Carrier-envelope phase stabilization and control of 1 kHz, 6 mJ, 30 fs laser pulses from a Ti:sapphire regenerative amplifier

Shouyuan Chen, Michael Chini, He Wang, Chenxia Yun, Hiroki Mashiko, Yi Wu, and Zenghu Chang*

J. R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan, Kansas 66506, USA

*Corresponding author: chang@phys.ksu.edu

Received 24 August 2009; revised 25 September 2009; accepted 25 September 2009; posted 28 September 2009 (Doc. ID 116036); published 12 October 2009

Carrier-envelope (CE) phase stabilization of a two-stage chirped pulse amplifier laser system with regenerative amplification as the preamplifier is demonstrated. The CE phase stability of this laser system is found to have a 90 mrad rms error averaged over 50 laser shots for a locking period of 4.5 h. The CE phase locking was confirmed unambiguously by experimental observation of the 2π periodicity of the high-order harmonic spectrum generated by double optical gating. © 2009 Optical Society of America

OCIS codes: 320.7090, 320.7100, 320.6629.

Pioneering experiments have recently explored nonlinear attosecond physics using attosecond pulse trains and high-order harmonics produced from high-energy driving lasers [1–4]. Extension of such experiments to the single isolated attosecond pulse regime is a subject of much interest, and several gating schemes have been demonstrated in recent years to produce such pulses from few-cycle and multicycle CE phase-stabilized driving lasers [5–7]. However, the pulse energy of isolated attosecond pulses has so far been limited to the nanojoule level [8], which is insufficient for the study of nonlinear physics. With CE phase stabilization of high-energy lasers, nonlinear attosecond physics and isolated attosecond pump-probe experiments could become attainable.

Regenerative amplification is an attractive choice for the generation of ultrafast laser pulses with multimicrojoule pulse energy at high repetition rates [9–11]. In fact, recent measurements of nonlinear autocorrelation in attosecond pulse trains were conducted with a regenerative amplifier [7]. In comparison with multipass amplifiers, the laser pulses generated from regenerative amplification have a better beam profile, pointing stability, power stability, and extraction efficiency. Regenerative amplification has been commonly used as the preamplifier for high-energy femtosecond laser systems. However, CE phase stabilization has been demonstrated only on multipass lasers [12,13]. Although the CE phase evolution after regenerative amplification has been explored to some extent [11], the CE phase drift caused by the amplification stage has not been corrected. Furthermore, no high-field CE phase-dependent experiments have been demonstrated with a regenerative amplifier. Here we report CE phase stabilization and control of the Manhattan Attosecond Radiation Source (MARS) regenerative amplification laser system and unambiguously confirm its stability by measurement of the CE phase dependence of the high-order harmonic spectrum generated by double optical gating (DOG) [14].

The MARS laser system consists of a commercially available Ti:sapphire Coherent Legend Elite Duo (Coherent, Santa Clara, California, USA) chirped pulse amplifier (CPA) that operates at 1 kHz, seeded by a Rainbow oscillator (Femtolasers, Vienna, Austria). The oscillator operates at a 78 MHz repetition rate with a 200 mW output power. The CE offset frequency

0003-6935/09/305692-04$15.00/0

(f_{CEO}) of the oscillator is stabilized using the monolithic CE phase-stabilization scheme [15]. With the assistance of the temperature feedback control, f_{CEO} of this oscillator can be locked for approximately 12 h on a daily basis [16]. As shown in Fig. 1, the amplifier consists of a grating based stretcher, two amplification stages, and a grating based compressor. The stretcher stretches the pulse to approximately 160 ps.

