Carrier-envelope phase shift caused by grating-based stretchers and compressors

Zenghu Chang

Simple analysis indicates that when the distance between gratings in optical stretchers and compressors varies by one half of the grating constant due to mechanical vibration or thermal motion, the change of the carrier-envelope phase is of the order of 2π rad. To suppress the phase noise, one feedback loop is needed to stabilize the compressor while two loops are required for the stretcher. When the phase drift is measured with an f-to-$2f$ interferometer, either the stretcher or the compressor can be feedback controlled to stabilize the carrier-envelope phase of the pulses from a chirped pulse amplifier. © 2006 Optical Society of America

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Carrier-envelope (CE) phase-stabilized, few-cycle laser pulses with millijoule-level energy are crucial for studying many atomic physics processes, such as attosecond pulse generation, above-threshold ionization, and molecular dissociation.[1–5] High-power sub-10 fs pulses can be generated with chirped pulse amplification (CPA) followed by hollow-core fiber (or filamentation) and chirped mirror nonlinear pulse compressors.[6,7] To stabilize the CE phase of the final output pulses, the phase variations in the oscillator, the CPA (stretcher, amplifier, and compressor), and the nonlinear compressor must all be controlled with high precision.

The self-reference technique for controlling the CE phase of the pulses in femtosecond oscillators was developed for frequency metrology and optical clocks.[8,9] The method stabilizes the CE offset frequency f_0 by locking it to a fraction of the repetition rate of the oscillator, f_{rep}, i.e., $f_0 = f_{\text{rep}}/n$. The CE phase increases by 2π (equivalent to no change) every n pulses. These pulses with an almost identical CE phase can be selected by a pulse picker.[3] The repetition rate of amplifiers f_{amp} is much lower than f_0. As long as $(f_{\text{amp}}/f_0) = (f_{\text{amp}}/f_{\text{rep}})n = n/m$, pulses from the oscillator with the same CE phases are amplified. m is another integer. It is worth mentioning that even when f_0 is perfectly stabilized, the CE phase of the few-cycle pulses may still vary with time because the CPA stage and the hollow-core fiber nonlinear compressor introduce additional errors to the phase.[3,10,11] In this paper we focus on the effects of the mechanical stability of the grating stretcher and compressor on the CE phase of the pulses at the exit of the CPA and before the hollow-core fiber.

At least three types of stretcher and compressor schemes have been developed for femtosecond CPA systems that operate at a kilohertz repetition rate. To generate low pulse energy at the 1–2 mJ level, the pulses can be stretched with a block of glass to ~10 ps and compressed with prism pairs.[12,13] Alternatively, the pulses can be stretched with a grating pair and compressed with a glass slab.[14] For even higher pulse energy, pulses are stretched to hundreds of picoseconds with grating stretchers and are compressed also with gratings,[15] which is considered here. For this configuration, it has been shown that the pointing stability of the laser beam on the gratings may introduce CE phase noise to the amplified femtosecond pulses; however, the effects are canceled out to a certain degree by the double-pass configuration.[10,16] In this paper we investigate the effects of the variation of the distance between the gratings on the CE phase of the amplified pulses, which have been overlooked so far.

The conventional grating compressor shown in Fig. 1 is studied first. For simplicity, input pulses are assumed to be transform limited and the grating pairs stretch the pulses instead of compressing them. The conclusions reached with the assumption are

The author is with the J. R. Macdonald Laboratory, Department of Physics, Kansas State University, Manhattan, Kansas 66506. His e-mail address is chang@phys.ksu.edu.

