Approaching the limits of carrier-envelope phase stability in a millijoule-class amplifier

Fabian Lücking,[1,2,*] Vincent Crozatier,[3] Nicolas Forget,[3] Andreas Assion,[1] and Ferenc Krausz[2,4]

[1]*Femtolasers Produktions GmbH, Fernkorngasse 10, 1100 Vienna, Austria*

[2]*Institut für Experimentalphysik, Ludwig-Maximilians-Universität München, Am Coulombwall 1, 85748 Garching, Germany*

[3]*Fastlite, Centre Scientifique d'Orsay, Bâtiment 503, Plateau du Moulon, 91401 Orsay, France*

[4]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching Germany*

**Corresponding author: fabian.luecking@femtolasers.com*

Received April 3, 2014; revised May 26, 2014; accepted May 26, 2014;
posted May 27, 2014 (Doc. ID 209534); published June 24, 2014

The demand for ever shorter light pulses presents a challenge to the detection and stabilization of the carrier-envelope phase (CEP) in amplifier systems. Here we present a combination of single-shot detection and a fast actuator that is capable of measuring and correcting the CEP in every single shot emitted by a millijoule-scale, multi-kHz femtosecond laser amplifier. The residual CEP noise within 50 s amounts to 98 mrad rms in-loop (fast detection, $5 \cdot 10^5$ shots) and 140 mrad out-of-loop (slow detection, 6250 shots), approaching the noise floor of the f-to-2f measurement. Both values represent a twofold improvement of the CEP stability over previously published results in comparable systems.

OCIS codes: (320.7090) Ultrafast lasers; (140.3280) Laser amplifiers; (320.7160) Ultrafast technology.
http://dx.doi.org/10.1364/OL.39.003884

The last decade has seen tremendous progress in the investigation of the fastest processes occurring in the microcosm. Few-cycle laser pulses with constant carrier-envelope phase (CEP) constitute a primary tool for accessing the highly nonlinear interactions underlying these processes. In order to achieve higher temporal resolution as well as higher field strengths, much effort is undertaken to confine the interaction to a single half-cycle of the driving laser field. Thanks to advancements in hollow-fiber compression, the duration of pulses used for attosecond experiments is approaching a single optical cycle. These developments place rising demands on the CEP stability of the laser at the front end of the experimental chain.

Several factors contribute to the overall CEP noise measured at the output of an amplifier. First, the oscillator CEP noise integrated over the temporal interval between two consecutive amplified pulses sets a lower limit to the pulse-to-pulse variation of the CEP of the amplified pulses. This CEP noise floor commonly amounts to about 100–140 mrad rms (when referring to statistical deviations from a constant value, rms values are given in this Letter unless otherwise noted) for stabilization using feedback [1], and has been shown to reach below 50 mrad using cavity-external frequency shifting in the so-called feed-forward scheme [2].

However, this limit set by the seed oscillator has remained a theoretical issue up to now. Rather, the overall CEP performance of millijoule-class sources has so far been dominated by CEP noise added during the amplification process. These secondary sources of CEP noise fall into one of two categories. On the one hand CEP can be affected by changes in dispersion through mechanical vibration of components (such as large grating stretchers and compressors) as well as variation of beam pointing and/or ambient conditions. These effects dominate at frequencies up to 1 kHz, often occurring in narrow frequency bands, or with $1/f$-like noise behavior. On the other hand are effects coupling pulse intensity to CEP through self-phase modulation (SPM). Intensity noise can be caused by pulse-switching electronics or pump power fluctuations. Beam pointing drifts can also act in this fashion by varying the overlap of the pump and seed beams. Except for the latter, these effects generate stochastic or high-frequency noise.

The impact of CEP noise sources from both categories can be reduced through careful design of the amplifier, e.g., by using bulk material for pulse stretching, low-vibration cooling systems, and keeping the accumulated nonlinear phase low. Furthermore, feedback correction loops can, in principle, be employed to cancel noise up to half the amplifier repetition rate. In practice, however, other limitations come into effect much earlier in both measurement and actuation. For instance, conventional CEP detection in a single-shot f-to-2f interferometer relies on the processing of a spectrogram [3], the acquisition and analysis of which typically takes milliseconds. This reduces the bandwidth of stabilization loops to typically a few hundred hertz. Only within the last decade have methods been invented to determine the shot-to-shot CEP fluctuations of amplified pulses at a repetition rate above the kilohertz range. These schemes either replace the time-consuming spectrogram evaluation in an f-to-2f interferometer [4,5] or directly measure a phase-sensitive effect [6].

