Research article

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Real-time terahertz meta-cryptography using polarization-multiplexed graphene-based computer-generated holograms

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Abstract: As one of the cutting-edge technologies in advanced information science, wave-based cryptography is a prerequisite to enable a plethora of secure encrypting platforms which can be realized by smart multiplexing techniques together with suitable metasurface holograms (meta-holograms). Here, relying on the polarization multiplicity and re-writability of a computer-generated meta-hologram, a fully secure communication protocol is elaborately developed at the terahertz spectrum to host unique merits for exploring real-time metasurface-based cryptography (meta-cryptography) where highly restricted access of information is imposed. The proposed meta-cryptography exploits two dynamic near-field channels of a meta-hologram whose information can be instantaneously re-written without any polarization rotation and with high contrast and acceptable frequency bandwidth. The computer-generated meta-hologram is constructed based on the weighted Gerchberg–Saxton algorithm via a two-dimensional array of vertical graphene strips whose anisotropic reflection is merely determined by external biasing conditions. Several illustrative examples have

been presented to demonstrate the perfect secrecy and polarization cross-talk of the proposed meta-cryptography. Numerical simulations corroborate well our theoretical predictions. As the first demonstration of dynamic THz meta-cryptography, the meta-hologram information channels can be deciphered into manifold customized messages which would be instrumental in data storage systems offering far higher data rates than electronic encryption can deliver.

Keywords: digital metasurface; graphene; hologram; meta-cryptography; terahertz.

1 Introduction

Holography pioneered by Dennis Gabor in 1948 [1], has been one of the most promising imaging techniques since its invention which enables recording and reconstruction of the information contained in the images via suitably-designed holograms. The recent developments in computer science and optoelectronics have yielded the computer-generated holography (CGH) [2] in which holograms are designed by numerical calculations, avoiding resorting to interferometric recording step in the conventional schemes. Although substantial efforts have been made in this context, most of the previous proposals still suffer from bulky profiles and poor image re-construction efficiencies. The reason stems from the inevitable loss caused by phase accumulation through long propagation distances inside the constitutive materials [3].

With strong competitiveness in construction of more efficient, more functional, easier-to-fabricate, and easier-to-integrate holograms from microwave to terahertz (THz) spectra, metasurfaces as 2D arrays of sub-wavelength scatterers [4–6], have recently grabbed considerable attention of the physics and optics research communities owing to unprecedented flexibility in arbitrary manipulation of phase [7, 8], amplitude [9, 10], polarization [11], and shape [12] of the local electromagnetic (EM) fields with less energy dissipation. Metasurfaces have become a rapidly

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growing field of research in recent years due to their exceptional abilities in various modern applications like absorbing meta-devices [13], antenna engineering [14], Bessel beam generation [15], wavefront shaping [16], and intelligent imaging/recognizing [17]. Emerging these powerful architectures has continuously been fueling the research efforts in stimulating ideas about metasurface-based holography or “Meta-holography” [3, 18].

The possibility of engineering the massive information capacity of meta-holograms provides a strong motivation for development of image encoding and information encryption techniques [19–25] in top secret communications where secure exchange of confidential information is highly demanded. Cryptography evolving from the discipline of computer science in 1882 transfigures an input plaintext into an output encrypted ciphertext [26]. With the well-recognized importance of information security, many encryption/decryption techniques have been developed [27]. Modern cryptography provides a robust set of techniques to ensure that the malevolent intentions of the adversary are thwarted while ensuring the legitimate users get access to information [28]. However, the conventional encryption techniques rely on nonlinear optics, implying high intensity, and energy requirements. State of the art communications have been moving toward wave-based cryptography [29] with a great potential in information security due to the availability of four degrees of freedom with various combinations, such as wavelength, polarization, amplitude, and phase. Recently, metasurfaces have been reported for image encoding with only one unitary element of either polarization or wavelength. By using a new independent physical dimension, Fang et al., introduced orbital angular momentum holography for high-security encryption [30]. As another example, ultrathin nonlinear plasmonic metasurfaces have been used to encrypt images at a near infrared wavelength [31]. In addition, polarization conversion metasurfaces have been suitable candidates for the implementation of polarization encryption, which is demonstrated by encoding a hidden image into the spatial polarization distribution [24]. For exploring the full capability for information storage/display and enhancing the encryption security of metasurface holograms, smart multiplexing techniques involving photon-spin channels or a pair of orthogonal linear polarization states are highly demanded. For instance, meta-holograms can be designed to produce different images upon altering the polarization [32, 33] or wavelength [34, 35] of the incident wave. By controlling the anisotropy of meta-atoms, polarization-controlled meta-holograms can be designed somehow that the polarization state of the incident light selects which image should be

projected [36]. While great progresses have occurred in this area, the full capacity of all polarization channels has not yet been explored and there is still a plenty of room to further boost the performance of secure meta-holograms [37]. Much progress thus is urgently needed to further expand capabilities and create practical deployable solutions. Reconfigurability in a real-time manner may dramatically enhance the capacity of secure meta-holograms. Although in previous studies, adjustability has been demonstrated by changing the propagation direction or polarization state of the incident light, the research endeavors have been mainly devoted to static metasurface devices, in which the properties of individual pixels cannot be reconfigured in real time, especially at THz spectrum [33]. Residing at a relatively unexplored region between the microwave and infrared, THz waves pose various advantages over traditional imaging wavelengths [38]. Static performance of THz meta-holograms only exploits a glimpse of opportunities that these information platforms can offer. Thus, dynamic exchange of confidential information with perfect secrecy remains a challenge which can be addressed by using real-time meta-cryptography.

Recently, by exploiting reconfigurable technologies such as diodes [39], electro-optical modulations [40], stretchable and mechanochromic architectures [41, 42], motion-sensitive sensors [43], thermal-sensitive phase change materials [44], and applied-voltage sensitive graphene [45, 46], many dynamic metasurfaces have been proposed to realize various EM functionalities from microwave to visible spectra. Despite the new opportunities, reconfigurable meta-holograms continue to face new challenges especially for higher frequencies. Particularly, electrically tunable meta-holograms have not been demonstrated at THz frequencies where, secure THz meta-holograms with the pixel-level independent control of active components, might be a key step in enabling future information devices with reconfigurable and programmable functionalities. To extend the dynamic meta-holography to THz spectrum, we exploit from the electrically controllable response of the graphene-based meta-atoms in this paper. Graphene is a flat mono-atomic layer of Carbon atoms bonded in a hexagonal structure [47, 48]. The arbitrary control of surface electric conductivity of graphene through external biasing or chemical doping has shown a great flexibility in achieving various functionalities. Because of having strong interaction with EM fields, the possibility of exploiting the array of graphene metasurfaces in a wide range of interesting applications from tunable/broadband absorption [49, 50] to THz wave tailoring [51] has been conceptually assessed. Despite the rapid progress in high frequency active metasurfaces, the

simultaneous realization of real-time reconfigurability, high efficiency, and polarization-multiplexing for realizing THz holograms have remained unsolved. One ongoing trend may be the control of multi-fold physical quantities of EM wave (like polarization, frequency, and phase) in order to achieve functionality multiplexing in single dynamic metasurface. Although we have recently reported a new information encryption scheme using the THz dynamic metasurfaces, our design exploited the limited capacity of the far-field patterns without any multiplexing performance [52]. Therefore, achieving re-writable and polarization-multiplexed secure meta-holograms remains a challenging problem, and this holy grail is still far from being well addressed or solved. The bottlenecks on the way of real-time meta-cryptography include designing a polarization-multiplexed meta-hologram with sub-wavelength pixels, independent control of the dynamic pixels at the same time, and so forth.

