Few-cycle carrier envelope phase-dependent stereo detection of electrons

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The spatial distribution of electrons emitted from atoms by few-cycle optical fields is known to be dependent on the carrier envelope phase, i.e., the phase of the field with respect to the pulse envelope. With respect to Paulus *et al.*[Phys. Rev. Lett. **91**, 253004 (2003)] we propose a greatly simplified device to measure and control the carrier envelope phase of few-cycle pulses with an accuracy of better than $\pi/10$ based on this principle. We compared different schemes to control the carrier envelope phase of our pulses. © 2006 Optical Society of America

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In recent years, powerful few-cycle pulses have become available for experiments. Because the temporal variation of the envelope is of almost the same order as the electric field, strong effects of the relative phase between the envelope and the carrier wave (CE-phase) are expected. In Ref. 1 the effect of the CE-phase on the spatiotemporal distribution of electrons from photoionization was demonstrated using correlation techniques with a non-phase-stable laser.

In other experiments in which the CE-phase of the laser system was stabilized, the effects of the CE-phase on high-order harmonic generation[2] were demonstrated, the CE-phase dependence of the spatiotemporal distribution of electrons in above-threshold ionization[3] was measured, and this method was also applied to measure the Gouy phase shift through the focus of a few-cycle laser beam.[4] Photoemission from a metal surface was demonstrated to be dependent on the CE-phase,[5] and control of quantum interference of injected photocurrents in semiconductors via the CE-phase[6] was demonstrated. The momentum distribution of the doubly charged ions in nonsequential double ionization in argon was demonstrated to show dependence on the CE-phase,[7] and the CE-phase dependence of terahertz radiation from a plasma[8] was measured. Also CE-phase dependence of electron localization in the dissociation of D_2^+ was demonstrated.[9] In other studies with non-phase-stable laser sources, the spatial distribution of electrons was shown to be CE-phase-sensitive,[10] while the total ionization yield demonstrated negligible dependence on the CE-phase.[11]

All the aforementioned methods may be used to measure the CE-phase of a few-cycle pulse, but most are not practical for controlling the CE-phase in an active feedback loop, either because the method requires too much of the total energy or because the time needed for the phase determination would be too long. The demonstration of the CE-phase dependence of high-order harmonic generation in Ref. 3 was also a precursor for experiments involving single attosecond soft-x-ray pulses, enabling measurements with timing resolution on time scales shorter than the optical cycle[12] and directly measuring the electric field of the optical pulse itself.[13] Experiments of this kind require exact reproduction of the optical waveform over very long periods of time, and the feasibility of those experiments is mostly limited by the time over which it is possible to phase stabilize the laser. To overcome the shortcomings of the conventional technique for phase stabilizing powerful few-cycle laser sources, slow active feedback based on the one in Ref. 3 has been demonstrated.[14] We demonstrate a greatly simplified technique based on Ref. 10 that is capable of replacing the conventional technique.

For our experiment we used a modified 3 kHz Femtolasers Ti:sapphire amplifier system, shown schematically in Fig. 1(a). Our amplifier was seeded with an ultrabroadband CE-phase-stabilized oscillator.[15]

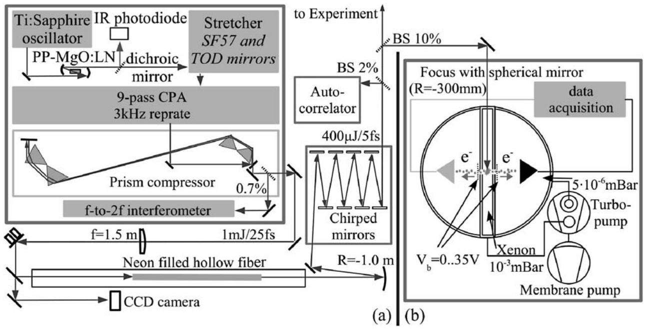

Fig. 1. (a) Schematic of the laser system delivering 400 μJ, 5 fs pulses TOD, third-order dispersion; CPA, chirped pulse amplifier; BS, beam splitter. The pulse duration is monitored with a second-order interferometric autocorrelator. (b) Schematic of the stereo phase detector.

