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HIGH POWER ULTRASHORT CEP STABLE PULSES VIA OPTICAL PARAMETRIC AMPLIFICATION

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FIZINIŲ IR TECHNOLOGIJOS MOKSLŲ CENTRAS

TOMAS STANISLAUSKAS

DIDELĖS GALIOS STABILIOS GAUBTINĖS FAZĖS ITIN TRUMPŲ IMPULSŲ FORMAVIMAS PARAMETRINIO STIPRINIMO SISTEMOSE

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Contents

List of the abbreviations

SHG	second harmonic generation
NOPA	noncollinear optical parametric amplifier
OPCPA	optical parametric chirped pulse amplification
APF	amplified parametric fluorescence
CEP	carrier-envelope phase
SHG	second harmonic generation
WLC	white light continuum
RMS	root-mean-square
AOM	acousto-optic modulator
BBO	β-barium borate (β-BaB_2O_4)
AOPDF	acousto-optic programmable dispersive filter

Introduction

Optical parametric chirped pulse amplification (OPCPA) [1] is a well established method to produce high-energy, sub-10 fs pulses for various applications in strong-field and attosecond science research. Generation of multimilijoule sub-10 fs pulses around 800 nm has already been demonstrated in OPCPA systems pumped by picosecond Nd:YAG [2, 3] and Ti:sapphire lasers [4]. In the majority of works devoted to the development of few-cycle OPCPA systems the main source of the broadband seed for the parametric amplification in vicinity of 800 nm was the output of a broadband mode-locked Ti:sapphire oscillator [5]. However the signal pulses amplified in active laser medium always has an inevitable part of the amplified spontaneous emission. An alternative source of broadband and background-free seed pulses around 800 nm is a white light continuum (WLC) generated in a bulk materials by femtosecond pulses of OPAs operated at longer wavelengths [6] or ytterbium-doped laser systems, which automatically provides the possibility to perform seed generation and amplification in a femtosecond non-collinear optical parametric amplifier (NOPA) [7, 8]. Employment of femtosecond pump pulses in the initial OPCPA stages is advantageous, since thinner crystals and narrower pump beams can be used, implying an increased amplification bandwidth [9] and a reduced level of amplified parametric fluorescence (APF) which is proportional to the pump beam area [10]. It is also important to point out that the recompressed APF resides within the time window defined by the duration of the femtosecond pump pulse. Carrier-envelope phase (CEP) control is another essential prerequisite for a number of few-cycle laser applications in strong-field research, in particular for experiments on generation of isolated attosecond pulses. Nowadays, both active and passive CEP stabilization is well established technique providing CEP control of different types of laser systems. However, only several CEP stable few-cycle OPCPA systems producing CEP-stable pulses with energies exceeding 1 mJ are reported [11–14].

This work aims at advancement of OPCPA technique for generation of high contrast CEP-stable few-cycle pulses at high peak and average power.

The main tasks of the thesis

1. To find out the optimum conditions for the white light continuum generation in sapphire crystal pumped by 200 fs pulses from Yb:KGW laser system.

2. To elaborate active CEP stabilization methods for the pulses produced by Yb:KGW laser and NOPA as well as to study the influence of the laser energy fluctuation on the precision of CEP measurements.

3. To develop a source of passively stabilized broadband pulses for seeding of the high energy OPCPA systems.

4. To investigate and optimize the femtosecond Yb:KGW laser pumped NOPA setup for operation as a frontend of a high power OPCPA system.

5. To develop terawatt-class OPCPA system generating sub-10 fs high energy few-cycle CEP stable pulses and adapt it for operation in high average power regime.

Practical novelty

Optimized active CEP stabilization of the Yb:KGW laser system and OPA setups pumped by this laser was demonstrated. To our knowledge, obtained result is the best for ytterbium-based amplifier systems. Compact NOPA setups seeded by CEP stabilized white light continuum pulses were developed. The bandwidth of the amplified signal supports the pulse duration of 6 fs. Amplified parametric fluorescence produced in a high gain BBO-based femtosecond noncollinear parametric amplifier was investigated and differences of amplification geometries affecting spatial walk-off of the pump beam were examined. The design and a number of OPCPA system modules were developed for producing terawatt peak power CEP stable few-cycle pulses at 1 kHz repetition rate.

Scientific novelty

1. The coupling coefficient between the energy of pulses generated in Yb:KGW laser system and measured carrier envelope phase was determined for f-to-2f interferometer employing white light generation in bulk sapphire.

2. The dependence of intensity level of amplified parametric fluorescence generated in BBO based NOPA on direction of optical axis of the crystal was demonstrated.

3. Passively CEP-stabilized continuum generator and femtosecond NOPA based frontend for few-cycle OPCPA systems was developed.

4. It was shown, that CEP noise of pulses centered at 1800 nm can by reduced down the 100 mrad for several hours of operation, when these pulses are generated in the difference frequency generator supplemented by a slow feed back loop for delay control.

5. The generation of >4 TW power CEP stabilized sub-9 fs pulses at repetition rate of 1 kHz was demonstrated.

Statements of defend

1. CEP noise of pulses generated in the Yb:KGW laser system and OPA setups pumped by this laser can by reduced down to 250 mrad by implementing the active feed back loops to the oscillator pump. Such stability corresponds to 140 as timing jitter between the carrier and the envelope.

2. Broadband passively CEP stabilized OPCPA seed pulses centered at 800 nm can be generated by Yb:KGW system driven by the two-stage white light generator with the difference frequency generator between them.

3. The intensity level of amplified parametric fluorescence generated in the noncollinear optical parametric amplifier is strongly affected by spatial walk-off of the narrow pump beam. This unwanted background radiation which deteriorates the temporal contrast of the amplified signal can be reduced by using Poynting vector compensating geometry of a type-I BBO crystal.

4. The temporal pulse contrast of the output of OPCPA systems can be substantially increased with reference to Ti:sapphire oscillator seeded OPCPA by the use of the seed from the femtosecond continuum generator amplified in short pulse NOPA.

Approbation

Scientific papers related to the topic of this thesis

[A1] **T. Stanislauskas**, R. Antipenkov, V. Martinėnaitė, L. Karpavičius, A. Varanavičius, P. Mišeikis, D. Grigaitis, D.Mikalauskas, R. Karkockas, V. Sinkevičius, L. Giniūnas, R. Danielius, T. Balčiūnas, A. Pugžlys, A. Baltuška,

B. Schmidt, Carrier-envelope phase control of Yb:KGW laser and parametric amplifers, Lithuanian Journal of Physics, **53**, 17-24 (2013).

[**A2**] **T. Stanislauskas**, R. Budriūnas, R. Antipenkov, A. Zaukevičius, J. Adamonis, A. Michailovas, L. Giniūnas, R. Danielius, A. Piskarskas, and A. Varanavičius, Table top TW-class OPCPA system driven by tandem femtosecond Yb:KGW and picosecond Nd:YAG lasers, Optics Express, **22**, 1865-1870 (2014)

[**A3**] T. Balčiūnas, T. Flöry, A. Baltuška, **T. Stanislauskas**, R. Antipenkov, A. Varanavičius, G. Steinmeyer, Direct carrier-envelope phase control of an amplified laser system, Optics Letters, **39**, 1669-1672 (2014).

[**A4**] R. Budriūnas, **T. Stanislauskas**, A. Varanavičius, Passively CEP-stabilized frontend for few cycle terawatt OPCPA system, Journal of Optics **17**(9), 94008-94013 (2015)

[**A5**] **T. Stanislauskas**, I. Balčiūnas, V. Tamuliene, R. Budriūnas, A. Varanavičius, Analysis of parametric fluorescence amplified in a noncollinear optical parametric amplifier pumped by the second harmonic of a femtosecond Yb:KGW laser, Lithuanian Journal of Physics, **56**(1), 1-8 (2016).

Other scientific papers

[**A6**] N. Šiaulys, V. Kudriašov, **T. Stanislauskas**, T. Malinauskas, A. Urniežius, and A. Melninkaitis, Holographic study of ultrafast optical excitation in GaN film induced by nonlinear propagation of light, Optics Letters, **37**, 4916-4918 (2012).

