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HIGH ENERGY BROAD BANDWIDTH OPTICAL PARAMETRIC CHIRPED PULSE AMPLIFICATION

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Introduction

After 50 years since the first laser was demonstrated [1] it becomes quite obvious that it was one of the greatest inventions of the last century. Laser technology improved drastically over years, it found its way to various areas of application and still new techniques are being discovered. Lasers are now widely used in IT and communications, manufacturing industry, material processing, metrology and biomedicine. The laser has acquired a significant place in the world of science: due to unique properties of coherent light new branches of microscopy and spectroscopy emerged, lasers are used for investigation of optical damage, light and matter interaction, nonlinear matter response, and also for development of new photonic devices.

Due to achievements in laser science and nonlinear optics, the available intensities of coherent radiation increased significantly over time. The main breakthrough was the invention and development of CPA (chirped pulse amplification) [2] and OPCPA (optical parametric chirped pulse amplification) [3, 4] techniques.

Once terawatt (TW) level intensities of ultrashort laser pulses were achieved, new range of applications became available in high field physics [5], generation of high order harmonics and isolated attosecond pulses [6], investigation relativistic optics effects in few optical cycle regime [7], electron acceleration in light field [8], etc. Therefore, development of compact and reliable TW-scale laser systems is a very important task, as such systems ensure faster progress in the above-mentioned new fields of science.

Main objectives of this thesis were to investigate optical parametric amplification of broadband seed pulses in femtosecond and picosecond regimes and to develop and optimize a compact TW-scale OPCPA system intended for applications in various areas of high-field physics.

Main tasks include:

- Characterization of spatial and temporal properties femtosecond Yb:KGW and picosecond Nd:YAG laser pulses, including measurements of output pulse temporal contrast ratio. Development and investigation of dual active element Yb:KGW regenerative amplifier. Optimization of direct optical synchronization of Yb:KGW and Nd:YAG amplifiers.

- Generation of white light continuum in bulk material, employing Yb:KGW laser, and using it as a seed for broadband optical parametric amplifier.
- Investigation and optimization of broad bandwidth optical parametric amplification. Investigation of pump and signal pulse front mismatch impact on amplified pulse spatial characteristics in noncollinear setup.
- Numerical calculations of temporal dispersion parameters in various optical elements and optimization of pulse stretching and compression setup. Measurements of pulse phase characteristics, estimation of higher order dispersion in the system and its compensation by means of acousto-optic programmable dispersive filter.

Innovations in this work

A new approach for power scaling of regenerative amplifiers by use of multiple active elements in prolonged resonator was verified, resulting in almost double output power of Yb:KGW regenerative amplifier.

Direct optical synchronization of Yb:KGW and Nd:YAG amplifiers was performed by implementation polarizing spectrum splitter at the output Yb:KGW oscillator to ensure the maximum seed energy for both amplifiers.

An Yb:KGW laser pumped system of white light continuum generator and noncollinear optical parametric amplifier was proposed and demonstrated as a source of broadband relatively high energy pulses at 800 nm central wavelength. Also the compressibility of these pulses to sub-10 fs duration has been verified.

A concept of stepwise increased pulse duration in multistage OPCPA has been proposed and demonstrated, promising high contrast and high energy few cycle output pulses.

Practical benefits

The concept of multiple active elements in single resonator is applicable for increasing average output powers of commercial short pulse laser systems.

It is shown that femtosecond Yb:KGW laser driven white light continuum generator and noncollinear parametric amplifier system might be a good alternative for conventional Ti:sapphire systems in few cycle pulse regime at 800 nm wavelength.

A table-top TW-scale system was developed, which can be applicable for research in various fields of physics and technologies. The proposed setup ensures long-term stability and compact dimensions. No fiber technology is applied in this system, making it tolerant to mechanical and thermal fluctuations.

Major part of presented results and technological innovations will be implemented in development of „NAGLIS“ – the ultrashort pulse laser facility for national and international access.

Statements to defend:

1. Employing of several active elements in regenerative amplifier allows for distributing the thermal load. This approach allows for increasing the output power of regenerative amplifier without deteriorating beam quality or stability of resonator, which is usually limited by thermooptic effects. Regenerative amplifier with dual active Yb:KGW elements pumped by laser diode arrays (total pump power ~200 W) in symmetrical resonator configuration, exhibited 30 W average output power at 100 kHz repetition rate, and the spectrum of amplified pulses corresponded to sub-300 fs pulse duration.
2. Employing of femtosecond Yb:KGW system for generation of white light continuum and its further optical parametric amplification in BBO crystal in non-collinear setup allows for generation broadband (680-950 nm) pulses of energies up to tenths of microjoules. Such pulses can be compressed down to sub-10 fs durations by implementing additional phase control. Suggested approach allows to avoid the difficulties of generating high energy few cycle pulses at 800 nm in conventional Ti:sapphire systems.
3. Non-collinear parametric amplification of highly chirped pulses in case of not matched signal and pump pulse fronts spatial chirp is the dominant phenomenon amongst occurring spatial spectrum distortions of signal pulse. For pulse chirp parameter $\gamma \approx 20$ and the ratio of pulse transversal and longitudinal dimensions close to 10, spatial dispersion $\frac{\Delta x}{\Delta \omega} \approx 1\,{}^{\mu\mathrm{m}}/_{\mathrm{nm}}$ of output signal pulse is observed, while angular dispersion remains negligible.

4. The concept of hybridly pumped multistage optical parametric chirped pulse amplification, comprising of pulse amplification in a sequence of OPA stages with step by step increased pulse duration is promising for generation of high contrast TW peak power pulses and is a good alternative for Ti:sapphire based systems. Based on this concept an OPCPA system was developed, employing optically synchronized femtosecond Yb:KGW and picosecond Nd:YAG lasers, and parametric amplification of ~ 10 nJ continuum pulses to 30 mJ energy have been demonstrated. The spectrum of amplified pulses allows for compression to 9,3 fs duration at 800 nm central wavelength.

The list of author's publications

Publications related to the topic of this thesis:

1. D. Stučinskas, R. Antipenkov, A. Varanavičius, 30 W dual active element Yb:KGW regenerative amplifier for amplification of sub - 500fs pulses, Proc. of SPIE **6731**, 67312Y (2007).
2. D. Stučinskas, R. Antipenkov, A. Varanavičius, Thermal lensing in high-power diode-pumped Yb:KGW laser, Lith J Phys **50** (2), 191-199 (2010).
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Other publications:

5. R. Antipenkov, D. Stučinskas, A. Varanavičius, ~5 W output power Q-switched Yb:YAG laser with elliptical mode geometry, Proc. of SPIE 6731, 67312Z (2007).
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7. D. Stučinskas, A. Varanavičius, R. Antipenkov, M. Grishin, J. Kodz, A. Melninkaitis, A. Vanagas, Thermal lens compensation in high average power diode pumped Nd:YVO_4 laser using aspheric mirror, Lith J Phys **49** (4), 433-438 (2009).

