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Carrier-envelope phase locking of 5 fs amplified Ti:sapphire laser pulse at 1 kHz repetition rate

DU Qiang, ZHU JiangFeng, TENG Hao, YUN ChenXia & WEI ZhiYi†

Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China

This paper reports the carrier-envelop phase (CEP) locking for the 5 fs re-compressed laser pulse generated from a chirped pulse amplified (CPA) Ti:sapphire laser at 1 kHz repetition rate. A phase locking feedback system with two loops was designed to control the fast fluctuation arising from the seeding laser and the slow fluctuation arising from the sub-mJ amplified pulse. The principle and structure of the phase control system, including the CEP detection, servo loop design and phase locking result, are analyzed. The experiment shows that our phase locking system can be well used to establish the stable phase locking of few-cycle amplified laser pulse, and the CEP variation of below 53 mrad (rms) was demonstrated during a locking period of more than 3 h.

few-cycle pulses, carrier-envelope phase, phase lock loop

OPTICS

1 Introduction

With the rapid progress of ultrashort laser technology in recent years, laser pulse of shorter than 10 fs has been generated by several groups in the world. For a carrier wavelength of about 800 nm, a 10-fs laser pulse only contains about 3 cycles of the optical oscillation. In such a case of few-cycle laser pulse, the relative phase between carrier and electric field envelope becomes an very important issue, and the so-called carrier-envelope phase (CEP) determines the shape of its electric field[1]. Stable CEP plays a key role in researches of optical frequency combs[2,3], attosecond physics[4−6], high field physics[7], etc. In 2002, the generation of isolated attosecond laser pulses has made it possible for people to investigate structures inside atoms in attosecond time scale (10^{-18} s), which is just the time scale of extranuclear electron orbits. Presently, the attosecond science has opened a novel research area to explore the processes of fundamental physical or chemical phenomena, and it also provides a powerful tool to probe ultrafast behavior inside atoms.

Drift of CEP is considered as the difference between group and phase velocities inside a laser oscillator. The variation of the laser's peak power brings changes in Kerr's effect inside the Ti:sapphire crystal, and in the envelope phase as well as the drift of the corresponding longitudinal mode in frequency domain. Practically, causes of CEP drift incorporate mechanical vibration, gas fluid, environmental temperature changing, and even variation of pump power. Techniques including self referencing (F-2F)[8,9] and different frequency generation (DFG)[10,11] were developed and applied to detecting and locking the CEP of laser pulse from oscillator through a phase-locked-loop (PLL), so that precise control of CEP could be realized. The method of F-2F uses a photonic crystal fiber (PCF) to broaden the laser's spectrum into octave-spanning, and then beats the low frequency and its second harmonic within the supercontinuum, while the DFG method uses nonlinear effects, such as phase-matched DFG and self phase modulation (SPM)

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†Corresponding author (email: zywei@aphy.iphy.ac.cn)
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introduced by a piece of PPLN crystal to detect the CEP frequency. Because of its simplicity, high efficiency and high stability, DFG method appears to have better performance and practicability in CEP measurement.

Although the precise CEP control method is routinely applied for femtosecond oscillators, it still has difficulty in CEP controlling amplified pulses because of extra perturbation induced by thermal drift, pointing instability and laser power vibration during amplification[12]. Typical range of this kind of CEP drift is in the order of 2π radian, which is a fatal error for applications of amplified few-cycle pulses. Nevertheless, the low repetition frequency (in the order of 1 kHz or below) of amplified lasers makes it impossible to use a common method to detect CEP as in the oscillators, so a single shot CEP measurement method must be applied. For instance, a method called spectrum interferometry (SI)[13] is a good option. To feed back CEP error, normally there are two ways: one is to modulate the feedback signal onto an acoustic-optical modulator (AOM) so that the pump power of oscillator is verified to change CEP; the other is to change the stretcher or the distance between gratings inside the compressor[14] using Piezo actuators. We choose the first one for its higher dynamic bandwidth.

This paper demonstrates a CEP control system for our 5 fs amplified Ti:sapphire laser.

2 Experimental setup and control principle

The experiment system for our amplified laser system and CEP control scheme is illustrated in Figure 1. The seed laser is a sub-10 fs Ti:sapphire oscillator pumped by a CW 532 nm laser (Verdi 5, Coherent Inc.) working at a repetiton rate of 80 MHz. An AOM is placed in the path of the pump laser. After amplifying and compressing the seed laser by a 1 kHz CPA system (Femtolaser Inc.), the laser is measured with energy of 0.8 mJ per pulse and pulsewidth of 25 fs. Next, the laser is spectrally broadened by a hollow fiber filled with Ne gas and is compressed by a set of chirped mirrors. Finally, laser pulses are generated with 5.1 fs pulse width and with 0.4 mJ pulse energy[15].

