Carrier-envelope phase stabilization and control using a transmission grating compressor and an AOPDF

Lorenzo Canova,[1] Xiaowei Chen,[1] Alexandre Trisorio,[1] Aurélie Jullien,[1,*] Andreas Assion,[2] Gabriel Tempea,[2] Nicolas Forget,[3] Thomas Oksenhendler,[3] and Rodrigo Lopez-Martens[1]

[1]*Laboratoire d'Optique Appliquée, Ecole Nationale Supérieure des Techniques Avancées, ParisTech, CNRS, Ecole Polytechnique, 91761 Palaiseau Cedex, France*

[2]*Femtolasers Produktions GmbH, Fernkongasse 10, 1100 Vienna, Austria*

[3]*Fastlite, Centre Scientifique d'Orsay, Bâtiment 503, Plateau du Moulon–B.P. 45, 91401 Orsay, France*

**Corresponding author: Aurelie.Jullien@ensta.fr*

Received February 4, 2009; accepted March 17, 2009;
posted March 26, 2009 (Doc. ID 107145); published April 20, 2009

Carrier-envelope phase (CEP) stabilization of a femtosecond chirped-pulse amplification system featuring a compact transmission grating compressor is demonstrated. The system includes two amplification stages and routinely generates phase-stable (~250 mrad rms) 2 mJ, 25 fs pulses at 1 kHz. Minimizing the optical pathway in the compressor enables phase stabilization without feedback control of the grating separation or beam pointing. We also demonstrate for the first time to the best of our knowledge, out-of-loop control of the CEP using an acousto-optic programmable dispersive filter inside the laser chain.

OCIS codes: 140.7090, 320.7090, 140.3280, 320.7160.

In the past few years, one major breakthrough in ultrafast laser science has been the ability to measure and stabilize the carrier-envelope phase (CEP) drift of amplified femtosecond laser pulses. The CEP is defined as the offset between the maximum of the electric field and its peak envelope. This feature, combined with few-cycle light pulses, whose envelope changes almost as quickly as the electric field, has enabled significant progress in strong field experiments and attosecond science [1–5]. In chirped-pulse amplification (CPA) lasers, the CEP can be locked for tens of minutes by stabilizing the CEP offset of the oscillator and by subsequently correcting the slow drift that occurs during amplification. CEP-stabilized pulses are now routinely generated at the millijoule level from laser chains including bulk (glass block and prisms) stretchers and compressors [6]. For the production of higher-energy pulses, extending the scope of CEP-dependent strong field experiments, grating-based CPA systems remain particularly attractive. In this direction, proofs of feasibility of CEP stabilization of such systems have been proposed [7,8]. Other studies have theoretically and experimentally demonstrated that the CEP drift stabilization in grating-based setups requires interferometric control of the grating separation, which introduces additional experimental complexity [9–11]. Nevertheless, this limitation can be overcome by using small pulse-stretching factors and keeping minimal optical paths. This solution has the advantage of minimizing the sources of dispersion fluctuations thereby offering better prospects for long-term CEP stability. In this Letter, we demonstrate CEP stabilization of a 2 mJ, 25 fs 1 kHz Ti:sapphire (Ti:Sa) CPA system featuring a bulk material stretcher, two amplification stages, and a compact compressor composed of transmission gratings and chirped mirrors. No active control of the grating position in the compressor is necessary for CEP stabilization. We also demonstrate arbitrary control of the relative CEP value using an acousto-optic programmable dispersive filter (AOPDF) [12]. The method opens the way to fully integrated control over both the spectral phase and the CEP of any CPA laser featuring an AOPDF.

The proposed laser system (Fig. 1) consists of a commercial 1 kHz CEP-stabilized amplifier (Femtopower Compact Pro CE Phase, Femtolasers GmbH) followed by a home-built Ti:Sa multipass amplifier. The amplification stages are pumped by 11 and 20 W, respectively, from a single 1 kHz frequency-doubled Q-switched Nd:YLF laser (DM 50 series, Photonics Industries). The oscillator pulses are CEP locked via pump-laser amplitude modulation and stretched to ~7 ps through a glass block unit and an AOPDF before amplification to the millijoule level in the subsequent commercial ten-pass amplifier. The AOPDF (low-jitter Dazzler HR800, Fastlite) is situated between passes 4 and 5 of the Femtopower amplifier. It is used both to balance gain narrowing in the second amplifier and to compensate and optimize the spec-

