Multiplexing Vectorial Holographic Images with Arbitrary Metaholograms

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Metasurfaces achieving arbitrary phase profiles within ultrathin thickness, emerge as miniaturized, ultracompact, and kaleidoscopic nanophotonic platforms. However, it is often required to segment or interleave independent sub-array metasurfaces to multiplex holograms in a single nanodevice, which in turn affects the device's compactness and channel capacity. Here, a flexible strategy is proposed for multiplexing vectorial holographic images by controlling the phase distributions of holographic images in far field. Benefitting from precisely controlling the phase difference of reconstructed images through the modified Gerchberg–Saxton algorithm, two different holographic images are independently designed for the circular light by two interleaved metasurfaces and an extra vectorial hologram is flexibly encrypted in far field without additional set of structures on the metasurface plane. An unlimited number of polarization can be achieved in the holographic image and additional information can be decrypted when different polarization-dependent holographic images overlap. By continually varying phase difference between the incident right and left circular polarized light, the image within the overlap area can be modulated. The silicon dielectric metahologram with record absolute multiplexed efficiency (>25%) is achieved in the experiment. This technique, as far as it is known, promises an enormous data capacity as well as a high level of information security.

1. Introduction

As 2D subwavelength nanostructures, metasurfaces have enabled tremendous potential to control both polarization, amplitude, and phase of light with high spatial resolution,[1–6] to realize unprecedented functionalities, such as beam shaping,[7–9] focusing,[10–12] information encrypting,[13–17] and so on. As an important application, metasurface holograms or metaholograms can reconstruct vivid and colorful images with high spatial resolution in far field.[18–22] In order to encode and reconstruct more holographic images, many multiplexing methods via wavelength, polarization, position, and angle have been demonstrated.[23–12] However, during the iteration process of conventional phase retrieval algorithms (e.g., Gerchberg–Saxton (GS) algorithm and Fienup algorithm[33,34]) to design metahologram, phases on the imaging plane are generally ignored and only amplitudes are guaranteed.[18–32] In fact, phase differences between two cross-polarization states on the imaging plane play an important role in determining the vectorial distribution. Up to now, only a few metasurfaces have been designed with controlling the phase distribution in far field to forming vectorial distributions.[35–37] In ref. [35], a vectorial holographic image is reconstructed in far field when two linear cross polarizations are controlled dependently. In ref. [36], two identical holographic images for two circular polarizations overlap with a spatially varying phase difference for the measurement of the beam polarization. In ref. [37], vectorial holographic images with polarization distributions were generated through continuously arranging the positions of same holograms designed for two circular polarizations, which are unable to discretely design the phase differences at the close position. Although the holographic images can be different from each other in theory as mentioned in ref. [37], the holographic images are still designed to be the same with each other in experiment. Vectorial holographic images with versatile polarizations can also be generated by adopting the super-pixels[38–40] and even multilayered structures.[41] However, the higher-order images are inevitable and the imaging quality is sacrificed due to the sub-arrays larger than the wavelength.[38–40] The multilayered structures are applied for GHez-bandwidth,[41] but it is not easy to extend the method.
to the visible light. It remains challenging to flexibly multiplex extra vectorial holographic images into two arbitrarily designed holographic images on the imaging plane with little influence on the imaging quality of original holographic images.

