Real-time ultrafast oscilloscope with a relativistic electron bunch train

In Hyung Baek, Hyun Woo Kim, Hyeon Sang Bark, Kyu-Ha Jang, Sunjeong Park, Junho Shin, Young Chan Kim, Mihye Kim, Key Young Oang, Kitae Lee, Fabian Rotermund, Nikolay A. Vinokurov & Young Uk Jeong

The deflection of charged particles is an intuitive way to visualize an electromagnetic oscillation of coherent light. Here, we present a real-time ultrafast oscilloscope for time-frozen visualization of a terahertz (THz) optical wave by probing light-driven motion of relativistic electrons. We found the unique condition of subwavelength metal slit waveguide for preserving the distortion-free optical waveform during its propagation. Momentary stamping of the wave, transversely travelling inside a metal slit, on an ultrashort wide electron bunch enables the single-shot recording of an ultrafast optical waveform. As a proof-of-concept experiment, we successfully demonstrated to capture the entire field oscillation of a THz pulse with a sampling rate of 75.7 TS/s. Owing to the use of transversely-wide and longitudinally-short electron bunch and transversely travelling wave, the proposed “single-shot oscilloscope” will open up new avenue for developing the real-time petahertz (PHz) metrology.
Real-time measurement of an ultrafast waveform has been a constant desire in many fields of fundamental science and technology. Although extreme ultraviolet pulses opened new frontiers for PHz optical metrology, offering a single-shot measurement is still challenging. Recently, temporal imaging with a time lens has emerged as a method for single-shot acquisition of optical waveform, but its temporal accuracy should be further improved for broader use. Also, in such nonlinear optical (NLO) conversion techniques for assessing broadband light waves, the reconstructed field distribution is prone to be distorted from the original waveform due to imperfect phase-matching features inside NLO materials during frequency conversion processes. In this context, a charged particle is considered as a most reliable probe of electromagnetic waves because its deflection motion in free space can directly reflect the spatiotemporal field distribution of optical waves without requiring the use of any NLO parametric media. Recently, direct visualization of ultrashort light oscillation was demonstrated by tracing the kinetic energy change of electrons released from molecules, metal tips, and photocathodes. However, for the reconstruction of an overall waveform, data should be collected by scanning the relative time delay of probe electrons because the size of electrons sources is not sufficiently large to visualize an entire waveform.

Here, we take a fresh approach to the real-time oscilloscope via momentary stamping of a traveling optical wave on a quasi-one-dimensional (Q-1D) array (i.e., short, vertically thin, and horizontally wide bunch) of relativistic (MeV) electrons whose velocity is close to the speed of light. Relativistic electrons are definitely beneficial for ultrashort bunch generation because their temporal broadening induced by the space charge effect can be significantly suppressed in the relativistic regime. For the temporal characterization of relativistic electron bunches, electromagnetic waves have extensively contributed in two diagnostic ways: electro-optic detection with near-infrared laser pulses and streaking with a radio frequency (RF) wave or a terahertz (THz) wave. In this study, we propose a concept that overturns the conventional streaking technique, i.e., measuring the instant longitudinal dependence of the electric field of a light wave by using an ultrashort relativistic electron bunch, and present a proof-of-concept experiment with optical wave packets oscillating at THz frequency.

**Results**

**Operation principle of real-time ultrafast oscilloscope.** The operation principle of our real-time ultrafast oscilloscope is shown in Fig. 1a. As an electron source, we used a laser-driven RF photocathode because it can generate relativistic electron bunches synchronized with an optical wave providing an ultra-short bunch duration, and low emittance and high brightness. Two subwavelength metal slits are placed along the path of the ultrashort electron bunches. The first thick slit trims the transverse beam shape from circular to line shaped and entirely blocks the residual portion of the circular electron beam. An unknown optical signal with a linear electric polarization is coupled laterally into the gap of the second thin metal slit. For a spectrally

