Stabilizing the carrier-envelope phase of the Kansas Light Source

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The goals of this aspect of the JRML program are (1) to generate high power, few-cycle laser pulses with stabilized carrier-envelope phase, (2) to increase the brightness of attosecond x-ray sources based on the polarization gating of high-order harmonic generation, and (3) to improve ultrafast x-ray streak cameras.

1. Stabilizing the carrier-envelope phase of amplified laser pulses – *C. Li, E. Moon, Z. Duan and Z. Chang*

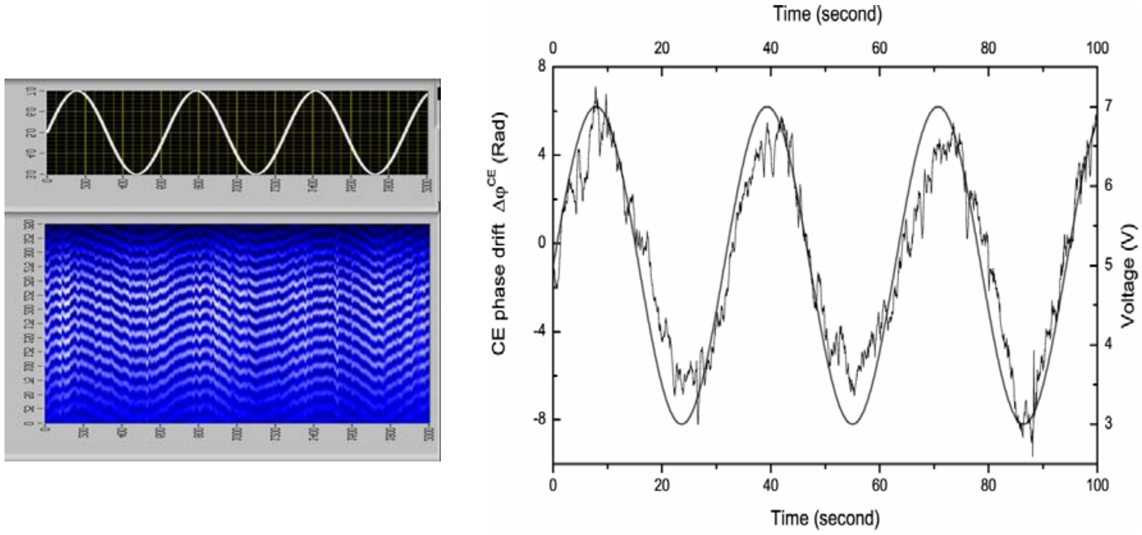
The high intensity laser facility, the *Kansas Light Source,* produces 25 fs pulses with 2.5 mJ energy by using the principle of chirped pulse amplification [1]. It also provides 6.2 fs pulses with 0.6 mJ energy by using an improved hollow-core fiber/chirped mirror compressor [2]. The dynamics in atoms [3], molecules [4, 5] and nanotubes [6] have been extensively studied using the facility. Since there are only few-cycle field oscillations under the 6 fs pulse envelope, it is crucial to control their carrier-envelope (CE) phase for strong field atomic physics studies. The CE phase errors can originate inside the oscillator, CPA amplifier, and the hollow-core fiber compressor of a laser system. We focused on the effects of the stability of the grating separation in the stretcher and compressor on the CE phase variation [7, 8], which have been overlooked so far.

For most stretcher and compressor designs, the incident angle is close to the Littrow angle. Considering the gratings with grating constant $d_s \approx \lambda$, It can be shown that amount of CE phase errors, $\Delta\varphi_{CE}$, introduced by the variation of the effective linear grating separation, Δl_{eff}, is,

$$\frac{\Delta\varphi_{CE}}{\Delta l_{eff}} = 2\pi \frac{\lambda}{{d_s}^2} \approx \frac{2\pi}{\lambda}. \tag{1}$$

It reveals that the CE phase change is significant when the variation of linear separation of the gratings is on the order of the laser wavelength.

The dependence of CE phase on the grating separation was measured experimentally by driving one of the telescope mirrors. To observe the phase shift caused by the variation of l_{eff}, we introduced a small change Δl_{eff} by moving the mirror in the grating based stretcher with a PZT driven mount. For a t mirror motion of Δ, it was estimated that $\Delta\varphi_{CE}/\Delta \approx 6$ rad/μm. When a sinusoidal wave with 60 volts peak to peak was applied to the PZT, the mirror moves back and forth with a 3.6 μm displacement amplitude. The measured CE phase variation is shown in Fig. 1 (a) and (b). It was deduced that $\Delta\varphi_{CE}/\Delta \approx \Delta\varphi_{CE}/\Delta l_{eff} \approx 6$ rad/μm, which agrees with the calculated results.