Here, we have proposed and experimentally realized a new scheme for multiplexing holographic images within a silicon metasurface that can encode extra vectorial holographic images via the phase difference of two arbitrary holographic images designed for the right circular polarized (RCP) light and left circular polarized (LCP) light on the imaging plane. Based on the modified Gerchberg–Saxton algorithm, the phase difference of reconstructed images are precisely controlled at the pixel scale. Two different holographic images designed for RCP and LCP are independently encoded by two interleaved metasurfaces and a third extra vectorial hologram is flexibly encoded in far field without adding additional set of structures on the metasurface plane. As phases of reconstructed images are unable to be detected directly, encoding vectorial distributions by the phase difference can further enhance the security of information encryption. The phase distributions are usually detected indirectly \(^{(42,43)}\) by transforming them into the intensity changes. In this work, only under the incidence of a linearly polarized light with specific phase difference between the RCP and LCP components, can extra encrypted images be correctly unmasked from the overlapping area of the two reconstructed images. To our knowledge, it is the first time to flexibly multiplex further vectorial distributions on the imaging plane in the form of phase difference of two different reconstructed images, providing a new degree of freedom for multiplexing and encrypting. Both the imaging quality of the original holographic images and the phase differences of spatial polarization distributions are well ensured by utilizing the method. In general, multiplexing more information requires more complex fabrication or design strategy. However, our method to encode the hologram utilizing the Pancharatnam–Berry (PB) phase avoids this problem and vectorial distributions can be flexibly modulated.

2. Design and Theory

2.1. Demonstration of Multiplexing Extra Vertical Images on the Imaging Plane

To multiplex extra vectorial distributions on the imaging plane, we utilize a modified GS-algorithm to simultaneously control phase distributions on both hologram and imaging planes, where the Fresnel diffraction instead of the Fraunhofer diffraction is adopted to retrieve the wavefronts for holographic images and the phase difference of reconstructed images is deliberately designed (see Note S1 in the Supporting Information). Figure 1 shows the schematic of a metahologram designed for the RCP and LCP light. Extra encrypted vectorial holographic images determined by the phase difference \(\Delta \phi = \phi_1 - \phi_2\) of the overlapping part of the two reconstructed images with phases \(\phi_1\) and \(\phi_2\) can also be obtained under the illumination of a linearly polarized light. As the metasurface is based on PB phase, two centrosymmetric holographic images are simultaneously reconstructed on the imaging plane. Here, only the reconstructed image on the target area is captured and the opposite one is ignored as usual. Although the overlapping part is usually a brighter “heart” pattern, an extra image (“Rubin face” or “vase”) hidden in the x-polarized component is revealed by selecting the phase difference \(2\Phi\) between the RCP and LCP components of the incident linearly polarized light. In order to get sharp intensity contrast, their phase difference \(\Delta \Phi\) is set as \(-\pi/2\) and \(\pi/2\) while their own phases \(\Phi_1\) and \(\Phi_2\) are almost random as presented in Figure 1b.

To confirm the working mechanism, silicon metasurface with PB phase is utilized to encode the holographic phases just by the orientation of the building block nanostructure. As shown in Figure 2, the metasurface is composed of 750 \(\times\) 750 metamolecules, consisting of subwavelength silicon nanoblocks on sapphire substrate. Standard electron-beam lithography is adopted to fabricate the sample. Details about the fabrication can be found in Method. The SEM images of the fabricated metasurface has been shown in Figure 2b.

In fact, the total metasurface can be regarded as multiplexing the metahologram 1 (M1) and the metahologram 2 (M2) for the RCP and LCP light. To ensure that the reconstructed images overlap correctly, pixels of M1 and M2 are positioned at “X” shape in metamolecules. Each pixel has two Si nanoblocks with the same orientation in metamolecules. The height of pillars is chosen as \(h = 300\) nm. The period of metamolecule is set as \(P = 400\) nm. Because the unit cell of metamolecules has the same dimensions, the real period of unit cells is 200 nm. The PB phases of the metaholograms are determined by the orientation angles \(\theta\) of building blocks. When RCP (LCP) light illuminates on the metasurface, the transmitted light generally contains two parts: one is the converted LCP (RCP) light, which acquires the phase shift \(\phi\); the other is the unconverted RCP (LCP) light, which has no phase delay. Here, \(\phi = \pm 2\theta\) and the signs “+” and “−” are corresponding to the RCP and LCP incident light, respectively. Hence, only the converted part is useful to reconstruct holographic images in far field. The reconstructed images is located at 5 mm away from the hologram. Thus, two phase masks \(\psi_1\) (“apple”) and \(\psi_2\) (“strawberry”) are generated by using the modified GS-algorithm. The phase mask \(\psi_1\) is directly encoded by M1 for the RCP incident light and the phase mask \(\psi_2\) is encoded by M2 for the LCP incident light. The phase profile of the metahologram is sampled at eight discrete levels with a step of \(\pi/4\).