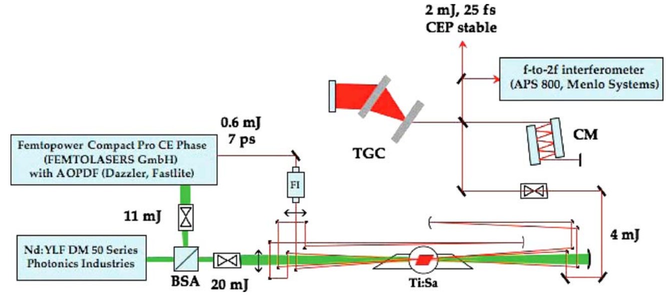

Fig. 1. (Color online) Experimental scheme of 2 mJ, 25 fs, 1 kHz CEP-stable CPA system with transmission gratings (TGC) and chirped mirrors (CM) compressor. (BSA, beam splitter and attenuator; FI, Faraday isolator).

tral phase of the output pulses. The pulses amplified in this first stage can be compressed through the commercial prism compressor. In this case, the measured rms value of the CEP stability is about 250 mrad. 600 μJ seed pulses from the Femtopower are boosted up to 4 mJ after three image-relayed passes in an 8 mm Ti:Sa crystal cut at Brewster angle and cooled down to 195 K. The compression in the transmission grating compressor is limited to ~0.8 ps pulses in order to avoid potential self-phase modulation effects. The compressor is composed of two 600 line/mm fused-silica holographic gratings (Wasatch Photonics) separated by about 70 mm, for a beam incident angle of 13.9°. The introduced spectral phases are $\varphi_{\mathrm{TGC}}^{(2)} \sim -50\,000\ \mathrm{fs}^2$ and $\varphi_{\mathrm{TGC}}^{(3)} \sim 70\,000\ \mathrm{fs}^3$. Final compression is then achieved after 32 bounces through a negatively chirped mirror pair ($-200\ \mathrm{fs}^2$ per bounce). The residual second-order phase and the positive third-order phase originating from the stretcher, the amplifier material, and the compressor are compensated by the AOPDF ($\varphi_{\mathrm{DAZ}}^{(2)} = -15\,100\ \mathrm{fs}^2$ and $\varphi_{\mathrm{DAZ}}^{(3)} = -140\,000\ \mathrm{fs}^3$).

The overall transmission of the compression stage is 53% (~60% for the gratings' compressor), which is comparable to usual multimillijoule pulse compressors. Temporal and spectral characterization of the 2.1 mJ output pulses was achieved using homemade spectral-phase interferometry for direct electric-field reconstruction (SPIDER) [Figs. 2(a) and 2(b)]. The spectrum does not exhibit any significant distortions over 100 nm bandwidth. The measured temporal duration is 25 fs, close to the Fourier transform limit (23 fs). Furthermore, the proposed compression scheme preserves a good spatial quality. The Gaussian spatial intensity distribution of the focused beam is represented in Fig. 2(c).

A few microjoules are split off and sent into a collinear f-to-$2f$ interferometer (APS 800, Menlo Systems) to monitor the relative CEP drift of the amplified pulses [13]. Figure 3(a) represents the single-shot fringe pattern registered at the output of the interferometer (2000 shots; the integration time of the spectrometer is 1 ms). No feedback loop is activated for this acquisition. The visible and well-contrasted interference figure demonstrates the effective CEP stabilization of the laser pulses. This observation is corroborated by the measurement (APS 800: acquisition time = 1 ms, cycle loop time = 100 ms) of the corresponding CEP drift on a short-time scale (1 min) [Fig. 3(b)]. To evaluate the long-term stability, the slow drift introduced by the amplifiers is then precompensated by a feedback loop to the oscillator locking electronics using the measured CEP. Figure 3(c) shows the typical CEP stabilization of the system with feedback control. The rms phase error over tens of minutes is 250 mrad, which is identical to that measured for the commercial amplifier featuring a standard prism compressor. The second amplifier and the compressor do not introduce additional phase noise. The small distance between the gratings reduces the sensitivity to beam pointing and air currents in the compressor. In our case, the reduced groove density of the gratings and the lower incident angle decrease CEP fluctuations associated with variations of grating separation (thermal or mechanical drift). This is consistent with the model developed in [9]. The detected phase-noise value includes both system noise (mainly limited by the oscillator stability) and detection noise. This last contribution is particularly dependent on energy fluctuations at the input of the interferometer (±3% in our experiment) [14]. Energy instability was found to come from the low AOPDF transmission in the first amplifier because of the important amount of third-order phase introduced. The use of third-order chirped mirrors will improve this feature later on.

