

High-Energy Subcycle Electron Emission Driven by Spatiotemporally Confined THz Fields

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(Received 4 November 2024; accepted 3 June 2025; published 18 June 2025)

Tip-based structures offer a pathway to strong-field, optical-driven field emission, holding the potential for generating high-brightness ultrashort electron sources. While direct optical-field-driven electron emission and acceleration within the single optical subcycle provides a straightforward solution for ultrafast electron generation, achieving precise control over the emission process to generate high-quality electron beams suitable for practical applications remains challenging. Here, we present THz-driven subcycle electron field emission in a ridged waveguide cavity, achieving the first practical high-energy femtosecond field-emission source. This ridged cavity is engineered to spatially and temporally confine the electric field, effectively minimizing dispersion and suppressing field leakage. Through carrier-envelope phase control of the THz field, we achieve subcycle field emission, generating, for the first time, isolated electron bunches with a 940-fs (FWHM) duration. Using dual 24 μJ ($2 \times 24 \mu\text{J}$) of THz energy, we achieve a peak field strength of approximately 23 GV/m, accelerating electrons to a record energy of 46 keV with a charge of 2 pC per bunch, thereby enabling single-shot imaging. The high-field strength suppresses emittance blowup due to space-charge effects, ensuring excellent beam quality. The generated electron pulse exhibits high stability. As an initial application, we investigate transient electric-field dynamics in real time and space using time-resolved schlieren radiography with this field-emission electron source. These proof-of-principle results signify a critical advancement in developing compact, high-performance electron sources for user-oriented applications.

DOI: [10.1103/wczq-ljv3](https://doi.org/10.1103/wczq-ljv3)

Subject Areas: Optics, Particles and Fields, Photonics

I. INTRODUCTION

The interaction between light and matter, especially in high-field optical-driven electron emission from metal surfaces, has been extensively investigated, ranging from strong-field physics [1–3] to attosecond science [4–6]. At the heart of this interaction lies the concept of the work function, which defines the energy required for electrons to overcome the potential barrier at the surface and escape into vacuum. When subjected to a strong light field, the electron surface potential undergoes transient tilting, thereby facilitating electron tunneling through the barrier [7–9]. This tunneling rate is exponentially dependent on the field-

dependent barrier width. While in condensed matter targets, extremely short emission durations have been demonstrated [4,7] using short visible or near-infrared laser pulses, the maximum drive intensity is limited by laser-induced surface and bulk damage, thereby restricting the transfer of electron momentum. To address this challenge, longer wavelength drivers have been used to reduce the optical intensities required to induce emission and accelerate electrons to high energies.

Recent advancements in strong-field terahertz (THz) generation [10] have significantly improved the control of electron emission and acceleration from nanotips [11–15], while also advancing the application of THz technology in electron acceleration [16–22] and manipulation [23–26]. Intense, single-cycle THz pulses, when applied to metal nanotips, induce a broadband local field enhancement localized at the tip apex. Field-emitted electrons leave the vicinity of the tip (and the enhanced field), and subsequently undergo rapid acceleration to high energy within the same optical cycle, providing a highly efficient method for generating ultrafast electron sources.

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Electrons accelerated in the enhanced local field of metallic nanotips can produce spatially and temporally localized bursts of high-energy electrons. In contrast to the optical or infrared regimes, true single-cycle drive fields at THz frequencies hold the potential to confine high-energy electron emission to a single, isolated burst. Under pulsed illumination, the threshold field for breakdown scales with the pulse duration [27], and with a single-cycle THz-powered device, the sustained field strength can reach several GV/m—a level that would cause catastrophic damage under conventional dc fields. Such high-field strength holds the potential to generate high-energy electron beams with substantial charge over micrometer-scale distances, while effectively mitigating space-charge effects. These beams will be particularly useful for near-single-shot operations [28], as well as serving as seeds for accelerators and sources for time-resolved electron diffraction [29,30].

Several studies have explored THz-driven field emission with metallic nanotips that exhibit extreme field enhancements and strongly localized field [11–13]. Enhanced field strength on the order of GV/m [12,13] was observed from THz-driven metallic nanotips generating sub-pC charge with energy approaching 5 keV. Direct injection of single-cycle THz pulses onto the nanotip can help reduce dispersion, thereby achieving subcycle electron emission. However, the lack of control over the acceleration process and the need for further concentration of the field strength currently prevent its application for high-energy acceleration. Although rectangular waveguide-based structures have been used for high-precision control of THz-electron interaction in THz-based photoguns [18,31,32], achieving higher field concentration in these devices requires reducing the waveguide dimensions, which raises the cutoff frequency and introduces dispersion, leading to multiple optical cycles in the driving wave. To date, the direct optical-driven electron-field-emission source is still far from producing a practical electron beam with sufficient electron energy, beam quality, and short pulse duration for practical application in modern ultrafast studies.

