

Electrically controlled real-time terahertz “microladder” integrated with VO₂ patches for broadband holographic encryption

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Abstract. High-quality and real-time holographic imaging based on dynamically tunable metasurfaces has attracted immense interest. Despite remarkable progress, the complex electrical pattern designs and slow-speed near-field scanning terahertz (THz) microscopy systems have significantly hindered the development of real-time electrically tunable metasurface holography in the THz band. We propose and experimentally demonstrate an electrically tunable vanadium dioxide (VO₂)-based active metasurface that can generate real-time bias-controlled holographic information via a THz focal plane imaging system. By elaborately designing “microladders” integrated with VO₂ pads, the device exhibits low power consumption (~0.8 W) and real-time imaging (~4.5 s). The quantitative method is theoretically utilized to investigate the thermal parameters dependent thermodynamics of the “ladder” metasurface based on theoretical analysis with the aid of thermal modelling. The calculated dynamic response time based on the quantitative thermodynamic model agrees well with experimental results. Our study can be used to propel the development of THz electrically tunable metasurfaces for low-power-consumption dynamic, real-time displays, and information encryption, providing crucial insights for future optimization of VO₂-based electrothermally tunable holographic metasurfaces.

Keywords: terahertz; electric tenability; VO₂ metasurface; holography; optical encryption.

Received Apr. 17, 2025; revised manuscript received Jul. 25, 2025; accepted for publication Aug. 21, 2025; published online Sep. 25, 2025.

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[DOI: [10.1117/1.AP.7.6.066003](https://doi.org/10.1117/1.AP.7.6.066003)]

1 Introduction

Terahertz (THz) radiation shares certain properties with infrared and microwave radiation in the electromagnetic spectrum. Effective manipulation of THz waves by functional devices

is important for next-generation technological applications such as wireless communications,^{1,2} sensing,^{3,4} and imaging.^{5,6} However, owing to the weak interactions between most natural materials with THz waves, the development of THz functional devices has been severely hindered.

Metasurfaces, which are 2D artificial planar devices composed of subwavelength units exhibiting novel physical properties beyond those of natural materials,^{7–10} have emerged as powerful platforms for manipulating THz waves at the subwavelength

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scale. Owing to the unique electromagnetic properties of metasurfaces, many attractive applications have been achieved, including beam manipulation, anomalous refraction or reflection,^{7,8,10–14} beam shaping,^{15–18} and holography.^{19–22} Holography is a 3D imaging technique and represents an essential direction for the future development of metasurfaces. Compared with broadly used spatial light modulators based on holograms, which suffer from modulation errors, high-order diffractions, and narrow viewing angles in their produced holographic images, THz metasurfaces are considered promising alternative candidates for solving the above problems. Owing to its subwavelength resolution and ability to control complex wavefronts, metasurface holography can achieve higher resolution, higher efficiency, and better imaging quality, eliminate high diffraction orders, and expand the field of view.^{23–28}

Metasurfaces are typically static devices with predefined fixed functionalities, unfavourable to the realization of the encryption system. Recently, actively tunable metasurfaces have been experimentally demonstrated with the aid of semiconductors,^{29–32} phase-change materials,^{33–38} liquid crystals,^{39–42} and 2D materials.^{43–46} Among them, VO₂ is particularly fascinating owing to its reversible insulator–metal transition (IMT) characteristic of a low critical temperature of 68°C.⁴⁷ At room temperature, VO₂ presents an insulating state with a monoclinic structure. When the temperature increases above its transition temperature, VO₂ transforms into the metallic state with a rutile structure. By decreasing its temperature below 68°C, VO₂ will return to its insulating state with a monoclinic structure. Therefore, VO₂ has been widely used in the development of active metamaterials at THz frequencies.^{48–51} For example, Zhao et al.⁵² demonstrated a THz modulator based on a Si-VO₂ hybrid metasurface that achieved thermal tuning of the transmitted wave and had excellent modulation capability in the range of 0.4 to 1.8 THz. Li et al.⁵³ designed a THz switch based on VO₂ embedded in a metasurface that could be dynamically altered from a broadband absorber to an efficient reflector under thermal management. THz dynamical holography has also been experimentally verified by thermal control based on VO₂-integrated metasurfaces. Under external heating, the insulator-to-metal transition property of VO₂ dynamically changes the overall generated holographic image to achieve thermally controlled holography⁵⁴ and encryption.⁵⁵ However, external thermal control requires complex working conditions, and its switching time is limited by global heating and cooling processes. In addition, the above THz active holography/encryption was measured via 2D scanning of the metasurface with the probe, which hinders real-time applications.

Owing to their flexibility and high speed, electrically controlled metasurfaces have become an attractive approach for the development of fast THz devices with different functionalities, such as angle deflection,^{56,57} modulation,^{58–61} and memory storage.^{62–66} More recently, the VO₂ phase-compensated metasurface has been numerically demonstrated to generate holographic information in the visible region and further applied in high-security digital encryption, but experimental verification is still lacking.⁶⁷ To date, real-time THz electrically controlled meta-holograms for reversible encryption have rarely been experimentally demonstrated.

In this work, VO₂ patches are integrated into a “ladder” design metasurface to attain electrically tunable transmissive holographic devices working within 0.47 to 0.7 THz. The conceptual design is shown in Fig. 1. Electrical control requires the strict

design of the electrodes applied to the meta-holograms, distinct from the design principle for thermal modulation.^{54,55} Here, a “ladder” design VO₂ integrated metasurface is purposely designed to achieve significant amplitude modulation at different bias currents. Our “ladder” design metasurface can be easily integrated with electrodes on a printed circuit board (PCB) to achieve a low threshold current via electrical modulation. We further achieved a real-time metasurface hologram based on a THz focal plane imaging system.^{68,69} The fabricated holographic metasurface experimentally demonstrated the feasibility of broadband encryption and holographic imaging by changing the bias current. Then, we employed a quantitative method to investigate the thermal parameters dependent thermodynamics of the “ladder” metasurface based on thermal simulations with the aid of theoretical analysis. The simulation results agree well with the experimental dynamic response of the holographic VO₂ metasurface.

