Carrier-envelope phase shift caused by variation of grating separation

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The effects of variation of the grating separation in a stretcher on the carrier-envelope (CE) phase of amplified pulses are investigated. By translating one of the telescope mirrors in the stretcher with a piezoelectric transducer, it is found that a 1 μm change of the distance causes a 3.7 ± 1.2 rad shift of the CE phase, which is consistent with theoretical estimations. The results indicate that optical mounts used for gratings and telescope mirrors must be interferometrically stable; otherwise their vibration and thermal drift will cause significant phase error. The CE phase drift was corrected by feedback controlling the grating separation.

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Chirped pulse amplification is a well-developed technique for generating high-power laser pulses with durations longer than 10 fs.[1] The pulses from the chirped pulse amplifier can be compressed to ~5 fs with ~1 mJ of energy at an ~750 nm center wavelength. For such intense, few-cycle pulses, it is crucial to control their carrier-envelope (CE) phase for strong-field atomic physics studies.[2] In this Letter we focus on the effects of the stability of the grating separation in the stretcher and compressor on the CE phase variation, which have been overlooked so far.

The experiments were done by using the Kansas Light Source laser system, as shown in Fig. 1.[3] The CE offset frequency, f_0, of the chirped-mirror-based femtosecond oscillator (Femtosource Pro) was locked to a quarter of the oscillator repetition rate (80 MHz). This was done by measuring f_0 with a Mach–Zehnder-type f-to-$2f$ interferometer. The signal was used to feedback control the power from the pump laser[4] (Coherent Verdi 6). The pulses with the same CE phase were selected by a Pockels cell and sent to the stretcher of the chirped pulse amplifier with a repetition rate of 1 kHz. The pulses with an ~100 nm bandwidth and 3 nJ of energy were stretched to ~80 ps. Then the stretched pulses were amplified to 5 mJ with a 14-pass amplifier. The Ti:sapphire crystal was cooled to liquid-nitrogen temperature to reduce the thermal lens effect. After amplification, the pulses were compressed by a pair of gratings to 2.5 mJ and 25 fs. A fraction of the output beam (<1 μJ) was used to measure the relative CE phase of the amplified pulses with a collinear f-to-$2f$ interferometer.[5] Compared with material- and prism-based stretchers and compressors, the grating-based stretcher and compressor are important for producing higher-energy pulses. Thus, understanding the effects of the stretcher and compressor on the CE phase has attracted a lot of attention.[5–7]

The stretcher configuration in our laser system is shown in Fig. 2(a). It uses mirrors for the telescope to avoid chromatic aberrations. The analysis given here can also be applied to a stretcher with a lens-based telescope as shown in Fig. 2(b). In the frequency domain, the input electric field can be expressed as $E(\omega)=E_0(\omega)\exp\{i[\varphi_{CE}+\phi(\omega)]\}$, where $|E_0(\omega)|^2$ is the power spectrum and φ_{CE} is the CE phase. The spectral phase is given by $\phi(\omega)$, which is equal to zero when the input pulses are transform limited as assumed here.

When the pulse propagates through the double-pass grating stretcher, its spectral phase becomes[8,9]

$$\phi'(\omega) = \omega\tau(\omega) - 4\pi(G_s/d_s)\tan[\gamma_s - \theta_s(\omega)], \quad (1)$$

where ω represents the frequency components of the pulse, τ is the group delay, G_s is the effective perpendicular distance between the gratings, d_s is the grating constant, γ_s is the angle of incidence, and θ_s is the acute angle between the incident and the diffracted rays, which is positive when the incidence angle is larger than the diffraction angle.

