Temperature feedback control for long-term carrier-envelope phase locking

Chenxia Yun, Shouyuan Chen, He Wang, Michael Chini, and Zenghu Chang*
J. R. Macdonald Laboratory, Department of Physics, Kansas State University,
Manhattan, Kansas 66506, USA
*Corresponding author: chang@phys.ksu.edu

Received 17 July 2009; accepted 17 August 2009;
posted 21 August 2009 (Doc. ID 114416); published 10 September 2009

We report a double feedback loop for the improvement of the carrier-envelope phase stabilization of a chirped mirror based femtosecond laser oscillator. By combining the control of the Ti:sapphire crystal temperature and the modulation of the pump power, the carrier envelope offset frequency, f_{CEO}, was locked for close to 20 h, which is much longer than the typical phase stabilization time with only pump power modulation. © 2009 Optical Society of America

OCIS codes: 320.7090, 320.7100, 320.7160.

Carrier-envelope phase (CEP) stabilized lasers are powerful tools for generating single isolated attosecond pulses and for studying above-threshold ionization. In recent attosecond streaking camera experiments, the accurate characterization of isolated attosecond pulses suffers from low photoelectron counts [1]. In experiments with few-cycle laser pulses interacting with ion beams, the count rate is also low [2,3]. To suppress the statistical noise, the data taking requires that the carrier-envelope phase of laser pulses with millijoule level energies be stabilized for hours [1,4,5]. Such high energy CEP controllable laser pulses are generated by selecting the CEP stabilized seed pulses from oscillators and boosting their energy in chirped pulse amplifiers [6]. Therefore long-term CEP stabilization of the oscillator is a prerequisite.

To stabilize the changing rate of oscillator carrier-envelope phase from pulse to pulse, the carrier-envelope offset frequency f_{CEO} is typically locked to a fraction of oscillator repetition rate f_{rep} [7], or to an external RF signal [8], by modulating the oscillator pump power with an acoustic optical modulator (AOM). However, due to temperature fluctuations, humidity changes, and mechanical misalignment, f_{CEO} drifts slowly and can drift out of the AOM control range, which makes the long term locking of the CEP difficult to access on a daily basis. We propose and demonstrate a double feedback scheme to solve this problem.

The long-term CEP locking scheme was implemented in a commercial oscillator, Rainbow from Femtolasers Produktions GmbH, using the setup shown in Fig. 1. The carrier-envelope offset frequency f_{CEO} was obtained by detecting the beat signal of difference-frequency generation (DFG) when the output laser beam was focused into a highly nonlinear periodically poled lithium niobate (PPLN) crystal [9,10]. Given the particular environment in our Kansas Light Source laboratory, the beat signal f_{CEO} was found to drift within a range of around 8 MHz in one day under the free running mode. When the driving voltage of the AOM was scanned across its usable range, it was found that the f_{CEO} can only be shifted over a range of 6 MHz, which is not sufficient to compensate the daily slow drift of f_{CEO}. This limits the typical oscillator CEP locking time to about 4 h when AOM alone was used.

There are several ways to compensate the slow f_{CEO} drift, such as adjusting the insertion of an intracavity prism [11,12] or a wedge [13]. However, the mode locking of a near-octave-spanning oscillator like the one we used can be disturbed by the mechanical vibration

---

0003-6935/09/275127-04$15.00/0

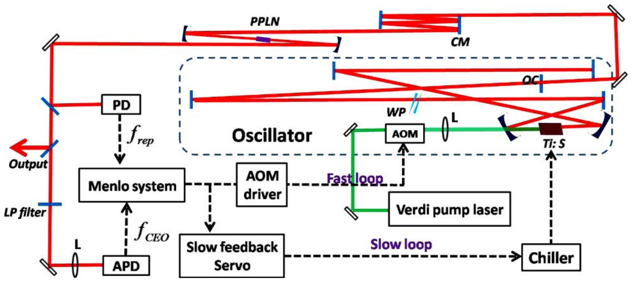

Fig. 1. (Color online) Layout of the octave-spanning oscillator and double feedback control loops. AOM, acousto-optic modulator; L, pump lens; OC, broadband output-coupler on a fused-silica wedge; WP, wedge pair; PD, photodiode; APD, avalanche photodiode; LP filter, low pass filter.

caused by moving these optical components. Instead we chose to use temperature control of the Ti:sapphire crystal as a slow feedback, which does not introduce any mechanical motion. When the temperature of the oscillator chiller was scanned from 13 °C to 21 °C, as shown in Fig. 2, the unlocked beat signal f_{CEO} changed nearly linearly and covered a range of 4.52 MHz. Adding the temperate control to the AOM control, the whole control range is comparable to the daily drift range of the f_{CEO}.