![Fig. 1 Conceptual illustration of the real-time ultrafast oscilloscope.](image)
Although the Q-1D electron array feels the longitudinally integrated thickness (\( \xi \)) describe the signal integrity of our electron oscilloscope. The electric motion of electrons because its magnetic polarization is parallel to the incident optical wave does not affect the electric component of the incident optical wave does not affect the electric field within the effective length of the gap. Being thin in y-direction and wide in x-direction, electron beam may be represented as an array of many thin round beams with different x-coordinates, or “columns”. Electrons of each such “column” experiences a different electric field value when it encounters the propagating wave inside the gap. Its deflection angle along the y-axis is determined by the integrated electric field along the x-axis within an effective thickness of the slit. As a result, the optical waveform of an unknown signal can be directly reconstructed on a screen by merging individual deflections of all electron “columns”. Note that the magnetic field component of the incident optical wave does not affect the motion of electrons because its magnetic polarization is parallel to the propagation direction of the electron beam.

Figure 1b shows the orthogonal electron-wave interaction to describe the signal integrity of our electron oscilloscope. The electric field enhancement factor inside the gap is determined by geometric parameters of the metal structure, such as the gap size (\( g \)) and the slit thickness (\( d \), for a given wavelength (\( \lambda \)) of the incident wave. Although the Q-1D electron array feels the longitudinally integrated field within the effective length of field which can be expressed as \( L_{\text{eff}} = \frac{g}{\xi} \), where \( \xi \) is the surface impedance of metal slit, while it propagates between both metal plates, no deformation of the waveform reconstructed by all electron columns occurs within the characteristic length (\( x_{\text{max}} < g/\xi \)) which means a distance from the entrance of waveguide, if \( L_{\text{eff}} \) is sufficiently shorter than \( \lambda \) (see Supplementary Note 1 for details). However, the rms length of the electron bunch (\( \sigma_z \)) induces the waveform distortion in this oscilloscope as follows. The continuous phase shift of the deflection field within the electron bunch duration causes temporal blurring of the waveform, as shown in Fig. 1c–e (see “Simulation” in “Methods” for details). Hence the time dependence of deflection field in the gap (Fig. 1c) leads to waveform distortion from a sinusoidal to square-like wave due to the horizontal superimposition effect of the traveling wave on the screen (Fig. 1d, e). In addition, the emittance of electron beam can cause blurring of the waveform if the beam pointing spread is larger than a single-pixel size in a CCD image.

**Visualization of single-shot THz waveform.** To demonstrate our idea experimentally, we utilized a relativistic electron accelerator and a THz wave as electron and light sources, respectively (see “Methods” and ref. 28 for details). A 1 mm-thick tantalum (Ta) slit with a gap of 30 \( \mu \text{m} \) is used for tailoring the transverse shape of the electron beam. The quasi-single-cycle THz pulse with a maximum field strength of 215 kV/cm is temporally synchronized with the electron bunch and then focused on a side of a copper (Cu) slit with a thickness of 25 \( \mu \text{m} \) and a gap of 30 \( \mu \text{m} \) (Fig. 2a). The Q-1D electron array, whose charge is estimated to be about 10 \( \mu \text{C} \), encounters the enhanced THz in-gap field. Subsequently, electrons carrying the THz waveform are detected by a p43 phosphor screen with an electron-photon conversion efficiency of 200 and an electron-multiplying CCD (EMCCD) camera. Optical delay tuning of the incident pulse provides real-time (50 Hz in this experiment) panning of the waveform, as shown in Fig.1c–e induces the waveform distortion in this graph as a function of the relative angle (\( \theta \)) of the wire-grid polarizer pair (orange dots). The blue solid curve is the quadratic sinusoidal fit to the experimental data. Time-varying \( E_{\text{in--gap}} \) from the single-shot data in the white box of (b). e, f Magnified plots of green and red boxes in (d) for presenting the accuracy of the vertical field amplitude (e) and temporal step per pixel of EMCCD camera (f).

