Long-term carrier-envelope phase stability from a grating-based, chirped pulse amplifier

Etienne Gagnon, Isabell Thomann, Ariel Paul, Amy L. Lytle, Sterling Backus, Margaret M. Murnane, Henry C. Kapteyn, and Arvinder S. Sandhu

Department of Physics and JILA, and NSF Engineering Research Center in EUV Science and Technology,
University of Colorado and NIST, Boulder, Colorado 80309-0440

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We demonstrate a carrier-envelope phase (CEP) stabilized, chirped pulse laser amplifier that exhibits greatly improved intrinsic long-term CEP stability compared with that of other amplifiers. This system employs a grating-based stretcher and compressor and a cryogenically cooled laser amplifier. Single-shot carrier envelope phase noise measurements are also presented that avoid underestimation of this parameter caused by fringe averaging and represent a rigorously accurate upper limit on CEP noise. © 2006 Optical Society of America

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Whereas the carrier-envelope phase (CEP) stabilization of femtosecond Ti:sapphire oscillators is now a well-established technology,[1–3] stabilization of laser amplifiers is new, and the technology is still under development. The appeal of high-power stabilized lasers is that they make possible many interesting strong field experiments.[4–6] Two designs have been demonstrated to date: Baltuska *et al.*[7] demonstrated a chirped pulse amplifier system[8] that uses material to stretch the pulse and prisms to compress it, while Kakehata *et al.*[9] showed preliminary work on a grating-based chirped pulse amplifier system. In principle, grating-based amplifier systems can be scaled to much higher output energies than can material- and prism-based systems; therefore it is important to address questions regarding their long-term stability. In previous work[10] in which only a laser oscillator was used, we showed that properly aligned grating-based stretcher–compressor pairs do not destroy CEP coherence.

In this Letter we demonstrate, for the first time to our knowledge, a CEP stabilized amplifier system that exhibits excellent intrinsic long-term coherence, i.e., with coherence time scales of the order of tens of minutes. The shot-to-shot rms phase jitter of pulses from the system is 650 mrad in 0.5 s and appears to be limited primarily by the laser oscillator's stability. The slow drift of the CEP can be tracked over long time intervals (>30 min). These results represent an order-of-magnitude improvement for long-term stability and shot-to-shot fluctuations over those reported previously for grating-based amplifier systems. Moreover, the measurements presented here represent to our knowledge the first true shot-to-shot reported characterization of carrier-envelope offset phase from a chirped pulse amplifier system. Previous measurements of carrier-envelope offset from both grating-[9] and material-based[7] systems presented data averaged over 16–30 shots, averaging out nearly all the actual CEP noise. In contrast, we present single-shot measurements, which yield accurate high-frequency phase noise estimates while also demonstrating a long coherence time. This amplifier design presents no barriers to scaling to much higher output energies. Finally, we note that the excellent long-term intrinsic CEP stability demonstrated here obviates the need for a slow feedback on the amplifier system in many situations while avoiding noise that could be introduced in additional feedback systems.

Methods used for CEP detection were reported previously[11–13] and can be implemented by use of either the time- or the frequency-domain setups. Time-domain phase detection and stabilization, used with high repetition rate oscillators, are achieved by beating together two frequency components of an octave-spanning laser pulse. One component is centered at $2f$, while the other is the second-harmonic signal of the component centered at f. The time delay between the two beams is set to near zero, and the signal is detected by a photodiode. The signal is

$$S(t) = E_f^{\,2}(t) + E_{2f}^{\,2}(t) + 2[E_f^{\,2}(t)E_{2f}^{\,2}(t)]^{1/2}\cos[2\varphi_f(t) - \varphi_{2f}(t) + \varphi_0], \tag{1}$$

where φ_0 is the CEP and the offset frequency, f_0, may then be determined from

$$f_0 = D\varphi_0 f_{\mathrm{rep}}/2\pi, \tag{2}$$

where f_{rep} is the repetition frequency and $\Delta\varphi_0$ is the slip in CEP from shot to shot. If the ratio of f_0 to f_{rep} is locked, the pulse-to-pulse CEP slip is fixed.

In frequency-domain detection, which is appropriate for a lower repetition rate pulse train from a laser amplifier, a spectrometer is used to measure the phase by introducing a time delay between the f and $2f$ beams. The signal is then given by

$$\tilde{S}(\omega) = E_f^{\,2}(\omega) + E_{2f}^{\,2}(\omega) + 2[\tilde{E}_f^{\,2}(\omega)\tilde{E}_{2f}^{\,2}(\omega)]^{1/2}\cos[2\tilde{\varphi}_f(\omega) - \tilde{\varphi}_{2f}(\omega) + \varphi_0]. \tag{3}$$

This signal produces an interference fringe pattern. Shifts in the fringe pattern mirror changes in the CEP.

