I. Introduction

Nowadays, the length of the shortest achievable laser pulses in the visible and near infrared region reached the cycle length of the light wave. The results of experiments using these so-called single-cycle pulses with a length of only a few femtoseconds strongly depend on the temporal shape of the electric field. For a quantitative description of the position of the electric field, the term Carrier-Envelope Phase (CEP) was introduced. Due to the well known fact, that the carrier wave propagates by the phase velocity, while the pulse envelope does by the group velocity, pulse train of a laser oscillator has a changing CEP from pulse to pulse.

The chase for generation of shorter and even shorter light pulses with well-controlled parameters (like CEP, spectra, pulse shape, beam profile, ...etc.) is not only a topic of fundamental scientific research and development. On the contrary, it is mostly driven by the need of the scientific community for exceptional measurement tools. Among those, the attosecond pulse generation and precision laser spectroscopy are to be emphasized, which are especially sensitive to changes of CEP.

Attosecond pulses are generated by a process called High Harmonic Generation, where multi-photon absorption provided by the high peak intensity of an ultrashort laser pulse pulls electrons off the targeted atoms, and when the electric field changes its sign, those electrons are collided into the atoms. At the recombination, radiation of short pulse trains in UV light and X-rays occurs. If the utilized laser pulse has only one optical cycle of the electric field, it depends on the correct CEP, whether one can generate a single attosecond pulse, or not. By using pulses of multiple optical cycles, trains of short pulses can be generated in the default case. But recently, techniques have been invented to overcome this limitation, and to generate single attosecond pulses by using longer laser pulses of multiple cycles. Naturally, the single attosecond pulses generated this way also depend on CEP.

For measurements in precision spectroscopy, more and more narrowband light sources are needed, which have a well-known wavelength. The traditional way of achieving this is the synchronization of some microwave devices and infrared lasers to an atomic clock, creating a complicated frequency-conversion chain. At the same time, at the field of ultrashort pulses, lasers with even broader spectral bandwidth were created, and new further spectral broadening solutions were invented. Paradoxically, these developments resulted in a breakthrough for narrow-band precision laser spectroscopy.

The ultimate sources of ultrashort pulses are usually laser oscillators emitting an evenly spaced pulse train. According to Fourier transform, this means, that the broad spectrum (seen on a spectrograph) consists of millions of very narrowband, regularly spaced spectral lines. The spacing of this frequency comb structure equals the repetition rate. If the absolute position of the comb (that depends on the carrier-envelope phase shift) is measured, one has millions of known optical frequencies to experiment with. Moreover, if the parameters of the oscillator are changed, for example, by pushing of a simple fused silica wedge inside the cavity, the frequency comb can be fine-tuned. The frequency comb can be converted by nonlinear optic methods to other wavelength regimes, from NIR to XUV, and even generation of a gamma-ray comb seems possible.

The widespread methods of CEP-shift measurement pose stringent requirements on the laser to be measured, like octave spanning spectra and high enough intensity to drive the involved nonlinear effects. These requirements imply, that precision laser spectroscopy experiments required the use of few-cycle titanium-sapphire lasers. A Ti:S laser is a rather complex device, which is sensitive to slight temperature changes, and needs lot of maintenance. Any further wavelength conversion step adds up to the complexity of the system.

Consequently, scientific topics of attosecond physics and precision laser spectroscopy would profit of a CEP-measurement device, which is capable of measuring laser pulses consisting of dozens of optical cycles, or even pulses with a length of some picoseconds.

II. Aims

The aim of the thesis is to develop a method for CEP-shift measurement, which employs a bandwidth-independent measurement principle, that is usable to measure CEP-shift of many-cycle laser pulses in a reliable manner. In addition, if I can ensure to apply only linear optical elements and processes, then the method would require significantly less input power.

In more details, as a starting point I took the at the that time recently introduced linear measurement method for a detailed investigation. That was based on spectrally and spatially resolved interferometry (SSRI), with a resonant ring in one arm of the Mach-Zehnder interferometer. The CEP shift was resulted from the visibility of the interference fringes. Although this was proven to work, but in practice it was cumbersome to operate and was also a subject of very frequent calibrations.