2.2. Theory of Multiplexing Information via Phase Difference on the Imaging Plane

When the RCP and LCP light are incident simultaneously, for example, a linearly polarized light with homogenous phase is described by Jones vector as \(L = (\cos \phi \sin \phi)\), where \(\phi\) represents the polarization angle between the polarized orientation and x axis and the phase difference between the RCP and LCP light is \(2\phi\). Holographic images designed for the RCP and LCP light can be simultaneously reconstructed. The incident light can be decomposed on the basis of circular polarizations

\[
\begin{align*}
\bar{L} &= \frac{\sqrt{2}}{2} [1 - i]^x, \quad \bar{R} = \frac{\sqrt{2}}{2} [1 i]^x
\end{align*}
\]
When two reconstructed images are overlapped with each other, the complex amplitude $\overline{PA}$ of the overlapping area can be obtained immediately:

$$\overline{P \Lambda} = \frac{1}{2} \left[ e^{i\phi_1} + e^{i\phi_2} \right] + \frac{1}{2i} \left[ e^{-i\phi_1} + e^{-i\phi_2} \right] = \frac{\sqrt{2}}{2} e^{-i\phi} (\hat{R} + e^{i\phi} \hat{L}) \quad (1)$$

Figure 1. Schematic of metahologram for encrypting additional scenes and simulation results. a) Schematic of metahologram to reconstruct extra vectorial holographic image. The metasurface is composed of silicon nanoblocks. Two holograms ("apple" and "strawberry") designed for RCP and LCP are reconstructed respectively and overlapped under the illumination of the linearly polarized light (LP), forming a pattern of "heart." Under the illuminations of the RCP and LCP light with different phase differences $2\phi$, the information ("Rubin face," "heart," or "vase") of vectorial holographic images is further decrypted at the overlapping area, which can be dynamically changed with the phase differences. b) Simulation results of the intensity of reconstructed images designed for the incident RCP, LCP, and LP lights, the corresponding phase distributions ($\phi_1$, $\phi_2$) on the imaging plane and the phase difference ($\Delta \phi = \phi_1 - \phi_2$) of reconstructed images. c) Simulation results of the intensity of encrypted $x$-polarized component and the corresponding phase differences $\phi$ between the incident RCP and LCP light.

$$I_{\text{out}} = |\overline{PA}|^2 = \frac{1}{2} (l^2 + r^2) \quad (3)$$

where $\phi_1$ or $\phi_2$ is the phase of the transmitted LCP or RCP light and $\Delta \phi = \phi_1 - \phi_2$, which is the phase difference between the transmitted LCP and RCP light at the overlapping area. $r$ and $l$ respectively represent the amplitudes of the RCP and LCP light at the overlapping area, which are corresponding to the holographic images. The amplitude of each holographic images are designed to distribute homogeneously. In order to obtain high intensity contrast at the overlapping area for dynamic reconstructions of the vectorial holographic image, the sizes of holographic images and the incident light powers are tuned in advance to make $r$ and $l$ appropriately equal ($r = l = 1$). Equation (2) shows that the vectorial distributions of the overlapping area are mainly determined by the phase difference $\Delta \phi$. Due to the fact that the phases on the imaging plane are often ignored in traditional metaholograms, the phase difference $\Delta \phi$ of holographic images are consequently distributed randomly, resulting in the random vectorial distributions at the overlapping area. Based on the modified GS-algorithm, the phase difference $\Delta \phi$ are precisely controlled and complex vectorial distributions can be flexibly encoded on the imaging plane. Equation (4) shows that the information of vectorial distributions are obviously hidden behind the uniform intensity $I_{\text{out}}$ but can be exposed by the $x$-polarized component whose relative...
intensity can be arbitrarily manipulated from 0 to 1 as shown in the following equation

\[ I_{\text{x-out}} = \frac{1}{2} \left( 1 + \frac{1}{2} \cos(\Delta \Phi - 2\varphi) \right) \]  

In this way, additional information is multiplexed and encrypted into the vectorial holographic images in far field and uncovered by the \( x \)-polarized component. It should be noted that the incident light with other polarized states can also be considered, but the range of the relative intensity is possibly unable to fully cover 0 to 1. More details about other polarized states can be found in ref. [36].