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**Fig. 2 Proof-of-concept experiments for THz optical waveform measurement.** A Simple layout of the experimental setup. As the incident optical signal for the proof-of-concept experiment, a vertically polarized THz wave was focused on the thin copper slit by a single spherical lens. A wire-grid polarizer pair was utilized to control the electric field strength of the input THz signal. The fabricated copper slit with a gap size of 30 \( \mu \text{m} \) is shown in the inset image with a scale bar of 100 \( \mu \text{m} \). b THz waveform measured by the EMCCD. The white box represents a single-shot time window (W) for \( L = 3.78 \text{ mm} \) at the gap. By adjusting the optical delay between the input signal and the electron bunch, the region of interest in the time domain can be easily changed. c The experimental results on the detection linearity of our oscilloscope. The positive maximum values of the deflected electron array in the left image are plotted in the graph as a function of the relative angle (\( \theta \)) of the wire-grid polarizer pair (orange dots). The blue solid curve is the quadratic sinusoidal fit to the experimental data. d Time-varying \( E_{\text{in--gap}} \) from the single-shot data in the white box of (b). e, f Magnified plots of green and red boxes in (d) for presenting the accuracy of the vertical field amplitude (e) and temporal step per pixel of EMCCD camera (f).
Electro-optic/g415c sampling modulation with a period of 147.5 ± 6.34 GHz (Fig. 3b). In and the GaP crystal. These echoes shorten the available time
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by measuring THz waveforms by varying the angle of a wire-grid
via phosphor screen. Additionally, the detection linearity was proven
for details). For the recorded waveform with a
pixel (c)
form, as shown in Fig.2b. By extracting the waveform from the
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waveform recorded by the electron beam (E-beam) oscilloscope, and time
 trace of the THz field obtained by the EOS technique with an optical delay
scan. The vertical dashed lines indicate the positions of the main and echo signals.

of a single-shot time window (W) of 12.6 ps over the entire wave-
form, as shown in Fig. 2b. By extracting the waveform from the
CCD image (Fig. 2d), this oscilloscope yields a THz field oscillogram
with a vertical field accuracy of 120 V/m and a temporal step per
pixel (R) of 13.2 fs, as shown in Fig. 2e, f (see Supplementary Note 2 for
details). For the recorded waveform with a W of 12.6 ps, one pixel
for the single temporal step is comprised of about 66 electrons
via phosphor screen. Additionally, the detection linearity was proven
by measuring THz waveforms by varying the angle of a wire-grid
polarizer from 0 to 90°. Figure 2c shows the positive peaks values of
the deflection strength in ten oscillograms are well fitted by the
square of a sine function.

To further evaluate our experimental results, we compared
THz waveforms measured by both the conventional electro-optic
sampling (EOS) technique and our real-time electron oscilloscope
under the same experimental environment (see “Methods” for
details). The electro-optically recorded waveform contains echoes
of the main signal with a time interval of 6.78 ± 0.21 ps (Fig. 3a)
coming from the multiple reflections at the boundary between air
and the GaP crystal. These echoes shorten the available time
window for the Fourier transform and lead to spectral modulation
with a period of 147.5 ± 6.34 GHz (Fig. 3b).

In contrast, the relativistic electron oscilloscope shows a clear
 distinction in the signal integrity because the direct electron-
field interaction in vacuum is inherently free from echoes,
bandwidth limitations of the electro-optic crystal29 and complex
distortions that typically originate from nonlinearities of the
optical medium30. As we expected from Fig. 1e, the THz
waveform measured by the relativistic electron oscilloscope is

Fig. 3 Waveform comparison with conventional EOS. a Single-shot THz
waveform recorded by the electron beam (E-beam) oscilloscope, and time
trace of the THz field obtained by the EOS technique with an optical delay
scan. The vertical dashed lines indicate the positions of the main and echo signals.

b) Fourier-transformed spectra of THz signals in the time domain
(a), and their phase information. The amplitudes of both spectra are
normalized for clarity of comparison. The vertical dashed lines indicate the periodicity of the spectral modulation.

absolutely distortion-free due to the extremely high \( \lambda/c\sigma_e \) of
~108. Moreover, together with our simulation results on \( d \) and
\( c\sigma_e \) for a given \( \lambda \), the almost analogous phase evolutions, central
frequencies of ~0.37 THz, and spectral bandwidths of ~0.44 THz
in both spectra guarantee the fidelity of our stamping technique.