Faster means of CEP detection also call for faster actuators. Suitable mechanisms include adding an offset to the seed oscillator stabilization [7], and shifting the phase in an acousto-optical programmable dispersive filter (AOPDF) [8] or an electro-optic crystal [9]. However, neither fast detection [10], fast actuation [7], nor their combination [11] have succeeded in reducing the system CEP noise to less than 250 mrad measured in-loop [4,7] and 294 mrad out-of-loop [10] on a single-shot basis. In what follows, we present a 10 kHz, millijoule-class amplifier whose CEP stability approaches the limit set by the seed oscillator.

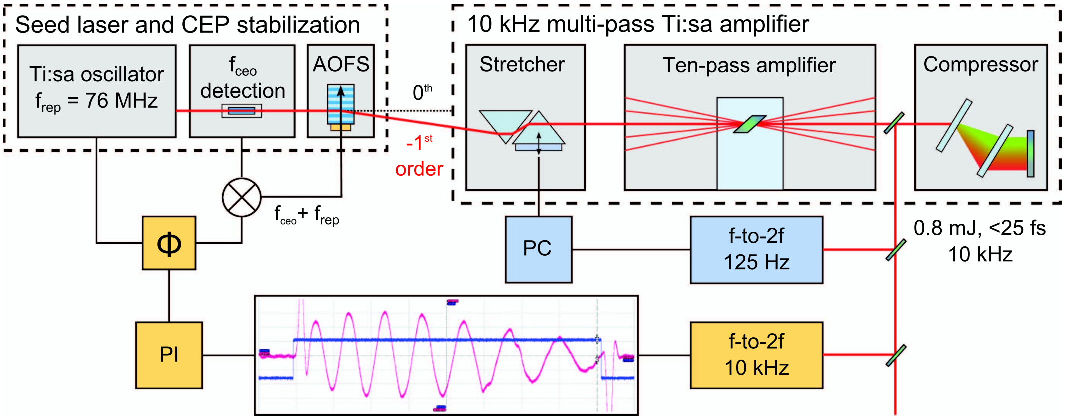

Fig. 1. Schematic layout of the experiment. A Ti:sapphire oscillator is CEP stabilized by frequency-shifting. Multi-pass amplification at 10 kHz yields pulses with 0.8 mJ energy and a duration of 25 fs. The CEP of the amplified pulses is measured by two collinear f-to-2f interferometers at 125 and 10 kHz acquisition rate, respectively. Feedback correction can be applied by varying either the stretcher dispersion or the RF phase of the AOFS driver signal. Φ, RF phase shifter; PI, proportional-integral controller; PC, personal computer. Inset, oscilloscope screen-shot of an interferogram acquired by the fast f-to-2f.

The layout of our experiment is depicted in Fig. 1. The seed oscillator (rainbow CEP4, Femtolasers) is CEP-stabilized by frequency-shifting all lines in the laser output spectrum by the measured carrier-envelope offset frequency f_{ceo}. This is accomplished using an acousto-optic frequency shifter (AOFS), imparting a Doppler frequency shift equal to its driving frequency to the diffracted light. As f_{ceo} cannot be conveniently filtered to reach the AOFS drive band of 85 MHz, the sum of f_{ceo} and the repetition rate f_{rep} is used instead. This equally results in a zero-offset comb in the −1st diffraction order. The seed laser CEP stability is estimated to be on the order of 50 mrad based on the previous characterization of an essentially identical system [12].

About 70 mW of average power within a 100 nm band centered around 800 nm is used to seed a single-stage multipass amplifier (Femtopower 10 kHz, Femtolasers). Bulk SF57 glass is used to stretch the pulses, and an AOPDF (low-jitter Dazzler HR, Fastlite) provides spectral shaping and compensation of higher-order dispersion. Mechanical construction and cooling of the gain medium were optimized to achieve minimal mechanical vibration. After 10 passes, the pulses are re-compressed by transmission gratings, resulting in 0.8 mJ pulses of 25 fs duration.

Beam splitters direct a small fraction of the output to two collinear f-to-2f interferometers [3]. One of the devices uses a commercial USB spectrometer running at 125 Hz, whereas the other is equipped with a prototype device capable of extracting CEP fluctuations from interferograms at the full amplifier repetition rate [13]. The integration times of both allow only one amplifier shot to contribute to each CEP measurement.