Conference presentations

Presented by Tomas Stanislauskas:

[**C1**] **T. Stanislauskas**, A. Varanavičius, Kontinuumo generacija safyre 1030 nm bangos ilgio 190 fs trukmės impulsais, 39-oji Lietuvos nacionalinė fizikos konferencija, Vilnius, Lietuva, (2011).

[**C2**] **T. Stanislauskas**, R. Antipenkov, L. Karpavičius, V. Martinėnaitė, P. Mišeikis, A. Varanavičius, Yb:KGW lazerio ir optinio parametrinio stiprintuvo gaubtinės fazinio poslinkio valdymas, 40-oji Lietuvos nacionalinė fizikos konferencija, Vilnius, Lietuva (2013).

[C3] **T. Stanislauskas**, R. Antipenkov, V. Martinėnaitė, L. Karpavičius, A. Varanavičius, V. Sinkevičius, P. Mišeikis, D. Grigaitis, T. Balčiūnas, Carrier-envelope phase control of Yb:KGW laser and parametric amplifiers, Conference on Lasers and the Electro-Optics (CLEO/Europe), Munich, Germany, (2013).

[C4] **T. Stanislauskas**, R. Budriunas, R. Antipenkov, A. Zaukevicius, J. Adamonis, A. Michailovas, L. Giniunas, R. Danielius, and A. Varanavicius, Continuum seeded OPCPA system driven by tandem fs Yb:KGW and ps Nd:YAG lasers, CLEO: Science and Innovations, San Jose, United States, (2014).

[C5] T. Balciunas, T. FlÃűry, **T. Stanislauskas**, R. Antipenkov, A. Varanavicius, A. Baltuska, and G. Steinmeyer, Direct carrier-envelope phase control of a sub-MHz Yb amplifier, CLEO: Science and Innovations, San Jose, United States, (2014).

[C6] **T. Stanislauskas**, R. Budriunas, R. Antipenkov, A. Zaukevicius, J. Adamonis, A. Michailovas, L. Giniunas, R. Danielius, and A. Varanavicius, Continuum seeded OPCPA system driven by tandem fs Yb:KGW and ps Nd:YAG lasers, ELI Beamlines Summer School, Prague, Czech Republic, (2014).

Co-author of the presentations:

[C7] N. šiaulys, A. Urniežius, **T. Stanislauskas**, T. Malinauskas, V. Kudriašov, A. Melninkaitis, Ultrafast nonlinear dynamics in thin GaN films studied by femtosecond digital holography, 18^{th} International Conference on Ultrafast Phenomena, Lausanne, Switzerland, (2012).

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[C9] T. Balčiūnas, T. Flory, **T. Stanislauskas**, R. Antipenkov, A. Varanavičius, A. Baltuška, and G. Steinmeyer, Direct carrier-envelope phase control of an amplified, Ultrafast Optics Conference 2013, Davos, Switzerland (2013).

[C10] T. Balčiūnas, T. Flory, **T. Stanislauskas**, R. Antipenkov, A. Varanavičius, A. Baltuška, and G. Steinmeyer, Direct Carrier-Envelope Phase Control of an Amplified Laser System, Conference on Lasers and the Electro-Optics (CLEO/Europe)), Munich, Germany, (2013).

[C11] R. Budriūnas, **T. Stanislauskas**, R. Antipenkov, A. Varanavičius, D. Kučinskas, Š. Straigis, Characterization of Stretched Ultrabroadband Pulses by Chirp Scan and Their Compression to Sub- 10fs Pulse Widths, XX Lithuanian - Belarussian seminar Lasers and optical nonlinearity, Vilnius, (2013).

[C12] T. Balčiūnas, T. Flory, **T. Stanislauskas**, R. Antipenkov, A. Varanavičius, A. Baltuška, G. Steinmeyer, Direct Carrier-Envelope Phase Control of a sub-MHz Yb amplifier, High Intensity Lasers and High Field Phenomena (HILAS), Berlin, Germany, (2014).

[C13] R. Budriūnas, **T. Stanislauskas**, Š. Straigis, A. Varanavičius, Passively CEP-stabilized OPCPA Front-End Based on Yb:KGW Laser, 2015 European Conference on Lasers and Electro-Optics - European Quantum Electronics Conference (CLEO/Europe), Munich, Germany (2015).

[C14] Arunas Varanavicius, Jonas Adamonis, Rimantas Budriunas, **Tomas Stanislauskas**, Table-top TW class 1 kHz repetition rate OPCPA system: development and future applications (Invited), Northern Optics and Photonics 2015 (NOP 2015), Lappeenranta, Finland, (2015).

Co-authors contribution

The majority of the experiments described in this thesis were performed in Vilnius University, Department of Quantum Electronics during the period of 2011–2015 by the author himself, however it is important to specify the significant contribution of these co-authors:

- dr. **A. Varanavičius**[1] headed entire research work process, adviced on scientific matters, contributed to the preparation of scientific publications and presentations at conferences;
- dokt. **R. Budriūnas**[1] participated in most of research on parametric amplification usig high-energy picosecond pulses. Realized diagnostic and optimization techniques for pulses shorter than 10 fs.
- dr. **R. Antipenkov**[2] handed his experience and laboratory stands designed for 10 Hz OPCPA system;
- dr. **T. Balčiūnas**[3] shared his experience and knowledge of CEP stabilization issues;

- **I. Balčiūnas**[1] together performed the amplified parametric fluorescence experiment and numerical simulation of nonlinear pulse propagation in glasses;
- dr. **A. Zaukevičius**[4] shared the experience gained in modeling of three wave interaction, participated in the research on the 10 Hz OPCPA system;
- dr. **J. Adamonis**[4] developed Nd:YAG based laser amplifiers and second harmonic generators for OPCPA pump.

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Thesis summary

The thesis consists of 6 sections: four chapters, conclusions and a list of references. Thesis is presented in 119 pages and contains 49 figures.

Chapter 1: Review of high energy ultrashort pulse laser systems and their applications

In this chapter the main techniques for generation and amplifications of high energy ultrashort pulses are reviewed and the most significant achievements in this field are highlighted. The motivation for choosing OPCPA technology [1] is outlined and important parameters of such systems are discussed along with the potential application including high harmonics and attosecond pulses generation. The main advantages of this technique are as follows:

- large bandwidth that could accommodate few-cycle pulses;
- no heat dissipation in the OPCPA crystal itself;
- high gain in a single pass amplification;
- no amplified spontaneous emission, ultra high contrast outside the time window defined by the pump pulse.

Chapter 2: Generation of carrier-envelope phase stable pulses

In this chapter, a carrier-envelope phase (CEP), which is a crucial parameter for a few-cycle laser pulse is discussed. CEP is defined as a relative phase between the envelope peak of a pulsed electric field and the closest peak of the carrier wave. Because the highest instantaneous field intensity of a few-cycle pulse depends on the carrier-envelope phase, control of the CEP of ultrashort laser pulses is of prime importance in the case of isolated attosecond pulse generation[15]. In this thesis we report the improved CEP-stabilized operation of a Yb:KGW laser system and present the results for active as well as for passive CEP stabilization of parametric amplifiers pumped by second harmonic of this laser.

In our experiments the diode pumped Yb:KGW MOPA system (PHAROS, Light Conversion Ltd.) providing ∼190 fs pulses with an average power up to 6 W and repetition rate in the range from 1 kHz to 1 MHz has been used. In order to implement active CEP stabilization scheme the carrier-envelope offset (CEO) frequency of Yb:KGW oscillator was locked to one quarter of the repetition rate by using the photonic-crystal fiber based f-to-2f interferometer and the phase-locked loop (PLL) electronics (XPS800, Menlo Systems Gmbh). A similar configuration has already been demonstrated to be functional [16], however the CEP noise could have still be reduced. The laser power supply had to undergo essential changes in order to isolate it from the electrical noise of the mains. Thus, in the final setup of our Yb:KGW MOPA system the active elements of the oscillator and amplifier were pumped by the laser diodes which were driven by a specially designed analog power supply featuring a low noise level in the frequency range of 0.1-30 kHz. The feedback signal was used to control the optical power of the pump diodes via direct modulation of the laser diode current. In order to enhance the oscillator response at higher frequencies a custom-made active high-pass filter has been used. The RMS phase noise as low 56 mrad was obtained using the data from the in-loop interferometer, while the measurements with inactive (out-of-loop) interferometer resulted in the phase jitter of 98 mrad. The achieved result is a significant improvement to the previously published results on CEP locking in femtosecond oscillators with ytterbium doped active elements and is comparable to the best reported values for the Ti:sapphire oscillators, CEP stabilized using servo-loop schemes [17, 18].

