Direct visualization of electromagnetic wave dynamics by laser-free ultrafast electron microscopy

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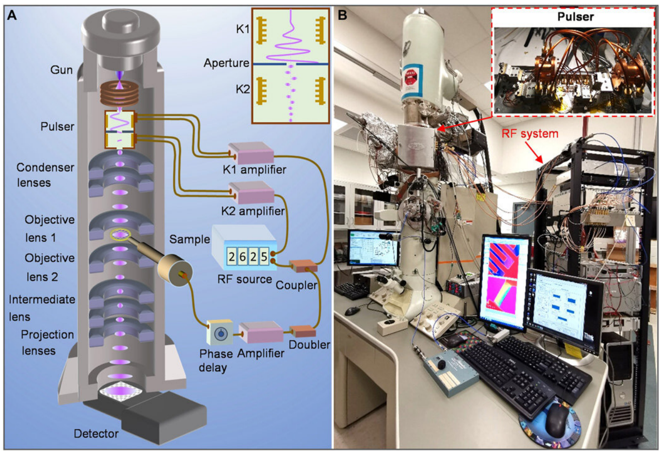
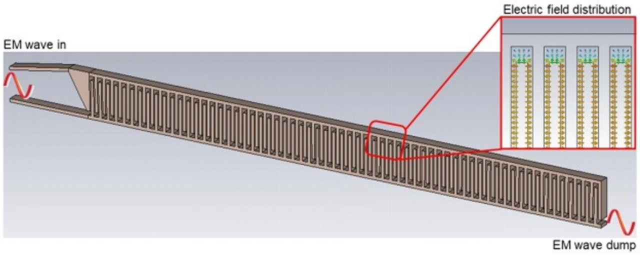


Laser-free UEM system. (A) Schematic of the conceptual design of the laser-free UEM. The TEM with the integration of an RF-driven pulser system and a frequency-doubled, delay-controlled RF circuit for the sample excitation is shown. The pulser is inserted between the electron gun and the standard column lens. The inset shows a schematic design of the pulser, which consists of two traveling wave metallic comb stripline elements: the modulator K1 and the demodulator K2, with a chopping aperture between them. The modulator K1 sweeps the continuous electron beam across the chopping aperture to create two electron pulses in each RF cycle, while the demodulator K2 compensates the K1-induced transverse momentum on the pulses to further rectify the shape of the chopped beam. (B) Photograph of our homebuilt laser-free UEM system based on a JEOL JEM-2100F Lorentz TEM. The TEM with the RF-driven pulser inserted between the electron gun and the standard column lens and the connected RF source are shown. The inset shows a picture of the modulator K1, the demodulator K2, and the chopping aperture inside the pulser. Photo credit: Xuewen Fu, School of Physics at Nankai University. Credit: Science Advances, doi: 10.1126/sciadv.abc3456

Femtosecond lasers can be integrated with electron microscopes to directly image transient structures and morphologies in materials in real time and space. In a new report, Xuewen Fu and a team of scientists in condensed matter physics, microsystems, nanotechnology and materials science in China and the U.S. developed a laser-free ultrafast electron microscope (UEM) offering similar potential but without the requisite femtosecond lasers or elaborate instrumental modifications. The team created picosecond electron pulses to probe dynamic events by chopping a continuous beam with a radiofrequency (RF)-driven pulser with a pulse repetition rate tunable from 100 MHz to 12 GHz. They studied gigahertz electromagnetic wave propagation dynamics as an application for the first time in this work and revealed the transient oscillating electromagnetic field on nanometer space and picosecond time scales with time-resolved polarization, amplitude and local field enhancement. The study showed the use of laser-free, ultrafast electron microscopy (UEM) in real-space visualization for multidisciplinary research—specifically in electrodynamic devices associated with information processing technology. The research work is now published in *Science Advances*.

Modern electron microscopy and laser-free ultra-fast electron microscopy

Modern electron microscopy can allow researchers to obtain images of matter with atomic resolution due to the picometer wavelength of the high-energy electron beams, advances in aberration-correction and direct detection techniques. The method is a central tool across materials science to biology, together with progressive advances in electron crystallography, tomography and cryo-single-particle imaging. Conventionally, the electron beam of a microscope is produced by a thermionic or field emission process and such electron sources produce static images or those captured at long time-intervals due to inherent limits of conventional electron detectors. Advanced electron microscopes therefore require a strong or greater temporal resolution to investigate reaction paths in physical and chemical transitions beyond the detector limits. In this work, Fu et al. developed laser-free, ultra-fast electron microscopy by combining a prototype RF-driven electron beam pulser to create short electron pulses with a tunable repetition rate ranging from 100 MHz to 12 GHz. This method will allow researchers to record ultrafast images and detect different patterns of structural transitions.