2 “Ladder” Metasurface Design and Modulation Performance

We first investigate the tunability of the THz “ladder” metasurface, which is designed to dynamically manipulate the amplitude of transmitted THz waves via an electrically controlled VO₂ metasurface. The 3D schematic of the electrically tunable VO₂ metasurface is illustrated in Fig. 2(a). The metasurface is fabricated on a square *c*-cut sapphire substrate with a thickness of 500 μm (see the fabrication details depicted in Sec. 8). The metasurface is designed to form a “ladder” shape. Here, the VO₂ patches are settled in the gaps of the handrail and ladder, so the surface currents flow along the left and right handrails and directly connect the VO₂ patches. The central step of a ladder (parallel to the *x* direction) can be regarded as a metallic wire to connect electrodes. According to the equivalent circuit model and further simulation implemented by Advanced Design System (see Sec. 1 in [Supplementary Material 1](#)), the handrail and ladder step resonators with VO₂ patches positioned in between in a single unit cell can be coupled with each other to form a plasmon-induced transparency (PIT) phenomenon at room temperature (insulating state of VO₂) and dipole mode at elevated temperature (metallic state of VO₂), which is suitable for active control (see Sec. 2 in [Supplementary Material 1](#)). The switching between PIT mode and dipole mode combined with dual handrails (wires) Joule heating from the currents, results in an increased absorption of THz waves and further reduces energy loss and the threshold current [see Fig. S1(d) in [Supplementary Materials](#)]. Under electrical control, a pair of Au electrodes is biased by a direct current source and is covered with the handrail of a ladder. When the bias current flows through each pair of electrodes, the VO₂ patches can change from an insulating state to a metallic state.⁶⁶ The optimized parameters are $P = 102\ \mu\text{m}$, $L = 96\ \mu\text{m}$, $l = 74\ \mu\text{m}$, $w_1 = 8\ \mu\text{m}$, and $w_2 = 6\ \mu\text{m}$. An optical microscopy image of the fabricated THz device is shown in Fig. 2(b). Here, the VO₂ patches can be easily differentiated, and each pair of electrodes is effectively connected to the global electrodes (see detailed micro-nano fabrication step in Sec. 3 in [Supplementary Material 1](#)). A photograph of the “ladder” design PCB chip with a size of 1.2 cm × 1.2 cm (comprising 8100 unit cells) is shown in Fig. 2(c), where the bonding pads on both sides of the PCB are bonded to the corresponding global electrodes on the metasurface to enable electrical control through an external power supply.

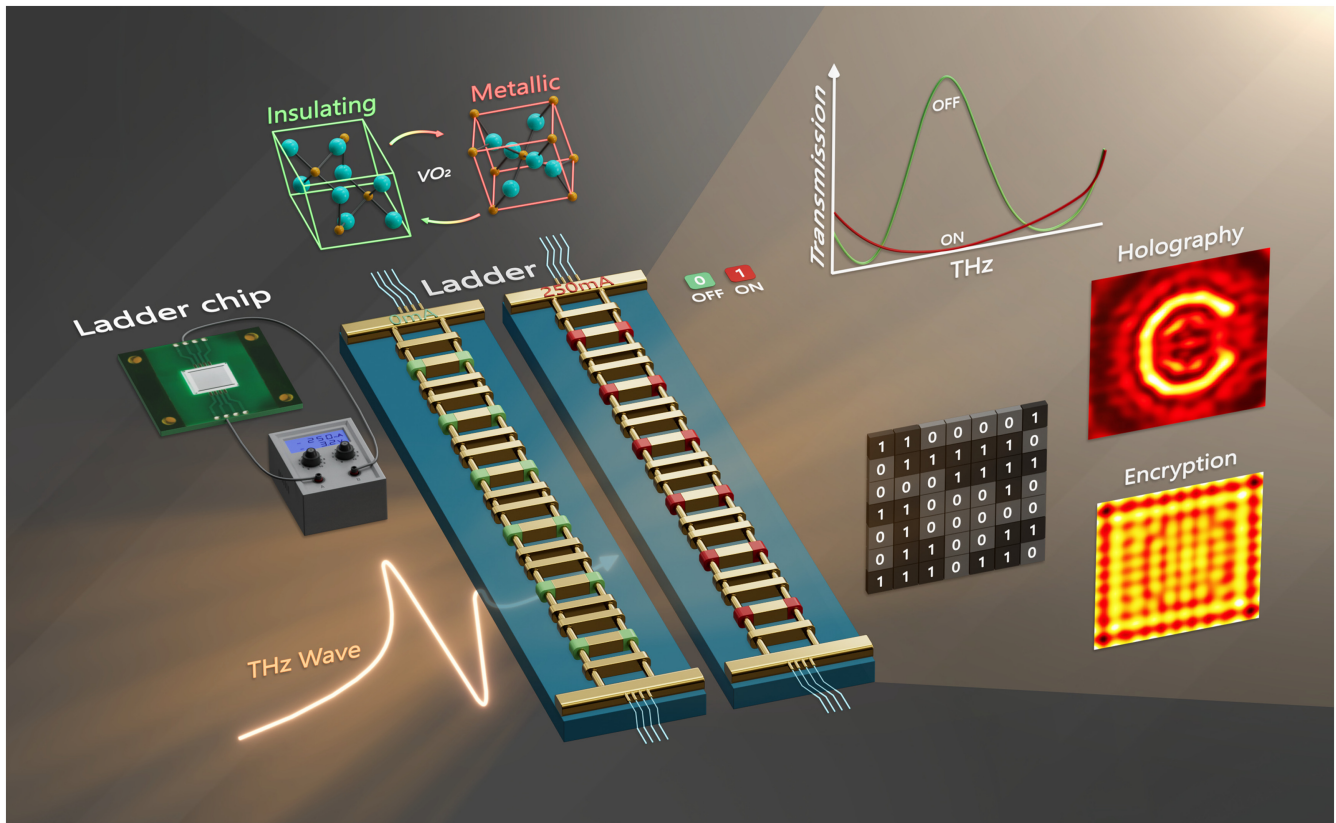


Fig. 1 Schematic illustration of an electrically tunable VO₂ ladder device. The dynamic modulation of a “ladder” device can be attained by electrically triggering the phase change of VO₂ at different currents, and holography and optical encryption can be achieved via programmable “ladder” units. An optical image of the fabricated ladder chip is shown on the left.

To characterize the electrically controlled performance, transmission spectra are collected under different bias currents via THz time-domain spectroscopy (THz-TDS), as shown in Fig. 2(d) (see Sec. 4 in [Supplementary Material 1](#) for the time-domain transmitted waveforms). At a bias current of 0 mA, a typical transmission spectrum of the PIT effect with a transparency window and two resonance dips is shown in Fig. 2(d).^{70–73} When the applied current increases from 0 to 380 mA, the Joule heating generated by the current flowing through the two-sided electrodes induces the insulator-to-metal transition of the VO₂ patches, progressively shortening gaps between the ladder handrail and step. The PIT effect also weakens due to the phase transition of the VO₂ patches. When the bias current is above 380 mA, only a dipole resonance dip is observed. Figures 2(e) and 2(f) show the simulated and fitted (the coupled Lorentz oscillator model,^{74,75} as shown in Sec. 5 in [Supplementary Material 1](#)) THz transmission spectra obtained by altering the conductivities of the VO₂ patches. Both results validate our experimental results. As shown in Fig. 2(g), we calculated the variation in the modulation depth with frequency under different currents. The modulation depth under different bias current regulations is defined as $M_d = [(T_0 - T)/T_0] \times 100\%$, where T_0 is the transmission when the bias current is 0 mA and T is the transmission at practical bias currents.⁶⁰ In our proposed “ladder” design-based metasurface, the modulation depth can reach a maximum of 81% at 500 mA and over 75% in the frequency range from 0.45 to 0.65 THz. To understand the