Here, borrowing the simplicity and versatility of the digital metasurfaces [53–58], we design a two-dimensional reflective array of vertical graphene-based meta-atoms with a hybrid electrostatic bias condition to realize dynamic phase-only THz meta-holography by exploiting from a couple of independent channels whose encrypted information is controlled via the polarization state of the incident wave. The information encoded in each near-field channel is independent and undetectable by the other and the projected images of each channel can be instantaneously and digitally switched by applying different multi-level biased voltages across the vertical graphene layers. We demonstrate the possibility of dynamic tuning the Fermi level of the graphene layers through a field programmable gate array (FPGA) so as to realize ultrathin, polarization-multiplexed, real-time pixel-level reconfigurable, and arbitrary meta-holography across an acceptable frequency bandwidth. To shape arbitrary THz wavefronts, we choose eight digital phase levels for the metasurfaces in this work. Multiple particles with spatially varying orientations making Pancharatnam-Berry phase shifts are already involved in the realization of meta-holograms. However, this approach is associated with polarization change, which limits the maneuverability of application [59]. Conversely, the sub-wavelength graphene-based units in this paper have the same size, and different chemical potentials can be arbitrarily adjusted to enable further facilitation of the design without any polarization rotation. To the best of our knowledge, it is for the first time that reconfigurability and polarization-multiplexing have been simultaneously addressed with a single THz hologram metasurface. Numerical simulations depict that the proposed meta-hologram features simplicity, dual information

channels, being re-writable, high image quality, and high efficiency. With far more combinations of independent diversities (both polarization multiplexing and reconfigurability) to encrypt information and obvious functionality expansion with respect to similar designs [19–25, 60], the proposed re-writable meta-hologram paves a novel pathway for escalating the security level of information with unprecedented degrees of freedom in multichannel information encryption, anti-counterfeiting, THz data storage, and information processing.

2 Re-programmable polarization-multiplexed meta-hologram

Most of the current design schemes rely on full-wave numerical simulations to associate a given sub-wavelength element with the respective equivalent digital status, yielding a complex lookup table that is established for coding metasurface realization [61]. Conversely, the primary objective of this work is to design a versatile coding metasurface in which the operational status of each occupying lattice can be individually set via a multi-stage DC voltage source, providing flexible and real-time control over reflected wavefront of orthogonal polarizations at THz frequencies (see Figure 1). This figure displays the sketch of the proposed re-writable meta-hologram comprising of 3-bit reflective graphene-based digital lattices. To suppress the corner-related scattering coupling effect, 3×3 meta-atoms are included to construct a half-wavelength lattice. In order to realize polarization-multiplexing, i. e., independent control of x - and y -polarized illuminations with minimum mutual coupling, each meta-atom consists of two perpendicularly-oriented graphene strips, as illustrated in Figure 1. The graphene strips with the width of $a = 5 \mu\text{m}$ are deposited on Quartz pillars with $l = 22 \mu\text{m}$ and $t = 1 \mu\text{m}$. It is worth mentioning that vertical growth of the graphene layer was successfully modeled [62, 63] and realized [64], adopting with the realm of current fabrication technologies. In our simulations, the relative permittivity and loss tangent of the Quartz substrate are $\epsilon_r = 3.75$ and $\tan\delta = 0.0184$, respectively. This particular arrangement of graphene strips with the periodicity of $p = 9 \mu\text{m}$ along both x and y directions is located on a metal-backed substrate of Quartz ($t = 1 \mu\text{m}$) acting as a reflector. The Au ground plane with the electrical conductivity of $\sigma = 4.1 \times 10^7 \text{ S/m}$ electromagnetically treats as an impenetrable surface at THz region. As seen in Supplementary Figure S2, the graphene strip, the polysilicon substrate with the thickness of $t_s = 0.1 \mu\text{m}$, the Alumina layer with the thickness of 65 nm,

and the top/bottom contacts made of Cr/Au effectively form a gated structure in each meta-atom [56]. The thickness of auxiliary layers is much smaller than the operating wavelength so that their impact on the phase and amplitude of reflection spectrum can be safely ignored. The external biasing voltages are differently applied between the polysilicon layer and conductive contacts. The chemical potentials of graphene strips in each meta-atom can be separately tuned through practical technologies such as electrical gating. Consequently, the graphene layers have identical dimensions but different Fermi energy levels, yielding a group of anisotropic bias-encoded meta-atoms. Interestingly, the electromagnetic response of the meta-atom to an y -polarized illumination is sensitive to the plasmonic resonances in the y -direction that are only affected by μ_c^y . While, x -polarized incident waves sense the plasmonic resonances of the meta-atom along the x direction which are only affected by μ_c^x . It should be noted that although the graphene strips in each meta-atom are differently fed, the co-oriented graphene layers in each lattice have the same biasing voltages. Moreover, because of being isolated from the poly-Si layers, the chemical potentials of graphene metasurfaces can remain constant for a long period after the external biasing voltages are disconnected. The geometrical parameters of the proposed meta-atom have been optimized so that it exposes our desired controllable anisotropic response.

Owing to its mono-atomic specification, graphene can be locally represented by a conductive sheet with complex surface conductivity σ_s modifying the boundary condition of tangential magnetic fields [65]. In the absence of magnetostatic bias fields, the off-diagonal components of the surface conductivity vanish, acting as an isotropic

surface. Using the Kubo formula with interband and intraband transition contributions, this conductivity reads as [47]

$$\sigma_s(\omega, \mu_c, \Gamma, \tau) = \sigma_s^{\text{intra}}(\omega, \mu_c, \Gamma, \tau) + \sigma_s^{\text{inter}}(\omega, \mu_c, \Gamma, \tau) \quad (1)$$

$$\sigma_s^{\text{intra}}(\omega, \mu_c, \Gamma, \tau) = -j \frac{e^2 k_B T}{\pi \hbar^2 (\omega - j2\Gamma)} \left[\frac{\mu_c}{k_B T} + 2 \ln \left(e^{\frac{\mu_c}{k_B T}} + 1 \right) \right] \quad (2)$$

$$\sigma_s^{\text{inter}}(\omega, \mu_c, \Gamma, \tau) = -j \frac{e^2}{4\pi \hbar} \frac{2|\mu_c| - (\omega - j2\Gamma)\hbar}{2|\mu_c| + (\omega - j2\Gamma)\hbar} \quad (3)$$

Here, k_B and $\hbar$ are the Boltzmann's and the reduced Planck's constants, respectively. Moreover, μ_c is the chemical potential, e denotes the electron charge, τ indicates the relaxation time, T refers to the environmental temperature, and ω is the angular frequency of the incident wave. In our simulations throughout this study, we set $\tau = 0.5$ ps, $T = 300$ K, and μ_c between 0.2 and 1.2 eV. According to Pauli exclusion principle [66], the interband contribution of the graphene conductivity can be neglected in low-THz spectrum on account of the photon energy.

