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Drift and noise of the carrier–envelope phase in a Ti:sapphire amplifier

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Abstract

We report on the drift and noise measurement of the carrier–envelope phase (CEP) of ultrashort pulses in a three-pass Ti:sapphire-based amplifier. Spectrally and spatially resolved interferometry makes it possible to investigate the absolute CEP changes due exclusively to the amplifier, that is, entirely separated from the incidental phase fluctuations of the oscillator. We found that propagation through the amplifier crystal could result in an increase up to 30 mrad noise depending on the repetition rate, cooling, and pumping conditions. Most of this noise is related to mechanical vibrations and thermal instabilities. The absolute CEP drift of thermal origin can be as large as 11 mrad/°C for each mm of the amplifier crystal, originating from inefficient heat conduction during the absorption of pump pulses. The noise of the thermal CEP drift is inversely proportional to the repetition rate, as was shown experimentally and proven by simulations.

Keywords: laser amplifier, carrier–envelope phase, spectral interferometry, thermal effect

(Some figures may appear in colour only in the online journal)

1. Introduction

The pulse-to-pulse change of the carrier–envelope phase (CEP) of few-cycle laser pulses ultimately defines the accuracy of phase-related experiments in high harmonic and attosecond pulse generation [1], coherent beam combination [2], and precise frequency metrology [3]. Most generally, the variation of CEP of ultrashort pulses can be characterized by its power spectral density integrated over a frequency range, which spans from the reciprocal of observation time to half of the repetition rate. To characterize the CEP stability of a pulse train by a single value, usually the residual CEP RMS noise is calculated over a time interval. Several methods have been developed so far for the measurement of CEP drift [4–7]. For laser oscillators based on Kerr-lens mode locking, the CEP measurement and control loop have been already well established, providing better than 30 mrad stability [8]. For multi-kHz repetition rate laser systems, several sources of CEP noise have already been determined, like pulse picking [9], and the stretcher-compressor systems [10–13]. The resulting CEP RMS noise of 250–350 mrad of commercial multi-kHz repetition rate CPA systems has been recently improved to 100 mrad with the use of a chirped mirror compressor and a fast detection system [14]. Interestingly enough, unlike for optical parametric amplification [15], no study has been published so far on the CEP noise due solely to the amplification effect in Ti:sapphire crystals.

Here we report on a systematic measurement of the absolute change and noise of CEP of ultrashort laser pulses attributed exclusively to a Ti:sapphire amplifier stage. To do this, it is satisfactory to measure the CEP change of the amplified pulses relative to the incoming ones. Hence, the absolute CEP value as well as its noise of the pulses before amplification is completely uninterested, ensuring a measurement with high accuracy and low noise.

2. Experiment

To measure the absolute changes of the CEP, we have chosen two-beam spectral interferometry, as one of the most efficient

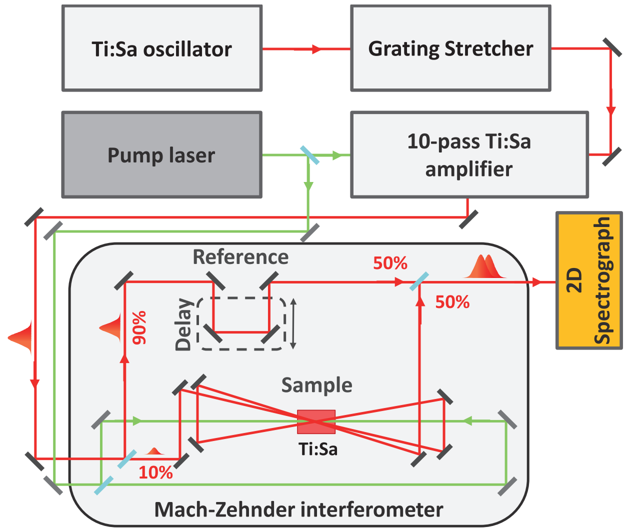

Figure 1. Experimental layout of the system, where the rounded box emphasizes the Mach–Zehnder interferometer with a three-pass Ti:sapphire amplifier in its sample arm.