mechanism of active manipulation of the PIT resonance, electric field distributions of the “ladder” metasurface at 0.51 THz are simulated under different VO₂ conductivities, as shown in Fig. 2(h). In the insulating state of VO₂ (500 S/m), the electric field is distributed mainly in the gap between the ladder step (quasi-dark mode) and the handrail (bright mode) due to the capacitance effect.^{74,76} Moreover, the damping rate of the quasi-dark mode is minimal, indicating negligible resonance loss. With increasing VO₂ conductivity, the damping rate of the quasi-dark mode gradually increases due to the reduction in the capacitance effect, which impedes destructive interference between the quasi-dark and bright modes during the modulation process. When the conductivity of VO₂ is high enough (150,000 S/m), the effect of the capacitance completely disappears, resulting in the elimination of the electric field in the gaps. Therefore, the damping rate of the quasi-dark mode is greatly increased, resulting in the complete suppression of ladder step excitation and elimination of the PIT resonance effect.

3 Electrically Controlled Holography and Encryption

After successfully validating the electrically controlled “ladder” design metasurface based on the IMT of VO₂, we utilize the “ladder” design to achieve holography and encryption, as shown in Fig. 3(a). Two types of “ladder” designs are employed to achieve holograms, i.e., static and dynamic pixels.⁵⁵ Both have

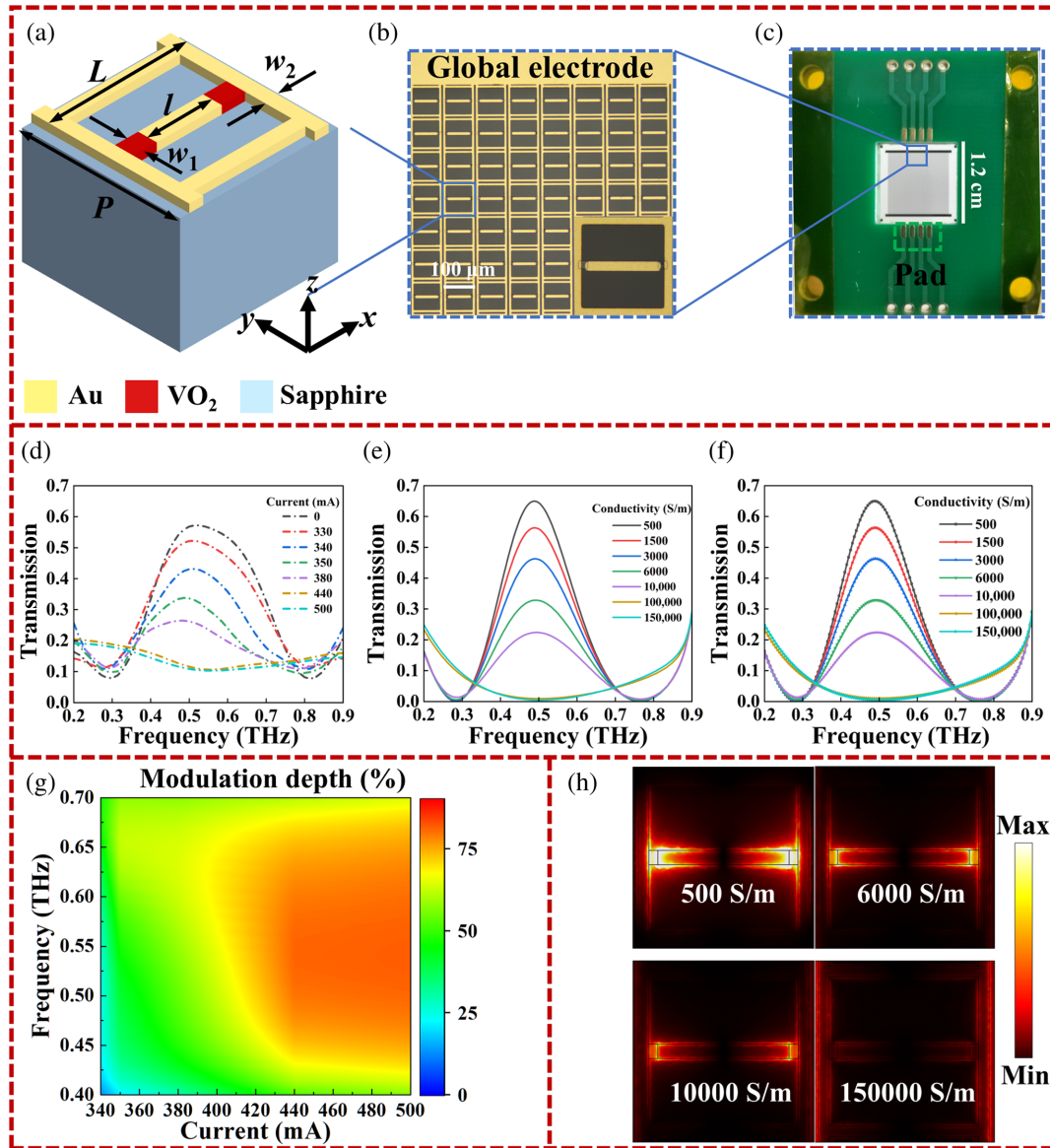


Fig. 2 Simulation and experimental demonstration of an electrically controlled “ladder” THz modulator. (a) Schematic diagram of the “ladder” design metasurface with the following parameters: $P = 102 \mu\text{m}$, $L = 96 \mu\text{m}$, $l = 74 \mu\text{m}$, $w_1 = 8 \mu\text{m}$, and $w_2 = 6 \mu\text{m}$. (b) Optical microscopy image of the fabricated “ladder” design PCB chip. (c) Image of the fabricated “ladder” design PCB chip. (d) Measured THz transmission spectra at different bias currents. (e) Simulated and (f) fitted THz transmission spectra at different VO₂ conductivities. (g) Modulation depth colour map under different currents. (h) Electric field distributions of the “ladder” metasurface at 0.51 THz with different VO₂ conductivities.

the same geometrical parameters and can achieve the PIT effect, with the following exception: the static “ladder” design does not have paired VO₂ patches; thus, a static pixel does not have a dynamic optical response with variation in the bias current. We simulate the transmission spectra of the static pixels and dynamic pixels in insulating and metallic states, respectively. The simulation results are plotted in Fig. 3(b) and validate the above analysis. For dynamic pixels, the PIT effect can switch between appearance and disappearance, similar to the “ON” and “OFF” states, whereas static pixels always maintain high transmission, which is consistent with dynamic pixels in the insulating state.

Notably, the transmission of the static pixels is slightly greater than that of the dynamic pixels, which may be attributed to the absorption of THz waves by the VO₂ film. Two types of fabricated pixel samples are shown in Fig. 3(c), and static and dynamic pixels can be easily differentiated, validating the quality of our processing. In addition, the size of the VO₂ patches is larger than that of the gaps for better connection.

