Research article

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Frequency-multiplexed pure-phase microwave meta-holograms using bi-spectral 2-bit coding metasurfaces

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Abstract: In this paper, a dual-band reflective meta-hologram is designed providing two distinct information channels whose field intensity distributions can be independently manipulated at the same time. The proposed pure-phase meta-hologram is composed of several frequency-dispersive coding meta-atoms possessing each of 2-bit digital statuses of “00”, “01”, “10”, and “11” at either the lower (X-band) or the higher (Ku-band) frequency band. Relying on the weighted Gerchberg-Saxton phase retrieval algorithm, different illustrative examples have been provided to theoretically inspect the dual-band performance of our coding meta-hologram. Numerical simulations validate the proposed frequency multiplexing meta-holography with the ability to project two different high-quality images with low cross-talk on two X-band and Ku-band near-field channels located at distinct pre-determined distances from the metasurface plane. As proof of concept, two meta-hologram samples are fabricated, and the experimental results corroborate well the numerical simulations and theoretical predictions. The designed meta-hologram features all fascinating advantages of the coding metasurfaces while its performance overcomes that of previous studies due to providing two information

channels rather than the conventional single-channel holography. The frequency multiplexing acquired by the proposed bi-spectral coding meta-hologram may provide great opportunities in a variety of applications, such as data storage and information processing.

Keywords: coding metasurface; microwave holography; frequency multiplexing.

1 Introduction

Metasurfaces are two-dimensional analogues of bulky metamaterials which have found greater potential in the quest for revolutionizing the wave manipulating schemes and showing counterintuitive performances that could never be realized by natural materials [1]. Within the sub-wavelength scale, a vast variety of metasurface-based devices have been designed with the aim of controlling the key properties of the incident electromagnetic (EM) fields such as amplitude [2], phase [3], and polarization [4]. Metasurfaces have become a rapidly growing field of research and open up unprecedented potential as the key building blocks in many modern EM applications including energy absorption [5, 6], radar cross section reduction [7, 8], antenna engineering [9], wave-based signal processing [10, 11], and so on. In 2014, Cui et al. introduced the concept of coding metasurfaces [12], in which the designed metasurfaces are characterized with n-bit digital coding particles possessing 2n-level reflection and/or transmission phase responses rather than being described with continuous EM parameters. It was demonstrated that the EM waves can be manipulated by changing the coding sequences of the digital meta-atoms. Numerous types of the field programmable metasurfaces operating in the microwave [13–18] to terahertz [19–23] spectra have been designed by simply implementing the corresponding coding sequences to carry out diverse EM functionalities including anomalous scattering [24], scattering diffusion [25], beam focusing [26], holographic imaging [27],

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and vortex beam generation [28], in reflection or/and transmission [29] windows. Although great diversity of achievements have been reported for coding metasurfaces, there is still plenty of room to conceive new interesting functionalities. One ongoing trend, as a demand for highly integrated systems with small size and low cost, is to seek different aspects of multiplexing (polarization [30, 31] or frequency [32, 33]) in a single shared aperture architecture to separately accomplish multiple missions at the same time. To fulfill such expectations, frequency diversity can be deliberately used in the field of coding metasurfaces to obtain different multispectral scattering phenomena including anomalous scattering and beam focusing. Although multispectral coding metasurfaces with bi-functional performances have been reported so far [15–18], those methods are difficult to be utilized when more advanced functionality like meta-holography is of interest. Holography is one of the most promising imaging techniques to record and reconstruct the image of objects by storing and releasing the phase information [33]. Based on different phase retrieval algorithms like Gerchberg-Saxton (GS), the computer-generated holograms can be elaborately designed with sub-wavelength meta-atoms to encode the holographic information of object pattern calculated by a computer [34]. The fascinating features of coding metasurfaces are particularly advantageous in this regard and can be used to expand the functionality of the holographic components, yielding digital meta-holography [26, 35]. Due to very small pixel sizes and sub-wavelength scale of coding particles compared with the conventional holograms having undesired diffraction orders [36], digital meta-holograms reveal unprecedented spatial resolution, much higher image efficiency, low noise, and high precision of the reconstructed images [26, 35]. Although several techniques for multiplexing information into a single anisotropic metasurface hologram have been demonstrated [33–40], most of them allow the storage of multiple images at a single frequency [26, 30, 35–38]. Additionally, the ability to engineer the nonlinear properties of meta-particles has enabled nonlinear holography [41]. However, to the best of the authors' knowledge, the frequency-multiplexed coding meta-holograms with independent control of images in each working band have not been reported yet. In this paper, by controlling the frequency dispersion of a 2-bit digital meta-atom, multiple simultaneous holograms can be encoded in a shared aperture coding metasurface. We propose a recipe to construct a bi-layered reflection-type coding meta-hologram that has the tendency to simultaneously project two separate images on two near-field channels of different locations and operating frequencies. By modifying the geometry of