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1. R. Antipenkov, D. Stučinskas, A. Varanavičius, ~5 W Output Power Q-Switched Yb:YAG Laser With Elliptical Mode Geometry, ICONO/LAT 2007 conference, Minsk (2007), L01-57.
2. R. Antipenkov, D. Stučinskas, A. Varanavičius, 30 W dual active element Yb:KGW regenerative amplifier for amplification of sub - 500fs pulses, ICONO/LAT 2007 conference, Minsk (2007), L01-56.
3. D. Stučinskas, R. Antipenkov, A. Varanavičius, Didelės vidutinės galios Yb:KGW regeneratyvinis stiprintuvas femtosekundinių impulsų stiprinimui, 37-th Lithuanian National Physics Conference, Vilnius (2007), S4-18.
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5. G. Kuncė, R. Antipenkov, N. Leonyuk, V. Maltsev, A. Varanavičius, V. Sirutkaitis, Lazerinio Yb:$YAl_3(BO_3)_4$ kristalo generacinių savybių tyrimas, 37-th Lithuanian National Physics Conference, Vilnius (2007), S4-25.
6. D. Stučinskas, R. Antipenkov, A. Varanavičius, Termolęšio tyrimas diodinio kaupinimo Yb:KGW lazeriuose su skirtingos optinės orientacijos aktyviais elementais, 38-th Lithuanian National Physics Conference, Vilnius (2009), S4-31.
7. R. Antipenkov, A. Varanavičius, A. P. Piskarskas, Superkontinuumo spinduliuotės, generuojamos femtosekundiniais impulsais safyro bei lydyto kvarco bandiniuose, sklidimo parametrų tyrimas, 38-th Lithuanian National Physics Conference, Vilnius (2009), S4-63.
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15. J. Adamonis, R. Antipenkov, Kolenda, A. Michailovas, A. Piskarskas, A. Varanavicius, Picosecond high power Nd:YAG amplifier system for OPCPA pump, 14th Laser Optics conference, St.Petersburg, Russia (2010) WeR1-p44.
16. J. Adamonis, R. Antipenkov, J. Kolenda, A. Michailovas, A. P. Piskarskas, A. Varanavičius, Clean 100 ps Pulse Formation and Contrast Enhancement in fs Yb:KGW Oscillator Seeded Nd:YAG Amplifiers, The 4th EPS-QEOD Europhoton Conference 2010, Hamburg (2010), ThP25.
17. R. Antipenkov, A. Varanavicius, J. Adamonis, A. Piskarskas, Development of Sub-10-fs 30 mJ Compact OPCPA System Driven by fs Yb:KGW and ps Nd:YAG Tandem Pump Sources, The 4th EPS-QEOD Europhoton Conference 2010, Hamburg (2010), ThC7.

Author contribution

Author performed or co-performed all experimental research and data processing, carried out numerical modeling of pulse stretching and compression, participated in interpretation of results and discussions, preparation of publications and presented results at conferences.

Contribution of co-authors

A. P. Piskarskas formulated new ideas and tasks for experiments, participated in interpretation of experiments, preparation of publications and conference presentations.

A. Varanavičius contributed in developing of experimental measuring setups, formulated tasks for experiment optimization, participated in discussions, interpretation of experiment results, preparation of publications and conference presentations.

A. P. Stabinis ir **V. Pyragaitė** carried out numerical and analytical investigation of specific cases of optical parametric amplification, participated in preparation of publications.

R. Butkus consulted on particular aspects of broad-band parametric amplification and compensation of pulse dispersion, participated in preparation of publications.

A. Zaukevičius carried out three-dimensional numerical simulations of non-collinear parametric amplification in case of sub-picosecond pulses, contributed to investigation of causes of spatio-temporal pulse distortions.

D. Stučinskas contributed in research of thermal lensing in diode pumped lasers, investigation of prospects of athermal Yb:KGW crystal orientation for high power diode pumped lasers, participated in testing of multiple active element concept, preparation of publications and conference presentations.

Thesis summary

The thesis comprises of introduction, four chapters, summary of main results and the list of references. Thesis is presented in 112 pages, contains 69 figures and 3 tables.

In the **first chapter** the topics of dissertation research and key elements of OPCPA system to be developed are discussed, advantages and disadvantages of proposed approach are analyzed and compared with achievements of other groups on this topic.

The development of reliable laser sources producing ultrashort light pulses of extreme parameters is the one of main factors advancing new research in already established and emerging fields of science. OPCPA since its first demonstration in 1992 [3] became widely recognized and rapidly developing optical pulse amplification technology allowing for generation of broad bandwidth pulses which could be compressed down to duration corresponding to few oscillations of carrier frequency and providing in this way ultrahigh peak powers.

Ti:sapphire lasers provide wide amplification bandwidth and pulse durations of less than 10 fs can be easily achieved in mode-locked oscillators. However, further amplification of these pulses in Ti: sapphire amplifiers results in pulse lengthening due to gain narrowing of spectrum, thus the duration of output pulses of Ti:sapphire amplifiers usually exceeds 20 fs.

High energy pulses of durations corresponding to few optical cycles can also be obtained by spectrum broadening of the Ti:sapphire laser output in continuum generator and further amplification in broadband optical parametric amplifier (OPA). However, in this case the continuum pulse exhibits strong modulation in intensity and phase at wavelengths close to fundamental pump (800 nm), and amplified pulses are extremely difficult to compress [9]. For this reason usually the part of the spectrum below or above 800 nm is amplified and compressed. However, the 800 nm wavelength is still of an interest for power amplification in Ti:sapph CPA system for even higher energies. White light continuum, generated by other fundamental wavelength, would not inflict such problem, thus continuum generation by femtosecond Yb-doped laser is important and had to be investigated.

Also, the contrast of generated pulses is of great importance, as many areas of high field and plasma physics require high energy few-cycle pulse sources with temporal contrast, which defined as ratio of light intensity before the pulse and the peak pulse intensity, of the order 10^{-10} at least [10, 11]. OPCPA has shown potential to satisfy these requirements and at present it is the leading technology for high energy few-cycle pulse table-top systems [12-14]. Main effects that can deteriorate the contrast of OPCPA system include generation of parametric superfluorescence and pump intensity noise transmission to signal pulse spectrum [15]. The pump noise is mainly determined by level of amplified spontaneous emission, thus the pump source with low ASE level is required. In order to minimize the superfluorescence generation, higher intensity seed and multiple amplification stages operating at low gain are preferable [16]. Also shorter pulse duration OPA stage may improve the contrast, as the pulse is not stretched too much and remains at high intensity than in picosecond setup.

Based on listed requirements and benefits of implementation of femtosecond Yb-doped laser and advantages of multistage setup, the following scheme of OPCPA system was developed (Fig. 1).