1. I proposed to develop a relative CEP-shift measurement method, that is based on pure linear optics. My further goals are to simulate the experiment and the effects of the environmental circumstances, and to design the experimental layout.

2. My second goal is to build and test the experimental set-up, and to compare the results of the simulation and the experiment. After that, to prove the function of the method, I intend to do some comparative measurements to one of the widespread CEP-shift measurement methods.

3. Finally, to prove the independence of the all-linear method from the bandwidth of the laser, I intend to do a CEP-shift measurement on a laser system, where this is impossible to do by the widespread methods.

III. Applied methods and tools

1. As the first step, I conducted a detailed numeric simulation in ***MathCad*** software. I made the conclusion, that the measurement method can be highly simplified. I made simulations on parameter changes of the incoming pulse train and changes of the experimental circumstances. In the numeric model, I considered (among others) the round-trip path length difference of the oscillator and the resonant ring, refractive index of air, dispersion of the optical elements in use, and reflectivity of the beam splitters. I calculated the effects of change of the repetition rate of the laser oscillator, and effects of thermal expansion caused by local ± 0.1°C temperature changes, too.

2. The experimental set-up consisted of a ***resonant ring***, a (CE-Optics model CEO-2D-800) imaging ***spectrograph*** and a Berkeley Nucleonics BNC1105 ***counter***, and was automatized using the National Instruments ***Labview*** framework. For the first proof of concept, a home-made ***Ti:S laser*** of the Department of Optics at University of Szeged was utilized. (Bandwidth was 60 nm, and repetition rate was 70,5 MHz.) In the experiment, I just modified the own CEP-shift of the resonant ring by moving the inserted ***isochronic wedge pair***. After successful experiments at Szeged, the set-up was tested in Max Born Institut in Berlin, where a Femtolasers Rainbow ***CEP-shift stabilized oscillator*** (at 84 MHz repetition rate) and an ***f-2f interferometer*** (as a widespread CEP-shift measurement method) was available. Results of the linear and the f-2f phase-shift measurement methods were recorded and compared, while the CEP shift was tuned by moving one element of the intracavity ***fused silica wedge pair***.

3. To prove the bandwidth independence, a ***Ti:S laser*** of LAL laboratory near Paris ***having 2-picosecond transform limited pulse length*** was used. (The oscillator itself was a modified Coherent Mira.) To record the pretty much narrow spectra of this laser, a ***home-made spectrograph*** was built, which employed a 1200 line/mm reflective grating and had a magnification of 15. To change the carrier-envelope phase shift, the ***temperature of the laser crystal***, ***power of the pump laser***, and an intracavity ***isochronic wedge pair*** was used.

IV. New scientific results

1. I modeled an all-linear optical relative carrier-envelope phase shift measurement method. Subsequent pulses of a pulse train can be nearly overlapped in time by a resonant ring. From the resulting spectral interference and the repetition rate of the oscillator one can calculate difference of the CEP shift from the initial value. [T1-T4]

2. I assembled the experimental set-up, and created an active length-stabilizer subsystem for the resonant ring. In a pilot experiment supervised by the widespread f-2f interferometry, I have used the resonant ring (set to 3,546 m

length and stabilized to ±10 nm) to measure CEP-shift of few-cycle pulses with an RMS error as low as ±149 mrad. [T3-T8].

3. I demonstrated the ability of the linear CEP-shift measurement method to control a stabilization method against slow CEP-shift changes of thermal origin. At the experiment an isochronic wedge pair was put into the cavity of a free-running Ti:S laser, and it was controlled through a feedback system by the developed method to eliminate the slow CEP-shift changes to a precision of ±47 mrad. [T3,T4,T9-T11].

