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Ghost spintronic THz-emitter-array microscope

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Abstract

Terahertz (THz) waves show great potential in nondestructive testing, biodetection and cancer imaging. Despite recent progress in THz wave near-field probes/apertures enabling raster scanning of an object's surface, an efficient, nonscanning, noninvasive, deep subdiffraction imaging technique remains challenging. Here, we demonstrate THz near-field microscopy using a reconfigurable spintronic THz emitter array (STEA) based on the computational ghost imaging principle. By illuminating an object with the reconfigurable STEA followed by computing the correlation, we can reconstruct an image of the object with deep subdiffraction resolution. By applying an external magnetic field, in-line polarization rotation of the THz wave is realized, making the fused image contrast polarization-free. Time-of-flight (TOF) measurements of coherent THz pulses further enable objects at different distances or depths to be resolved. The demonstrated ghost spintronic THz-emitter-array microscope (GHOSTeam) is a radically novel imaging tool for THz near-field imaging, opening paradigm-shifting opportunities for nonintrusive label-free bioimaging in a broadband frequency range from 0.1 to 30 THz (namely, $3.3\text{--}1000\text{ cm}^{-1}$).

Introduction

The unique properties of terahertz waves (0.1–10 THz)^{1,2}, such as the nonionizing photon energy, spectral fingerprint, and transparency for most nonpolar materials, have attracted much research interest and enabled many applications, such as nondestructive testing³, biodetection^{4–6}, and cancer imaging⁷. However, the long wavelength of THz waves (1 THz $\sim$ 300 μm) typically limits the resultant imaging resolution to greater than the millimetre scale in conventional far-field imaging methods due to the well-known Rayleigh diffraction limit, therefore restricting their use in many emergent applications such as cellular imaging. On the other hand, near-field imaging by mapping the object-modulated evanescent waves paves the way towards deep subwavelength resolution and is particularly desirable at long wavelengths, for example, at THz frequencies. AFM-

or STM-tip-enhanced THz probes^{8,9} or microantenna/aperture THz probes¹⁰ have achieved micrometre- or even atomic-scale resolution⁹. Nevertheless, these techniques require mechanical raster scanning of the surface of an object pixel by pixel, with a relatively poor signal-to-noise ratio (SNR). Recently, near-field ghost imaging techniques^{11–14} have been experimentally demonstrated to increase the SNR by $\sqrt{N}$ times (where N denotes the pixel number of a digital picture) over that in raster scanning¹⁵. In these approaches, THz images are spatially encoded in the near field with deterministic patterns (e.g., the Walsh-Hadamard matrix^{11–17}). Then, the total intensities (or electric field amplitudes) of encoded THz images are collected and detected with a single-pixel detector in the far field. After postprocessing via computational algorithms to correlate the detected THz intensities (or electric field amplitudes) with the deterministic patterns^{18,19}, near-field images can be reconstructed. In this scheme, the sub-wavelength spatial information “hidden” in the diffracted far-field distribution can be recovered from the intensities (or amplitude fields) recorded by a mere single-pixel detector.

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To encode THz images in a single pixel, the conventional method is to use photogenerated spatial THz wave modulators as reconfigurable masks^{11–13}. However, the THz wave amplitude passing through the subwavelength apertures of modulators follows the scaling rule $1/a^3$ (where a denotes the diameter of the apertures on the mask)²⁰, which fails to image deep subwavelength structures.

Alternatively, directly detecting THz images¹⁴ or generating patterned THz waves^{16,17} by encoding femtosecond (fs) laser pulses in nonlinear electrooptic (EO) crystals (such as ZnTe) has been proposed to bypass the scaling rule. However, subwavelength structures are rapidly blurred upon propagation in hundreds of micrometre-thick EO crystals¹⁴ (Supplementary Fig. S1). Recently, the time-resolved single-pixel detection of THz pulses has been theoretically proposed¹⁶ and experimentally demonstrated¹⁷ to recover higher-resolution images. However, suffering from the millimeter-scale-thick nonlinear crystal, THz-wave generation along with diffraction occurs across the entire volume of the crystal, leading to a limited spatial resolution of 50–100 μm . Although the spatial resolution can be further improved by the inverse propagation algorithm, this requires full-wave measurements of THz pulses in the time domain with extra cost in terms of detection resources and involves an inverse problem. Furthermore, it only applies to recovering 2D-structured images. In addition, constrained by the electromagnetic boundary conditions (Supplementary Fig. S2), the distribution of the polarized THz field in subwavelength structures presents a “distorted” image^{11–14} that might lead to misrecognition of the object’s morphology.