The first amplification stage is a 14 round-trip regenerative amplifier that amplifies the laser pulse to 4 mJ. The second stage is a single-pass amplifier to boost the laser pulse energy to 8 mJ. The Ti:sapphire crystals in both amplification stages are thermoelectrically cooled to −12 °C. The regenerative amplifier and single-pass amplification stages are each pumped by 50% of a 45 W Coherent Evolution high-energy pump laser. After compression, the final output pulse energy is 6 mJ with a central wavelength of 800 nm and a spectral bandwith of 37 nm, which supports a Fourier transform-limited pulse duration of 28 fs. The pulse duration as measured with frequency-resolved optical gating (FROG) is 30 fs. The CE phase drift of the amplified pulse is measured by sending part of the output beam to the f-to-$2f$ interferometer [17]. The feedback signal is then sent to a piezoelectric transducer (PZT) stage on the compressor grating to stabilize the CE phase slow drift by controlling the grating separations [13,18]. Because of the high output power of the MARS laser system, the laser beam is typically split by a 50/50 beam splitter to support two experiments simultaneously.

During the CE phase stabilization process, it was found that the CE phase of the final output laser pulse from this laser system is sensitive to mechanical vibration and acoustic noise. However, by moving the pump laser further away from the amplifier, padding the laser cover with sound absorption materials, and improving the stability of the optical mounts in the stretcher and compressor, the CE phase stability was achieved. The rms error of the locked CE phase was measured to be 90 mrads over a period of 4.5 h with a 50 ms spectrometer integration time as shown in Fig. 2. Since the measured CE phase error is inversely proportional to the square root of the integrated shot number, we estimate the single-shot CE phase error to be 600 mrads. The locking duration is sufficient for many low count rate experiments, such as attosecond streaking and laser ion

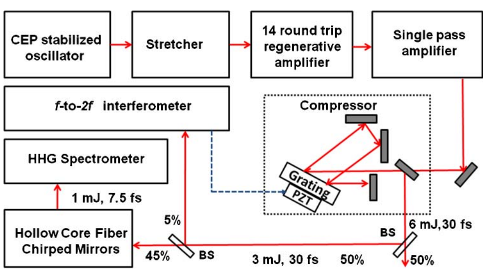

Fig. 1. (Color online) Layout of the MARS laser system. BS: beam splitter.

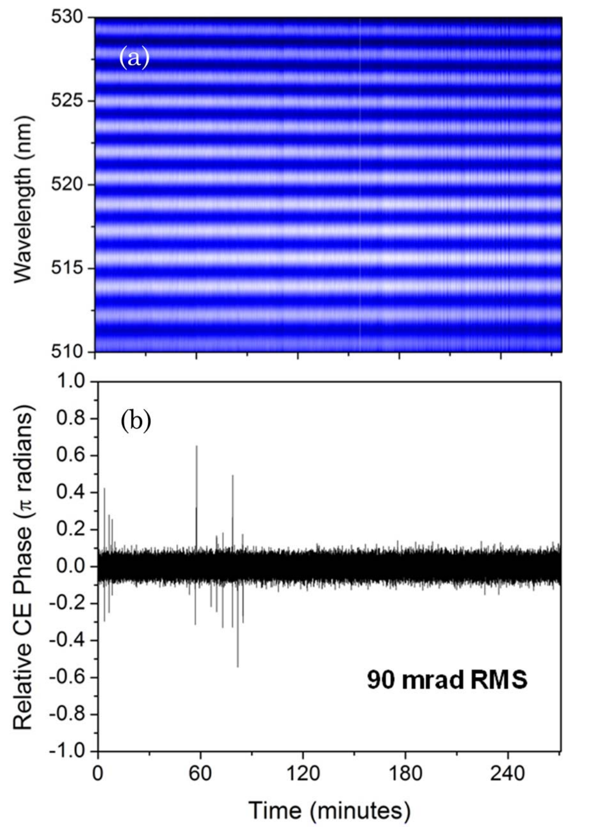

Fig. 2. (Color online) Long-term CE phase stabilization: (a) f-to-$2f$ interference fringes, (b) retrieved CE phase from the fringes, which has a 90 mrad rms averaged over 50 laser shots.

beam interaction experiments, which can require several hours of CE phase stabilization [19,20]. To control the CE phase in the experiment, the grating separation of the compressor was stabilized at preset values. As shown in Fig. 3, the CE phase was swept from $-\pi$ to π for many cycles that can be used to observe the CE phase effects in high harmonic and attosecond pulse generation experiments [21]. Some regions in Figs. 2(a) and 3(a) show transient reductions of the fringe visibility, which are likely due to acoustic noise and vibration in the laboratory that could not be avoided over such a long locking period. However, such small disturbances did not affect the quality of the CE phase control.