4. I measured CEP-shift changes of many-cycle, 2 picosecond pulses for the first time [T3, T4, T12-T14]. By utilizing three different physical effects to change the CEP-shift, I have unambiguously demonstrated, that the developed method is detecting the carrier-envelope phase-shift indeed, even if such long pulses are used. Thus, the method is really bandwidth-independent. By utilizing the experimental device developed to the CEP-shift measurements, I have demonstrated, that gain in a high finesse (F=28000) cavity (used for pulse-stacking) clearly depends on CEP-shift. [T15, T16]

V. Publications

Scientific publications related to the thesis:

[T1] Péter Jójárt, Károly Osvay : *Carrier-envelope phase shift measurement by linear optical method*, National Scientific Students' Associations Conference in Physics, April, 2009. (in Hungarian)

[T2] P. Jójárt, K. Osvay: *A simple linear optical measurement of carrier-envelope phase shift*, International School of Quantum Electronics, Erice, Italy, 10-16 July, 2009

[T3] Péter Jójárt , Ádám Börzsönyi , Károly Osvay : *Carrier-envelope phase shift measurement and stabilization by linear optical method*, Conference of Hungarian Physicists (2013), paper 20.12. (in Hungarian)

[T4] Péter Jójárt , Ádám Börzsönyi , Károly Osvay : *Linear method for measurement of carrier-envelope phase shift,* Fizikai Szemle, 2014 / 7 (in Hungarian)

[T5] P. Jójárt, Á. Börzsönyi, B. Borchers, G. Steinmeyer, K. Osvay: *Agile linear interferometric method for carrier-envelope phase drift measurement*, Optics Letters, **37** (2012) 836-838

[T6] Á. Börzsönyi, P. Jójárt, S. Koke, M. Görbe, K. Osvay: *A simple linear optical measurement of carrier envelope phase shift*, High-Intensity Lasers and High-Field Phenomena (HILAS) 16-18 February, 2011, Istanbul, Turkey, Pres. number: HThD5

[T7] P. Jójárt, Á. Börzsönyi, S. Koke, M. Görbe, K. Osvay: *A Simple Linear Technique for Measuring the Carrier-Envelope Offset Phase of Ultrashort Pulses*, CLEO Science and Innovations, USA, Baltimore, Maryland, 1-6 May, 2011, paper CWI6

[T8] P. Jójárt, Á. Börzsönyi, B. Borchers, G. Steinmeyer, K. Osvay: *General Linear Method for Carrier-Envelope Offset Phase Measurements*, Ultrafast Optics, Monterey, California, September 26-30, 2011, paper Mo12

[T9] P. Jójárt, Á.Börzsönyi, M. Merő, B. Borchers, G. Steinmeyer, K. Osvay: *An all-linear-optical technique for intracavity stabilization of CEP drift*, ISTC-GSI YOUNG SCIENTISTS SCHOOL 2011, Darmstadt, Germany, 10-15 Oct, 2011

[T10] P. Jójárt, A. Börzsönyi, M. Merő, K. Osvay: *An all-linear-optical technique for intracavity stabilization of CEP drift*, Light at Extreme Intesities (LEI) 2011 Conference, Szeged, Hungary 14-18 Nov. 2011, paper L2.9

[T11] P. Jójárt, A. Börzsönyi, M. Merő, K. Osvay : All-linear-optical technique for *intracavity stabilization of CEP drift* CLEO 2012 San Jose, USA 6-8 May 2012 CW1D.5

[T12] P. Jójárt, Á. Börzsönyi, K. Osvay, R. Chiche, E. Cormier, R. Flaminio, C. Michel, L. Pinard, V. Soskov, A. Variola, F. Zomer: *An all-linear-optical technique for relative CEP-shift measurement of picosecond pulses*, Lézer Tea (2014), poster

[T13] P. Jójárt, Á. Börzsönyi, V. Soskov, F. Zomer, R. Chiche, E. Cormier, K. Osvay: *Carrier-envelope phase drift measurement of picosecond pulses by an all-linear-optical means*, Optics Letters **39** (2014) 5913-5916

[T14] Á. Börzsönyi, P. Jójárt, R. Chiche, V. Soskov, F. Zomer, E. Cormier, K. Osvay: *Carrier-envelope Phase Drift Detection of Picosecond Pulses*, XVIIIth International Conference on Ultrafast Phenomena, 8 - 13 July 2012, Lausanne, Switzerland

