We present the first demonstration of a carrier-envelope phase (CEP) stabilized, chirped pulse laser amplifier system that exhibits intrinsic long term stability. 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, for the first time, to our knowledge. Our results represent a significant improvement over previously demonstrated phase coherence for grating-based, femtosecond laser amplifier systems.

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CEP stabilization of femtosecond Ti:sapphire oscillators is now a well established technology\textsuperscript{1-3}, stabilization of laser amplifiers is new and the technology is still undergoing development. The appeal of high-power stabilized lasers is that they make possible many interesting strong field experiments\textsuperscript{4-6}. Two different designs have been demonstrated to date. Baltuska, et al.\textsuperscript{7} demonstrated a chirped pulse amplifier (CPA) system\textsuperscript{8} that used material to stretch the pulse and prisms to compress it, while Kakehata, et al.\textsuperscript{9} showed preliminary work on a grating-based CPA system. In principle, grating-based amplifier systems can be scaled to much higher output energies compared with material and prism-based systems; therefore questions regarding their long term stability are important to address. In previous work using only a laser oscillator, we demonstrated that use of a grating-based pulse stretcher and compressor does not introduce any strong coupling mechanism between the CEP and beam pointing through the stretcher/compressor.\textsuperscript{10}

In this letter, we demonstrate for the first time a CEP stabilized amplifier system that exhibits excellent intrinsic long term coherence, i.e. with coherence time on 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 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 CEO phase from a CPA system. Previous measurements of CEO from both grating\textsuperscript{8} and material-based\textsuperscript{7} systems presented data averaged over 16-30 shots, averaging out nearly all of 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 have been reported previously\textsuperscript{11-13} and can be implemented using either the time or the frequency domain setups. Time domain phase detection and stabilization, used with high repetition rate oscillators, are obtained by beating together two frequency components of an octave-spanning laser pulse. One component is centered at 2\(f\) 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 -

\begin{equation}
S(t) = E_f^2(t) + E_{2f}^2(t) + 2[E_f^2(t)E_{2f}^2(t)]^{1/2} \cos[2\phi_f(t) - \phi_{2f}(t) + \phi_0].
\end{equation}

where \(\phi_0\) is the CEP and the offset frequency \(f_0\), may then be determined from:

\begin{equation}
f_0 = \frac{\Delta\phi_0 f_{rep}}{2\pi},
\end{equation}

where \(f_{rep}\) is the repetition frequency and \(\Delta\phi_0\) 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 -

\begin{equation}
\tilde{S}(\omega) = \tilde{E}_f^2(\omega) + \tilde{E}_{2f}^2(\omega) + 2[\tilde{E}_f^2(\omega)\tilde{E}_{2f}^2(\omega)]^{1/2} \cos[2\tilde{\phi}_f(\omega) - \tilde{\phi}_{2f}(\omega) + \phi_0].
\end{equation}

This signal produces an interference fringe pattern. Shifts in the fringe pattern mirror changes in the CEP. While the absolute phase cannot be measured using this approach, the phase drift over time can be detected.
In our experiment, the front end of the laser system consists of a stabilized, prism-based, laser oscillator incorporating a piezo-actuator controlled end mirror (see Figure 1). The oscillator output has an average power of approximately 750 mW at 98 MHz. Part of the oscillator beam is used to derive a signal to phase-lock the oscillator, by first coupling through a micro-structured fiber to broaden the spectrum to more than an octave. An f-to-2f interferometer then feeds the CEP noise-dependent signal to the locking electronics. The resulting CEP frequency, \( f_0 \), was \( \frac{3}{8} f_{\text{rep}} \), or 36 MHz. When the CEP slip is locked, the out-of-loop rms CEP noise of our oscillator is \( \sim 500 \) mrad for 16 s integration time, under conditions of minimal acoustic noise (when equipment such as vacuum pumps are turned off).