The CE phase change is caused by the shift of electric field oscillation with respect to the pulse enve-

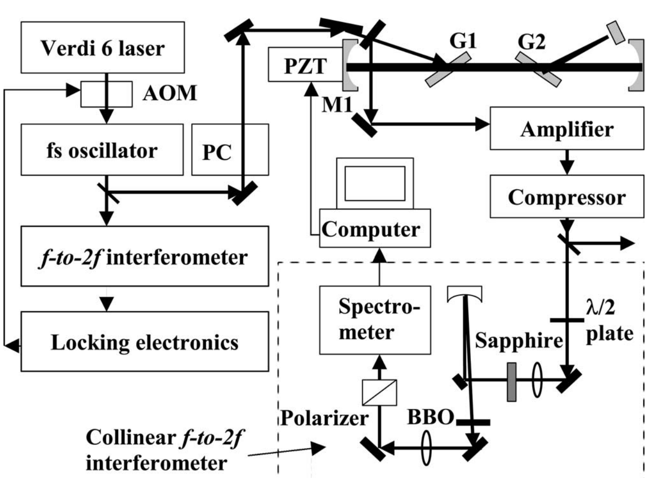

Fig. 1. Kansas Light Source laser system for testing the effects of the grating separation of the stretcher on the CE phase stability. G1 and G2 are the gratings. M1 is one of the telescope mirrors driven by a piezoelectric transducer (PZT). The oscillator CE offset frequency f_0 is stabilized by feedback controlling the acousto-optic modulator (AOM). Pulses with the same CE phase are selected by the Pockels cell (PC) and are sent to the chirped pulse amplifier.

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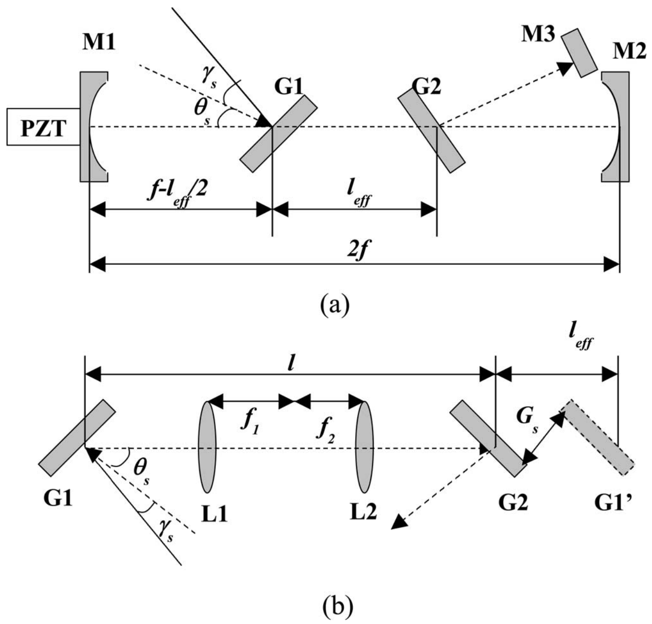

Fig. 2. Parameters of the grating stretcher. Mirrors are used in (a) to form the telescope. G1 and G2 are the gratings; γ_s is the incidence angle on the first grating; θ_s is the angle between the diffracted beam and the incident beam; M1 and M2 are mirrors for the telescope; l_{eff} is the effective distance. (b) Conventional stretcher with a lens-based telescope. G1′ is the image of the G1 formed by the telescope. G_s is the effective perpendicular distance between the gratings.

lope. As is shown in Ref. 8, the carrier wave oscillation of the output pulse at the observation plane is described by the phase given in Eq. (1) at ω_0, whereas the group delay that represents the time for the envelope to propagate thought the stretcher is $\tau(\omega_0)$, which is the derivative of the phase with respect to frequency evaluated at ω_0. To compare the carrier wave oscillation with the envelope in phase space, we can rewrite the group delay in $\omega_0\tau(\omega_0)$. Thus, the CE phase change is $\omega_0\tau(\omega_0)-\phi'(\omega_0)$, which yields

$$\varphi'_{\mathrm{CE}} - \varphi_{\mathrm{CE}} = \omega_0\tau(\omega_0) - \phi'(\omega_0) = 4\pi(G_s/d_s)\tan[\gamma_s - \theta_s(\omega)]. \quad (2)$$

In the previous expression, φ'_{CE} is the CE phase at the exit and ω_0 is the carrier frequency. The variation of γ_s due to laser beam pointing stability can change φ'_{CE}, which has been studied before.[5,6] In a double-pass configuration, the net effect of the incident angle variation on the CE phase is small. Equation (2) is also valid for grating compressors. The only difference is the sign of G_s.

