Reduction of fast carrier-envelope phase jitter in femtosecond laser amplifiers

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Abstract: The phase noise of the *f-to-2f* interferometer used for stabilizing the carrier-envelope phase of a femtosecond laser oscillator was studied by adding a He-Ne laser beam co-propagating with the short pulse laser beam. The noise was reduced to ~60 mrad by stabilizing the optical path length difference of the interferometer. This suppressed the fast jitter of the carrier-envelope phase of the amplified laser pulses from 79 to 48 mrad.

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1. Introduction

Carrier-envelope (CE) phase is a very important parameter affecting the outcome of many strong field processes, such as attosecond pulse generation and above threshold ionization [1-4]. Stabilization of the CE phase is also important for optical frequency metrology and optical clocks [5, 6]. In laser systems based on chirped pulse amplification, the CE phase of a laser oscillator can be stabilized by locking the carrier-envelope offset frequency, f_0, to a fraction of the pulse repetition rate, f_{rep}, or to an external RF clock [7, 8]. The timing of the laser system can be arranged so that only pulses with almost identical CE phase are amplified. Many factors contribute to the phase jitter of the amplified pulses. One of them is the instability of the *f-to-2f* interferometer used for locking f_0, which is the focus of this work.

2. Experiment and discussion

The experiments were carried out at the Kansas Light Source facility [9]. The laser system is shown in Fig. 1. The Ti:sapphire oscillator (Femtolasers's Femtosource Pro) had a spectral FWHM of 100 nm centered at 790 nm. Half of the output power from the oscillator (200 mW) was focused into a photonic crystal fiber (Menlo Systems). The spectrum of the white light emerging from the fiber extended from 500 nm to ~1130 nm. An octave-spanning spectrum is needed for stabilizing f_0 by the self-referencing *f-to-2f* scheme [10]. In the home-built Mach-Zehnder *f-to-2f* interferometer, the infrared light was frequency doubled by a Type I BBO crystal. The second harmonic beam interfered with the 532 nm component from the short wavelength arm. The beat signal near the offset frequency was filtered from the avalanche photodiode output in the locking electronics (Menlo Systems XPS 800). The offset frequency was compared to $f_{rep}/4$, the quarter-repetition rate value, yielding a phase error signal that controlled an acousto-optic modulator placed in the beam of the oscillator pump laser. The offset frequency was stabilized by varying the pump power using the acousto-optic modulator.
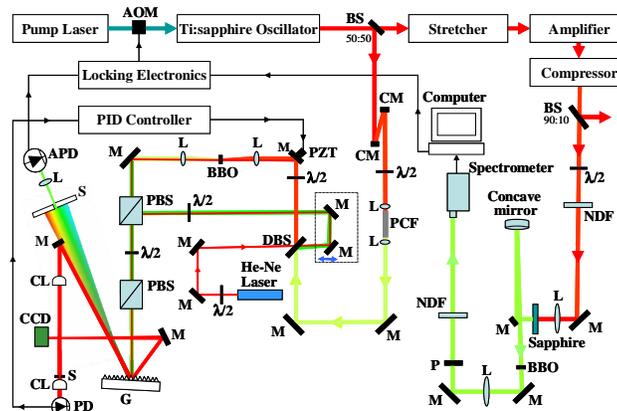

Fig. 1. The Kansas Light Source CE phase stabilized kilohertz femtosecond laser system. A He-Ne laser beam was added to investigate the f-to-2f interferometer stability. M: mirror, S: slit, BS: beam-splitter, PBS: polarizing beam-splitter, CM: chirped mirror, G: grating, CL: cylindrical Lens, DBS: dichroic beam splitter, PCF: photonics crystal fiber, NDF: neutral density filter, P: polarizer

Even if the locking electronics are working properly, phase noise from the *f-to-2f* interferometer and the photonic crystal fiber will be written onto the pulses exiting the oscillator. The noise will then contribute to the phase error of the amplified pulses. While the phase noise of the fiber has been previously investigated extensively [11, 12], only one published work on the study of the CE phase noise originating from the *f-to-2f* interferometer was found in literature [13].

The optical path length difference of the two arms, ΔL, in the *f-to-2f* interferometer may change with time due to the vibration of the mirror mounts and the change of air pressure/temperature. As a result, the relative phase of the optical beams in the two arms is time dependent. The time dependent phase is given by: $\varphi(t) = 2\pi \Delta L(t)/\lambda$.