The prototype is based on a typical grating spectrometer. It is built in Czerny–Turner configuration with an arm length of 75 mm and an entrance slit width of 25 μm. The detector is a 512 pixel CMOS array with fast-readout capability (line reading scan time <85 μs) receiving a 30 nm band centered at 520 nm. The f-to-2f interference pattern is converted into an electronic signal by the CMOS array. After filtering it appears as a pseudo-sine wave. Such a signal is easily processed to extract the phase deviation as an analog voltage. The acquisition is triggered synchronously with the q-switch of the amplifier pump laser. The maximum acquisition rate exceeds 10 kHz and is limited by the detector read-out and phase extraction process.

In order to correct the CEP jitter induced during amplification, feedback can be applied in two ways. First, the error signal provided by the slow conventional measurement is fed to a Piezo stage, changing the insertion of a prism into the stretcher. The bandwidth of this feedback loop is limited to half the acquisition rate (62.5 Hz). The second method exploits both the fast acquisition device and the acoustic grating phase, a free parameter previously unused in the CEP stabilization technique employed here.

In addition to modifying the frequency of the diffracted light, the acoustic-wave imprints its phase on that of the optical wave. Thus, by changing the phase of the acoustic wave, the AOFS can be employed not only to produce pulses with constant CEP, but also to arbitrarily set its value. This effect does not rely on material dispersion and hence does not modify the pulse temporal envelope. The drawbacks of using material dispersion to influence the CEP, aggravated with decreasing pulse duration, can thus be circumvented. In practice, the phase of the AOFS driving signal is controlled by a standard voltage-controlled radio frequency (RF) phase shifter (Sigatek), allowing 360° of electronic phase shift with linear voltage-to-phase response and a specified modulation bandwidth of 1 MHz.

In order to test the open-loop performance of both the fast phase measurement and the actuator, a triggered square wave at half the amplifier repetition rate was applied to the RF phase shifter, its amplitude chosen such as to produce phase jumps of roughly π. The CEP of every single shot in the output beam was measured using the fast f-to-2f. The results are depicted in Fig. 2 (red trace). The experiment illustrates that the method can be used to choose an arbitrary CEP of the output pulse from one pulse to the next. One possible application is lock-in detection of CEP-sensitive effects, scalable to a much higher repetition rate depending on the amplifier being seeded. Providing fast CEP control

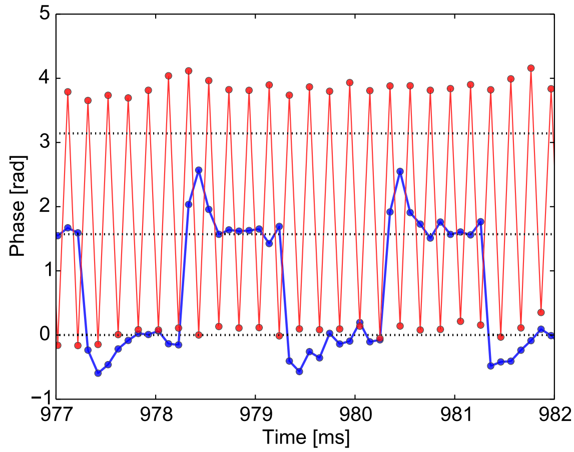

Fig. 2. Acoustic grating phase actuator in open and closed loop operation, recorded by fast f-to-2f. Red trace, amplified pulse CEP switched by 1.2π from shot-to-shot by triggered square wave applied to RF shifter. Blue trace, closed-loop operation, target phase switched by $\pi/2$ every 10 shots.

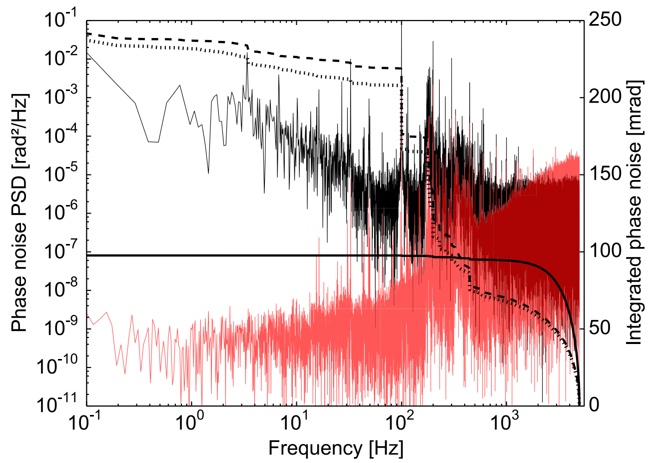

Fig. 3. Fourier transform of the CEP data collected using the fast f-to-2f device. Black/dashed trace, open loop PSD/IPN; Dotted trace, IPN of loop closed using 125 Hz f-to-2f and prism actuator; red/solid trace, PSD/IPN of loop closed using 10 kHz f-to-2f and grating phase actuator.

without changing the pulse envelope or introducing additional losses, this actuator renders the use of dispersive elements for CEP control obsolete.