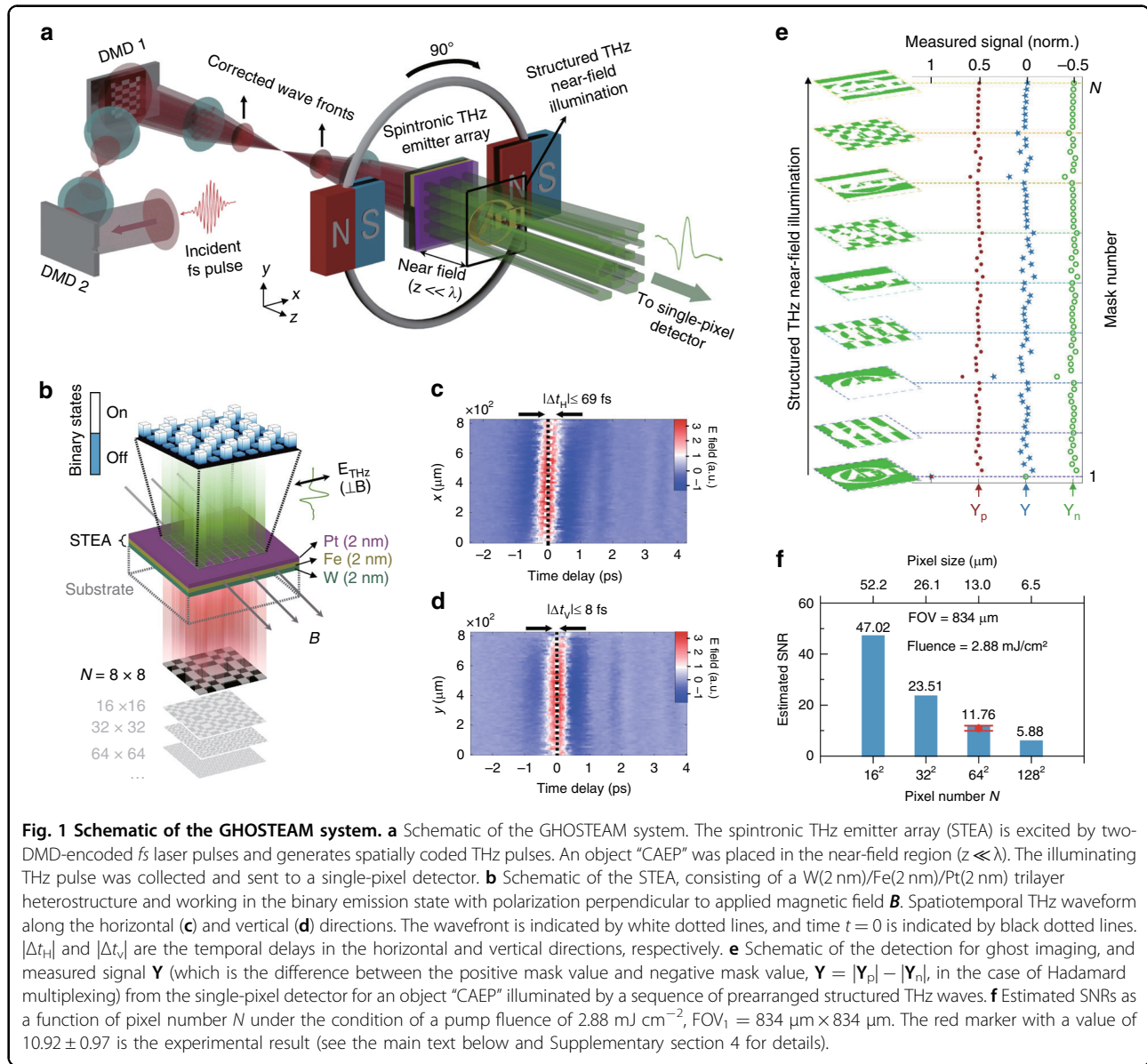
In this work, we utilize a spintronic THz emitter (STE) to illuminate an object in the near field. STEs are a novel type of THz emitter based on the spin-related effects^{21,22} in ferromagnetic/nonmagnetic (FM/NM) heterostructures^{23–26}, which are only a few nanometres thick but offer generation efficiency comparable to conventional millimetre-thick EO crystals. In principle, an STE can fully cover the 0.1–30 THz frequency range²⁴ without phonon absorption, which is superior to all the current solid emitters. Limited by the 1-mm-thick ZnTe used as the detector (3-THz detection bandwidth) and the pulse duration of the pump laser (~ 90 fs), the STE in our work provided a bandwidth of up to 2 THz. To date, all applications of STEs have only focused on their far-field properties, whereas the highly efficient few-nanometre-thick STE is capable of illuminating an object at an extremely near field, which naturally breaks the diffraction limit. The key challenge for using STEs in near-field imaging is how to map the object-modulated THz field without near-field scanning probes. In view of this, we developed a near-field illuminating “array” (STEA) whose “elements” are coherent and individually programmable in binary states of either “on” or “off” by photoexcitation. Combining the programmable near-field illuminating STEA and far-field single-pixel detection, we

designed and demonstrated a novel ghost spintronic THz-emitter-array microscope (GHOSTTEAM) for THz wave imaging with deep subdiffraction resolution. A minimum resolution of 6.5 μm at a single pixel was demonstrated with a contrast of more than $57 \pm 21\%$ ($>20\%$ required by the Rayleigh criterion¹⁴) in a 6- μm metal gap. In addition, polarization effects on the subdiffraction-limited image were eliminated via postprocessing of two images with mutually orthogonal polarizations. In addition, TOF microscopic topography was demonstrated with a 3D silica structure.

