High-Speed Carrier-Envelope Phase Control in a 10 kHz, mJ-Class Amplifier

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Abstract: We present a fast spectrometer enabling the carrier-envelope phase measurement of every single shot emitted by a 10 kHz, mJ-class amplifier. Using a free parameter in the feed-forward stabilization technique, we demonstrate arbitrary phase control and closed-loop integrated phase noise on seed oscillator level (98 mrad, $5 \cdot 10^5$ shots, 50 s).

OCIS codes: (320.7090) Ultrafast lasers; (140.3280) Laser amplifiers.

Within the last years, experiments investigating processes on the ultrafast timescale have shown a trend towards ever shorter driving pulses. In conjunction with new developments in hollow fiber compression, state-of-the-art laser sources are approaching the single-cycle limit at millijoule energy level. This combination of high energy and short duration enables more efficient use of high-order processes with increased temporal resolution when used as a probe. However, it also aggravates the impact of carrier-envelope phase (CEP) fluctuations emerging at any point in the amplification chain from the seed oscillator to the amplifier and subsequent compression.

The CEP stability of oscillators has been notably improved with the advent of the feed-forward technique [1]. The amplifier output, on the other hand, shows only a slight gain in CEP precision when seeded with such an oscillator. The reason for this is the high susceptibility of the macroscopic optical components in the amplifier to all forms of mechanical noise that efficiently couple to variations in dispersion (e.g., in grating stretchers or compressors) or energy (e.g., beam pointing changes influencing pump overlap). The result is increased CEP noise up to the kHz range. Traditional feed-back stabilization in amplifiers is based on phase retrieval of the intrapulse interference spectra from collinear f-to-2f interferometers This evaluation is performed on a PC, making it necessary to transfer the spectral intensity data from the spectrometer, usually via serial connection. In addition to the processing on the computer, this limits the acquisition rate to a small fraction of the amplifier repetition rate, commonly 100–300 Hz. Consequently, any kind of correction is limited to half that value. Actuators employed for such corrections need not be fast, and often rely on moving a macroscopic element in order to change dispersion. Lately, interest in faster actuators has increased as faster means of measuring the CEP have become available [3–5], identifying acousto- and electro-optic modulation of the phase as promising alternatives. However, first attempts at combining fast detection and actuation did not significantly improve the stability available at the level of millijoule pulses [6].

In our experiment, the seed pulses are provided by a feed-forward stabilized Ti:sapphire oscillator (rainbow CEP4, Femtolasers) [2]. A nine-pass amplifier with a bulk stretcher and transmission grating compressor provides 25 fs, 0.8 mJ pulses at 10 kHz repetition rate. The CEP measurement relies on a typical single-shot f-to-2f interferometer. To overcome the most time-consuming steps in the CEP error calculation, the interferogram phase is processed at the spectrometer itself. The device is based on a typical grating spectrometer optical bench, but fitted with dedicated electronics. A fast CMOS detector (512 pixels, $<85\,\mu$s readout time) receives a 30 nm band centered at 520 nm. The phase error is extracted on the fly and is provided as an analog signal. The spectrometer is triggered synchronously with the q-switch of the amplifier pump laser, ensuring single-shot detection and processing [7]. In order to shift the phase at a high bandwidth, we employ a free parameter previously unused in the feed-forward scheme, the acoustic grating phase. The CEP4 system produces a train of pulses with constant CEP by subtracting the comb offset from every line in the comb spectrum. This is accomplished with an acousto-optic frequency shifter (AOFS), the light experiencing a Doppler frequency shift due to the density grating propagating in the acousto-optic crystal. In addition, the acoustic phase is imprinted on the optical phase. As the overall pulse envelope is not affected by an acoustic phase modulation, changing the acoustic phase is equivalent to changing the CEP of the pulse diffracted by the AOFS. The drawbacks of using material dispersion to influence the CEP, aggravated with decreasing pulse duration, can thus be circumvented.

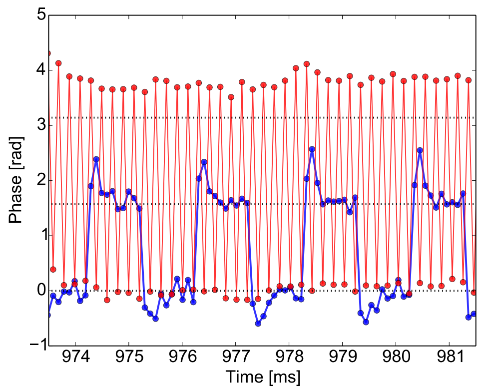

Fig. 1: CEP values acquired at 10 kHz. Red trace and data points: Phase shifter in open-loop configuration. Blue trace: Closed-loop step response. The target CEP is switched by $\pi/2$ every 10 shots.

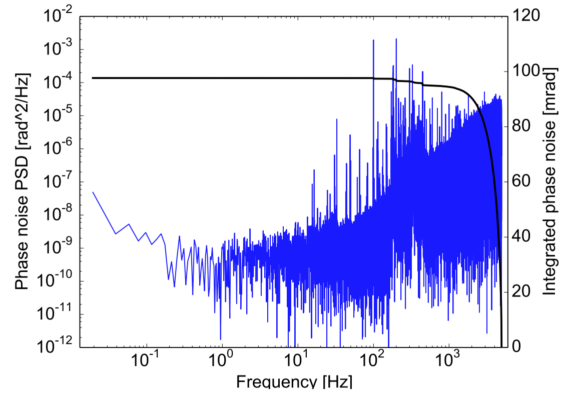

Fig. 2: Fourier transform of the CEP values of $5{\cdot}10^5$ consecutive shots stabilized with the fast feed-back loop. Red trace: Phase noise power spectral density. Black trace: Integrated phase noise.

Practically, the AOFS driving signal phase is controlled by a standard voltage-controlled radio frequency (RF) phase shifter, allowing 360° of electronic phase shift with linear voltage-to-phase response, and MHz modulation bandwidth.

In open-loop operation, a triggered square wave at half the amplifier repetition rate was applied to the RF shifter, its amplitude chosen such as to produce phase jumps of 1.2π. The CEP of every single pulse in the output train was measured using the fast f-to-2f (Fig. 1, red curve and data points). The phase shifter enables an arbitrary CEP change from one pulse to the next, enabling fast lock-in detection. Next, a feed-back loop was closed on this actuator using the CEP signal provided by the fast spectrometer. The analog error signal was processed by a proportional-integral filter stage before being fed back to the RF phase shifter. In a step response test, the target phase was switched by $\frac{\pi}{2}$ every 10 shots. The blue curve in Fig. 1 shows the CEP data acquired during the lock. The loop is fast enough to lock to the new target within 3–4 shots, corresponding to an overall control bandwidth of more than 2.5 kHz. When leaving the CEP target unchanged, the correction loop achieves a precision of 98 mrad rms for a measurement of every single pulse emitted within 50 s ($5{\cdot}10^5$ shots). The Fourier analysis of the dataset is displayed in Fig. 2.

In conclusion, we have shown that it is practically feasible for amplifier CEP stability to approach the limit of the phase accumulated by the seed oscillator between two consecutive amplifier pulses. The result clearly demonstrates the potential of combining a fast, reliable measurement with a matching actuator. Shot-to-shot, dispersion-free control opens up new possibilities to experimenters. A comparison to conventional stabilization is currently under preparation.

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