The wavelength is $\lambda \sim 532$ nm. Here the light field from the short wavelength arm is chosen as the reference. It can be expressed as

$$E_1(t) = E_{01}(t)\cos[2\pi(nf_{rep} + f_0)t] .$$ (1)

Where $E_{01}(t)$ is the amplitude and n is an integer that is determined by the wavelength λ.

Similarly, the second harmonic of the infrared beam with amplitude $E_{02}(t)$ is

$$E_2(t) = E_{02}(t)\cos[2\pi(nf_{rep} + 2f_0)t + \varphi(t)] .$$ (2)

The frequency of the beat signal is deviated from f_0 and is also time dependent:

$$f(t) = f_0 + \frac{1}{2\pi}\frac{d\varphi}{dt} .$$ (3)

The locking electronics stabilize f not f_0. Hence, the CE phase of the *m*th pulse to a reference, *0*th pulse, from the oscillator is

$$\varphi_{CE,m} - \varphi_{CE,0} = \int_0^{m/f_{rep}} 2\pi\left(\frac{f_{rep}}{4} - \frac{1}{2\pi}\frac{d\varphi}{dt}\right)dt = \frac{m}{4}2\pi + \varphi\left(\frac{m}{f_{rep}}\right) - \varphi(0) .$$ (4)

It is clear the phase error of the interferometer is transferred to a change of the CE phase of the pulses produced by the laser oscillator. The contribution of the interferometer stability to the CE phase noise can be reduced by using other configurations [14, 15]. However, the Mach-Zehnder setup is still widely used in f-to-2f interferometers.

To measure the phase noise of the interferometer and to stabilize the *f*-to-2*f* interferometer, a He-Ne beam (5 mW) was added that co-propagated with the short pulse beam. This is the major difference between our *f-to-2f* interferometer and others. A photodiode (PDA500, Thorlabs) was used to measure the interference signal. This measured signal was sent to an analogue PID controller (SIM960, SRS). The output from PID controller drove the PZT (15 μm/100V, AE0505D18, Thorlabs) to control the displacement in the long wavelength arm. The *f-to-2f* interferometer was placed in a well engineered enclosure to reduce the effects of the airflow. The optical table was not floated.

The optics used in the interferometer was not designed for the 632.8 nm He-Ne wavelength. The beam in the long wavelength arm suffered angular deviation in the BBO crystal. This was fixed by using focusing lenses and mirrors to overlap the two beams, allowing them to interfere. A high contrast in the interference was observed, which showed that power loss was not an issue. The interference fringes captured from a CCD camera are shown in Fig. 2(a). The shift of the fringes with time was clearly seen.

To measure the fringe stability quantitatively, a slit was used to select a vertical slice of one fringe in another interference location shown in Fig. 1. The amplified photodiode signal was sent to a dynamic signal analyzer to measure the phase noise of the interferometer. The results are shown in Fig. 2(b). There is significant amount of noise from DC to 1 kHz, which presumably originated from the vibration of the mirror mounts and the air flow. The

integrated phase error reaches 0.37 radians in 10 ms, shown in Fig. 2(b), which is caused by the noise peak at ~100 Hz. This phase error is significant for many applications.
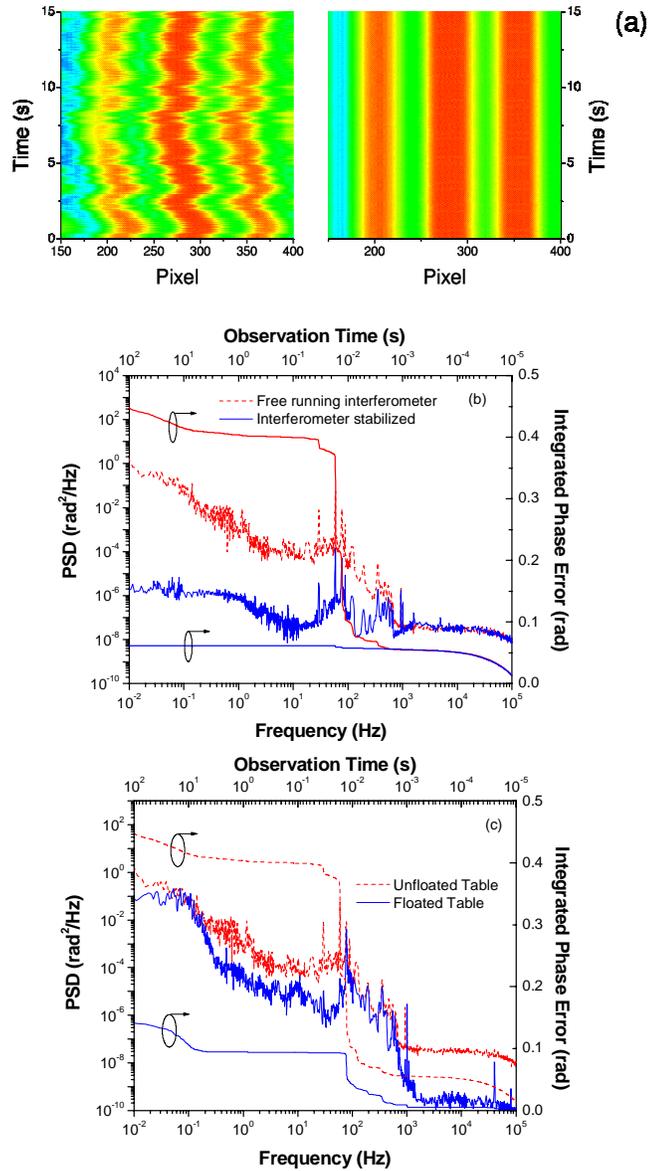