Results

Concept design

In our design, as shown in Fig. 1a, the STEA under external magnetic field $\mathbf{B}$ generates spatially structured THz pulses upon fs-laser-pulse spatial photoexcitation. The STEA, consisting of a W(2 nm)/Fe(2 nm)/Pt(2 nm) trilayer heterostructure on a transparent MgO substrate (Fig. 1b), provides great THz conversion efficiency in terms of output amplitude, comparable to that of 1-mm ZnTe²⁴. The STEA is capped with a 150-nm SiO_2 layer ($n = 1.97$) to protect it from being damaged by the fs laser. The output THz electric field $\mathbf{E}(t)$ is linearly polarized perpendicular to the applied magnetic field $\mathbf{B}$, as described by $\mathbf{E}(t) \propto (\mathbf{J}_c = \mathbf{J}_s \times \mathbf{B})^{21–26}$, where $\mathbf{J}_s$ represents the spin current induced by the fs laser and $\mathbf{J}_c$ represents the charge current converted in the NM metals under $\mathbf{B}$. To perform ghost imaging (see “Materials and methods” for details), the Walsh–Hadamard matrix²⁷ was used to code the STEA due to its unrivalled noise suppression performance among various measurement matrices^{11–17}. The patterns, programmed in the order of the Walsh–Hadamard masks, were spatially encoded on the excitation fs laser beam by a digital micromirror device (DMD) with a switching time of 5 μs . On the exit surface of the STEA, the profile of the output THz pulse is as accurate as that of the excitation fs laser because the 150 nm propagation distance in the SiO_2 protective layer is too thin for the THz wave to be diffracted ($150 \text{ nm} \approx 5 \times 10^{-4} \lambda_0/n$, where $\lambda_0 = 600 \mu\text{m}$ and $n = 1.97$; see Supplementary Fig. S1 for the theoretical calculation of the near-field evanescent wave). The spatial near-field profile of the THz pulse from the STEA consists of individually real-time programmable “elements” up to 128×128 (see Supplementary Fig. S3) in either “on” or “off” binary emission states, as shown in Fig. 1b. The pixel size of each “element” is $6.5 \mu\text{m} \times 6.5 \mu\text{m}$ in our experiments, which can be zoomed in or out by using an optical projection imaging system depending on the practical requirements. After being transmitted through an object placed in the near-field region ($z = 150 \text{ nm}$), the structured THz pulses were collected and focused onto a 1-mm-thick (110) ZnTe crystal for single-pixel coherent detection by EO



sampling. The peak electric amplitudes were recorded for reconstructing THz subdiffraction ghost images.

After reflection upon a DMD, the fs laser pulse suffers from wavefront tilt in the DMD deflection direction (horizontal) since the DMD is essentially a reflective blazed grating²⁸. The resultant fs laser pulse with a tilted wavefront will badly lose its temporal coherence among individual micromirrors along the deflection direction. To correct the wavefront tilt, another DMD (DMD₂) was imaged onto the encoding DMD (DMD₁) by a 4f system with a 1:1 imaging ratio, as shown in Fig. 1a. Due to the fixed time delay of ghost imaging (corresponding to the peak of the THz pulses), the DMD-induced temporal smearing should be minimized. Otherwise, decoherence (large time delay in the wavefront) would result in severely distorted images (see Supplementary Fig. S6). The temporal delay in the

horizontal direction $|\Delta t_H|$ was ultimately corrected to less than $69 \pm 13 \text{ fs}$ (Fig. 1c) but could not be completely eliminated due to the manufacturing tolerance of the tilt angles of the two DMDs (see Supplementary Fig. S6). Meanwhile, the temporal delay in the vertical direction $|\Delta t_V|$ was measured to be less than 8 fs (Fig. 1d), which is expected because the two DMDs only deflect in the horizontal direction. The spatiotemporal THz waveforms (Fig. 1c, d) were measured by ghost imaging using 64-order Walsh–Hadamard coding 1-D masks (see “Materials and methods” and Supplementary Fig. S5 for detailed information and Supplementary GIFs. 1 and 2 for raw data).

An object was illuminated by the coherent programmable STEA using a sequence of prearranged Walsh–Hadamard masks, and the computational ghost

imaging algorithm was applied to correlate the peak amplitude measured by a single-pixel detector with the sequence of predetermined incident THz wave patterns (Fig. 1e, with the detailed procedure shown later). The reconfigurable area on the STEA, defined as the first imaging field of view FOV_1 , was measured as $834\ \mu\text{m} \times 834\ \mu\text{m}$, with up to 128×128 coding pixels. The SNRs of reconstructed images encoded by Walsh–Hadamard masks were numerically determined as a function of the pixel number (or pixel size in FOV_1 ; see “Materials and methods”), which gave a reasonable value of ~ 47.02 when FOV_1 was coded into 16×16 pixels under our experimental conditions (pump fluence $\sim 2.88\ \text{mJ cm}^{-2}$, dynamic range of peak field ~ 1043 , and pulse fluctuation $\sim 0.7\%$), as shown in Fig. 1f. It is worth noting that although the detected THz band was less than 2 THz due to the 90-fs pulse and 3-THz detection bandwidth (1-mm ZnTe), the STE has demonstrated complete coverage of the entire THz region, i.e., 0.1–30 THz, when a shorter pump pulse (10 fs) and a wide-band detector are used^{24,26}. More experimental details are given in “Materials and methods” and Supplementary section 2.

Subdiffraction ghost imaging

The STEA was experimentally reconfigured in a 64×64 -order Walsh–Hadamard matrix sequence to acquire THz subdiffraction-limited images of an object (see Fig. 2a) positioned $z = 150\ \text{nm}$ from the STEA (thickness of the protective SiO_2 layer on top of the STEA). The field amplitudes of spatially coded THz waves that passed through the object were measured at a fixed time delay of 0 ps (as indicated by the black dotted lines in Fig. 1c, d). The reconstructed 64×64 ghost images in $FOV_1 = 834\ \mu\text{m} \times 834\ \mu\text{m}$ with mutually orthogonal polarizations are shown in Fig. 2b, c, whose pixel sizes are both $13.0\ \mu\text{m} \times 13.0\ \mu\text{m}$. The reconstructed 64×64 ghost image in a smaller area $FOV_2 = 417\ \mu\text{m} \times 417\ \mu\text{m}$ (indicated by the black dashed box in Fig. 2a) with a smaller pixel size of $6.5\ \mu\text{m} \times 6.5\ \mu\text{m}$ is shown in Fig. 2d. The y -dependent THz field distribution across the slit region (indicated by the black dashed arrow in Fig. 2b) was extracted from the associated pixels, as shown in Fig. 2e. Note that every pixel value was averaged from the identical-row pixels within the slit region, with prior knowledge about the object’s horizontal homogeneity in the slit region. A contrast ratio of $57 \pm 21\%$ ($>20\%$ required by the Rayleigh criterion¹⁴ for distinguishing slits) was observed in the narrowest 6- μm metal slit within FOV_2 (see Supplementary section 5 for the quantification process and Supplementary GIFs. 3–5 for the raw data), which clearly proves that our GHOSTEAM system deeply breaks the diffraction barrier of $\sim 366\ \mu\text{m}$ for the 600- μm THz wave (Rayleigh resolution of $0.61\lambda_0/\text{NA}$). The spatial resolution of the GHOSTEAM system using this