Since $G_s=-l_{\mathrm{eff}}\cos(\gamma_s-\theta_s)$,[9] the amount of CE phase error introduced by the variation of the effective linear grating separation, Δl_{eff}, is $\Delta\varphi_{\mathrm{CE}}=-4\pi\sin(\gamma_s-\theta_s)\Delta l_{\mathrm{eff}}/d_s$. The change of the value of l_{eff} can originate from the motion of either the lenses or the gratings. For most stretcher and compressor designs, the incident angle is close to the Littrow angle γ_l, i.e., $\theta_s=0°$ and $\sin(\gamma_l)=\lambda/(2d_s)$. Considering the gratings having $d_s\approx\lambda$, the CE phase shift is given by

$$\frac{\Delta\varphi_{\mathrm{CE}}}{\Delta l_{\mathrm{eff}}} = 2\pi\frac{\lambda}{d_s^2} \approx \frac{2\pi}{\lambda}. \quad (3)$$

The analysis reveals that the CE phase change is significant when the variation of the linear separation of the gratings is of the order of the laser wavelength. On the other hand, the compressed pulse duration does not change much when $\Delta l_{\mathrm{eff}}\approx\lambda$. This is because

$$(\tau'_p)^2 = \tau_p^2 + \left(\frac{\tau_s}{l_{\mathrm{eff}}}\Delta l_{\mathrm{eff}}\right)^2, \quad (4)$$

where τ'_p is the compressed pulse duration with the varied grating separation and τ_s is the stretched pulse duration. For our laser, $\tau_p\approx 20$ fs, $\tau_s/l_{\mathrm{eff}}\approx 1$ fs/μm; changing the grating separation by an amount of the order of the laser wavelength can cause an increase of only a fraction of a femtosecond in laser pulse duration. Thus, for CE phase stabilized amplifiers, the requirement for mechanical stability is much stricter than for conventional chirped pulse amplification.

To measure the phase shift caused by the variation of l_{eff}, we introduced a small change Δl_{eff} by moving mirror M1. When M1 moves away from G1 by an amount Δ, it can be shown with the imaging equations that the change of l_{eff} is

$$\Delta l_{\mathrm{eff}} = -\Delta - (l_{\mathrm{eff}}/2f)^2\Delta. \quad (5)$$

The first term is from the increase of the distance between the first grating to the first mirror, while the second term originates from the increase of the mirror separation. Since $l_{\mathrm{eff}}<2f$, the contribution from the latter is small, which can be neglected for our stretcher. Thus the CE phase shift is given by

$$\frac{\Delta\varphi_{\mathrm{CE}}}{\Delta} \approx \frac{\Delta\varphi_{\mathrm{CE}}}{\Delta l_{\mathrm{eff}}} = 4\pi\sin(\gamma_s-\theta_s)\frac{1}{d_s}. \quad (6)$$

For our stretcher, the groove density of the two ruled gratings is $1/d_s=1200$ lines/mm. The focal length of the two telescope mirrors is $f=250$ mm. When the two mirrors are confocal, the effective linear distance between the gratings is $l_{\mathrm{eff}}=130$ mm. This is the distance between the second grating and the image of the first grating. The incident angle of the beam on the first grating, G_1, is $\gamma_s=33.5°$, and the diffraction angle is $(\gamma_s-\theta_s)=23.3°$. Using these parameters, it was estimated that $\Delta\varphi_{\mathrm{CE}}/\Delta\approx 6$ rad/μm.

The dependence of CE phase on the grating separation was measured experimentally by driving one of the telescope mirrors with a PZT stage. M1 was chosen because of its small size. When a sinusoidal wave with 60 V peak-to-peak amplitude was applied to the PZT, it moved back and forth with a 3.6 μm displacement amplitude. The measured CE phase variation is shown in Figs. 3(a) and 3(c). As a reference, Figs. 3(b) and 3(d) are the measured CE phase of the amplified pulses when a dc voltage was applied. It was deduced from the results shown in Fig. 3(c) that $\Delta\varphi_{\mathrm{CE}}/\Delta\approx\Delta\varphi_{\mathrm{CE}}/\Delta l_{\mathrm{eff}}\approx 3.7\pm1.2$ rad/μm,