The working principle of the proposed anisotropic graphene-based meta-atom can be explained as follows. When a plasmon wave propagates along the z -direction on a graphene strip with the complex propagation constant of k_p and the strip width of w , the dispersion relation can be expressed as $k_p \approx -j\omega\epsilon_0 \frac{1+\epsilon_s}{\sigma_s}$ when $k_p \gg k_0$ [62]. The reflection phase shift imparted on the $x(y)$ -polarized illumination originates from the propagation delay of the plasmon waves on the graphene strip oriented along the same $x(y)$ direction. As signatures of two-dimensional electron gases and massless Dirac electrons [62], the resonant frequency

Figure 1: Demonstration of the designed re-writable THz meta-holography. The 3-bit coding metasurface is composed of vertical graphene ribbons independently controlled by external biasing DC voltages. A controlling computer produces the digital phase maps required for generating two differently-polarized images at the near-field channels. The coding schemes are stored in a field-programmable gate array (FPGA) in advance and are recalled to sequentially configure the designed meta-hologram.

of ω_p depends on $\sqrt{W}$, ϵ_r , and $\sqrt{L}$, which in turn, is inversely proportional to μ_c where, L denotes the surface inductance of the graphene sheet. Based on this scaling law, we can anisotropically optimize our meta-atom to operate in the vicinity of the desired working frequency by changing the chemical potential or strip width. In this way, one can select the appropriate chemical potential that results in the desired phase difference for each of major polarization given the working frequency and geometrical parameters of the structure.

The numerical simulations characterizing the designed meta-atom have been accomplished by using the electromagnetic commercial software, CST Microwave Studio. Periodic boundary conditions were applied in both x and y directions, while the perfectly matched-layer (PML) boundary condition was applied in the z direction. The graphene layers are numerically modeled by an ultra-thin layer with the thickness of Δ and the relative permittivity of $\epsilon_{rg} = 1 + \sigma_s/j\omega\epsilon_0\Delta$. The amplitude and phase spectra of the x -polarized and y -polarized reflection coefficients have been plotted in Supplementary Information A for different values of μ_c^x or μ_c^y when the other one is kept constant. The optimum set of the chemical potentials for the 0–7 anisotropic digital elements are found as $\mu_c^{x(y)} = \{0.46, 0.56, 0.62, 0.7, 0.8, 0.96, 1.2, 0.22 \text{ eV}\}$, respectively. As can be noticed, tuning μ_c^x will affect the reflection properties of the x -polarized wave while keeping the y -polarized wave unchanged. Similarly, according to the symmetrical structure of the proposed unit-cell, μ_c^y will only affect the reflection properties of the y -polarized wave. The corresponding results are not given just for the sake of brevity. With modulating the chemical potentials of graphene layers within the range of 0.2–1.2 eV, a high reflectivity above -2 dB and a wide reflection phase span of 315° have been acquired upon illuminating by both x - and y -polarized incidences. The key point is that all our designed coding elements depict a high reflectivity over the operating bandwidth as they function far from their resonance frequency. Since the effective guided index of such structure is nearly independent of the frequency [63], the reflection phase responses have a nearly linear trend, which is very crucial for designing multi-bit bias-encoded meta-atoms with identical geometries. Since the intrinsic loss of graphene layers, the full reflection phase span of 360° has not been achieved; however, the phase span of 315° is sufficient to provide good performance in holographic applications [67]. Moreover, such a wide phase modulation range has been accomplished without need to any imposed polarization conversion seen in the conventional architectures [68]. The DC voltage needed for tuning the chemical potential

of graphene is additionally studied in Supplementary Information B to ensure no breakdown occurs in the structure.

Therefore, we conclude that the reflectivity and reflection phases of x - and y -polarized waves can be manipulated independently by tuning of μ_c^x and μ_c^y , respectively. A set of eight designs with 45° phase shift is extracted for each polarization to construct the 3-bit graphene-based metasurface hologram. The linear phase region of the designed meta-atoms spans an acceptable frequency bandwidth which is wide enough for many imaging applications. Accordingly, controlling the DC voltages applied to two perpendicularly-oriented graphene surfaces, all digital lattices can be independently and anisotropically programmed to mimic the ‘000’, ‘001’, ‘010’, ‘011’, ‘100’, ‘101’, ‘110’, and ‘111’ states for each orthogonal polarization. In fact, each lattice should be identified with two different digital codes specifying its operational status under x - and y -polarized incidences. There are two reasons to set the phase step as near as 45° . First, such a high phase level can decrease the variation of the parameters for adjacent structures, resulting in the reduction of undesired coupling effect. Second, since a higher phase level is chosen, the phase distribution of the resultant metasurface can approach more closely to theoretical values, thus improving the holography performance [69]. Using a proper electrostatic bias circuit, the anisotropic digital status of each meta-particle can be dynamically toggled between eight possible modes, providing an unprecedented degree of freedom in real-time wavefront manipulation of THz waves. In this way, the information of the metasurface can be recorded in a digital way, which creates the connection between the physical meta-atom and digital codes. The digital description of metasurfaces has changed the way of describing, analyzing, and designing metasurface in the following aspects [70]. Firstly, as scattering properties are uniquely determined by the coding sequence applied on the metasurface, the specific structures of coding particles are no longer needed to be considered, which can significantly simplify the design process. Secondly, as the real-time reconfigurability is a very appealing character for THz meta-holograms, a digital description allows to implement a metasurface with digital logic devices and to be controlled by a field-programmable gate array (FPGA).

Figure 1 depicts the polarization-multiplexed THz holography by using a 3-bit re-writable metasurface comprising of 30×30 half-wavelength digital lattices. To suppress the undesired effects caused by the partial interaction of adjacent lattices, each of them is occupied

with 3×3 anisotropic meta-atoms of the same operational states whereby eight interchangeable reflection phases of $0, \pi/4, \pi/2, 3\pi/4, \pi, 5\pi/4, 3\pi/2$, and $7\pi/4$ are simply achieved against x - and/or y -polarized incidences. All sub-units of a lattice are electrically linked together so that we can simply control the chemical potential of a lattice with one electrostatic voltage instead of tuning all the sub-units independently. A field-programmable gate array (FPGA) hardware can be utilized to provide the desired electrostatic bias voltages at its output pins and set the operational status of each digital lattice, independently. Accordingly, through a real-time switch among arbitrary coding patterns already registered into the internal memory of FPGA, different holograms can be realized via a single reflective interface.

3 Real-time meta-cryptography for advanced information encryption

The two degrees of freedom of the designed metasurface hologram including anisotropy and reconfigurability allow for realizing a great variety of THz images. In fact, we have designed a digital metasurface hologram exposing two orthogonally-polarized independent channels whose field intensities can be arbitrarily manipulated with proper arrangement of the anisotropic coding particles in a real-time manner. As a great flexibility, the image planes for each polarization can be located either at identical or different distances from the metasurface plane. Hereafter, we intend to demonstrate different appealing aspects of the performance for the designed hologram. In order to reduce calculation time and memory consumption, the metasurface holograms with 30×30 lattices ($810 \times 810 \mu\text{m}$) was used for numerical simulations. A weighted Gerchberg–Saxton (WGS) algorithm discussed in the Method section is

utilized to extract the required phase distribution of the meta-hologram to generate the desired orthogonally-polarized images. Three parameters are adopted here to evaluate the image quality quantitatively. The imaging efficiency, which indicates how much incident energy is converged to designated points, is calculated by the fraction of the intensity concentrated in the holographic pattern divided by the value referenced to the reflectance intensity. Signal-to-noise ratio (SNR), the ratio between the peak intensity in the image to the standard deviation of the background noise. Root-mean-square error (RMSE) as the deviations between the simulated intensity ratios and theoretical values to describe the manipulation capacity of energy allocation of focal points [69].

