Complete analog control of the carrier-envelope-phase of a high-power laser amplifier

C. Feng,[1] **J.-F. Hergott,**[2,4] **P.-M. Paul,**[3] **X. Chen,**[3] **O. Tcherbakoff,**[2] **M. Comte,**[2] **O. Gobert,**[2] **M. Reduzzi,**[1] **F. Calegari,**[1] **C. Manzoni,**[1] **M. Nisoli,**[1] **and G. Sansone**[1,*]

[1] *CNR-IFN Dipartimento di Fisica Politecnico, Piazza Leonardo da Vinci 32 20133 Milano Italy*
[2] *CEA-Saclay, IRAMIS, Service des Photons, Atomes et Molécules, 91191 Gif-sur-Yvette, France*
[3] *Amplitude Technologies, 2-4 rue du Bois Chaland CE 2926, 91029 Evry, France*
[4] *jean-francois.hergott@cea.fr*
[*] *giuseppe.sansone@polimi.it*

Abstract: In this work we demonstrate the development of a complete analog feedback loop for the control of the carrier-envelope phase (CEP) of a high-average power (20 W) laser operating at 10 kHz repetition rate. The proposed method combines a detection scheme working on a single-shot basis at the full-repetition-rate of the laser system with a fast actuator based either on an acousto-optic or on an electro-optic crystal. The feedback loop is used to correct the CEP fluctuations introduced by the amplification process demonstrating a CEP residual noise of 320 mrad measured on a single-shot basis. The comparison with a feedback loop operating at a lower sampling rate indicates an improvement up to 45% in the residual noise. The measurement of the CEP drift for different integration times clearly evidences the importance of the single-shot characterization of the residual CEP drift. The demonstrated scheme could be efficiently applied for systems approaching the 100 kHz repetition rate regime.

OCIS codes: (320.7080) Ultrafast devices; (320.7090) Ultrafast lasers.

References and links

1. F. Krausz and M. Ivanov, "Attosecond physics," Rev. Mod. Phys. **81**, 163–234 (2009).
2. G. G. Paulus, F. Lindner, H. Walther, A. Baltuška, E. Goulielmakis, M. Lezius, and F. Krausz, "Measurement of the phase of few-cycle laser pulses," Phys. Rev. Lett. **91**, 253004 (2003).
3. X. Liu, H. Rottke, E. Eremina, W. Sandner, E. Goulielmakis, K. O. Keeffe, M. Lezius, F. Krausz, F. Lindner, M. G. Schätzel, G. G. Paulus, and H. Walther, "Nonsequential double ionization at the single-optical-cycle limit," Phys. Rev. Lett. **93**, 263001 (2004).
4. A. Baltuška, T. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, C. Gohle, R. Holzwarth, V. S. Yakoviev, A. Scrinzi, T. W. Hänsch, and F. Krausz, "Attosecond control of electronic processes by intense light fields," Nature **421**, 611–615 (2003).
5. L. Xu, C. Spielmann, A. Poppe, T. Brabec, F. Krausz, and T. W. Hänsch, "Route to phase control of ultrashort light pulses," Opt. Lett. **21**, 2008–2010 (1996).
6. R. Holzwarth, T. Udem, T. W. Hänsch, J. C. Knight, W. J. Wadsworth, and P. S. J. Russell, "Optical frequency synthesizer for precision spectroscopy," Phys. Rev. Lett. **85**, 2264–2267 (2000).
7. D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis," Science **288**, 635–639 (2000).

#193205 - $15.00 USD Received 1 Jul 2013; revised 9 Sep 2013; accepted 23 Sep 2013; published 15 Oct 2013

