Summary of the Ph.D. thesis

Amplification of ultrashort pulses in next generation Ti:Sapphire laser systems

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Szeged

2018

I. Introduction

Investigation of ultrafast physical, biological, and chemical processes in time was made possible by utilizing short light flashes, which can be generated by lasers. These ultrashort light pulses can possess extremely large peak power by increasing the energy stored in them, reaching even the petawatt (1 PW = 10^{15} W) regime. By using high intensity lasers, investigation of the nonlinear response of matter could have been performed, which led to the observation of light fields pulsating in a shorter time scale, than the femtosecond (1 fs = 10^{-15} s) pulses produced by lasers. This way, attosecond (1 as = 10^{-18} s) pulses were obtained in the extreme ultraviolet and x-ray region of the electromagnetic spectrum, and a new level of spatio-temporal localization of light pulses was reached.

Beside the amplitude, the phase of the electric field gains a significant role in case of experiments and secondary radiation sources, driven by ultrashort pulses. For light pulses containing only a few optical cycles, or just a single cycle, the phase between the carrier wave and the envelope of the electric field, the so-called *carrier-envelope phase (CEP)* has a significant effect on the light-matter interaction. Fluctuation of the phase, the temporal duration, and so the peak intensity also plays a critical role in the outcome of different experiments. The operation of a laser system depends on the environmental conditions, which affect the stability of pulse parameters, as well.

Generation of high intensity femtosecond pulses is mostly performed by using laser systems based on sapphire crystals doped with titanium ions (*Ti:Sapphire, Ti:Sa*). Due to the excellent physical properties and broad emission spectrum of Ti:Sa, it can support the generation of high peak and average power laser pulses.

The aim of my thesis was the investigation of phase instabilities upon Ti:Sa amplification, and the study of high peak and average power amplifier stages. Experimental results presented in this thesis were obtained in the *TeWaTi Femtosecond Laser Laboratory* of the Department of Optics and Quantum Electronics of the University of Szeged, and in the *Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy im Forschungsverbund Berlin e.V.* Numerical simulations were performed by using the computational infrastructure of the ELI-ALPS Research Institute (ELI-HU Non-Profit Ltd.).

II. Preliminaries and objectives

My scientific results are part of the research and development project dedicated to the design and realization of the second arm of the High Field Laser of the ELI-ALPS infrastructure, providing high pulse energy at a high repetition rate. According to the planned laser parameters, the HF-100 system will provide CEP-stabilized pulses with at least 50 TW peak power at 100 Hz repetition rate, and with 10 fs pulse duration. The objectives for the scientific work presented in this thesis are listed in the following.

Investigation of the CEP-stability issues in the subsystems of Ti:Sa based *chirped pulse amplification* (*CPA*) systems has been carried out for the oscillators, stretcher and compressor stages. On the other hand, the CEP drift and noise originating from the crystals of Ti:Sa amplifier stages has never been investigated in detail before.

C1. The first aim of my thesis was to investigate the CEP drift in the crystals of water-cooled Ti:Sa amplifiers. I will determine the effects of laser amplification on the CEP, experimentally. Furthermore, I will determine the effects of cooling instabilities of the gain medium on the CEP of the amplified pulses.

In high average power Ti:Sa amplifiers the gain medium is exposed to high thermal load due to the high power pumping. The increased temperature in the pumped volume leads to beam distortions due to changes in the refractive index, thermally originated mechanical stress and depolarization effects. However, if the temperature of Ti:Sa is decreased to cryogenic values (< 80 K), the thermal conductivity of this material becomes substantially higher, which leads to lower thermal gradients. On the other hand, cryogenic cooling of the laser crystal requires vacuum technology to be applied, which can lead to mechanical vibrations in the optical setup.

C2.a. I will investigate the effects of amplification on the spectral phase noise in a cryogenically cooled Ti:Sa amplifier. I will determine the spectral phase noise contributions of the vacuum and cryogenic systems. Also, I plan to identify the noise sources of mechanical origin in the different operational stages of the amplifier.

C2.b. I will determine the thermally and mechanically originated CEP noise contributions of the Ti:Sa amplifier. Moreover, I will investigate the statistical distribution of the CEP noise of amplified pulses for different repetition rates of operation.

