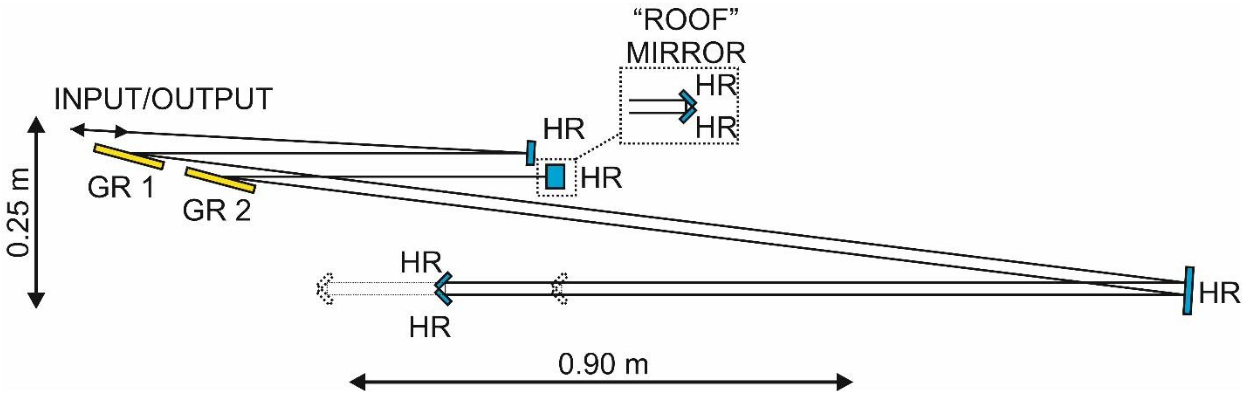

Fig. 18. Layout of the compressor. HR – high reflectivity mirror, GR1, GR2 – diffraction gratings.

the first stage of the power amplifier. A single pass double end-pumped Nd:YVO$_4$ pre-amplifier was used to maximize the output pulse energy of this single stage power amplifier. Beam shaping was also ditched for the same reason. Output pulse energy of 63.5 mJ before compression was achieved. Compressor was based on two diffraction gratings with 550 nm period (1818 lines/mm) manufactured by Fraunhofer IOF (Germany). The distance between gratings was ~3 m and it was folded for compactness (Fig. 18). Total efficiency throughput of the compressor was around 61%, with output pulse energy reaching ~38 mJ. The pulses were compressed to ~18.3 ps duration.

The following part of the chapter describes experiments on optimization of the CPA based system. Several things were done to improve the performance of the setup. The stretcher was changed to a 1000 ps/nm CFBG, as a compromise between reduced stretched pulse duration and consequently larger B integral value in the amplifier and reduced distance between the gratings in the compressor. The shorter distance travelled by the beam reduced the influence of diffraction on its intensity distribution. In the modified amplifier the beam shaper was changed to 14th order super Gaussian, as a compromise between larger fill

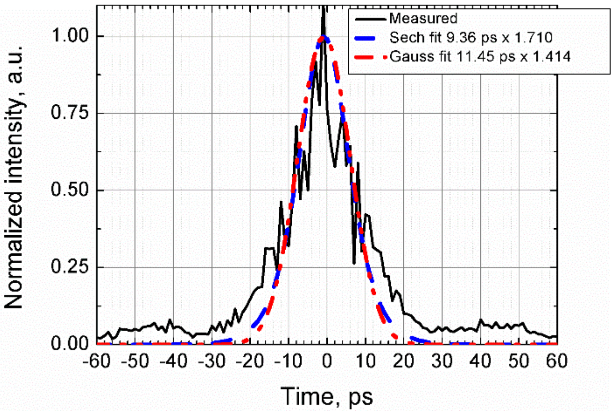

Fig. 19. Compressed pulse autocorrelation function with Gaussian and hyperbolic secant fits.

factor, and the distance the beam is able to travel without experiencing severe intensity profile modulation due to diffraction. To increase that distance even more the beam can was magnified about 4 times after the amplification system to a diameter of around 20 mm and relay imaged to the middle of the compressor and then relay imaged from that plane to the output of the system. The relay imaging helped preserve the spatial intensity distribution of the beam. Diffraction gratings of larger dimensions (60 mm x 150 mm) were required due to the increased dimensions of the beam. These were manufactured by Fraunhofer IOF (Germany). A new method for preservation of chirped pulse spectrum during amplification in a saturated amplifier was realized. The bandwidth of the pulses during amplification was preserved by tuning the central wavelength of the signal at the input of the amplifier setup. This was done by controlling the temperatures of the Bragg grating inside the mode-locked fiber oscillator and the chirped fiber Bragg grating used as the stretcher.