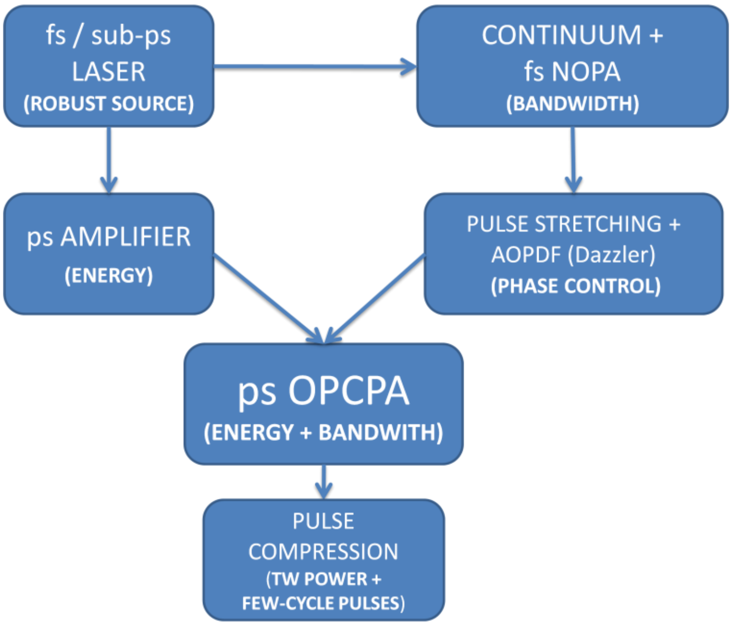

Fig. 1. The main concept of the TW-class table-top system.

The Yb:KGW laser system has shown potential to fulfill all the requirements to be at front end of this system. The picosecond Nd:YAG system has been chosen as a pump source for high energy OPCPA stages as it is well developed and reliable. As of OPA concept in general, a multistage setup was introduced, starting from white light continuum generation and its amplification in femtosecond noncollinear optical parametric amplifier (NOPA) and then proceeding to picosecond high energy OPCPA. The final pulse compression is proposed to be performed in normal dispersion compressor as it exhibits less losses, therefore the stretching of pulses has to be performed it down-chirp setup. Also an additional phase control device, an AOPDF for example, has to be introduced for compensation of higher order dispersion, as it becomes significant if the spectrum of the pulse is broad. Based on this concept the investigation and development of final concept had to be performed.

First of all the development, optimization and synchronization of pump lasers was carried out and the results are presented in the **second chapter** of the thesis. Special attention was taken for investigation of ASE levels in these lasers.

In the first section of this chapter the results on increasing the average output power of Yb:KGW femtosecond regenerative amplifier by introducing multiple active elements is investigated. Thermal load in active element usually is the main factor, which limits the output power of the laser and deteriorates its beam quality. The distribution of thermal load into separate active elements in replicated resonator setup (Fig. 2) raises the upper limit of applicable pump power without affecting the beam quality or resonator stability.

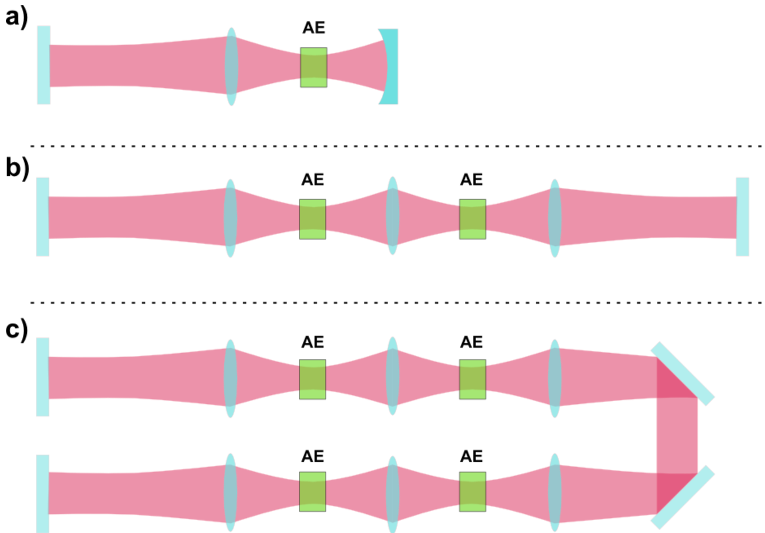

Fig. 2. The concept of implementing multiple active elements (AE) in replicated resonator: a) the original resonator with single AE, b) replicated resonator with two active elements, c) replicated resonator with four active elements.

However, the concept increases the overall complexity of the system, thus it should not be extended to significant number of replicas. The performance of this concept was investigated in diode pumped dual active element Yb:KGW regenerative amplifier setup (Fig. 3). Four 50 W power diode pump modules (LD) were used, which resulted in 200 W total pump power.

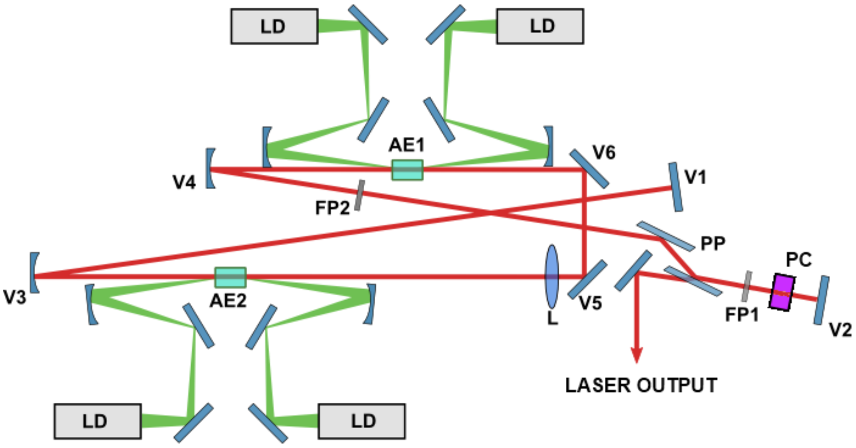

Fig. 3. The setup of dual active Yb:KGW regenerative amplifier. AE1, AE2 – Yb:KGW active elements, LD – laser diode stacks, V1-V6 – resonator mirrors, L – lens, FP1 – λ/4 waveplate, FP2 - λ/2 waveplate, PP – a pair of parallel thin film polarizers, PC – Pockels cell.

In general this setup consists of two resonators, that could function independently, which are joined by replacing their concave end mirrors by a lens (L). This setup was tested in continuous wave, quality switched and regenerative amplification modes. It has been demonstrated that the gain in dual active element resonator is nearly doubled. Femtosecond pulses from Yb:KGW oscillator were stretched and seeded to this regenerative amplifier at 100 kHz repetition rate, which resulted in maximum output power of 30 W and the spectrum of pulses still allowing for ~300 fs duration (Fig. 4).