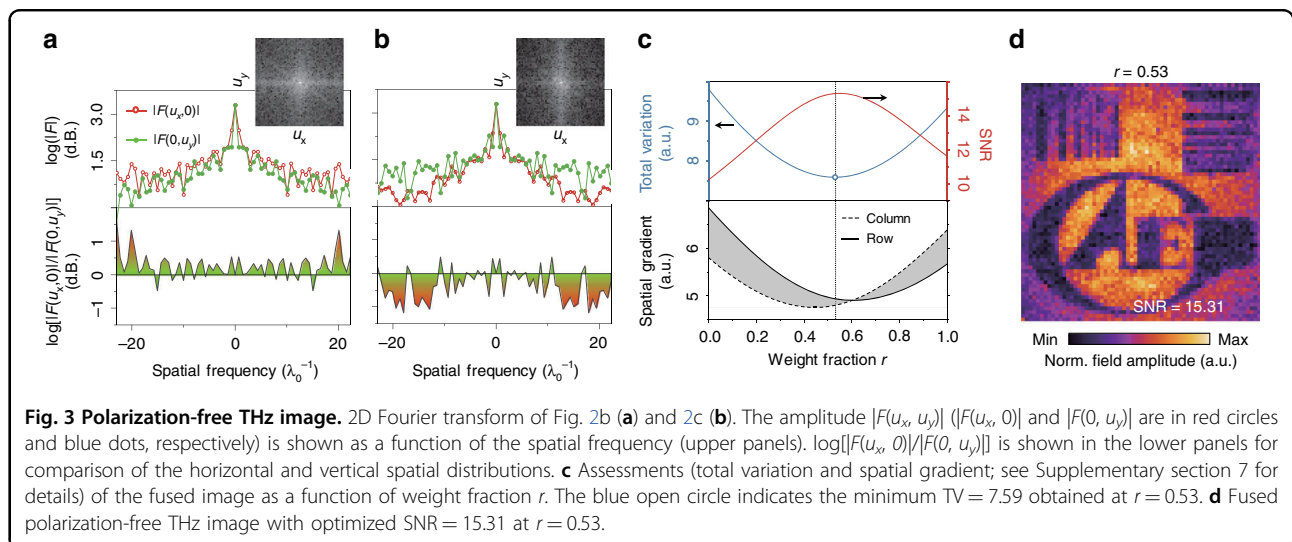
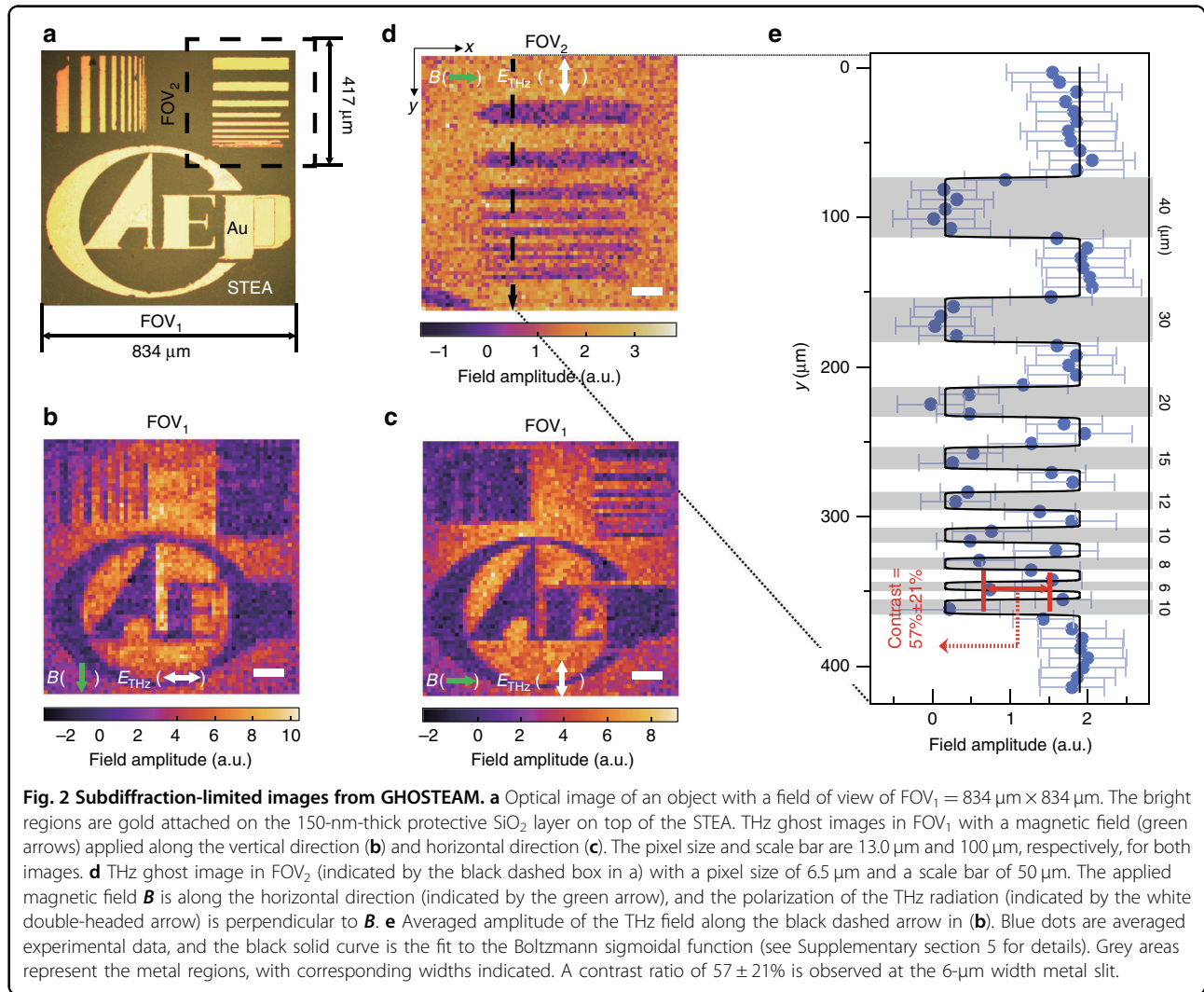
experimental setup is limited to the minimum available pixel size of $6.5\ \mu\text{m}$, which depends on the accuracy of the mask patterns on the STEA projected by the DMD. As the micromirrors of the DMD are arranged in the diamond orientation, the accuracy of the coding profile on the STEA is decreased since a mask pixel is formed by fewer micromirrors (see Supplementary Fig. S3). Regardless of the diffraction of the coding optical light, the resolution of GHOSTEAM is limited by the propagation distance between the emission surface of the STEA and the object (the thickness of the protective 150-nm-thick SiO_2 layer in this experiment), which is theoretically estimated as submicrometer (see Supplementary Fig. S1).