relative CEP detection methods [16–18]. An asymmetrically split Mach–Zehnder interferometer (MZI) was built around a three-pass Ti:sapphire amplifier, where 10% of the incoming beam was sent through the amplifier as the sample arm, while the rest of the beam propagated in the reference arm set to almost equal arm length (figure 1). At the output of the interferometer the beams were properly combined with the use of a 50%–50% beamsplitter, and sent to the entrance slit of a high resolution imaging spectrograph. A small, few tens of μm difference in the arm lengths ensured that a densely modulated pattern is created in the spectrally resolved interferogram. From the position and density of the fringes the CEP difference between the overlapping pulses from the two arms can be unambiguously determined.

The three-pass amplifier was designed to achieve a gain factor of around 10, balancing for the asymmetrical split of the MZI. The rectangular cut Ti:sapphire crystal had an absorption coefficient of 2.3 cm^{-1}, dimensions of 8 mm × 8 mm × 14 mm, and AR coatings for both 532 and 800 nm. Under standard conditions, the crystal was tempered to 16 °C by the use of an independent chiller.

The MZI was seeded with the non-compressed output pulses from the frontend of a CPA system. Specifically, 60 nm bandwidth seed pulses of a home-made Ti:sapphire oscillator were stretched to 250 ps time duration with a grating stretcher. The stretched pulses were amplified in a 10-pass Ti:sapphire amplifier to an energy level of 2 mJ with pump pulses from a Photonics Industries DM32-527 Nd:YLF laser. This custom tailored pump source has an energy stability better than 0.2% RMS and enough pulse energy to saturate the 10-pass amplifier without using its full capacity. The remaining part of this 527 nm beam was used for pumping the sample arm amplifier after passing through an appropriate delay line. The energy of the seed and the sample arm pump pulses could be independently varied from each other.

The interferometer was covered completely to eliminate the air flow around the experimental setup. The measurement processes, including the recording of the interference fringes and on-the-fly pattern evaluation, have been running for several hours without any interruption. Evaluation of these patterns is based on the well-established Fourier-transformation method [17, 18].

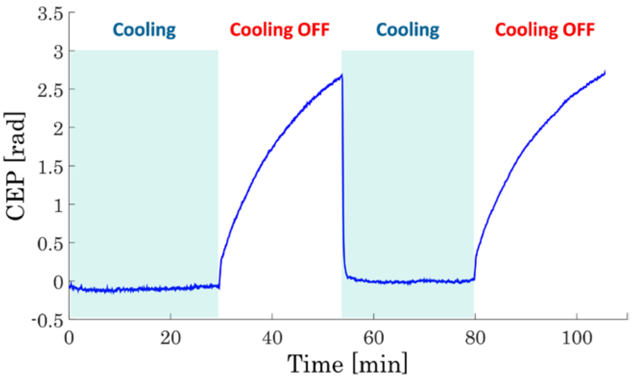

Figure 2. CEP in the Ti:sapphire amplifier with (shaded areas) and without cooling. After switching off the cooling, a slow drift starts and changes the CEP by 2.6 radians in 30 min. Turning the cooling on again, a fast exponential drop in CEP can be observed. These phase changes are very reminiscent of Newton's law of cooling.

The experimental arrangement has in theory ensured that the CEP changes induced only by the Ti:sapphire amplifier are measured relatively to the CEP shift of the reference arm. In practice, mechanical vibrations, residual air flow, and thermal drift in the MZI also have effects on the measured CEP. Induced change of the refractive index of air in the vicinity of the Ti:sapphire crystal is negligible, so is the related effect on CEP of the pulses under measurement. The image capturing system and the evaluating algorithm set further limits on the achievable accuracy [19, 20], too. In order to account for all these effects, the CEP was thus measured under the standard conditions of the experiment, as 65 μJ seed pulses and 16 °C crystal temperature, but without pumping the Ti:sapphire crystal. The resulting CEP noise of 25 mrad RMS can be regarded as the background noise of the experimental setup. This RMS value represents the lowest CEP noise that can be measured in our setup. Thus the background noise is incorporated in the values of the measured CEP for all the further experiments.