each reflection-type coding particle, the lookup table of our design consists of a group of 16 frequency-dispersive digital elements (00–00 to 11–11) constructed by metallic patches of different sizes. The first and second digits indicate the operational statuses of the coding particle at the lower (X-band) and higher (Ku-band) frequency bands. Our pure-phase bi-spectral meta-hologram is then formed by grouping together these digital meta-atoms based on the coding sequence extracted by the weighted GS (WGS). Unlike most studies in this field [37, 42], the presented designs in this paper do not resort to the Pancharatnam-Berry elements [27], and hence, the proposed meta-holography can be elaborately accomplished without inevitable change in the incident wave polarization. Several illustrative examples are demonstrated to evaluate the frequency multiplexing performance, the low cross-talk, and the high image quality of the designed coding meta-hologram. In accordance with the theoretical and numerical results, our proof-of-concept experiments demonstrate that any two desired holographic images can be generated at the lower and higher frequency bands with only a single coding metasurface.

2 Design method of the coding meta-atoms

The schematic representation of the proposed coding meta-hologram is depicted in Figure 1. The key step to realize the proposed dual-band meta-hologram is to deliberately design meta-atoms capable of obtaining separately adjustable phase responses in each of X and Ku frequency bands. The building blocks employed to compose the proposed

Figure 1: The schematic sketch of the dual-band coding elements as well as the proposed coding meta-hologram creating two different information channels at the lower and higher working frequency bands upon illuminating by normal plane waves. Different images (“H” and “V”, here) can be simultaneously projected in these near-field channels.

dual-band meta-hologram are a set of reflection-type digital meta-atoms, as depicted in Figure 2A. Each coding meta-atom is a multilayered metal-insulator-metal structure [43–48] consisting of two rectangular (and/or square) metallic patches, two F4B supporting dielectrics ($\epsilon_r=2.65$, $\tan\delta=0.001$, and $h=1$ mm), and a copper ground plane with the thickness of $t=0.018$ mm, eliminating the power transmission across the frequency band of study. The coding particles have the periodicity of $p=7$ mm in which the side lengths of the top and middle metallic patch resonators along the x and y axes are indicated with (w_1, w_2) and (l_1, l_2) parameters, respectively. Although each patch resonator is essentially responsible for manipulating the phase response in each frequency band, due to the near-field coupling among layers, the combined effects cannot be thought of as a simple superposition. Four-level phase shift meta-atoms are optimized by varying the geometries to cover the range between 0° and 290° . Therefore, a comprehensive parametric study has been accomplished on w_1, w_2, l_1 , and l_2 to form a lookup table for designing the required bi-spectral coding elements exposing arbitrary 2-bit reflection phases of $0^\circ, 90^\circ, 180^\circ$, and 270° at each of X- and Ku-bands. The 16 coding meta-atoms were extracted at the output of this process which can be digitally described by

$$M_{2\text{-bit}} = \begin{pmatrix} 00/00 & 00/01 & 00/10 & 00/11 \\ 01/00 & 01/01 & 01/10 & 01/11 \\ 10/00 & 10/01 & 10/10 & 10/11 \\ 11/00 & 11/01 & 11/10 & 11/11 \end{pmatrix} \quad (1)$$

Here, the binary numbers before and after the slash denote the operational status of the coding particle at the lower

Figure 2: Reflection-type digital meta-atoms and EM response of all 16 coding particles.