[T15] P. Jójárt, A. Börzsönyi, R. Chiche, V. Soskov, A. Variola, F. Zomer, E. Cormier, K. Osvay: *Carrier-envelope Phase Drift of Picosecond Frequency Combs from an Ultrahigh Finesse Fabry-Perot Cavity*, Conference on Lasers and Electro-Optics 2013. jun. 9-14, San Jose, USA

[T16] Á. Börzsönyi, R. Chiche, E. Cormier, R. Flaminio, P. Jójárt, C. Michel, K. Osvay, L. Pinard, V. Soskov, A. Variola, F. Zomer: *External cavity enhancement of ps pulses with 28000 cavity finesse*, Appl. Optics. **52** (2013) 8376-8380

Further publication is referred journal:

[A] H. Tóháti, Á. Sipos, G. Szekeres, A. Mathesz, A. Szalai, P. Jójárt, J. Budai, Cs. Vass, A.Kőházi-Kis, M. Csete, Zs. Bor, *Surface plasmon scattering on polymer-bimetal layer covered fused silica gratings generated by laser induced backside wet etching*, Applied Surface Science **255** (2009) 5130-5137

Further conference proceedings:

[B] Péter Jójárt, Katalin Kopasz, Mihály Görbe, Károly Osvay: *Development of a control-software for a pulsed, frequency-doubled Nd:YAG laser*, National Scientific Students' Associations Conference in Computing, April 2007. (in Hungarian)

[C] H. Tóháti, Á. Sipos, G. Szekeres, A. Mathesz, A. Szalai, P. Jójárt, J. Budai, Cs. Vass, A. Kőházi-Kis, M. Csete, Zs. Bor, *Surface plasmon coupling on polymer - bimetal layer covered fused silica gratings generated by laser induced backside wet etching*, EMRS 2008, Strasbourg, France, paper B/PI/56

[D] Á. Börzsönyi, P. Jójárt, M. Kovács, M. Görbe, K. Osvay , *Independent Control of Arbitrary Dispersion Order of High Intensity Laser Pulses*, High-Intensity Lasers and High-Field Phenomena (HILAS) 16-18 February, 2011, Istanbul, Turkey, Pres. number: HWC9

[E] M.Görbe, Á. Börzsönyi, P. Jójárt, M. Kovács, K. Osvay, *Independent control of arbitrary orders of dispersion at the high power end of CPA lasers* ,XXXI ECLIM 2010, Budapest, Hungary, paper: P13.

[F] Á. Börzsönyi, M. Görbe, P. Jójárt, M. Kovács, K. Osvay: *Independent control of arbitrary high order dispersion of high intensity laser pulses*, ICUIL, 26 Sept - 01 Oct, 2010, Watkins Glen, USA

[G] M. Kovács, Á. Börzsönyi, P. Jójárt, K. Osvay *Independent control of arbitrary dispersion order of high power ultrashort pulses*, Light at Extreme Intesities (LEI) 2011 Conference, Szeged, Hungary 14-18 Nov. 2011, paper L2.11

[H] Á. Börzsönyi, R.S. Nagymihály, P. Jójárt, K. Osvay: *Carrier-Envelope Phase Noise of Ultrashort Pulses in a Ti:Sapphire Amplifier*, Conference on Lasers and Electro-Optics 2013. jun. 9-14, San Jose, USA

[I] Ádám Börzsönyi, Roland Sándor Nagymihály, Péter Jójárt, Károly Osvay: *Phase noise of ultrashort laser pulses in a Ti:S amplifier,* Conference of Hungarian Physicists (2013), paper 20.4. (in Hungarian)

[J] Á. Börzsönyi, R.S. Nagymihály, P. Jójárt, K. Osvay: *Carrier-Envelope Phase Noise Increment Due to Thermal Issues of a Ti:Sapphire-Based Amplifier*, Advanced Solid-State Lasers 2013, Oct. 27- Nov. 1., Paris, France