The repetition rate of the Yb:KGW regenerative amplifier was locked to that of the oscillator in such a way that it always picked pulses of the same phase. In our setup an additional common-path f-to-2f interferometer was employed for the slow feedback loop which pre-corrected the oscillator pulse phase for the phase drift during amplification in the regenerative amplifier. The effect of the slow feedback is clearly evident in Fig. 1, which depicts the amplified pulse CEP evolution in time. The slow CEP drift over 1 min of acquisition in the case when the slow feedback loop was turned off leads to >700 mrad measured phase jitter RMS values. With the slow loop turned on, this value was reduced to 170 mrad.

Parametric amplification, in conditions close to perfect phase matching, maintains the phase of the amplified signal pulses [11]. However, CEP variation caused by the environmental instabilities in the experiment setup should be taken in to account and requires to be mitigated. In our experiment a single stage NOPA based on

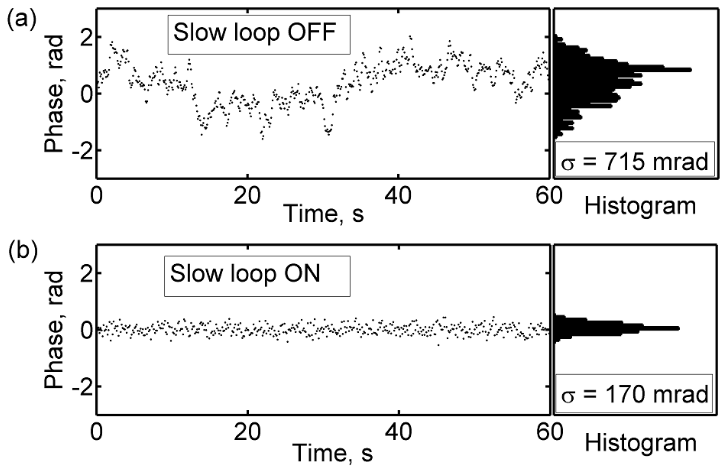

Figure 1: CEP noise after RA (a) without and (b) with additional slow feedback loop enabled.

1.5 mm BBO was pumped by the second harmonic of CEP stabilized Yb:KGW laser. The pulses of a broadband continuum generated by focusing a fraction of the fundamental pulses into a sapphire plate was used as the CEP stable seed and directed to a BBO crystal at ∼2 deg with reference to the pump beam. The CEP stability of the parametrically amplified chirped pulses at 900 nm was tracked by using the same f-to-2f interferometer and CEP retrieval procedures. Realization of slow feedback loop by measuring CEP variation after NOPA and sending the feedback signal to the oscillator through the Menlo Systems lock-box allowed us to reduce the CEP noise after NOPA from ∼1 rad, when only laser oscillator is CEP-locked, down to 220 mrad. This value is only moderately higher than the phase jitter of phase-stabilized pump laser and the difference can be reasonably explained by the higher NOPA output pulse energy and beam pointing instabilities. We should note that the CEP variation induced by air turbulence or mechanical perturbation of NOPA continuum generator was much more pronounced as compared to the CEP instabilities caused by perturbation of continuum generator in the f-to-2f interferometer.

CEP locking of oscillator pulses involves tight focusing into photonic crystal fiber for spectral broadening. Previously discussed feed-back scheme works reasonably well in relatively short periods of time, but it is difficult to maintain efficient coupling into this fiber (∼5 μm diameter) for time periods of over an hour. In order to avoid this bottleneck two other CEP stabilization methods were investigated. First of them is so called feed-forward CEP stabilization scheme [19]. The concept seem like passive CEP stabilization via difference frequency generation, only in this case it is a difference frequency generation between an optical wave and an acoustic wave using a frequency shifter. In this scheme (see Fig. 2) the offset frequency of the oscillator is measured in the f-to-2f interferometer and sent to the acousto-optic modulator that subtracts the offset frequency from the oscillator frequency comb and produces a train of pulses with the constant CEP in the diffracted beam. In

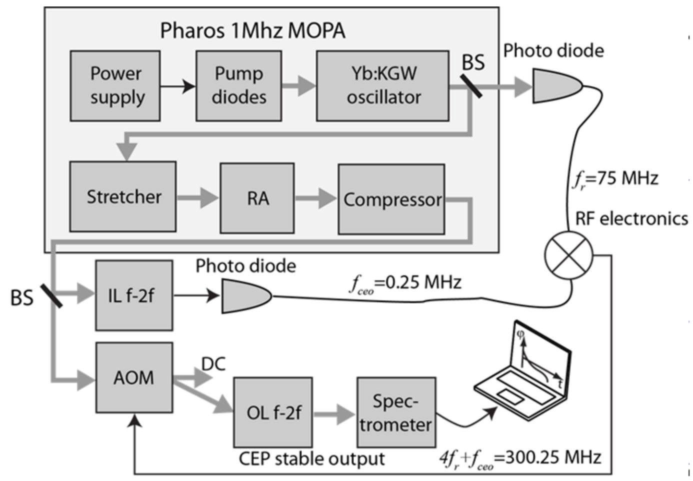

Figure 2: General scheme of the frequency synthesis for the CEP stabilization of pulses from a sub-MHz regenerative amplifier (RA). IL - in loop , OL - out of loop.

this case there is no need to lock the CEP of oscillator and the f-to-2f interferometer involving spectrum broadening in the photonic crystal fiber can be avoided. Due retentively low bandwidth of the CEP noise of our Yb:KGW oscillator pulses (not exceeding few 10's of kHz) we were able to measure the carrier-envelope offset (CEO) frequency for the first time directly after laser amplifier system, when its repetition rate frequency was set for 500 kHz or higher. Signals detected by a slow photo diode after the in loop f-to-2f interferometer is shown in Fig. 3. We used an AOM with central frequency at around 300 MHz. Therefore modulator was driven by a signal synthesized by combining the fourth harmonic of 75 MHz oscillator repetition rate signal with the filtered out carrier-envelope offset sideband. The CEP stable pulses were detected in a diffracted beam by using an out of loop f-to-2f interferometer. CEP stability below 100 mrad was obtained and this is an unprecedented results for an amplified ytterbium-based amplifier system. The scheme is currently applicable for intermediate laser pulse energy in the μJ range, essentially limited by self-phase modulation and optical damage in the AOM. However this energy level of CEP stable pulses is sufficient to generate white light continuum in sapphire or YAG crystals, and use it for seeding of the OPCPA system.