Next, the fast control loop was closed using the measurement provided by the fast spectrometer. The error was processed by a proportional–integral (PI) controller (integration time constant $\tau_i = 0.2$ ms) before being fed back to the RF phase shifter. For this test the target phase was switched by $\pi/2$ every 10 shots. The blue trace in Fig. 2 shows the CEP data acquired during the lock for optimized servo gain. At this setting the closed loop step response is fast enough to lock to the new target within 3–4 shots. The response speed indicates a large feedback bandwidth at the expense of a low damping factor, as indicated by the overshoot. The deviation of the CEP from the upper and lower target amounted to 246 and 217 mrad ($2 \cdot 10^4$ shots, 2 s).

We then characterized the CEP stability of the amplified pulses for different configurations of measurement and actuator. First, the amplifier feedback loop was left open, yielding the noise power spectral density (PSD) of the overall system as measured by the fast f-to-2f (Fig. 3, black trace). The integrated phase noise (IPN) amounts to 242 mrad within 10 s. As can be seen from the step-like features of the IPN curve (dashed trace), the dominant contributions stem from two narrow-band spikes at 100 and 200 Hz as well as from a broad continuum spanning from 100 to 500 Hz. These correspond to mains leakage and acoustic vibration of the mechanical components inside the amplifier, respectively.

Second, the loop is closed using the 125 Hz measurement and the prism actuator, with the fast f-to-2f providing an out-of-loop measurement. As most of the CEP error accumulates at frequencies beyond that of the in-loop detection, the difference between open- and closed-loop performance is marginal. The resulting IPN of 237 mrad (10 s, dotted trace in Fig. 3, PSD trace not shown) agrees with the in-loop value to within 10% and can typically be maintained over tens of hours in everyday operation. The main purpose of such a low bandwidth loop is to avoid slow drifts and a long time-scale.

In a third experiment, feedback was applied using the full repetition rate CEP measurement and the grating phase actuator. Exceeding 2.5 kHz the estimated loop bandwidth is sufficient to cancel a significant part of the CEP fluctuations occurring during amplification. This is clearly demonstrated by the PSD (red trace) and IPN (solid black trace) plotted in Fig. 3. Within 50 s, evaluation and correction of the CEP of $5 \cdot 10^5$ shots resulted in a residual phase error of 98 mrad. No notable steps occur in the IPN curve in this case. The base level of the PSD keeps falling from high to low frequency, meaning that the control bandwidth spans the entire measurement range. In the absence of a second fast-acquisition system, no equivalent out-of-loop comparison could be performed. Still, using the slow-detection apparatus, CEP fluctuations were simultaneously measured to be below 140 mrad. Even for hours-scale datasets, out-of-loop noise did not exceed 150 mrad. Note that this figure, although markedly higher than the in-loop value, still represents a 100 mrad improvement over the residual noise obtained with the conventional loop.

A closer look at Fig. 3 suggests that the loop still offers room for optimization. Clearly, the fast-loop PSD level exceeds that of the free-running system upward of 2 kHz, meaning that the stabilization system actually adds noise not present in the other cases, which can be explained as follows. Stochastic shot-to-shot fluctuations of the amplifier-pump laser energy cause intensity jitter on the femtosecond output. In an f-to-2f measurement this jitter is translated to the CEP via SPM [14]. The measured CEP noise spectrum therefore contains a white-noise background at high frequency that sets the measurement noise floor. In the present amplifier, the shot-to-shot intensity fluctuations were measured to 0.5% rms. Assuming the coupling constant of 160 mrad/% given in [14], the stochastic noise background of the measurement can be estimated to 80 mrad, which is in excellent agreement with the open loop IPN at high frequencies (Fig. 3). A feedback loop acting on such a stochastic error adds noise instead of suppressing it, and the high-frequency integration stage ($\tau_i = 0.2$ ms) used in our experiment provided gain at a region where the f-to-2f signal was already dominated by such noise. Tailoring the loop-filter high-frequency response to the crossover point of the two PSD curves in Fig. 3 could result in modest reduction of the CEP jitter. Eventually, a measurement with a lower noise floor would enable the use of the fast loop at its full potential, likely pushing the residual CEP noise closer to the oscillator limit.