The temperature dependence of the f_{CEO} can be understood by examining the effects of temperature on the material dispersion. Due to the difference between the phase velocity and group velocity for each round trip of an optical pulse inside the oscillator cavity, the offset frequency f_{CEO} can be expressed as [14]

$$f_{\mathrm{CEO}} = f_{\mathrm{rep}} L \frac{\mathrm{d}n}{\mathrm{d}\lambda}, \tag{1}$$

where f_{rep} is the repetition rate of the oscillator cavity, and n is the refractive index. L is the effective medium distance inside the oscillator cavity, which can be approximately treated as the length of the Ti:sapphire crystal that is 2 mm in our case. Since the refractive index is not only a function of optical wavelength λ, but also a function of temperature T, the change of f_{CEO} resulting from temperature control can be expressed as

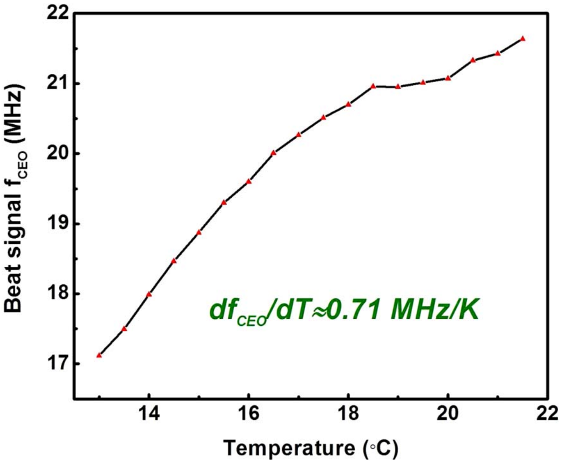

Fig. 2. (Color online) Relationship of beat signal f_{CEO} and temperature.

$$\begin{aligned}\frac{\mathrm{d}f_{\mathrm{CEO}}}{\mathrm{d}T} &= f_{\mathrm{rep}} \frac{\omega_0^2 L}{2\pi c} \frac{\mathrm{d}^2 n(\omega, T)}{\mathrm{d}\omega \mathrm{d}T} + \frac{\mathrm{d}f_{\mathrm{rep}}}{\mathrm{d}T} \frac{\omega_0^2 L}{2\pi c} \frac{\mathrm{d}n(\omega, T)}{\mathrm{d}\omega} \\ &= f_{\mathrm{rep}} \frac{\omega_0^2 L}{2\pi c} \frac{\mathrm{d}^2 n(\omega, T)}{\mathrm{d}\omega \mathrm{d}T} + \frac{\mathrm{d}n(\omega, T)}{\mathrm{d}T} \frac{\omega_0^2 L^2}{\pi c^2} \frac{\mathrm{d}n(\omega, T)}{\mathrm{d}\omega},\end{aligned} \tag{2}$$

where ω_0 is the carrier frequency of the laser pulse, and c is the speed of light in vacuum. Using the Sellmeier equation for sapphire in [15], we found the change rate of $\mathrm{d}f_{\mathrm{CEO}}/\mathrm{d}T = 0.86\,\mathrm{MHz/K}$, which is close to the measured value of $0.71\,\mathrm{MHz/K}$ shown in Fig. 2.

To examine whether the temperature change disturbs the mode locking, the oscillator output spectrum and average power were measured with a temperature scan step of 1 °C. The oscillator output spectrum and average power were found to remain the same from a temperature range of 12 °C to 22 °C. When the temperature range was further increased or decreased, a CW peak started to appear in the oscillator output spectrum. To maintain an optimized oscillator operation, the temperature control range was set from 13 °C to 21 °C.

By taking advantage of the temperature dependence of the f_{CEO}, a double feedback loop was applied for long term stabilization of the CEP. The AOM feedback loop is the fast one, whereas the temperature control served as the slow loop. Since it took f_{CEO} several minutes to respond to the temperature change, only a binary control, rather than the proportional-integral-derivative control, was necessary to assist the AOM and control the slow CEP drift. As is shown in Fig. 1, the control signal from the locking electronics (Menlo Systems) to the AOM was measured by a data acquisition card every 10 s.