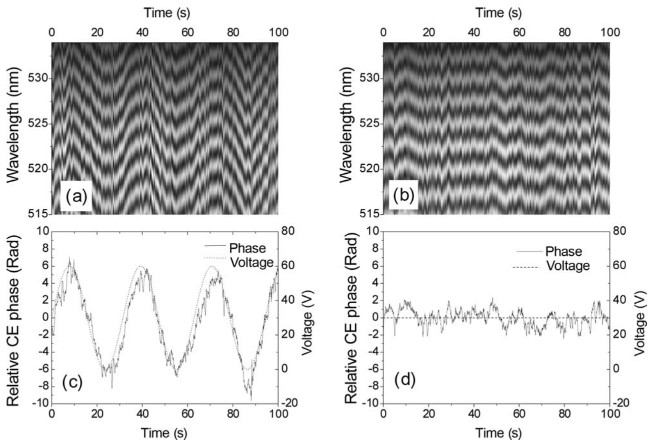

Fig. 3. Dependence of the CE phase of the amplified pulses on the grating separation. (a), (c) Fringe pattern of the collinear f-to-$2f$ interferometer and the corresponding relative CE phase obtained when a 60 V sinusoidal voltage is applied to the PZT, which caused the PZT to move 3.6 μm; (b), (d) with a 30 V dc voltage applied to the PZT.

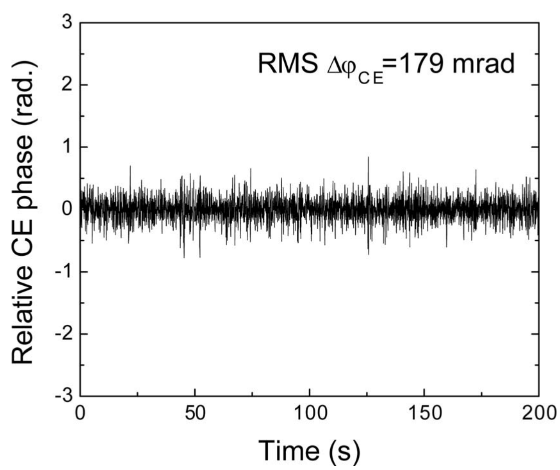

Fig. 4. CE phase of the amplified pulses stabilized by feedback controlling the grating separation. The rms phase error in 200 s is 179 mrad. The CE phase drift without the stabilization is shown in Fig. 3(d).

which agreed with the calculated results within a factor of 2. The origin of the discrepancy and large error is from the PZT uncertainty (6.1 ± 1.5 μm/100 V) and from the random drift of the CE phase. The results demonstrate that a subwavelength change of the grating separation can indeed cause significant CE phase variation. Since the gratings in the stretchers and compressor are not interferometrically stable, their vibration and thermal drift contribute to the variation of the CE phase in Fig. 3(d). Previously, the slow CE phase drift introduced by the chirped pulse amplifier was precompensated by adding a feedback loop to the oscillator f_0 locking electronics, using the measured CE phase from the collinear f-to-$2f$ as the input.[2] We chose to feedback control the grating separation in the stretcher, instead. There are two advantages to our method. First, it does not disturb the oscillator, which should yield a more stable output power from the oscillator because of reduced pump power modulation. Second, the feedback bandwidth is not limited by the channel of the oscillator locking electronics for the slow feedback. The relative CE phase with the feedback control is shown in Fig. 4. The RMS phase error is 179 mrad over 3 min. This can be improved further in the future.

In conclusion, it was found that the carrier-envelope (CE) phase of the pulses from a chirped pulse amplifier with 1 kHz repetition rate is susceptible to variation of the grating separation in the stretchers and compressors, which can be estimated by a simple expression $\Delta\varphi_{CE}/\Delta l_{eff} \approx 2\pi/\lambda$. For our stretcher, the measured value is $\Delta\varphi_{CE}/\Delta l_{eff} \approx 3.7 \pm 1.2$ rad/μm, which is close to the calculated value (6 rad/μm). We demonstrated that the CE phase of the amplified pulses can be stabilized to 179 mrad by feedback controlling the grating separation in the stretcher. The effects of the mismatch of repetition rates between the oscillator and the amplifier on the CE phase were studied in Ref. 10.

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