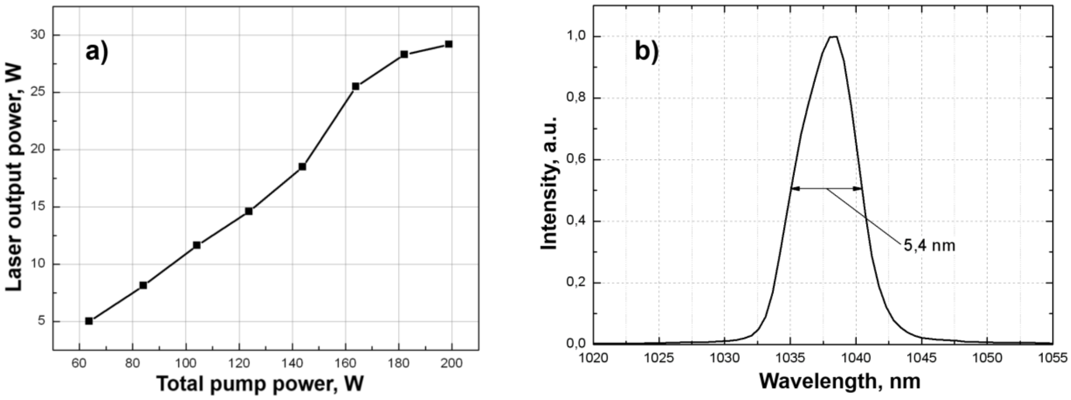

Fig. 4. Regenerative amplifier output parameters: a) the average laser output power versus total pump power; b) the spectrum of amplified pulses at maximum output power.

In spite of achieved results this regenerative amplifier was not employed in main OPCPA system due to several reasons. First of all the OPCPA system would operate at relatively low repetition rates, at which the available pulse energies of Yb:KGW laser would be limited by nonlinear effects, such as Raman scattering, rather than by thermal load. Furthermore, stable operation of this laser is crucial as it is used in the very first stage of the system, and this cannot be expected from the prototype. Therefore commercially available Yb:KGW femtosecond laser was used instead.

In the second section of this chapter results on characterization and optical synchronization of Yb:KGW and Nd:YAG lasers are presented.

One of the advantages of implementing Yb:KGW laser in the system is the possibility of direct optical synchronization without additional spectrum broadening due to partially overlapping emission spectra of Yb:KGW and Nd:YAG. The third order autocorrelation measurements at the output of Nd:YAG regenerative amplifier seeded by Yb:KGW femtosecond oscillator have been performed in order to estimate the ASE level (Fig. 5).

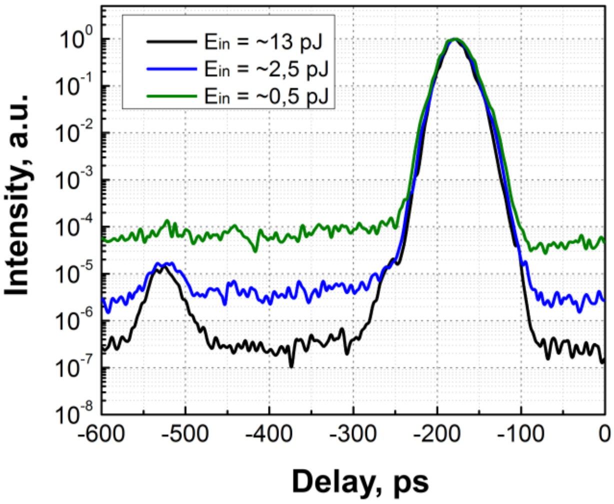

Fig. 5. Third order autocorrelation of Nd:YAG regenerative amplifier output for different seed energies.

The results clearly show that as the seed energy is decreased the ASE level rises drastically. This means that higher energies of seed are preferable.

However, to achieve best performance of both Yb:KGW and Nd:YAG amplifiers the maximum energy of seed has to be provided for both of them at the same time. To ensure this, polarizing spectrum splitter, consisting of specially designed λ/2 waveplate and a polarizing cube, was introduced at the output of Yb:KGW oscillator. This resulted in separation of 1030 nm and 1064 nm wavelengths with maximum efficiency (Fig. 6).

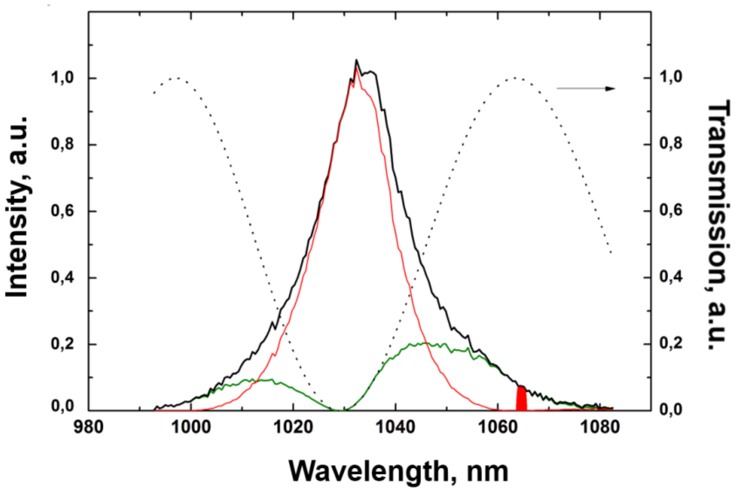

Fig. 6. Separation of Yb:KGW oscillator spectrum for seeding Nd:YAG and Yb:KGW amplifiers. Black curve – oscillator output spectrum; red curve – part of the spectrum for seeding Yb:KGW amplifier; green curve – part of the spectrum for seeding the Nd:YAG amplifier; dotted curve – transmission characteric of polarizing spectrum splitter, red area – the actual spectrum needed for seeding into Nd:YAG.

As for contrast ratio of Yb:KGW laser, the measurement results show that ASE level is ~10^{-8} comparing to the peak pulse. However, multiple peaks at ~10^{-4} intensity level before the main pulse have been detected. The pulses of this laser are intended to use for white light continuum generation and pumping of OPA by second harmonic. In this case the impact of detected pre-pulses should be negligible.

Also the results on measurement beam quality and output pulse durations of both Yb:KGW and Nd:YAG regenerative amplifiers are presented in this section. Also, the main setup and characteristics of flash-lamp pumped Nd:YAG power amplifier are described.

The **third chapter** of the thesis is dedicated to continuum generation and its amplification in noncollinear parametric amplification setup.

At first the investigation of continuum generation in bulk material has been carried out. It has been found out empirically that sapphire crystal performed better than YAG and SiO_2 in terms of smooth spectrum distribution and long-term stability. The supercontinuum spectrum extended from 1030 nm to ~550 nm wavelength (Fig. 7), which is more than enough for seeding the broadband parametric amplifier at 800 nm. Beam quality parameter M^2 of supercontinuum was measured at several wavelengths from 700 nm to 900 nm and its value did not exceed 1,5.