In our experiment, the front end of the laser system consists of a stabilized, prism-based laser oscillator incorporating a piezoactuator-controlled end mirror (see Fig. 1). The oscillator output has an aver-

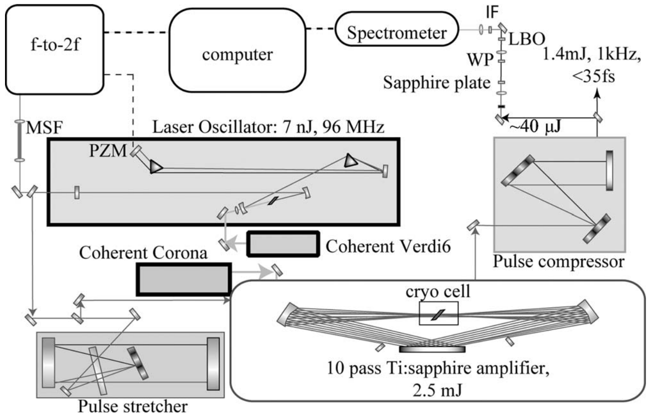

Fig. 1. Schematic of the CEP stabilized laser amplifier system: MSF, microstructured fiber; PZM, piezoactuated mirror; WP, wave plate; IF, interference filter.

age power of approximately 750 mW at 98 MHz. Part of the oscillator beam is used to derive a signal to phase lock the oscillator. When the CEP slip is locked, the out-of-loop rms CEP noise of our oscillator is ~500 mrad for 16 s integration time, under conditions of minimal acoustic noise.

Most of the oscillator energy is used to seed the amplifier system. Timing for the pump lasers and a Pockels cell is derived from the offset frequency, f_0, rather than the repetition rate, f_{rep}, to ensure that a pulse with the same CEP is always injected into the amplifier. A Faraday isolator is also inserted, to prevent optical feedback into the oscillator. The cryogenically cooled amplifier cell is pumped by a diode-pumped YAG laser (Coherent Corona), delivering 14 W of power at 1 kHz, with a power stability better than 1% rms. The output of the amplifier system is 1.4 mJ at a repetition rate of 1 kHz, with a FWHM pulse duration below 35 fs and an rms power stability of 0.8–1.2%.

Part of the amplifier output (4%) is used for phase detection.[13] Frequency-domain detection of the CEP of the high-energy pulse is done by focusing part of the output beam into a 5 mm thick sapphire plate to generate a white-light continuum. A 10 mm lithium triborate (LBO) crystal is then used for doubling the IR component, and the interference signal between the doubled IR and the short wavelength part of the continuum is detected with a high-resolution spectrometer after the wave has passed through an interference filter. The spectrometer's integration time can be varied from 1 ms to 10 s, allowing for single-shot detection at 1 kHz.

For the following measurements, the detected values of rms CEP noise provide an upper limit, since they includes both system and detection noise. Power fluctuations of the amplifier will introduce CEP fluctuations through the self-phase modulation that occurs in the sapphire plate used to broaden the spectrum. Interferometric instabilities will also result in added CEP fluctuations.

Figure 2 (top) shows the interference fringe's visibility in the cases when the oscillator was CEP locked and unlocked versus integration time. Figure 2 (bottom) shows the corresponding rms CEP noise in the case when the oscillator was CEP locked. The fringe visibility for longer integration times was normalized to single-shot visibility. In these measurements, no active feedback from the output of the amplifier was implemented. Fringe visibility in the unlocked case drops rapidly. In the locked case, after an initial decrease of 1 to 5 ms integration time, it remains constant for as long as 500 ms. Thus most of the phase noise arises from frequencies greater than ~200 Hz. The data for 1 s integration time show a modest loss in visibility. However, it should be noted that noise from the detector (power-fluctuation-induced CEP noise plus electronic noise) becomes important at such a long integration time.