Without a feedback loop, the CEP drift of the amplified pulses is small enough over several minutes to demonstrate that the AOPDF inserted in the Femtopower enables CEP control by changing the CEP of

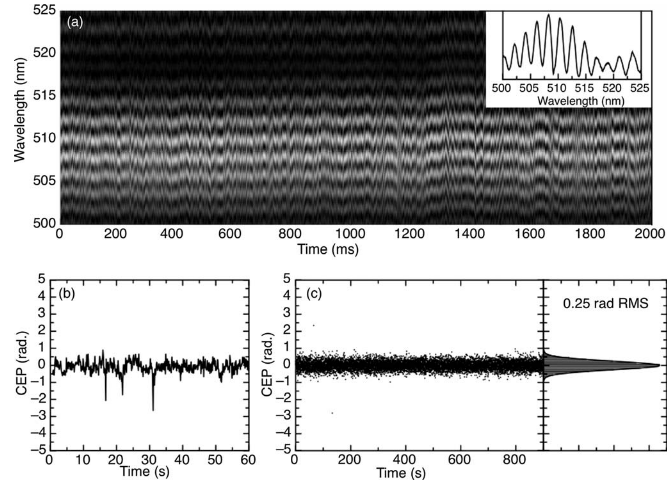

Fig. 3. CEP stability measurements (spectrometer integration time: 1 ms). (a) Single-shot fringe pattern from the collinear f-to-$2f$ interferometer for 2000 consecutive shots. One typical spectrum is shown in the inset for illustration. (b) Measured relative CEP drift of amplified pulses without a feedback loop. (c) Measured stabilized CEP drift of amplified pulses with feedback control over 15 min (250 mrad rms). The stabilization of the CEP over 1 h has been measured with an rms error of 290 mrad.

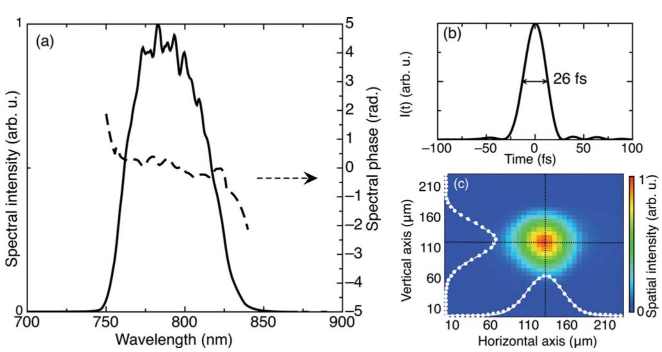

Fig. 2. (Color online) Temporal and spatial characterization of the compressed 2.1 mJ pulses. (a) Spectral intensity (solid curve) and phase (dashed curve) obtained from SPIDER measurement. (b) Temporal intensity profile (SPIDER). (c) Spatial intensity distribution in the far field (the 7 mm diameter output beam is focused by a 1 m lens). Vertical and horizontal profiles are fitted by a Gaussian distribution (white curves). The measured value for the M^2 factor is ~1.2.

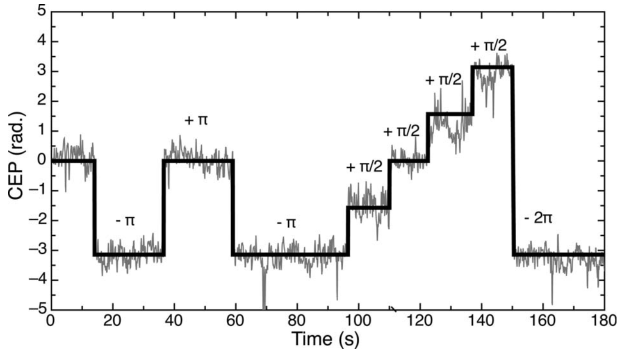

Fig. 4. Measured CEP (gray curve) of amplified pulses and successive phase steps applied by the AOPDF (black curve).

the acoustic wave in the AOPDF. The principle of the AOPDF is based on a stringent acousto-optic phase-matching relationship between the acoustical and optical wave vectors [12]. Obviously, this relationship has its counterpart in terms of spectral phase. The acoustical and optical spectral phases are linked by the following expression:

$$\varphi_{\text{opt,in}}(\omega_{\text{opt}}) + \varphi_{\text{acc,in}}(\omega_{\text{acc}}) - \varphi_{\text{opt,diff}}(\omega_{\text{opt}}) = \pi/2, \quad (1)$$

