Measurement and control of phase in ultrashort laser pulses

Summary of PhD theses

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2008

1. Preliminaries and goals

Ultrashort laser pulses opened new horizons in two fields. At the *research on fast processes*, the barrier determined by the resolution limit of electronic devices (a few tens of picoseconds) has been broken through. At the *investigation of light-matter interaction*, the high intensities never experienced before (10^{10} W/cm^2) made possible study nonlinear processes already foretold. Many applications and sub-disciplines came into existence.

Fulfilling the requirements claimed by the newest applications of 10 fs and shorter pulses is a hard challenge. One of the proven methods for the amplification of ultrashort pulses, which is necessary for far-UV or near-X-ray pulse generation, is the *chirped-pulsed amplification* scheme. These amplification systems are based on the effect of dispersion: the pulses are steered through optical assemblies having large negative and positive *group-delay dispersion* (GDD), which must compensate each other in order to achieve good pulse quality

When developing chirped-pulse amplification systems difficulties arise, because *there is no single technique for monitoring the residual dispersion upon alignment, while it varies over several orders of magnitude*. Nowadays for the initial adjustment, in the pulse length regime of 10–500 ps streak cameras can be used for estimation, and under 100 fs, for the fine tuning e.g. autocorrelators, but these are essentially different devices.

My first goal is to develop a novel adjusting method of residual dispersion in pulse stretcher–compressor systems, that uses the same, real-time monitoring capable optical setup both for the coarse and the fine elimination of dispersion.

Spectrally and spatially resolved interferometry (SSRI) is based on the combination of a two-path interferometer and an imaging spectrograph. It has been successfully used for determination of dispersion of optical elements and materials (glasses, even gases). One of the variants of SSRI is the *stationary phase point method* (SPP method), which has already been proved useful especially for examining high-dispersion objects e.g fibers. The SPP method is founded on reading the spectral position of the center of the SSRI fringes, but *the information included by the two-dimensional shape of the fringes is unused*.

I investigate the possibility of a fast estimation of the object dispersion based on the shape of the fringes produced by the stationary phase point method. I use the estimation method for real time monitoring during the adjusting method expressed in my previous goal.

Some of the newest applications of ultrashort laser pulses such as the above threshold ionization experiments and optical frequency-metrology, are related to few-cycle pulses. For stable experiments, it is essential to have pulses with the same initial phase, or expressed in another way, to have pulses with the carrier wave at the same position inside the envelope, that is with the same *carrier-envelope phase* (CEP).

The measurement of pulse-to-pulse variation of CEP (that is the *CEP-slippage*) of pulse trains having at least octave bandwidth is nowadays mostly carried out using the *f*-to-2*f* interferometry. In the case of narrower spectra it is necessary to broaden the bandwidth at the cost of one more nonlinear conversion step. *All these methods are quite demanding both in bandwidth and in intensity, which excludes the CEP-measurement by the f-to-2f method of many lasers*.

I develop a novel method based on spectrally and spatially resolved interferometry for the measurement of carrier-envelope phase slippage virtually independent of bandwidth and pulse power. I analyze the influence of experimental settings and circumstances on the characteristics of the new method by numerical modeling and demonstrate its usability.

Beyond the ability to measure, it is advantageous to have a device for the tuning of CEP, that does not change the group delay and group delay dispersion of the transmitted pulses as a side effect. *The tuning of carrier-envelope phase is nowadays mostly done by means of fused silica wedges*, that are built into the light path pairwise, and one of them can be translated perpendicular to the beam. *This technique also varies the group delay and GDD in the wedges*. On intra-cavity use this causes repetition rate changes and timing detuning on extra-cavity use in attosecond pump-probe experiments. The variation of wedge material amount in the beam path affects the phase modulation of the pulses, too. These may necessitate additional diagnostic and compensation devices.

I design and realize a novel carrier-envelope phase tuning setup, that does not detune the group delay and the group delay dispersion of the transmitted pulses as a side effect.

In pulse amplifier systems the quality of the pre-amplification depends strongly on the angle of the signal and pump beams to each other and to the pre-amplifier crystal. The optical experiments, especially the ones utilizing nonlinear effects and the ones that need exact initial phase settings, claim stringent beam pointing requirements, too. Often these can be fulfilled only by using active stabilization. Nowadays the beam pointing stabilization is mostly carried out by the automated monitoring of *far field* by *quadrant detectors*. *The quadrant detector is a rather rigid device:* if the direction of the monitored beam is modified due to adapting the elements of the laser system to the given experiment, the detector has to be realigned, in order to have a laser spot exactly at the meeting point of the four sensing areas.

I develop and realize an active beam-pointing stabilization system for the signal and pump beams of the TeWaTi system, that is flexible, without the need of readjusting in the case of beam modifications due to system development, and that has enough accuracy to keep the amplified energy stability better than 3 % and to cancel the effects of beam-pointing drifts in the carrier-envelope phase of the amplified pulses.