To confirm the reconfigurable ability of the metasurface at $f = 5.8 \text{ THz}$, two words of ‘ALI!’ and ‘IUST’ are utilized as the target holographic images of the x - and y -polarized channels, respectively. Relying on the re-writable feature of the designed hologram, each group of ‘A/I’, ‘L/U’, ‘I/S’, and ‘!/T’ letters can be instantaneously generated through modulating the external electrostatic biasing voltages. The imaging distances of two information channels are similarly set as $z_d = 7.5\lambda_0$ at $f = 5.8 \text{ THz}$. According to the definition of the far-field region, the considered observation channels are located within the near-field region. The reflection phase maps of four different holograms for x and y polarizations obtained by the GSW algorithm are given in the Supplementary Information C, in which different colors represent eight different digital states. The designed graphene-based lattices are exploited to locally realize each pixel of the reflection phase map. In near-field simulations, we used from an electric incident field with the polarization angle of 45° to excite both x - and y -directed responses of the meta-atoms. The designed holograms are characterized with open boundary conditions at $f = 5.8 \text{ THz}$ and the electric field intensity distribution of both major

Figure 2: The simulation results of the holographic images of ‘ALI!/IUST’ captured at x -polarized (top row) and y -polarized (bottom row) channels which are located at the same distance.

polarizations on the imaging plane are drawn in Figure 2, wherein each pattern has been normalized to its maximum value. In accordance with our theoretical results, the x - and y -polarized field intensities clearly shows the letters ‘ALI’ and ‘IUST’. For the sake of a better comparison, Supplementary Information C depicts the theoretical results through the superposition of electric field components generated by digital lattices allocated with the calculated phase profiles. The details of theoretical calculation of the near-field intensities are described in the Method section. The high quantities of the imaging efficiencies further verify the superior image quality compared with the previous metasurface hologram designs in the THz spectrum. Apparently, there is a small deviation of the optimal imaging conditions from the theoretical design, due to the phase-quantization losses, the meta-atom size, and the writing fields (number of meta-atoms).

To inspect the versatility of the proposed metasurface hologram for polarization-multiplexed intensity manipulation, we exploit from the full potential of the anisotropic holograms, i.e., projecting two differently-polarized images at two different near-field observation channels at $z_{d1} = 5\lambda_0$ and $z_{d2} = 10\lambda_0$ ($f = 6.2$ THz). Here, five different holograms aim to project the words ‘HAMID’ and ‘KASRA’ on the x - and y -polarized channels, respectively. The x - and y -polarized reflection phase profiles required for constructing these five holograms are optimized after multiple iterations of WGS algorithm and reported in the Supplementary Information C. By setting the corresponding phase distributions across each phase-encoded hologram and on the illumination of incident fields with 45° polarization angles, the coding metasurface can reconstruct the ‘HAMID’ and the ‘KASRA’ on the x - and y -polarized image channels, respectively. The electric field intensities are captured over the observation channels located at $z_{d1} = 5\lambda_0$ and $z_{d2} = 10\lambda_0$ utilizing the time domain analysis of CST Microwave Studio (see Supplementary Information C). Upon comparing with the theoretical results depicted in Supplementary Figure S7, one can deduce that clear images (‘HAMID’ and ‘KASRA’) of different polarizations with very high fidelity and almost no distortion have been obtained at two different imaging planes, resulting in a dual channel metasurface hologram. Although the quality of the reconstructed images are good enough, it is still possible to enhance image qualities by enlarging writing fields, since the larger writing fields allow for higher resolution, higher imaging efficiency, and more complex holograms. In this section, we have demonstrated that the projected images can be distributed among two orthogonally-polarized channels of different imaging distances with high potential in near-field information processing and communications, rather than being focused on a single

channel. At the end, it should be noted that we can also use from distance diversity to achieve clearer holographic images. Indeed, the quality of holographic image can be dramatically improved by 4–5 dB through adaptively reprogramming the metasurface hologram for the observation distance of interest [67].

Up to now, we have designed a re-writable meta-hologram which has the ability to superimpose two differently-polarized images at the same/different spatial and spectral locations. Such superposition has the ability to conceive a different meaning in the reconstructed image, hosting unique merits for encryption. The ability to endow graphene-based metasurface pixels with polarization-controlled dynamics allows advanced information encryption and data storage. The crypto-storage metasurfaces in this paper are aimed at building a couple of independent channels with apparently-indiscoverable images, which escalates the security level of information encryption and data storage, significantly. Being at the same spectral location, the information encoded in either of orthogonally-polarized channels is instantaneously interchangeable, independent, and thus undetectable by the other. To reach this ultimate goal, we demonstrate a series of crypto-storage meta-holograms by defining a coding rule in which the original message can be securely mapped to a union set of two encrypted images of different polarizations. As schematically depicted in Figure 3, based on a powerful encryption rule called *cipher* [71], different combinations of letters (plaintexts) will be encrypted into a set of hotspots (cipherimages) in each channel. The cipherimage of each channel is converted into reflection phase profiles using the WGS algorithm and then encoded into the biasing voltages of vertical graphene ribbons on the meta-hologram. To think along this line, use of both re-writability and polarization diversity can undoubtedly boom the number of available cipherimages, which would enhance the security of such graphene-based data storages, enormously.

Let us consider the following scenario. Hamid intends to privately send Kasra a secure message, without loss of generality, a four-letter plaintext like “NANO”. Mono-alphabetic Substitution (MS) is firstly utilized to replace each letter in the plaintext to a certain cipher letter, according to an 8×8 look-up Table (fixed key). The substitution of single letters separately can be demonstrated by writing out the alphabet in some order to represent the substitution. A sorted dictionary of letters and symbols in Table 1a (see Supplementary Figure S13) is scrambled (diffused) in a complex fashion, yielding a key Table with 64 different elements. We assume that they have already shared this key dictionary table (Figure 3) with 64 elements. Also, only those who possess this secret key can

Figure 3: The proposed meta-cryptography scheme for THz information encryption and decryption. Hamid encrypts all characters of the plaintext “NANO” in the images produced by a re-writable crypto-storage metasurface through a key table and a convolutional encoding function. Kasra captures the orthogonally-polarized images including two undiscoverable maps of dots whose information can be unlocked by the polynomial generators associated with the convolutional encoder.

decipher the encrypted message into the plaintext. The rows and columns of the key table are called with the digital array of {000, 001, 010, 011, 100, 101, 110, 111} so that a unique string of length six is enough to completely disclose the address of each character. For example, the sequence “001111” indicates the character “N” of the shared table, where “001” and “111” denote the corresponding row and column, respectively. For sending a four-letter message like “NANO”, four 3-bit binary segments are needed to describe the row of each character and four other ones are also required to address the corresponding columns. The polarization state of the incident wave will provide another security lock to the image information. Furthermore, a couple of differently-polarized cipherimages will be generated in each of which four rows of three switchable spots are observable. By re-writing the phase profiles of the meta-hologram, it can independently control the field intensities at the spots for both cipherimages. If one denotes the strong field intensity as digital symbol “1” and the weak field intensity as digital symbol “0”, each row in the cipherimages can be thought of as a 3-bit string. As stated, these strings in the x - and y -polarized

channels digitally manifest the addresses of rows and columns of the plaintext characters in the key table, respectively. For example, Figure 4 depicts x - and y -polarized cipherimages required for storing the plaintext “NANO”. The corresponding theoretical results are shown in Supplementary Figure S9. The first and second channels carry the digital addresses of “001/011/001/101” and “111/010/111/100”, respectively. Accordingly, each letter of the word can be represented by a symbol, comprising a unique arrangement of hotspots in the holographic image. Although Hamid and Kasra only have the key table, there is still a little possibility that the plaintext be covertly intercepted by others. Supposing an extreme case that both dictionary and coding rule are stolen, the eavesdropper can thus completely decipher the stored data. In order to escalate the security level of data storage, a convolutional function [52] is employed here to map the binary strings of each cipherimage onto unrecognizable but recoverable parity strings doing the same task that the parity bits have in the digital communication. The parity strings which could not be eavesdropped and reverse-engineered are only sent over the channels instead of storing the original