The function of the temperature control was to confine the AOM locking point to a narrow range (+/ − 10% of the full control range) around the middle point of the full control range. When the feedback signal was detected above the upper limit of the AOM locking point range, the chiller's temperature was increased in steps of 0.1 °C to compensate the slow drift of the f_{CEO} until the AOM driving voltage returned to within the range. Similarly, the chiller temperature was decreased when the feedback signal was detected below the lower limit of the control point range. The delay time between each step of the temperature change was set at 300 s, which guaranteed that the oscillator reached thermal equilibrium gradually. We chose 0.1 °C as the step size because it was the minimum step that the chiller could control, and a small step size minimized the perturbation on the mode locking of the oscillator.

As shown in Fig. 3(a), the wide dynamic range of temperature control assisted the long term CEP stabilization for almost 20 h. Furthermore, we tested

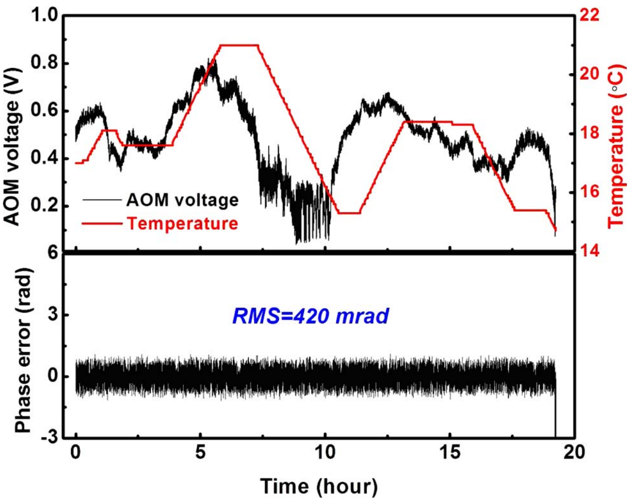

Fig. 3. (Color online) (a) 20 h CEP stabilization achieved by employing the double feedback loop; the black curve shows the AOM driving voltage output; the red curve shows the temperature of the chiller; (b) Phase error during the process of CEP stabilization, and the rms of the CEP error is 420 mrad.

the robustness of this double feedback loop. We found that CEP can be stabilized for more than 12 h on a daily basis, which can be attributed to the reduction of the disturbance to the oscillator by adding temperature control as a slow feedback. Twelve hours of CEP stabilization is three times longer than the typical CEP stabilization time of ~4 h under the same conditions, and was sufficient for the data acquisition of current attosecond streaking and ion beam experiments. In Fig. 3(a), when the temperature control reached the preset limit after 20 h of operation and failed to assist the CEP stabilization by AOM, the CEP locking was finally broken. Figure 3(b) shows the in-loop phase error during the process of CEP stabilization, and the rms of the CEP error is 420 mrad. We also measured the power spectral density (PSD) of the beat signal using a RF spectrum analyzer in the range of 102 kHz to 0.9765 mHz. The integrated phase error was 370 mrad over a 1024 s observation time, as shown in Fig. 4.

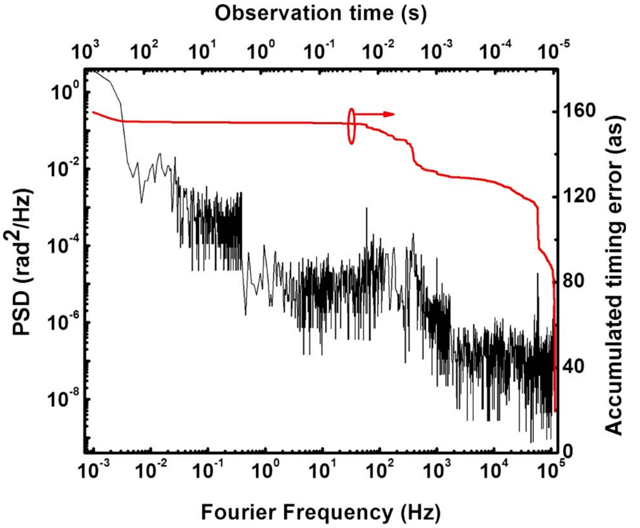

Fig. 4. (Color online) Phase-noise power spectral density (PSD) and integrated CE-phase error calculated from $\Delta\varphi_{\mathrm{RMS}} = [2\int_{-\infty}^{(-1/\tau_{\mathrm{obs}})} S_\varphi(\nu)\mathrm{d}\nu]^{1/2}$. $S_\varphi(\nu)$, power spectral density; $\Delta\varphi_{\mathrm{RMS}}$, root mean square (RMS) fluctuations in the carrier-envelope phase; τ_{obs}, observation time.

