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2014 Chinese Phys. Lett. 31 084204

(http://iopscience.iop.org/0256-307X/31/8/084204)

CHIN. PHYS. LETT. Vol. 31, No. 8 (2014) 084204

Long-Term Stabilization of Carrier-Envelope Phase for Few Cycles Ti:Sapphire Laser Amplifier *

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(Received 7 May 2014)

We realize a long-term carrier-envelope phase (CEP) stabilization for a chirped pulse amplified Ti:sapphire laser by locking the oscillator and amplifier independently. Based on the measurement of CEP by employing f-to-2f interference technique between the octave-spanning spectrum which is generated from a rare gas filled hollow fiber, continuous locking time up to 7.2 h with 85 mrad fluctuation is demonstrated. Finely compensating the dispersion by a set of chirped mirrors, quasi-mono cycle pulses as shorter as 3.8 fs are obtained. Further experimental research on high harmonic generation dependence on CEP shown the waveform of laser pulses has been successfully controlled.

PACS: 42.65.Re, 42.65.Ky, 78.47.J– DOI: 10.1088/0256-307X/31/8/084204

Control of waveform of high energy few-cycle laser pulses has received considerable interest in recent years.[1−3] The waveform of laser pulses are determined by carrier-envelope phase (CEP) which is the offset between the peak of carrier wave oscillation (ωt) and envelope ($E_0(t)$) in the function of electric field of pulse $E(t) = E_0(t)\cos(\omega t + \varphi)$. Field-sensitive phenomena such as high-order harmonic generations (HHG), tunneling ionization exhibit a strong dependence on the waveform of driving laser pulses.[4−6] For the few-cycle laser pulses, minor change of CEP affects intensity of electric field. The controlled electric field waveform offers control of strong field driven atomic, molecular and plasma dynamics. In ultrafast applications, it is necessary to accumulate many laser shots and improve the signal to noise ratio, therefore, a long-term CEP stabilization is a key factor to the ultrafast pump-probe experiments with amplified femtosecond laser.[7−9]

In conventional schemes for the active CEP stabilized high power femtosecond laser, the phase-stabilized seeding laser pulses from oscillator are firstly amplified with a chirped-pulse amplification (CPA) technology. Following the compressor, a small part laser split from the main beam is broadened to a full octave-spanning spectrum by focusing into a sapphire plate, and injected into f-to-2f interferometer to extract the slow phase drift.[10−12] Phase error signal is feedback to the phase-locking electronic system which is also used to stabilize the pulses from oscillator. In such a scheme, the CE-phase jitter emerged in the hollow fiber after the compressor has not been taken into consideration, and the spectrum in f-to-2f interferometer will induce an extra artificial phase jitter.[13,14] Moreover, the slow phase drift feedback is actually superimposed on the fast phase drift control loop for the oscillator. This superposition will interfere with the long-term CEP stability.

In this Letter, we realized a long-term CEP phase stabilization based on CEP locking for the pulses from femtosecond oscillator and multi-pass amplifier independently. A small part of white light from Neon-filled hollow fiber is directly injected into an f-to-2f interferometer. The slow drift of the CE phase can be retrieved from the recorded pattern generated by the f-to-2f spectral interference. The feedback control signal is extracted by the Labview program, and the CEP control is realized by changing the insert of prism in compressor. Rather than needing of spectrum to be broadened in a filament by focusing the compressed laser pulses into the sapphire plate, the artificial phase noise in the detection induced by filament will be eliminated, and the phase changing induced in the hollow fiber will be accounted, thus long-term CEP stabilization with high accuracy can be achieved. Based on this scheme, the long-term CEP control with 85 mrad (rms) phase error over 7.2 h is realized. HHG experiments with changes of CEP proved that this CEP stabilization result can be used in the ultrafast phenomena with attosecond resolution and generation of isolated attosecond pulses.