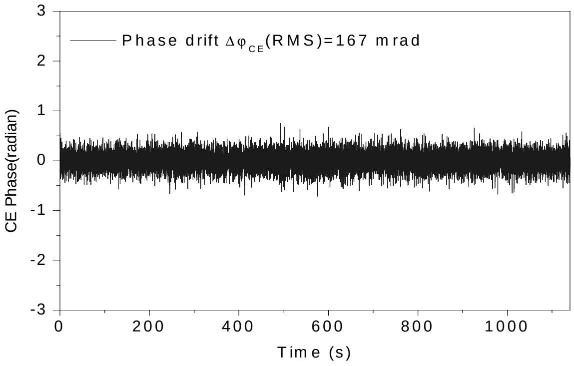


(a) (b)

Fig. 1 . The dependence of the CE phase of the amplified pulses on the grating separation. (a) and (b), the fringe pattern of the collinear *f-to-2f* interferometer and the corresponding relative carrier-envelope phase obtained with a 4 volts peak to peak sinusoidal voltage, which caused the PZT to move 3.6 μm.

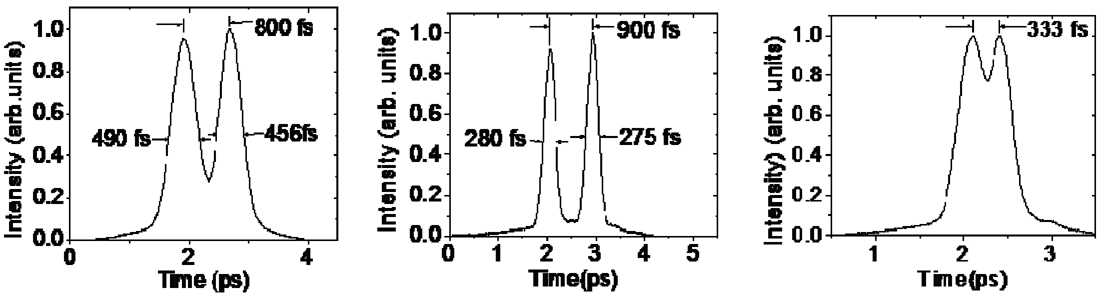
Since the gratings in the stretchers and compressor are not interferometrically stable, its vibration and thermal drift contributes to the variation of the CE phase. To produce CE phase stabilized pulses from a CPA system, one either has to fix the grating separation with an interferometrical accuracy, or correct the phase error. Stabilization the separations of the gratings and mirrors in the stretcher and compressor need three feedback loops which can be costly and complicated, we thus took the latter approach. Previously, the slow CE phase drift introduced by the CPA amplifies was precompensated by adding a feedback loop to the oscillator offset frequency locking electronics using the measured CE phase from the collinear *f-to-2f* as the input. We chose to feedback control the grating separation in the stretcher instead. The advantage of our method is that it does not disturb the oscillators, which should yield more stable output power from the oscillator since it reduces the pump power modulation. The relative CE phase with the feedback control is shown in Fig. 2. The RMS phase error is 167 mrad over 18 minutes. This can be improved further in the future.

Fig. 2. The CE phase of the amplified pulses stabilized by feedback controlling the grating separation. The RMS phase error in 18 minutes is 167 mrad.



2. Dependence of attosecond spectra on the CE phase of the driving laser – *M. Shakya, S. Gilbertson, H. Mashiko and Z. Chang*. We demonstrated that attosecond XUV supercontinuum can by generated by polarization gating of high harmonic generation [9]. Our numeric simulation predicted that the change of the CE phase of the driving laser pulse can result in either single or double electron ion recollisions in the gated harmonic generation process [10]. If the XUV spectrum can be measured and analyzed for every laser shot, then it is possible to determine the shot to shot variation of the CE phase. The measurement of the single shot CE phase is important for studying CE phase effects in many experiments when the CE phase of the few-cycle laser pulses are not locked. For a CE phase locked laser system, the measurement gated harmonic spectra are useful for observing fast variations of the CE phase. It is worth mentioning that the conventional *f-to-2f* setup measures the relative CE phase change, while it is possible to determine the absolute CE phase from the XUV spectrum. The major challenge for measuring the single shot XUV spectrum was to obtain enough XUV photons per laser shot, which is what we plan to work on. In the mean time, we are also trying to measure the attoseocnd pulse duration by measuring the momentum shift and of the photoelectrons [11, 12].

3. Calibration of an accumulative x-ray streak camera with high harmonic pulses– *Mahendra Shakya, S. Gilbertson and Z. Chang*. We show experimentally that the deflection dispersions are a major limiting factor for streak cameras with resolutions approaching 100 fs [13]. The deflection aberrations can be reduced by reducing the beam size of the electron in the deflection plates. We demonstrated that a resolution of 280 fs FWHM was achieved when with a 5 μm wide slit was used, as shown in Fig. 3. To the best of our knowledge, this is the highest resolution ever achieved with an accumulative streak camera. The high resolution is critical in experiments with synchrotrons [14, 15].



(a) (b) (c)

Fig. 3. The measured temporal resolution with various slits. (a) The slit width is 50μm. (b) and (c) The slit width is 5μm. The two pulses are produced by a Mach-Zehnder interferometer.

We plan to characterize the camera using the soft x-ray pulses from the high order harmonic generation. We will continue the collaboration with Prof. J. Rocca at Colorado State University. The x-ray streak camera is an idea too for studying the dynamics of the x-ray laser [16]. Progress is also made on applying the camera to the pico-pulse project, i.e., accelerating the ultrashort ion pulses producing by intense laser pulses in a tandem accelerator.

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