Here we present the first practical, direct THz field-driven electron source from a metallic microtip in a ridged waveguide cavity. This approach facilitates spatially sub-wavelength field concentration and broadband coupling. Furthermore, the waveguide provides well-defined field confinement for the accelerating electric field rather than relying on free-space interaction. This enables precise control over the acceleration process, resulting in higher electron energies. The concentration of the field along the ridge also helps suppress the leakage of the field during propagation. Carrier-envelope phase (CEP) control via the $\chi^{(2)}_{333}$ orientation of the LiNbO₃ crystal and Gouy phase shift with a THz lens system ensures subcycle field emission, confining high-energy electron emission to a single, isolated burst with a duration of 940 fs (FWHM). With $2 \times 24 \mu\text{J}$ THz, a field strength of 23 GV/m has been

achieved, producing a maximum electron energy of 46 keV, nearly an order of magnitude higher than previous THz-driven field emission. The high-field strength extracts a record charge of 2 pC per bunch and suppresses initial electron blowup due to space-charge effects, which reduces the emittance [33,34] and enables single-shot imaging. The generated electron pulse exhibits high stability and is optically synchronized with the incident optical waveform. The first real ultrafast application of this technique has been demonstrated by observing field-induced plasma dynamics with time-resolved electron schlieren radiography. To the best of our knowledge, this is the first practical application of an optical-driven field-emission source, offering a potential solution for future compact, high-brightness electron beams in next-generation ultrafast electron diffraction and advanced accelerator concepts.

II. RESULTS

A. Experimental setup

The experimental setup (Fig. 1) consists of two single-cycle THz generation stages and a field-emission cavity. Single-cycle THz pulses centered at 0.3 THz were generated by optical rectification in lithium niobate crystals (LiNbO₃) using the tilted-pulse-front method [35]. The THz pulses from two independent setups were coupled into the device transversely by the ridged horn antenna. The electron bunch length is measured via the THz-based streaking [24] (see Supplemental Material Fig. S1 [36] for detailed information). The tip cathode is made of tungsten with a diameter of 2 μm and mounted on a precision xyz stage.

Electrons are generated only during negative cycles of the THz wave, while the field strength is above the field-emission threshold and accelerated away from the tip. In order to generate ultrashort pulses, a THz wave with only one negative half cycle for optical-driven subcycle field emission is desired. This requires not only a single-cycle THz wave but also a cavity that has a broad bandwidth for THz wave coupling and propagation. A ridged horn antenna and waveguide, commonly used in rf transmission lines [37], have been utilized for the first time in THz-driven subcycle field emission. These components were redesigned according to the impedance matching principle, enabling ultrawideband (UWB) coupling and efficient transition of the THz wave (see Supplemental Material Fig. S2 [36] for detailed structural information). This ensures temporally single-cycle excitation, hence, subcycle optical-driven electron field emission and spatially sub-wavelength concentration of the field into the acceleration region. Two THz pulses are coupled into the device from the sides along the y axis [Fig. 1(a)] with the electric field set parallel to the electron propagation direction. A movable tip cathode is inserted into the center of the ridged waveguide. The tip cathode introduces field enhancement,