To unambiguously confirm the CE phase stabilization of the MARS laser system, the dependence of the high-order harmonic spectrum generated in argon from DOG was measured with an extreme-ultraviolet transmission grating spectrometer [22]. To generate the short pulse (<10 fs) required by DOG, half of the laser pulse with an energy of 3 mJ was sent to a 1 m long hollow-core fiber with an inner diameter of 400 μm and filled with neon at a pressure of 2 atm. After self-phase modulation, the laser pulse spectrum was broadened from 600 to 950 nm. The FROG measurement shows that the pulse duration is 7.5 fs after compression by the chirped mirrors, which is short enough to generate a single isolated attosecond pulse [23]. The final

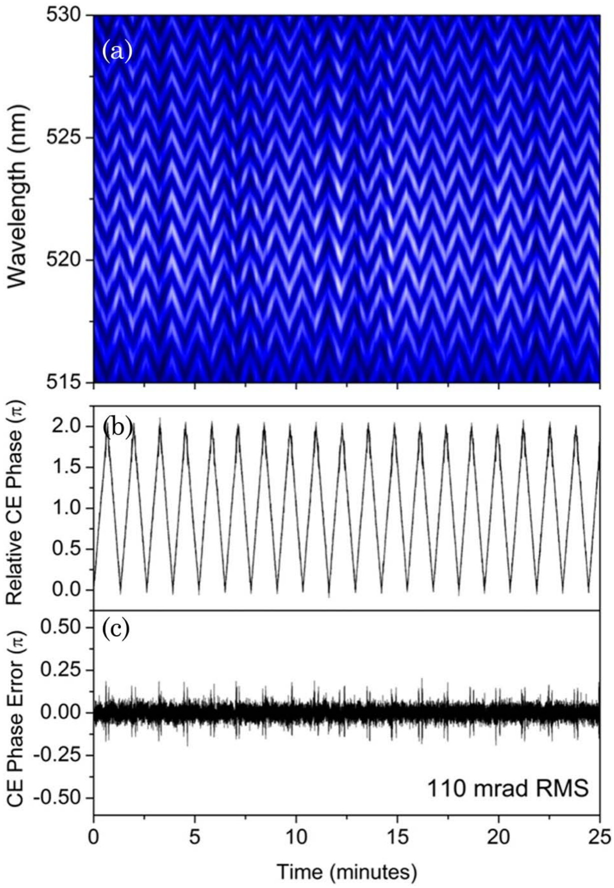

Fig. 3. (Color online) Periodic CE phase sweep from $-\pi$ to π: (a) f-to-$2f$ interferometer fringes, (b) scanning phase value retrieved from the fringes, (c) CE phase error of the retrieved phase relative to the preset scanning phase. The periodic increases in error are due to the PZT response at the turning points of the control curve.

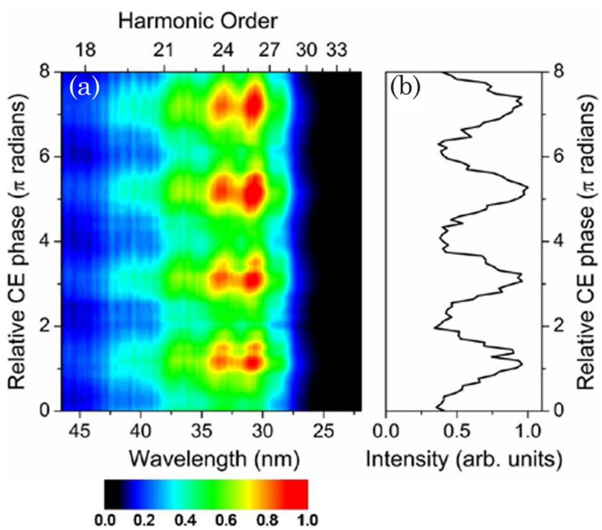

Fig. 4. (Color online) (a) DOG harmonic spectra taken with the CE phase scanned from 0 to 8π. (b) Line out of the normalized integrated spectrum. The integration range is from 48 to 20 nm. The 2π periodicity is consistent with the asymmetric electric field of DOG.