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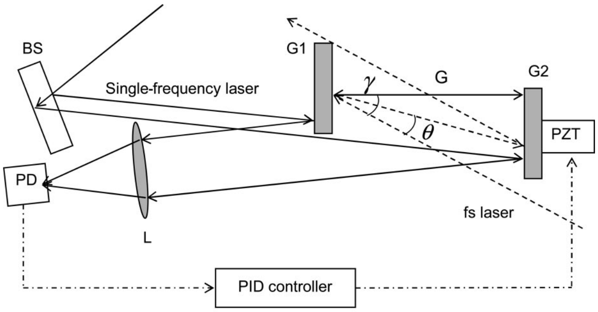

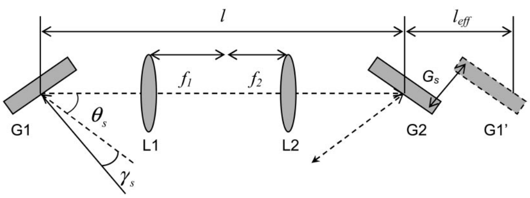

Fig. 1. (a) Grating compressor with a stabilization scheme, and (b) the grating stretcher. G1 and G2 are gratings. G is the perpendicular distance between the gratings and G_s is the effective perpendicular distance between the gratings. γ and γ_s are the incident angles of the femtosecond (fs) beam on the first grating. θ and θ_s are the angles between the diffracted beam and the incident beam (only one frequency component is shown). In (a), a single-frequency cw laser beam and a feedback loop are added to stabilize the distance between the gratings. BS, beam splitter; L, lens; PD, photodiode; PZT, piezoelectric transducer; PID, proportional, integral, and derivative. The dashed lines and solid lines represent the femtosecond beam and single-frequency beam, respectively. The dashed–dotted line is the electric wire. In (b), L1 and L2 are lenses for a telescope. G1′ is the image of the G1 formed by the telescope. l_{eff} is the effective distance.

valid for the conventional case that the incident pulses are positively chirped. In the time domain, the input pulse can be expressed as

$$\varepsilon(t) = \varepsilon_0(t)\exp[i(\omega_0 t + \varphi_{\mathrm{CE}} + \Phi(t))], \tag{1}$$

where $|\varepsilon_0(t)|^2$ is the envelope of the laser pulse, ω_0 is the carrier frequency, and φ_{CE} is the carrier-envelope phase. $\Phi(t)$ is the temporal phase, which equals zero under our assumption. In the frequency domain, the electric field is the Fourier transform of Eq. (1), i.e.,

$$E(\omega) = E_0(\omega)\exp[i(\varphi_{\mathrm{CE}} + \phi(\omega))], \tag{2}$$

where $|E_0(\omega)|^2$ is the power spectrum and $\phi(\omega)$ is the spectral phase, which is also equal to zero.

When the pulse propagates through the double-pass grating compressor, its spectral phase becomes[17]

$$\phi(\omega) = \omega\tau(\omega) - 4\pi \frac{G}{d} \tan[\gamma - \theta(\omega)], \tag{3}$$

where ω is the frequency components of the pulse, τ is the group delay, G is the perpendicular distance between the gratings, d is the grating constant, γ is the angle of incidence, and θ is the acute angle between the incident and diffracted rays.

The difference of the phase velocity and the group velocity introduces a CE phase shift in the compressor, which is

$$\varphi_{\mathrm{CE}}' - \varphi_{\mathrm{CE}} = \omega_0\tau(\omega_0) - \phi(\omega_0) = 4\pi \frac{G}{d} \tan[\gamma - \theta(\omega_0)]. \tag{4}$$

φ_{CE}' is the CE phase at the exit. The variation of γ due to laser beam pointing stability can change φ_{CE}', which has been studied before.[10,16] In a double-pass configuration, the increase of incident angle in the first pass leads to the decrease of the incident angle in the second pass. Thus the net effects of the incident angle variation on the CE phase are small.

It is important that φ_{CE}' depends linearly on G. Suppose that the separation between the gratings is changed by an amount ΔG due to thermal drift and mechanical vibration. The subsequent CE phase variation is

$$\Delta\varphi_{\mathrm{CE}} = 4\pi \frac{\Delta G}{d} \tan[\gamma - \theta(\omega_0)]. \tag{5}$$

When the incident angle is near the Littrow angle at which the gratings are most efficient, $\theta(\omega_0) \approx 0$, Eq. (5) can be simplified to

$$\Delta\varphi_{\mathrm{CE}} \approx 4\pi \tan(\gamma)\frac{\Delta G}{d}. \tag{6}$$

Many compressors use gratings with $d^{-1} = 1200$ lines/mm. If the grating mounts are not interferometrically stable, the magnitude of ΔG can reach a fraction of a laser wavelength, which is of the order of half of the grating constant $d/2 \approx 0.4\ \mu\mathrm{m}$. Thus $\Delta\varphi_{\mathrm{CE}} \approx 2\pi \tan(\gamma)$, which is of the order of 2π rad since $\gamma > 45°$ for most compressors.