As shown in Fig. 1, a CEP stabilized Ti:sapphire oscillator based on f-to-0 interferometer[15] provides pulse train as seed pulse for the amplifier which

*Supported by the National Basic Research Program of China under Grant Nos 2013CB922401 and 2013CB922402, the National Natural Science Foundation of China under Grant No 11074298, and the Instrument Developing Project of the Chinese Academy of Sciences under Grant No 2010004.
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is a 9-pass amplification pumped by 10 W double-frequency Nd:YLF laser at repetition rate of 1 kHz (Femtolasers GmbH). The amplified laser pulses are injected into the compressor which consists of double-prism pair to obtain compressed pulses with energy of 0.8 mJ in 25 fs. By focusing the pulses from compressor into a differentially pumped hollow fiber filled with neon gas,[16] spectrally broadened pulses with octave-spanning spectrum which covers from 400–1000 nm are obtained, as shown in Fig. 2(a), and are re-compressed down to 3.8 fs with chirped-mirrors and a pair of wedges as shown in Fig. 2(b). After the hollow fiber, the quasi-monocycle laser pulses contain 0.5 mJ, and have nearly diffraction-limited beam quality.

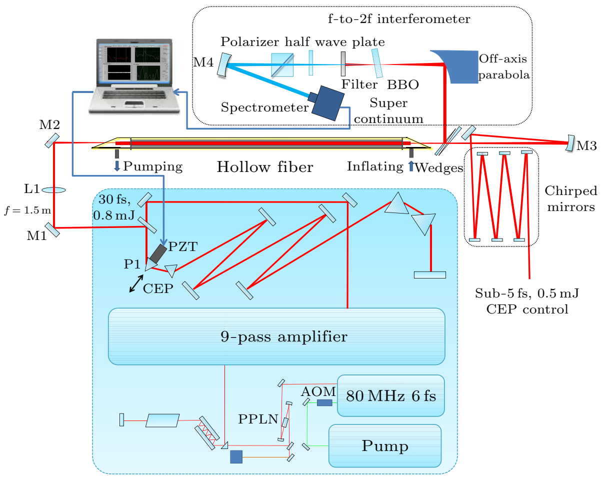

Fig. 1. The scheme of CEP stabilization for the whole laser system.

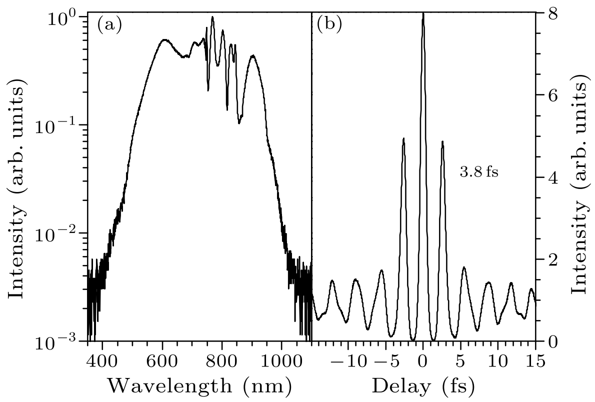

Fig. 2. Super continuum generated by neon filled hollow fiber and the duration of compressed pulses measured by an autocorrelator.

Since the spectral broadening pulses already have a one-octave spectrum spanning the hollow fiber, the white light can be used for detection of CEP errors based on an f-to-2f interferometer without an additional filament in the sapphire plate. About 3 µJ white light by the reflection of the first wedge is directly focused into a 300 µm BBO crystal by an off-axis parabolic mirror; a green pass filter, half-wave plate and polarizer are introduced to realize the spectral interference fringe, which is detected by a spectrometer. By tuning the half-wave plate and polarizer, the optimization of spectral interference fringes is obtained, as shown in Fig. 3. Slow CE-phase drift error is obtained by Fourier transform analyzing of the spectral interference fringes. After a PID control algorithm, the phase error signal is fed back to drive a PZT stage on which a prism is installed in the compressor to realize the stability of the CEP of the pulses after the hollow fiber.

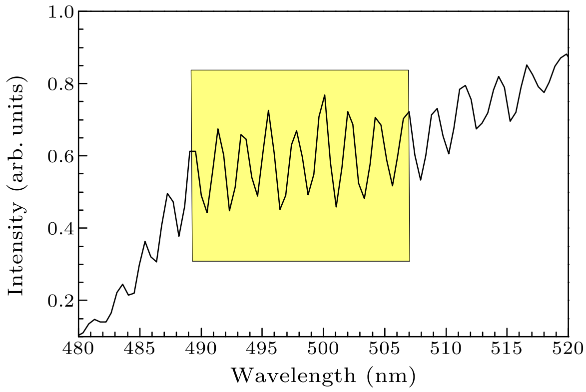

Fig. 3. Spectral interference fringes obtained in the f-to-2f interferometer in the setup.