8. S. Koke, C. Grebing, H. Frei, A. Anderson, A. Assion, and G. Steinmeyer, "Direct frequency comb synthesis with arbitrary offset and shot-noise-limited phase noise," Nature Photon. **4**, 462–465 (2010).
9. B. Borchers, S. Koke, A. Husakou, J. Herrmann, and G. Steinmeyer, "Carrier-envelope phase stabilization with sub-10 as residual timing jitter," Opt. Lett. **36**, 4146–4148 (2011).
10. A. Baltuška, M. Uiberacker, E. Goulielmakis, R. Kienberger, V. S. Yakovlev, T. Udem, T. W. Hänsch, and F. Krausz, "Phase-controlled amplification of few-cycle laser pulses," IEEE J. Sel. Top. Quantum Electron. **9**, 972–989 (2003).
11. M. Mehendale, S. A. Mitchell, J. P. Likforman, D. M. Villeneuve, and P. B. Corkum, "Method for single-shot measurement of the carrier envelope phase of a few-cycle laser pulse," Opt. Lett. **25**, 1672–1674 (2000).
12. M. Kakehata, H. Takada, Y. Kobayashi, K. Torizuka, Y. Fujihira, T. Homma, and H. Takahashi, "Single-shot measurement of carrier-envelope phase changes by spectral interferometry," Opt. Lett. **26**, 1436–1438 (2001).
13. S. Koke, C. Grebing, B. Manschwetus, and G. Steinmeyer, "Fast f-to-2f interferometer for a direct measurement of the carrier-envelope phase drift of ultrashort amplified laser pulses," Opt. Lett. **33**, 2545–2547 (2008).
14. T. Fordell, M. Miranda, C. L. Arnold, and A. L'Huillier, "High-speed carrier-envelope phase drift detection of amplified laser pulses," Opt. Express **19**, 23652–23657 (2011).
15. C. Li, A. Schill, F. Emaury, J. Chu, P. Fru, J.-M. Hritier, and W. Tulloch, *Single Shot Carrier Envelope Phase Stabilization of a 10 kHz, 10 W Regenerative Amplifier* (Springer Berlin Heidelberg, 2012), vol. 125 of *Springer Proceedings in Physics*, chap. 2, pp. 9–13.
16. A. M. Sayler, T. Rathje, W. Müller, K. Rühle, R. Kienberger, and G. G. Paulus, "Precise, real-time, every-single-shot, carrier-envelope phase measurement of ultrashort laser pulses," Opt. Lett. **36**, 1–3 (2011).
17. C. Q. Li, E. Moon, and Z. H. Chang, "Carrier-envelope phase shift caused by variation of grating separation," Opt. Lett. **31**, 3113–3115 (2006).
18. M. G. Schätzel, F. Lindner, G. G. Paulus, H. Walther, E. Goulielmakis, A. Baltuška, M. Lezius, and F. Krausz, "Long-term stabilization of the carrier-envelope phase of few-cycle laser pulses," Appl. Phys. B **79**, 1021–1025 (2004).
19. F. Verluise, V. Laude, Z. Cheng, C. Spielmann, and P. Tournois, "Amplitude and phase control of ultrashort pulses by use of an acousto-optic programmable dispersive filter: pulse compression and shaping," Opt. Lett. **25**, 575–577 (2000).
20. N. Forget, L. Canova, X. Chen, A. Jullien, and R. Lopez-Martens, "Closed-loop carrier-envelope phase stabilization with an acousto-optic programmable dispersive filter," Opt. Lett. **34**, 3647–3649 (2009).
21. O. Gobert, P. M. Paul, J. F. Hergott, O. Tcherbakoff, F. Lepetit, P. D. 'Oliveira, F. Viala, and M. Comte, "Carrier-envelope phase control using linear electro-optic effect," Opt. Express **19**, 5410–5418 (2011).
22. J. F. Hergott, O. Tcherbakoff, P. M. Paul, P. Demengeot, M. Perdrix, F. Lepetit, D. Garzella, D. Guillaumet, M. Comte, P. D. Oliveira, and O. Gobert, "Carrier-envelope phase stabilization of a 20 w, grating based, chirped-pulse amplified laser, using electro-optic effect in a linbo3 crystal," Opt. Express **19**, 19935–19941 (2011).
23. T. Oksenhendler, D. Kaplan, P. Tournois, G. M. Greetham, and F. Estable, "Intracavity acousto-optic programmable gain control for ultra-wide-band regenerative amplifiers," Appl. Phys. B **83**, 491–494 (2006).