output power of the short pulse is 1 mJ after compression of the chirped mirrors. The short pulse was then focused by a 300 mm spherical mirror into a 1.5 mm gas cell filled with argon at 40 Torr to generate the high-order harmonics. When the CE phase was scanned linearly from 0 to 8π, the harmonic spectra varied with a 2π periodicity as shown in Fig. 4, which is consistent with the 2π periodicity of the electric field generated by DOG [24]. The total time to perform the CE phase scan was 30 min.

In conclusion, the CE phase stabilization of a 6 mJ, 30 fs, 1 kHz regenerative amplifier has been demonstrated with a 90 mrad rms over a period of 4.5 h. The DOG spectral dependence on the CE phase unambiguously confirms the stability. This paves the way for the realization of high-power CE phase-stabilized lasers and high-flux single-isolated attosecond pulse generation, which are critical steps toward the study of nonlinear physics and pump-probe experiments with single attosecond pulses.

The authors gratefully thank Alan Fry and Chengquan Li at Coherent, Incorporated for their technical support and valuable discussions. This material is supported by the U. S. Army Research Office under grant W911NF-07-1-0475, and by the Chemical Sciences, Geosciences, and Biosciences Division, Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy.

References

1. T. Okino, K. Yamanouchi, T. Shimizu, R. Ma, Y. Nabekawa, and K. Midorikawa, "Attosecond nonlinear Fourier transformation spectroscopy of CO_2 in extreme ultraviolet wavelength region," J. Chem. Phys. **129**, 161103 (2008).
2. Y. Nabekawa, T. Shimizu, Y. Furukawa, E. Takahashi, and K. Midorikawa, "Interferometry of attosecond pulse trains in the extreme ultraviolet wavelength region," Phys. Rev. Lett. **102**, 213904 (2009).
3. Y. Nomura, R. Hörlein, P. Tzallas, B. Dromey, S. Rykovanov, Zs. Major, J. Osterhoff, S. Karsch, L. Veisz, M. Zepf, D. Charalambidis, F. Krausz, and G. D. Tsakiris, "Attosecond phase locking of harmonics emitted from laser-produced plasmas," Nature Phys. **5**, 124–128 (2009).
4. A. Peralta Conde, J. Kruse, O. Faucher, P. Tzallas, E. P. Benis, and D. Charalambidis, "Realization of time-resolved two-vacuum-ultraviolet-photon ionization," Phys. Rev. A **79**, 061405(R) (2009).
5. E. Goulielmakis, M. Schultze, M. Hofstetter, V. S. Yakovlev, J. Gagnon, M. Uiberacker, A. L. Aquila, E. M. Gullikson, D. T. Attwood, R. Kienberger, F. Krausz, and U. Kleineberg, "Single-cycle nonlinear optics," Science **320**, 1614–1617 (2008).
6. G. Sansone, E. Benedetti, F. Calegari, C. Vozzi, L. Avaldi, R. Flammini, L. Poletto, P. Villoresi, C. Altucci, R. Velotta, S. Stagira, S. D. Silvestri, and M. Nisoli, "Isolated single-cycle attosecond pulses, " Science **314**, 443–446 (2006).
7. S. Gilbertson, X. Feng, S. Khan, M. Chini, H. Wang, H. Mashiko, and Z. Chang, "Direct measurement of an electric field in femtosecond Bessel–Gaussian beams," Opt. Lett. **34**, 2390–2392 (2009).
8. H. Mashiko, S. Gilbertson, C. Li, E. Moon, and Z. Chang, "Optimizing the photon flux of double optical gated high-order harmonic spectra," Phys. Rev. A **77**, 063423 (2008).