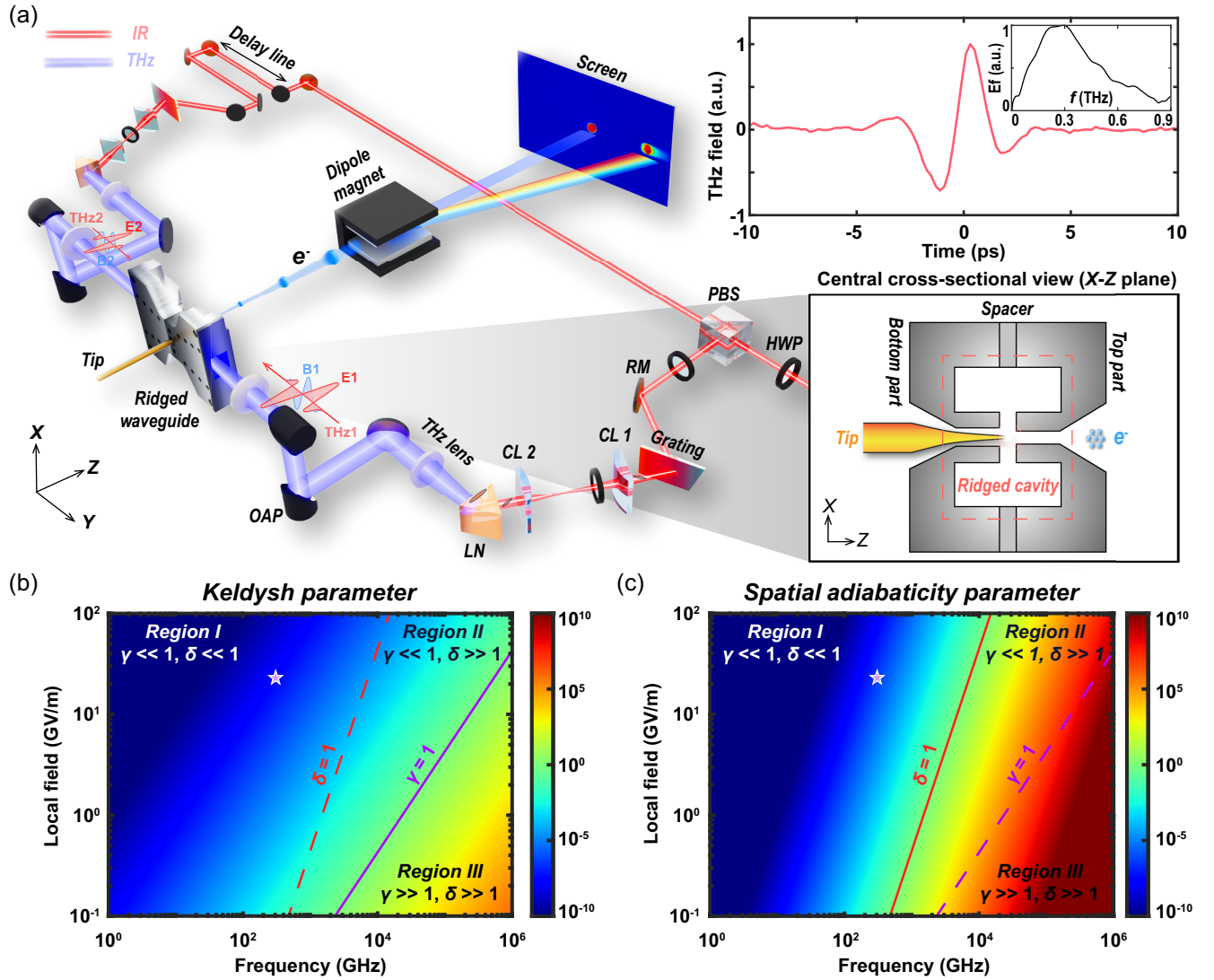


FIG. 1. Experimental setup. (a) Schematic diagram of the experimental setup showing the THz generation and acceleration cavity. Two THz pulses generated from the same infrared laser source are injected symmetrically into the cavity along the Y axis from opposite sides. The electrons are accelerated along the Z axis. A dipole magnet is used to measure the electron energy with an MCP detector. HWP, half wave plate; CL, cylindrical lens; RM, reflection mirror; LN, LiNbO₃ crystal; PBS, polarized beam splitter; OAP, off-axis-parabolic mirror. Inset top: electro-optical sampling of the injected THz wave (THz1 and THz2). Inset bottom: Cross-sectional view of the ridged waveguide cavity along the X - Z plane. The cavity consists of three main components (top part, spacer, and bottom part) with a central hole for insertion of the tip cathode and electron emission. The coordinate system shown here is consistently used throughout the entire paper. For more structural details, see Supplemental Material Fig. S2 [36]. (b), (c) The calculated Keldysh parameter (γ) (b) and the spatial adiabaticity parameter (δ) (c) are plotted in logarithmic coordinates across the driving frequencies and local field strength. The purple and orange curves represent the turning points of γ and δ in logarithmic coordinates, respectively. Star-shaped markers indicate the operational conditions for the high-energy field emission discussed in the work.

generating GV/m field strength that extracts electrons from the tip. The extracted electrons experience the electric field for acceleration and deceleration. The two counterpropagating THz pulses are set to ensure that the electric field constructively interferes at the center of the cavity, while the magnetic fields are 180° out of phase and cancel each other [18,38]. The relative timing of the two THz pulses can be precisely controlled by tuning the delay of the two THz pulses. The tip-cathode-to-anode distance determines the

THz-electron interaction length, ensuring that the electron bunch experiences only the negative cycle of the THz electric fields, resulting in a continuous acceleration.

Electron charge and energy were measured by a Faraday cup and a dipole magnet, respectively. The spatial profile of the accelerated electrons was analyzed using a micro-channel plate (MCP) and phosphor screen that was monitored by a CCD camera (see Supplemental Material Sec. I [36] for more details).

B. Optical-driven subcycle field emission

In the cold-field emission of electrons from metal nanotips, as described by the Fowler-Nordheim theory [39], the instantaneous THz field tilts the vacuum potential through the Schottky effect, causing significant electron tunneling and subsequent exposure to the intense localized THz fields for acceleration. Specifically, for materials such as tungsten, the critical field strength given by $F_c = 4\pi\epsilon_0\Phi^2/e$, required to drop the potential barrier down to the Fermi energy, typically falls within the range of a few GV/m. In this process, the electron dynamics are governed by two key parameters: the Keldysh parameter (γ) and the spatial adiabaticity parameter (δ). The Keldysh

parameter [14] defined as $\gamma = \sqrt{\Phi/2U_P}$ characterizes the electron emission process, where Φ is the work function of the material, and U_P is the ponderomotive energy. The spatial adiabaticity parameter [1,40,41] $\delta = l_F/l_q$ describes the interaction of electrons with the strong localized field, where l_F is the field decay length, and l_q is the electron quiver length. To achieve simultaneous high-field emission and large momentum transfer, it is desirable for the interaction to enter the deep tunneling regime, which requires long driving wavelengths and small values of the Keldysh parameter (γ) and the spatial adiabaticity parameter (δ) [Figs. 1(b) and 1(c)]. In our current experiment, we have achieved a peak local field strength of