Fig. 2. Comparison of the phase noises of the *f*-to-*2f* interferometer between the free running and the stabilized mode. (a) The interference pattern of the He-Ne beam used to monitor the stability of the *f*-to-*2f* interferometer. The left image was taken when the interferometer was free running. The right was obtained when the interferometer was stabilized. (b) The power spectrum of the interferometer phase noise and the integrated phase. (c) Comparison of phase noise measurement when optical table was floated and not floated.

The phase error in the 0.01 Hz to 10 kHz frequency range is 0.45 rad, which is larger than that reported in Ref. [13] where the measured phase noise of their interferometer is 0.12 rad at a

frequency range of 0.01 Hz to 104 Hz. Our measurements covered a much larger frequency range, especially the noise peaks in the 100-1000 Hz range, which can be one of the reasons that our phase error is larger. Another major cause of the difference is that during our measurements the optical table that support the *f-to-2f* interferometer was not floated. Unlike the frequency metrology work in Ref. [13], our oscillator is for seeding chirped pulse amplifiers. Since many of our experiments vacuum chambers are fixed on the ground (not floated), the optical table that support the CPA laser are not floated to avoid laser beam drifting on the targets. Even under favorite conditions in Ref. [13], the 0.12 rad phase error is a major contributor to the difference between the in-loop and out-loops measurements. Figure 2(c) shows the effects of the vibration of the phase noise. When the table was floated, the power spectrum decreased significantly at the high frequency range but the low frequency noise did not drop significantly. The integrated phase error was 0.14 rad and agreed well with Ref. [13]. It reveals that vibration is the dominating source of the *f-to-2f* instability.

The optical path length difference of the interferometer was stabilized by using a feedback loop to control a PZT driven mirror placed in the long wavelength arm. When the *f-to-2f* was stabilized, there was no visual shift of the He-Ne interference fringes as shown in Fig. 2(a). The effects are shown quantitatively in Fig. 2(b) by the noise power density spectrum and by the integrated phase error. The dominating noise peak at ~100 Hz was reduced by more than two orders of magnitude. As a result, the integrated phase error was reduced to ~60 mrad over a 100 second observation time. Our experiments show that feedback control is an effect approach to reduce the effects of the vibration.