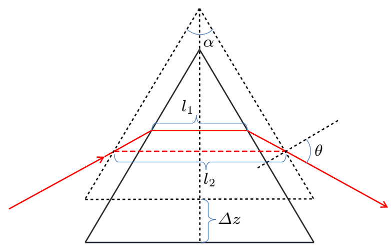

Fig. 4. Optical path in the prism with different insertions.

To avoid loss of the reflection laser, the prism in the compressor is designed with the minimum deviation at the Brewster angle of incidence. For a definite material, the incidence angle θ and apex angle α are determined. The length of the insert of the prism is shown in Fig. 4. The relationship between the changing of the optical length (Δl) and the corresponding CEP with the insertion of the PZT stage (Δz) are expressed as

$$\Delta l = l_2 - l_1 = 2\Delta z \cos\left(\frac{\pi-\alpha}{2}\right) \cdot \cos(2\theta - \pi/2)/\cos(\theta), \quad (1)$$

$$\Delta\phi_{\rm CE} = k\Delta l = 2k\Delta z \cos\left(\frac{\pi-\alpha}{2}\right) \cdot \cos(2\theta - \pi/2)/\cos(\theta), \quad (2)$$

$$k = \frac{\omega^2}{c}\frac{\partial n}{\partial \omega}, \quad (3)$$

where ω is the carrier frequency, n is the refractive index, and c is the vacuum speed of light. The material of the prism is LAK16, the central wavelength is 800 nm, and $k = 0.20\,\mathrm{rad/\mu m}$. The apex angle of the LAK16 prism is 61.3°, the incidence angle of the laser is 59.4°, and the changing of CEP by 2π corresponds to the length of 17.5 µm for the insertion of the PZT stage according to function 2. The maximum travel length of the PZT stage employed in our case is 90 µm, thus the shift of CEP can be controlled.

In comparison with a locked CEP based on the present scheme with the unlocked CEP of amplified pulses, the phase error in time intervals of 360 s are recorded in these two cases, as shown in Fig. 5. The rms phase error is 677.1 mrad for unlocked pulses. When the lock program is switched on, the CEP is kept straight with an error of only 53.1 mrad, as shown in Fig. 5(a). From the fast Fourier transform of these two phase drift curves, as shown in Fig. 5(b), the frequency noise below 4 Hz can be well compensated for by this scheme, otherwise the noise is too low to be compensated.

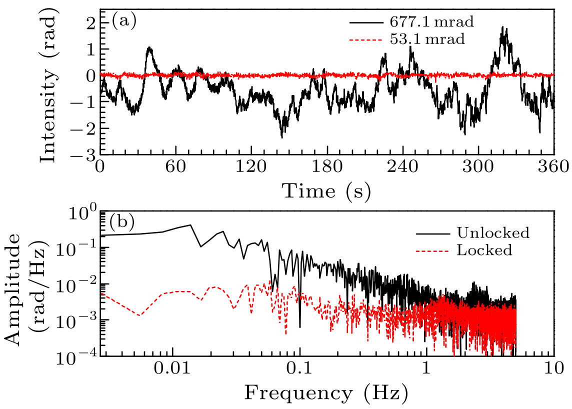

Fig. 5. Short time CEP change under the lock and unlock situation (a) and fast Fourier transform of CEP drift (b).

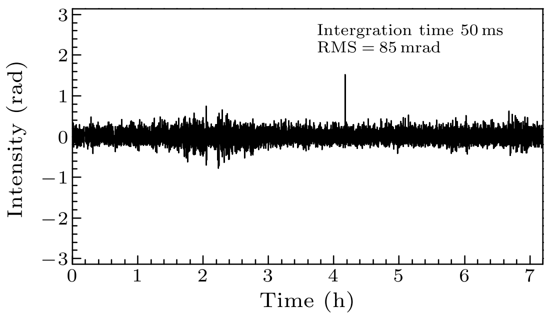

Fig. 6. Long time CEP locking with high accuracy over 7.2 h.

Based on this scheme of stabilization of the CEP, long-term stabilization of the CEP is realized. The phase error within 7.2 h is recorded, as shown in Fig. 6. Around 2 h, temperature variation reduced the accuracy for CEP locking for about 1 h. When the temperature was controlled, the locking accuracy was recovered. At the moment of 4 h, an artificial vibration was caused by an accident, the CEP loses control instantly while it recovered quickly. During the whole locking process, the phase error is 85 mrad (rms) with a integration time of 50 ms. The result shows that this scheme of locking the CEP after the hollow fiber and oscillator independently will be a sufficient response for the environmental and artificial vibration or noise from the vacuum pump and keep the stability of the CEP.