Most of the oscillator energy is used to seed the amplifier system. Timing for the pump lasers and Pockels cell is derived from the offset frequency, \( f_0 \), rather than the repetition rate, \( f_{\text{rep}} \), to ensure that a pulse with the same CEP is always injected into the amplifier. Mechanical stability was improved by using 1” (or greater) thick pedestal mounts for all reflective optics, and further acoustic isolation was provided by appropriately enclosing and isolating all the components of the amplifier system. A Faraday isolator was also inserted to prevent optical feedback into the oscillator. The cryogenically cooled amplifier cell was pumped by a diode-pumped YAG laser (Coherent Corona), delivering 14 W at 1 kHz, with a power stability better than 1% rms. The output of the amplifier system was 1.4 mJ at a repetition rate of 1 kHz, with a FWHM pulse duration below 35 fs, and an rms power stability of between 0.8 and 1.2%.

Part of the amplifier output (4%) is used for phase detection\(^{13} \) while the rest is used for experiments. Frequency domain detection of the CEP of the high energy pulse was done by focusing part of the output beam into a 5 mm thick sapphire plate to generate a white light continuum. A 10 mm LBO crystal was then used for doubling the IR component, and the
interference signal between the doubled IR and the short wavelength part of the continuum was detected with a high resolution spectrometer after passing through an interference filter. The spectrometer 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. The noise measured is that of the system plus that of the detection method. Power fluctuations of the amplifier will introduce CEP fluctuations through self-phase modulation (SPM) occurring in the sapphire plate used to broaden spectrum. Interferometric instabilities will also result in added CEP fluctuations.

Figure 2 (top) shows the interference fringe visibility in the cases where the oscillator was CEP locked and unlocked versus integration time. Figure 2 (bottom) shows the corresponding rms CEP noise in the case where the oscillator was CEP locked. To analyze the data, the fringe visibility for longer integration times was normalized to the single-shot visibility determined by 1 ms integration time. Care was taken to account for the spectral shape while measuring the fringe visibility. In these measurements, no active feedback from the output of the amplifier was implemented. The fringe visibility in the unlocked case drops rapidly after the oscillator CEP is interrupted. In contrast, when the oscillator phase is locked with respect to the pulse envelope, after an initial decrease in fringe visibility for integration times between 1 ms and 5 ms, the fringe visibility remains constant for up to 500 ms. This implies that most of the contribution to the phase noise arises from frequencies greater than ~200Hz. The data for 1 s integration time shows 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 long integration times.
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 minutes. For a single shot, the inter-fringe distance corresponds to a $2\pi$ 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 was collected without active feedback 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 on 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. We note that single-shot CEP measurements also demonstrate the possibility of using an unstabilized laser to study CEP effects in cases where the data can also be acquired on a shot-to-shot basis. While data in Figs. 3 (top) and 3 (bottom) were collected at 2 Hz, faster acquisition is possible.

It was also noted during these experiments that long term stability of the CEP was correlated to the signal-to-noise ratio of the f-to-2f beat node used to stabilize the oscillator. As coupling into the micro-structured 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 power output beyond the manufacturer’s specifications and an rms noise of less than 1% was achieved. However, we believe the main cause of excellent long term stability is the cryogenic cooling of the Ti: sapphire crystal\textsuperscript{14}, which is unique to this system. It is known that cryogenic cooling\textsuperscript{15}
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 temperature due to pump power fluctuations\textsuperscript{16}. 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 the more important effect of cryogenic cooling is in reduction of beam pointing fluctuations out of amplifier crystal. Since thermal beam pointing drifts can lead to substantial CEP changes in a slightly misaligned compressor, the reduction of this effect could be an explanation for good long term stability of our amplifier.

In conclusion, we have presented 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 or corrected. These results represent an order of magnitude improvement over those reported previously. We also reported the first ever CEP noise measurements and single-shot measurements in a grating-based CPA system, which is necessary for accurate estimation of CEP 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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References


Figure Captions

**Figure 1:** Schematic of CEP stabilized laser amplifier system. **MSF:** micro-structured fiber, **PZM:** piezo-actuated mirror, **WP:** waveplate, **IF:** interference filter.

**Figure 2:** (Top) Plot of fringe visibility versus integration time of the detector for the case of a locked and unlocked oscillator. (Bottom) Accumulated rms CEP corresponding to the case of the locked oscillator.

**Figure 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.
Figure 1
Figure 2
Figure 3