Carrier-Envelope Phase Stabilization of a 10 Hz, 20 TW Laser for High-Flux Attosecond Pulse Generation

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Abstract: We developed a method to stabilize the carrier-envelope phase of a 20 TW Ti:Sapphire laser operating at 10 Hz. Phase-dependent features were observed in the high-order harmonic spectrum generated using Generalized Double Optical Gating.

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1. Introduction

Isolated attosecond pulses with high photon flux are required to perform attosecond pump – attosecond probe experiments. In order to scale up the isolated attosecond pulse energy, we have developed a Ti:Sapphire laser system optimized to provide both high-energy (350 mJ) and short-duration (13.9 fs) pulses for implementing Generalized Double Optical Gating (GDOG) [2]. For this system, direct carrier-envelope phase (CEP) locking is not feasible since the system is operating at a repetition rate of 10 Hz, which is too slow for the sampling and active feedback. Without CEP stabilization, the GDOG technique ensures isolated attosecond pulses can be generated by every shot of the driving laser, but the CEP fluctuations alter the energy of each pulse. This variability is unacceptable when initiating nonlinear XUV dynamics or dressing states in an attosecond pump - attosecond probe scheme.

2. Experiments and discussions

In an effort to make this high-energy laser system more suitable for high-field experiments and attosecond pulse production, we propose a method capable of locking the CEP for high-energy, low repetition-rate chirped-pulse amplification (CPA) systems. The basic principle of this method is to have a CEP sampling beam bypass the low repetition rate amplifier stage (Fig. 1), thus maintaining the high repetition rate for CEP stabilization. Since the high-repetition and low-repetition beams share the same pulse stretcher and compressor, the CEP errors caused by mechanical changes in the grating stretcher and compressor are encoded in both beams. Thus by locking the CEP of the high-repetition sampling beam, the CEP of the low-repetition amplified beam will also be stabilized.

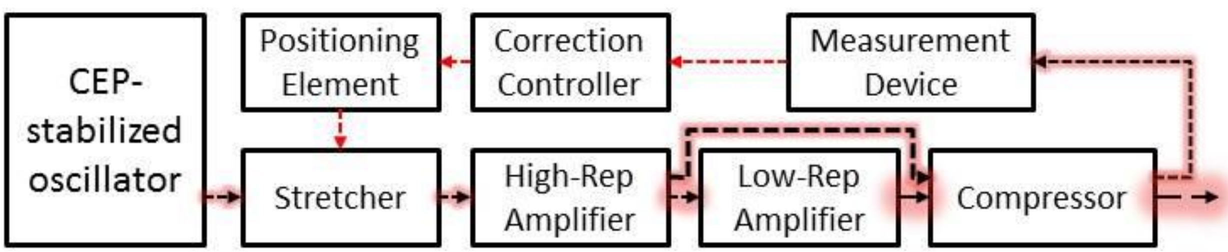

Fig. 1 Block diagram of the CEP locking scheme. The output pulses from a CEP-stabilized oscillator are stretched in time and then amplified at a high repetition rate common to CEP-stabilizing systems (i.e. 1 kHz). While a portion of the beam is further amplified at a low repetition rate atypical of CEP-locked lasers (i.e. 10 Hz), a small sampling beam bypasses the low repetition amplifier stage in order to maintain a repetition rate fast enough for CEP stabilization.

The effectiveness of this technique was demonstrated on our 20 TW, sub-14 fs double CPA system, in which output pulses from the 1 kHz front-end CPA seed the 10 Hz back-end CPA after spectral broadening in a hollow-core fiber [1]. In this case, the sampling of the 1 kHz beam occurs after the front-end compressor and before the hollow-core fiber. Therefore, this high-repetition sampling beam must pass through the back-end stretcher in addition to the compressor in order to carry the same phase error information as the 10 Hz beam. Bulk glass was inserted in the sampling beam line in order to match the amount of dispersion accrued by the 10 Hz beam in the amplification stages, thus allowing both pulses to be compressed by the same grating configuration. The sampling beam is directed to an f-to-2f interferometer, and the retrieved phase is used to stabilize the CEP using feedback to a grating shaker [2] in the front-end stretcher.