(A) The perspective view of the designed coding element along with (B) the top view of all 16 digital elements. Each binary number along the horizontal and vertical axes indicates the operational state of the coding meta-atom in the lower and higher frequency bands.

and higher frequency bands, respectively. Meanwhile, the digital states of 00, 01, 10, and 11 stand for reflection phases of $0^\circ, 90^\circ, 180^\circ$, and 270° , respectively. The detailed structural parameters of the 16 meta-atoms are given in Table 1. The effect of the thickness of dielectric spacers on the phase states of the lower and upper frequency bands have been investigated in Supplementary Information A. A commercial software, CST Microwave Studio, was employed to characterize the EM response of all 16 coding particles (see Figure 2B) by applying unit cell boundary conditions in x - and y -directions and Floquet ports shining x -polarization along z -direction. The reflection phase and reflection amplitude spectra of the designed coding elements have been plotted in Figure 3A–D for different frequency ranges between 9.5 GHz and 10.5 GHz (lower band) and between 14.5 GHz and 15.5 GHz (higher band), respectively. As the first deduction from Figure 3A, owing to using low-loss dielectric substrates, negligible energy absorption occurs across both bands, resulting in the high reflectivity of the coding inclusions which, in turn, guarantees the high efficiency of the reflection-type meta-hologram. Also, the first immediate observation from Figure 3B is that for each reflection phase in the lower band, four operational statuses with a $90^\circ \pm 10^\circ$ phase step exist in the higher band, and vice versa. The consecutive coding elements in each row of $M_{2\text{bit}}$ exhibit identical/different reflection phases in the lower/higher imaging bands. Contrarily, the consecutive coding meta-atoms in each column of $M_{2\text{bit}}$ expose identical/different reflection phases in the higher/lower bands. For example, at the lower band, the first four phase states with identical bit before slash are represented by the first row in the matrix $M_{2\text{bit}}$ (00/00, 00/01, 00/10, and 00/11). These meta-atoms have almost the same reflection phase at the lower frequency band as depicted in Figure 3C by four green colors, i.e. solid, dash, dotted, and dash dotted green lines, while they possess a 270° phase coverage at the higher frequency band where each state is in $90^\circ \pm 10^\circ$ phase difference with its neighboring state. The digital state of these four phases at the higher band is denoted by the binary digits after the slash in the first row of the matrix $M_{2\text{bit}}$.

Another important point is the ratio between the lower and upper frequency bands. In order to increase the ratio $f_{\text{upper}}/f_{\text{lower}}$, a numerical optimization involving all contributing geometrical parameters, i.e., the period “ p ” of the unit cell, the dielectric thickness “ h ”, and the side lengths “ l_1 ”, “ w_1 ”, “ l_2 ”, and “ w_2 ” of both metallic patches, is required. Nevertheless, the dominant parameters to enlarge or reduce this frequency band separation are the period “ p ” of meta-atom and the thickness “ h ” of the dielectric substrate. Thus, by increasing the values of “ p ” and “ h ”,

Table 1: The detailed structural parameters corresponding to the 16 frequency-multiplexed 2-bit meta-atoms.