3. Results

First we were curious to learn what range the CEP can be expected to change when the cooling of the crystal is turned off and on upon normal conditions of amplification. The amplifier hence was driven close to the saturated regime, with pump pulses of 8 mJ at 200 Hz repetition rate, resulting in a gain of 13. The CEP of the amplified pulses remained constant with a noise of around 40 mrad (including the aforementioned 25 mrad background noise) during the time the cooling system of the crystal was operating (shaded areas in figure 2). When cooling was turned off, the CEP increased over 2.6 radians in about half an hour (non-shaded areas in figure 2). The CEP noise introduced by the non-cooled three-pass amplifier has also increased and reached 75 mrad, although the gain did

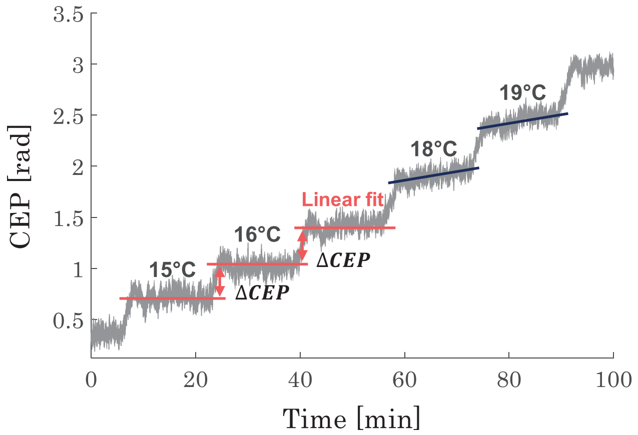

Figure 3. Measured CEP shift without pumping the Ti:sapphire amplifier upon the variation of the crystal temperature. By linear fitting on plateaus we could calculate CEP changes caused by the temperature variation. Temperature values above the curve are related to the Ti:sapphire crystal. We kept the flow rate of the coolant at a constant value during the experiments, therefore at higher coolant temperatures the cooling efficiency suffered some degradation. This effect can be seen in the higher temperature (18–19° C) area of the phase curve: the CEP drift is building up because of the insufficient cooling efficiency.

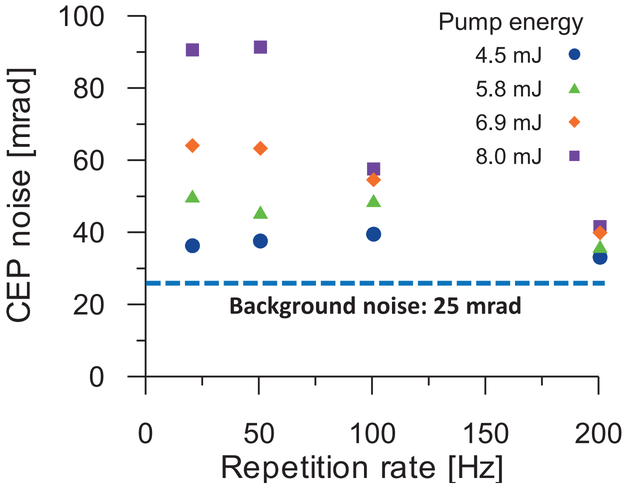

Figure 4. The CEP noise of the cooled three-pass amplifier at different repetition rates and pump energies.

not change noticeably. It means that the CEP stability of the pulses leaving the amplifier does not correlate directly to the stability of the gain close to the saturation.