Absorbed pump power in the gain medium in case of ultrahigh peak power Ti:Sa laser systems significantly limits the repetition rate, and so the average power of amplified pulses. State-of-the-art 100 TW class amplifiers can operate maximally at 10 Hz, while PW class stages at 1-3 Hz repetition rates. However, increasing the number of pulses per second is highly beneficial for many applications, by which the time duration of a measurement could be decreased, and the stability of amplified pulse parameters could be improved, substantially. For this, a highly efficient cooling scheme needs to be applied, which could be reached by using the *thin disk (TD)* concept, developed for average power scaling of Yb-doped lasers. Application of the TD technique to Ti:Sa could decrease the temperature gradient in the crystal, and mitigate the spatial distortions of the amplified pulses.

C3.a. I will investigate the possibilities of the realization of ultrahigh peak power TD Ti:Sa amplifier stages. I will perform simulations on the temperature distribution in conventional and TD amplifier stages.

C3.b. I will investigate the amplification in a water-cooled TD laser head experimentally. I will measure the temperature change and the steady-state temperature profile in the Ti:Sa crystal during pumping. Finally, I will determine the wavefront distortion due to thermal effects in the amplifier crystal induced by the pump pulses.

The TD concept could support amplification of pulses at significantly higher repetition rates, and so with much higher average power, than the currently available values with Ti:Sa amplifiers. To determine the scaling limits of this technique, simulations are required for possible geometries and laser parameters.

C4.a. I will build a numerical model for a possible TD Ti:Sa final amplifier of the HF-100 system. I will determine the effect of water-cooling on the temperature profile in the gain medium with single- and double-sided cooling arrangements.

C4.b. My final aim was to investigate the upscaling prospects of the double-sided cooling scheme for TD Ti:Sa amplifiers. I plan to determine the thermal conditions of amplifiers with higher output energy at different repetition rates, with single and double disk laser heads.

III. Methods of investigation

During my research activity, several experimental techniques, devices and software were used, which are summarized in the following points.

M1. I have performed measurements on the CEP drift and noise of water-cooled Ti:Sa amplification by using the method of *spectrally resolved interferometry (SRI)*. I have built an asymmetrically split Mach-Zehnder interferometer with a three-pass amplifier in its sample arm. Stretched and amplified pulses of a CPA system were coupled to the interferometer. As a pump source, a Nd:YLF laser with a long term energy stability of 0.2% r*oot mean square (RMS)* was used. For the detection of the interference fringes I have used a high-resolution imaging spectrograph. The interference fringes were averaged along the spatial axis, which resulted in spectrally resolved fringes. The fringes were evaluated by using the Fourier-transformation method, for which I have compiled a code in MATLAB environment. Based on the spectral phase extracted from the fringes, I have performed polynomial fitting to determine the phase derivates, and the CEP drift. I have conducted measurements on a second amplifier stage pumped with more energetic pulses, in which a Ti:Sa crystal with smaller thickness was investigated. By using the temperature and frequency dependence of the refractive index of the crystal, I have built a simple model to compare the experimentally obtained results on the effect of cooling on the CEP with theory.

M2.a. I have investigated the spectral phase fluctuations of a cryogenically cooled, double-pass Ti:Sa amplifier by using the SRI technique. To decrease the noise of the measurement, I have built the amplifier in the sample arm of a compact Michelson-type interferometer. The Ti:Sa crystal in its copper mount was placed in a compact vacuum chamber, and attached to the cold finger of a cryogenic refrigerator, which was operated with liquid helium, and had a minimal temperature of around 30 K. During the operation of the cryogenic cooler, I have reached a minimal pressure of 10^{-6} mbar. I have built and calibrated a high-resolution spectrometer with a line scan camera capable of reaching 70 kHz frame rate for the detection of the interference fringes. For the evaluation, I have used the Fourier-transformation method. I have measured the spectral phase noise during different operation stages of the setup, i.e. operation of the vacuum and cryogenic systems, without pumping the Ti:Sa crystal. To measure the effect of amplification on the spectral phase, I have coupled stretched and amplified pulses from CPA system to the interferometer. For the investigation of the phase noise spectrum of the amplifier, I have performed a high-speed measurement with 10 kHz acquisition rate of the interference fringes, by using pulses from the Ti:Sa oscillator of the CPA system. I have also measured the mechanical vibrations by using an accelerometer attached to the optical table.