To validate the CE phase stabilization of the 10 Hz laser system, the dependence of the high-order harmonic spectrum generated in argon was measured with a flat-field soft x-ray spectrometer and a charge-coupled device detector. The high-power laser beam was loosely focused through GDOG optics with a 6.5 m-focal length mirror into a 100 mm-long gas cell, where argon is held at 4 Torr. When the CE phase was scanned linearly from 0 to 6π, the harmonic spectra varied with a 2π periodicity as shown in Fig. 2, which is consistent with the 2π periodicity of the electric field generated by GDOG.

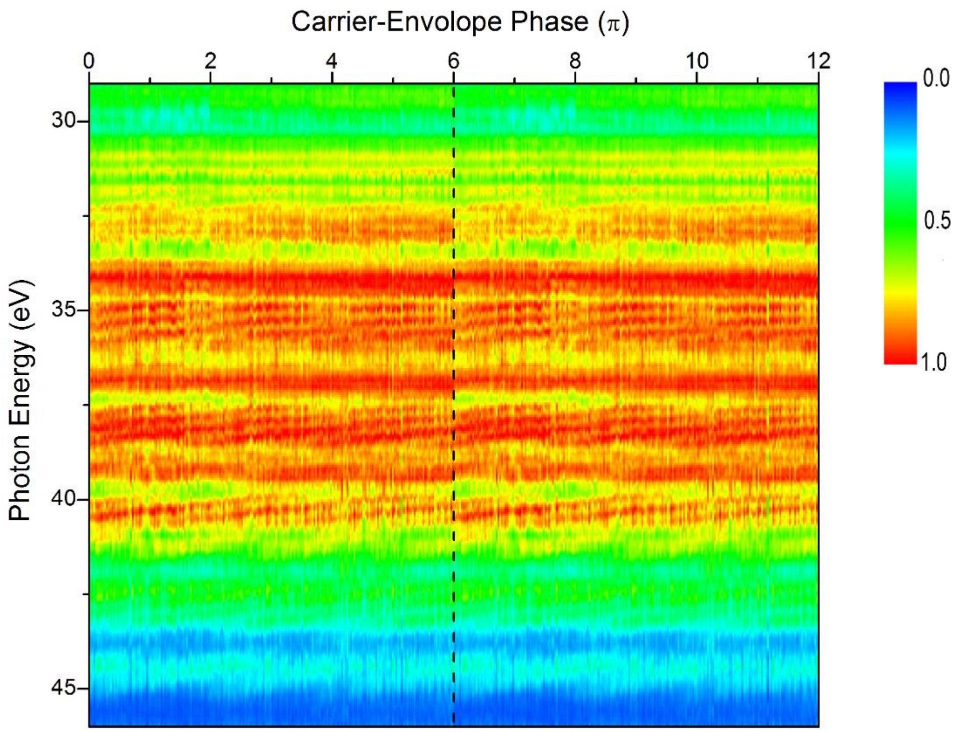

Fig. 2 The dependence of the XUV generation on the carrier-envelope phase of the driving laser. The 2π periodicity is consistent with the asymmetric electric field of GDOG. The plot is repeated once after 6π to show up the effect.

3. Conclusions

In conclusion, we have demonstrated a method for locking the CEP of a low-repetition high-power laser system. To the best of our knowledge, this 10 Hz, 20 TW CPA laser system currently represents the CEP-locked laser with the highest peak power in the world. This material is supported by the U. S. Army Research Office, the National Science Foundation and the DARPA PULSE program by a grant from AMRDEC.

[1] Y. Wu, E. Cunningham, H. Zang, J. Li, M. Chini, X. Wang, Y. Wang, K. Zhao, and Z. Chang, "Generation of high-flux attosecond extreme ultraviolet continuum with a 10 TW laser," Appl. Phys. Lett. **102**, 201104 (2013).

[2] C. Li, E. Moon, and Z. Chang, "Carrier-envelope phase shift caused by variation of grating separation," Opt. Lett. **31**, 3113 (2006).