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Carrier-envelope phase stabilization by controlling compressor grating separation

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Previously, we demonstrated the stabilization of the carrier-envelope (CE) phase of the laser pulses from a chirped pulse amplifier by controlling the effective grating separation in the stretcher. In this work, we show that the CE phase can also be stabilized to $\sim$230 mrad by controlling the grating separation in a compressor. The cutoff frequency of the piezoelectric transducer mounted grating for the phase stabilization system was found to be higher than 60 Hz. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2929743]

The rapid development in few-cycle femtosecond laser technology over the last few years has led to the generation of much shorter optical pulses in the attosecond timescale.[1,2] To generate single isolated attosecond pulses, the carrier-envelope (CE) phase φ_{CE} of the few-cycle femtosecond pulse, which can be described by an electric field $E(t) = E_0(t)\cos(\omega_0 t + \varphi_{CE})$, must be stabilized and controlled.[1] Consequently, controlling the CE phase leads to the generation of identical laser pulses with reproducible electric field profiles. Previously, the CE phase stabilized laser pulses were generated from prism-based chirped pulse amplification (CPA) laser systems, where the pulse energy was limited by the prism material itself.[1] On the other hand, grating-based CPA lasers can generate femtosecond pulses with much higher power than material-based laser systems. In our previous work, the CE phase of a grating-based CPA system was stabilized by feedback controlling the effective grating separation in a stretcher.[3–5] However, for some stretcher designs, implementation of this technique might be difficult if the size of the controllable optics in the stretcher is much larger and heavier than that in the compressor. Thus, it is beneficial to translate the smaller optics in the compressor to reduce the response time and to stabilize the CE phase.

The laser system, the Kansas Light Source (KLS), for demonstrating the CE phase locking is shown in Fig. 1. It consists of two multipass amplifiers sharing one oscillator and one grating-based stretcher. The laser is designed for synthesizing two amplified pulses in the future, which will require locking the CE phase of the two amplifiers simultaneously and independently. It cannot be accomplished by controlling the dispersion in the shared stretcher because the phase error introduced by the two amplifiers is not the same.
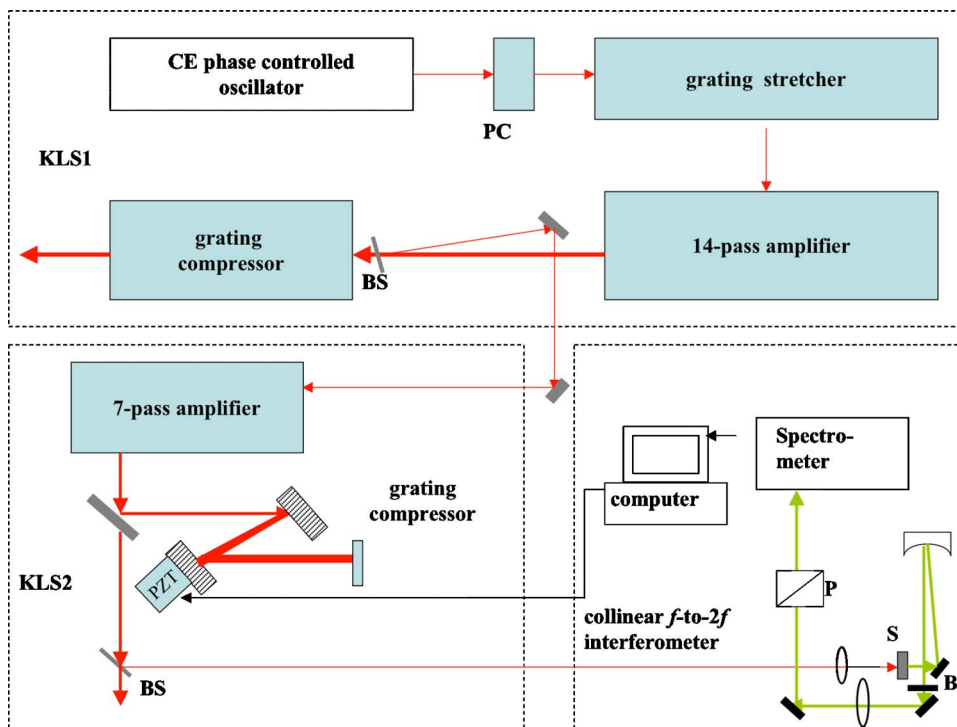

FIG. 1. (Color online) Experimental setup for controlling the CE phase of the amplified laser pulses. PC: Pockels cell; PZT: piezoelectric transducer; BS: beam splitter; S: sapphire plate; B: frequency doubling crystal; P: polarizer.

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For this application, it is highly desirable to lock the CE phase through feedback control of the grating separation in the compressor, which is the focus of this work.