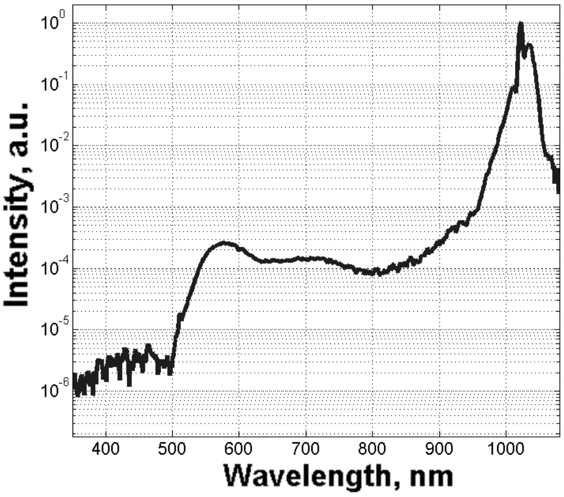

Fig. 7. The spectrum of white light continuum, generated in 4 mm sapphire crystal by 300 fs 2,2 μJ pulses at 1025 nm wavelegth.

Then the optical parametric amplification of broad band seed pulse was investigated. Generally two possibilities for achieving broad bandwidth OPA gain are available: an employment of type I phase-matching in OPA operating close to degeneracy, or the use of noncollinear optical parametric amplifier that can be designed also for non-degenerate broadband pulse amplification [17]. The latter method together with BBO crystals was the obvious decision.

At first, the simple expressions for the case of pump depletion have been derived, which allow for estimation of optimal initial pulse durations. After that an optimization of noncollinear OPA was performed both numerically and experimentally and the results were compared. It has been determined that the broadest spectrum of amplified pulses is achieved at a phase matching angle $\theta = 24{,}7°$, when the noncollinearity angle is $\alpha = 2{,}44°$. Also, a multistage design of the amplifier due to earlier discussed benefits was implemented. In our setup commercially available Yb:KGW laser system (“Pharos”, Light Conversion Ltd.) providing 300 fs pulse duration, 1025 nm wavelength pulses was used both for WLC generation and pumping of successive NOPA at 1 kHz repetition rate (Fig. 8). Part of output pulse was split into continuum generator channel and waveplate-polarizer attenuator and was used to achieve optimum conditions for the continuum generation. A prism compressor had to be introduced before amplification to optimize signal and pump duration ratio. In order to separate the remaining fundamental pulse from continuum, spectral filtering was introduced in the prism compressor by the sharp edge knife near the compressor folding mirror.

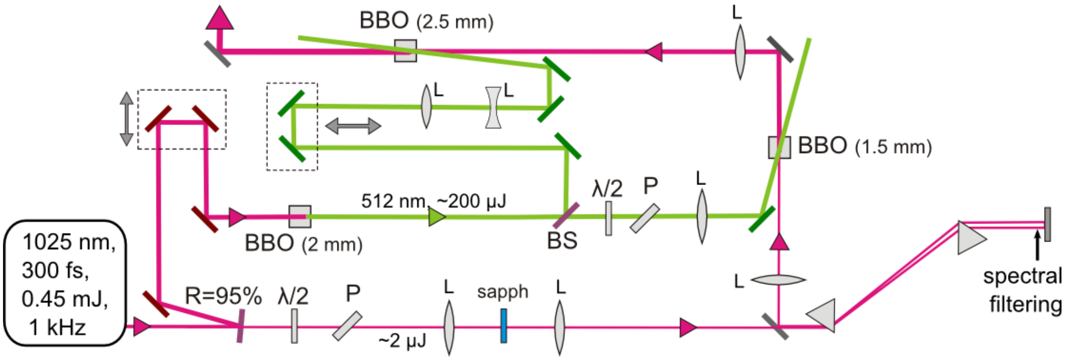

Fig. 8. Experimental setup of the two stage femtosecond NOPA. (BS marks the beam splitter, P – thin film polarizer, L – lenses or spherical mirrors).

In the first amplification stage both seed and pump were loosely focused into 1,5 mm BBO crystal. In order to minimize the superfluorescence, the first stage was operated in relatively low gain regime, and the available pump of 20 μJ was reduced to ~14 μJ, amplifying signal pulses to ~1 μJ energy. Further the signal was collimated to the second NOPA stage. Pump and signal beam sizes were matched to ~1 mm. The signal in second stage was amplified up to 20 μJ with spatial beam profile close to Gaussian. However, still some modulation in spectrum and in beam of profile was observed at maximum output energy, so the pump intensity was reduced, thus reducing the energy of amplified pulse to ~17 μJ. The spectrum of amplified pulse (Fig. 9) corresponded to ~6,5 pulse duration.

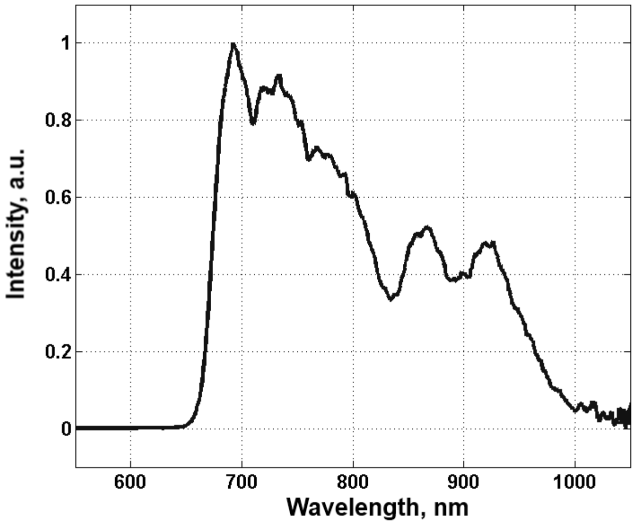

Fig. 9. The spectrum of amplified to 17 μJ energy pulses at the output of second OPA stage.

In general case the signal pulse in noncollinear setup may be distorted due to spatial mismatch in amplitude fronts between pump and signal pulses. It is commonly believed that signal acquires pulse front tilt, which can be determined from pulses angular dispersion [18-20]. However, it has been shown that the pulse can be tilted without angular dispersion by simultaneously introducing temporal and spatial chirp [21]. Also parameters for defining of spatial chirp were introduced: a spatial dispersion $\frac{dx_0}{d\omega}$ and a frequency gradient $\frac{d\omega_0}{dx}$ [22], where x is the transversal coordinate, x_0 is the centre position of the beam at given frequency, ω - spectral frequency and $\omega_0$is the central frequency at given coordinate.