Digital code	00/00	00/01	00/10	00/11	01/00	01/01	01/10	01/11
W_1	6 mm	5.1 mm	4.7 mm	3.5 mm	6 mm	5.2 mm	4.9 mm	4 mm
W_2	6.7 mm	6.7 mm	6.7 mm	6.7 mm	2 mm	6 mm	6.2 mm	6.2 mm
L_1	6.7 mm	6.7 mm	6.7 mm	6.7 mm	6.6 mm	6.5 mm	5.6 mm	6 mm
L_2	6.7 mm	6.7 mm	6.7 mm	6.7 mm	6.6 mm	6.5 mm	5.6 mm	6 mm
Digital code	10/00	10/01	10/10	10/11	11/00	11/01	11/10	11/11
W_1	5.5 mm	5.4 mm	3.9 mm	4.9 mm	3 mm	4 mm	5.2 mm	3 mm
W_2	4.9 mm	5.5 mm	6.7 mm	5.5 mm	4.9 mm	2 mm	5.9 mm	5.9 mm
L_1	4.9 mm	5.5 mm	6 mm	6 mm	4.9 mm	6 mm	2 mm	6.5 mm
L_2	4.9 mm	2.5 mm	1 mm	6 mm	4.9 mm	6 mm	1 mm	1.5 mm

The index before and after “/” indicates the digital bits in the lower and upper frequency bands, respectively.

Figure 3: The reflection phase and reflection amplitude spectra of the designed coding elements plotted for different frequency ranges. (A) The amplitude spectra of all 16 coding meta-atoms in the lower and higher frequency bands. (B) The reflection phase spectra of the last four meta-atoms where the shaded regions refer to the operating bands. The reflection phase spectra of all 16 coding particles in the (C) lower and (D) higher working bands. In the proposed coding metasurface (MS), there are 16 meta-atoms, each of which represents a specific digital phase state at the lower and upper frequency bands. Indeed, at the lower or upper frequency band, there are a total of 16 digital states in four groups of four phase curves in which each group has almost the same values (and so the same digital states).

the operating frequency can be moved downward. Subsequently, through optimizing the sizes of both patches, the dual band behavior can be obtained at two frequencies of different ratios, which could be at larger distance compared to the current results. As a consequence, enlarging the frequency separation can be attained at the expense of increasing the unit cell size and also the overall thickness which is not generally desired for these two reasons: 1) Increasing the spatial periodicity of the meta-atom would lead to the excitation of unwanted high-order Floquet harmonics [49]. Moreover, the unit cell has more sensitivity

to the variation of incident wave angle in this case. 2) A thick profile contradicts with the current efforts to design miniaturized and compact architectures, and meanwhile, it may lead to the excitation of unwanted surface waves propagating on the substrate. These degrading factors are the upper limitations for setting the frequency ratio. Contrarily, the spectral coupling between the upper and lower frequency bands can be named as an important restriction in achieving small frequency separations. Furthermore, there is always a tradeoff between increasing the distance between the operating frequencies and the size of the MS.

Furthermore, the full control over the digital states of the coding meta-atoms in the two different working bands, as shown in Figure 3C and D, gives freedom to have quite independent functionalities in each band via sharing the same aperture.

3 Design method of the coding meta-hologram

For designing the dual-band digital meta-hologram of Figure 1, the optimum distribution of the binary reflection phases in each imaging band can be separately derived using different retrieval methods such as Fienup Fourier algorithm [50], and GS algorithm [51]. The proposed bi-spectral coding meta-hologram is aimed at producing two different holographic channels with different working frequencies once programmed by proper coding masks. Actually, the frequency of the incident wave selects which channel is to be excited and which image is to be generated in that holographic channel. The observation planes (so-called holographic channels) can be placed at either identical or different locations. In the inverse problem, we deliberately exploited a WGS phase retrieval approach [36] to seek for the best 2-bit coding patterns required for uniformly modulating the field intensities in the near-field channels of X- and Ku-bands. It should be noted that the iterative optimization procedures pertaining to the lower and higher frequency bands are separately managed with different target images. The two output coding patterns will be superimposed based on the coding rule of Figure 2B to construct a digital map for programming the frequency-multiplexed coding meta-hologram. The small imaging distances with respect to the working wavelengths in this paper make the propagation of EM field to deviate from the Fresnel approximation in diffraction optics [30]. Instead, to extract the holographic image reconstructed by the coding metasurface in each band, the Rayleigh-Sommerfeld diffraction propagation formula can be employed as the superposition of the fields radiating by each supercell:

$$U(x_0, y_0) = \frac{1}{j\lambda} \iint_S U(x, y) \cos \langle \mathbf{n}, \mathbf{r} \rangle \frac{\exp(jkr)}{r} dS \quad (2)$$

in which $U(x_0, y_0)$ and $U(x, y)$ are the electric field distributions over the holographic channel and the meta-hologram plane; (x_0, y_0) and (x, y) indicate the location of observation and excitation pixels and $r = [(x - x_0)^2 + (y - y_0)^2 + z_{d2}]^{0.5}$ is the distance between them; λ is the operating

wavelength for each frequency band; $\cos \langle \mathbf{n}, \mathbf{r} \rangle = z/r$ is the inclination factor; and finally, z_d remarks the imaging distance. For each near-field channel, the design procedure is as follows. Firstly, the intensity of the target image, $I(x_0, y_0)$, is mixed with a quadratic phase distribution rather than conventional random phase profiles to accelerate the convergence. This means that the algorithm is started with $U(x_0, y_0) = I(x_0, y_0) \exp[j\Psi(x_0, y_0)]$ 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

$$U(x, y) = \frac{1}{j\lambda} \iint_{S_0} U(x_0, y_0) \cos \langle \mathbf{n}, \mathbf{r} \rangle \frac{\exp(-jkr)}{r} dS_0 \quad (3)$$

The binary phase information of the equation above is only used as the input of Eq. (2), to proceed with the design cycles. If the reconstructed image is not acceptable, its amplitude information is deliberately replaced with the weighted intensity profile of the target image, i.e. $U(x_0, y_0) = \mathbf{w} \cdot I(x_0, y_0) \exp[j\phi(x_0, y_0)]$, to continue with the iterations through Eq. (3). This weighting vector should be elaborately chosen in each iteration so as to reduce the number of weak-intensity observation pixels and the deviations of $|U|$ from $\langle U \rangle$ by equitable distribution of energy among different image hotspots. Hence, this vector should read

$$w(x_m, y_n) = \sum_m \sum_n |E(x_m, y_n)| / N^2 E(x_m, y_n) \quad (4)$$

Here, x_m and y_n denote the location of bright pixels in the channel, while N^2 is the total number of observation pixels. The iterative algorithm will continue until the least mean square error between the target and the reconstructed image becomes less than a pre-determined threshold. Once the iterations pertaining to each of channels (at lower and higher frequency bands) converge, the binary meta-hologram will be constructed based on the combination of the optimized coding masks $M_{2\text{-bit}}^{f, \text{low}}$ and $M_{2\text{-bit}}^{f, \text{high}}$.

4 Results and discussion

To inspect the performance of the dual-band coding meta-hologram, the proof-of-concept simulations present several illustrative holographic imaging examples in this section. The sketch of the phase-only coding meta-hologram is depicted in Figure 1 (right side) in which to suppress the corner-related coupling effects, 2×2 identical

coding particles are grouped to form the building supercells. The bi-spectral meta-hologram is composed of 20×20 digital supercells whereby the field intensities of two near-field channels can be separately manipulated at each frequency band. Therefore, the overall dimensions of the meta-hologram are $280 \text{ mm} \times 280 \text{ mm}$. The quality of images projected by the proposed dual-band meta-hologram strongly depends on the phase quantization losses and the size and number (writing fields) of supercells. Hence, the overall dimensions of the supercells are chosen as $0.44\lambda \times 0.44\lambda$ and $0.67\lambda \times 0.67\lambda$ corresponding to the lower (10 GHz) and higher (15 GHz) frequencies, respectively, and the quantization levels were set to be 4 (0° , 90° , 180° , and 270°). Choosing such specifications for the designed field programmable meta-hologram is the consequence of a logical compromise between accurate holographic imaging requiring high number of phase levels [36] and simple fabrication along with low sensitivity to the possible fabrication tolerances requiring aggressive phase quantization [26, 35]. Four illustrative examples are considered in which the phase-only coding meta-hologram opens two near-field channels for generating two distinct images of “L”/“four disordered hotspots”, “S”/“C”, “H”/“V”, and “U”/“i”. The letters before and after slash are desired to be projected at the lower and higher working bands, respectively. In order to demonstrate the flexibility of our design, the imaging distances are arbitrarily chosen as $z_{d1}=180 \text{ mm}/z_{d2}=120 \text{ mm}$, $z_{d1}=200 \text{ mm}/z_{d2}=200 \text{ mm}$, $z_{d1}=220 \text{ mm}/z_{d2}=180 \text{ mm}$,