Figure 4: The simulation results of the unsecured holographic images of “NANO/AEML” captured at x -polarized (top row) and y -polarized (bottom row) channels which are located at the same distance. In a different proposal for storing the messages, the right panel shows the secured maps of bright dots with different polarizations which are projected at two orthogonally-polarized channels. The maps of the top row securely carry the information of “NANO” letter together while the maps in the bottom row secretly include the information of the “AEML” letter. All holographic images are generated via a single graphene-based coding metasurface.

cipherimages. As illustrated in Figures 3 and 4, Hamid would like to store different messages into the meta-hologram including “NANO” and “AEML”. Due to the re-writable property of the designed metasurface, these messages are all encrypted on one meta-hologram. Hamid first encodes the plaintext “NANO” into two different cipherimages by using the dictionary table. Then, he concatenates the binary strings in each of x -polarized (rows) and y -polarized (columns) cipherimages to obtain two different 12-bit sequences as the inputs of convolutional encoder. More detailed information about convolutional encoding can be found in [52]. Hamid shares the utilized generator polynomials with Kasra and turns each of two 12-bit parity sequences at the output of this process into four series of 3-bit strings represented by several hotspots in the x - and y -polarized cipherimages. These hardly encrypted holographic images carry the information about the rows and columns of characters in the dictionary table.

Upon receipt of the crypto-storage at a safe place, Kasra illuminates the meta-hologram with both polarizations to see the hotspots of the cipherimages, extracting the convolutionally encoded 12-bit strings of each channel. If an x -polarized incidence is used, KASRA will read out the hotspots of Figure 4 (right panel, left column), whereas the cipherimage of Figure 4 (right panel, right column) is noticed by him when the incident wave has y -polarization. Using the shared generator polynomials, Kasra decrypts each 12-bit parity string through the Viterbi decoding algorithm [72]. Finally, KASRA can successfully rebuild the plaintext “NANO” by using the primary cipherimages and the dictionary table. Relying on the re-writable property of the proposed meta-holograms, Hamid uses the same crypto-storage and the same encryption rule for sending the message “AEML”. In overall, all characters of the dictionary table can be sent by specific holographic images that are reconstructed from the same meta-hologram based on the above-mentioned mechanism. The procedure can be further expanded where, other receivers can receive different cipherimages through using distinct generator polynomials during the convolutional encoding. They can decipher their respective messages using their own keys. Without knowing the polarization rules, dictionary table, and generator polynomials, the plaintext reconstruction process will fail even if the dictionary table has been 100% stolen. For instance, the eavesdropper will wrongly discover “\GJ” and “AHK3” messages if he quite steals the dictionary table along with the polarization rules but without knowing the shared generator polynomials.

With exploiting the above-mentioned encryption scheme, Hamid only employs a single metasurface to send a four-letter message to KASRA, while the conventional

schemes requires four different meta-holograms to do the same mission as depicted in Figure 4 (left panel). This elucidates an unprecedented level of data compactness and allows for more flexible and reliable information encryption which will be very useful for modern cryptography applications.

For authentication purpose in a multi-user network shown in Figure 5 (left panel), we can exploit an irreversible thumbprint called hash or digest, securely allowing the recipient to distinguish “who sends the message?” Besides, this helps to ensure the message stored in the meta-hologram is not altered or tampered by any third party. Security checking is accomplished by computing the digest of the sender’s name using a one-way hash function. Cryptographic hash functions are those which produce a randomized output string, with a fixed length regardless of the input length, from which reaching the input one is almost impossible. No matter how many times we employ the hash function, the outcome will be the same digest as long as the input does not change. Consider that Ali Abdolali intends to send an encrypted message to Shuo Liu. Based on the security protocol discussed before, Ali Abdolali encrypts the message into two different maps of dots and sends the hash of his name alongside the message itself. As depicted in Figure 5 (part1), using a truncated version of SHA-1 algorithm shared between the users, the personal digest of “Ali Abdolali” is computed as “ao09”. Referring to the same procedure discussed before, the digital addresses of “ao09” string is also converted to two orthogonally-polarized maps of dots, Figure 5 (part2), whose information will be saved on the meta-storage using the WGS algorithm, Figure 5 (part3). Indeed, the meta-hologram playing the role of meta-storage is programmed so that frames 1, 2 include the information of the decrypted message while frames 3, 4 contain the hash of the sender’s name. It should be remembered that the intensities of different points in each frame can be modulated in a real-time manner by changing the x - and y -polarized coding schemes. These holographic planes can be thought of as communication channels whereby digital messages can be stored in a new paradigm of high frequency meta-cryptography schemes. Figure 6 demonstrates the numerical simulations of x -polarized and y -polarized scattered fields upon shinning the meta-hologram by normal incident waves. The corresponding theoretical results are illustrated in Supplementary Figure S11 which depict an excellent agreement with the full-wave simulations. As can be seen, the programmed meta-hologram successfully projects two independent dot maps of orthogonal polarizations which securely carry the hash information

of the sender. Every perturbation, even the smallest one, should change the hash value and so the maps of dots. Let's see what happens when we switch the letters "d" and "o" in the word "Ali Abdolali". The new digest will be "oabk" that yields radically different dots maps from the first couple. Therefore, the personal digest is a reliable digital signature for authentication purpose. Thanks to the irreversible property of the hash values, the eavesdropper will discover nothing about the sender of the message even if he quite catches the frames 3, 4 and steals the key table, Figure 5 (part4). On the other hand, the recipient, Shuo Liu, receives both the encrypted message and the sender's name digest. First, he uses his decrypting key to again convert the message into a readable format.

Then, in a signature checking process, he creates the hash values of all possible senders in the network using the same hashing algorithm employed by the sender and compare them with those captured on frames 3, 4, Figure 5 (part5). At the end of this procedure, Shuo Liu finds Ali Abdolali as the sender of this message. There is no way that any other sender has the same hash and there is no chance for a hash to be different for the same sender. The proposed meta-cryptography and meta-holography protocols hold the reins of privacy and other anonymity related issues, thereby mitigating the opportunities offered to the

criminals and fake surveillance entities to decode the confidential information.