1. Introduction

The control of strong-field phenomena down to the attosecond regime relies on the generation and application of ultrashort intense laser pulses characterized by a well-defined and reproducible wave-form, i.e. by a stable and controllable carrier-envelope-phase (CEP) [1]. Tailoring the electric field of few-cycle pulses allows one to steer the electronic motion inside atoms and molecules with unprecedented temporal resolution thus offering control over different processes such as above threshold ionization [2], non-sequential double ionization [3], and high-order harmonic generation [4]. The application of these sources for the investigation of strong-field phenomena is triggering the development of high repetition rate lasers (from few kHz up to the MHz range) with high energy per pulse (from hundreds of μJ up to tens of mJ) leading to high average powers ($>$ 10 W) that challenge the possibility to control the CEP through the entire amplification process. The control of the CEP in amplified laser systems is usually based on the combination of two feedback loops operating on the oscillator and on the amplifier(s), respectively, that compensate for the CEP drift, i.e. the variation of CEP between two consecutive pulses. The train of pulses delivered by a mode-locked oscillator is characterized by a constant CEP drift determined by the difference between the group and the phase velocities in a round trip of the cavity. Intensity noise fluctuations induce variations of the CEP drift due to the intensity-phase coupling inside the active medium of the oscillator [5]. The CEP

#193205 - $15.00 USD Received 1 Jul 2013; revised 9 Sep 2013; accepted 23 Sep 2013; published 15 Oct 2013

variation between consecutive pulses delivered by the oscillator can be fixed making use of a feedback loop based on a nonlinear interferometer, that measures the CEP drift, and either an acousto-optic modulator or a piezo-stage that modulates the power of the pump laser [6] or tilts an end mirror of the cavity [7], respectively. Recently, a new approach based on a frequency shifter has been developed [8, 9].

The amplification process introduces additional CEP noise mainly due to mechanical instabilities in the stretcher-compressor setup, beam pointing instabilities or power fluctuations of the pump laser [10]. A second feedback loop is required for the compensation of this noise. High repetition rate, high average power lasers call for large correction bandwidth of the CEP-feedback loop that is limited either by the detection system or by the actuator. The CEP drift at the output of the amplifier can be characterized using a visible-infrared spectrometer that acquires the interference pattern generated by a spectrally broadened continuum and by its second harmonic in a nonlinear interferometer (f-2f interferometer) [11, 12] after the final compression stage. In this scheme the CEP drift is measured by applying a Fourier-based algorithm on the interference pattern. Alternatively the interference pattern can be sampled using two photomultipliers [13], a photodiodes array [14] or a single photodiode [15] replacing the visible-infrared spectrometer thus ensuring a faster acquisition rate. Strong-field effects such as ATI have also been used for single-shot CEP drift characterization of kHz-rate laser systems [16].

Several actuators acting only on the amplifiers have been proposed and experimentally demonstrated to correct the CEP noise induced by the amplification process including the adjustment of the distance between gratings in the stretcher/compressor [17], the variation of the amount of glass in the beam path by moving a glass wedge [18], or the modulation of the pump-power of the oscillator [4]. In the first two cases, as massive moving mechanical parts are included in the loop, the feedback bandwidth is limited to few Hertz; instead, in the last case, as two feedback loops (one for the oscillator and one for the amplifier) are acting on the same parameter, possible cross-talk might be unavoidable. Recently a new method, based on the use of a programmable acousto-optic dispersive filter (Dazzler) [19] inserted into the beam path, was proposed for the stabilization of the CEP of amplified pulses [20]. An electro-optic modulator was also successfully implemented in the correction of the CEP drift introduced by the amplification chain [21, 22]. The main advantage of these devices is the absence of moving parts, that could allow feedback bandwidths up to few tens of kHz.

In this work we demonstrate a complete analog feedback loop for correcting the CEP drift introduced by a high-average power amplifier by combining a fast single-shot detection system and a fast actuator. In section 2 we present the experimental setup. In section 3 we compare the results obtained for the in-loop measurements using different approaches and the data acquired using an independent out-of-loop measurement of the CEP drift, discussing the importance of a single-shot characterization of CEP noise for high repetition rate laser systems. Finally, in section 4 we present our conclusions.