Next, the effect of pump pulses on the CEP were investigated. We have naturally assumed that the absorbed pump turns into heat that affects the CEP. However, intense pump pulses could influence the spectral phase of seed pulses through Kerr-effect inside the amplifying material, or any other nonlinear optical ways, too. In order to decide, two similar measurement campaigns have been made, one was without pump and another was with 8 mJ pump pulses at 200 Hz repetition rate. In both cases, the crystal temperature was set at temperatures 14 °C, 15 °C, etc, up to 20 °C. We left the system running at the given temperature for 15 min at least. The CEP difference between the arms of the interferometer became stationary at different cooling temperatures, corresponding to the actual temperature of the crystal (figure 3). The relative change ΔCEP caused by the temperature jumps was determined as the difference between the linear fits to the plateaus of the phase curve. For both the non-pumped and pumped cases, we have found the same value of 0.45 rad/°C for ΔCEP, which corresponds to 11 mrad/°C/mm normalized to the pathlength in the crystal. Moreover, this value agrees very well to the value calculated from the temperature dependent refractive index of Ti:sapphire [21].

It is worth mentioning that this result can be used rather generally, e.g. to determine the temperature of the crystal from the CEP drifts independently from the pump energy. For instance, one can calculate from figure 2, that the seed pulses have experienced a thermal change of the crystal from 16 °C to circa 23 °C during the non-cooled drift period.

To countercheck, the nonlinear phase contribution induced by the gain medium and also the air in the vicinity of the gain crystal has been calculated. We have created a simple model, that includes the dispersion of the nonlinear refractive index of the Ti:sapphire crystal, the absorption and nonlinear refractive index of air, and also the effect of intensity evolution of seed pulses inside the amplifier. Taking into account the 0.1 GW cm^{-2} peak intensity of the seed pulses at the entrance of the gain medium, the total nonlinear phase shift was calculated to be around 12 mrad, from which the overwhelming majority was contributed from the Ti:sapphire crystal. These findings support that other than the thermal load in the crystal, neither the signal nor the pump pulses have any other effect on CEP, within the accuracy of the measurement.

Finally, the effects of saturation and repetition rate have been investigated. To account for the former one, the seed pulse energy was varied between 10 and 120 μJ with an attenuator. The amplifier was pumped by 8 mJ energy pulses at 200 Hz repetition rate. The CEP noise was effectively independent of the energy of the seed pulse. Similar was found when the pump energy was changed between 4.5 and 8 mJ, while the seed energy was kept at the standard 65 μJ level (figure 4). Hence we can conclude that saturation itself does not have an effect on the CEP noise.

The thermal load on the crystal can be obviously varied with changing the repetition rate and pump pulse energy. As expected, the CEP noise at each repetition rate correlates mostly linearly with the pump pulse energy (figure 4).

Regarding the dependency on the repetition rate, a decreasing tendency can be observed, especially at higher pump energies. The overall decrement of the CEP noise with the increasing repetition rates can be explained by the small thermal variations during the cooling of the pumped volume of the Ti:sapphire crystal. Namely, at higher repetition rates there is less and less time between pulses to accumulate mechanical and thermal instabilities, which eventually results in lower phase noise values. The CEP noise varies between 30 and 13 mrad per pass, for repetition rates of 20 and 200 Hz, respectively.

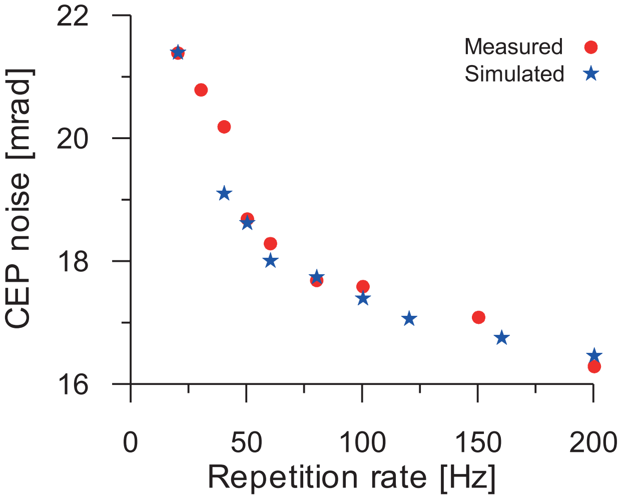

Figure 5. Measured (red dots) and simulated values (blue stars) of single pass CEP noise in a Ti:sapphire amplifier with a crystal path length of 5 mm, at 20 mJ pump energy.