Another method adapted to generate broadband CEP stable pulses for OPCPA seeding is based on a difference frequency generation between two optical pulses, experiencing the same phase fluctuations. In this case OPA setup (see Fig. 4) was pumped by the second harmonic of Yb:KGW amplifier pulses. Continuum pulses

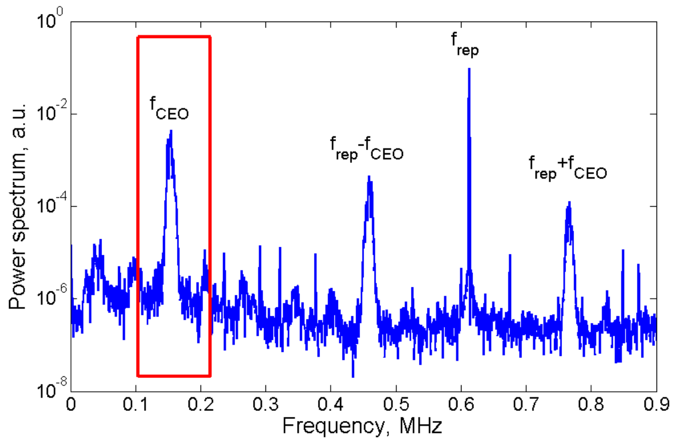

Figure 3: Power spectrum of signal detected by slow photo diode after the in loop f-to-2f interferometer. Part of the signal used to drive acousto-optic modulator is marked in red.

for the seeding of OPA were generated in 4 mm thick sapphire plate pumped by part of the same input pulse at 515 nm. In this arrangement the CEP value of idler

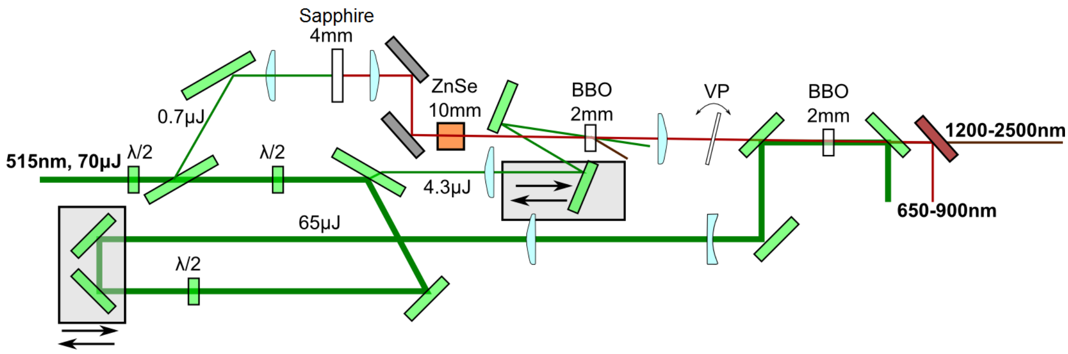

Figure 4: OPA setup for generation of CEP stable pulses tunable in range of 1200-2600 nm. VP - rotating glass plate used for delay control during compensation of slow CEP drift of idler pulses.

pulses was constant regardless of any pulse-to-pulse CEP fluctuations in the pump laser pulses [20]. First BBO based OPA stage was optional and used in order to increase efficiency and saturate the generation of idler pulses in the second OPA stage. The obtained energy was higher than 4 μJ for the most of the tuning range (1400-1900 nm). The measurement of the CEP stability was performed by directing the OPA idler pulses to the common-path f-to-2f interferometer. The continuum was generated by pulses of 1.8 μm central wavelength and interference was observed in the 700-800 nm spectral region between components of continuum and frequency-doubled part of it from 1.4 μm to 1.6 μm. The single-shot measurement of the CEP jitter of the OPA idler pulse without any laser CEP stabilization activated is presented in Fig. 5 (a). The CEP stability of <60 mrad over short time scales has been recorded, however the phase drift due to the changes in environment conditions on a longer time scale exceeds several radians. This slow CEP drift was compensated

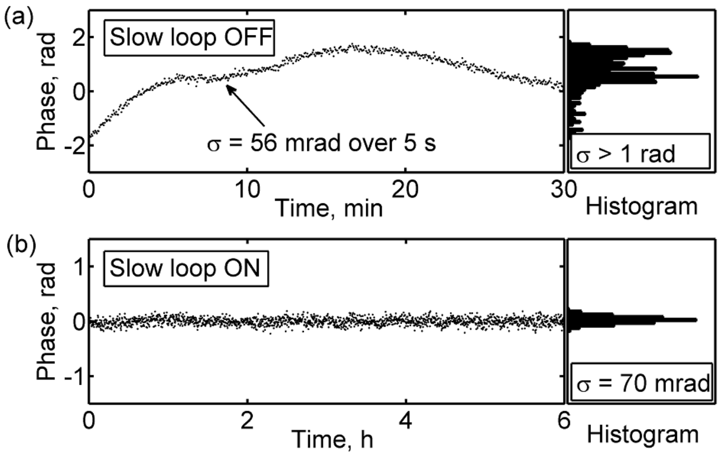

Figure 5: Measured CEP variation of idler pulses at 1800 nm (a) without and (b) with compensation of slow phase drift.

by employing the additional feedback loop to control the temporal delay between pump and seed pulses in the last OPA stage. Additionally we have isolated all the system from the surrounding air currents and reduced the range of temperature as well as humidity variation in the laboratory down to a few percents during the day. As a result, we significantly reduced the CEP drift level and demonstrated CEP-stable OPA operation with RMS phase error as low as 70 mrad during 6 hours of measurements that is below the reported values for CEP stabilized OPA systems.

Chapter 3: Generation and pre-amplification of broadband seed pulses

In this chapter, a research on the white light continuum (WLC) generator pumped by fundamental pulses of Yb:KGW laser amplifier is presented first. 1 kHz pulse repetition rate was set in order to obtain the highest possible pulse energy for the future use as a pump for noncollinear amplification stages. The pulse duration of ∼200 fs at FWHM was measured, while ∼ 15 nm spectral bandwidth was centered at 1030 nm. Sapphire crystal is one of the most commonly used bulk material for generating white light continuum, due to a very high optical damage threshold. We tested sapphire samples with thickness from 2 mm to 8 mm and found that the thickness of the sample does not have a significant impact on the generated continuum energy spectrum in region of our interest from 650 nm to 950 nm. 2 mm thick sapphire experienced an optical damage after several minutes of operation. So, in order to keep group delay dispersion for the generated broadband pulses as low as possible, 4 mm thick sapphire crystal was chosen as optimal. Then different focal length of lens in the input beam of 5 mm diameter (at $1/e^2$) was tested. Fig. 6 presents the contin-

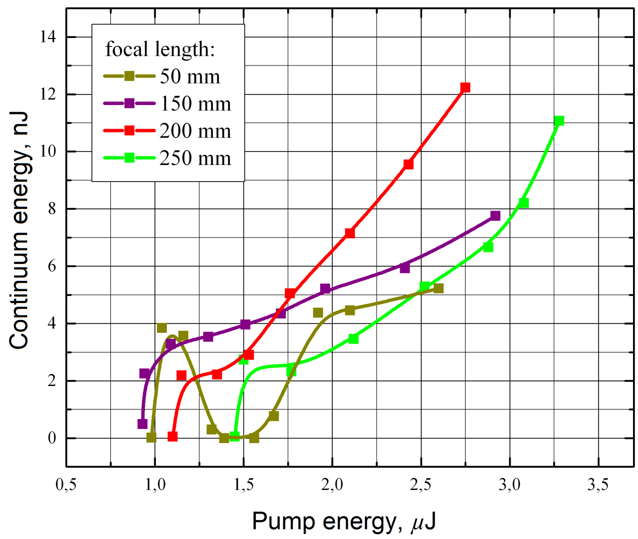

Figure 6: White light continuum energy versus pump energy at different focusing conditions.

uum energy measured for the focal lengths varying from f=+50 mm to f=+250 mm. The focal length of 150 mm corresponding to a numerical aperture of NA≈0.017 was found optimal for the lowest sensitivity of the generated continuum to pump energy. When shorter (f=+50) focal length was used, WLC was stable only at the lowest pump energy, while further increasing of pump energy suppressed continuum generation. The reason for this could be the higher density of the electron plasma. In the case of focusing with lenses having longer focal lengths (f=+200 or f=+250) the high spatial quality continuum with smooth spectrum was produced only in a narrow pump energy range that is in the vicinity the WLC generation threshold. At higher pump energy spatial distortion of the visible part of the continuum was observed. After choice of a 4 mm thick sapphire sample and f=+150 focusing lens the full bandwidth of the WLC was measured (see Fig. 7). For the measurements in 200 - 1100 nm spectral range we used a grating-based spectrograph with a silicon CCD detector, for 900-1500 nm spectral range a grating-based spectrograph with a thermo-electrically cooled InGaAs detector array was used. The spectral sensitivity of both spectrometers was calibrated by recording the spectra of a black-body radiation source. Stable and smooth spectrum covering wavelength range from 600 nm to 950 nm was detected when tuning pump pulse energy from 1.4 to 2.8 μJ until interference of double pulse was observed at 2.9 μJ of pump energy. The results of these investigations provided essential information for the reliable broadband signals generation for f-to-2f interferometers and seeding of noncollinear parametric amplifiers.