The pulse picker in the amplifier is triggered such that only pulses with the same CE-phase are amplified. At the output, where the pulses are compressed to ~25 fs, an *f*-to-2*f* phase detector is implemented.[3] In our experiment we used this phase detector both for measuring the CE-phase drift and for active feedback. The response time of this device is approximately 30 ms. The 25 fs, 800 μJ pulses from the amplifier were focused into a neon-filled hollow fiber for spectral broadening and compressed to 5 fs using chirped mirrors.

The stereo electron detection system operates with about 30 μJ pulses, corresponding to less than 10% of the available laser pulse energy. This makes the device suitable for monitoring and/or controlling the CE-phase during experiments. With a variable-aperture iris the focal intensity inside the apparatus can be controlled. The phase detector itself [Fig. 1(b)] consists of two compartments, an inner interaction chamber and a surrounding detection chamber. The arrangement fits into a standard CF63 cube, which shrinks the device to about 10% of the size of the apparatus used in Ref. 3. Only one small turbomolecular pump and a membrane pump are necessary for the vacuum system.

The detection and interaction chamber are differentially pumped using the sealing gas connection (or Hohlweck port) of the turbo pump (Pfeiffer TMU 071 P) for the relatively high-pressure (10^{-3} Torr) interaction chamber, while maintaining a pressure of 4×10^{-6} Torr in the detection chamber with the turbo pump, which is necessary to safely operate the microchannel plates. Horizontally polarized pulses are focused by a spherical mirror of 15 cm focal length into the interaction region. At 2 mm to the left and right of the focus, 0.5 mm holes allow electrons resulting from strong field ionization to leave the interaction chamber and to enter the detector chamber. An adjustable blocking potential (0–35 V) can be applied within these holes to select only the higher-energy rescattered electrons, which show a stronger phase dependence compared with low-energy electrons.[3] In our experiment a blocking potential of –25 V was applied to detect only electrons with a kinetic energy of >25 eV. At 2 cm from each exit hole a commercial dual microchannel plate detector (Hamamatsu F4655) is placed so that it faces the other one. These detectors are operated in reversed bias mode with a weak bias to allow for electron detection in linear response mode so that the signal strength measured is kept roughly proportional to the number of electrons hitting the detector.

The voltage divider and the coupling capacitors for these detectors are placed inside the vacuum on printed circuit boards, electrostatically well shielded from the electron drift region (detailed technical information is available from ML). The signals from the microchannel plates are measured shot by shot with an 8 channel sample and a hold card (Becker&Hickl SHM180) that is connected to a computer and evaluated online.

Milošević *et al.*[16] presented a thorough theoretical treatment of the CE-phase dependence of above-threshold ionization with few-cycle optical pulses. Previous measurements concentrated on measuring the spatiospectral distribution of the emitted electrons.[3] However, the data from that experiment and the theoretical treatment in Ref. 17 show that the asymmetry in the number of electrons emitted as a function of CE-phase can be described with a sin function. The spectral information is necessary to unambiguously derive the CE-phase from a single measurement, though a series of measurements with a known phase shift lifts the ambiguity when only the number of electrons is measured.[10] No asymmetry is expected for pulses with a CE-phase $\phi_0 \approx -0.3\pi$. Maximal asymmetry is expected for pulses with a CE-phase of $\phi_M \approx 0.2\pi$. For our measurement, the CE-phase $\phi = \arcsin[A(N_1 - N_r)/(N_1 + N_r)] + \phi_0$, where N_1 is the number of electrons flying to the left, N_r is the number of electrons flying to the right, and A is a correction factor that is to be chosen such that the argument of the arcsin function is 1 or −1 at the maximal asymmetry. From Ref. 17, it can be clearly seen that A strongly depends on the pulse duration and the pulse intensity. The asymmetry gets stronger for shorter pulses and weaker for more intense pulses. However, weaker pulses do not guarantee a better measurement, since the total number of measured electrons gets smaller as well, decreasing the quality of the measurement. The intensity stability of the laser system (better than 5% RMS) is such that constant value of A can be assumed during the experiment.