M2.b. To determine the CEP drift in the amplifier, I have measured the dependence of the zero and first order spectral phase derivates on the length of the reference arm of the interferometer, and on temperature of the Ti:Sa crystal. I have investigated the effect of amplification on the phase by exciting the Ti:Sa crystal with pump pulses of constant 10 mJ energy. I have set a gain of ten, to compensate for the asymmetrical split of the interferometer. For pumping the amplifier, I have used the same pump laser, which was utilized in the water-cooled amplifier experiments. By turning off the cryogenic refrigerator, I have also investigated the effect of amplification on the spectral phase noise around the minimal temperature with a decreased measurement noise.

M3.a. I have built a numerical model by using the *finite element method (FEM)* in the COMSOL Multiphysics software for the investigation of cooling in TD and conventional Ti:Sa final amplifier stages. By using a constant temperature boundary condition at the cooled surfaces, I have obtained stationary temperature results for the two types of amplifiers, with ideal cooling.

M3.b. I have contributed to the experimental demonstration of the first TD Ti:Sa amplifier stage with the *extraction during pumping (EDP)* method by building the optical setup and performing diagnostics. The EDP-TD amplifier was operated by using the seed and pump pulses of the final cryogenically cooled amplifier of a 100 TW peak power laser system. The active mirror geometry consisted of three passes for the seed pulses, and two passes for the pump pulses from three pump lasers with 2 J pulse energy at a maximal repetition rate of 10 Hz, each. By using a photodiode in front of the Ti:Sa disk, I have measured the scattered fluorescence from the crystal to investigate transversal lasing. By using a thermal camera, I have investigated the temperature changes in the Ti:Sa crystal during pumping. I have used a Shack-Hartmann wavefront sensor to measure the wavefront distortion due to the temperature gradient in the crystal induced by pump pulses. For this, I have used the beam of a He-Ne laser, which was reflected from the back side of the Ti:Sa crystal.

M4.a. I have built a two dimensional FEM numerical model, which simulated the cooling of the Ti:Sa crystal in a 100 TW class amplifier module. I have tested single- and double-sided cooling arrangements, where both the coolant water flow and the heat transfer in both the crystal and the coolant were incorporated to the model. The geometry of the laser head was provided the engineers of ELI-ALPS. I have optimized the cooling efficiency by changing with the coolant flow velocity inside the coolant channels.

M4.b. I have performed simulations for amplifier modules with higher peak power by increasing the pump energy, and the Ti:Sa disk size. I have set the diameter of the Ti:Sa crystal and the pump beam in order to obtain the same pump energy fluence in all cases. Moreover, I have also investigated the effect of contra-directional flows, multiple crystals and coolant channels on the temperature distribution in the laser head.

IV. New scientific results

My scientific results are summarized in the following thesis points.

T1. I have investigated the CEP stability of water-cooled Ti:Sa amplification for different laser parameters. I have found a CEP drift of 11 mrad/°C/mm for unit temperature change, normalized to the length of the crystal. I have measured a linear increase of the CEP noise with the pump energy, and an exponential like decrease with the repetition rate. Within the sensitivity of the measurement, I have not found any effect of the seed energy on the CEP drift and noise [TP1].

T2.a. I have measured the spectral phase noise of a cryogenically cooled Ti:Sa amplifier in different operational stages of the vacuum- and cooling systems. Spectral phase noise contributions of around 50 mrad RMS for both the vacuum-, and the cryogenic systems have been found, individually [TP2]. Moreover, I have compared the spectral phase noise spectra with the frequency distribution of the mechanical noise measured in the optical setup, and I have identified the main noise sources.

T2.b. I have measured the spectral phase noise of the amplified pulses for different repetition rates. Statistics of the thermally and mechanically originated CEP noise contributions of the amplifier have been determined. I have found CEP noise values less than 12 mrad

RMS for the thermal, and less than 1 mrad RMS for the mechanical contributions, respectively [TP2].

T3.a. I have suggested the EDP method to be used in combination with the TD technique for the average power scaling of Ti:Sa final amplifiers. By using numerical simulations, the thermal conditions of 2 PW peak power amplifiers operated with conventional and the EDP-TD methods have been compared. I have found, that the EDP-TD technique significantly improved the distribution of temperature in the gain medium [TP3].

T3.b. I have experimentally demonstrated the operation of a 100 TW class Ti:Sa EDP-TD final amplifier. By performing single shot experiments, an amplified pulse energy of 2.6 J with 5 J of absorbed pump and 0.5 J of input seed energy has been reached. I have measured the temperature change in the Ti:Sa crystal in case of pumping with pulses of 4 J energy at 10 Hz repetition rate, without amplification of seed pulses. I have found a uniform distribution of temperature with a peak value of 30.3 °C. Finally, I have measured the wavefront distortion due to pump pulses for two passes through the crystal [TP4].