2. Experimental setup

The amplified laser system delivers ultrashort pulses (FWHM=25-30 fs) at 10 kHz repetition rate with a pulse energy of 2 mJ after compression. The system is based on a commercially available CEP-stabilized oscillator (Rainbow-Femtolasers) with a residual CEP standard deviation $\sigma = 90$ mrad. The pulses are strechted by an Öffner triplet up to 360 ps; a programmable acousto-optic modulator (Dazzler) is placed after the stretcher to control the high-order phase dispersion terms. The pulses are then injected into a regenerative amplifier with an output power of about 1.2 W. A second acousto-optic modulator (Mazzler) [23] is inserted in the cavity for shaping and broadening of the amplified spectrum. At the output of the regenerative amplifier, a first water-cooled 4-pass pre-amplifier and a second 4-pass amplifier boost the energy up to

#193205 - $15.00 USD Received 1 Jul 2013; revised 9 Sep 2013; accepted 23 Sep 2013; published 15 Oct 2013

4.5 W and 29 W, respectively. The latter amplification stage is based on a cryo-cooled (-180° C) crystal mounted in a vacuum chamber; at this low temperature the thermal lens introduced by the pump-laser is on the order of few meters and can be easily corrected. The pulses are finally injected in a grating-compressor with a throughput of about 70% for an output power of 20 W. The pulse duration was characterized using the second harmonic frequency-resolved optical gating technique. For the experiment, a small fraction (few μJ) of the compressed

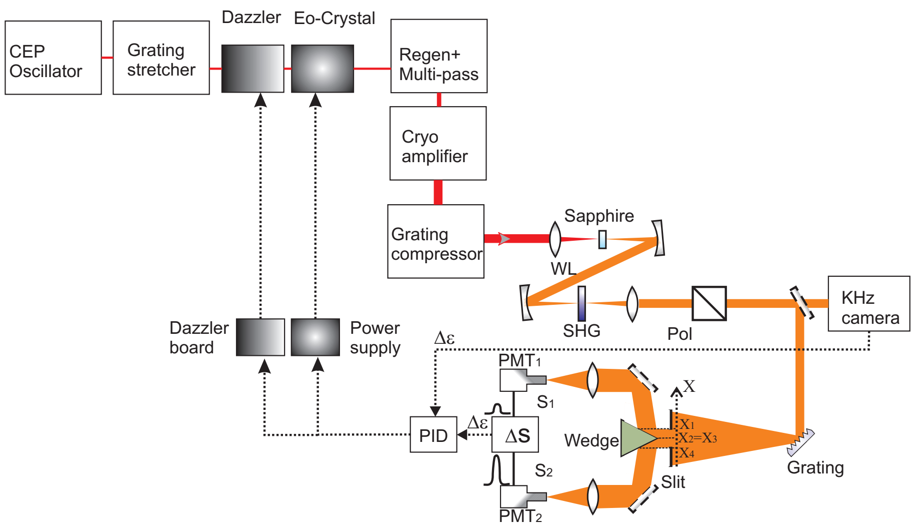

Fig. 1. Experimental setup. WL: white light; SHG : second harmonic generation crystal; Pol: polarizer; PMT: photomultiplier; PID: proportional-integrative-derivative.