Parametric amplification allows one to reach a gain of more than 10^6 in a single pass of a few millimetre long crystal. However, this gain is attainable only by using

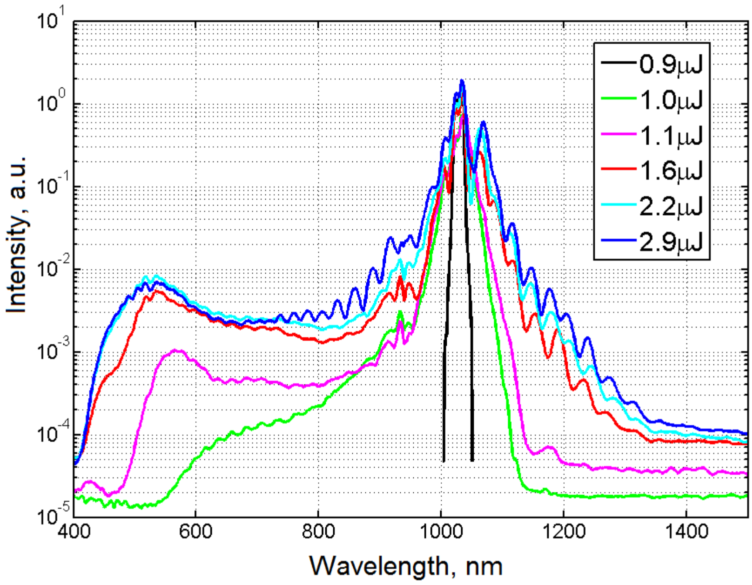

Figure 7: The spectra of white light continuum generated by 200 fs pulses at 1030 nm while pump energy tuned from 0.9 to 2.9 μJ.

high pump intensities in the amplifier crystal, which in turn increases the probability of efficient parasitic generation and amplification of the optical parametric fluorescence. Consequently, amplified parametric fluorescence (APF) degrades signal stability and reduces extractable signal energy due to transfer of the pump energy to the incoherent pedestal [21]. Broad-band parametric amplification in the BBO crystal can be achieved by directing the signal beam at the so called magic angle to pump beam, which is about 2.5° (inside the crystal) in the case of 515 nm pump. However, due to crystal birefringence the direction of the pump Poynting vector differs from that of the pump wave vector and the degree of spatial overlap between pump, signal, and idler beams depends on the orientation of the nonlinear crystal. In one orientation, the Poynting vector walk-off leads to a better spatial overlap of pump and signal beams (see Fig. 8(a)); this geometry is called Poynting vector walk-off compensation geometry (PVWC) [22]. In the case of other orientation of the optical axis (see Fig. 8(b)) - tangential phase-matching geometry (TPM) - the pump beam propagates very close to that of the angular dispersed idler beam. We have investigated the properties of APF produced in a single stage high-gain BBO-based femtosecond noncollinear optical parametric amplifier (NOPA) pumped at 515 nm and examined the differences of APF levels in both PVWC and TPM amplification geometries. Parametric amplification was carried out in a 2.5 mm type-I BBO crystal into which pump beam was focused to a spot size of 110 μm at FWHM. When the seed was blocked, the cone of APF was clearly observed (see Fig. 9 (a)), while the pump was blocked by a dielectric mirror after the crystal. In this case silicon

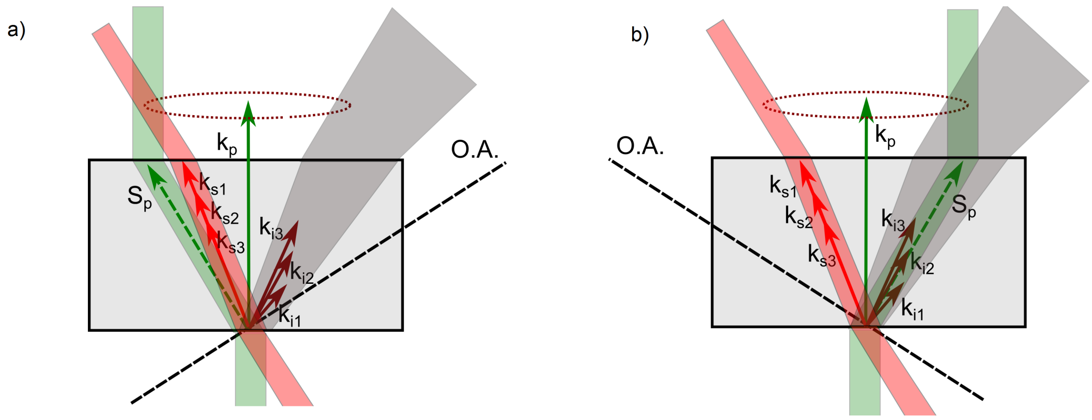

Figure 8: Relative positions of the waves in Type I BBO crystal-based NOPA. (a) Poynting vector walk-off compensation geometry (PVWC), (b) tangential phase-matching geometry (TPM). k_p, k_s, and k_i are wavevectors of pump, signal and idler waves correspondingly. S_p is the pump beam Poynting vector. Signal and idler waves are indicated by sets of wavevectors representing different spectral components of broadband pulses. O.A. is the optical axis of the crystal. The dotted circles indicate the APF cone. The angles between the vectors are exaggerated for clarity.

based CCD highlights mostly the short wavelength range of APF. The half-angle of the cone centered on the pump beam was set to ∼4.1° (≈71 mrad) by tuning the phase matching angle of the crystal. Since the refraction index of BBO crystal is ∼1.66 at 800 nm, this corresponds to an internal signal-pump noncollinearity angle of ∼2.5° and provides the broadest spectral amplification band. The difference between the APF amplitudes on the right and left sides of the cone arises due to varying pump beam spatial overlap with an amplified signal or idler waves of parametric fluorescence. The amount of APF in the amplification channel measured by blocking the seed is the worst case assessment of amplified pulse energy contrast. The presence of the seed at the input of an OPA suppresses APF since even small depletion of the pump pulse due to energy transfer to the injected signal reduces the amplification of the parametric fluorescence [23]. We have examined the APF suppression by measuring the APF intensity at the top part of the APF cone that was away from the signal amplification channel. APF suppression up to 6 times was measured when pump-to-signal energy conversion reached 11.5 % at pump intensity of 170 GW/cm^2. In order to verify the finding, that level of APF in PVWC and TPM noncollinear parametric amplification geometries differs considerably, we have measured the energies of both amplified signal and APF (by blocking the seed) for the both amplification geometries. In order to evaluate the APF energies on the level lower than some pJ we used a spectrometer collecting the light propagating in the signal amplification channel. The energies of APF were calculated by taking spectra integrals over the range of 670-950 nm and scaling it by a factor, which was found

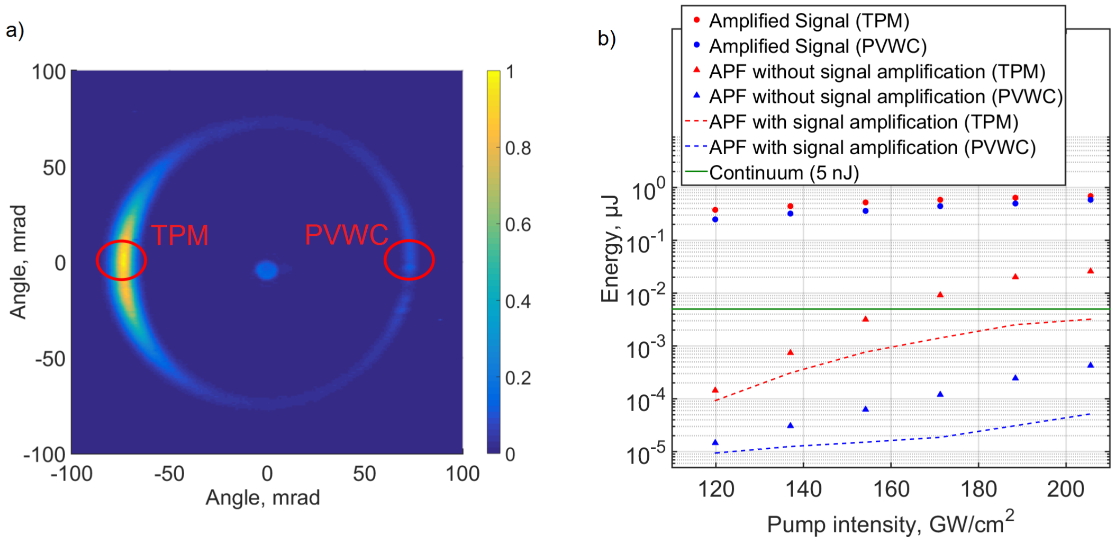

Figure 9: An image of APF cone (a). Energies of amplified signal and APF background for different amplification geometries and pump intensities (b).