The timing of the KLS amplifier was adjusted to amplify an integer of every fourth pulse yielding a phase-stabilized pulse train at a 1 kHz repetition rate and more than 2 mJ pulse energy with 20 fs pulse duration. The pulse can be further compressed to 6 fs with 0.5 mJ pulse energy (not show) [9]. The CE phase drift of the pulses from the chirped pulse amplifier was measured with a standard collinear f-to-2f interferometer, shown in Fig. 1. For a given pulse, i, its phase relative to a reference pulse, 0, was extracted from the measured interferogram by Fourier transform spectral interferometry [16, 17]. Figure 3(a) shows the measured relative CE phase, $\Delta\varphi_{CE}=(\varphi_{CE,i}-\varphi_{CE,0})$, of the amplified pulses. The framing transfer speed of the CCD camera in the spectrometer is 20 Hz, thus each CE phase data was taken by integrating 50 laser shots. Consequently, the Nyquist critical frequency of the CE phase measurements is $f_c=10$ Hz. The CE phase noises with frequency higher than 10 Hz were aliased to the 0-10 Hz range. The longest time of phase stabilization we demonstrated is about 30 minutes [18].
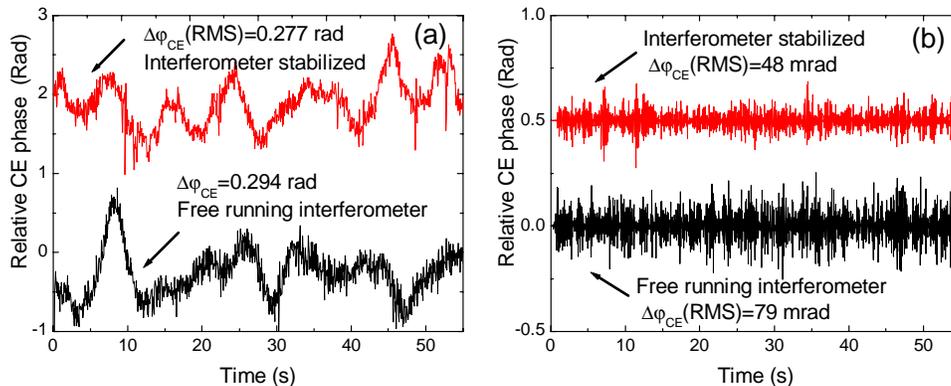

Fig. 3. Comparison of the CE phase noises of the amplified laser pulses between the free running and the stabilized the *f-to-2f* interferometer. The slow drift of the CE phase in the amplifier was corrected by an additional feedback. (a) The relative CE phase measured by the collinear *f-to-2f* interferometer. (b) The fast jitter of the CE phase obtained by applying a high pass filter to the spectra in (a).

There are three possible sources of phase noise contributing to the measured CE phase fluctuation: the oscillator, amplifier and the collinear *f-to-2f* interferometer. The CE phase drift of amplified pulses was pre-compensated 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. In our system, the frequency bandwidth of this loop was limited by the speed that the CE phase was measured (f_c=10 Hz) and the phase error integration in the software for stabilizing the CE phase. The frequency bandwidth of the software integration control is lower than 10 Hz. Thus only the low frequency components of the CE phase drifts introduced by the oscillator and the amplifier could be corrected. Since the stability of the Mach-Zehnder *f-to-2f* interferometer contributes to the phase noise of the pulses from the oscillator, it should also affect the CE phase of the amplified pulses. The high frequency components should have more significant effects because it could not be suppressed effectively by the slow feedback loop.

The top plot of Fig. 3(a) was taken when the Mach-Zehnder *f-to-2f* interferometer was stabilized while the bottom curve was obtained when the *f-to-2f* was not stabilized. In both cases, the carrier-envelope offset frequency of the oscillator was locked and the slow feedback was applied. Although the RMS phase jitter did not change much when the He-Ne fringe was stabilized, the fast jitter of the CE phase was significantly suppressed. This is easy to understand because the RMS phase in our system is dominated by the slow variation of the phase. The effects of the *f-to-2f* interferometer can be studied by filtering out the low frequency components (< 3Hz) and plotting the noise in the time domain. The results are shown in Fig. 3(b). The RMS phase jitter of the fast components was reduced from 79 mrad to 48 mrad. The reduction of the fast phase drift is important for two reasons. First, it may lead to even better CE phase stabilization if the slow phase drift can be reduced by improving the slow feedback loop. Second, the CE phase is always measured by integrating many laser shots (50 in our measurement). The contrast of the fringe is enhanced when the fast noise is reduced, improving the precision of measurements.

Conclusion

In conclusion, the Mach-Zehnder *f-to-2f* interferometer used to stabilize the CE phase of the laser oscillator was found to be a major contributor to the CE phase noise of the pulses generated from the oscillator. By adding a He-Ne laser to the interferometer and stabilizing the interference fringes, the contribution of the interferometer to the CE phase noise was reduced to a negligible level. The stabilization of the Mach-Zehnder *f-to-2f* interferometer also significantly reduced the fast jitter of the CE phase of the amplified pulses. This discovery is useful for further improvement of CE phase stabilization, which is crucial to many ultrafast, intense laser applications.

Acknowledgments