pulses is directed to a f-2f nonlinear interferometer (see Fig. 1), similar to the setups shown in refs. [11, 12, 13]. The pulses are focused in a 2-mm-thick sapphire plate for the generation of white-light (WL), corresponding to the signal at frequency f, which is collimated and then focused by two 100-mm focal length spherical mirrors in a 500-μm-thick BBO crystal cut for second harmonic generation at 1064 nm. The infrared part of the WL is frequency doubled leading to a new component (2f signal) around 500 nm with perpendicular polarization with respect to the initial WL. The lens placed after the second harmonic crystal focuses the diverging beam in correspondence of the slit position. A polarizer projects the polarization of the two pulses along the same direction and a 50 % broadband beamsplitter separates the signals in two parts: the first one is focused in a spectrometer coupled with a line scan kHz camera that measures the spectral interference pattern between the f and the 2f components. The position of the fringes is directly related to the CEP of the laser pulse at the input of the f-2f interferometer. The line scan camera and acquisition software allows single-shot acquisition up to a sampling rate (i.e. the maximum frequency at which single-shot data can be acquired) of 180 Hz. It is important to point out that a single laser pulse is sufficient to determine the CEP, avoiding average over consecutive pulses that might wash out fast CEP variations. The sampling rate of the system drops to 100 Hz when the acquisition software is also used to feedback the laser system to stabilize the CEP; it is mainly limited by the time required by the algorithm to retrieve the CEP drift $\Delta\varphi$ that determines the error signal $\Delta\varepsilon$, and by the communication with the control card which sends the correction voltage to the proportional-integrative-derivative (PID) device.
The second part of the radiation is diffracted by a grating, that spatially resolves the spectral fringes along the direction indicated with x in Fig. 1. We have verified that the fact that a non-collimated beam is diffracted by the grating does not appreciably deteriorate the spatial

#193205 - $15.00 USD Received 1 Jul 2013; revised 9 Sep 2013; accepted 23 Sep 2013; published 15 Oct 2013

dispersion of the different spectral components at the slit position. A single fringe is selected by a slit, separated in two parts by the apex of a prism, and sent to two photomultipliers (PMTs) that integrate the signal over two ranges (x_1, x_2) and (x_3, x_4). Then, on a single-shot basis, the outputs of the PMTs are analogically integrated and subtracted, providing $\Delta S = S_2 - S_1$ and the signal error $\Delta\varepsilon$. For a symmetric alignment of the prism with respect to the slit (i.e. $x_4 - x_3 = x_2 - x_1 = \Delta x$ and $x_2 = x_3$), it is possible to demonstrate analytically that the difference signal depends on the CEP, φ, according to the relation:

$$\Delta S(\varphi) \propto \frac{1}{\alpha} \sin^2(\alpha \Delta x/2) \sin(\alpha x_1 + \varphi) \tag{1}$$

where α is determined by the grating dispersion and by the distance between the grating and the detectors. Calculations simulating this detection scheme show that a misalignment up to 20% of the slit from the symmetric configuration introduces a negligible error in the estimation of the CEP. Experimentally, we took care that the slit misalignment from symmetric configuration was less than 10%.

The error signals $\Delta\varepsilon$, delivered either by the kHz camera or by the PMTs detection system, is sent to a PID controller whose output drives either the Dazzler or an electro-optic (EO) crystal ($LiNbO_3$) [21] introduced between the stretcher and the regenerative amplifier. In the first case, the voltage applied to the analog input of the board driving the Dazzler selects a suitable acoustic wave that is sent to the acousto-optics for the correction of the CEP variation. In the second case, the signal drives a voltage amplifier connected to the EO crystal modulating the refraction index experienced by the laser pulses. The two systems allow to pre-compensate for the CEP drift measured at the output of the system. It is important to point out that in the case of the PMTs-based feedback the complete analog manipulation of the signal and the absence of any Fourier-based algorithm for the retrieval of the CEP drift make the scheme scalable to laser repetition rates up to a few hundreds of kHz. As stated in the introduction, the combination of a fast CEP detector (already exploited in refs. [13, 15]) with fast actuators, like the Dazzler and the EO crystal, should allow for a larger correction bandwidth of CEP noise, while avoiding cross-talk issues that might occur when the feedback loops compensating for the noise introduced by the amplifier and by the oscillator operate on the same actuator [13, 15]. The combination of the two detection and analysis systems allows one to compare the performances of the feedbacks based on the kHz camera and on the PMTs acquisition devices. Great care was paid in minimizing air vibrations and mechanical instabilities occurring between the two detection systems.