In order to evaluate out and minimize the undesirable effects the second NOPA stage was investigated both in front matched and non-matched cases. The pulses in this stage are around 1 mm is diameter, which is approximately 10 times the dimension of the pulse in propagation direction. For pulse front matching a BK7 prism with 67 degree apex angle was introduced into pump beam. This resulted in front tilting by 3,5 degrees which is close to the external noncollinearity angle. For measurements of angular and spatial beam characteristics we used a combination of imaging spectrometer and a CCD camera in a setup similar to one described in Ref. [23]. Depending on required spectral range either a grating or a reflective coated prism were used. The CCD camera was placed in image plane of spectrograph and the spectral coordinate was calibrated in the range from 700 to 900 nm. For the angular dispersion measurement the spherical mirror was placed at a focal distance from the spectrograph entrance slit. As for spatial chirp measurement, the BBO crystal output plane had to be imaged into spectrograph input, so the position of focusing element was adjusted accordingly.

The experiment showed that the pulse had not acquired any significant angular dispersion after amplification. The very slight residual angular dispersion that would lead to pulse front tilt of 0,03 - 0,04 degrees was present in all cases. Such numbers are at the detection limit of the device and considered to be negligible comparing to almost 4 degrees of external noncollinearity angle. However, in the case of not matched pulse fronts the amplified signal had acquired spatial chirp which corresponds to spatial dispersion parameter of ~1 μm/nm and marginal wavelength shifted for around 200 μm (see Fig. 10).

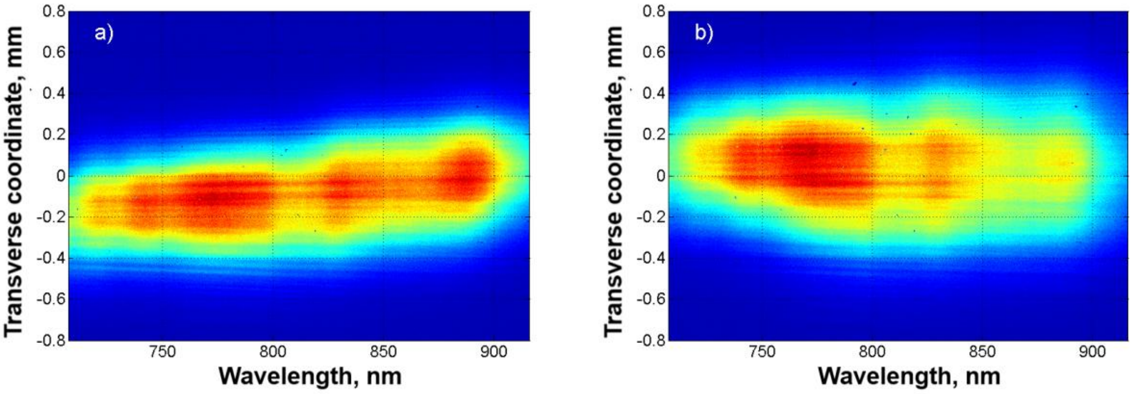

Fig. 10. Measured spatial spectral distributions of amplified signal pulse in cases of not matched (a) and matched pulse fronts (b).

As there is virtually no angular dispersion involved, the spatial chirp should “smudge” after some propagation in space due to diffraction of the beam.

Next, the experiments on pulse compression were carried out, in order to test the phase characteristics of pulses at this amplification stage. The output pulse was compressed using SF57 prism pair compressor together with acousto-optic programmable dispersive filter (AOPDF “Dazzler”, Fastlite). The prisms were needed to compensate the dispersion introduced by AOPDF. Unfortunately, still some clipping of spectra occurred due to limited length (25 mm) AOPDF, which led to transmission of the spectral window from 700 to 900 nm at programmed group delay. A SHG FROG apparatus was used to control the compression and to fine tune AOPDF parameters. In this approach pulses were compressed to 9,8 fs (Fig. 11), while the Fourier transform limited duration of the clipped spectrum pulse was equal to ~9 fs.

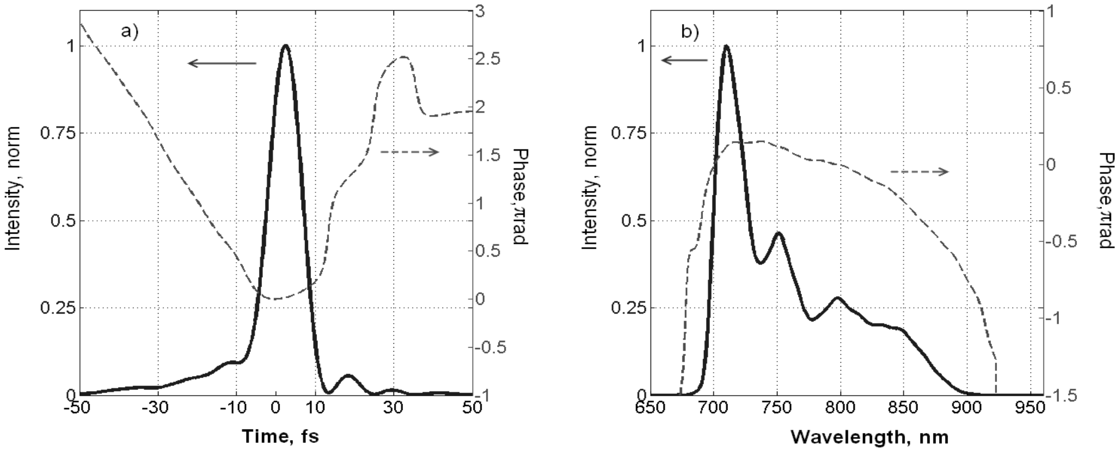

Fig. 11. Intensity profile (solid) and phase (dashed) of compressed pulse in temporal (a) and spectral (b) domains, retrieved by FROG measurement.

These results prove the compressibility of the pulse and further pulse amplification is feasible. In the stationary case the use of AOPDF at this stage is required for pulse compression by conventional pulse compressors only, whereas implementation of chirped mirrors would result in same durations but much lower energy losses. It is also obvious that such setup can be used instead of Ti:sapphire laser in cases when broadband pulses of microjoule energies are needed. Talking about the architecture of the whole system, the AOPDF is still needed and it has to be introduced in early stages of pulse amplification, as the crystal used in this filter has quite low damage threshold. Also, the losses introduced by AOPDF can be easily compensated in next amplification stages.

In the **fourth chapter** results on numerical simulations of pulse stretching and compression schemes are presented and programming parameters for AOPDF are estimated. Also the experiments on high energy OPCPA are carried out.

Before the pulse amplification in picosecond OPCPA stage the stretching setup had to be developed. As some of the elements may introduce serious limitations on the scheme, the compression part of the system had also to be taken into account. In order to minimize the losses in final compression stage it has been decided to stretch the pulse in negative dispersion stretchers (the so called “down-chirp” setup), and to compress the pulse after amplification in bulk glass. The whole stretching setup comprised of double pass transmission grating stretcher and a prism pair stretcher to compensate the third order dispersion. However, the calculations have shown that in the optimal setup without additional phase correction the pulse exhibits residual group delay of hundreds of femtoseconds throughout the spectrum (Fig. 12).