and $z_{d1}=190 \text{ mm}/z_{d2}=160 \text{ mm}$, respectively. These locations demonstrate the great flexibility of the coding meta-hologram in providing near-field channels with arbitrary positions. The optimized coding masks obtained based on the GSW phase retrieval algorithm are plotted in Figure 4A–H for each imaging band. Figure 5A–H also depicts the theoretical results through the superposition of electric field components scattered by the digital supercells allocated with the calculated binary phase profiles. The theoretical field distributions have been calculated with the resolution of $1.75 \times 1.75 \text{ mm}^2$ based on a MATLAB homemade code. As can be observed, the GSW algorithm successfully reveals the coding masks responsible for generating the target images with great qualities. In the numerical simulations, each coding meta-hologram is launched by an x -polarized normal plane wave, and the scattered electric field is captured on the observation channels of the lower and higher frequency bands at $f_{\text{Low}}=10 \text{ GHz}$ and $f_{\text{High}}=15 \text{ GHz}$, respectively. The simulation results have been accomplished using the Time domain solver of the CST Microwave Studio. The scattered fields of both near-field channels in each meta-hologram are recorded in an area of $280 \times 280 \text{ mm}^2$ (see Figure 6A–H). The simulation results are in a good agreement with the theoretical predictions, clearly reconstructing the images “L”/four disordered hotspots, “S”/“C”, “H”/“V”, and “U”/“i” on the near-field channels. Moreover, the simulated holographic imaging has a span range of 0.5 GHz around both working frequencies that affords

Figure 4: The binary phase maps of the reflective coding meta-hologram for low-frequency (top row) and high-frequency (bottom row) holographic images of (A), (E) “L”/four disordered hotspots, (B), (F) “S”/“C”, (C), (G) “H”/“V”, and (D), (H) “U”/“i” letters. The phase-only profiles have been extracted by using the GSW retrieval algorithm and could be realized with the 2-bit coding elements of Figure 2B. Indeed, there are in total four different designs of metasurfaces, each of which was imparted with two phase maps given in each column at two frequencies of 10 GHz and 15 GHz.

Figure 5: The theoretical results of different sets of holographic images projected at the low-frequency (top row) and high-frequency (bottom row) channels.

The binary phase profile of the holograms are given in Figure 3. The first, second, third, and fourth coding meta-holograms are aimed at generating (A), (E) “L”/four disordered hotspots, (B), (F) “S”/“C”, (C), (G) “H”/“V”, and (D), (H) “U”/“i” letters in the reflection side. Indeed, there are in total four different designs of metasurfaces, each of which was imparted with two phase maps given in each column at two frequencies of 10 GHz and 15 GHz.

Figure 6: The simulated results of different sets of holographic images projected at the low-frequency (top row) and high-frequency (bottom row) channels.

The binary phase profile of the holograms are given in Figure 3. The first, second, third, and fourth coding meta-holograms are aimed at generating (A), (E) “L”/four disordered hotspots, (B), (F) “S”/“C”, (C), (G) “H”/“V”, and (D), (H) “U”/“i” letters in the reflection side. Indeed, there are in total four different designs of metasurfaces, each of which was imparted with two phase maps given in each column at two frequencies of 10 GHz and 15 GHz.

a reasonable degree of freedom to the meta-hologram designer. The apparent discrepancies between the simulated and calculated holographic images may also be attributed to the mutual coupling between the adjacent supercells, non-ideal phase response of the coding particles, and the high-order diffraction effects. Though the

digital meta-hologram is characterized with simple 2-bit coding masks, the proof-of-concept simulations validate its frequency multiplexing performance as a reliable platform for generating frequency-dispersive holographic images. To show the z -dependence nature of the holographic images, the simulated fields have been plotted at

different observation planes. The corresponding results are demonstrated in Supplementary Information B.