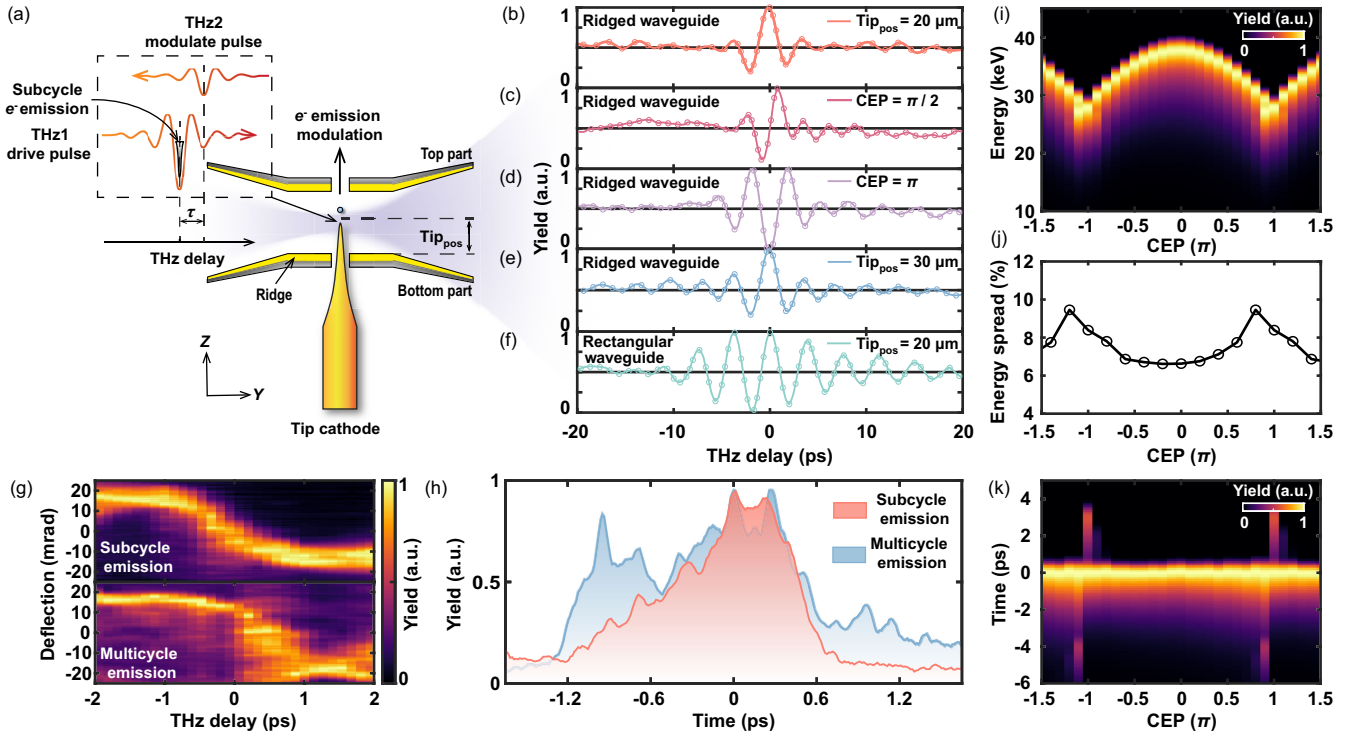


FIG. 2. Field emission with the UWB ridged cavity. (a) THz1 enables subcycle field emission. Two counterpropagating THz waves (one strong driving pulse and one smaller modulation pulse) are injected from opposite sides along the Y axis into the horn structure of the waveguide. They meet at the center of the waveguide, with their relative delay (THz delay) controlled via a motorized delay line. The delay scan of THz2 reveals the correlation between the two THz arms. Schematic side view (Y - Z plane) illustrating the tip and waveguide structure. The view is not to scale and is intended solely for visualization purposes. The vertical separation between the top and bottom components is exaggerated to enhance the depiction of the THz waves. For actual waveguide dimensions, see Supplemental Material Fig. S2 [36]. (b)–(f) Measured electron yield as a function of the relative time delay between the two THz arms: with a ridged cavity (b), with carrier-envelope phase of THz2 shifted by 90° (c), with field polarity of THz2 flipped by 180° (d), with excessive insertion of the tip cathode that induces resonances inside the cavity (e), and with a rectangular cavity without the ridged design (f). The electron yield represents the cumulative intensity on the phosphor screen and is cross-calibrated with the Faraday cup. Electrons can be emitted only during the negative part of the THz cycle. The constant offset arises from the electron emission driven by the strong THz pulse (THz1). Panels (b)–(d) show the direct mapping of the field envelope through the delay scan, while (e) and (f) reveal the correlation between two multicycle THz waves. (g),(h) Time-dependent deflection and retrieved electron-pulse duration were measured with THz-based streak camera (4 mm away from the tip cathode) operating at 0.2 THz (see Supplemental Material Fig. S1 [36] for the temporal profile of the THz wave). Because of the different frequencies of the THz for field emission and streaking, the emitted electron-pulse train from the multicycle THz may not sweep exactly across the zero-crossing region of the streaking THz wave, resulting in the observed wiggles in (h) (blue curve). (i)–(k) Simulated effect of the evolution of the THz carrier-envelope phase on the electron energy, energy spread, and temporal distribution with the phase of the two THz arms synchronized.

23 GV/m at a driving wavelength of 1 mm. Under these conditions, γ and δ are calculated to be 10^{-5} and 10^{-3} , respectively, indicating deep tunneling and efficient electron acceleration (see Supplemental Material Sec. II [36] for a detailed calculation). This is further confirmed by the pulse duration measurement using the THz-based streaker [24], which is positioned approximately 4 mm away from the tip cathode. The measured pulse duration of 940 fs (FWHM) is less than half a cycle of the THz wave [Fig. 2(h)], providing strong evidence for subcycle ultrafast field emission.