The CEP locking of the oscillator is carried out by a 'fast loop' PLL (Menlo Systems Inc.) to lock CEP frequency to 1/4 of the laser repetition rate by means of DFG method. For amplified pulses, a second 'slow loop' PLL is introduced to feed back the CEP drifts during amplification. The CEP frequency is measured through SI method in the second PLL, and the control signal is output onto the reference point of the fast loop so that a cascaded control loop is formed. Different loop parameters are optimized for the two PLLs, and closing them simultaneously would finally lock the CEP of amplified laser pulses.

If we consider the CEP drift as the process variable, the control model of the cascaded control loop could be expressed as shown in Figure 2. The goal of the control system is to attain zero steady state error ($E(s)=0$) in case of small external perturbation. $G_{\mathrm{p}}(s)$ is the transfer function of CEP change of AOM-mounted oscillator, $H_1(s)$ is the CEP detection process by DFG method, and $H_2(s)$ is the CEP detection by SI method. $G_{\mathrm{c1}}(s)$ and $G_{\mathrm{c2}}(s)$ are loop filters for the two PLLs. External perturbations to the laser oscillator is expressed by $D_1(s)$, while $D_2(s)$ stands for perturbations to the amplification process. The locked CEP could be expressed by eq. (1) through analyzing the close loop transfer function:

$$\begin{aligned} C(s) = {} & \frac{G_{\mathrm{c1}}(s)G_{\mathrm{c2}}(s)G_{\mathrm{p}}(s)}{1+G_{\mathrm{c1}}(s)G_{\mathrm{p}}(s)H_1(s)+G_{\mathrm{c1}}(s)G_{\mathrm{c2}}(s)G_{\mathrm{p}}(s)H_2(s)}R(s) \\ & + \frac{G_{\mathrm{p}}(s)}{1+G_{\mathrm{c1}}(s)H_1(s)G_{\mathrm{p}}(s)}D_1(s) \\ & + \frac{1+G_{\mathrm{c1}}(s)H_1(s)G_{\mathrm{p}}(s)}{1+G_{\mathrm{c1}}(s)H_1(s)G_{\mathrm{p}}(s)+G_{\mathrm{c2}}(s)H_2(s)G_{\mathrm{p}}(s)}D_2(s). \end{aligned} \tag{1}$$

When PLL is locked, i.e. the reference point of process variable $R(s)=0$, supposing that $D_1(s)$ and $D_2(s)$ are both step input, we have the zero steady state error:

$$e_{ss} = \lim_{t\to\infty} E(t) = \lim_{s\to 0} sE(s) = 0, \tag{2}$$

$$\lim_{s\to 0}\left(\frac{sG_{\mathrm{p}}(s)}{1+G_{\mathrm{c1}}(s)H_1(s)G_{\mathrm{p}}(s)}\cdot\frac{1}{s} + \frac{s+sG_{\mathrm{c1}}(s)H_1(s)G_{\mathrm{p}}(s)}{1+G_{\mathrm{c1}}(s)H_1(s)G_{\mathrm{p}}(s)+G_{\mathrm{c2}}(s)H_2(s)G_{\mathrm{p}}(s)}\cdot\frac{1}{s}\right)=0. \tag{3}$$

Therefore, supposing $\left\|G_{\mathrm{c1}}(s)H_1(s)\right\| >> 1$ and $\left\|G_{\mathrm{c1}}(s)H_1(s)G_{\mathrm{p}}(s)\right\| >> 1$, if only 'fast loop' is locked, contributions from $D_1(s)$ to $E(s)$ might be neglectable. But the second term still exists, which is just the CEP drift induced by the amplification process. Only when both loops are locked and meet eq. (4), could all perturbations be suppressed.

$$\left\|\left(G_{\mathrm{c2}}(s)H_2(s)-G_{\mathrm{c1}}(s)H_1(s)\right)G_{\mathrm{p}}(s)\right\| >> 1. \tag{4}$$