5 Fabrication and measurement

In order to experimentally verify the performance of the designed coding meta-holograms, two different structures corresponding to Figure 6A and E and Figure 6B and F have been fabricated and measured. The samples consists of 40×40 unit cells with an overall size of $280 \text{ mm} \times 280 \text{ mm}$ that are responsible for generating “L/four hotspots” and “S/C” letters in the near-field channels of the lower and higher imaging bands. The standard printed circuit board technology was employed in the fabrication process where each contributing layer was manufactured separately and then combined with the help of several plastic screws to obtain the final meta-hologram sample. The photographs of the top and middle layers of the fabricated samples can be found

in Figure 7A and C and Figure 7B and D, respectively. Separate experiments were performed in a microwave anechoic chamber with the size of $4 \times 8 \times 4 \text{ m}^3$ to capture the holographic images of the two operating bands for both samples. In the first stage, we fixed the fabricated sample labeled “MS1” on a wooden support as shown in Figure 8A. The sample “MS1” was encoded with proper 2-bit coding pattern so as to project the letter “L” at $f_{\text{Low}} = 10 \text{ GHz}$ and four disordered hotspots at $f_{\text{High}} = 15 \text{ GHz}$. A linearly polarized feeding horn antenna with the working bandwidth of 8 GHz to 12 GHz was fixed on another wooden support to launch x -polarized quasi plane waves on the sample “MS1”. A standard movable microwave probe connected to an Agilent vector network analyzer (VNA) through two 4-m-long 50Ω coaxial cables was also employed to scan the near-field observation channels as a receiver. In our imaging experiments, the VNA is used to acquire the response data by measuring the S_{11} coding meta-hologram, which is less than $\lambda/16$, providing a quasi plane wave incidence as assumed in the far-field

Figure 7: (A), (C) The top and (B), (D) middle layers of the two different fabricated meta-holograms labeled as MS1 (top row) and MS2 (bottom row).

The samples MS1 and MS2 are designed to project two different letter sets of “L”/four disordered hotspots and “S”/“C”, respectively. The images before and after the slash appear at the low- and high-frequency channels, respectively.

Figure 8: Measurement setup.

The measurement setup for extracting the low-frequency and high-frequency holographic images of two fabricated coding meta-holograms of (A) MS1 and (B) MS2 in an anechoic chamber that includes a horn antenna, a standard microwave probe as a receiver, and a vector network analyzer. (C)–(F) Experimental results for the holographic images of “L”/four disordered hotspots and “S”/“C”, letters in the reflection side. The measured field intensities of the fabricated meta-holograms (C), (D) MS1 and (E), (F) MS2 at the (C), (E) low-frequency (10 GHz) and (D), (F) high-frequency (15 GHz) near-field channels illustrated in Figure 6.

numerical simulations. The standard probe was positioned $z_d = 180$ mm away from the sample “MS1” along the z axis which could scan an area of 300×300 mm² to collect the reflected waves.

The reflected fields from the sample “MS1” are plotted in Figure 8C at $f_{\text{Low}} = 10$ GHz which clearly shows the letter “L” with acceptable accuracy. Similarly, to validate the functionality of “MS1” in the higher working band, another high-frequency horn antenna was used, shining x -polarized quasi plane waves in the frequency range of 13 GHz to 18 GHz on the sample “MS1”. Based on the position of the high-frequency channel, the near-field probe was adjusted at the position $z_d = 120$ mm scanning the whole area of 300×300 mm² on the reflection side. The reflected fields of the high-frequency channel ($f_{\text{High}} = 15$ GHz) for this scenario are illustrated in Figure 8D, disclosing well four hotspots of identical intensities in good conformity with the simulated results. To illustrate the design flexibilities afforded by the proposed bi-spectral coding meta-hologram, the