Real-time control of signal sampling rate. The convenient
zoom-in and -out of the measured waveform are fascinating
functions of this electron oscilloscope because R depends on the
electron beam divergence. Figure 4a illustrates the principle of
time-base control and waveforms recorded on the EMCCD for
three different divergences of the electron beam. The horizontally
over-focused electron beam enables the oscilloscope to obtain a
higher temporal accuracy per pixel of the EMCCD by a factor of
1 + (2Dtan\( \theta \)/\( L_{s l i t} \)) compared to the case of the collimated
electron beam, where D is the distance from the slit to the screen and
\( \theta \) is the divergence half-angle of the electron beam. A quadrupole
magnet is employed for controlling \( \theta \) and the corresponding \( L_{s l i t} \)
to control both R and W, as shown in Fig. 4b, c. We observed that
both R and W increase with the horizontal focusing strength (k).
For configuration III (\( k = 89 \mathrm{~m}^{-2} \)) in Fig. 4a, our oscilloscope visualizes the THz waveform with R of 0.565 fs in W of 273 fs,
corresponding to a sampling rate of 1.77 PS/s in real time.

Discussion

Although the bandwidth of this oscilloscope is estimated to be
~1 THz due to a limited bunch duration of our electron source
and an insufficient effective length of field, our simulation pro-
vides a possibility to improve the overall performance for
detecting an ultrarapid waveform (see Supplementary Note 4 in
details). Superconducting waveguide can be a simple way to
increase the characteristic length for measuring a waveform with
higher frequency. We believe that technical advances in attosecond electron bunch generation and ultra-sensitive electron
detector34 can overcome the current limitation in the near future.

In conclusion, we devised a real-time ultrafast oscilloscope based
on an ultrashort electron bunch train and successfully demonstrated
single-shot measurement of a THz wave with a frame rate of 50 Hz
as a proof-of-concept experiment. The direct imprinting of an in-gap
field preserving the incident waveform on a moving electron beam
allows us to observe a distortion-free full-field of light wave. Since
the demonstrated concept can be further available for the char-
dacterization of optical signals with any frequency or longitudinal
shape, future works will be focused on the experimental demon-
stration at higher frequency, for instance, in the near- and
mid-infrared frequency regions. We expect that our study will be the first
step towards real-time PHz oscilloscope technology.

Methods

Experimental setup. We used a 1 kHz Tisapphire regenerative amplifier ( Spitfire
Ace-35F1K, Spectra Physcis) delivering 35 fs (FWHM) laser pulses at a wavelength of
800 nm. The laser beam with an average power of 5 W was divided by a 9:1 beam
splitter to generate a THz pulse and an electron bunch. From a Cu cathode, the initial
electron bunch with a charge of 1 pC was generated by irradiating the third harmonic
radiation (150 μJ per pulse) of the fundamental laser pulse and then accelerated up to
3.1 MeV by a 1.5 cell RF cavity fed by an S-band (2.856 GHz) klystron at a repetition
rate of 50 Hz. The duration of the ultraviolet pulse was measured to be 130 fs (FWHM)
with a 60 mm F2.8D microlens.

The electron bunch was compressed down to 25 fs (rms) using its energy
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The THz waveforms were detected by a high-speed phosphor screen. These phosphor
tubes were reflected by a flat gold mirror with an incident angle of
45° and then detected by an EMCCD (Andor iXon Ultra 888, Oxford Instruments)
with a 60 mm F2.8D microlens.