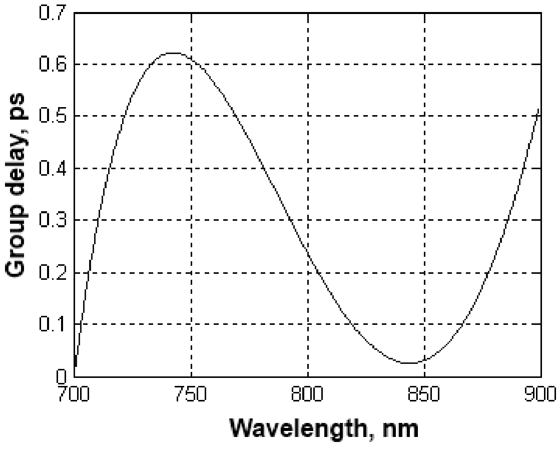

Fig. 12. Residual group delay of stretching and compression setup without additional phase control.

Introduction of AOPDF into the system would improve the situation, however at this spectrum bandwidth the dispersive filter cannot completely compensate the dispersion introduces by itself. Thus the stretching and compression scheme had to be re-optimized.

For further amplification a multistage OPCPA module (Fig. 13) was implemented, pumped by 100 ps Nd:YAG flash lamp amplifier. The seed for this stage was stretched to ~30 ps in the transmission grating and prism stretchers and passed through AOPDF “Dazzler” for high order dispersion compensation. After this only 2 μJ of total energy of seed was left due to losses both in AOPDF and stretcher.

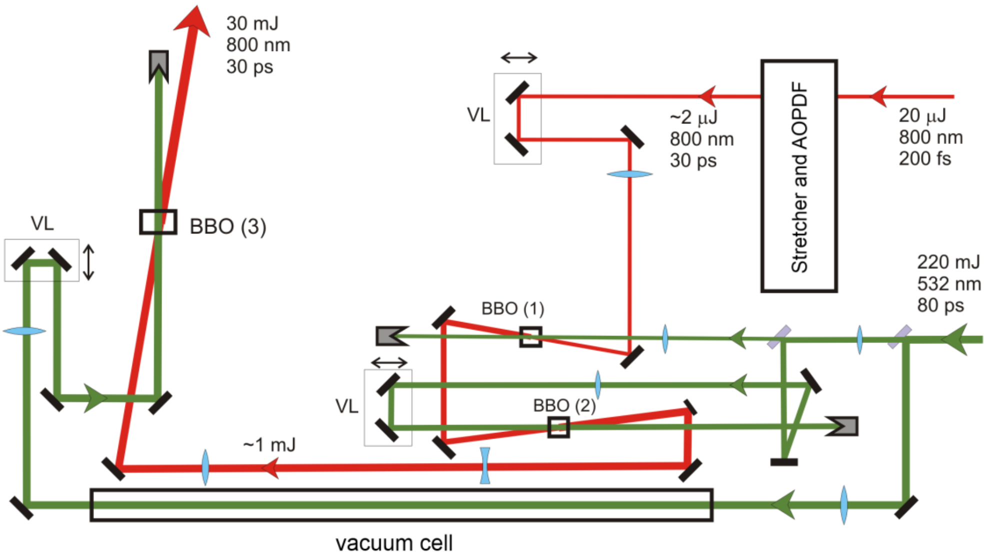

Fig. 13. High output energy multistage OPCPA setup (VL marks delay stages).

The amplification was carried out in three stages, first 6×6×5 mm^3 , then 6×6×4 mm^3 and finally 15×15×5 mm^3 BBO crystals (marked as (1), (2) and (3) in Fig. 13). The pump energy used ~ 2,8 mJ, 9 mJ and 220 mJ respectively. The external noncollinearity angle in all stages was set close to 3,9 degrees and phase-matching angle was adjusted respectively. As the Nd:YAG output beam exhibit quite sharp edge profile, an image translation setup had to be used for pump beam in each stage. This was accomplished by introducing 4f lens setup. To make it more compact the image translation stages for the first two stages shared the front lens of the system. Due to high energy in the third pump channel, a vacuum cell had to be used between the lenses. The pump beam sizes in the first two stages were ~0,7 mm and ~1 mm. The signal pulse was loosely focused by f = 800 mm lens and beam diameter was matched by changing the lens position. After amplification in the first stages, the beam was expanded and collimated by Galilean type telescope to 9 mm diameter and then amplified up to 30 mJ maximum energy in the final stage. The Fourier transform limit of the amplified pulses spectrum corresponds to 9,3 fs pulse duration. The spectrum of amplified pulses is depicted in Fig. 14.

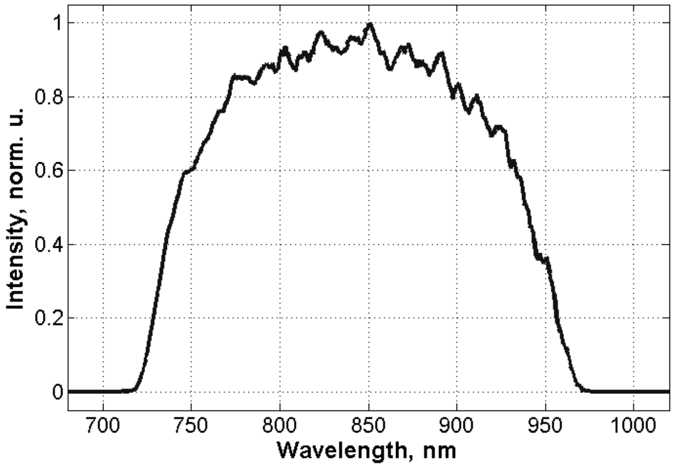

Fig. 14. Amplified pulse spectrum after final amplification stage. Pulse energy equals to 28 mJ. The Fourier transform of spectrum yields the pulse duration limit of 9,3 fs.

The final compression of the pulse is intended to be performed in bulk glass compressor. In order to avoid the nonlinear phase accumulation due to high intensities of the pulse, the value of so called B integral has to be evaluated. It is considered that phase distortions are negligible if the integral value is below 1. Setting this as a boundary condition, one can calculate the maximum input intensities that are allowed at the input of compressor. Such evaluation yields that for 30 mJ pulses and SF57 bulk glass compressor, beam diameters of at least 60 mm are required. To avoid any aperture effects the glass itself has to be at least twice the diameter of the beam. Considering the cost of the glass and the fact that the system is constantly improved and even higher energies might be available, the compression of amplified pulses was not performed. At present another approach, of implementing glass compressor together with chirped mirrors is being developed, which would allow for reducing of the required glass volume.