Polarization-free image

Polarization impacts the subwavelength imaging (see the dark region where the slits are along the wave polarization in Fig. 2b, c), which is expected due to the electrical field boundary conditions at the subwavelength scale^{11,13,14} (see Supplementary Fig. S2) and hinders accurate resolution of the object’s morphology. With advancement of the in-line rotating THz wave polarization by an external magnetic field, we secured two images with mutually orthogonal polarizations. This feature allows us to achieve a higher-contrast polarization-free image through postfusion of the two images. To do this, 2D Fourier transform was applied to Fig. 2b, c individually to quantify the distribution in the spatial frequency domain $|F(u_x u_y)|$ along the x and y directions. The amplitude $|F(u_x u_y)|$ as functions of spatial frequencies u_x and u_y is shown in Fig. 3a, b, which indicates loss of the high spatial frequency ($>10/\lambda$) components parallel to E_{THz} in the polarization images. To acquire polarization-free THz image $\mathbf{X}_F$, the THz ghost images with horizontal polarization $\mathbf{X}_H$ (Fig. 2b) and vertical polarization $\mathbf{X}_V$ (Fig. 2c) were fused by the weighted average method, namely, $\mathbf{X}_F = r\mathbf{X}_H + (1-r)\mathbf{X}_V$, where r represents the weight fraction and lies within $[0, 1]$. The total variation (TV), which is a common assessment parameter for image clearness, was chosen to guide the optimization of the fusion process. The TV of $\mathbf{X}_F$ was calculated by

$$\text{TV} = \left(\sum_{i=2}^{64} \sum_{j=2}^{64} [(\nabla_H \mathbf{X}_F(i, j))^2 + (\nabla_V \mathbf{X}_F(i, j))^2] \right)^{1/2} \quad (1)$$

where ∇_H and ∇_V are the discretized gradient operators along the horizontal and vertical directions, respectively. At the ratio of $r = 0.53$ in Fig. 3c, the minimal TV was achieved, and the corresponding optimal fused image is shown in Fig. 3d. In addition, the SNR (see Supplementary Fig. S13) and directional spatial gradients²⁹ of the fused image are also given in Fig. 3c. The directional spatial



gradients of $\mathbf{X}_F$ were used to quantify the spatial information of the fused image and were calculated by

$$G_{\text{row}} = \left(\sum_i^{64} \sum_{j=2}^{64} [(\nabla_H \mathbf{X}_F(i, j))^2] \right)^{1/2} \quad (2)$$

$$G_{\text{col}} = \left(\sum_{i=2}^{64} \sum_j^{64} [(\nabla_V \mathbf{X}_F(i, j))^2] \right)^{1/2} \quad (3)$$

As shown in Fig. 3c, the fused image at $r = 0.53$ shows more homogeneous spatial information in the vertical and horizontal directions, as visually presented in Fig. 3d, which proves that the polarization impacts are effectively overcome and that the original object's morphology is better reproduced.