T4.a. I have conducted two dimensional numerical simulations on the cooling efficiency of a possible EDP-TD Ti:Sa final amplifier of the HF-100 laser. I have investigated single- and double-channel cooling arrangements. I have shown, that by using a 4 mm thick crystal in case of the double-channel cooling, the temperature difference can be lowered down to 35 °C [TP5].

T4.b. I have investigated EDP-TD amplifiers with higher peak power at different repetition rates, up to the 8.5 PW level. I have further increased the cooling efficiency by using double crystal arrangements with three coolant channels. This technique holds promise on making amplifiers with multiple kW average, and multiple PW peak powers feasible [TP5].

V. Publications

Articles in peer reviewed journals related to the thesis points

TP1. A. Borzsonyi, R. S. Nagymihaly, K. Osvay, “Drift and noise of the carrier-envelope phase in a Ti:Sapphire amplifier,” Laser Phys. Lett. **13**, 015301 (2016).

TP2. R. S. Nagymihaly, P. Jojart, A. Borzsonyi, K. Osvay, “Spectral Phase Noise Analysis of a Cryogenically Cooled Ti:Sapphire Amplifier”, Opt. Express **25**, 6690-6699 (2017).

TP3. V. Chvykov, R. S. Nagymihaly, H. Cao, M. Kalashnikov, K. Osvay, “Design of a thin disk amplifier with extraction during pumping for high peak and average power Ti:Sa systems (EDP-TD),” Opt. Exp. **24**, 3721-3733 (2016).

TP4. V. Chvykov, H. Cao, R. Nagymihaly, M. P. Kalashnikov, N. Khodakovskiy, R. Glassock, L. Ehrentraut, M. Schnuerer, and K. Osvay, „High peak and average power Ti:sapphire thin disk amplifier with extraction during pumping,” Opt. Letters **41**, 3017-3020 (2016).

TP5. R. S. Nagymihaly, H. Cao, D. Papp, G. Hajas, M. Kalashnikov, K. Osvay, and V. Chvykov, “Liquid-cooled Ti:Sapphire Thin Disk amplifiers for high average power 100 TW systems,” Opt. Express **25**, 6664-6677 (2017).

Other articles in peer reviewed journals

P1. R. S. Nagymihaly, H. Cao, P. Jojart, M. Kalashnikov, A. Borzsonyi, V. Chvykov, R. Flender, M. Kovacs, and K. Osvay, “Carrier-envelope phase stability of a polarization-encoded chirped pulse Ti:Sapphire amplifier,” J. of the Opt. Soc. of Am. B, megjelenés alatt (2018).

P2. H. Cao, M. Kalashnikov, K. Osvay, N. Khodakovskiy, R. S. Nagymihaly, and V. Chvykov, “Active spectral shaping with polarization encoded Ti:Sapphire amplifiers for sub 20-fs multi-TW systems,” Laser Phys. Lett., megjelenés alatt (2018).

Important conference presentations

KE – *oral presentation*, * – *presenter*

KE.1. R. Nagymihaly, P. Jojart, A. Borzsonyi*, and K. Osvay, "Increase of Carrier-Envelope Phase Noise in Water and Cryogenically Cooled Ti:Sapphire Amplifiers," in *High-Brightness Sources and Light-Driven Interactions*, 20-22 March 2016, Long Beach, California, USA, paper HS3B.4.

KE.2. M. P. Kalashnikov*, H. Cao, K. Osvay, V. Chvykov, N. Khodakovskiy, and R. Nagymihaly, "Polarization Encoded Chirped Pulse Amplification in Ti:sapphire - a Way Towards Few Cycle PW Lasers," in *Conference on Lasers and Electro-Optics*, 5-10 June 2016, San Jose, USA, paper SM1M.2.

KE.3. V. Chvykov*, H. Cao, R. Nagymihaly, M. Kalashnikov, N. Khodakovskiy, K. Osvay, "New Generation of Ultra-High Peak and Average Power Laser Systems," in *25th Annual International Laser Physics Workshop*, 11-15 July 2016, Yerevan, Armenia, invited talk, paper S4.1.1.

KE.4. V. Chvykov*, H. Cao, R. Nagymihaly, M. Kalashnikov, N. Khodakovskiy, K. Osvay, "Extraction During Pumping for Thin Disc Ti:Sapphire Amplifiers (EDP-TD)," in *25th Annual International Laser Physics Workshop*, 11-15 July 2016, Yerevan, Armenia, paper S4.1.2.