In our design, two iteration processes are used to retrieve the wavefront for two different holograms and the phase difference \( \Delta \Phi \) are simultaneously controlled as expected. The holographic image of each iteration process can be flexibly designed. Accordingly, additional information is multiplexed and encrypted into the vectorial holographic images via the phase difference of two reconstructed images without extra structures on the metasurface plane. This design strategy significantly extends the simultaneous control of phase distributions on hologram and imaging planes for multiplexing. Moreover, multiplexed and encrypted information can be decoded and unmasked only under the illumination of the light with specific polarization state \( \varphi \).

By utilizing the degree of freedom of phase manipulation on the imaging plane, four different cases with dynamic intensity of vectorial holographic images are reconstructed under the simultaneous illumination of RCP and LCP light (see Table 1).

| Case | \( \Delta \Phi \) | \( 2\varphi \) | \( I_{\text{x-out}} \) | Case | \( \Delta \Phi \) | \( 2\varphi \) | \( I_{\text{x-out}} \) |
|------|-----------------|-----------------|----------------------|------|-----------------|-----------------|----------------------|
| A    | \( \pi/2 \)     | \( -\pi/2 \)    | 0                    | B    | \( \pi/2 \)     | 0               | 1/2               |
|      | \( -\pi/2 \)    | 1               | 1/2                  |      | \( -\pi/2 \)    | \( \pi/2 \)     | 1/2               |
| C    | \( \pi/2 \)     | \( \pi/2 \)     | 1                    | D    | \( \pi/2 \)     | \( \pi/2 \)     | 1/2               |
|      | \( -\pi/2 \)    | 0               | \( -\pi/2 \)         |      | \( -\pi/2 \)    | 0               | \( -\pi/2 \)         |

Table 1. The intensity of \( x \)-polarized component under four incident polarized states.
are selected as $L = 125 \text{ nm}$ and $W = 65 \text{ nm}$. Although the structure is designed for the wavelength of 532nm, the diffraction efficiency at other wavelengths is also taken into consideration. In experiment, the multiplexed efficiency at the working wavelength 532 nm is 26.3% (see Figure 2d), which is higher than those mentioned.\[36,37\] More details about the diffraction efficiency can be found in Note S2 in the Supporting Information.

3. Results

3.1. Characteristics of Multiplexed Extra Vertical Metahologram

The optical setup of characterization is demonstrated in Figure 3a. First, we characterize the performance of multiplexing metahologram under the incident circular light and without the polarizer LP2. As shown in Figure 3b, an image of “apple” (“strawberry”) appears on the imaging plane when RCP (LCP) light illuminates on the metasurface, which is consistent with the numerical results in Figure 1b. As the linearly polarized light directly illuminates on the metasurface, “apple” and “strawberry” images are simultaneously reconstructed and overlapped with each other, to form a uniform pattern of “heart” without further information. Even when the RCP and LCP light with specific phase difference $2\varphi$ simultaneously illuminate on the metasurface, the encrypted images are still securely hidden behind the uniform intensity of the reconstructed images.