As the field strength already exceeds GV/m with one arm of the THz, field emission can be observed even with single-sided excitation (THz1). For the other arm of the THz, the field strength is lowered below the field-emission threshold and acts as a modulating pulse (THz2). Given

this, we can directly map the field envelope for electron emission by scanning the relative THz delay and measuring the yield of electrons [Figs. 2(b)–2(d)], which enables further coherent control of THz-driven field emission. As shown in Fig. 2(b), the clear single-cycle envelope indicates that both arms exhibit a single cycle, with a near-zero carrier-envelope phase, resulting in optical-driven subcycle field emission. When there is a phase shift from 0° , such as the $\pi/2$ phase shift shown in Fig. 2(c), subcycle field emission still occurs, though with a slightly lower field strength. The small phase shift can be tuned via the Gouy phase shift caused by the beam confinement near the focus. However, when there is a 180° phase difference [Fig. 2(d)], this CEP results in a reduced acceleration field. Using this configuration for field emission leads to a broader temporal distribution with increased noise [Fig. 2(h)]. Achieving a

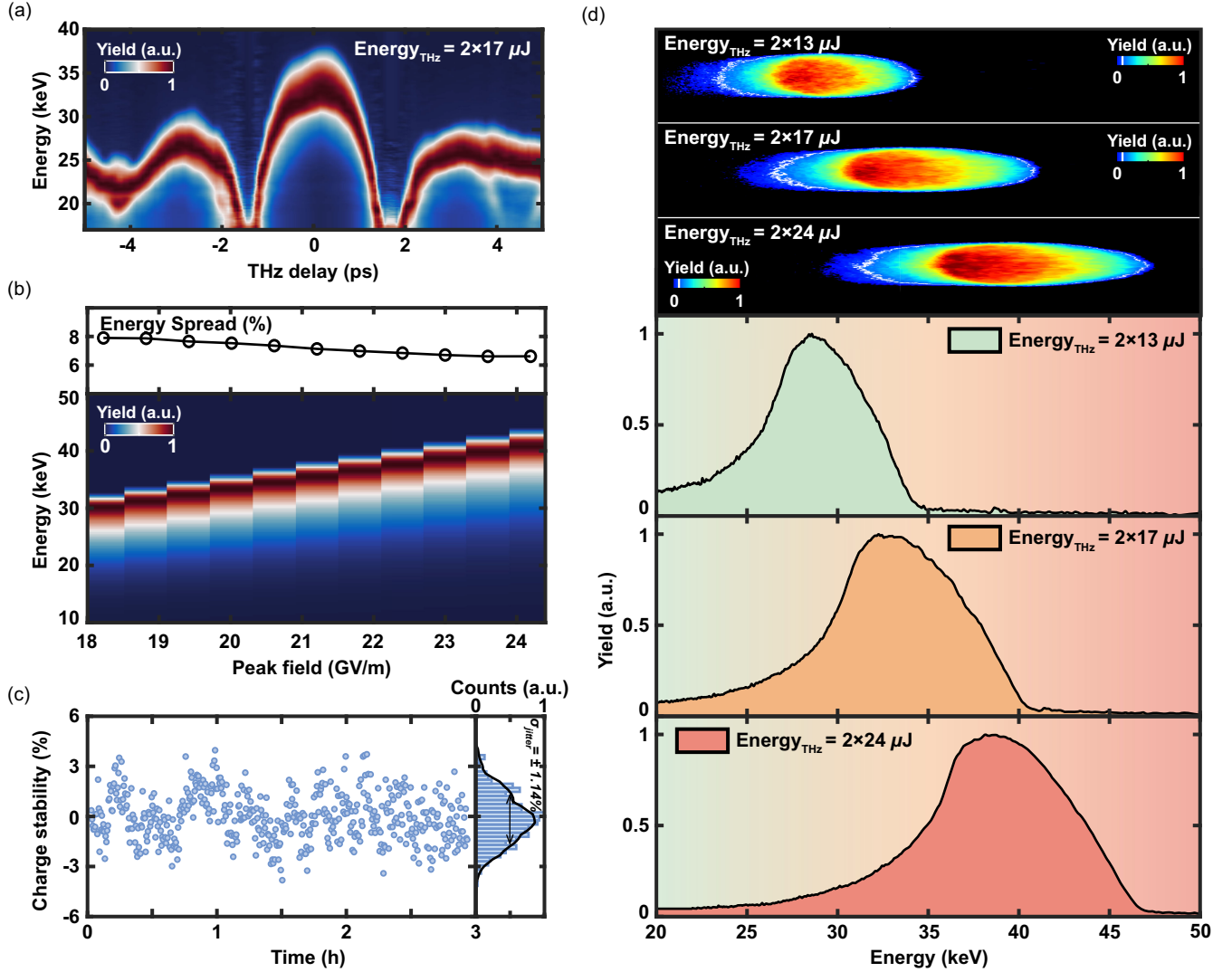


FIG. 3. High-energy field emission. (a) Measured electron energy as a function of the THz delay between the two THz arms. (b) Simulated electron energy and energy spread with the increase of peak field strength. (c) Charge stability statistics over three hours of measurement. (d) Electron energy achieved with different THz energy.

180° carrier-envelope phase shift via the Gouy phase shift requires significant displacement of the beam before or after the focus, which would reduce the field strength. To achieve a large phase shift without influencing the field strength, the field polarity can be inverted by reversing the $\chi^{(2)}_{333}$ orientation of the LiNbO₃ crystal.

The electron emission is also sensitive to the alignment of THz and the position of the tip cathode. For example, while bringing the tip cathode closer to the anode aperture, a higher field enhancement can be achieved. However, this leads to resonances [Fig. 2(e)] inside the waveguide generating multiple electron pulses [42]. Figure 2(f) shows a multicycle waveform developed in a rectangular waveguide [16,21,31]. To reach a comparable high-field strength in a rectangular cavity, the waveguide dimension should be reduced to concentrate the field. However, this will increase dispersion in the cavity, leading to the generation of multiple electron bunches and resulting in a much longer electron bunch with a larger energy spread. Figures 2(i)–2(k) show the simulated result of the evolution of the THz CEP on the electron energy, energy spread, and temporal distribution with the two THz arms synchronized.