3. Experimental results

The single-shot CEP drift measured by the kHz camera using the feedback loops based on the PMTs and kHz camera acquisition systems are shown in Fig. 2. The CEP noise introduced by the amplification process is controlled using either the Dazzler (Fig. 2(a),2(b)) or the EO crystal (Fig. 2(c),2(d)). When using the kHz camera to feedback the Dazzler or the EO crystal (Fig. 2(b),2(d)), the sampling rate is reduced to 100 Hz, due to the software processing time; a higher sampling rate (180 Hz) can be achieved when the kHz camera only detects the single-shot CEP variations (Fig. 2(a),2(c)). The measured CEP standard deviations σ using the PMTs-based feedback are 330 mrad for the Dazzler and 320 mrad for the EO crystal, indicating an improvement of 26% and 42% with respect to values of 450 mrad (Dazzler) and 560 mrad (EO crystal), respectively, measured using the kHz camera-based feedback. It is worth to remark that these values are based on single-shot measurements, thus ensuring a meaningful comparison between data acquired with different detection systems and actuators.

#193205 - $15.00 USD Received 1 Jul 2013; revised 9 Sep 2013; accepted 23 Sep 2013; published 15 Oct 2013

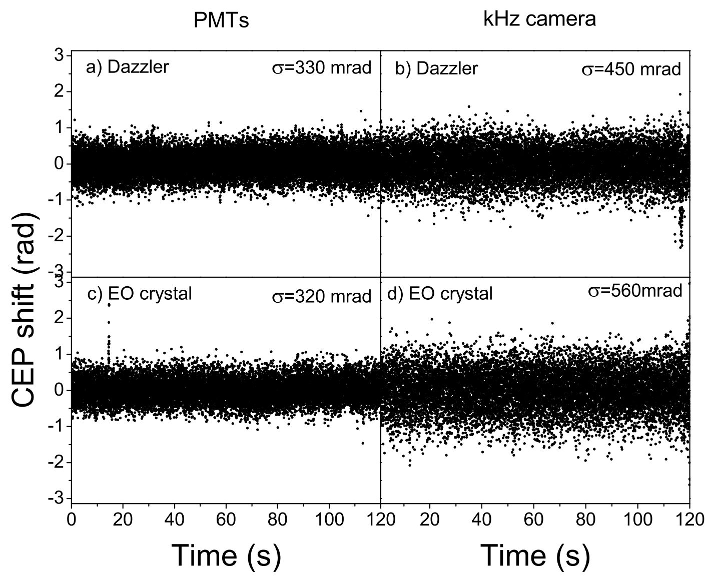

Fig. 2. Single-shot CEP variation measured by the kHz camera at an acquisition rate of 180 Hz (a,c) and 100 Hz(b,d). The feedback signal correcting the noise introduced by the amplifier system was provided by the PMTs (a,c) or the kHz camera (b,d) detection systems acting on the Dazzler (a,b) and on the EO crystal(c,d).

The improvement can be understood by comparing the power spectral densities (PSDs) of the CEP noise shown in Fig. 2(a),2(b) (see black curves of Fig. 3(a),3(b)). The PSDs without feedback on the amplifier (but with the fast feedback loop operating on the oscillator) are also shown for comparison (red curves). The kHz camera feedback allows one to efficiently reduce CEP noise up to a frequency of about 10 Hz, confirming the results presented in ref. [22]. Higher frequency components are not affected by the feedback loop due to the limited sampling rate of the error signal $\Delta\varepsilon$. The PMTs feedback, on the other hand, shows a clear reduction of the CEP noise up to the limit of 90 Hz, imposed by the sampling rate of 180 Hz of the digital measurement. The phase noise integrated over the frequency range (blue-dashed curves) confirm that the PMTs based feedback allows for a better control of the CEP with respect to the kHz camera system. The PSDs for the EO crystal-based feedback loop present a similar behaviour (not shown). The analog feedback loop allows one to achieve comparable final CEP stability using either the Dazzler or the EO crystal.

In order to verify that the PMTs feedback loop allows for correction of even higher frequency components, we recorded the PMTs error signal during the stabilization feedback based on the PMTs and the Dazzler. The oscilloscope resolution allows for a single-shot acquisition at the full repetition rate of the laser. In Fig. 3(c) the PSD of the analog signal with (black curve) and without feedback loop (red curve) is presented. We show the PSDs in the frequency range between 0.1 Hz up and 5 kHz, evidencing that the correction of the analog loop is effective over a large frequency range up to frequencies as high as 1 kHz.