In cryptography, the "keyspace" of an encryption system is defined simply as the set of all possible (distinct) keys that the algorithm can accept. We apply three different encryption ways for which the keyspaces are different so that the overall keyspace has as much space as the product of the individual keyspace sizes. (1) Monoalphabetic Substitution: It is a well-known cryptography algorithm. Encryption of four letters (the same done in the submitted manuscript) with monoalphabetic substitution ciphers over a random 64 characters leads to $4^{64} = 2^{128}$ different possible keys. Therefore, the keyspace has 2^{128} elements, each of which can be represented by a general 128-bit key. (2) Convolutional encoding: Each convolutional encoding function is represented by a polynomial of order n (the number of shift registers), which specifies the manner of combination of the input bits to give the output bits. The details are described in one of our previous works [52]. In this paper, we arbitrarily use a 6-bit key for the convolutional decryption, which results in a keyspace with 2^6 different possible keys. (3) Hashing: Applying the SHA-1 function requires an n -bit key to make the hash of input plaintext. In this paper, we arbitrarily use a 3-bit key for the convolutional decryption, which results in a keyspace with

Figure 5: Demonstration of the real-time meta-cryptography in a multi-user network using multiple frames projected by the designed programmable secure data storage. The digital metasurface is dynamically controlled by using an external field programmable gate array. The holographic message contains two major parts: (1) Cipher message (Frames 1 and 2) and (2) User-specific hash (personal digest) information (Frames three and 4).

Figure 6: The secure protocol of generating the personal digest of the message sender by using the third (x-polarized) and fourth (y-polarized) frames projected by the re-writable meta-hologram. The orthogonally-polarized maps of dots appear at the arbitrary distance of $9\lambda_0$ from the metasurface. Combining the information of the x-polarized and y-polarized channels together discloses the name of Ali Abdolali as the message sender.

2^3 different possible keys. Consequently, the overall meta-cryptography can be characterized by a $3 + 6 + 128 = 137$ -bit key, yielding a massive keyspace with 2^{137} different possible keys. As can be deduced, the proposed meta-cryptography is secure enough even when the employed types of encryption (and the other information like the fact that the first two frames include the information of the message and the last two ones include the information of the message sender) leak out, and the eavesdropper does not access only to the associated keys. In most encrypting methods, the output cipher bits may be large, and the holographic images must have sufficient capacity to include the $m \times 3$ spots with large m . With a pre-defined size for the imaging planes, the holographic imaging should provide a finer spatial resolution to embed a more crowded set of smaller spots. As a well-known fact, the resolution of the holographic imaging can be further enhanced by increasing the metasurface cells contributing to the reconstruction of the encrypted images [73]. As an important factor, the small number of metasurface pixels yields a coarse resolution (spot size), restricting the number of usable spots or, more specifically, the capacity of the data storage. In summary, the following suggestions can be applied to enhance the security level of the proposed meta-cryptography.

- (1) One can exploit from the other modern cryptography types, such as Advanced Encryption System (AES), which are known as hardly breakable encryption algorithms [74].
- (2) A key dictionary Table with more symbols or alphabetic letters can be exploited to increase the overall size of the keyspace.
- (3) One can utilize a polynomial with a longer key for the convolutional encryption system.
- (4) The other Hash functions with longer associated keys can be established to empower both the keyspace and the cryptographic algorithm.

All in all, enhancing the security level of the proposed meta-cryptography may require larger number of accessible bright spots which can be simply provided through a meta-hologram with more number of contributing pixels.

4 Conclusions

In this work, using vectorial holograms rather than scalar intensity information, we demonstrated a re-writable computer-generated meta-hologram which allows independent and real-time process of two orthogonally-polarized channels with significantly different information and low cross-talk at THz frequencies. Relying on the

polarization multiplicity and re-writability of a computer-generated meta-hologram, a fully secure communication protocol is also developed to host unique merits for exploring real-time meta-cryptography where highly restricted access of information is imposed. The re-writable feature of our design stems from control of the biasing voltages applied to each graphene-based addressable pixel. Use of both reconfigurability and polarization multiplexing enables encoding two separate but interchangeable images into a single meta-hologram and reconstructing them under proper conditions, allowing us to implement real-time meta-cryptography for the first time. A WGS algorithm was utilized to retrieve the quantized phase profiles of the meta-hologram pertaining to each information channel. The information encoded in each near-field channel is independent and undetectable by the other. Aside from imaging purpose, we have shown that the proposed meta-hologram have the potential to serve as a re-writable crypto-storage, where a single metasurface can be deciphered into manifold messages with customized keys, featuring a high level of information security. Polarization multiplexing successfully introduces an additional security lock in the proposed wave-based encryption scheme. Several illustrative examples were presented to verify the robustness of our encryption scheme with vulnerability tests and prove the highly-efficient (>70%), polarization-multiplex, broadband, and switchable functionalities of the presented meta-holography. Comprehensive discussions regarding the possible realization methods, the security level, and the polarization cross-talk were also presented. In addition, polarization switching along with re-programmability of the proposed meta-device can be readily exploited for other interesting functionalities including dynamic beam steering, focusing, shaping, as well as dynamic optical vortex generations, largely enriching the functionality breadth of current metasurface systems. With stronger robustness than the conventional metasurface-based encryption techniques, this work features a paradigm for implementing compact, re-writable, multitasking, and multichannel information encryption architectures and may lead to a new frontier for applications like anti-counterfeiting data storages.

5 Methods

5.1 Cross-talk analysis

For any polarization multiplexing device, the crosstalk between the orthogonal polarizations should be carefully evaluated in both

meta-atom and metasurface scales. In the meta-atom level, the “crosstalk” of orthogonal polarization happens whenever the magnitude of the cross-polarized reflection coefficient is not negligible or the structural parameters for controlling each of polarizations also affect the reflection properties pertaining to the other polarization. To inspect the performance of the carefully designed meta-atom, both possible sources of polarization crosstalk are studied, here. The amplitude spectra of the cross-polarized reflected fields are shown in Supplementary Figure S14a, when the related chemical potential varies between 0.2 and 1.2 eV. As seen, the magnitude of the cross-polarized components in all cases is far less (at least about 20 dB) than that of the co-polarized components, meaning that the information devoted to each polarization will not be coupled to the other differently-polarized channel. The other examination is performed by plotting the reflection phase response of one channel for different chemical potentials associated with the orthogonal channel. The corresponding results are given in Supplementary Figure S14b, demonstrating that the variation of structural parameters related to the x-polarized channel does not affect the performance of the y-polarized channel and vice versa. The results presented in Supplementary Figures S14a,b prove that the designed graphene-based meta-atom exposes nearly negligible polarization cross-talking, such that the proposed meta-cryptography can be safely accomplished for each channel in an independent manner. To further show the importance of our design, we present the previous results for another geometry in which the width of graphene ribbons (a) is increased (see Supplementary Figures S14c,d). As noticed, both cross-polarization and isolation effects are more degrading in this case as the result of coupling enhancement between the graphene ribbons when the widths are increased.