The THz field was measured by a THz streak camera25. The normalized emittance of the electron beam was measured to be
0.25 mm mrad in both axes. The deflected electrons generated photons at the phos-
phor screen. These photons were reflected by a flat gold mirror with an incident angle of
45° and then detected by an EMCCD (Andor iXon Ultra 888, Oxford Instruments)
with a 60 mm F2.8D microlens.
Simulations. When the synchronized ultrashort electron bunch passes through the slit, it obtains vertical momentum, which is induced by the incident optical field. This in-gap field, $E_{\text{gap}}(t)$, is given by the following incident equation:

$$E_{\text{gap}}(t) = E_p \sin(\omega t)e^{-t/\tau_{\text{FWHM}}}$$

where $E_p$ is the peak electric field, $\omega = 2\pi/c$ is the angular frequency, $c$ is the speed of light, $\lambda$ is the wavelength of the incident field, and $\tau_{\text{FWHM}}$ is the duration of the laser pulse. The gain of the electron vertical momentum is

$$\Delta p_y(t) = \frac{e}{\mathcal{E}_{\text{gap}}}E_{\text{gap}}(t)/c,$$

where $L_{\text{eff}}$ is the effective length of the induced electric field inside the slit and $t$ is the moment of time when electron passes the middle of the slit. We assumed that the electron bunch has a longitudinal Gaussian distribution. The initial vertical beam divergence ($\gamma_{\text{ini}}$) of the electron beam and the kinetic energy $k$ of the electron bunch in the propagation direction are set to 40 rad and 3.1 MeV, respectively. The vertical divergence angle of electrons after the slit is $\gamma = \gamma_{\text{ini}} + \Delta p_y / p$.

Slit fabrication. The metal slit structure was fabricated by the careful alignment of two 25 μm-thick Cu foils with a purity of 99.8% (46365, Alfa Aesar) in parallel. This Cu slit was mechanically mounted by polyethylene plates for electric isolation.

THz pulse generation and characterization. The quasi-single-cycle THz pulse was generated by optical rectification in a 1.3 mol% MgO-doped stoichiometric LiNbO$_3$ crystal. A diffraction grating with a groove density of 1800 mm$^{-1}$ and a single spherical lens ($f = 150$ mm) were used for tilting the pulse front of the 800 nm pulse. The average power of the 50 Hz THz pulse train was measured to be 83.5 μW by a calibrated pyroelectric detector (THZ5B-MT-DZ, Gentec-EO) at the focal point of 50 mm. Its focal spot diameter was 1 mm (FWHM), as measured by a pyroelectric CCD camera (IR/V-T0831, NEC Corp.). The maximum THz electric field strength of the 215 kV/cm was analytically estimated (see Supplementary Note 3 for details). The THz time trace and its corresponding spectrum were obtained by EOS with a 0.3 mm-thick GaP crystal located at the same position as the Cu slit for a reliable comparison with the electron oscilloscope.

Data analysis. All waveforms were imprinted on a single electron bunch, so the relative timing jitter between the optical wave and the electron bunch at the slit can be considered negligible for distortion. The scales for both the time and field strength ($E_{\text{gap}}(t)$) on the EMCCD were calibrated by moving the high-accuracy optical delay stage (M-ILS200HA, Newport Corporation) and by using the formula

$$E_{\text{gap}}(t) = p c \Delta y / (c D L_{\text{eff}})$$

where $\Delta y$ is the amount of $y$-axis deflection, and $p$ is the momentum of electron, $L_{\text{eff}} = \int_{-d/2}^{d/2} E_x(x,0,z)dx / (kdc / E_x(x,0,0))$ is calculated effective length of the field. Each dot composing the THz waveform in Fig. 2d is the central value, which is obtained by a Gaussian fit along the deflection axis in the CCD image of Fig. 2b. For extraction of the single-shot time window size and the temporal resolution per pixel in all measured images, a pixel pitch of 32 μm was used, where the focal length of the light-collection lens was 60 mm.

Data availability

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Code availability

The codes and simulation files that support the plots and data analysis within this paper are available from the corresponding author upon reasonable request.

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Author contributions
I.H.B., H.W.K., S.P., K.Y.O., N.A.V. and Y.U.J. carried out the real-time electron oscil-loscope experiment. I.H.B., Y.C.K., M.K., K.L. and F.R. led the generation and char-acterization of THz field. J.S. contributed to the temporal stability improvement of electron bunch train. H.W.K., H.S.B., K.H.J. and K. Y. O. carried out the simulations and data analysis. I.H.B. and Y.U.J. wrote the manuscript, with input from all authors.

Competing interests
The authors declare no competing interests.

Additional information

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