Our analysis revealed that the gratings must be interferometrically stable to amplify CE phase-stabilized pulses. In Ref. 16, a subset of the CPA system (without the amplifier) is studied. Vibration sources such as the vacuum pumps and laser cooling systems may not exist in this case. If the optical table is floated, the vibration caused by the ground is also suppressed. A solid grating mount design and well-damped vibration may explain the good phase stability. Many CPA lasers are designed to send amplified pulses to vacuum chambers fixed on the ground. Consequently, the optical tables that support the CPA lasers may not be vibration isolated from the ground. Under such circumstances, it is difficult to maintain the subwavelength stability of gratings.

The grating separation in the compressor of the CPA systems can be actively stabilized when vibration and thermal motion are a problem. This can be done by mounting one of the gratings on a PZT drive stage and feedback controlling the distance between the gratings with a proportional, integral, and derivative circuit. The stability of the distance can be monitored by the interference pattern of a single-frequency laser beam reflected from the gratings, as shown in Fig. 1(a). The coherence length of the laser must be long enough ($>2G$) to produce the interference signal on the photodiode. The frequency response of the PZT and grating assembly limits the bandwidth of the CE phase variation that can be stabilized.

The situation of the grating stretcher is more complicated. The phase of pulses after a double-pass grating stretcher can also be expressed by Eq. (4) except that the distance between the gratings G needs to be replaced by the effective perpendicular distance $G_s = l_{\mathrm{eff}} \cos(\gamma_s + \theta_s)$.[18,19] $(\gamma_s + \theta_s)$ is the diffraction angle as shown in Fig. 1(b). l_{eff} is the effective linear distance between the gratings, which is the distance between the second grating and the image of the first grating. When the two lenses are confocal,

$$l_{\mathrm{eff}} = [l - 2(f_1 + f_2)]\left(\frac{f_1}{f_2}\right)^2, \tag{7}$$

where f_1 and f_2 are the focal lengths of the lenses (mirrors) that form the telescope between the gratings and l is the geometrical distance between the two gratings. For most stretchers, $f_1 = f_2 = f$, then Eq. (7) can be simplified to $l_{\mathrm{eff}} = l - 4f$. Consequently, the amount of CE phase errors introduced by the variation of the effective grating separation Δl_{eff} is $\Delta\varphi_{\mathrm{CE}} \approx 4\pi \sin(\gamma_s)(\Delta l_{\mathrm{eff}}/d_s)$. The incident angle γ_s and grating constant d_s of the stretcher can be different from those of the compressor.

The change of the l_{eff} value can originate from the motion of either the lenses or the gratings. Suppose that the second lens moves by Δs while the physical distance between the gratings is fixed; this will change the image position of grating G1. Using the lens equation, it can be shown that the subsequent change of the effective grating separation is

$$\Delta l_{\mathrm{eff}} \approx \left(\frac{l_{\mathrm{eff}}}{2f} + 1\right)\Delta s, \tag{8}$$

where $l_{\mathrm{eff}}/2 < f$. It is clear that the amount of Δl_{eff} caused by the displacement of lenses is similar to that caused by the gratings. Thus, two stabilizing feedback loops are needed to stabilize the effective grating separation. One feedback loop fixes the separation of the two lenses (mirrors) to $2f$ and the other locks the geometrical grating separation.

Implementing one feedback loop to stabilize the compressor and two in the stretcher is expensive and challenging. In most CE phase-stabilized amplifiers, the CE phase of the amplified pulses is measured by an f-to-$2f$ interferometer. The measured phase variation is used as a feedback signal to control f_0 of the oscillator. The disadvantage is that the feedback disturbs the oscillator operation. We suggest that the same CE phase signal be used as a feedback signal to control the grating separation G or l_{eff}. This scheme also corrects the phase drift introduced by the whole CPA stage but does not interfere with locking f_0 of the oscillator. In this case, the bandwidth of the feedback loop is limited by the speed of the CE phase measurements, the response of the PZT, and the feedback electronics.