4. Simulations and discussion

In order to verify the latter findings, we performed numerical simulations by using the finite element method (COMSOL Multiphysics). By simulating the heat dissipation of absorbed pump pulse energy, the heat distribution and the temperature fluctuations in the Ti:sapphire crystal were computed. The steady-state solutions of heat distribution and thermal lens properties in a Ti:sapphire crystal have been exhaustingly analyzed in [22]. These results were also taken into account upon modeling of the heat transfer in the crystal, where we assumed direct cooling on the boundaries. A 2D axisymmetric model was created with cylindrical, rectangular cut crystal geometry. Among the input variables, the spatial intensity distribution and energy stability of the pump pulses as well as variation of the coolant temperature were also incorporated. Thermal properties of the crystal were taken from built in temperature dependent material data of the simulation software (35.4 W $(\mathrm{m}\cdot\mathrm{K})^{-1}$ thermal conductivity, 764.1 J $(\mathrm{kg}\cdot\mathrm{K})^{-1}$ heat capacity at constant pressure and 3989.7 kg m^{-3} density, all given at 20 °C temperature). The model provided us with the exact temperature profile for each amplification event due to a pump pulse, from which the temperature fluctuation was determined. The phase noise was hence calculated from the temperature dependence of CEP via the thermal refractive index of Ti:sapphire.

For the simulations, a Ti:sapphire crystal with a path length of 5 mm, radius of 3 mm and an absorption coefficient of 4.2 1 cm^{-1} was chosen, while the pump pulse energy was set to 20 mJ and the repetition rate was varied between 20 and 200 Hz. The pump beam was taken to be Gaussian-type with a radius of 400 μm along the complete path length. The crystal is pumped from both sides with 150 ns FWHM pump pulses. The coolant temperature was varied randomly with a standard deviation of 0.001, around the mean value of 16 °C. The dissipated pump energy was calculated to be 15 mJ per pulse.

Meanwhile, the experimental setup was correspondingly modified, that is, the crystal was changed for another one with parameters taken in the simulation mentioned above and the single pass CEP drift was measured. As seen in figure 5, the agreement between the simulated and measured values is excellent.

The CEP noise arising from thermal fluctuations is significant only for low repetition rates. Simulations revealed an increment of the crystal temperature instability between two subsequent pulses, resulting in higher thermal fluctuation. Moreover, thermal fluctuation of the coolant can cause more significant CEP drift of the amplified pulses at a lower repetition rate than at a higher one, which further increases the CEP noise at low repetition rate. At high repetition rates we may conclude that the significant part of the CEP noise is related to mechanical vibrations and other, non-thermal effects in the amplifier. The drift of the CEP can be limited effectively with precise cooling techniques close to room temperature and also with cryogenic cooling. Furthermore, noise of the CEP can be also kept under control by working at high repetition rate. From another point of view, the most affected systems are the low repetition rate, high pump energy amplifiers, since the CEP noise gradually increases in these cases. For practical reasons, in many of such systems, cryogenic cooling has been used or is under consideration. From the increased thermal conductivity of Ti:sapphire at low temperatures and from the stability of the cryogenic cooling [23], one may predict a radical decrease of CEP noise due to thermal instability. The trade-off could be the increased mechanical vibrations due to the vacuum pump attached to the cryo-head.

5. Conclusion

In summary, we presented an experimental study on the absolute CEP changes originating exclusively from a three-pass Ti:sapphire amplifier. We have found that the thermal instability of the amplifier crystal is the key factor for the CEP drift of the pulses. Regarding the noise of the thermal CEP drift, our study showed an inversely proportional dependence to the repetition rate of the amplifier system. This means that at lower repetition rates, besides the mechanical vibrations, the thermal instability can contribute significantly to the noise of the CEP. Besides, the CEP noise is linearly proportional to the gain, while the level of saturation does not affect it.

Acknowledgments

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