To prove the long-term stabilization of the CEP based on this scheme, the HHG based on this system was measured due to the fact that it is very sensitive to the electric field of the laser pulse. The CEP stabilized laser beam is gently focusing into a quasi-static gas cell filled with neon gas at a pressure of ~200 mbar. Through a 1-mm-thickness fused silica window, the beam is focused into a vacuum chamber, which contains the target at the focus, by using a 50 cm focal length silver-coated spherical mirror with a high transmission broadband coating. A pulse with an energy of ~0.35 mJ on the target is focused to a spot with a $1/e^2$ diameter of ~100 µm, corresponding to an intensity of about $\sim 10^{15}\,\mathrm{W/cm^2}$ on the beam axis. The HHG radiation produced collinearly with the laser beam passed through a 1-mm aperture into a grazing incidence flat-field spectrometer. The flat-field spectrometer is equipped with a 1200 lines/mm (mean value) varied line-spacing concave grating and a soft-x-ray CCD (PIXIS-XO, Princeton Co.). To block the laser light completely, a 200-nm-thickness zirconium foil is inserted in the XUV beam before the slit in the spectrometer.

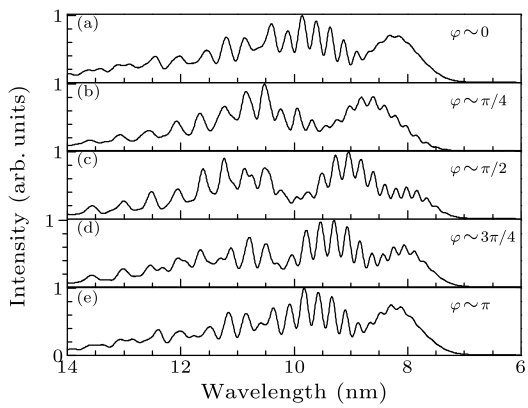

Fig. 7. High harmonic spectra dependence on CEP. XUV spectra for the CEPs $\phi = 0$, $\phi = \pi/4$, $\phi = \pi/2$, $\phi = 3\pi/4$, $\phi = \pi$ are shown in panels (a), (b), (c), (d) and (e), respectively.

By changing the CEP of laser pulses with a wedge in the optical beam, the HHG spectra were recorded for different settings of the CEP. Figure 7 shows a series of typical HHG spectrum distributions recorded at different CEPs of laser pulses, from 0 to π, stepped in increments of $\pi/4$. With the change of CEP, the cut-off HHG spectrum gradually transforms from discrete modulated harmonic peaks to a continuum spectral distribution. As the CEP is slowly varied between zero and π by inserting a wedge in the optical path, the continuum spectrum in the cut-off region becomes much modulated and has discrete harmonic peaks, and this modulation will become maximum when the phase is equal to $\pm\pi/2$. This behavior is periodic and was observed to repeat upon subsequent full π phase shifts.

A broad structure-less continuum spectrum appeared in the cut-off region when the CEP is close to zero. The continuum spectrum in the cut-off region was selected by a 200-nm Zr foil and is demonstrated to support 160 as pulses by an attosecond photoelectron spectroscopy.[17]

The data of the HHG spectrum with the CEP and attosecond streak spectrogram from the attosecond photoelectron spectroscopy are recorded over 1 h, thus the results prove that the long-term stabilization of CEP based on the scheme is successfully realized.

In conclusion, the long-term CE phase stabilization of few-cycle laser pulses from a gas filled hollow fiber is realized, which is based on CEP locking of the oscillator and amplifier independently. To utilize the octave-spanning spectrum from the hollow fiber, the f-to-2f interference technique is employed to stabilize the CEP without additional spectra broadening in the filament. Compared with previous schemes, there are two advantages: the phase noise induced by the filament in the sapphire plate is eliminated, and the phase shift from the hollow fiber is accounted for. With this scheme, the CE-phase stability of 85 mrad (rms) over 7.2 h is achieved. HHG dependence on the CEP, which shows the waveform of few-cycle laser pulses based on this scheme, has been successfully controlled.

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