Direct carrier-envelope phase control of an amplified laser system

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Abstract: Direct carrier-envelope phase stabilization of an Yb:KGW MOPA laser system is demonstrated with a record-breaking residual phase jitter below 100 mrad, opening a new avenue towards high-energy CEP-stabilized parametric sources.

Since its original demonstration over a decade ago, carrier-envelope phase (CEP) control of mode-locked lasers has come out of age, with a recently demonstrated timing jitter between the carrier and the envelope pushed down to sub-10-attosecond range [1]. Despite such impressive progress, CEP control is still limited to a rather narrow class of lasers, including Ti:sapphire and some other selected broadband solid-state materials as well as some mode-locked fiber lasers. Moreover, CEP control becomes increasingly complex for amplified laser sources with energies in the millijoule range [2]. Typically, stabilization of a CPA laser source relies on an intricate combination of two servo loops, a fast oscillator loop and a slow amplifier loop [3]. While the second loop is necessary to remove residual phase drift in the amplifier, unfortunately, it also corrupts the residual phase noise in the amplified pulse train due to the limited feedback bandwidth as a consequence of a low repetition rate of the amplifier and a slow readout of a nonlinear phase meter [4]. While oscillators can nowadays be stabilized down to ≈10 mrad residual CEP jitter, a 100 mrad stability for an amplified laser source is already a challenge, with a tendency of significantly higher jitters above 1 mJ pulse energy. Here we demonstrate a direct method to stabilize the CEP of an Yb:KGW MOPA laser system, resulting in sub-100 mrad stability. To the best of our knowledge, this value surpasses most previously measured CEP jitter for Ti:sapphire CPA systems as well as any previous attempt to stabilize Yb-based oscillator and amplifier systems [5].

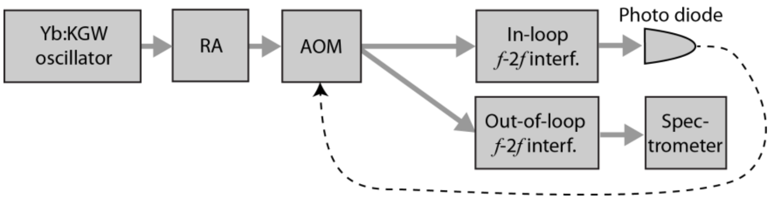

Figure 1. A general scheme of the frequency synthesis for the stabilization of a sub-MHz frequency comb from a regenerative amplifier (RA).

Analyzing the problems of the CEP control in amplified lasers, the measurement of CEP after amplification appears to be a major bottleneck. Typically, a spectral-interferometry based scheme is employed for the purpose, which virtually always requires averaging over at least ten subsequent laser shots to avoid severe degradation from detection shot noise and suffers from low bandwidth. Any attempt to improve on the stability of the stabilized oscillator of the CPA system appears futile, as the phase detectivity in the amplifier scheme is intrinsically inferior to the phase detectvity in the oscillator heterodyne scheme. Therefore, an opportunity to extend an oscillator-type stabilization scheme behind the amplifier would result in a significant improvement. Our detection scheme consists of an in-line interferometer as used frequently in amplifier stabilization, yet replaces the spectrally resolved detection scheme by a simple photo-diode, as is customary in oscillator stabilization. The resulting beat note in the frequency range between 0 and 100 kHz is filtered out and up-converted to the carrier frequency for an acousto-optic modulator (300 MHz).

In our experiments, we employed a commercial Yb:KGW regenerative CPA system (Light Conversion Ltd.) seeded by a solid-state Yb:KGW Kerr-lens mode-locked oscillator [6]. The repetition rate of the amplifier is freely tunable up to 1 MHz. An in-line f-2f interferometer based on white-light generation in a bulk sapphire is used for beat-note detection and out-of-loop CEP stability verification. This signal is then used to drive an acousto-optic modulator, which corrects the measured CEP in the amplified pulse train using the technique introduced in [7]. The resulting performance is depicted in Fig. 2. Using out-of-loop characterization we measure a residual phase noise of 87 mrad, see Fig. 2(a). The inset of Fig. 2(a) shows a spectral interference pattern to further illustrate the vanishing phase jitter of our scheme. Figure 2(b) shows a noise spectrum induced by the amplifier in the terms standard for characterization of oscillator stability. The amplifier noise spectrum was measured by stabilizing only the oscillator using the feed-back scheme and then measuring the noise spectrum after the amplifier. The spectrum exhibits discrete distortions at the repetition rate of 1 kHz and its overtones, which evidently do not contribute much to the integrated phase noise, but will nevertheless require some further investigation. The significant part of the amplifier phase noise power spectrum extends beyond 50 kHz and corresponds to an ≈200 mrad integrated phase jitter. This measurement shows the necessity of the wide bandwidth phase control for the efficient suppression of the phase noise induced by the CPA laser system.

In summary, we demonstrated an unprecedented CEP jitter from an amplified Yb:KGW system. To the best of our knowledge, this is the first stabilized fs amplifier to reach a meaningful phase jitter value in an out-of-loop CEP measurement. This is a crucial step in widening the utility of amplifier femtosecond Yb sources, which are easily scalable in average power and pulse energy but until now could not be meaningfully employed in attosecond optics due to the difficulties with their CEP control.

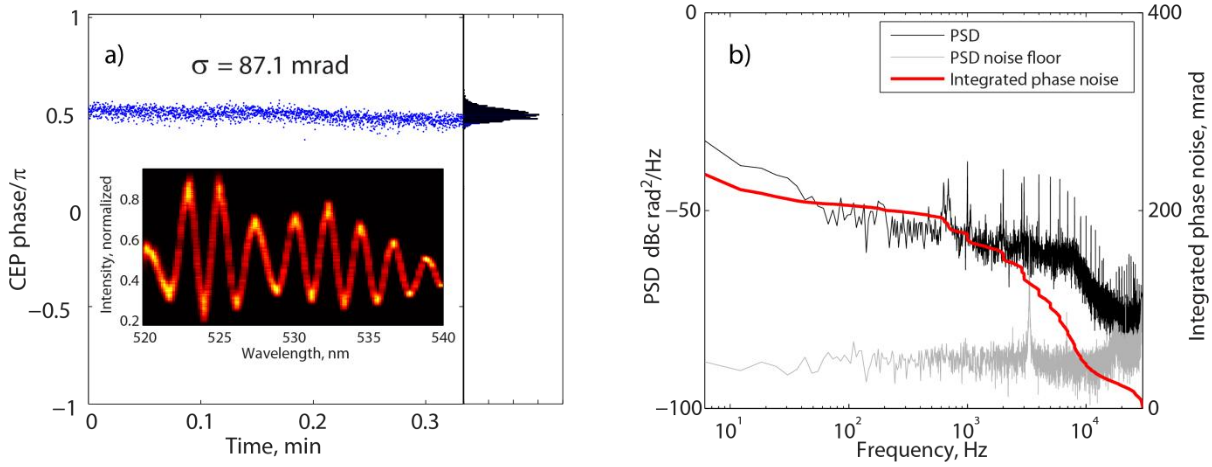

Figure 2. a) Out-of-loop CEP jitter measurement after the amplifier, inset: *f-2f* interferogram fringes. The spectrometer integration time was kept minimum and averaging is done over 6 laser pulses. b) measured amplifier phase noise spectrum when the oscillator CEP was locked with a feed-back loop.

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