by comparing amplified signal energy values measured with the spectrometer and power meter at high pump intensity levels above 160 GW/cm^2. The obtained data (see Fig. 9 (b)) shows that one obtains a bit higher amplified signal energy in the TPM geometry. However, the APF energy level for different interaction geometries differs significantly and the APF energy content at the OPA output is less than 0.1% even in strong amplification saturation regime in the PVWC configuration. When accounting for APF suppression effect (dashed lines in Fig. 9 (b)) one can expect several times lower values of parametric fluorescence. The amplified pulse contrast steadily drops with increasing pump intensity: seed amplification saturates, while the steadily rising contribution of APF from the temporal areas where the level of the seed is low leads to monotonous increase of an incoherent background. Therefore, looking for the best trade-off between high output energy and low APF level, we consider the pump level of 140-170 GW/cm^2 to be an optimum. Further amplification of the white light continuum pulses was performed in two stage NOPA setup and the energy of broadband signal increased up to 25 μJ by using 160μJ of pump pulses.

Benefits of seeding 515 nm pumped NOPA with continuum driven by 1500 nm pulses was also investigated. In this case two-stages NOPA setup (see Fig. 10) had two inputs: frequency doubled 430 μJ pulses at 515 nm from Yb:KGW laser system and a few microjoule energy pulses at 1500 nm from the difference frequency generator pumped by the same laser (see Fig. 4 for details). Beam diameter of the continuum generated in 4 mm sapphire was reduced and slightly focused close to the amplification crystal by the telescope of two spherical mirrors R=+100 mm and R=+20 mm. Noncollinear parametric amplification was carried out in Type-I 2 mm

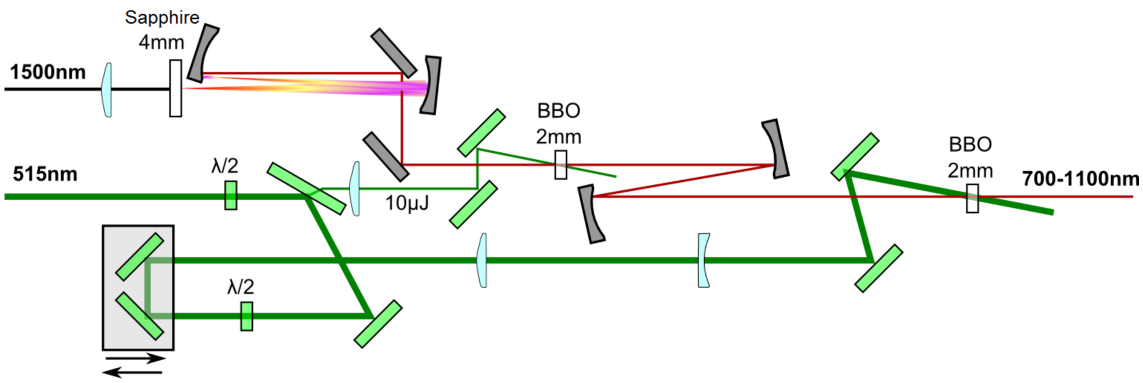

Figure 10: Two-stages NOPA setup.

long BBO crystals. Longer wavelength driven white light generator produced the

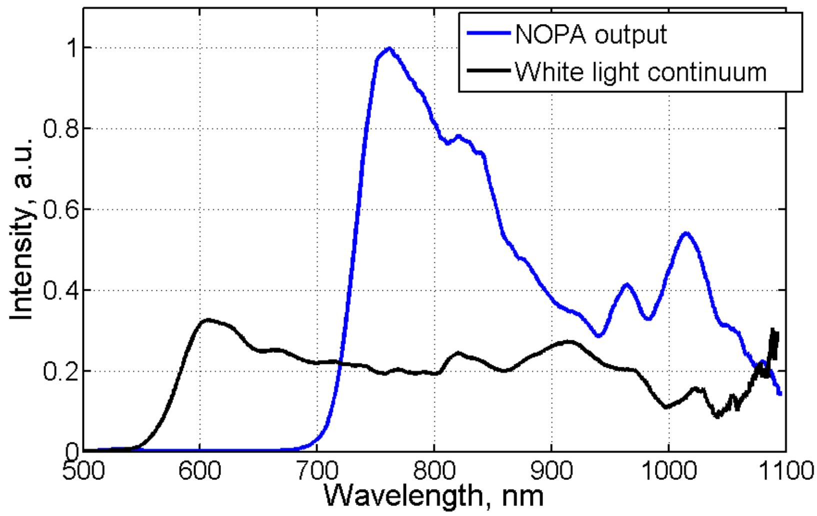

Figure 11: Output spectrum from two-stages NOPA and spectrum of white light continuum seed generated by pulses at 1500 nm.

seed pulses with smooth spectrum over all amplification bandwidth (see Fig. 11). This NOPA setup did not require the use of any filter to block the remaining pump radiation. This helped to reduce the chirp of NOPA seed pulses and the pulses with broader bandwidth could be amplified under the same short pump pulse. In NOPA seed pulses were amplified up to 70 μJ, while the Fourier limit of the spectrum (shown in Fig. 11) was <5 fs FWHM, which corresponds to sub-two cycle pulse centered at $\sim$850 nm.

Chapter 4: High average and peak power OPCPA systems

The fourth chapter presents the results on development of high power OPCPA system that is based on tandem femtosecond and picosecond parametric amplifiers.

The spectrum of the mode-locked Yb:KGW oscillator pulses overlaps well with the spectral amplification bands of Yb:KGW and Nd:YAG amplifiers. Therefore, all-optical synchronization of our system is straightforward and reliable. Regarding pulse stretching and compression, we utilize the down-chirped pulse amplification scheme, where pulses are negatively chirped prior to amplification and compressed in bulk glasses after being amplified. The main rationale for this decision is the higher throughput of properly AR-coated glasses, as compared to a diffraction grating compressor. In our setup, the main part of the stretching is performed by a grism pair because of the good match of the dispersion shapes of glasses and grisms [24]. An AOPDF (Dazzler, Fastlite Inc.) is inserted before the first picosecond amplification stage for fine dispersion control. Amplified pulses were compressed in a series of glasses down to about 600 fs, and finally compressed to minimum duration by the positive dispersion chirped mirrors.

The multi-stage power amplifier is designed to provide the bandwidth for sub-10 fs pulses with energy of 35-50 mJ. Therefore numerical model of the pulse compression in bulk of glass was applied in order to find a save intensity level avoiding self-action effects during pulse shortening. The split-step Fourier method was used for solving generalized nonlinear Schrödinger equation and parameter of B-integral was calculated by accumulating maximum values of nonlinear phase shift. It was found that, in case of pulse compressor consisting of 400 mm long SF57 glass, 100 mm long fused silica and chirped mirror with total GDD of +350 fs^2, final pulse intensity should be kept below 150 GW/cm^2 in order to say that the nonlinear effects are negligible. Therefore the super-Gaussian beam of 50 mJ, 8 fs pulses has to be enlarged to at least 75 mm diameter at FWHM before entering in to compressor.

The first of two OPCPA system (see Fig. 12) was build by employing flashlamp pumped Nd:YAG amplifiers operating at 10 Hz repetition rate (Ekspla Ltd., for details see [25]).