Owing to significant differences in the optical response between static and dynamic pixels at different VO₂ states, we encode a secret image into the holographic “ladder” design metasurface using these two types of pixels, which can represent

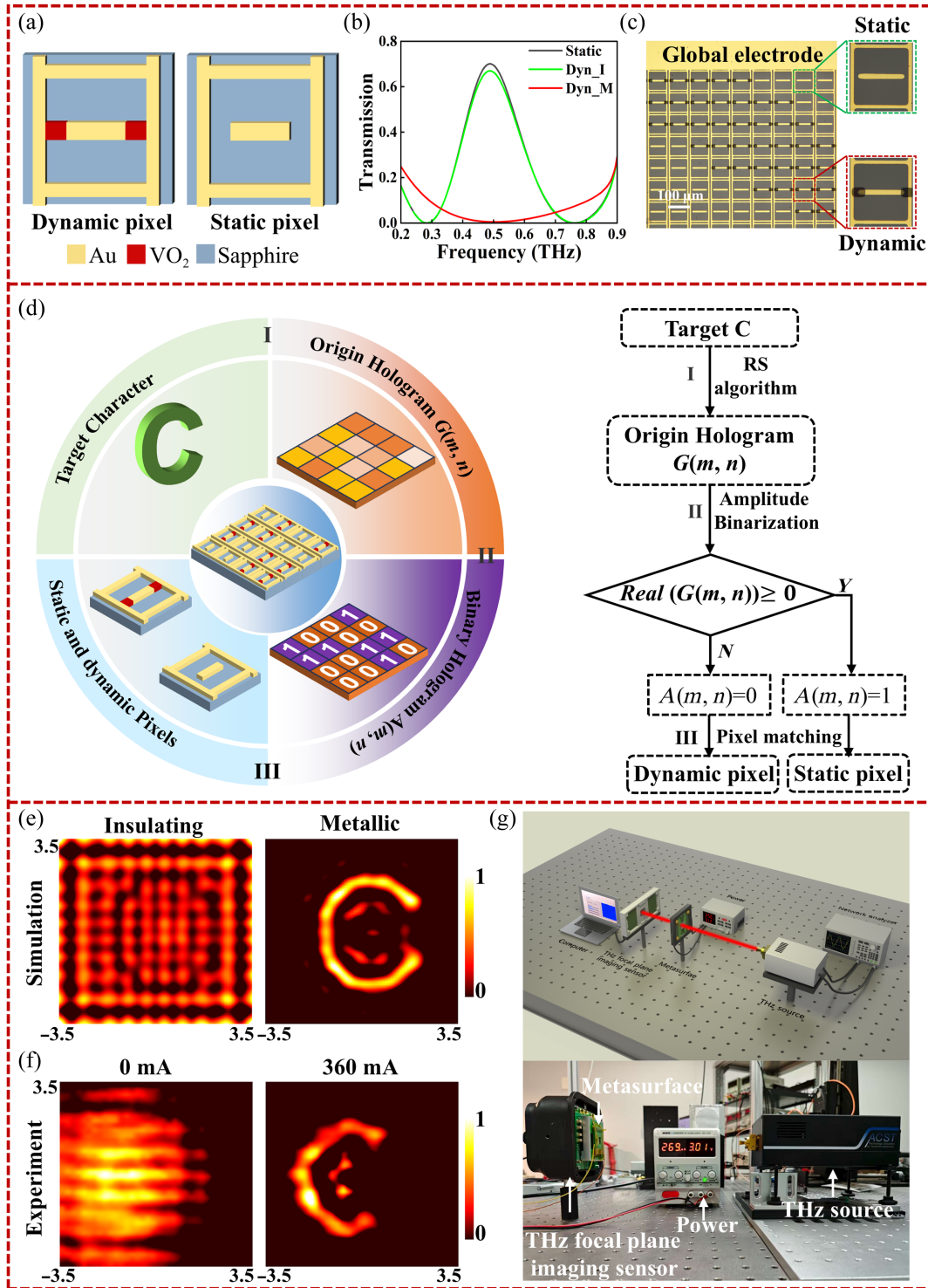


Fig. 3 Electrically controlled dynamic “ladder” design for holography and encryption. (a) Schematic of the static and dynamic pixels. (b) Transmission spectra of dynamic pixels in insulating and metallic states and static pixels. (c) Optical images of the fabricated holographic “ladder” design metasurface and enlarged images of static and dynamic pixels. (d) Design schematic of the “ladder” design hologram, and its flow chart includes the following processes. I: The Rayleigh-Sommerfeld (RS) formula is used to calculate the hologram $G(m, n)$ of the target character “C”. II: The complex amplitude $G(m, n)$ is binarized into the binary hologram $A(m, n)$ according to Eq. (2). III: The static or dynamic pixel is matched according to the obtained binary hologram. (e) Simulation results at different VO₂ states. (f) Experimental results at 0 and 360 mA, consistent with the simulation results. (g) Optical path schematic and corresponding experimental equipment for the THz focal plane imaging system.

different information similar to 0 and 1. In addition, the binary amplitude holography algorithm is adopted to obtain the “ladder”-based hologram.⁵⁵ The overall design flowchart is shown in Fig. 3(d). First, the target image plane is set to $d = 3$ mm away from the metasurface at a working frequency of 0.51 THz, and the Rayleigh-Sommerfeld formula is applied to relate the amplitude distribution of the metasurface to the target character “C”²⁵:

$$U(r_0) = \frac{d}{i\lambda} \iint_{\Sigma} U(r_1) \frac{\exp(ikr_{01})}{r_{01}^2} ds, \quad (1)$$

where $U(r_0)$ and $U(r_1)$ represent the electric field distributions at point R_0 on the metasurface and point R_1 on the image plane, respectively; Σ is the target object region; λ is the wavelength in vacuum; and r_{01} is the distance between R_0 and R_1 . According to Eq. (1), we obtain the electric field distribution on the “ladder” design and then extract its complex amplitude distribution $G(m, n)$, where m and n correspond to the positions of the rows and columns of pixels on the “ladder” design, respectively. Next, we binarize the complex amplitude distribution $G(m, n)$ according to the following criteria:

$$A(m, n) = \begin{cases} 0, & \text{real}(G(m, n)) < 0 \\ 1, & \text{real}(G(m, n)) \geq 0 \end{cases} \quad (2)$$

where $A(m, n)$ is the distribution of the final binary amplitude hologram. Using Eq. (2), the pixels of the complex amplitude distribution $G(m, n)$ with a real part less than 0 can be set to $A(m, n) = 0$, and the pixels whose real part is greater than or equal to 0 are set to $A(m, n) = 1$. We then match suitable pixels with the obtained binary amplitude hologram, where $A(m, n) = 1$ corresponds to static pixels, $A(m, n) = 0$ corresponds to dynamic pixels, and the dynamic pixel value can switch from 0 to 1 with an increase in the bias current. Finally, we obtain a complete “ladder” design PCB chip that includes 90×90 pixels.