In conclusion, we studied the temperature dependence of the carrier-envelope offset frequency of a femtosecond laser oscillator. This effect was used to improve the long-term CEP stabilization. The temperature control of the oscillator Ti:sapphire crystal served as a slow feedback to assist the conventional AOM control. It was found that the temperature control had a sufficient dynamic range to correct the slow drift of f_{CEO} and had a negligible perturbation to the normal operation of the near-octave-spanning oscillator. This double feedback scheme has enabled the long-term CEP stabilization close to 20 h. Without adding any moving optical components that disturb the operation of the oscillator, this scheme is compact, easy to operate, and economical. By improving the long term stability of the oscillator CEP, more freedom and higher accuracy were provided to the study of CEP-sensitive high field phenomena, such as attosecond pulse generation and applications.

This material is supported by the U. S. Army Research Office under grant number 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. 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).
2. 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).
3. X. Feng, S. Gilbertson, H. Mashiko, H. Wang, S. D. Khan, M. Chini, Y. Wu, and Z. Chang, "Generation of isolated attosecond pulses with 20 to 30 femtosecond lasers," submitted to Phys. Rev. Lett.
4. V. Roudnev, B. D. Esry, and I. B. Itzhak, "Controlling HD^+ and H_2^+ dissociation with the carrier-envelope phase difference of an intense ultrashort laser pulse," Phys. Rev. Lett. **93**, 163601 (2004).
5. J. Mckenna, A. M. Sayler, F. Anis, B. Gaire, N. G. Johnson, E. Parke, J. J. Hua, H. Mashiko, C. M. Nakamura, E. Moon, Z. Chang, K. D. Carnes, B. D. Esry, and I. B. Itzhak, "Enhancing high-order above-threshold dissociation of H_2^+ beams with few-cycle laser pulses," Phys. Rev. Lett. **100**, 133001 (2008).
6. D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," Opt. Commun. **56**, 219–221 (1985).
7. A. Baltuska, T. Udem, M. Uiberacher, M. Hentschel, E. Goulielmakis, C. Gohle, R. Holzwarth, V. S. Yakovlev, A. Scrinzi, T. W. Hansch, and F. Krausz, "Attosecond control of electronic processes by intense light fields," Nature **421**, 611–615 (2003).
8. 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).

9. T. Fuji, J. Rauschenberger, A. Apolonski, V. S. Yakovlev, G. Tempea, T. Udem, C. Gohle, T. W. Hansch, W. Lehnert, M. Scherer, and F. Krausz, "Monolithic carrier-envelope phase-stabilization scheme," Opt. Lett. **30**, 332–334 (2005).
10. T. Fuji, J. Rauschenberger, C. Gohle, A. Apolonski, T. Udem, V. S. Yakovlev, G. Tempea, T. W. Hansch, and F. Krausz, "Attosecond control of optical waveforms," New J. Phys. **7**, 116 (2005).
11. T. Yu, K. Hong, H. Choi, J. Sung, I. Choi, D. Ko, J. Lee, J. Kim, D. Kim, and C. Nam, "Precise and long-term stabilization of carrier-envelope phase of femtosecond laser pulses using an enhanced direct locking technique," Opt. Express **15**, 8203–8211 (2007).
12. J. Lee, Y. Lee, J. Park, T. Yu, and C. Nam, "Long-term carrier-envelope-phase stabilization of a femtosecond laser by the direct locking method," Opt. Express **16**, 12624–12631 (2008).
13. R. Ell, J. R. Birge, M. Araghchini, and F. X. Kartner, "Carrier-envelope phase control by a composite plate," Opt. Express **14**, 5829–5837 (2006).
14. E. Moon, H. Wang, S. Gilbertson, H. Mashiko, M. Chini, and Z. Chang, "Advances in carrier-envelope phase stabilization of grating-based chirped-pulse amplifiers," Laser Photon. Rev. **3** (2009).
15. M. E. Thomas, S. K. Andersson, R. M. Sova, and R. I. Joseph, "Frequency and temperature dependence of the refractive index of sapphire," Infrared Phys. Technol. **39**, 235–249 (1998).