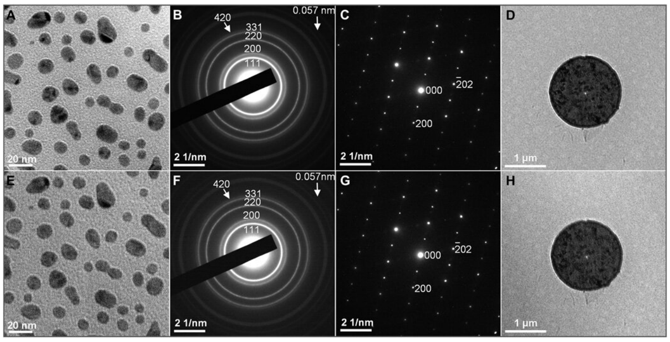


Sample modelling of a microstrip of two interdigitated combs with the same geometry and materials used in the experiment for numerical simulation. Credit: Science Advances, doi: 10.1126/sciadv.abc3456

Using the method, the research team optimized the input radiofrequency (RF) power and frequency for the pulser to achieve a time-resolution of 10 picoseconds (ps) in the instrument and used the same broadband tunable RF signal to facilitate sample excitation. During the initial demonstrations of its capability to study ultrafast dynamics, Fu et al. conducted a pump-probe study on electromagnetic wave propagation dynamics in a microstrip specimen with two interdigitated combs—a basic building block of radiofrequency microelectromechanical systems (MEMS). By combining experimental outcomes with numerical simulations, the team showed the electrodynamics of a gigahertz electromagnetic (EM) wave propagation in the microstrip specimen. This phenomenon can fundamentally contribute to the functionality of most information processing devices and other imaging techniques that presently remain inaccessible for imaging due to size constrictions.

Conceptual design—new prototype

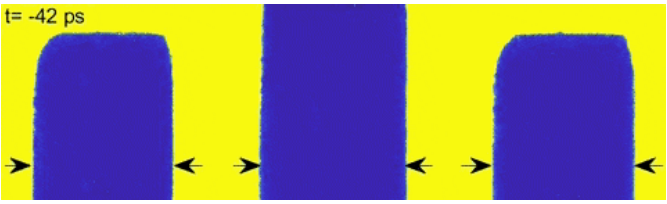
In the laser-free UEM (ultrafast electron microscope) the RF-driven pulser system interfaced with a transmission electron microscope (TEM). The pulser contained two traveling wave metallic comb stripline elements with a small chopping aperture between them. When the pulser was driven by a radiofrequency signal, the team recorded the generation of a sinusoidal electromagnetic wave (EM) in the modulator, while introducing an oscillating transverse momentum kick to the incoming continuous electron beam. The chopping aperture of the system partitioned the continuous beam into periodic electron pulses. Using the current design, they established a broadband EM field with a frequency ranging from 50 MHz to 6 GHz. The scientists tested the performance of the TEM after integrating the pulser to record a set of imaging and diffraction results under a continuous beam mode and pulsed beam mode. The team examined bright-field images of gold nanoparticles in both modes that were comparable in both intensity profile and contrast. Comparable imaging quality between the pulsed beam mode and continuous beam mode showed good performance and versatility of the new laser-free UEM prototype.



Comparison of imaging and diffraction quality between the continuous beam mode and the pulsed beam mode. Images and diffraction patterns acquired at the continuous beam mode: (A) bright-field image of gold nanoparticles, (B) diffraction pattern of gold nanoparticles, (C) diffraction pattern of a VO2 single crystal (along [010] zone axis), and (D) out-of-focus Fresnel phase image of magnetic vortex in a circular ferromagnetic permalloy disc. Images and diffraction patterns acquired at the pulsed beam mode with the repetition rate of 5.25 GHz: (E) bright-field image of gold nanoparticles, (F) diffraction pattern of gold nanoparticles, (G) diffraction pattern of a VO2 single crystal (along [010] zone axis), and (H) out-of-focus Fresnel phase image of magnetic vortex in a circular ferromagnetic permalloy disc. Credit: Science Advances, doi: 10.1126/sciadv.abc3456