The dynamic steady error in continuous disturbing is

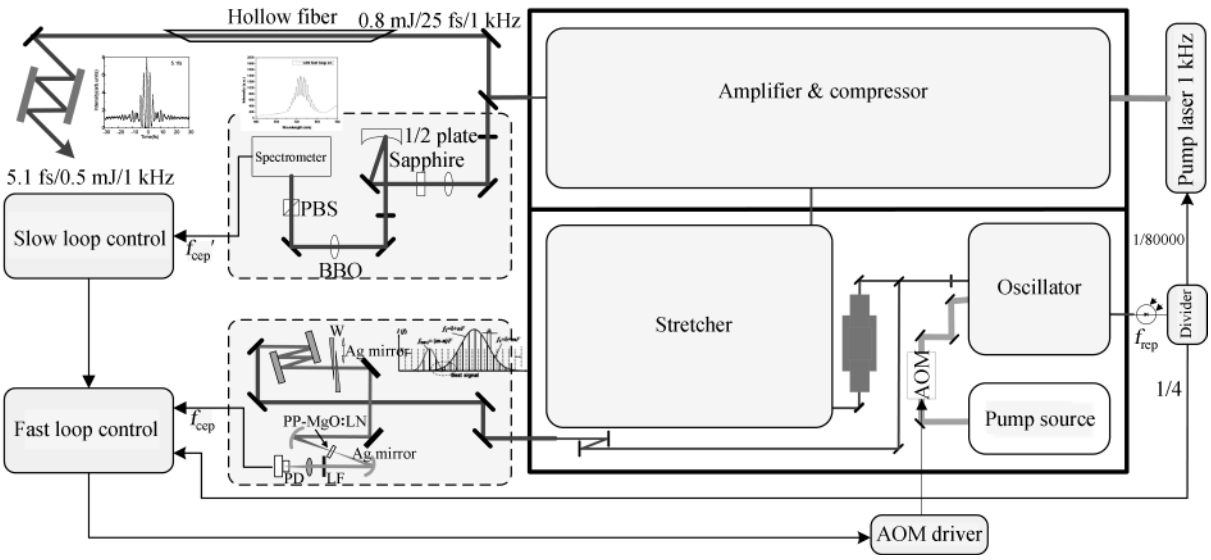

Figure 1 Experimental setup for CEP control of amplified laser system.

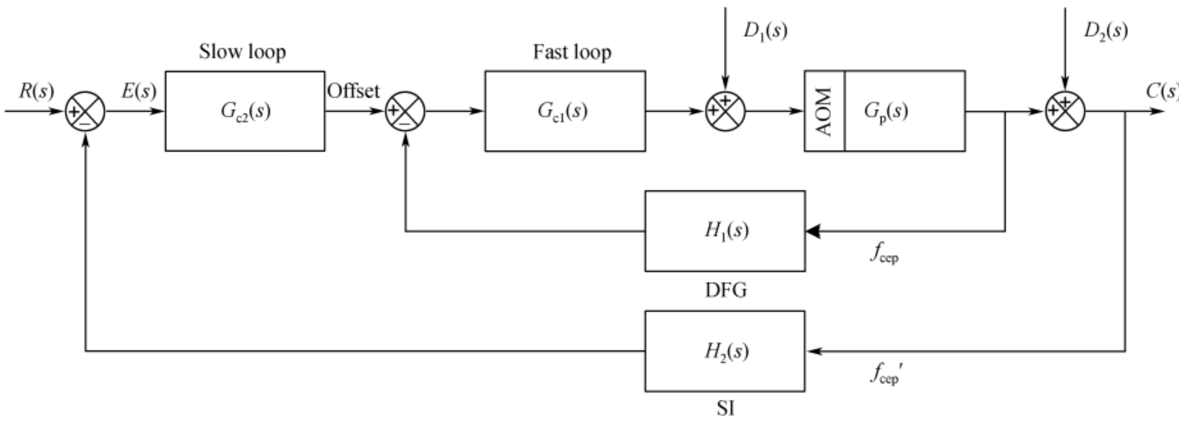

Figure 2 Block diagram of CEP control model.

dependent on the rise time and maximum overshot of the system's step response, so a better control precision requires smaller steady errors, which requires best optimization of $G_{c1}(s)$ and $G_{c2}(s)$ on premise of loop stability and meets eq. (4).