holographic images of the fabricated sample labeled as “MS2” were also measured with the test configuration displayed in Figure 8B. The sample “MS2” was fabricated based on a proper coding pattern to reflect the “S” letter in the lower band and the “C” letter in the higher band at two specified near-field channels. For testing purpose, we fixed this sample on the wooden support, while the feeding horn antenna was fixed on another wooden support (see Figure 8B) so that the sample “MS2” could receive the linearly x -polarized plane waves. The standard microwave probe in the case for lower band was adjusted at $z_d = 200$ mm away from the sample “MS2”. In this case, the holographic image for the low-frequency channel ($f_{\text{Low}} = 10$ GHz) is plotted in Figure 8E which explicitly displays an “S” letter shape in a good agreement with the numerical simulations. Similarly, in order to capture the information of the high-frequency channel ($f_{\text{High}} = 15$ GHz), both the receiving probe and the horn antenna are adjusted in the frequency range of 13 GHz to 18 GHz. The position of the probe was fixed at the same location of $z_d = 200$ mm since the sample “MS2” opens two simultaneous information channels at identical positions.

The corresponding field intensities are plotted in Figure 8F in which the letter “C” can be found with a persuasive accuracy. Three different parameters are adopted here to assess the measured image qualities, quantitatively [36]: (1) 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 dashed lines referenced to the reflectance intensity; (2) signal-to-noise ratio (SNR), the ratio between the peak intensity in the image to the standard deviation of the background noise; and (3) root-mean-square error (RMSE) as the deviations between the measured intensity ratios and theoretical values to describe the manipulation capacity of energy allocation of hotspots. The imaging efficiencies have values as high as 72.4%/75.32% and 68.5%/65.8% for the meta-hologram samples of “MS1” and “MS2”, respectively. In addition, the corresponding SNR ratios are calculated as high as 11.9/12.5 and 11.8/11.5 from the simulated results, which further verifies the superior image quality compared with the previous metasurface hologram designs in microwave regime [26, 35]. It should be noted that the normalized RMSE levels at the last iteration in the MATLAB software reached 2.1%/1.2% and 2.2%/2.4%, respectively. Overall, the measurements corroborate well the theoretical predictions as well as the numerical simulation, where the experimentally observed holographic images of “S/C” and “L/four hotspots” by setting suitable binary phase distributions across the coding meta-hologram have

admissible image qualities. The performance of the proposed meta-device is obviously expanded from those presented in [26, 35, 36], sharing only one near-field channel for the application of holography. Obviously, the slight deviations of the measured data from the theoretical and simulation results can be attributed to inevitable fabrication tolerances as well as possible measurement errors. The quality of the holographic images can be further enhanced by using larger writing fields at the expense of more simulation time and extending the operational states of the coding elements to 3-bit.

6 Conclusion

In this work, the frequency dispersion of the 2-bit meta-particles were elaborately engineered to form the constitutive blocks of a bi-spectral coding meta-hologram at microwave frequencies. Through design of 16 frequency-dispersive digital meta-atoms, the 2-bit coding meta-holograms judiciously open two near-field channels with low cross-talk at the lower (X-band) and higher (Ku-band) frequency bands to independently show two arbitrary images at the same time. In order to obtain uniform field intensities, the WGS retrieval algorithm was utilized to extract the coding masks of the coding meta-holograms. The experimentally measured images are in a good agreement with the theoretical and numerical results in imaging features, and the imaging efficiencies as well as the RMSE merit verify the high image qualities. The performance of the designed coding meta-hologram is dramatically improved with respect to the previous studies since they enabled only one processing channel [36] or had low quality images due to the use of aggressive (1-bit) phase quantization [26]. Moreover, our approach can be extended from static to dynamic meta-holography via several well-established switchable diodes at microwave or graphene material at terahertz frequencies and may be of great interest for various applications in modern meta-surface-based communication architectures [52], security, and data storage.

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