As shown in Fig. 3(e), we simulate the reconstructed images before and after the VO₂ phase change at $d = 3$ mm. In the simulation, the values 0 and 1 in the binary amplitude hologram represent transmissivities of 0.004 and 0.663/0.694 at 0.51 THz, respectively. At the insulating state in VO₂, the values in both static and dynamic pixels are 1, resulting in nearly the same transmission for each pixel. Therefore, only numerous light spots appear in the holographic image without the desired information. When VO₂ changes to the metallic state, the transmission of dynamic pixels decreases from high to low, and the corresponding value switches to 0, whereas static pixels still maintain high transmission, and the value in static pixels is 1. At this moment, a binary amplitude hologram is obtained, and a clear reconstruction of the character “C” is obtained. The dynamic response time is about 4.5 s [see Sec. 6 in [Supplementary Material 1](#) and [Video 1](#) (“dynamic energy hologram” MP4, 1.66 MB [URL: <https://doi.org/10.1117/1.AP.7.6.066003.s1>]]]. The experimental results illustrated in Fig. 3(f) effectively agree with the simulation results, thus verifying the practical feasibility of our “ladder” design. As the bias current increases from 0 to 360 mA, the complete character encryption-decryption process can be implemented via electrical modulation. Notably, the bias current of 360 mA is higher than that of the triggering VO₂ phase change in our “ladder” holographic metasurface, ensuring the steady state of the VO₂ and the

imaging quality. In addition, the phase transition current of VO₂ in the holographic metasurface is lower than in the metasurface with all dynamic pixels [Fig. 2(d)], which is attributed to the difference in the number of VO₂ patches between the two metasurface structures (see [Supplementary Material 1](#), Sec. 7 for detailed discussion).

Figure 3(g) presents a schematic and photo of the focal plane imaging system for characterizing the optical encryption metasurface. The x -polarized THz radiation generated by the THz source is beam-expanded and collimated via a horn antenna, subsequently covering and transmitting through the object to be imaged. Here, we employed two sources covering 0.47 to 0.70 THz: WR2.2 (frequency range: 0.325 to 0.5 THz) and WR1.5 (frequency range: 0.5 to 0.75 THz). After passing through the PCB chip, the signal is focused onto the entire terahertz focal-plane imaging sensor, which has the following specifications: each pixel detector features a gate length of 0.9 μm , a gate-to-antenna spacing of 0.6 μm , and a pixel pitch of 200 μm , with the focal-plane chip measuring 8.5 mm $\times$ 8.5 mm. In addition, the sensor’s operational frequency range covers 0.3 to 0.8 THz. The “ladder” metasurface is positioned 3 mm from the detector, providing a 7 mm $\times$ 7 mm imaging area. The measured “ladder” design is integrated on the PCB, and two conducting wires extended from the electrodes in the PCB are connected to the power supply, which can enable electrical modulation. The obtained time-domain signals can be transformed into the desired electrical field distributions via the Fourier transform, and from these data, we can extract the intensity distributions of the final reconstruction image character “C” at the working frequency. The clear holographic image can be obtained by using Lanczos interpolation algorithm.⁷⁷

4 Broadband Imaging and Electrical Modulation

The optical encryption based on the “ladder” design also has a large working bandwidth. Figure 4(a) shows the measured results from 0.47 to 0.7 THz at 0 and 360 mA, respectively, where the electrically controlled holographic image character “C” and optical encryption are also observed, indicating a broad working bandwidth. These images are also obtained 3 mm above the “ladder” design hologram. As the frequency changes, encrypted and holographic images can still be clearly distinguished, and these results can be attributed to the significant transmission difference between 0 and 360 mA at 0.47 to 0.7 THz. In Fig. 4(a), the “C” pattern remains faintly visible in the hologram at 0 mA bias; this phenomenon arises from slightly increased VO₂ conductivity at 0 mA bias (see [Supplementary Material 1](#), Sec. 8 for details). We also examine the electrical modulation process of the holographic image with increased current, as illustrated in Fig. 4(b). At 235 mA, only an encrypted image is obtained in the image plane; this result is consistent with that at 0 mA. As the bias current increases to 238 mA, a partial contour of the character “C” appears. With further increasing the current to 245 mA, a complete contour of the character “C” begins to appear in the image plane. Afterwards, the intensity is independent of the bias current, indicating that 250 mA is the threshold current for our electrically controlled encrypted holography (see details in Sec. 9 in [Supplementary Material 1](#)). Notably, the “ladder” design results in a trigger current as low as 250 mA, demonstrating itself much lower power consumption than any other THz active imaging device achieved in the literature.⁶⁵

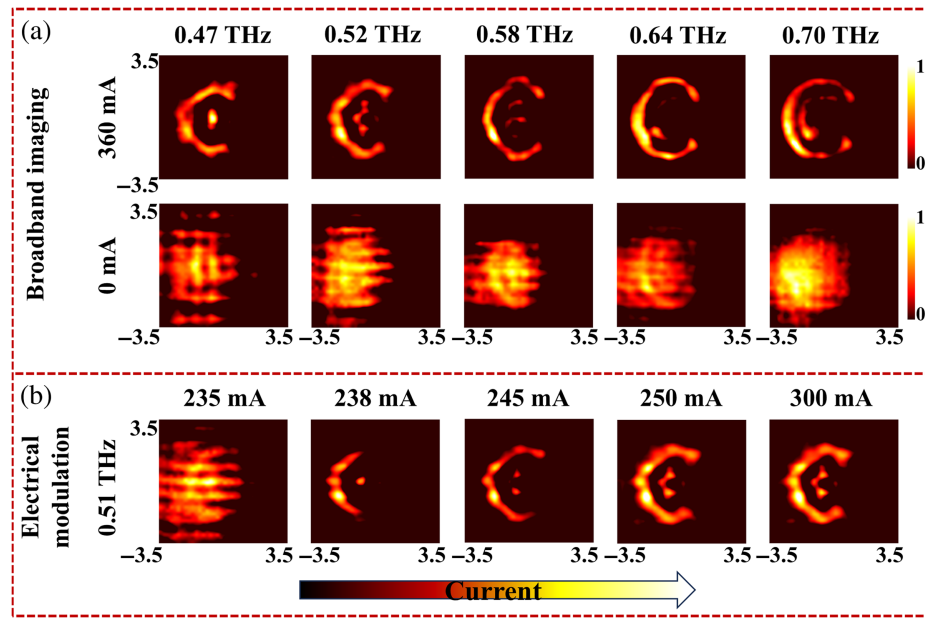


Fig. 4 Broadband imaging and electrical modulation process. (a) Measured holographic images at 360 mA and encrypted images at 0 mA at frequencies of 0.47, 0.52, 0.58, 0.64, and 0.7 THz. (b) Measured electrically controlled holographic images at 0.51 THz under currents of 235, 238, 245, 250, and 300 mA.