Recent analysis of the CEP noise added in hollow fiber compression [15,16] suggests that further benefit could result from including these in a fast correction loop.

In conclusion, we have presented a millijoule-scale femtosecond amplifier system in which fast feedback elements almost completely compensate for the CEP noise emerging in the amplification process. It relies on an f-to-2f device capable of measuring the CEP of pulses at an acquisition rate exceeding 10 kHz. The cavity-external CEP stabilization technique was augmented to allow fast CEP modulation, providing arbitrary CEP shift from one amplifier shot to the next. The resulting integrated CEP noise of 98 mrad constitutes a substantially improved performance as compared to previous CEP-stabilized systems. Our results indicate that there is room for further reduction of the CEP jitter.

The authors would like to thank the group of M. Kling at LMU for kindly providing equipment and support during the experiment. The presented work was partially funded by the European Research Council (grant agreement no. 238362-ATTOFEL) and the Munich Center for Advanced Photonics.

References

1. T. Fuji, J. Rauschenberger, C. Gohle, A. Apolonski, T. Udem, V. S. Yakovlev, G. Tempea, T. W. Hänsch, and F. Krausz, New J. Phys. **7**, 116 (2005).
2. S. Koke, C. Grebing, H. Frei, A. Anderson, A. Assion, and G. Steinmeyer, Nat. Photonics **4**, 462 (2010).
3. M. Kakehata, H. Takada, Y. Kobayashi, K. Torizuka, Y. Fujihira, T. Homma, and H. Takahashi, Opt. Lett. **26**, 1436 (2001).
4. S. Koke, C. Grebing, B. Manschwetus, and G. Steinmeyer, Opt. Lett. **33**, 2545 (2008).
5. T. Fordell, M. Miranda, C. L. Arnold, and A. L'Huillier, Opt. Express **19**, 23652 (2011).
6. M. Möller, A. M. Sayler, T. Rathje, M. Chini, Z. Chang, and G. G. Paulus, Appl. Phys. Lett. **99**, 121108 (2011).
7. L. Canova, X. Chen, A. Trisorio, A. Jullien, A. Assion, G. Tempea, N. Forget, T. Oksenhendler, and R. Lopez-Martens, Opt. Lett. **34**, 1333 (2009).
8. N. Forget, L. Canova, X. Chen, A. Jullien, and R. Lopez-Martens, Opt. Lett. **34**, 3647 (2009).
9. O. Gobert, P. Paul, J. Hergott, O. Tcherbakoff, F. Lepetit, P. d'Oliveira, F. Viala, and M. Comte, Opt. Express **19**, 5410 (2011).
10. D. Adolph, A. M. Sayler, T. Rathje, K. Rühle, and G. G. Paulus, Opt. Lett. **36**, 3639 (2011).
11. C. Feng, J.-F. Hergott, P.-M. Paul, X. Chen, O. Tcherbakoff, M. Comte, O. Gobert, M. Reduzzi, F. Calegari, C. Manzoni, M. Nisoli, and G. Sansone, Opt. Express **21**, 25248 (2013).
12. F. Lücking, A. Assion, A. Apolonski, F. Krausz, and G. Steinmeyer, Opt. Lett. **37**, 2076 (2012).
13. V. Crozatier, N. Forget, and T. Oksenhendler, in *CLEO/Europe and EQEC 2011 Conference Digest* (Optical Society of America, 2011), paper CF1-4.
14. C. Li, E. Moon, H. Mashiko, H. Wang, C. M. Nakamura, J. Tackett, and Z. Chang, Appl. Opt. **48**, 1303 (2009).
15. W. A. Okell, T. Witting, D. Fabris, D. Austin, M. Bocoum, F. Frank, A. Ricci, A. Jullien, D. Walke, J. P. Marangos, R. Lopez-Martens, and J. W. G. Tisch, Opt. Lett. **38**, 3918 (2013).
16. F. Lücking, A. Trabattoni, S. Anumula, G. Sansone, F. Calegari, M. Nisoli, T. Oksenhendler, and G. Tempea, Opt. Lett. **39**, 2302 (2014).