The broadband seed pulses are generated and pre-amplified in a white light continuum seeded femtosecond NOPA. A two-stage cascaded second harmonic (SH) generation scheme was used for the conversion of 380 mJ of the fundamental Nd:YAG harmonic (FH) pulse into two SH pulses with different temporal shapes. After the first SHG (Type I, 10 mm long DKDP crystal), SH pulses with a nearly Gaussian envelope (70 ps FWHM) were generated with 50% efficiency. In the second SHG stage (Type I, 20 mm long DKDP crystal) the remainder of the FH pulse were used for generation of a flat-top SH pulses [26]. This pulse shaping technique providing a favourable conditions for mitigation of the spectral gain narrowing in the high-gain stage of the OPCPA was introduced for the first time. Both picosecond OPCPA

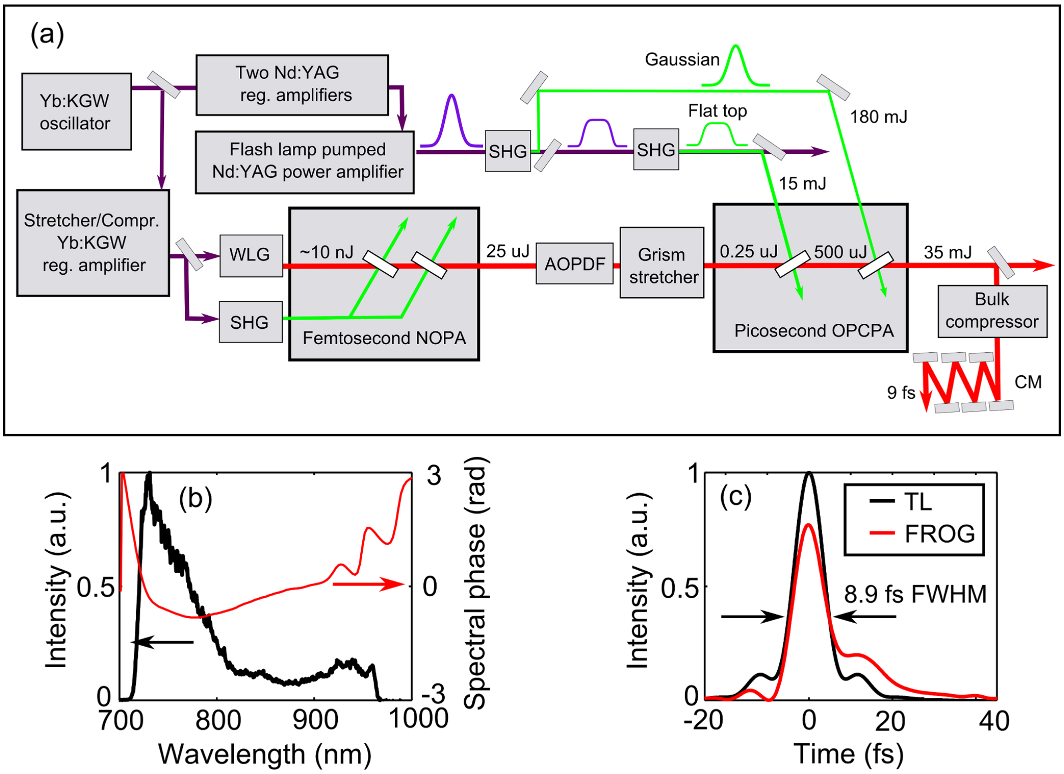

Figure 12: OPCPA system pumped by flashlamp based Nd:YAG laser operating at 10 Hz. (a) General setup. (b) Spectrum of the signal amplified to energy of 35 mJ. (c) Temporal pulse shape as measured by FROG and a transform-limited pulse (TL) with the same spectrum.

stages are based on 5 mm long BBO crystals. The first stage, pumped with 15 mJ, 100 ps pulses focused to a spot of 0.8 mm diameter (FWHM), amplifies the seed pulses to 0.5 mJ. Next, the signal beam is expanded to a diameter of 8 mm (FWHM) to match the main pump beam and amplified to 35 mJ in the second OPCPA stage. This stage is operated at a low gain and a strong saturation to avoid narrowing of the signal spectrum. A typical OPCPA output spectrum is shown in Fig. 12 (b). Wavelengths above 970 nm have undesirable spectral phase modulation, caused by a filter inserted after the WLC generator to block the 1030 nm pump pulses. Therefore, these wavelengths are intentionally filtered out in the grisms. The asymmetry of the spectrum results from the slight asymmetry of the pump pulse in the last OPCPA stage and from the dispersion of the stretcher, since in our case, the shorter wavelengths are more dispersed in time as compared to longer ones, and thus interact with more pump energy per unit spectral interval.

The pulse compressor consists of several rods of H-ZF52A glass (SF-57 equivalent), adding up to a total length of 420 mm, and a 100 mm of fused silica. The final stage of the compression is performed by 6 bounces from the chirped mirrors with a group delay dispersion (GDD) of approximately +50 fs^2/bounce. Due to the small aperture of the H-ZF57A glass rods available in our laboratory at that time, the

OPCPA output was attenuated to 50 μJ before being sent to the compressor, thus avoiding nonlinear propagation effects.

The compressed pulses were characterized simultaneously by chirpscan [27], utilizing the AOPDF in the stretcher, and Frequency Resolved Optical Gating (FROG) [28]. The chirpscan trace of the compressed pulse exhibits good left-to-right symmetry, which is a strong indication of a nearly transform-limited pulse. The FROG trace was measured without altering dispersion settings of the system and the corresponding FROG inversion results are shown in Fig. 12 (c). Although the FROG measurement shows a certain amount of residual chirp, the measured pulse duration differs by less than 9% from the transform limit and ∼60% of the pulse energy is delivered within a ±5 fs temporal window.

In the last section of the fourth chapter a brief description of OPCPA system delivering passively CEP stabilized few cycle pulses with energies up to 45 mJ at 1 kHz repetition rate is presented. This amplification chain (see Fig. 13) of broadband

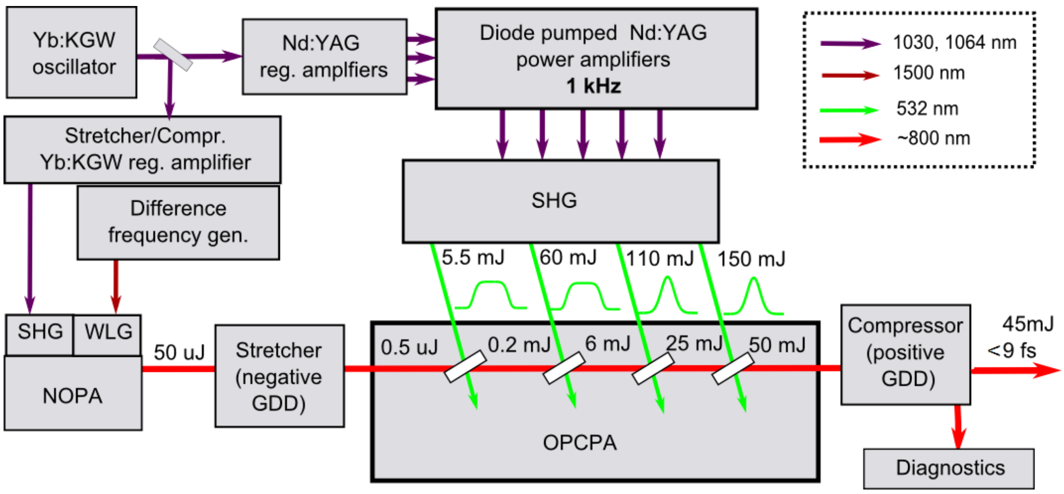

Figure 13: The layout OPCPA system delivering passively CEP stabilized few cycle pulses with energies up to 45 mJ at 1 kHz repetition rate.

signal pulses consists of a femtosecond frontend pumped by an Yb:KGW laser system (Pharos, Light Conversion Ltd.) and 4 picosecond amplification stages pumped by an Nd:YAG laser system (Ekspla Ltd.). All diode pumped double-pass Nd:YAG amplifiers deliver five beams of ∼80 ps pulses at 1064 nm, four of them with energies up to 120 mJ. The energy up to 150 mJ of pulses at 532 nm for pump of last OPCPA stage was obtained by combining two fundamental pulses in one BBO crystal. The femtosecond frontend, described in detail in Chapter 2 and 3, delivers broadband, background-free, passively CEP-stabilized pulses, which are stretched in a grism setup fallowed by AOPDF and amplified to 50 mJ in the BBO based noncollinear OPCPA stages. The spectrum of amplified signal is shown in Fig. 14 (a). The beam after last amplification stage is expanded to diameter of ∼80 mm and