2. Methods of investigation

The unamplified beam of a home built Ti:sapphire oscillator was used for characterizing the pulse stretcher and the stretcher–compressor system of the TeWaTi laser system. The central wavelength was 800 nm, the temporal length of the pulses was 15 fs and the repetition rate was 71 MHz. Both the stretcher and the compressor consist of two gratings of a density of 1200 mm^{-1}, and the stretcher includes a spherical mirror of a focal length of 500 mm. When using the stationary phase point method for GDD measurement in the stretcher, I used a modified Jobin–Yvon H-20 monochromator with an Electrim EDC–2000N CCD camera (resolution 652 pixel × 494 pixel) in the image plane. The spectral resolution of this system was 0.1 nm. For the GDD elimination of the laser system I used a home-built spectrograph (f_{coll}=50 mm, f_{obj}=100 mm, grating: 650 mm^{-1}) with a spectral resolution of 1 nm.

For the theoretical investigations of the novel linear CEP slippage measuring method a numerical code was run in MathCAD. In the experimental demonstration I used a 10 fs FemtoPower Compact Pro oscillator operating at the central wavelength of 803 nm and at a repetition rate of 87.4 MHz. For the independent measurement of the CEP slippage rate I used a home-built *f*-to-2*f* interferometer and a spectrum analyzer (Rohde & Schwarz FSP7), which measured the *carrier-envelope offset frequency* (CEO frequency) with an accuracy of 0.2 MHz. I calculated the CEP slippage from the CEO frequency in view of the repetition rate. The latter was measured using a fast photodiode and a universal frequency counter (Agilent 53131A) with an accuracy of 1 Hz.

When designing the isochronic CEP-tuning wedgepair I used the data sheets of the Schott optical glasses to find a combination of materials suitable for both izochronic and GDD-neutral CEP tuning, and a ray-tracing code written in MathCAD to find the appropriate apex angles of the wedges. This program considered the nearly Brewster-angle incidence on the surfaces and the dispersion of ambient laboratory air. In the experimental demonstration the CEO frequency and the repetition rate was measured again using the same system as in the previous measurement.

I used two Electrim EDC–2000N CCD cameras for capturing the location of the focused laser spots of the signal and pump beams. The focusing lenses have focal lengths of 300 mm and 500 mm, respectively. The feedback is provided by Newport Picomotor actuators built into the mirror mounts right after the lasers' output. The stabilization algorithm runs as a part of the control program of the

TeWaTi system, which is written in LabVIEW. The pump beams are attenuated by combinations of halfwave plates and polarization beam-splitter cubes. The beam energies are controlled with high precision by rotating the halfwave plates using Owis DRT 40 rotary stages with an accuracy of 0.2°. The rotary stages are controlled also by the control program of the laser system.

3. Results

1. I have proposed a new elimination method of residual dispersion in chirped-pulse amplification systems [1,10]: I have taken part in the development of a two-dimensional extension of the stationary phase point method. I have described spectrally and spatially resolved interferometric methods based on the same single optical setup for the quantitative measurement of dispersion, and for its qualitative monitoring during the coarse and fine tuning of the group delay dispersion of the stretcher–compressor system, which tasks otherwise use fundamentally different measurement techniques. I have also demonstrated the developed elimination and measurement methods experimentally on the TeWaTi laser system.

2. I have developed a novel method for measuring the carrier-envelope phase slippage [2–4,7,8,11–17]: I have created a numerical model for computing the visibility of the spectrally and spatially resolved fringes from the combination of a two-path and a multiple-path interferometer as the function of the carrier-envelope phase slippage rate. Using this model, I have investigated the influence of the finesse of the multiple-path interferometer, of the finite integration time of the detector, of the detuning of the multiple-path interferometer from resonance, of its path length fluctuations, of the dispersion of ambient air, and of other experimental and environmental conditions on the visibility vs. CEP slippage function.

3. I have demonstrated the measurement technique developed in the previous point in the case of the pulse train of a laser oscillator. In excellent agreement of the model results, I have shown, that the visibility of the spectrally and spatially

resolved interference fringes depends uniquely on the carrier-envelope phase slippage rate.

This is the first and so far the only method for CEP-slippage measurement in the world, that depends solely on linear optics. As a consequence, its usability is to a great extent independent of input bandwidth and intensity, hence it can be applied for the CEP-characterization of picosecond lasers and pulsed lasers with rather low peak power as used, e.g., in telecommunication applications.

4. I have developed a novel setup and technique for the isochronic tuning of the carrier-envelope offset frequency, that does not detune the group delay and group delay dispersion of the transmitted pulses as a side effect [5,9]. I have demonstrated the method experimentally by assembling the device consisting of the wedge-pair made of two different optical glasses. I have aligned the wedge pair for intra-cavity use in an oscillator that originally used two identical fused silica wedges for CEP-tuning. I have reduced the detuning of the repetition rate when tuning the CEO frequency by nearly two orders of magnitude with respect to the factory built-in fused silica CEP-tuning wedges altering the output bandwidth and power only by negligible amount.

5. I have developed and realized an active beam-pointing stabilization system based on image processing, which is able to stabilize the direction of both the signal and the pump beam of the TeWaTi laser system [18]. Hereby on the one hand I have made the carrier-envelope phase of the amplified pulses independent of the beam pointing drift of the signal and pump beams. On the other hand, the stabilized beam of the pump laser by itself can be used for high precision material processing [6]. By keeping the beam pointing stable, and by other improvements of laser control, the further development of the laser system has been eased, its operation is simpler and better to learn.

4. Publications related to the theses

In refereed journals

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