where $\varphi_{\text{opt,in}}(\omega_{\text{opt}})$ and $\varphi_{\text{opt,diff}}(\omega_{\text{opt}})$ are the spectral phases of the input and diffracted optical pulses. $\varphi_{\text{acc,in}}(\omega_{\text{acc}})$ is the spectral phase of the acoustic pulse. In the low-jitter configuration, the electronic generator of the AOPDF is able to control the CEP of the acoustic wave within 160 mrad (rms time jitter between the trigger and the rf clock). Consequently, in the optical domain, the CEP of the diffracted pulse can be changed with respect to the CEP of the input pulse by an arbitrary amount with 160 mrad ($\pi/20$) accuracy. As a proof of feasibility, Fig. 4 shows the effects of successive CEP jumps of $-\pi$, $+\pi$, $-\pi$, $+\pi/2$, $+\pi/2$, $+\pi/2$, $+\pi/2$, and -2π applied by the AOPDF. The CEP measured at the output of the laser chain reproduces the same phase steps, thereby successfully demonstrating the ability of the AOPDF to exert control over the CEP. The feedback control loop was turned off to avoid automatic correction of the CEP jumps by the oscillator locking electronics. These phase steps were performed at a low repetition rate, i.e., not limited by the refresh rate of the AOPDF. By precomputing and preloading a set of rf waves with different CEP values (e.g., 64 waves covering the $0-2\pi$ interval), the rf generator should be able to correct any CEP drift at repetition rates as high as the trigger rate (1 kHz). This could open the way to closed-loop slow CEP drift corrections at high repetition rates without activating any optical or mechanical part of the system.

In conclusion, we have presented the CEP stabilization of a transmission grating-based CPA system generating 2 mJ, 25 fs pulses at 1 kHz. The rms phase noise is 250 mrad. We have demonstrated that laser systems conceived with a low stretching factor and compact grating-based devices, by decreasing sources of noise and fluctuations in the optical pathway, do not require feedback on the grating separation for CEP stabilization over 1 h. When combined with a chirped mirror compressor to prevent self-phase modulation in the grating material, the overall transmission stays above 50%. The compressed pulse energy is limited in our case by the 4 mJ input coming from the second amplifier stage. Our compression scheme is thus scalable to higher output pulse peak powers. Furthermore, we have shown that the relative CEP value can be fully controlled by an AOPDF inserted in the laser chain. In the future, the correction of the slow CEP drift directly with the AOPDF will prevent a second retroaction on the oscillator locking device and thereby improve final CEP stability.

Financial support from the Canadian National Research Council–Centre National de la Recherche Scientifique (CNRS) 2007 program and from the Agence Nationale pour la Recherche, through programs BLAN06-3_134072 (ILAR) and Chaire d'Excellence 2004, is gratefully acknowledged.

References

1. A. Baltuska, T. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, C. Gohle, R. Holwarth, V. S. Yakovlev, A. Scrinzi, T. W. Hansch, and F. Krausz, Nature **421**, 611 (2003).
2. G. Sansone, E. Benedetti, C. Vozzi, S. Stagira, and M. Nisoli, New J. Phys. **10**, 025006 (2008).
3. M. F. Kling, J. Rauschenberger, A. J. Verhoef, E. Hasovic, T. Uphues, D. B. Milosevic, H. G. Muller, and M. J. J. Vrakking, New J. Phys. **10**, 025024 (2008).
4. C. A. Haworth, L. E. Chipperfield, J. S. Robinson, P. L. Knight, J. P. Marangos, and J. W. G. Tisch, Nat. Phys. **3**, 52 (2007).
5. A. Jullien, T. Pfeifer, M. J. Abel, P. M. Nagel, M. J. Bell, D. M. Neumark, and S. R. Leone, Appl. Phys. B **93**, 433 (2008).
6. A. Baltuska, M. Uiberacker, E. Goulielmakis, R. Kienberger, V. S. Yakovlev, T. Udem, T. W. Hansch, and F. Krausz, IEEE J. Quantum Electron. **9**, 972 (2003).
7. M. Kakehata, H. Takada, Y. Kobayashi, K. Torizuka, H. Takamiya, K. Nishijima, T. Homma, H. Takahashi, K. Okubo, S. Nakamura, and Y. Koyamada, Opt. Express **12**, 2070 (2004).
8. E. Gagnon, I. Thomann, A. Paul, A. L. Lytle, S. Backus, M. M. Murnane, H. C. Kapteyn, and A. S. Sandhu, Opt. Lett. **31**, 1866 (2006).
9. Z. Chang, Appl. Opt. **45**, 8350 (2006).
10. C. Li, E. Moon, and Z. Chang, Opt. Lett. **31**, 3113 (2006).
11. C. Li, H. Mashiko, H. Wang, E. Moon, S. Gilbertson, and Z. Chang, Appl. Phys. Lett. **92**, 191114 (2008).
12. F. Verluise, V. Laude, Z. Cheng, C. Spielmann, and P. Tournois, Opt. Lett. **25**, 575 (2000).
13. M. Kakehata, H. Takada, Y. Kobayashi, K. Torizuka, Y. Fujihira, T. Homma, and H. Takahashi, Opt. Lett. **26**, 1436 (2001).
14. C. Li, E. Moon, H. Wang, H. Mashiko, C. M. Nakamura, J. Tackett, and Z. Chang, Opt. Lett. **32**, 796 (2007).