We also performed an out-of-loop measurement of the CEP drift using a second independent nonlinear interferometer (not shown in Fig. 1). A small fraction of the compressed pulse was used to generate the f-2f interference pattern that was measured by a visible-infrared spectrometer connected to a software for the retrieval of the CEP. The CEP was stabilized using

#193205 - $15.00 USD Received 1 Jul 2013; revised 9 Sep 2013; accepted 23 Sep 2013; published 15 Oct 2013

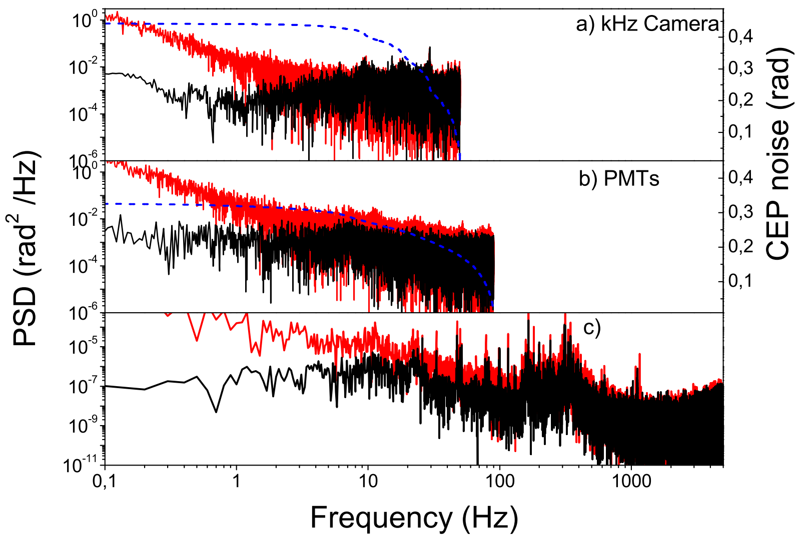

Fig. 3. Power spectral density (left axis) measured by the kHz camera with (black curves) and without (red curves) feedback loop operating on the amplifier. The error signal was provided to the Dazzler by the kHz camera (a) or by the PMTs detection system (b). The integrated phase noise (dashed blue curve ; right axis) as a function of frequency. (c) Power spectral density measured by an oscilloscope sampling the error signal $\Delta\varepsilon$ with (black curve) without (red curve) feedback on the amplifier. The feedback loop was provided to the Dazzler by the PMTs detection system.

the PMTs and the kHz camera connected to the Dazzler. In this case the CEP standard deviation measured by the spectrometer integrating over 10 pulses were 385 mrad and 440 mrad, respectively. The improved stability by the fast analog feedback reduces to about 14%, due to additional noises that we attribute to the different conditions for the WL generation in the two independent interferometers. In spite of this, the out-of-loop measurements definitely confirm the improved CEP stability using the PMTs feedback.

The importance of a fast feedback loop based on a single-shot CEP detection can be fully understood by analyzing the CEP variations for different integration times of the acquisition system as reported in Fig. 4. The CEP was stabilized using the PMTs-based feedback and the data were acquired using the kHz camera for increasing integration times corresponding to an average over N laser shots. It is evident that even integration over few shots determines a remarkable reduction of the measured CEP drift with respect to the single-shot value. In particular, averaging over a large number of shots (>20 in our experimental conditions) leads to a CEP standard deviation that is independent on the number of laser pulses. In these conditions it is not possible to draw any conclusion about the residual CEP noise drift, indicating that a single-shot high repetition rate acquisition system is of primary importance for a reliable characterization of the CEP noise. We also numerically evaluated the expected CEP standard deviation after averaging over N shots. We considered a train of pulses characterized by CEP values with zero average and standard deviation of 320 mrad, corresponding to the single-shot CEP fluctuation measured experimentally. To account for the long-term fluctuation of the laser, the CEPs of the closest consecutive pulses are also weakly correlated. For all choices of N,

#193205 - $15.00 USD Received 1 Jul 2013; revised 9 Sep 2013; accepted 23 Sep 2013; published 15 Oct 2013

the average CEP has zero mean; the standard deviation, on the contrary, strongly depends on N, as evidenced by the red curve of Fig. 4. This simple model is in well agreement with the experimental data, and confirms that for large numbers of N the fluctuations of the averaged CEP are well below its jitter recorded with single-shot detection.