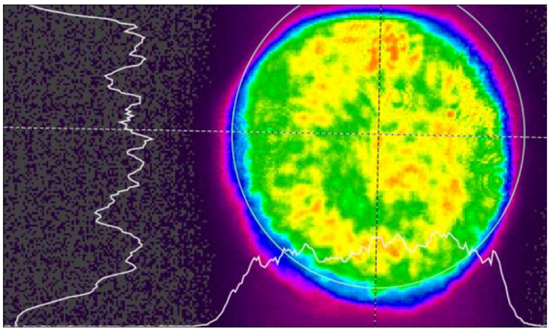

Fig. 20. Intensity distribution at the output of the system after pulse compression.

All of these modifications, allowed us to preserve the initial seed pulse spectrum after all stages of amplification. Pulse energy at the output of our amplification system after compression reached 85 mJ (compression efficiency of ~66%). Sub-20 ps pulse duration was demonstrated. (Fig. 19). A quite homogeneous output beam profile was achieved (Fig. 20). In conclusion, a new technique for obtaining sub-20 ps pulses with a homogeneous super Gaussian beam profile and up to 85 mJ pulse energy was demonstrated in an Nd:YAG based amplifier system operating at 1 kHz repetition rate.

Main results and conclusions

1. Double pass amplification stage employing relay imaging between the active medium and the back reflecting mirror and a 45 degree Faraday polarization rotator is well suited for depolarization compensation in an amplification system using high average pump power amplification modules utilizing naturally non-birefringent active media. Using this amplifier layout depolarization losses are reduced to only a couple of percent. Accumulated population inversion is used more efficiently than in a traditional single pass through two amplification modules with active media working in same conditions layout.
2. A variation of this amplification stage using double-pass through two consequently placed laser modules, instead of a single laser module, with a 90 degree polarization rotator between the amplification modules, two relay imaging telescopes, between the amplification modules and between the amplification module and the back reflecting mirror, and a 45 degree Faraday polarization rotator, allows for efficient depolarization compensation and reduces the thermal load on the Faraday rotator.
3. An easy to setup and flexible super Gaussian beam shaping method, employing nanogratings formed in fused silica by femtosecond pulses, demonstrating high efficiency (up to 50% total throughput) was proposed and implemented in real high average power laser amplifier systems operating at 1 kHz repetition rate. Optical elements used to implement this beam shaping method demonstrate high resistance to both average and peak powers.
4. Using three double pass amplification stages employing depolarization compensating using relay imaging and 45 degree Faraday polarization rotator, 1 mJ 50 ps pulses were amplified to 80 mJ at 1 kHz repetition rate, while quite homogeneous output beam profile, well suited for OPCPA pumping was achieved.
5. Output beam quality (described by M^2 parameter) of a laser amplifier system employing high average pump power side pumped laser modules shows weak dependence on the intensity distribution of the amplified beam, but strongly depends on thermal lens aberrations, which are mainly determined by amplification module pumping geometry.

6. Use of adaptive optics doesn‘t offer great improvement of beam quality at the output of a high average power laser amplifier system with a highly aberrated thermal lens of high optical power and has detrimental side effects on beam intensity distribution during free space propagation.
7. Chirped pulse amplification technique allows to generate high energy pulses of short durations, which would be very problematic to amplify directly, using active media of relatively small diameters, even using narrow bandwidth gain media such as Nd:YAG or Nd:YVO_4.
8. During amplification of chirped pulses, tuning of the central wavelength of the seed radiation, and/or central wavelength of the gain line of any of the individual active media used in the system, allows to preserve broad bandwidth of output pulses, compressible to durations of under 20 ps. This tuning can be done by implementing temperature control.
9. Optimization of parameters of a CPA layout and utilization of relay imaging into and out of the compressor allows to achieve super Gaussian beam intensity distribution, well suited for OPCPA pumping, at the output of a relatively compact laser amplification system.
10. Output pulses of 130 mJ of energy and ~150 in duration were achieved using the described amplification system. After compression with efficiency of 66%, pulses of 10-20 ps in duration were achieved with 85 mJ energy.