Optimizing the experiment and proof-of-concept

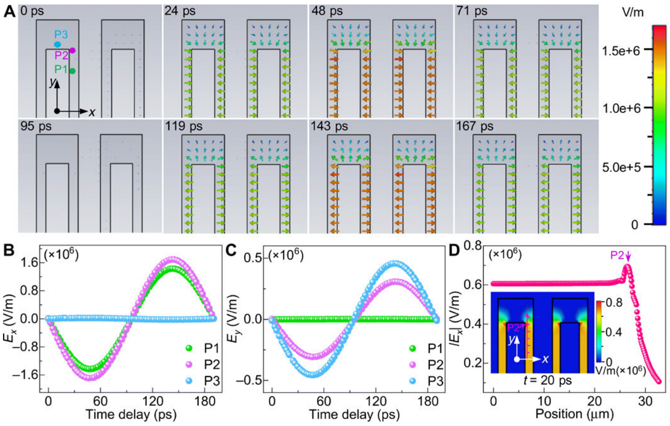
The resolution of the laser-free UEM depended on the duration of the chopped electron pulses, which in turn depended on the duty cycle of the chopped electron beam. Fu et al. varied this parameter by independently changing the input RF power frequency and/or the chopping aperture size. In principle, they could use higher input RF power and a higher RF frequency with a smaller chopping aperture to achieve shorter, as well as sub-picosecond or femtosecond electron pulses to further improve the quality and resolution of imaging. The team then demonstrated the ultrafast pump-probe measurement capability of the laser-free UEM to understand the oscillating currents and fields needed to operate almost any information processing device. Fu et al. noted time-resolved images of EM propagation in the interdigitated comb structure for the first time at a magnification of 1200x, with an integral time of 1.5 seconds. They then studied the dependence of EM wave propagation dynamics on the excitation power, where the amplitude increased with increasing excitation power.



Real-time breathing of one active tine and two adjacent ground tines in the interdigitated comb structure under a 5.25 GHz electromagnetic wave excitation (power of ~1 W). Credit: Science Advances, doi: 10.1126/sciadv.abc3456

Simulated electric field distribution

To further understand the experiments, Fu et al. performed numerical simulations of EM wave propagation in a microstrip of two interdigitated combs with similar geometry and materials to the experiments, and carried out the simulation using a 3-D EM finite element analysis package. The team observed snapshots of the simulated electric field distribution around the interdigitated combs at different delay times. Since the sample is nonmagnetic, the effects of magnetic fields were negligible in the experiment. As the EM wave propagated through the interdigitated combs under investigation, a temporal oscillating electric field established between the gaps of the interdigitated combs. The simulated results were in good agreement with the experiments.



Numerical simulations on the EM wave propagation dynamics in two interdigitated combs. (A) Typical snapshots of the simulated electric field distribution (projected in the x-y plane at the mid-comb thickness) around the active and ground tines at different delay times (movie S2). The arrows indicate the direction of the electric fields with encoded color for the field strength. (B) Plots of the electric field Ex as a function of time at three representative positions (P1, P2, and P3) around a ground tine. The field strength near the corner of the tine is stronger than other positions, indicating a local field enhancement near the corner. (C) Plots of the corresponding electric field Ey as a function of time at the three representative positions. The field strength of Ey at

P1 is nearly zero and that of Ex at P3 is almost zero, which indicates that the established local field vectors are vertical to the tine's surfaces along the beam-pass direction. (D) Plot of the electric field strength of |Ex| (in absolute value) as a function of position along the red line with an arrow (inset) near the surface of a ground tine. The sharp increase of the field strength near the corner (position P2) indicates a remarkable local field enhancement. The field strength in the inset is color-coded with the color bar in the inset. Credit: Science Advances, doi: 10.1126/sciadv.abc3456

In this way, Xuewen Fu and colleagues engineered a laser-free ultrafast electron microscope (UEM) with high resolution in space-time, by combining a radiofrequency (RF)-driven pulser with a commercial transmission electron microscope (TEM). Using the laser-free UEM, Fu et al. studied the gigahertz electromagnetic (EM) wavelength propagation process in a microstrip containing two interdigitated combs. The team showed direct visualization of EM field oscillation with time to reveal field amplitude, polarization direction and wave propagation at the nanometer-picosecond timescale, which was hitherto inaccessible with other imaging techniques. The laser-free UEM provides a powerful path to understand electrodynamics in small devices that function across megahertz to gigahertz frequencies, such as wireless antennas, sensors and RF microelectromechanical systems (MEMS). Further optimization will allow sub-picosecond and even femtosecond wave-packets to enable femtosecond time-resolution for laser-free UEM. The work will have broad implications across materials physics to biology and mobile communication technologies.

More information: Xuewen Fu et al. Direct visualization of electromagnetic wave dynamics by laser-free ultrafast electron microscopy, *Science Advances* (2020). DOI: 10.1126/sciadv.abc3456

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