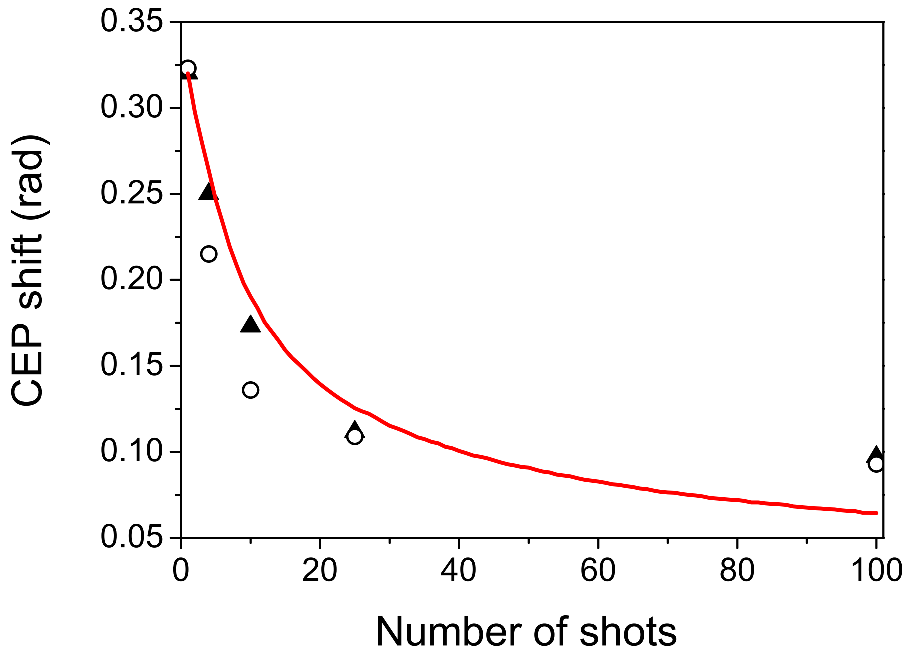

Fig. 4. Effect of the integration time on the shot-to-shot CEP standard deviation for the Dazzler analog feedback (open circle) and EO crystal analog feedback (full triangle). The solid curve indicates the expected standard deviation evolution as a function of the number of shots N, assuming a single-shot standard deviation of 320 mrad.

4. Conclusions

We have demonstrated a novel, complete analog feedback loop for CEP drift stabilization of a high average power amplifier operating on a single-shot basis at the full repetition rate the laser system (10 kHz). The feedback is based on a fast acquisition detection setup in combination with either an acousto-optic or an electro-optic crystal. The absence of moving parts allows one to correct frequency noise up to 1 kHz leading to CEP residual noise of 320 mrad. The demonstrated method should be scalable to systems operating at repetition rates up to few hundreds of kHz. Out-of-loop measurements confirm the improvement of the CEP stability. Further measurements exploiting extreme nonlinear effects such as above-threshold ionization and high-order harmonic generation driven by few-cycle pulses will be performed in order to investigate the additional CEP noise introduced by the nonlinear techniques (hollow fiber or filamentation) used for the compression of ultrashort pulses.

Acknowledgments

Financial support by the Alexander von Humboldt Foundation (Project ”Tirinto”), the Italian Ministry of Research (Project FIRB No. RBID08CRXK),the European Research Council under the European Community’s Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement n. 227355 - ELYCHE, the MC-RTN ATTOFEL (FP7-238362)ATTOFEL and the LASERLAB-EUROPE II (grant agreement n. 228334) is gratefully acknowledged. The authors also want to thank F. Viala from CEA for lending the $LiNbO_3$ crystals and S. De Silvestri for fruitful discussions.

#193205 - $15.00 USD Received 1 Jul 2013; revised 9 Sep 2013; accepted 23 Sep 2013; published 15 Oct 2013