To intuitively showcase the advantages of the “ladder” design in current regulation, we compare it with the recently reported VO₂-based THz metasurfaces in Table 1. Here, the power consumption in this work can be calculated by $P = U \cdot I$, where the $U - I$ relationship for holographic metasurface has been measured, as shown in Sec. 10 in [Supplementary Material 1](#). The threshold current is 250 mA, corresponding to an applied tension of 3.2 V, resulting in a power consumption for phase change of VO₂ of about 0.8 W. Our “ladder” design requires the lowest current and power, offering advantages in terms of power consumption. Notably, this work manifests the first application of a terahertz focal plane imaging system for holographic encryption characterization.

Table 1 Comparison of THz tunable VO₂ hybrid devices.

Test system	Current (mA)	Power (W)	Ref.
THz-TDS and OPTP ^a	750	1.125	63
THz-TDS and OPTP ^a	420	Unavailable	66
THz-TDS	290	>5.8	60
THz-TDS and OPTP ^a	350	>1	58
THz-TDS	500	1.75	61
NSTM ^b	/	/	54
NSTM ^b	/	/	55
THz focal plane imaging system	250	0.8	Ours

^aOPTP: optical-pump terahertz-probe spectroscopy.

^bNSTM: near-field scanning terahertz microscopy.

5 Quantitative Thermodynamics Model

The temperature of VO₂ patches raised directly by narrow thin heating-electrodes can be understood by two processes. (1) Self-heating process, which can be described by Eq. (5) in Sec. 7 in [Supplementary Material 1](#). In our metasurface, this process could finish in a short time on the scale of 10^{-6} s,⁷⁸ giving a very limited temperature rise of VO₂. (2) Mutual heating or collective heating process,^{79,80} where all neighbours of a VO₂ patch will contribute to its final temperature rise, because the thermal field is scalar and can be directly summed up. This process finally determines the steady-state temperature of each VO₂ patch orders of magnitude higher than the self-heating process when the heaters are in a large number, at the cost of a relatively long time of thermal diffusion.

As an electric field can trigger instantaneous current flow in all 180 electrodes, the current distribution in all electrodes is almost identical. As all electrodes are heated up at the same time, the main factor that limits the thermal switching speed is the thermal diffusion within the metasurface, whereas the geometry of electrodes will mainly affect the self-heating process by modifying the effective radius in Eq. (5) in Sec. 7 in [Supplementary Material 1](#).

To systematically study the thermal diffusion dictated thermodynamics of the metasurface, we perform simulations with finite-element-method software COMSOL, Heat Transfer in Solids module. The schematic model used in thermodynamics study is shown in Fig. S9 in [Supplementary Material 1](#), and the structures’ dimensions and the corresponding thermal properties are summarized in Table S2 in [Supplementary Material 1](#). It is worth noting that a thermally homogenous metasurface is used to simplify and accelerate the simulation, to avoid the meshing problem for 8100 unit cells and 16,200 electrodes [as seen in Figs. 2(a)–2(c)]. We believe that the choice of this model is

reasonable as the temperature distribution within periodical heaters in large numbers is almost homogenous but decorated with peaks at the position of the local heaters.^{64,79} Such thermal treatment has been successfully applied to our previous works.^{80–82} The thermal property of the metasurface is calculated by a simplified model comprising the gold electrode unit cell and an air layer with the same height, thus rendering the volume ratio of gold about 0.288. Considering volume weighted density and thermal conductivity of the metasurface and mass weighted heat capacity, we can readily obtain the values for thermal simulation, as given in Table S2 in [Supplementary Material 1](#). Other conditions adopted in this simulation are a heat flux of 20 W/(m² · K) assigned to all outer surfaces accounting for heat convection from surfaces to the environment, and fluidic air with a wind speed of 0.38 m/s (light-air level according to Beaufort Scale) in *x* and *z* directions, representing the flowing nitrogen atmosphere in the THz-TDS system.

We first perform the thermodynamics simulation of the system under periodic rectangular-shaped current pulses measurement in order to characterize the thermodynamic properties of our metasurface. The corresponding temporal transmission response is depicted in Fig. 5(a). In Fig. 5(b), one switching cycle is displayed, and it can be found that the dynamic response time of the “ladder” shaped metasurface with all “dynamic pixels” is around 1.9 to 2 s. The heat distributions in the *yz* and *xy* planes at *t* = 3.5 s of the modeled system are plotted in Figs. 5(e) and 5(f). We can see that the variation of temperature within the metasurface is quite limited due to the periodically distributed heaters in large numbers and the high thermal diffusivity of the metasurface. As seen in Figs. 5(e) and 5(f), the temperature conducts fastest from the metasurface to sapphire and air due to their large diffusivities. Especially, heat conducts much more slowly in the PCB due to its poor diffusivity. As discussed above, the temperature of the electrodes and VO₂ might be slightly higher than their neighbours. Consequently, we could take $\Delta T = 40$ K as the full phase transition threshold in our thermodynamics analysis with our room temperature around 25°C. Besides, based on the observation from Fig. 2(d) that the detectable decrease of transmittance of the metasurface happens when the bias current reaches *I* = 330 mA, equivalent to the temperature rise threshold for partial phase transition of $40 \times (330/440)^2 = 22.5$ K. Figure 5(c) shows that *t* = 3.5 s, the full phase transition only occurs in the central/small area. At a time lapse of ~1 s, almost all the heating electrodes surpassed the full phase transition threshold. We also plot in Fig. 5(d) the thermodynamic behavior of the central point (0, 0, 50 nm) compared to that of the averaged temperature within the whole metasurface during 0 to 10 s. Rapid temperature rise of both the central point and the whole metasurface lasts in the whole 0 to 5 s and gradual temperature decrease occurs in the range of 5 to 10 s, where the central point reaches the full phase transition threshold at *t*₁ = 2.15 s after reaching the partial phase transition in the temperature rise process and drops below the partial phase transition at *t*₂ = 1.65 s after passing the full phase transition in the temperature drop process, respectively. Thermodynamics of the modeled system in *xz* plane and temperature rise and drop during multiple periods can be found in Fig. S10 in Sec. 12 in [Supplementary Material 1](#) with discussion given thereafter. These typical values perfectly align with experimental results as shown in Fig. 5(b). As the temperature of the local heaters is actually higher than that of the metasurface,^{64,79} the full phase transition of VO₂ patches has occurred before *t*₁. Similarly, at

the end of *t*₂, the local temperature of heaters is still higher than the threshold, so that the full phase transition during the temperature decrease process can only occur after 1.65 s. Consequently, our above analysis leads to the conclusion that the full phase change of our metasurface can be realized between 1.65 and 2.15 s, which perfectly aligns with our experimental observation of 1.9 to 2 s. Besides, we think more efforts should be devoted to accurate thermodynamics study by replacing the simplified model with the one with true geometrical parameters and properly dealing with the fluidic environment surrounding the studied device in the future.