Time-of-flight topography

Since the THz emission from the STEA used in our GHOSTEAM system is coherent, TOF measurements³⁰ of THz pulses from the STEA can be adopted to enable microscopic topography of objects with depth resolution. TOF topography utilizes the optical path differences among different media to acquire the depth (z axis) distribution of a 3D object. For the sake of illustration, a 3D object made of silica by fs laser manufacturing (see “Materials and methods”) with three SiO_2/air interfaces with air depths of 0, 100 and 200 μm (illustrated in Fig. 4a) was used to demonstrate TOF microscopic topography using the GHOSTEAM system. The structured silica was attached to the external surface of the STEA. Transient THz waveforms from the STEA that passed through the object within and outside the region of the trilayer structure were measured and are shown in Fig. 4b. Three THz ghost images relevant to the three interfaces, under the field of view FOV_1 , were measured at fixed time delays of 0, -0.33 and -0.66 ps (indicated by the three solid circles in Fig. 4b), as shown in Fig. 4c–e. The reconstructed images agree with the simulated electrical field distributions (Fig. 4f–h; see “Materials and methods” for simulation details). The subwavelength structures (scale of $\sim \lambda_0/6$) of the three interfaces are well resolved both experimentally and theoretically (note that diffraction leads to distortion in reconstruction of the middle interface).

Discussion

In conclusion, we have presented a novel GHOSTEAM system for THz wave near-field microscopic topography. Compared with other existing THz wave near-field imaging systems, the GHOSTEAM system utilizes a real-time, reconfigurable, coherent STEA for structured near-field illumination. It was numerically and experimentally demonstrated that such a system can feature both micrometre-scale-resolved microscopy ($\leq 6.5 \mu\text{m}$) and

depth-resolved topography. Further optimized optical projection imaging systems could enable submicrometre-scale resolution. Polarization-free subdiffraction-limited imaging was also achieved owing to the flexible tunability of the STEA.

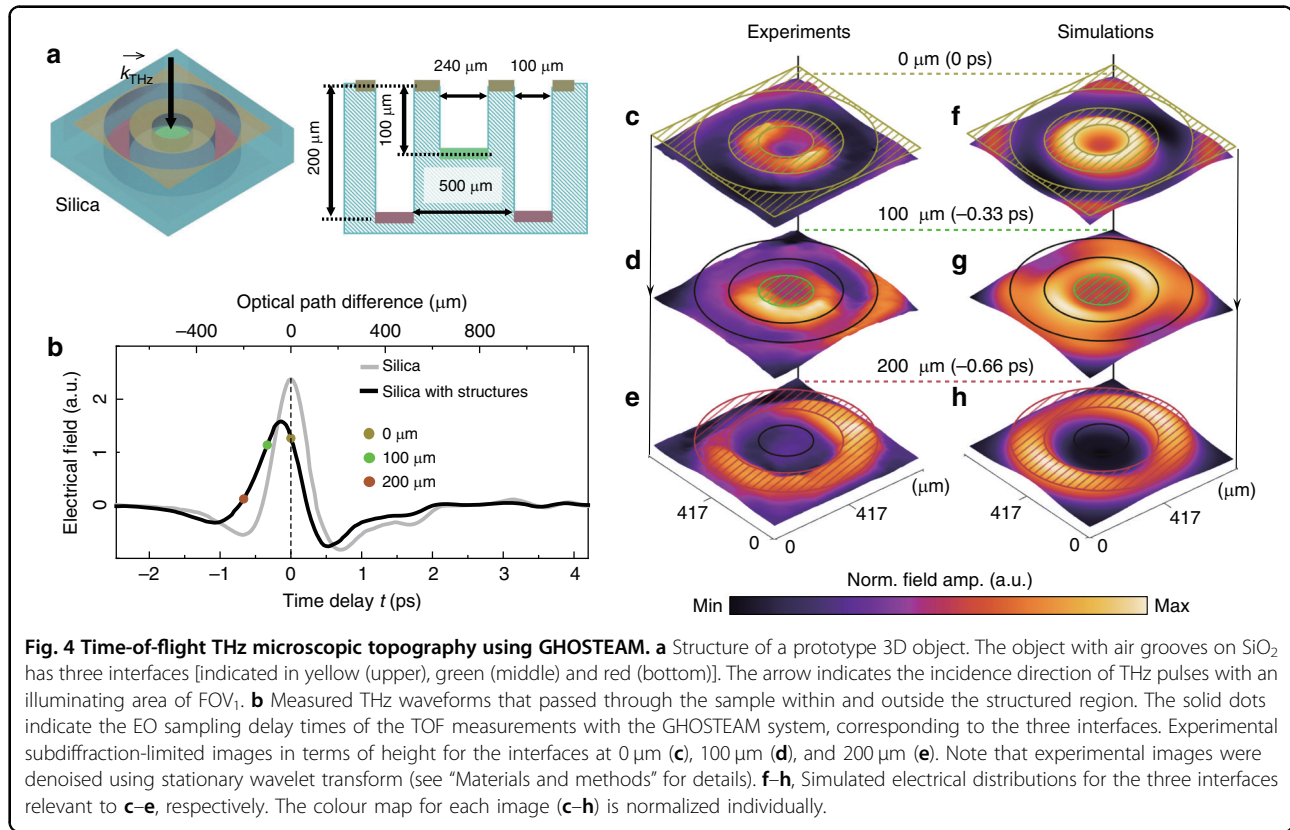
The capacity of an STE to provide efficient THz pulses would further enable label-free cellular imaging or ultra-precise topography, a feature lacking in the current THz near-field imaging systems. STEs fabricated on flexible substrates³¹ would extend our GHOSTEAM system to imaging of objects with curved surfaces. Oscillator fs lasers have been demonstrated to drive STEs with a dynamic range above 60 dB (1000:1)²⁶. Taking advantage of the MHz repetition rate and stable pulse energy of oscillators, the GHOSTEAM system is endowed with a much faster acquisition speed (in principle, an 18-fold improvement can be expected; see “Materials and methods” and Supplementary Fig. S9 for the estimation) than all other existing THz wave subdiffraction ghost imaging systems^{11–14,16,17}, which require an amplified fs laser with a few-kilohertz repetition rate, leading to a slow acquisition speed and a complex system. In addition, using a shorter fs pulse and a wide-band detector, the ultra-broadband property of STEs, fully covering 0.1–30 THz frequencies²⁴, has great potential for broadband THz applications. In addition, the GHOSTEAM system is compatible with compressive sensing (see Supplementary GIFs. 1–5), adaptive sampling^{12,32}, parallel acquisition in k -space³³ and coherent time-resolved full-wave detection in the time domain^{16,17}.