Main results and conclusions

An approach for power scaling of regenerative amplifiers by use of multiple active elements enables to boost the output of Yb:KGW regenerative amplifier to 30 W average output power at 100 kHz repetition rate, which corresponds to 0,3 mJ energy per pulse.

Direct optical synchronization of Yb:KGW and Nd:YAG amplifiers by implementation of polarizing spectrum splitter at the output Yb:KGW oscillator ensures the maximum seed energy and minimum amount of generated ASE. The ASE level was $<10^{-8}$ for Yb:KGW laser, whereas for Nd:YAG system it was $<10^{-6}$ after the first and $\sim10^{-5}$ after the second regenerative amplifier.

Employment of Yb:KGW laser for white light continuum generation and its further amplification in noncollinear parametric amplifier enables to generate pulses of up to 20 μJ energy at 800 nm central wavelength, compressible to sub-10 fs duration.

Spatial spectrum distortions of highly chirped signal pulse, appearing in femtosecond non-collinear parametric amplifier due to not-matched fronts of pump and signal pulses, take the form of spatial chirp mainly, while the angular dispersion remains negligible.

A concept of stepwise increased pulse duration in multistage OPCPA enables for amplification of broadband pulses to multi-milijoule energies and is promising for achieving high temporal contrast ratio. Amplification of supercontinuum pulses to 30 mJ energy was demonstrated and the spectrum of amplified pulse allows for compression to sub-10 fs duration. No optical fiber elements were used in proposed setup, thus providing higher stability and tolerance to mechanical and thermal effects.

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Santrauka

DIDELĖS IŠVADINĖS ENERGIJOS PLATAUS SPEKTRO ČIRPUOTŲ IMPULSŲ OPTINIS PARAMETRINIS STIPRINIMAS

Stiprių laukų fizikos srities tyrimams, aukštų eilių harmonikų ir pavienių atosekundinių impulsų generavimui yra reikalingos kompaktiškos teravatų smailinės galios kelių optinių ciklų išvadinių impulsų lazerinės sistemos. Optinis parametrinis moduliuotos fazės (taip vadinamų „čirpuotų“) impulsų stiprinimas yra vienas pagrindinių metodų, leidžiančiu pasiekti šiems taikymams reikalingus lazerinių sistemų parametrus.

Šios disertacijos darbo tikslas – ištirti femtosekundinės ir pikosekundinės trukmės impulsų stiprinimą optiniuose parametriniuose stiprintuvuose, užkratui naudojant itin plataus spektro signalą ir, remiantis šių tyrimų rezultatais, sukurti ir optimizuoti moduliuotos fazės impulsų parametrinio stiprinimo sistemą, užtikrinančią patikimą teravatų smailinės galios impulsų formavimą.

Disertacija susideda iš įvado, keturių pagrindinių skyrių, po kurių seka rezultatų apibendrinimas ir išvados. Įvade yra išdėstoma darbo motyvacija, nurodomas darbo tikslas bei pagrindiniai uždaviniai, pristatomi ginamieji teiginiai.

Pirmame skyriuje yra pateikiama bendra TW smailinės galios sistemos koncepcija, aptariami tokios sistemos privalumai ir trūkumai, nustatomos tyrimų kryptys, apžvelgiami kitų mokslinių grupių pasiekimai, kuriant panašių išvadinių parametrų sistemas.

Antrame skyriuje aprašomas kelių aktyvių elementų naudojimo metodas, leidžiantis didinti regeneratyvinių stiprintuvų išvadinę galią. Šio metodo taikymas leido padidinti Yb:KGW regeneratyvinio stiprintuvo galią iki 30 W vidutinės išvadinės energijos, esant 100 kHz impulsų pasikartojimo dažniui. Taip pat šiame skyriuje aprašomi Yb:KGW ir Nd:YAG lazeriai, naudoti kaupinimo impulsų formavimui, pateikiami jų charakterizavimo ir optimizavimo rezultatai. Matavimų rezultatai rodo, kad silpnesnis užkrato signalas lemia didesnio sustiprintos spinduliuotės kiekio generavimąsi regeneratyviniame stiprintuve. Pritaikytas poliarizacinis Yb:KGW osciliatoriaus

spinduliuotės spektro atskyrimas užtikrina didžiausią užkrato energiją Yb:KGW ir Nd:YAG stiprintuvų užkratui bei patikimą šių lazerių optinę sinchronizaciją.

Trečias skyrius yra skirtas baltos šviesos kontinuumo generavimo ir plataus spektro signalų parametrinio stiprinimo tyrimams, kaupinimui naudojant Yb:KGW femtosekundinio lazerio spinduliuotę. Šiame skyriuje pateikiami > 200 nm spektro pločio impulsų parametrinio stiprinimo energinių, erdvinių, spektrinių charakteristikų teorinių ir eksperimentinių tyrimų bei sustiprintų impulsų spūdos eksperimentų rezultatai. Yra išvedamos palyginti paprastos analitinės išraiškos, aprašančios impulsų stiprinimą nuskurdinto kaupinimo sąlygomis. Sukurtos Yb:KGW femtosekundiniu lazeriu kaupinamos baltos šviesos kontinuumo generavimo ir nekolinearaus kaupinimo optinio parametrinio stiprinimo sistemos išvadinių impulsų energija siekia 20 mikrodžaulių, o impulsai suspaudžiami iki mažesnės nei 10 fs trukmės ties 800 nm bangos ilgiu. Tokia sistema gali būti gera alternatyva šiuo metu plačiai naudojamoms Ti:safyro lazerinėms sistemoms. Šiame skyriuje taip pat parodoma, kad nagrinėtomis nekolinearaus parametrinio stiprinimo sąlygomis stiprinant smarkiai faziškai moduliuotą impulsą tarp galimų erdvinių laikinių impulso iškraipymų dominuoja taip vadinamas „erdvinis čirpas“.

Ketvirtame skyriuje pateikiami plataus spektro impulsų laikinės plėtros ir jų spūdos sudėtingose dispersinėse sistemose skaitmeninio modeliavimo rezultatai, bei plačios spektrinės juostos parametrinio stiprintuvo, kaupinamo pikosekundiniais kelių šimtų mildžaulių energijos impulsais, eksperimentinio tyrimo rezultatai. Darbe pasiūlyta ir pritaikyta hibridinio kaupinimo koncepcija, kuomet impulsų trukmė yra nuosekliai didinama keliose parametrinio stiprinimo pakopose, tokiu būdu užtikrinant optimalų užkrato intensyvumą kiekvienoje iš jų, pasiekiant didelę sistemos išvadinio impulso energiją ir sudarant prielaidas didelio energinio kontrasto itin trumpų impulsų formavimui. Pasiekta 30 mJ išvadinė sistemos energija, o impulsų spektras leidžia suspausti impulsus iki mažesnės nei 10 fs impulsų trukmės.

Paskutiniame skyriuje yra apibendrinami atliktų tyrimų rezultatai ir pateikiamos disertacijos išvados.

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