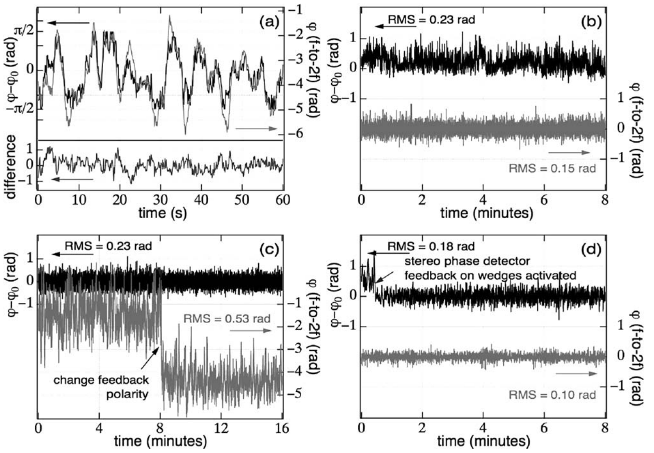

Fig. 2. Evolution of the CE-phase measured with the stereo phase detector (black) and the *f*-to-2*f* interferometer (gray). (a) Only the seed oscillator phase stabilized. (b) Active feedback with *f*-to-2*f* interferometer. (c) Active feedback with our stereo phase detector. (d) Active feedback with both *f*-to-2*f* and the stereo phase detector.

In Fig. 2(a) we show a measurement of CE-phase evolution with both the *f*-to-2*f* interferometer and our stereo phase detector, with only the seed oscillator phase stabilized. The stereo phase detector accumulated data over 300 laser pulses for every datapoint. From the detector peak current we estimate that about 100 electrons with kinetic energy >25 eV reached the detector per laser shot. For comparison, Schätzel *et al.*[14] integrated over 10^4 laser pulses for their measurement. It can be clearly seen that our phase detector restricts the phase measurement between ±$\pi/2$. At most times both methods are in agreement with each other; only at a few occasions is there a disagreement, which is probably due to short-term instabilities of the laser system. Intensity fluctuations and beam-pointing instabilities can cause measurement errors in the f-to-$2f$ device and/or phase shifts arising in between the amplifier output and our stereo phase detector.

In Figs. 2(b)–2(d) we show measurements of the CE-phase evolution in which an active feedback loop gives a slow feedback signal stabilizing the CE-phase of the amplifier system. In Fig. 2(b) the f-to-$2f$ interferometer is used for active feedback. In Fig. 2(c) active feedback is provided by our stereo phase detector. In Fig. 2(d) the phase drifts in the amplifier are compensated for with the f-to-$2f$ interferometer, and our phase detector is used to provide additional feedback to a pair of wedges right after the hollow fiber. The RMS of the phase measurement with our phase detector in this last case is 0.18 rad (after the feedback was switched on and 0.27 rad before the feedback was switched on); in the other two cases it is 0.23 rad. This is to be expected, since the two feedback loops operate independently. The few occasions in Fig. 2(a) where the phase measurements with the f-to-$2f$ interferometer and the stereo phase detector disagree suggest that the small phase excursions seen in Fig. 2(b) are independent of the quality of the phase lock with the f-to-$2f$ interferometer. These small phase excursions are compensated for in Fig. 2(d), yielding a smaller RMS value, although measured in-loop. The feedback with the stereo phase detector also comepensates for a slow phase drift,[14] which is possibly not detected with the f-to-$2f$ interferometer. The ability of the phase detector to exactly reproduce the CE-phase is verified in Fig. 2(c), where after 8 min we inverted the error signal to shift the CE-phase by π. Since the error signal is proportional to the measured phase, inversion of the error signal causes the feedback to run away from the point where it locked and to relock at the next zero crossing of the asymmetry function (of the CE-phase), which implies a π phase shift. This is indeed visible in the measured phase with the f-to-$2f$ interferometer as a π shift.

Summarizing, we have developed a very compact device with which we can measure and control the phase of few-cycle pulses with an accuracy much better than $\pi/10$.

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