The CE phase offset frequency of the oscillator was stabilized by using a standard Mach–Zehnder f-to-$2f$ interferometer.[6] Pulses from the oscillator with the same CE phase were selected by a Pockels cell for amplification at a repetition rate of 1 kHz and sent to the stretcher. The seed pulses had ∼100 nm bandwidth centered at 800 nm and were stretched to ∼80 ps. The stretched pulses were amplified to 5 mJ via a 14-pass liquid nitrogen cooled Ti:sapphire amplifier (named as KLS1). After amplification, the pulses were compressed by a pair of gratings to 30 fs with 2.5 mJ energy. The output energy was stabilized by feedback controlling the Pockels cell transmission to reduce the error of the CE phase measurements caused by the laser energy fluctuation.[7,8]

A small portion (3%) of the amplified beam was split by a beam splitter in front of the grating compressor of KLS1. This beam was used as the seed for another liquid nitrogen cooled seven-pass Ti:sapphire amplifier (named as KLS2), which yielded 2 mJ pulses after amplification. The amplified pulses were compressed by a grating-pair compressor to 38 fs with 1 mJ energy. In the compressor, one of the gratings was mounted on a piezoelectric transducer (PZT) stage for the KLS2 CE phase stabilization. To measure the CE phase shift $\Delta\varphi_{CE}$ of the pulse from the second amplifier, a fraction of the output beam from its compressor (<1 μJ) was sent to a collinear f-to-$2f$ interferometer.[9] In the f-to-$2f$ interferometer, the beam was focused into sapphire plate to generate the required broadband white light, which covered a spectral octave. The interferogram between the green portion of the white light and the second harmonic of the infrared portion was recorded by a spectrometer (HR2000+, Ocean Optics). For a given pulse, its CE phase relative to a reference pulse was extracted from the interferogram by Fourier transform spectral interferometry.[10]

The CE phase shift $\Delta\varphi_{CE}$ caused by the variation of the compressor grating separation ΔG can be written as[3–5]

$$\Delta\varphi_{CE} = 4\pi \frac{\Delta G}{d} \tan[\gamma - \theta(\omega_0)], \qquad (1)$$

where d is the grating groove density, γ the incident angle, θ the angle between the incident and diffracted beams, and ω_0 the central angular frequency of the laser beam, respectively. Equation (1) shows that the CE phase φ_{CE} has a linear relation with the grating separation G. In our experiments, the grating was translated by the PZT at different voltages.

For simplification, the PZT can be considered as a linear translation stage controlled by an applied driving voltage V, i.e., $\Delta G(f) = H(f)V(f)$, here f is the driving frequency. In order to stabilize the slow drift of the CE phase of the amplified pulses, the frequency response of the PZT mounted grating must be within the bandwidth of the CE phase drift. Figure 2 shows the frequency response of the grating, $H(f)$, measured with a Michelson interferometer and a cw laser. The resonant frequency is about 90 Hz. The amplitude modulation at the low frequency range is due to the PZT hysteresis.[11]

The measured CE phase shift can be expressed as $|\Delta\varphi_{CE}(f_d)| = K(f_d)|V(f_d)|$, where $V(f_d)$ is the Fourier transform of the driving voltage sent to PZT driver (MDT694A,

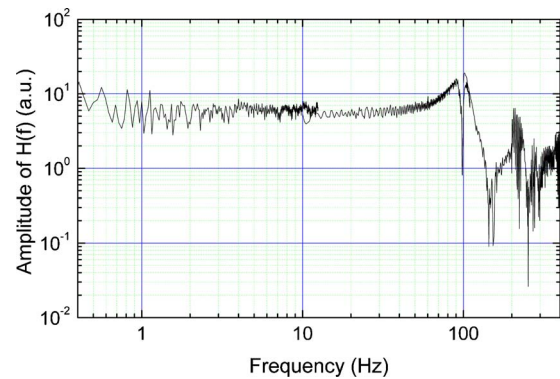FIG. 2. (Color online) The frequency response of the PZT mounted grating. The resonant frequency is about 90 Hz.

Thorlabs) and $\Delta\varphi_{CE}(f_d)$ is the Fourier transform of the retrieved CE phase drift at the frequency f_d. $K(f)$ shows the frequency response of the CE phase drift introduced by the PZT displacement, which is determined by $H(f)$ and the response time of the phase detection. Experimentally, we measured $K(f)$ by measuring $\Delta\varphi_{CE}$, while the grating was translated by a sinusoidal voltage at different frequencies. The experimental result of the coefficient K as a function of the driving wave frequency f is shown in Fig. 3. The integration time of our spectrometer was 5 ms at the range of 3–35 Hz and changed to 2 ms in the range of 40–120 Hz. A dip can be found at 60–70 Hz, which is very close to the resonant frequency of the PZT mounted grating (90 Hz). This result implies that the CE phase drift lower than 60 Hz can be compensated by moving the grating.