At a CEP of 0°, the accelerating field reaches its maximum, and electron emission is confined to a single cycle. This results in not only the highest electron energy but also the lowest energy spread and shortest bunch length, corresponding to the operating point shown in Fig. 2(b).

C. High-energy field emission

The electron energy as a function of the relative delay between the two THz pulses was measured [Fig. 3(a)], confirming that both THz arms generate single-cycle waveforms. A maximum electron energy of approximately 46 keV was achieved using $2 \times 24 \mu\text{J}$ THz energy, as shown in Fig. 3(d). At higher field strength, it takes a shorter time for the electrons to arrive at the anode; hence, the field-emitted electrons will sweep smaller components of the accelerating phase, which will help suppress the energy spread [Fig. 3(b)].

For a ridged cavity, the field is more concentrated around the ridge (Fig. 4), while for the normal rectangular waveguide-based devices [21,25,31], more fields extend toward the sidewalls. Simulation shows that the THz field is enhanced by the ridged waveguide by a factor of

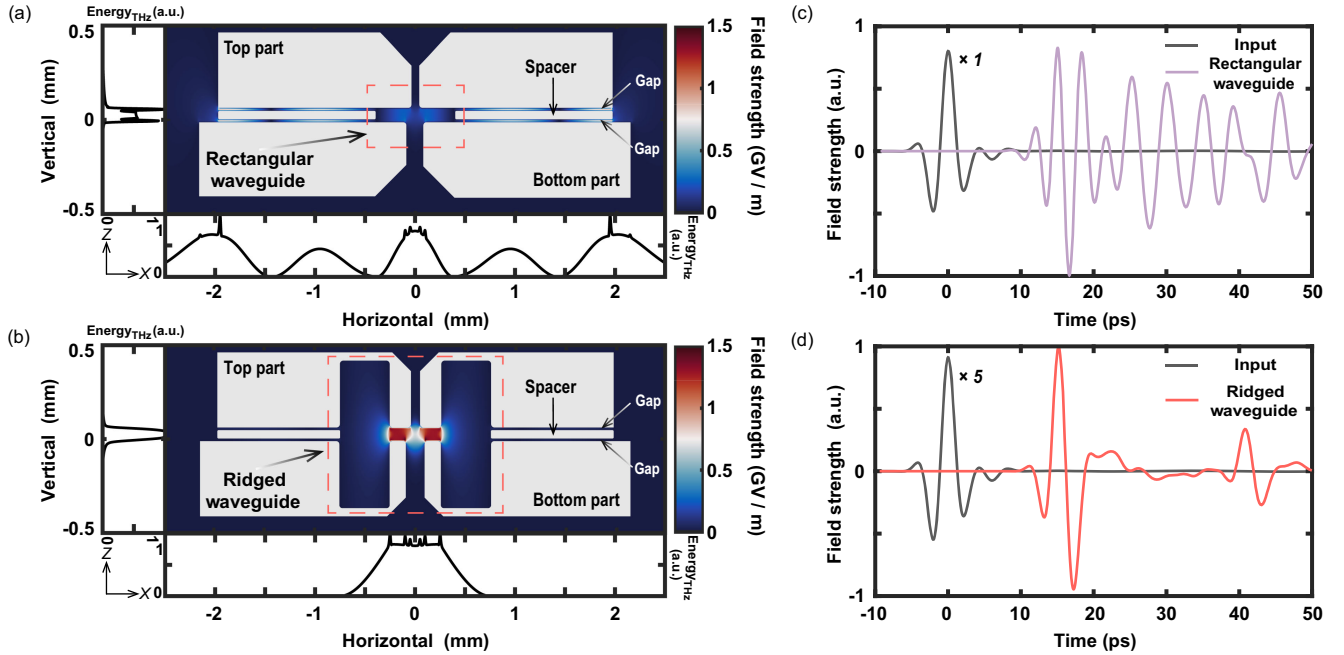


FIG. 4. Field distribution in the acceleration cavity. (a),(b) Cross section of the simulated field distribution for a rectangular waveguide (a) and ridged waveguide (b) with 10- μm gaps on the sidewalls. The gaps are formed between the top part, spacer, and bottom part, as marked in (a) and (b). The figure shows an enlarged cross-sectional view of the center region for simulation purposes. Please refer to Fig. S2 in Supplemental Material [36] for detailed structural information. The tip cathode has been excluded to isolate the field confinement properties of the waveguide structures. The gray shading represents the metal structures, showing their assembly in relation to each other, while the red dashed square represents the specific waveguide shapes formed in the center. The two THz pulses are injected symmetrically from both sides along the Y axis, with their electric field polarized along the Z axis. The projection of the energy distribution is also plotted onto the X and Z axis using the same coordinate system as shown in the inset of Fig. 1(a) and Supplemental Material Fig. S2 [36]. (c), (d) Simulated field amplitude at the entrance of the horn coupler (input), at the center interaction region of rectangular waveguide (c) and ridged waveguide (d) considering the 10- μm gaps on the sidewalls. To facilitate comparisons in the same coordinate frame, the incident field is scaled up by a corresponding factor as labeled.