Next, the phase was monitored over long periods of time. Figure 3 (top) shows the evolution of the phase-dependent interference fringes measured for more than 30 min. For a single shot, the interfringe distance corresponds to a 2π shift. Each point represents an integration time of 1 ms and was collected at 2 Hz. As was the case for the visibility measurement, the data were collected without active feedback

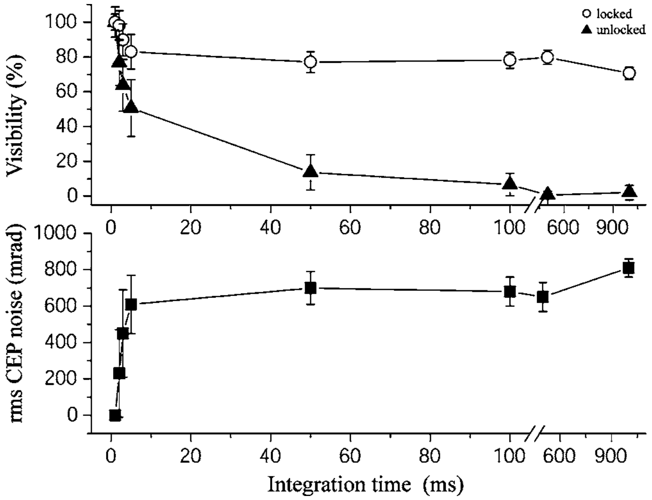

Fig. 2. Top, fringe visibility versus integration time of the detector for locked and unlocked oscillators. Bottom, accumulated rms CEP corresponding to a locked oscillator.

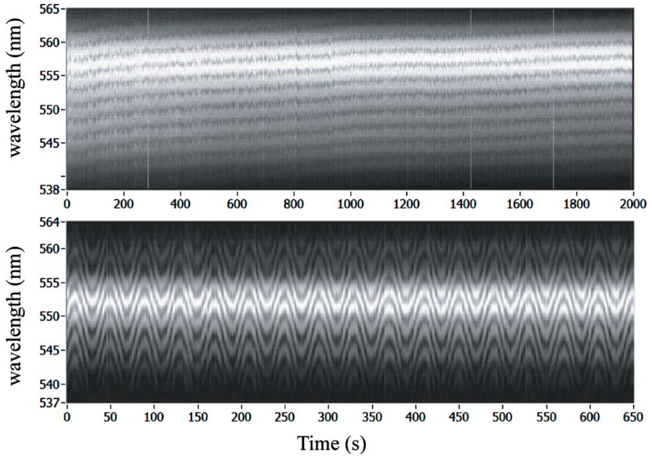

Fig. 3. Evolution of the fringe pattern derived from the output of the amplifier as a function of time, when (top) the oscillator is phase locked and when (bottom) a sinusoidal voltage is applied to the oscillator locking electronics.

on the amplifier output. Figure 3 (bottom) shows the results of using the computer that measures the CEP to supply a sinusoidal voltage signal with a period of ~40 s to the oscillator locking electronics. Such a time-domain modulation of the CEP can be used in conjunction with lock-in analysis techniques, with no further long-term stabilization of the CEP. The absence of active feedback in the amplifier simplifies the design considerably without significantly limiting usefulness. It also ensures that no additional noise from the amplifier CEP retrieval algorithm is introduced into the system.

It was also noted during these experiments that long-term stability of the CEP is correlated to the signal-to-noise ratio of the *f*-to-2*f* beat node used to stabilize the oscillator. As coupling into the microstructured fiber drifted, the amplifier CEP drifted. Active stabilization of this parameter might thus result in an improvement in long-term CEP stability.

We investigated several explanations for the excellent long-term stability of our system compared with previous results. Great care was taken to stabilize the pump laser's power output beyond the manufacturer's specifications, and a rms noise of less than 1% was achieved. However, we believe that the main cause of excellent long-term stability is cryogenic cooling of the Ti:sapphire crystal,[14] which is unique to this system. It is known that cryogenic cooling reduces thermal lensing (by >2 orders of magnitude over room temperature) and allows for higher average power. Calculations were made to compare the CEP slip in sapphire at different temperatures that were due to pump power fluctuations.[15] While the effects were an order of magnitude bigger at room temperature than at cryogenic temperature, they were overall 1–2 orders of magnitude too small to produce a significant change in the CEP. We believe that the more important effect of cryogenic cooling is the reduction of beam pointing fluctuations out of amplifier crystal. As thermal beam pointing drifts can lead to substantial CEP changes in a misaligned compressor, the reduction of this effect could be an explanation for the good long-term stability of our amplifier.

In conclusion, we have presented what is to our knowledge the first demonstration of a CEP stabilized, grating-based amplifier system with excellent intrinsic long-term coherence. The remaining slow drift of the CEP can be easily monitored. We have also reported the first CEP noise measurements for a grating-based chirped-pulse amplification system that includes single-shot measurements as required accurate estimation of this noise. Finally, we demonstrated an ability to control and modulate the CEP of the amplified pulse. The use of a grating-based stretcher and compressor also allows for scaling to much higher output energies.

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