2.1 'Fast loop' CEP control system

The CEP of the oscillator is locked by the first PLL, i.e. 'fast loop'. Figure 3 shows the principle of CEP detection through DFG method. The laser pulse train in frequency domain is a series of modes with a gap of its repetition rate F, and the first mode is located at the CEP offset frequency δ. Therefore, the frequency of mode with index n is $f_n = \delta + nF$. The modes with index n and m are beaten in PPLN crystal to get DFG frequency $f_{\mathrm{DFG}} = (m-n)F$, where the CEP offset frequency is eliminated. The SPM effect generates a low frequency of $f_{m-n} = \delta + (m-n)F$ so that it can beat again with DFG signal to yield CEP frequency by $f_{\mathrm{CEP}} = f_n - f_{\mathrm{DFG}} = \delta$.

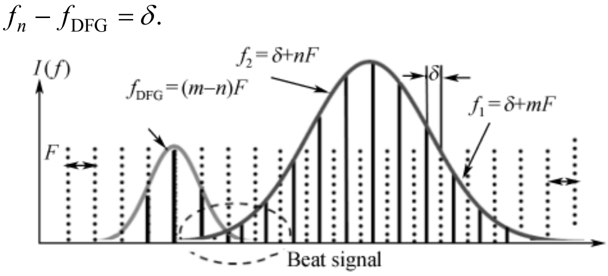

Figure 3 CEP detection through DFG method in 'fast loop'.

Sampled by an avalanche photodiode (APD), the CEP signal is phase-compared by the 1/4 of laser's repetition rate, and the phase error voltage is then acquired. The process of phase detection can be mathematically expressed by product of RF signals, which is filtered by a low-pass-filter to get their frequency difference:

$$H_1(\varphi_{\rm CE}) = K_1 \sin(\varphi_{\rm CE}), \quad H_1(s) = K_1 \cdot \frac{1}{s^2+1}. \qquad (5)$$

The loop controller $G_{c1}(s)$ uses proportional-integration control, i.e. $G_{c1}(s) = K_{p1} \cdot \left(1 + \frac{1}{T_{i1}s}\right)$. Experiment has proven that the loop bandwidth is about 400 kHz, and the close loop steady state error is less than 50 mrad (rms).

2.2 'Slow loop' CEP control system

Since the repetition rate of the amplified pulses is only 1 kHz, it is difficult to use F-2F or DFG method to detect the CEP signal. In the year 2001, Kakehata et al.[13] proposed a method of SI to measure CEP for single shot pulses. The method uses a dispersive medium to delay and spectrally broaden the pulses such that the interference between the short wavelength portion and its second harmonic could be detected as a periodical curve, from which the CEP frequency could be calculated. The electric field of a Gaussian profile ultrashort laser pulse is expressed as

$$E_{\rm F}(\omega) = \sqrt{2\pi} \exp\left\{-\left[(\omega - \omega_{\rm c})/2\right]^2\right\} \exp(j\varphi_{\rm CE}), \qquad (6)$$

where ω_c is the center frequency in its spectrum, and $\varphi_{\rm CE}$ is the CEP.

Considering the long wavelength portion and its harmonic, when passing through a dispersive media, the short wavelength portion delays τ and appears as a phase delay $\exp(-j\omega\tau)$. Calculating its 1st and 2nd order of electric dipole, the intensity of interference curve is

$$I(\omega) \propto \left|P_\tau^{(1)}(\omega) + jP^{(2)}(\omega)\right|^2 \propto I_{\rm F} + I_{\rm SH} + 2\left[I_{\rm F} I_{\rm SH}\right]^{1/2} \cos\left[\omega\tau + \varphi_{CE} + \pi/2\right]. \qquad (7)$$

For a specific dispersive medium, the delay time τ is constant. Therefore $\varphi_{\rm CE}$ is able to be extracted by Fourier transforming the interference signal. Moreover, the gap of the interference streak is inversely proportional to the delay time, which indicates that only the short delay could get large streak gaps to be identified by interferometers.

The Fourier transform of interference signal (for clearance, the Fourier frequency is k) is

$$F\left(I(\omega)\right) \propto \exp\left[\frac{k - \tau/2\pi}{2}\right]^2 \exp(j\varphi_{\rm CE}), \qquad (8)$$

$$\arg\left[F\left(I(\omega)\right)\Big|_{k=\tau/2\pi}\right] \propto \tan^{-1}(\varphi_{\rm CE}). \qquad (9)$$

The control process is implemented by a real-time software running on a PC, which acquires the output of the interferometer (Ocean Optics, HR2000) and output of the control signal by D/A conversion. Firstly, the system samples the interference curve and applies FFT to spectrum region of interest to get CEP power and phase spectrum. Secondly, the peak frequency offset of CEP spectrum k is automatically evaluated from the Fourier spectrum so that the corresponding $\varphi_{\rm CE}$ could be calculated. By eq. (9), the transfer function of 'slow loop' phase detection process is

$$H_2(\varphi_{\rm CE}(t))\Big|_{\varphi_{\rm CE}<<1} \approx K_2 \varphi_{\rm CE}(t), \;\; H_2(s) \approx K_2 \frac{1}{s^2}. \quad (10)$$