The thermodynamic behaviour of the holographic metasurface at current threshold *I* = 250 mA is given in Fig. S11(a) in Sec. 13 in [Supplementary Material 1](#), where we can see that the phase transition may occur around *t* = 56 s, unacceptable for practical application of dynamic holographic imaging. We can also deduce that 250 mA is somehow too large to be the threshold of phase transition of the metasurface as the temperature seems to increase continuously after *t* = 56 s. We attribute this problem to a slightly unstable nanofabrication process, which may change the resistance of the device. Other issues can be taken into consideration including the air circulation in the experiment room which may augment the heat convection of air and the imperfect contact between the sapphire substrate with the PCB which could accelerate the thermal response of the heated metasurface [increased contribution of air with lowered contribution of PCB, as can be seen in Fig. S12(c) in Sec. 14 in [Supplementary Material 1](#) and the corresponding discussion].

The temperature rise of the holographic metasurface under electrical stimulation with *I* = 360 mA has been plotted in Fig. S11(b) in Sec. 13 in [Supplementary Material 1](#), where the time for full phase transition can be found at *t* = 4.85 s. Considering the heaters are slightly hotter than the metasurface, we can deduce that the true full phase transition occurs before *t* = 4.85 s, agreeing well with our experiment results. It should be noted that increasing the bias current can further reduce the full phase transition time in the experiment. In addition, the detailed influence of materials’ thermal properties on switching dynamics can be seen in Sec. 14 in [Supplementary Material 1](#).

6 Discussion

Compared with traditional passive THz metasurfaces, the proposed “ladder” design has the advantages of active manipulation, electronic compatibility, and multiple functionalities and is suitable for developing integrated and multifunctional dynamic THz devices. By utilizing the transmission difference before and after the IMT of VO₂, we can achieve amplitude modulation, holography, and encryption. Therefore, dynamic control is an effective way to extend the diverse applications of metasurfaces. In terms of the “ladder” hologram design, the bias currents flowing in the electrodes do not affect the static pixels and successfully manipulate the dynamic pixels. The flexible binary coding enables the attainment of a high degree of freedom to design the target information. With respect to the dynamic response, probe scanning severely limits the speed response of our holographic metasurface. Here, we used a THz focal plane imaging system to obtain images at high speed, meeting the needs of real-time imaging in optical encryption and secret imaging. In addition, the robustness of our dynamic metasurfaces must be emphasized. The robustness can be described by two points: (1) dozens of hours of electrically

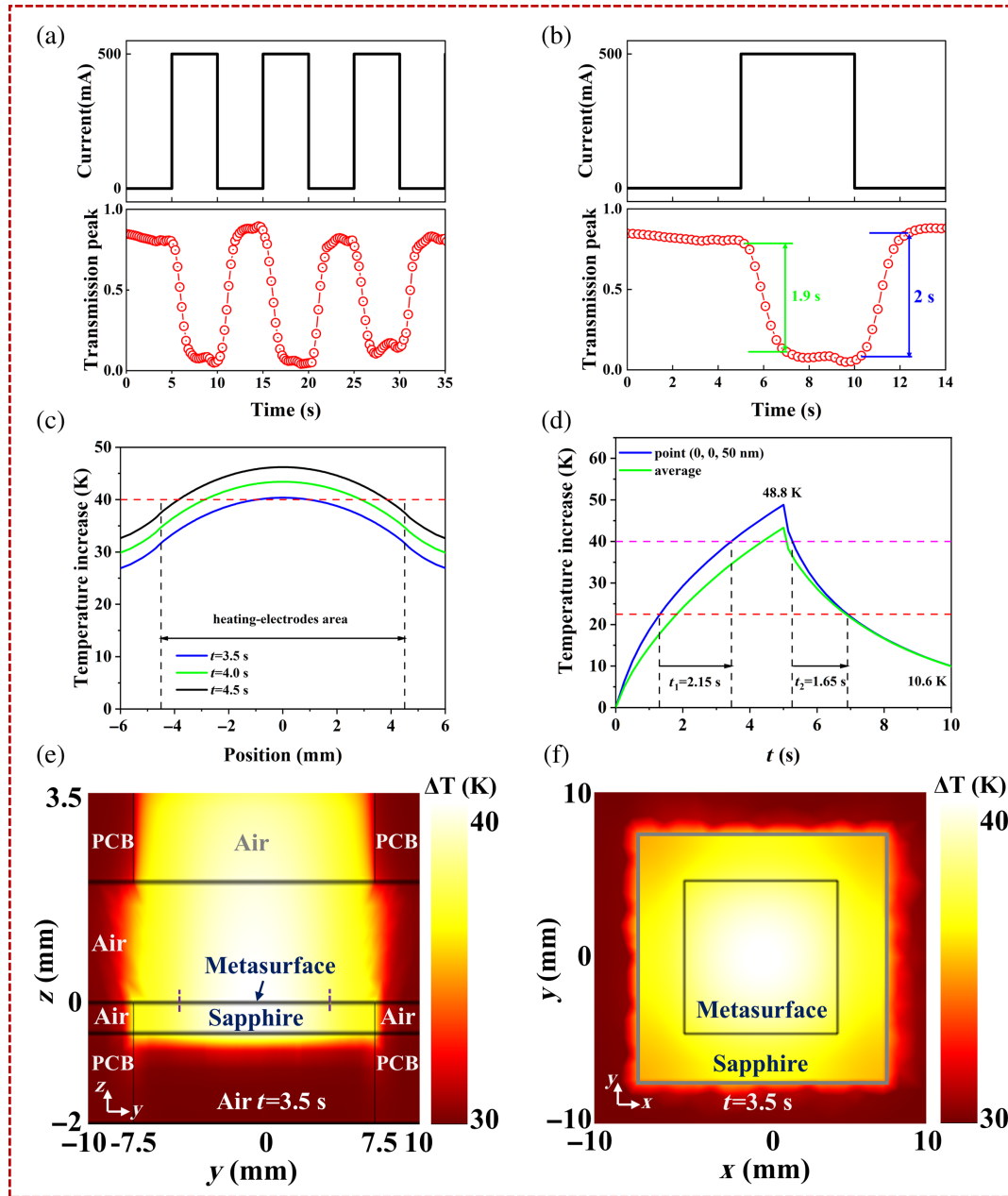


Fig. 5 Thermodynamics study of electrically heated metasurface. (a) Periodically applied current (upper panel) and the measured transmittance (bottom panel). (b) Zoomed-in single period of applied current (upper panel) and the measured transmittance (bottom panel). (c) Temperature plot along the line passing through the center of the metasurface in y-direction at 3.5 s (blue curve), 4 s (green curve), and 4.5 s (black curve). (d) Temperature evolution of the central point (blue curve) and the averaged value of the metasurface (green curve). (e), (f) Temperature distribution in yz plane (e) and xy plane (f) at $t = 3.5$ s.

modulated image quality remain unchanged and (2) the THz focal-plane imaging system exhibits measurement robustness, indicating that the imaging performance remains largely unaffected by variations in the source-to-chip or chip-to-detector distances.