approximately 5, and further enhanced by the tip by a factor of 60, resulting in peak accelerating fields reaching approximately 23 GV/m. Such a device is typically constructed from two half plates containing multiple segments [Figs. 4(a) and 4(b) and Supplemental Material Fig. S2 [36]]. Because of fabrication tolerances, gaps on the order of several 10 s of micrometers often form along the sidewalls, leading to significant leakage of THz energy into these gaps [Fig. 4(a)]. For a ridged design, the power is more localized around the ridge, and it is much weaker next to the sidewalls [Fig. 4(b)], resulting in a lower energy loss during THz propagation inside the waveguide. Furthermore, we have measured the achieved electron energy from two relative devices. The achieved peak

electron energy from the rectangular waveguide is about 40% lower than that from the ridged design. Simulation also shows that the ridged waveguide provides about 4 times higher field strength compared with a rectangular waveguide [Fig. 4(c)] assuming 10- μm gaps on the sidewalls.

With the increase of THz field strength, there is an increase of the charge and electron energy. The energy spread achieved here is about 7% (rms), which is larger compared to a conventional dc gun with photoemission pumped with a short UV laser. Detuning from the optimal acceleration can partially mitigate the broadening of the energy spectrum [Fig. 3(a)]. By integrating multiple layers into the ridged design, various functionalities can be incorporated within

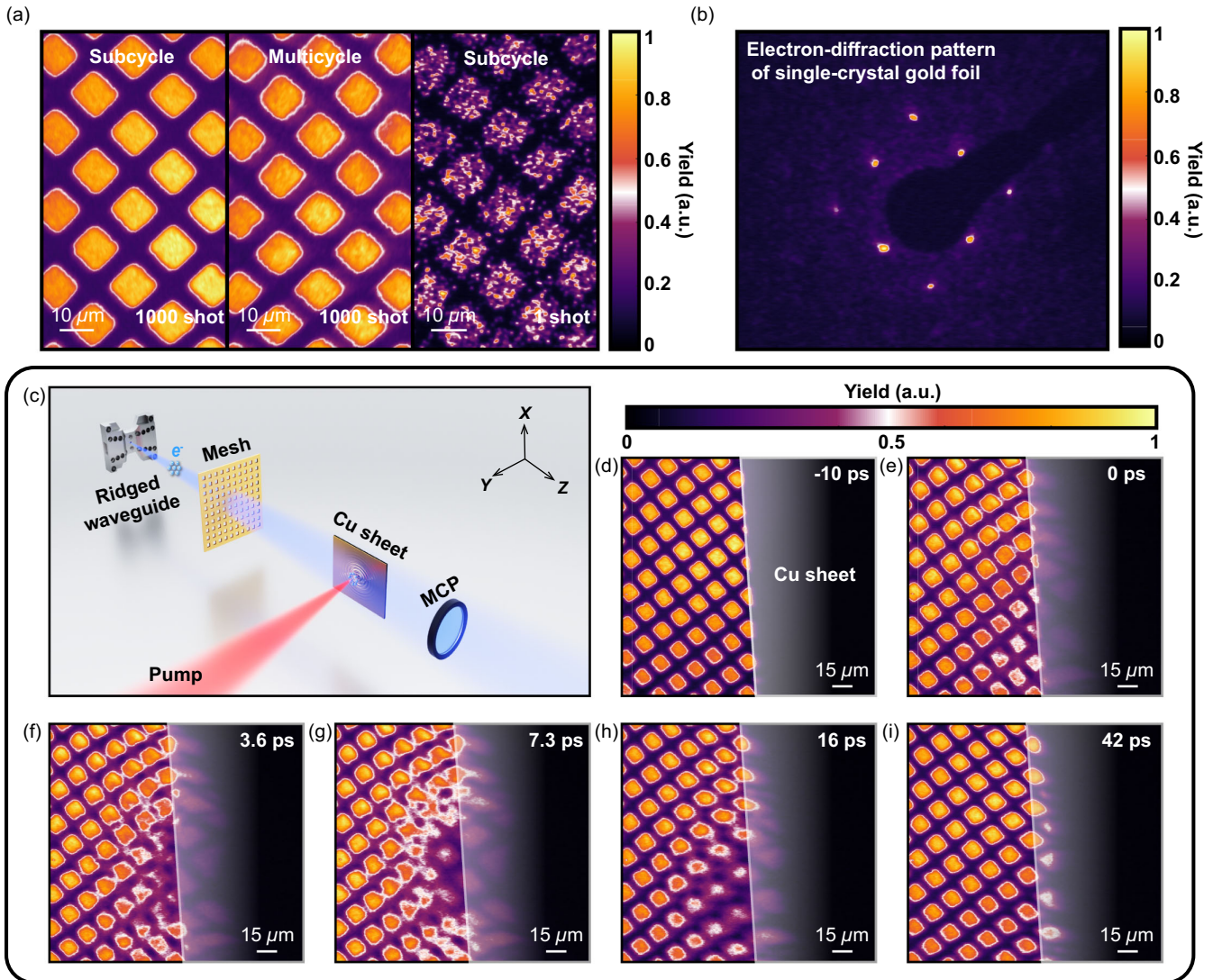


FIG. 5. Ultrafast imaging and diffraction. (a) Projection imaging of 1500 copper mesh with subcycle field emission (1-s exposure time with 1000 shots), multicycle field emission (1-s exposure time with 1000 shots), and subcycle field emission (single shot). (b) Electron diffraction from single-crystal gold. (c) Time-resolved schlieren radiography with charged-particle pulses from the ultrafast field-emission gun. (d)–(i) Snapshots of time-resolved schlieren images after penetrating through the Cu mesh and laser produced plasma at different time delays.

different cells, enabling bunch compression, compensation of the energy spread, and the achievement of higher electron energies (see Supplemental Material Secs. 6 and 7 [36] for more details).