Materials and methods

Experimental details

THz pulses (0.2–1.7 THz with a central frequency of 0.5 THz) were generated in $\text{W}(2 \text{ nm})/\text{Fe}(2 \text{ nm})/\text{Pt}(2 \text{ nm})$ trilayer heterostructures [placed in a rotatable dc field ($|\mathbf{B}| = 80 \text{ mT}$)] by an 800-nm laser (duration of 90 fs, repetition rate of 1 kHz, and pump pulse energy of 20 μJ). The THz signals were electrooptically sampled by 1-mm-thick ZnTe (110) in combination with a balanced detector and were eventually recorded by a lock-in amplifier with an integration time of 100 ms (see Supplementary Fig. S4 for details). All the THz ghost images were multiplexed using the Walsh–Hadamard matrix and operated at respective fixed time delays (e.g., the peak time delays for Fig. 2b–d and appropriate time delays for Fig. 4c–e indicated in Fig. 4b). The acquisition time for each mask was 2 s, and the imaging time for each 64×64 ghost image (Fig. 2b–d) was ~ 4.5 h.

To optimize the wavefront of fs pulses, three steps were adopted to determine the positions of DMD₁ and DMD₂ (Wintech DMD4500, which contains 1140×912 diamond-arrayed micromirrors with a tilt angle of $12 \pm 1^\circ$ and a micromirror pitch of 7.6 μm). First, we acquired the



one-to-one image of DMD₂ by placing a CCD (see Supplementary Fig. S4c) at the presupposed position of DMD₁ to adjust and determine the positions of DMD₂ and two lenses (focal lengths of 100 mm). Second, by adjusting the position of DMD₁, it could be determined when the images (at the presupposed position of the STE) shaped by DMD₁ and DMD₂ individually were simultaneously sharp. Third, their positions were accurately adjusted by measuring the waveforms of the Walsh–Hadamard masks of #2p and #2n (see Supplementary section 3) until reaching the minimal peak time delay difference between the two waveforms. The tilt angle difference between DMD₁ and DMD₂ was measured as 0.40° by comparing the zero-order diffraction angles of the two DMDs in the case of normal incidence.

Computational ghost imaging

Let $\mathbf{O}$ represent the pixelated imaging target, consisting of N unknown elements $\mathbf{O}(i)$ at pixel i . $\mathbf{O}$ is a vector reshaped from the initial $L \times L$ image matrix $\mathbf{O}_m$, where $L \times L = N$. The DMD is used to display the Walsh–Hadamard masks $\phi_1, \phi_2, \dots, \phi_N$ in sequence. ϕ_i with mask number i ($1 \leq i \leq N$) is an $L \times L$ matrix reshaped from the i th row of the N -order Walsh–Hadamard matrix Φ . Then, the correlation between the mask and object, which is recorded by a single-pixel detector, can be

mathematically described by their inner product

$$y_i = \langle \phi_i, \mathbf{O} \rangle \quad (4)$$

where ϕ_i is an N -length vector reshaped from Φ_i . The complete measurement vector is then given by

$$\mathbf{Y} = \Phi \mathbf{O} \quad (5)$$

In the experiments, the Walsh–Hadamard matrix consisting of “+1” and “−1” elements was realized by

$$\Phi = \Phi^{(p)} - \Phi^{(n)} \quad (6)$$

since the DMD can only modulate the amplitude of the incident light. In Equation (6), $\Phi^{(p)}$ is constructed by substituting all “−1” elements in Φ with “0”. $\Phi^{(n)}$ is acquired by $\Phi^{(p)} - \Phi$.

Ultimately, the ghost image can be reconstructed by

$$\mathbf{X} = \Phi^{-1} \mathbf{Y} = \Phi^{-1} (\Phi \mathbf{O}) = \mathbf{O} \quad (7)$$

Spatiotemporal THz waveform mapping

Let $E(\xi, t)$ represent the THz spatiotemporal waveform to be measured, where ξ and t represent the spatial and

temporal coordinates, respectively. $E(\xi, t)$ consists of N time-dependent vectors

$$E(\xi, t) = \begin{bmatrix} E_1(t) \\ E_2(t) \\ \vdots \\ E_N(t) \end{bmatrix} \quad (8)$$

The sequentially recorded signals $S(\xi, t)$ can be written as

$$S(\xi, t) = \begin{bmatrix} s_1(t) \\ s_2(t) \\ \vdots \\ s_N(t) \end{bmatrix} = \Phi E(\xi, t) \quad (9)$$

Once the complete measurements are obtained, $E(\xi, t)$ can be calculated as

$$E(\xi, t) = \Phi^{-1} S(\xi, t) \quad (10)$$

In the experiments, the i th mask had $N = 64$ identical rows (columns) for spatiotemporal waveform mapping in the vertical (horizontal) direction, and every row (column) of the mask was the i th row of Φ . The spatial and temporal resolutions were $13 \mu\text{m}$ and 33 fs , respectively, for both Fig. 1c, d. The wavefront was then regarded as a linear fit of the peak time delay in $E_i(t)$ to the corresponding spatial coordinate ξ (see Supplementary Fig. S5).