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Santrauka

Disertaciją sudaro 5 skyriai ir literatūros sąrašas. Kiekvieno skyriaus pabaigoje yra pateikiami pagrindiniai to skyriaus rezultatai ir išvados. Disertacijos apimtis yra 122 puslapiai, joje yra 94 iliustracijos ir 5 lentelės. Literatūros sąrašą sudaro 72 pozicijos.

Pirmame disertacijos skyriuje yra pateikiama literatūros apžvalga. Kituose keturiuose skyriuose yra aprašomi eksperimentiniai darbai.

Disertacijoje yra aprašomi eksperimentai, kurių tikslas buvo sukurti lazerinę sistemą gerai tinkamą optinio parametrinio čirpuotų impulso stiprintuvo (angl. *Optical Parametric Chirped Pulse Amplification – OPCPA*) kaupinimui. Tokia lazerinė sistema turi išsiskirti didele impulso energija (darbe siekta 100 mJ vertės) aukštu pasikartojimo dažniu (darbe aprašomi eksperimentai sistemai dirbant 1 kHz pasikartojimo dažniu) ir homogenišku erdviniu intensyvumo skirstiniu. OPCPA sistemoms kaupinti priklausomai nuo norimų išėjimo parametrų gali būti tinkami skirtingų trukmių impulsai.

Antrame disertacijos skyriuje aprašomi eksperimentai, kurių tikslas buvo pasirinkti efektyviausią stiprinimo sistemos optinių elementų išdėstymą, kuris leistų suvaldyti parazitinius šiluminius reiškinius susijusius su aukšta vidutine kaupinimo galia, tokius kaip šiluminis lęšis ir pluošto depoliarizacija.

Trečias disertacijos skyrius pristato naują homogeniško erdvinio intensyvumo skirstinio (aprašomo super Gauso funkcija) formavimo metodą naudojant nanogardelių įrašomų kvarciniame stikle femtosekundiniais impulsais savybes.

Ketvirtas disertacijos skyrius aprašo lazerinę sistema stiprinančią ~50 ps trukmės impulsus. Tokios sistemos išėjime pavyko gauti 80 mJ išėjimo impulso energiją. Šiame skyriuje taip pat aprašomi eksperimentai, kurių tikslas buvo pagerinti didelės vidutinės kaupinimo galios šoninio kaupinimo stiprintuvo išėjimo pluošto kokybę. Tam tikslui panaudojamas erdvinis filtravimas ir deformuojamas veidrodis.

Penktame disertacijos skyriuje aprašoma sistema sukurta su tikslu gauti 10–20 ps trukmės impulsus. Tam tikslui, siekiant išvengti netiesinės pluošto saviveikos buvo panaudota čirpuotų impulsų stiprinimo technologija (angl. *Chirped Pulse Amplification – CPA*). Gauta ~85 mJ išėjimo impulso energija ir 10 ps eilės išėjimo impulso trukmė. Vaizdo

pernešimo su pluošto didinimu prieš kompresorių panaudojimas leido sistemos išėjime po impulsų spūdos išsaugoti homogenišką erdvinį intensyvumo skirstinį.

Asmeniniai duomenys (Personal information)

1988 07 29 – gimimo data (date of birth)

2007 – baigė Vilniaus „Juventos“ gimnaziją (finished Vilnius „Juventos“ gymnasium)

2011 – įgijo fizikos bakalauro (taikomoji fizika) laipsnis Vilniaus universitete (bachelor‘s degree in Physics (Applied physics) at Vilnius University)

2013 – įgijo medžiagų inžinerijos (lazerinė technologija) magistro laipsnį Vilniaus universitete (master‘s degree in material engineering (laser technology) at Vilnius University)

2009–2011 – dirbo techniku Fizikos institute (technician at Institute of Physics)

2011–2013 – dirbo inžinieriumi Fizinių ir technologinių mokslų centre (engineer at Center for Physical Sciences and Technology)

2011–... – dirba inžinieriumi UAB „Ekspla“ (engineer at „Ekspla“)