7 Conclusion and Prospect

In conclusion, we proposed and experimentally demonstrated an electrically controlled broadband THz VO₂ metasurface

based on a focal plane imaging system to achieve real-time holography and encryption. The fabricated metasurface is composed of “ladder” structures that have a broadband modulation depth of 75% between 0.45 and 0.65 THz. By utilizing the optical response difference between the static and dynamic pixels at different bias currents, we encode the target character “C” into the metasurface hologram via the binary amplitude algorithm. The simulation and experimental results are consistent with each other, validating the feasibility of our electrically

controlled THz holographic metasurface. In addition, the experimental results also indicate that the holographic metasurface features a broadband image ranging from 0.47 to 0.7 THz and that the dynamic response varies with the bias current. The quantitative thermal model was also proposed to verify the measured dynamic response time of electrothermally heated objects, providing crucial insights for future optimization of VO₂-based electrically controlled tunable holographic metasurfaces. The proposed “ladder” design combined with a focal plane imaging system has remarkable advantages in terms of electronic integrability, low power consumption, active modulation, real-time imaging, and robustness. Therefore, this electrically controlled holography platform is promising for optical encryption, anticounterfeiting, and next-generation wireless communications. Finally, the current design employs a single global electrode, restricting dynamic pixel-level control. In the future prospect, individual addressing of metasurface elements is critical for advanced dynamic display applications. Detailed pixel-level addressing schemes for the proposed “ladder” design [including the damascene process,⁸³ 1D pixel-level thermal control method based on thermal insulators with low thermal diffusivity,⁸⁴ and artificial intelligence (AI)-based methods^{85–87}] can be seen in Sec. 15 in [Supplementary Material 1](#). Besides, positioning the metasurface on a smaller and thinner sapphire substrate with larger air holes cut from the PCB board under a static air environment can be a good method to optimize the thermal operation condition. If possible, changing the sapphire substrate to THz-transparent materials with much smaller thermal conductivity, mass density, and heat capacity, and somehow making a metasurface suspended between the PCB boards, can be technical issues that can be taken into consideration.

8 Experimental Section

8.1 Numerical Simulation

The transmission spectra simulations were conducted via the radiofrequency module of COMSOL Multiphysics. We applied Floquet periodic boundary conditions and assumed that a plane wave is incident normally from the top. Gold (Au) was modelled as a perfect electrical conductor (PEC), whereas the sapphire substrate was characterized by a relative permittivity of $\epsilon = 11.7$. In the THz range, the relative permittivity of VO₂ is described via the Drude model.⁸⁸ For the simulation of holographic images, we utilized CST Microwave Studio 2019 to reconstruct the images. A plane wave was employed as the excitation source, and the polarization was set to linear in the x -direction. We selected the time-domain solver and placed an electric field monitor at 0.51 THz. Thermodynamics simulations were performed with finite-element-method software COMSOL 6.3, Heat Transfer in Solids module. The thermal properties of the metasurface, PCB, sapphire, and air are listed in Table S2 in [Supplementary Material 1](#). In thermal simulations for the THz-TDS experiment, additional fluidic air with a speed of 0.38 m/s in the x -direction was introduced to mimic the flowing nitrogen atmosphere. In all thermodynamics simulations, a heat flux of 20 W/(m² · K) was assigned to all outer surfaces. 3.5, 0.8, and 1.81 W of heating powers were set to thermodynamics simulation for THz-TDS, phase transition threshold determination, and THz imaging experiments, respectively.

8.2 Experimental Measurements for “Ladder” Metasurface Holographic Encryption

The THz radiation emitted from THz sources [VDI Module: 325 to 500 GHz (WR 2.2), 500 to 750 GHz (WR 1.5)] is collimated onto the sample via a horn antenna. The sample, electrically connected to a power supply through conducting wires, enables dynamic electrical modulation. The transmitted THz wave is then collected by a THz focal-plane imaging sensor (Parameters: 32 × 32 arrays, 30 frame rate, gate length 0.9 μm, gate-to-antenna spacing 0.6 μm, and pixel pitch 200 μm) positioned 3 mm behind the sample, with real-time imaging monitored and recorded by a computer.

8.3 Sample Fabrication

A 200-nm-thick VO₂ thin film is grown on a 500-μm-thick sapphire substrate via magnetron sputtering. First, the VO₂ thin film is uniformly spin-coated with the photoresist S1818. After baking, the photoresist was exposed via mask-1 under ultraviolet light and then developed. The VO₂ layer is subsequently patterned via an inductively coupled plasma (ICP) etcher. The photoresist is then removed and cleaned via ultrasonic cleaning and plasma to form the VO₂ pattern. Finally, the gold ladder steps and handrails are successively patterned via the same photolithography processes, followed by a lift-off process.

8.4 Electrical Driving Methods

In the “ladder” design, the Au handrails are adhered to the global electrodes. Then, using the “ladder” design PCB chip with a size of 1.2 cm × 1.2 cm (comprising 8100 unit cells), the bonding pads on both sides of the PCB are bonded to the corresponding global electrodes on the metasurface to enable electrical control through an external power supply (Model: KKS-152D, input AC 220 V/50 Hz, output DC 0 to 15 V/0 to 2 A). We employed the power supply for electrically controlled holographic imaging, with the protection current set to 550 mA. In the holographic imaging experiments, we applied the voltage in ascending order from low to high. Within the 230 to 250 mA current range, we set a current step of 2 mA. After allowing the power supply to stabilize, the corresponding electric field intensity distribution was acquired at each current setting using the dedicated software of the THz focal-plane array detection system. For the 250 to 300 mA current range, the current step was set to 10 mA, whereas a 50-mA step was adopted for measurements in the 300 to 550 mA range.

Disclosures

The authors declare that they have no competing interests.

Code and Data Availability

The data that support the findings of this study are openly available in [Supplementary Material 2](#).

Author Contributions

S.M. and L.C. conceived the idea. S.M. performed the optical simulation, metasurface design, and electro-thermal experiments and wrote the manuscript. Y.F. performed thermal simulations and provided thermodynamics analysis. J.S. performed real-time holographic experiment. L.C., Y.F., and D.L. revised

the initial draft. All the authors discussed the results and commented on the manuscript.

Acknowledgments

This project was supported by the National Natural Science Foundation of China (Grant Nos. 62588201 and 62275157), the National Key R&D Program of China (Grant No. 2023YFF0719200), the Natural Science Foundation of Guangdong Province (Grant Nos. 2023A1515012793 and 2024B1515020117), the 111 Project (Grant No. D18014), the Shuguang Program supported by the Shanghai Education Development Foundation and the Shanghai Municipal Education Commission, China (Grant No. 18SG44), and the Research Grants Council of Hong Kong through an Area of Excellence grant (Grant No. AoE/P-502/20).

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