When the computer-generated hologram is illuminated by both x- and y- incidences (slant polarization), the cross-polarized fields for each polarization, if any, can distort the information contained in the co-polarized imaging plane of the counterpart polarization, as a noise-like effect. However, diminishing the cross-talk in the meta-atom level allows us to safely manipulate the phase map of each polarization in an independent manner. The holographic images chosen for this demonstration carry “A” and “L” letters in x- and y-polarized channels, respectively. In one simulation run, the letters are set to be projected on the same imaging planes ($z_d = 390 \mu\text{m}$) while in the other

one, the holographic images are reconstructed at separate distances ($z_d = 250 \mu\text{m}$, $z_d = 450 \mu\text{m}$) from the metasurface plane. Figure 7 (same plane) and Figure 8 (separate planes) depict the retrieved holograms of the co- and cross-polarized channels at their respective imaging planes by shining plane waves with 0° , 45° , and 90° polarization angles in a direction normal to the hologram plane. For the illumination with $0^\circ(90^\circ)$ polarization angle, the co- and cross-polarized fields at both imaging planes are presented. Also, with 45° polarization angle, both x- and y-polarized channels are excited and the corresponding images will be simultaneously projected on the pre-defined planes. From the figures, the following remarks can be concluded:

- (1) In the case of $0^\circ(90^\circ)$ polarization angle, the image reconstruction is mainly performed with the same polarization and at the respective imaging plane. The information leaking out to the cross-polarized fields, y (x) polarization, is quite negligible at both imaging planes.
- (2) In the case of 45° polarization angle, the holographic images are well reconstructed at their own observation plane with negligible noise-like effects arising from the cross-polarized fields. We utilized Pearson correlation coefficient (PCC) to quantitatively measure the similarity between the normalized y-polarized holographic images reconstructed under the illumination of 45° and 90° polarization angles. Based on the results given in Figure 7 and Figure 8, the PCCs are calculated as high as 98.99%/96.24 and 99.23%/99.31% for in- and out-plane images, respectively. The values before and after slash correspond to x- and y-polarized images, respectively. The PCC describing the holographic images with separate distances is slightly better than that of images with identical observation planes. Anyway, the high PCCs in the case of 45° polarization angle demonstrate that the information contained in the x-polarized channel does not play a noise-like role for the y-polarized channel. Similar results have been obtained for 0° and 45° polarization angles but are not given here for the sake of brevity. One can adjust the imaging distances, separately, to further minimize the “cross-talk” for polarization-controlled dual images. The polarization cross-talk in the metasurface level can also be reduced by diminishing the near-field coupling through making the contributing meta-atoms away from each other, a solution which is not usually preferable for applications with a limited size of imaging screen.

Figure 7: Cross-talk analysis in the metasurface scale. Demonstration of polarization cross-talk when the designed meta-hologram is illuminated by normal plane waves of 0° , 45° , and 90° polarization angles. The x- and y-polarized fields are plotted at the imaging planes which are set at the same distance from the metasurface plane.

Figure 8: Cross-talk analysis in the metasurface scale. Demonstration of polarization cross-talk when the designed meta-hologram is illuminated by normal plane waves of 0° , 45° , and 90° polarization angles. The x - and y -polarized fields are plotted at the imaging planes which are set at different distances from the metasurface plane.

5.2 Meta-holography algorithm

The phase-only meta-holography [75–77] has been widely employed by using an iterative or point source algorithm in order to optimize the uniformity of the intensity. By adding random phase masks to mimic the diffuse reflection of objects, one can calculate the phase-only CGHs by neglecting the amplitude information. Given a target image at a pre-determined observation plane, there are diverse algorithms to retrieve the required reflection phase map of the pure-phase metasurface hologram such as random superposition algorithm, Fienup Fourier algorithm, Yang–Gu algorithm, direct search algorithm, Gerchberg–Saxton (GS) algorithm [78–80], to name a few. Among them, the weighted Gerchberg–Saxton (WGS) algorithm has been widely used in metasurface holograms because of its simplicity, high imaging efficiency, and focal uniformity. Relying on the polarization-multiplexed performance of the designed meta-atoms, two independent information channels of different polarizations can be simultaneously devoted to the holography. The schematic diagram of the theoretical analysis adopted to retrieve the required phase maps of both orthogonally-polarized channels is given in Supplementary Information F. Since the limited focal length with respect to the working wavelength and metasurface dimensions with respect to the imaging distance, the propagation of electromagnetic field is beyond the Fresnel approximation in diffraction optics. Therefore, the propagation formula is replaced by the Rayleigh–Sommerfeld diffraction instead of the paraxial approximations:

$$E(x_0, y_0) = \frac{1}{j\lambda} \iint_S E(x, y) \cos \langle \mathbf{n}, \mathbf{r} \rangle \frac{\exp(jkr)}{r} dS \quad (4)$$

in which, $E(x_0, y_0)$ and $E(x, y)$ indicate the electric field distribution over the observation plane and the metasurface hologram, (x_0, y_0) and (x, y) represent the location of observation and excitation pixels, λ is the operating wavelength, $r = \sqrt{(x - x_0)^2 + (y - y_0)^2 + z_d^2}$ denotes the distance between observation and excitation pixels, z_d is the imaging distance, and finally, $\cos \langle \mathbf{n}, \mathbf{r} \rangle = z_d/r$ remarks the inclination factor. Based on the equation above, the field intensities on the image plane (observation pixels) is defined as the superposition of electric fields reflected from each digital lattice (excitation pixel) under the normal incidence. Let us consider $I(x, y)$ as the intensity of the desired image.

Firstly, the phase map of the electric fields on the metasurface hologram for both channels is initiated by a quadratic phase distribution rather than being initialized with random phase distributions to accelerate the convergence. This means that the algorithm is started with $E(x_0, y_0) = I(x_0, y_0) \exp[j\psi(x_0, y_0)]$ in which ψ denotes the quadratic phase profile. Using the inverse propagation operator, the distribution of the electric field over the meta-hologram plane can be calculated by

$$E(x, y) = \frac{1}{j\lambda} \iint_{S_0} E(x_0, y_0) \cos \langle \mathbf{n}, \mathbf{r} \rangle \frac{\exp(-jkr)}{r} dS_0 \quad (5)$$

Considering the phase-only property of the metasurface hologram, the binary phase information of the equation above is only used as the input of Equation (4) to proceed the design cycles. After evaluating the reconstructed image – if it is not satisfactory – mixing the weighted amplitude of the target image $\mathbf{w} \cdot \mathbf{I}(x, y)$ with the calculated phase distribution $\phi(x_0, y_0)$ yields the input data of the inverse process, i. e., $E(x_0, y_0) = \mathbf{w} \cdot \mathbf{I}(x_0, y_0) \exp[j\phi(x_0, y_0)]$. In order to avoid weak-intensity observation pixels, the GSW algorithm is utilized to manipulate the focal intensity ratios achieving uniform distribution on the observation plane. Indeed, the vector $\mathbf{w}$ with the components of $w(x_m, y_n) = \sum_{m,n} |E(x_m, y_n)| / N^2 E(x_m, y_n)$ is adjusted in each iteration to reduce the deviations of $|E|$ from $\langle E \rangle$. Here, x_m and y_n denote the location of bright observation pixels and N^2 is the total number of observation pixels. The iterative algorithm will continue until the least mean square error between the target and reconstructed images becomes less than a pre-determined threshold. The iterative optimizations for two differently-polarized channels are separately managed and then combined to construct the final polarization-multiplexed metasurface. Once the iterative optimization pertaining to each channels converges, the metasurface hologram will be anisotropically programmed based on the obtained coding masks (M^{x-pol} and M^{y-pol} in Supplementary Information F).

