Controlling the motion of strong-field, few-cycle photoemitted electrons in the near-field of a sharp metal tip

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Abstract: The real-time probing of electron motion in solid nanostructures or the visualization of nanoplasmonic field dynamics may come into reach using electron pulses generated by strong-field tunneling from sharp gold tips irradiated by few-cycle laser pulses. The acceleration of the ultrashort electron wavepackets in the near field of the sharp gold tips introduces new possibilities of steering and control of electron wavepackets by light, which is expected to pave the way towards such ultrafast probing. Here we discuss the motion of these highly accelerated electrons in the near-field and demonstrate how the carrier-envelope phase admits a new control mechanism for their motion.

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1. Introduction

Sharp nanometer-sized metallic tips recently emerged as a test bed for exploring strong-field phenomena such as high-harmonic generation and photoemission [1-5]. When they are illuminated with few-cycle laser pulses of sufficient field strength, optical field enhancement at the tip apex results in tunnelling of electrons out of the tip. The subsequent acceleration of these electrons within the local near-field gradient can be so strong that the typical quiver motion of the electrons in an oscillating laser field is fully suppressed, resulting in sub-cycle electrons, traversing the near field within less than one half-cycle of the laser field [3,4,5].

Under these conditions, we enter a whole new regime of electron emission, which is characterized by the motion of the electrons in the oscillating, fast decaying near-field with a decay length of only a few nm. We discuss this new regime and in particular emerging novel control mechanisms on the electron motion. We follow the electron motion numerically using a modified Simpleman model. Experimentally, we observe a spatial steering of the fastest electrons along the field lines and we show how the CEP of few-cycle pulses affects their acceleration. We expect that our results will pave the way to the steering and controlling of electron motion around metallic nanoparticles on nanometer-length and sub-femtosecond-time scales.

2. Experimental setup

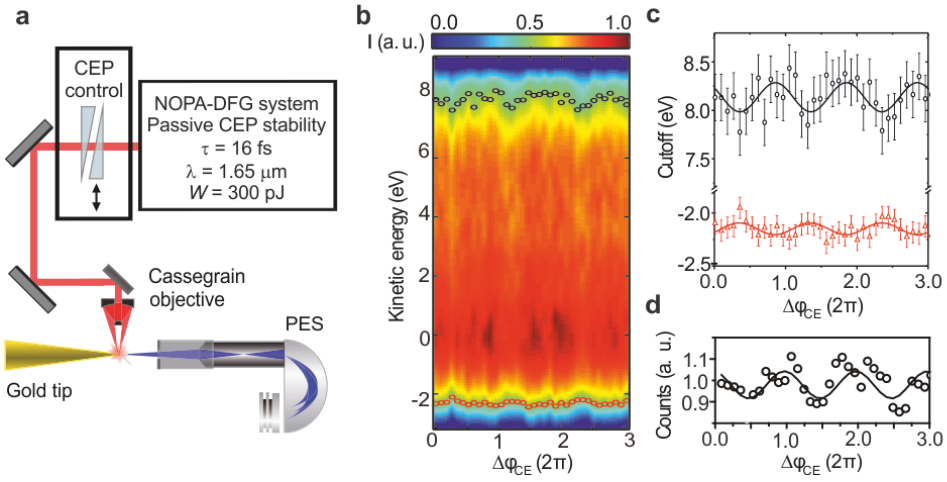

Fig. 1 a, Experimental setup. **b,** Electron kinetic energy spectra when the CEP is varied via the fused silica wedges. **c,** High- and low energy cutoffs and **d,** total electron yield extracted from (a), showing a clear modulation with the CEP.

We study photoemission from sharply etched, single-crystalline gold tips, which have an apex radius of down to 5 nm. Due to the small radius of curvature, the tips show a large field enhancement factor of ~9 and a short decay length of the local near field of ~2 nm [4,5]. The gold tips are irradiated with 16-fs pulses (corresponding to 2.6 optical cycles) at a wavelength of 1.65 μm from a noncollinear optical parametric amplifier (NOPA) system followed by difference frequency generation (Fig. 1a). The combination of frequency conversion stages [6] ensures that the pulses have a highly stable CEP. Residual phase fluctuations were measured in a conventional *f*-to-2*f* interferometer to be as low as ~50 mrad over a time span of 20 min. The CEP is controlled via a pair of fused silica wedges, and the energy spectra of the emitted and accelerated electrons are measured as a function of CEP using a photo-electron spectrometer (PES).

Our experimental observations are corroborated by simulations of the energy spectra performed within a modified three-dimensional Simpleman model, taking into account the repulsion between electrons [5]. We take an analytical model for the optical near-field distribution around the apex. The local generation yield is deduced from a Fowler-Nordheim equation and the ejected electrons are accelerated as classical particles within the temporally oscillating and spatially varying near field. Electron kinetic energy spectra are generated by calculating the terminal kinetic energies of the electrons.

3. Results

Under these experimental conditions, we enter the sub-cycle regime, where electron emission predominantly takes place by strong-field tunneling, and where the electrons subsequently experience a strong acceleration allowing electrons to traverse the near-field within one optical half-cycle. The characteristic signature of sub-cycle electrons is the emergence of a high-kinetic-energy plateau in the measured kinetic energy spectra.

Kinetic energy spectra recorded while varying the CEP (Fig. 1b) show a clear modulation of the high- and low-energy cutoff. We see a high-energy cutoff variation by more than 1 eV, while the low-energy cutoff variation is less pronounced and amounts to 0.3 eV. Plotting both quantities together as a function of the CEP (as red and black circles in Fig. 1c), clearly inversely phased oscillations can be seen and thus a periodic broadening and narrowing of the spectrum. The same periodicity is found in the total electron yield (Fig. 1d).

From numerical simulation of the electron trajectories in the oscillating near-field we find that the acceleration of optical field-emitted electrons in the spatial near-field gradient is of key importance, and that this acceleration is governed by the CEP and the electron birth time with respect to the negative amplitude maximum of the driving laser field. The energetic width of the spectra is determined by the acceleration the sub-cycle electrons gain during the negative half-cycle of their generation. Their terminal kinetic energy depends on the field maximum of the respective half-cycle, and hence strongly on the CEP.

4. Conclusion

Taken together, our results present the first demonstration of CEP effects on the optical field emission of electrons from a single metallic nanostructure. The CEP controls the local amplitude of the near field during the generation cycle and therefore the electron acceleration within the near field gradient on a sub-cycle time scale. Previously we have shown that the fastest electrons are also spatially steered to follow the electric field lines, which was observed as a distinct narrowing of the emission angle [4]. This steering effect in principle allows influencing the electron trajectories via the nanostructure. Together, the spatial steering via the nanostructure and temporal steering via the laser pulse electric field constitute new control mechanisms on the spatial-temporal motion of electrons. We believe that such field-driven control of the electron motion in the near field of solid state nanostructures can be seen as a new form of quantum electronics, paving the way towards the generation, measurement, and application of attosecond electron pulses.

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