KE.5. R. S. Nagymihaly*, H. Cao, M. Kalashnikov, N. Khodakovskiy, L. Ehrentraut, K. Osvay, V. Chvykov, "Proof-of-principle experiment on a Thin Disk Ti:Sapphire amplifier with Extraction During Pumping (EDP-TD)," in *7th EPS-QEOD Europhoton Conference*, 21-26 August 2016, Vienna, Austria, paper SSL-3.7.

KE.6. H. Cao*, R. S. Nagymihaly, M. Kalashnikov, V. Chvykov, N. Khodakovskiy, K. Osvay, "Towards few cycle PW peak and kW average power Ti:Sapphire laser systems," in *International Conference on Coherence and Nonlinear Optics / International Conference on Lasers, Applications, and Technologies*, 26-30 September 2016, invited talk, paper IWB1.

KE.7. R. S. Nagymihaly*, H. Cao, M. Kalashnikov, N. Khodakovskiy, L. Ehrentraut, K. Osvay and V. Chvykov, "Thin Disk Ti:Sapphire amplifiers for Joule-class ultrashort pulses with high repetition rate," in *SPIE Optics + Optoelectronics*, 24-27 April 2017, Prague, Czech Republic, paper 10238-11.

KE.8. H. Cao*, M. Kalashnikov, K. Osvay, N. Khodakovskiy, R. S. Nagymihaly, and V. Chvykov, "Active spectral pre-shaping with polarization encoded amplifiers," in *SPIE Optics + Optoelectronics*, 24-27 April 2017, Prague, Czech Republic, paper 10238-09.

KE.9. R. S. Nagymihaly*, P. Jojart, A. Borzsonyi, K. Osvay, "Measurement of spectral phase noise in a cryogenically cooled Ti:Sa amplifier," in *SPIE Optics + Optoelectronics*, 24-27 April 2017, Prague, Czech Republic, paper 10238-12 (2017).

KE.10. R. S. Nagymihaly, P. Jojart, A. Borzsonyi*, K. Osvay, "Spectral phase instabilities during amplification in Ti:Sapphire," in *Conference on Lasers and Electro-Optics*, 14-19 May 2017, San Jose, California, USA, paper SM3I.7.

KE.11. V. Chvykov*, R. Nagymihaly, H. Cao, M. Kalashnikov, K. Osvay, "High Repetition Rate Thin Disk Ti:Sa Amplifiers for Sub-PW class Laser Systems," in *Conference on Lasers and Electro-Optics*, 14-19 May 2017, San Jose, California, USA, paper STu1O.5.

KE.12. V. Chvykov*, R. Nagymihaly, H. Cao, M. Kalashnikov, and K. Osvay, "High Peak Power and Repetition Rate Laser Systems with Thin Disk Ti:Sa Amplifiers," in *Frontiers in Optics 2017*, 18-21 September 2017, Washington, D.C. USA, paper LW5F.2.

KE.13. V. Chvykov*, R. Nagymihaly, H. Cao, M. Kalashnikov, K. Osvay, "Ti:Sapphire as Perspective Active Media for Thin Disk Lasers and Amplifiers," in *Advanced Solid State Lasers Conference*, 1-5 October 2017, Nagoya, Aichi, Japan, paper AW4A.2.

KE.14. R. Nagymihaly, H. Cao, P. Jojart, M. Kalashnikov, A. Borzsonyi, V. Chvykov*, K. Osvay, "Carrier-Envelope Phase Stability in a Polarization-Encoded Ti:Sa amplifier," in *Advanced Solid State Lasers Conference*, 1-5 October 2017, Nagoya, Aichi, Japan, paper AW1A.5.

KE.15. R. S. Nagymihaly*, P. Jojart, A. Borzsonyi, H. Cao, M. Kalashnikov, V. Chyvkov, J. Limpert, T. Mocek, and K. Osvay, "Investigation of spectral phase stability issues in ultrafast laser systems by spectrally resolved interferometry," *International Conference on Extreme Light*, 6-9 November 2017, Szeged, Hungary.

KE.16. M. Kalashnikov*, V. Chvykov, H. Cao, R. Nagymihaly, N. Khodakovskiy, "Future of Ti:Sapphire lasers: combining high peak and average power," *International Conference on Extreme Light*, 6-9 November 2017, Szeged, Hungary.