The PI controller, $G_{c2}(s) = K_{p2} \cdot \left(1 + \frac{1}{T_{i2}s}\right)$, compensates for the phase error and outputs control signal for 'fast loop' to change its reference point so that both PLLs could be closed. To meet eq. (4) and tune the controller's parameter for different experiment conditions, the design of controller must have the adaptivity. An algorithm of auto-tuning method based on setpoint relay is applied to optimizing the P/I parameter for the shortest rise time and minimum overshot.

For even lower repetition rate lasers, although the SI method is still able to effectively detect CEP, the feedback loop bandwidth is limited by the repetition rate, so the performance of noise suppressing is also limited.

3 CEP locking results

With the CPA Ti∶sapphire laser system at 1 kHz repetition rate, 25 fs pulse with energy of 0.8 mJ was obtained with a typical bandwidth (FWHM) of 40 nm and center wavelength of 780 nm. After locking the 'fast loop', 10 μJ pulse energy is used for SI detection by splitting the output pulse with a 1% beam splitter. In the SI setup, a diaphragm and a medium density attenuator are inserted to adjust the beam intensity. After a half wave plate the beam is focused into a 1 mm thick sapphire plate for spectrum broadening into an octave-spanning. Next, the supercontinuum spectrum is focused into a piece of BBO crystal to generate second harmonic (SHG) of the long wavelength portion. The SHG crystal is a phase-matched BBO crystal of type I (θ = 22.9°, φ = 0°), with a thickness of 0.5 mm, and phase matching wavelength is near 1 μm. Finally, the beam is collimated and passes through a polarized prism into the fiber interferometer. Figure 4 shows the sampled interference curve after locking 'fast loop'.

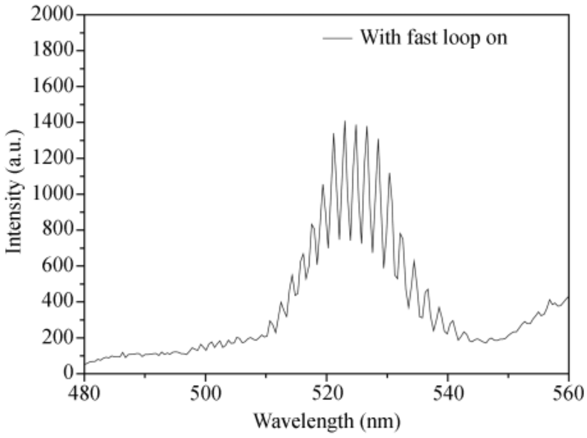

Figure 4 Interference curve after locking 'fast loop'.

In Figure 5, curve A shows CEP drift of the amplified pulses during 5 min when only locking the oscillator by 'fast loop', and curve B is the result after locking 'slow loop'. It is clear that the CEP is changing greatly in the former state, while the rms error of CEP is only 53 mrad in the latter. The system is able to lock for over 3 h.

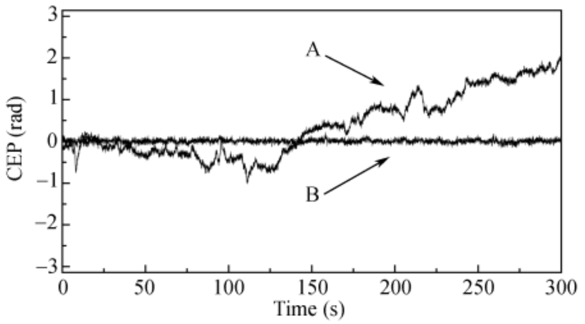

Figure 5 CEP error by time. Curve A is only locking the oscillator; curve B is locking two PLLs simultaneously.

4 Conclusion

In summary, CEP locking of amplified 5 fs laser pulses at 1 kHz repetition rate is demostrated. Two cascaded PLLs are applied to locking CEP for the oscillator and the amplified laser through 'fast loop' and 'slow loop'. Experiment results show that the CEP error of the amplified laser pulses could be controlled within 53 mrad, and the locking time is over 3 h. This result may have important applications in researches on the interactions between high power laser and matter, attosecond laser generation, and coherent controlled ultrafast dynamics, etc.

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