D. Ultrafast imaging and diffraction

To demonstrate the performance of the setup, we measured the electron projection imaging and diffraction. Figure 5(a) shows the projection imaging of a 1500 copper mesh with optical-driven subcycle field emission of 1000-shot accumulation and 1 shot, and with multicycle field emission. Multicycle field emission leads to multiple pulses with different electron energy and emittance, hence, poor beam quality. Single-crystal gold is also used to look at the electron-diffraction signal.

The system also exhibits good stability [Fig. 3(c)] that shows about 1.14% fluctuation over three hours of measurement, ensuring its suitability for ultrafast studies. We demonstrated its capability to probe the ultrafast process of the transient plasma dynamics prompted by strong laser field with the time-resolved electron schlieren radiography, as proposed by Chen *et al.* [43]. By placing a mesh grid to divide the probing electron beam into an array of electron beamlets [Fig. 5(c)], we can trace the deflection of each beamlet deflected by local electromagnetic fields and yield a spatially resolved schlieren-type pattern. The structural and temporal evolution of the transient plasma dynamics is visualized with the time-resolved electron schlieren images [Figs. 5(d)–5(i)] at different time delays following laser irradiation obtained by the fs electron beamlets. Before laser irradiation [Fig. 5(d)], the beamlet array is undisturbed. After irradiation, the copper surface is ionized. A fraction of the hot electrons escapes from the surface, resulting in a redistribution of the residual charges. The evolution of the escaped electrons and the remaining ions in the foil leads to the charge-separated transient electric field that deflects the probe electron beams, forming a hole in the center of Fig. 5(g). With the increase of the delay time, the escaped electrons move away from the row, and the displacement of the row decreases [Figs. 5(h) and 5(i)]. The average velocity of the emitted hot electrons is estimated to be 1.5×10^6 m/s. This proof-of-principle demonstration already surpasses previous efforts using conventional dc gun systems [43], offering the potential for imaging transient field dynamics near surfaces and paving the way for probing ultrafast charge-carrier dynamics. To our knowledge, this is the first time that optical-driven field emission has been developed for practical application.

IV. CONCLUSIONS

We have demonstrated the first practical femtosecond field-emission source based on the ultrawideband ridged cavity and coherent control of the THz wave. The field is spatially confined into the subwavelength region while

temporally preserving its single-cycle property along its propagation. The acceleration phase is detected through cross-correlation of the THz wave. CEP control is achieved via the $\chi^{(2)}_{333}$ orientation of the LiNbO₃ crystal, enabling large-scale phase manipulation, while Gouy phase-shift adjustments through the THz lens system allow for precise fine-tuning of the CEP.

This approach enables subcycle field emission, producing, for the first time in field emission, an isolated electron bunch with a duration of 940 fs. The THz field is further enhanced by a movable tip cathode, which also controls the acceleration distance and enables continuous acceleration. The concentration of the field along the ridge also helps to suppress the leakage of the field. Using 2×24 μ J of THz energy, we achieved a peak field strength of 23 GV/m, accelerating electrons to 46 keV—3 times higher than previous THz-driven photoguns [18]. The generated bunches carried a charge of 2 pC, an order of magnitude greater than earlier demonstrations [18]. Compared to multicycle field emission and acceleration at lower field strength, we have observed significant improvement in beam quality with optical-driven subcycle field emission. The system shows high stability over several hours of measurement. We were able to present its first real application in observing the transient plasma dynamics with high spatiotemporal resolution. Compared with a photogun, these THz-based field-emission guns afford much higher field strength and enable electron emission and acceleration within the same optical cycle, paving the way for a more compact system. The next steps will be further improving the structure design with cascaded cells as well as generating high-energy terahertz sources and systematically working toward MeV electron energy. The current demonstration paves the way for pursuing high-brightness, ultrashort electron sources for future ultrafast electron diffraction, ultrafast transmission electron microscopy, and free-electron laser technologies at the smallest scales.

ACKNOWLEDGMENTS

This work has been supported by the Science and Technology Commission of Shanghai Municipality (Grant No. 22JC1401900), the National Natural Science Foundation of China (Grant No. 12174255), the Fundamental Research Funds for the Central Universities, Research Projects No. E1Z1D101 and No. E2Z2D101 of the Aerospace Information Research Institute, Chinese Academy of Sciences, and Project No. E33310030D of the Chinese Academy of Sciences. D. Z. would also like to thank the sponsorship from the Yangyang Development Fund. J. Y. is supported by a T. D. Lee Scholarship.

D. Z. and H. X. conceived and coordinated the project. J. Y., D. S., X. H., and L. Z. designed the experimental setup and carried out the experiments. L. L. and J. Y. contributed on the cavity design and simulation.

The manuscript was written by D. Z. and J. Y. with input and feedback from all authors.

The authors declare no competing interests.

DATA AVAILABILITY

The data that support the findings of this paper are available via figshare [44]. All other data used in this study are available from the corresponding authors upon reasonable request.

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