5.3 Theoretical validation

Here, we intend to validate the performance of the proposed meta-holography through a fully theoretical framework involving the near-field

considerations. Relying on the Huygens' principle, each contributing tile of the digital metasurface is replaced with an electrically small secondary source calculated based on the induced surface current, $\mathbf{J}(x', y')$ [81]. The field radiated by the Huygens' sources can be extracted by solving the well-known inhomogeneous wave equation, i. e., $\nabla^2 \mathbf{A} + k^2 \mathbf{A} = -\mu \mathbf{J}(x', y')$. Referring to $\mathbf{H} = \frac{1}{\mu} \nabla \times \mathbf{A}$ and $\mathbf{E} = \frac{1}{j\omega\epsilon} \nabla \times \mathbf{H}$, the electric field scattered by each digital tile can be analytically computed based on the auxiliary potential solution and the Green's function tensor pertaining to the host medium [82]

$$\mathbf{E}(x, y, z) = \frac{1}{j4\pi\omega\epsilon} \left[(x-x')^2 \frac{3 + j3k|\mathbf{r}-\mathbf{r}'| - k^2|\mathbf{r}-\mathbf{r}'|^2}{|\mathbf{r}-\mathbf{r}'|^5} \mathbf{G}_1 - \frac{1 + jk|\mathbf{r}-\mathbf{r}'| - k^2|\mathbf{r}-\mathbf{r}'|^2}{|\mathbf{r}-\mathbf{r}'|^3} \mathbf{G}_2 \right] \quad (6)$$

in which, $\mathbf{r} = (x, y, z)$ and $\mathbf{r}' = (x', y', z')$. Eventually, the contribution of all digital lattices can be written in a closed form expression [82]

$$\mathbf{E}(x, y, z) = \frac{1}{j4\pi\omega\epsilon} \sum_m \sum_n \left[(x-x')^2 \mathbf{G}_1 - \mathbf{G}_2 \right] e^{j\phi(m,n)} e^{-jk|\mathbf{r}-\mathbf{r}'|} \quad (7)$$

5.4 Possible fabrication methods

The fabrication feasibility of the proposed real-time meta-cryptography should be evaluated from the aspects of: (1) manufacturing the vertically aligned graphene layers and (2) organizing the 2D biasing network. The metasurface body can be fabricated through two different approaches. In the first fashion, the graphene layers are initially manufactured by the same methods conventionally accomplished for flat graphene horizontally etched on a specific substrate [83, 84]. As observed from (Figure 1), the proposed metasurface includes two orthogonally connected arrays along the x and y directions, in each of which, a graphene ribbon and a thin Quartz layer are vertically placed on the grounded Quartz substrate. Regarding the current fabrication technology, the fabrication method for each of orthogonally connected arrays may follow the steps below. First, the thick Quartz dielectric is coated on a silicon wafer through a spin-coating solution. Then graphene layer can be synthesized by chemical vapor deposition (CVD) on a Cu foil and transferred onto a 65 nm insulating Al_2O_3 dielectric. The graphene monolayer can be uniformly deposited by the atomic layer deposition on an ultra-high resistivity p -type poly-Silicon wafer. The excess graphene is eliminated after the transfer process by exploiting a 100 keV electron beam lithography in Polymethyl methacrylate (PMMA), followed by an oxygen plasma etch. Therefore, just the graphene ribbon will remain on the structure surface. Furthermore, the Au contacts were evaporated by the electron beam deposition to prepare the Au- Al_2O_3 -poly-Silicon capacitor for applying the electrostatic fields on the graphene layer (see Supplementary Figure S2). After being prepared, the x - and y -directed arrays are perpendicularly aligned on the grounded Quartz substrate (the lowest layer), provided that the suitable bonding or adhesive assemblies are utilized.

As the second approach, relying on the recently developed fabrication strategies, the graphene nanosheets can also be vertically grown from the beginning. Compared with flat graphene layers lying on substrates, vertical graphene nanosheets (VGNs) are normally

composed of one to several layers arranged perpendicularly to the substrate surface. In recent years, several methods have been fostered to synthesize VGNs [85–93]. Low-temperature plasma-enhanced chemical vapour deposition (PECVD) [94] has been among the most successful techniques to produce the engineered networks of controllable VGNs in a low-temperature, highly-efficient, and catalyst-free manner, making the growth amenable to diverse materials such as SiO_2 , Quartz, Al_2O_3 (dielectric), and Si (semi-conductor) [95]. PECVD growth of VGNs can be conducted on virtually any substrates ranging from macro-sized to micrometer- and even nanometer-sized planar structures [95]. In this paper, the microwave electron cyclotron resonance PECVD is suggested as a promising technique to fabricate VGNs on SiO_2/Si and quartz substrates. With ultra-high pure CH_4 and commercial grade Ar plasma gases, the growth of VGNs on SiO_2/Si and quartz substrates can be performed in an inductively coupled PECVD reactor with schematic diagram illustrated in Supplementary Figure S16. Ar is let into the chamber as a dilution gas because it enhances the C_2 radical production, which helps to grow high-quality VGNs. The procedure can be performed by using 1200 W of microwave power. The source gas CH_4 is sent through a circular showerhead that uniformly injects gas into the reaction chamber. Ultrasonically, cleaned substrates are loaded into the substrate holder, and the chamber was pumped down to a base pressure 5×10^{-4} Pa. The substrate temperature is increased to 750 °C due to the plasma heating effect, and after 20 min, the substrates are pre-cleaned by Ar plasma under 20 sccm flow rate for 10 min at 200 W microwave power. No external substrate heating is required. After pre-cleaning the substrates, CH_4 is introduced to the chamber through a circular showerhead at 2.5 sccm flow rate, and subsequently, Ar flow is reduced to 2.5 sccm. The operating pressure of the reactor chamber is maintained at about 0.1 Pa. After growth, the plasma can be shut down, and the substrates are annealed at the same growth temperature. Finally, the samples are cooled down to the ambient temperature under argon flow. According to the above-mentioned discussion, one can deduce that the fabrication of the main body of the proposed graphene-based metasurface is quite feasible.

As another viewpoint, the biasing grid seems to be an important part of the practical implementation of such reconfigurable meta-devices. The computer-generated phase maps are realized by biasing the graphene layers of each metasurface pixel with suitable DC voltages. Each metasurface pixel is characterized by two distinct biasing voltages related to each graphene layer. The voltage levels of each metasurface cell are dynamically addressed via a field-programmable gate array (FPGA). As shown in Supplementary Figure S3, we have borrowed the concept of phased array [51, 96] based on individual biasing and managing the progressive phase-delay of nano-antennas in an array to dynamically control the phase map of each polarization. The employed meta-atoms are connected through wire links inserted in between so that the biasing voltages can be feasibly applied from one side of the structure. The DC voltage is separately applied across the top metal contact and the bottom poly-Si layer for each graphene layer. The required voltages are given in Supplementary Information B, and the thickness of biasing lines is chosen as 100 nm (greater than the skin depth of gold in the operating frequency). In [56], we demonstrated that since the width of connecting wires is very thin (up to 300 nm) with respect to the operating wavelength, they expose negligible artifacts either on the individual response of the contributing meta-atoms or on the macroscopic behavior of the programmable metasurface. In addition, the biasing wires resemble current lines parallel to the ground surface, whose radiation will be canceled based on the destructive interferences justified by the well-known image theory.

Overall, we expect the near-field pattern of the designed metasurface not to be remarkably degraded by the presence of connecting wires. The biasing grid is depicted in Supplementary Figure S3 in which the DC voltage level of each line is specified by the FPGA.

Author contribution: Hamid Rajabalipanah, Kasra Rouhi, and Ali Abdolali conceived the idea. Hamid Rajabalipanah and Kasra Rouhi carried out the theoretical calculations and numerical simulations. Shahid Iqbal, Lei Zhang, and Shuo Liu helped in analytical modeling. Hamid Rajabalipanah wrote the manuscript based on the input from authors. Ali Abdolali Supervised the project. All authors participated in the data analysis and read the manuscript.

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