Estimation of the SNR and potential frame rate of ghost images

The SNRs of ghost images obtained via Hadamard multiplexing (Fig. 1f) were estimated by the following equation (see Supplementary section 4 for the detailed mathematical derivation):

$$\text{SNR}_H = \sqrt{\frac{k}{2N[\gamma_d^2 + (\gamma_s/2)^2]}} \quad (11)$$

where γ_d denotes the ratio of the dark noise to the THz peak, γ_s denotes the ratio of the peak root mean square error to the THz peak, N denotes the pixel number of the ghost image and k denotes the number of measurements for each mask. In our experimental setup, γ_d was measured as 1×10^{-3} , and γ_s was measured as $\sim 7 \times 10^{-3}$, as indicated in Fig. 1f. Each mask value was averaged for $k = 15$. With these parameters, the SNR_H was estimated as 11.76 in the case of $N = 64 \times 64$, according to Eq. (11).

The frame rate equals $\text{FPS} = 1/(2Nr_c t_{\text{mask}})$, where t_{mask} represents the acquisition time for each mask and r_c

represents the compressive ratio. t_{mask} can be expressed as

$$t_{\text{mask}} = 2N(\gamma_{d0}^2 + \gamma_{s0}^2/4)t_0 \text{SNR}_H^2 \quad (12)$$

where t_0 denotes the pulse period and γ_{d0} and γ_{s0} denote the ratio of the dark noise to a single THz peak and the pulse fluctuation ratio within the “integration time” of t_0 , respectively. For an 80-MHz-oscillator-driven GHOS-TEAM system, reasonable values are $t_0 = 12.5 \text{ ns}$, $\gamma_{d0} = 2.83$ (corresponding to a dark-noise-to-peak ratio of $\gamma_d = 1 \times 10^{-3}$)²⁶, and $\gamma_{s0} = 3.8 \times 10^{-3}$ (see Supplementary Fig. S8). With these parameters and $\text{SNR}_H = 11.76$, the acquisition time $2Nt_{\text{mask}}$ for a 64×64 ghost image was calculated as $\sim 15 \text{ min}$, yielding an imaging speed improvement by a factor of ~ 18 (4.5 h/15 min).

Fs laser manufacturing

The silica sample with three air/silica interfaces for topography was manufactured by the femtosecond laser ablation method. In this method, a Ti-sapphire laser beam (800-nm central wavelength, 30-fs pulse width, 1-kHz repetition rate and 100-mW average power) was focused onto a silica substrate (1-mm thickness) using an objective lens (10 $\times$, numerical aperture NA = 0.25). The silica substrate travelled along multicircular trajectories at a speed of $100 \mu\text{m/s}$ (original radius r_0 was $10 \mu\text{m}$, interval between two adjacent circular trajectories Δr was $10 \mu\text{m}$, travel number n_r was 10, and the radius of the inner circular was $r = r_0 + \Delta r(n_r - 1) = 100 \mu\text{m}$). The laser ablation depth under the above parameters was $\sim 50 \mu\text{m}$, and the same ablation process was repeated to obtain an ablation depth of $100 \mu\text{m}$, while the silica substrate was moved $50 \mu\text{m}$ up from the laser spot. Using the same laser fabrication method, the outer circular was produced with $R_0 = 250 \mu\text{m}$, $\Delta R = 10 \mu\text{m}$, $n_r = 15$, and $R = R_0 + \Delta R(n_r - 1) = 400 \mu\text{m}$. The process was repeated to obtain a deeper interface.

Denosing and simulating near-field ghost topography

The results of near-field ghost topography (Fig. 4c–e) were denoised using the MATLAB toolbox Stationary Wavelet Transform Denoising 2-D. A five-level Haar wavelet was used to decompose the images. The selected threshold method was penalized low soft thresholding.

The electromagnetic field distributions as the THz pulse propagates in the near field (Fig. 4f–h) were simulated using the Wave Optics module of the commercial software COMSOL Multiphysics. Certain THz waves acquired in the experiment were set as the incident source, and the time-dependent solver was used to resolve the electromagnetic field distributions at discrete times (the time step was 33 fs). The study domain was a rectangle that was divided into silica ($n_{\text{silica}} = 1.97$) and air ($n_{\text{air}} = 1$), as illustrated in Fig. 4a.

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Author contributions

L.-G.Z., S.-C.C., Z.F., J.L. and W.T. conceived the project. S.-C.C., J.L. and Z.-H.Z. designed and performed the imaging experiments. Z.F. and W.T. designed and realized the STE-related module. J.W.C., Y.C.M., K.H. and H.F.D. fabricated the STE samples, 3D silica structure and metal patterns. Z.-R.L., C.-W.Q. and X.-C.Z. helped design the concept. All authors discussed the results and reviewed the manuscript.

Conflict of interest

L.-G.Z. is a named inventor on Chinese patent number 201310442738.9 (publication date 27.05.2015, filing date 26.09.2013). L.-G.Z., J.L., L.-H.D., Z.-H.Z. and Z.-R.L. are named inventors on Chinese patent number 201410815227.1 (publication date 25.03.2015, filing date 24.12.2014), which is related to the THz wave ghost microscope. L.-G.Z., S.-C.C., J.L., L.-H.D., Z.-H.Z. and Z.-R.L. filed a Chinese patent (number 201911281187.6, filing date 11.12.2019), which is related to the concept demonstrated in this work.

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