Attosecond Electron Microscopy

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Electrodynamics on ultrasmall and ultrafast ranges of space and time determine the macroscopic functionalities of a material. Understanding and controlling electronic motion on sub-cycle and sub-wavelength dimensions, that is, attoseconds and nanometers, is therefore essential for modern optics and nanophotonics, but advances crucially rely on our ability to see and measure the electromagnetic part of material responses as a function of space and time.

Here we report the advance of transmission electron microscopy to attosecond time resolution for visualizing optical field oscillations in space and time [1]. Figure 1a depicts the experiment. A continuous-wave laser (red) with a wavelength of 1064 nm is used to periodically accelerate and decelerate the electron beam (blue) in a transmission electron microscope into a train of high-contrast attosecond pulses [2,3]. The specimen (black), for example a nanophotonic resonator, is excited by the same continuous-wave laser. Since the probing electron pulses are phase-locked to the laser [2] and shorter than half a cycle of the exciting laser wave [3], the local electromagnetic fields in and around the specimen appear approximately frozen in time and can be imaged in a post-column energy-filter. Scanning the time delay Δt allows to obtain a spatio-temporal movie of the specimen's near-field response in real space and real time on attosecond and nanometer dimensions.

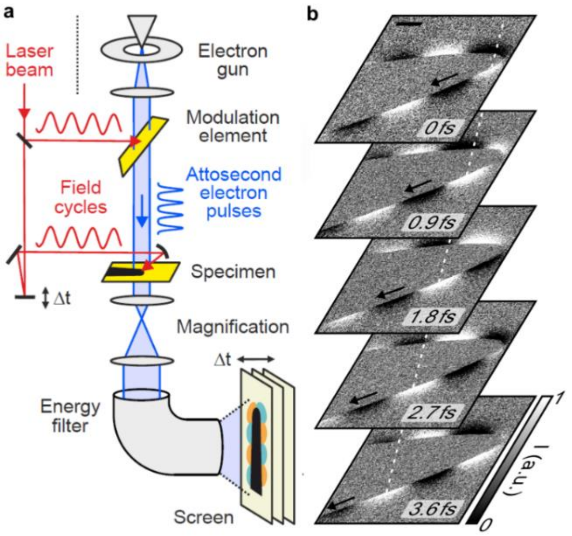

Fig. 1. Attosecond field-cycle-contrast electron microscopy. ***a,*** *Concept and experiment.* ***b,*** *Measured energy-filtered images for varying times within one optical cycle of the exciting laser wave. Regions of energy gain (white) and energy loss (black) are resolved with nanometer and attosecond precision. Scale bar, 500 nm.*

Figure 1b depicts some first results. The specimen is a tungsten needle with a tip radius of ~150 nm. The energy-filtered images reveal at the surface a set of local regions with energy gain (white) and energy loss (black) as a function of time on attosecond dimensions. These maxima and minima correspond to the structure's time-frozen electric near-fields in longitudinal direction. When time goes on (upper to lower panels), we see that the optical cycles of the surface wave (black arrows) travel from the tip towards the shaft in space and time (white dotted line). The polarity of the optical cycles is opposite on top and bottom, because the tip acts effectively as a dipole source.

We conclude that our electron microscopy can resolve the dynamics of optical field cycles in real space and real time on attosecond and nanometer dimensions. The approach is non-invasive; no additional scattering or sensing object has to be put close to the specimen. The ability to directly measure the electromagnetic functionality of natural or artificial materials should be valuable for advancing modern optics and nanophotonics towards novel application regimes.

References:

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[3] M. V. Tsarev, A. Ryabov, P. Baum. *Phys. Rev. Research* **3**, 043033 (2021).