9. G. Vaillancourt, T. B. Norris, J. S. Coe, P. Bado, and G. A. Mourou, "Operation of a 1 kHz pulse-pumped Ti:sapphire regenerative amplifier," Opt. Lett. **15**, 317–319 (1990).
10. C. P. J. Barty, T. Guo, C. Le Blanc, F. Raksi, C. Rose-Petruck, J. Squier, K. R. Wilson, V. V. Yakovlev, and K. Yamakawa, "Generation of 18 fs, multiterawatt pulses by regenerative pulse shaping and chirped-pulse amplification," Opt. Lett. **21**, 668–670 (1996).
11. M. Kakehata, H. Takada, Y. Kobayashi, K. Torizuka, H. Takamiya, K. Nishijima, T. Homma, H. Takahashi, K. Okubo, S. Nakamura, and Y. Koyamada, "Carrier-envelope-phase stabilized chirped-pulse amplification system scalable to higher pulse energies," Opt. Express **12**, 2070–2080 (2004).
12. A. Baltuka, Th. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, Ch. Gohle, R. Holzwarth, V. S. Yakovlev, A. Scrinzi, T. W. Hänsch, and F. Krausz, "Attosecond control of electronic processes by intense light fields," Nature **421**, 611–615 (2003).
13. C. Li, H. Mashiko, H. Wang, E. Moon, S. Gilbertson, and Z. Chang, "Carrier-envelope phase stabilization by controlling compressor grating separation," Appl. Phys. Lett. **92**, 191114 (2008).
14. H. Mashiko, S. Gilbertson, C. Li, S. D. Khan, M. M. Shakya, E. Moon, and Z. Chang, "Double optical gating of high-order harmonic generation with carrier-envelope phase stabilized lasers," Phys. Rev. Lett. **100**, 103906 (2008).
15. T. Fuji, J. Rauschenberger, A. Apolonski, V. S. Yakovlev, G. Tempea, and F. Krausz, "Monolithic carrier-envelope phase-stabilization scheme," Opt. Lett. **30**, 332–334 (2005).
16. C. Yun, S. Chen, H. Wang, M. Chini, and Z. Chang, "Temperature feedback control for long-term carrier-envelope phase locking," Appl. Opt. **48**, 5127–5130 (2009).
17. 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).
18. Z. Chang, "Carrier-envelope phase shift caused by grating-based stretchers and compressors," Appl. Opt. **45**, 8350–8353 (2006).
19. H. Wang, M. Chini, S. D. Khan, S. Chen, S. Gilbertson, X. Feng, H. Mashiko, and Z. Chang, "Practical issues of retrieving isolated attosecond pulses," J. Phys. B **42**, 134007 (2009).
20. J. McKenna, A. M. Sayler, F. Anis, B. Gaire, Nora G. Johnson, E. Parke, J. J. Hua, H. Mashiko, C. M. Nakamura, E. Moon, Z. Chang, K. D. Carnes, B. D. Esry, and I. Ben-Itzhak, "Enhancing high-order above-threshold dissociation of H beams with few-cycle laser pulses," Phys. Rev. Lett. **100**, 133001 (2008).
21. C. Li, E. Moon, H. Mashiko, C. M. Nakamura, P. Ranitovic, C. M. Maharjan, C. L. Cocke, Z. Chang, and G. G. Paulus, "Precision control of carrier-envelope phase in grating based chirped pulse amplifiers," Opt. Express **14**, 11468–11476 (2006).
22. B. Shan and Z. Chang, "Dramatic extension of the high-order harmonic cutoff by using a long-wavelength driving field," Phys. Rev. A **65**, 011804(R) (2002).
23. S. Gilbertson, H. Mashiko, C. Li, E. Moon, and Z. Chang, "Effects of laser pulse duration on extreme ultraviolet spectra from double optical gating," Appl. Phys. Lett. **93**, 111105 (2008).
24. Z. Chang, "Controlling attosecond pulse generation with a double optical gating," Phys. Rev. A **76**, 051403(R) (2007).