In order to stabilize the CE phase of the laser pulses of KLS2, the output of the f-to-$2f$ interferometer served as the error signal for feedback controlling the compressor grating separation. The measured CE phase drift when the feedback loop was turned off is shown as the dotted curve in Fig. 4(a). During the measurement, the CE phase of the KLS1 was not stabilized. The CE phase stability after the feedback signal was applied to the PZT is represented by the solid line; where it is vertically shifted from 0 to π to avoid the dip at 0 Hz in its Fourier transform spectrum [see Fig. 4(b)]. The phase was stabilized over 270 s with a 230 mrad rms error. This residual error is at the same level as the one in KLS1 when the grating separation in the stretcher was used to compensate the phase drift.[4,5] The locking time is determined by the phase locking condition of the oscillator. In our experiment, we locked the CE phase of KLS2 over 30 min then the
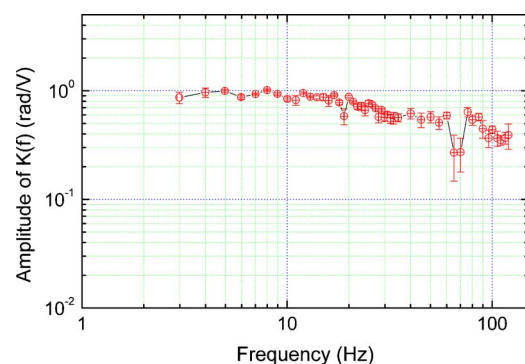

FIG. 3. (Color online) The frequency response of the retrieved CE phase drift when the PZT was driven at different frequencies.
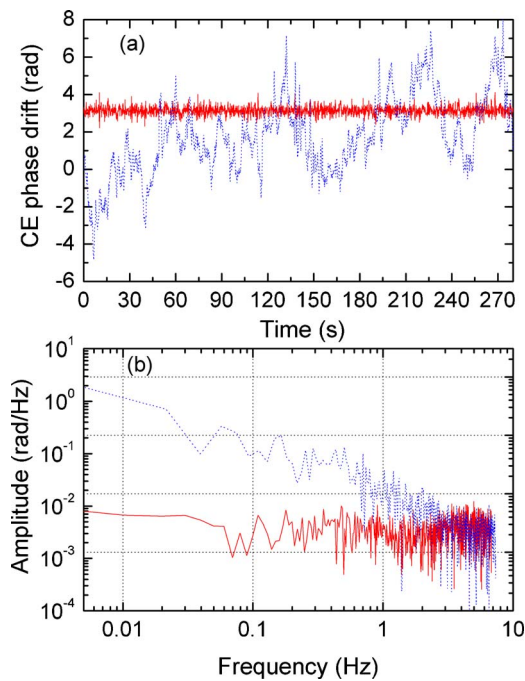
FIG. 4. (Color online) (a) The evolution of the free drifted (dotted line) and stabilized (solid line) CE phase drifts. (b) The fast Fourier transform of the CE phase drift under the free running (dotted line) and stabilized conditions (solid line).
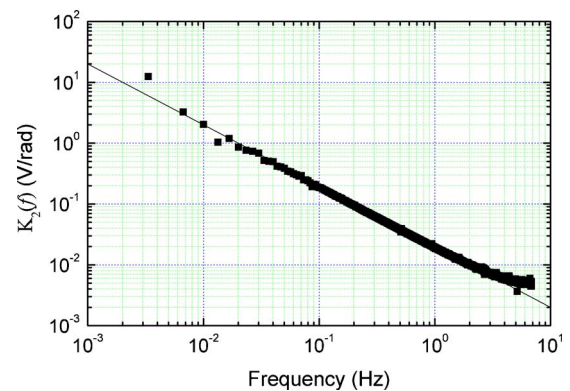

FIG. 5. (Color online) The frequency property of the feedback controller. The dots are the experimental results and the solid line represents the vertically shifted plot of the function $1/f$.

oscillator CE phase locking was lost. Figure 4(b) is the Fourier transform spectra of the CE phase drift under the free running and stabilized conditions. It is clearly shown that the phase drift with a frequency lower than 4 Hz can be well compensated. Furthermore, this result confirmed that the movement of the PZT mounted grating is fast enough for the CE phase stabilization.

In our CE phase stabilization software, the measured phase errors were integrated to generate the control voltage $V_c(t)$ for translating the grating. The frequency property $K_c(f)$ of the feedback control can be derived from the Fourier transform of the control voltage $V_c(t)$ sent to PZT driver and stabilized CE phase shift $\Delta\varphi_{CE}$ as $K_c(f)=V_c(f)/\Delta\varphi_{CE}(f)$. Figure 5 shows the $K_c(f)$ as a function of frequency. The solid line in Fig. 5 is a plot of the function $1/f$, which is shifted vertically for comparison. The experimental result agrees well with the $1/f$ function in the low frequency range (<4 Hz), whereas the high frequency noise is too small (<10 mrad/Hz) to be compensated by translating the grating.

In conclusion, the CE phase of the pulses from a CPA laser was stabilized by feedback controlling the grating separation in the compressor. The phase stability is as good as that obtained by controlling the grating separation in the stretcher. The technique is useful for laser systems where the stretcher optics is not accessible for phase locking. It has also paved the way for the simultaneous locking of two amplifiers who share the same oscillator and stretcher. The two compressed beams can also be manipulated and combined for high power laser field synthesizing.

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