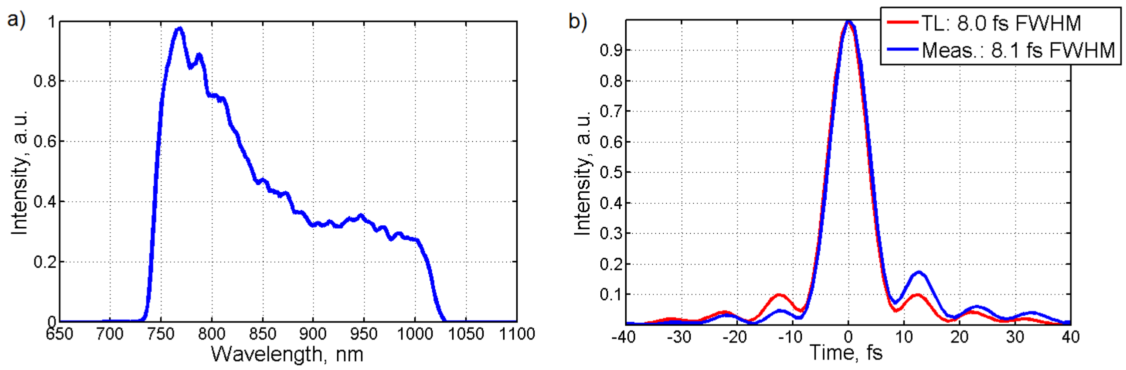

Figure 14: OPCPA system pumped by flashlamp based Nd:YAG laser operating at 10 Hz. (a) General setup. (b) Spectrum of the signal amplified to energy of 35 mJ. (c) Temporal pulse shape as measured by FROG and a transform-limited pulse (TL) with the same spectrum.

passed through a two piece of 175 mm long SF57 glass and 100 mm long fused silica with a clear aperture of 100 mm. Then 3.5 % of the signal energy was reflected from

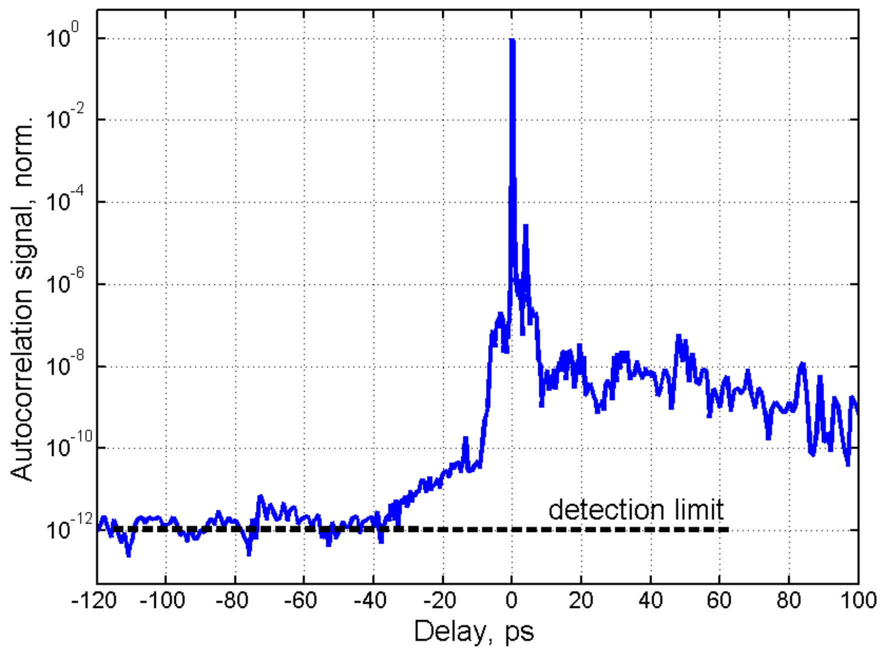

Figure 15: Measurement of the pulse contrast.

an uncoated fused silica window for diagnostic purpose, while the main part of the pulse was directed to a vacuum chamber towards setup of application. The final compression of pulses from ∼500 fs to <10 fs was implemented in both channels by sets of 8 chirped mirrors. Fig. 14 (b) shows a pulse profile measured by self-referenced spectral interferometry [29]. The measured pulse duration is 8.1 fs corresponding to <3 optical cycles at 850 nm. Output pulse CEP stability <250 mrad has been measured over tens of minutes employing slow phase drift by controlling acoustic wave delay in AOPDF. The temporal contrast of the compressed pulse was measured by high dynamic range third order autocorrelator [30]. An amplified fluorescence background is observed between -35 and +100 ps (see Fig. 15), however the background magnitude ratio to the main pulse intensity at 10 ps before the main pulse is only 5×10^{-11}, and stays below the detection limit of $\sim 5 \times 10^{-12}$ before the onset of the pump pulse induced APF at -35 ps. Such a high contrast ratio is essential advantage trying to avoid the creation of a preformed plasma prior the main pulse reaches the target.

This OPCPA system will be installed in the Extreme Light Infrastructure laser facility ELI-ALPS [31].

Main results and conclusions

1. The numerical aperture of NA≈0.017 was found to be an optimum for the reliable broadband continuum generation in 4 mm long sapphire plate pumped by of ∼200 fs pulses centered at 1030 nm providing the lowest continuum sensitivity to pump energy fluctuations.

2. Optimized active CEP stabilization of the Yb:KGW laser system and OPA setups pumped by this laser was demonstrated. Realization of the two feedback loops allowed us to reduce the CEP noise down to 170 mrad for pulses amplified in Yb:KGW laser amplifier and down to 220 mrad for pulses amplified in continuum seeded NOPA.

3. We have demonstrated a direct CEP stabilization of an Yb:KGW laser system with residual phase jitter reduced to <100 mrad level. The CEP noise was measured after laser amplifier operating at 600 kHz repetition rate and compensated by difference frequency generation between the optical wave and an acoustic wave in a frequency shifter.

4. The source of the broadband passively CEP stabilized seed pulses for the OPCPA system with spectra spanning over an octave was developed. These white light continuum pulses with CEP noise reduced bellow 100 mrad were generated by the pulses from difference frequency generator driven by the second harmonic of Yb:KGW laser system and supplemented with slow feed back loop for delay control.

5. We have demonstrated that the intensity level of the amplified parametric fluorescence generated in the noncollinear optical parametric amplifier is strongly affected by a spatial walk-off of the narrow pump beam. This unwanted background radiation which deteriorates the temporal contrast of amplified signal can be reduced by an order of magnitude when Pointing vector compensating geometry of type-I BBO crystal is used.

6. A table-top OPCPA system pumped by fs Yb:KGW and ps Nd:YAG lasers and operating at 10 Hz repetition rate was developed. By employing a femtosecond

Yb:KGW laser driven WLC generator and NOPA stages, a compact grism and an AOPDF based pulse stretcher, we have obtained high spatio-temporal quality output pulses with the energy of up to 35 mJ. Attenuated output pulses were compressed down to 8.9 fs. The minimum aperture of glass blocks for 50 mJ pulse compression in bulk material without significant pulse envelope and spectrum distortion was evaluated by numerical modeling pulse propagation in a nonlinear Kerr media.

7. We have developed the OPCPA system operating at 1 kHz employing broadband seed pulses from passively CEP stabilized frontend and high energy pump from multi-beam diode pumped Nd:YAG laser amplifiers. The signal pulses were amplified up to 50 mJ and compressed down to sub 9 fs with compressor throughput of ∼90 %. CEP noise was reduced down to 250 mrad by controlling delay of acoustic wave in AOPDF. The seed pulse pre-amplified by femtosecond pulses enables to get temporal contrast as high as 10^{10} at 10 ps before the main pulse.

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