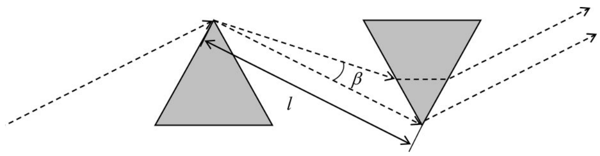

Fig. 2. Prism compressor. l is the distance between the apexes of the prisms. The reference ray propagates from the apex of the first prism to that of the second prism. β is the angle between the ray with frequency ω to the reference ray.

When the pulses are stretched with a glass slab and are compressed with a pair of prisms as in Ref. 12, the change of the prism separation also effects the CE phase. The prism compressor is shown in Fig. 2, where l is the distance between the apexes of the two prisms and β is the angle between a ray with frequency ω that is used for the analysis and the reference ray that propagates from the first apex to the second one. In a double-pass configuration, the spectral phase change introduced by the prism pair for the considered ray is[20]

$$\phi(\omega) = 2\,\frac{\omega}{c}\, l \cos\beta(\omega). \tag{9}$$

The CE phase shift is

$$\begin{aligned}\varphi_{\mathrm{CE}}{}' - \varphi_{\mathrm{CE}} &= \omega_0 \left.\frac{\partial\phi}{\partial\omega}\right|_{\omega_0} - \phi(\omega_0) \\ &= 2l\,\frac{\omega_0{}^2}{c}\left.\frac{\mathrm{d}\beta}{\mathrm{d}n}\right|_{\omega_0}\left.\frac{\mathrm{d}n}{\mathrm{d}\omega}\right|_{\omega_0} \sin[\beta(\omega_0)],\end{aligned} \tag{10}$$

where n is the index of refraction of the prism glass and c is the speed of light in vacuum. For most prism compressors that are configured with minimum deviation and Brewster-angle incidence to avoid reflection loss, $\mathrm{d}\beta/\mathrm{d}n = -2$. Replacing frequency with wavelength and using $\mathrm{d}n/\mathrm{d}\omega = -2\pi(c/\omega^2)\mathrm{d}n/\mathrm{d}\lambda$, we obtain the variation of the CE phase due to the change of prism separation by Δl:

$$\Delta\varphi_{\mathrm{CE}} = 8\pi \sin(\beta)\Delta l \left.\frac{\mathrm{d}n}{\mathrm{d}\lambda}\right|_{\lambda_0}. \tag{11}$$

It is interesting to compare this result with Eq. (6) for grating compressors. Here the susceptibility of the CE phase to the distance variation is determined by the material dispersion $\mathrm{d}n/\mathrm{d}\lambda$ instead of the groove density of the gratings $1/d$. For a fused-silica glass prism as used in Ref. 12, $\mathrm{d}n/\mathrm{d}\lambda = -0.0173\ \mu\mathrm{m}^{-1}$ at 800 nm, which is orders of magnitude smaller than

$1/d = 0.83\ \mu m^{-1}$ for a 1200 line/mm grating. The angle β is typically 10 mrad or less to avoid overfilling the second prism; thus sin(β) in Eq. (11) is also orders of magnitude less than tan(γ) in approximation (6). Consequently, the requirement on the stability of the prism distance is much less strict than that for grating separation. The same conclusion can be reached when the pulses are stretched by a prism pair and compressed by a block of glass. The downchirped amplification concept was implemented in Ref. 14.

In conclusion, simple analysis shows that a very small variation of the grating separation (of the order of subwavelengths) in the stretcher and compressor causes a large change in the CE phase of a chirped pulse amplifier. In other words, the requirements of the mechanical stability of the grating mounts and the temperature and pressure stability of the air in the stretchers and compressors for stabilizing the CE phase of CPA systems are the same as in conventional interferometers. Unlike the effects of beam pointing stability, the phase errors in a double-pass configuration are additive. To produce phase-stabilized amplified pulses, one can either lock the grating separation or feedback control the separation with the measured CE phase.

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