The encrypted information (“Rubin face” or “vase”) of vectorial holographic images is decoded by the $x$-component of the transmitted light filtered by the vertical polarizer LP2. By rotating the HWP, the incident phase difference $2\varphi$ between the RCP and LCP light is deliberately manipulated as expected to vary the vectorial distribution on the imaging plane. As depicted in Figure 3c, an optical illusion with opposite intensity contrast respectively emerges from holographic images at $2\varphi = -\pi/2$ or $\pi/2$ (case A and case C in Table 1) and the overlapping area is reverted back to the “heart” pattern at $2\varphi = 0$ or $\pi$ (case B and case D in Table 1), resulting from dynamic changes of polarization distributions in the vectorial holographic images. In other cases, although the scene of optical illusion can also be observed, the intensity contrast and the imaging quality are very low.

![Figure 3](image-url)
Since the metahologram is based on PB phase, which is wavelength-independent, it works at a broad bandwidth as shown in Figure 4. Under the illumination of a supercontinuum laser (FIU-15, NKT Photonics) ranging from 490 to 650 nm, colorful optical illusions with high intensity contrast and image quality are clearly reconstructed on the imaging plane. Obviously, the design strategy has potential ability for encoding and multiplexing information on the imaging plane. In addition to the two reconstructed holographic images, additional scenes can be encrypted and dynamically displayed via the control of the incident phase difference between the RCP and LCP light.

### 3.2. The Potential Ability to Encode and Encrypt Information

To further show the ability of encoding and encrypting information, a second sample is designed and fabricated as depicted in Figure 5. When RCP (or LCP) light illuminates on the metasurface, an image of two apples (or strawberries) which are identical to each other is reconstructed on the target plane (Figure 5b). However, only the phase difference of the apple and strawberry at the left side is elaborately controlled, which encodes the encrypted information of the word “PKU.” The phase difference $\Delta \Phi$ of three letters (“P,” “K,” “U”) is set as $\pi/4$, $-\pi/4$, and $\pi/4$, respectively. By selecting out the component polarized along $x$ axis, the encrypted information is unveiled at the overlapping area where the phase difference of reconstructed images is controlled as expected (Figure 5c). Benefiting from further controlling the incident phase difference $2\phi$, the three letters actually has four different combinations to encode “00” “01” “10” and “11” using dark and bright states “0” and “1.” Details about the intensity distributions can be found in Note S3 in the Supporting Information.

Herein, the first letter is acted as an identification code for the message transmission, representing the specific variations of the incident polarization state. The incident polarization state is regarded as the initial polarization state when the identical code has the brightest intensity ($\phi = \pi/8$). For example, the identification code “P” represents $\pi/8$ ($3\pi/8$, $5\pi/8$, or $7\pi/8$), which means the polarization state of the incident light is rotated by $\pi/8$ ($3\pi/8$, $5\pi/8$, or $7\pi/8$) at clockwise from the initial polarized state. As a result, it can be obtained that the incident phase difference $2\phi$ is 0 ($-\pi/2$, $-\pi$, or $-3\pi/2$). At first, Alice encrypts the information into the metasurface via the phase difference $\Delta \Phi$ of reconstructed images. Then, Bob can immediately obtain the encrypted information “11” (“10”, “00”, or “01”) while receiving the metasurface and characterizing with the predesigned process. It is worth noting that only when the special meaning of identification code is known, can the encrypted message “11” be correctly decoded. Otherwise, the incorrect message of “10”, “00”, or “01” is obtained. The above experimental results just show a simple example to demonstrate the ability of encryption. More complex spatial distributions can also be achieved by utilizing the method based on the precise control of phase difference on the imaging plane (see Note S5 in the Supporting Information). This group for four combinations is composed by an identification code and two encoding codes. If $N$ groups are encoded, $2^{2N}$ bits can be constituted for encoding information, encrypting enormous information into the metasurface. As the initial polarization states and identification codes of each group are independently designed, the security for message transmission is significantly guaranteed.

### 4. Conclusion

In summary, by exploring the simultaneous controllability of phase distributions on both hologram and imaging planes, we have successfully demonstrated a novel way for multiplexing vectorial holographic images by the phase difference of two different circular polarization-dependent reconstructed images on the imaging plane. A modified GS-algorithm is adopted to precisely control the phase difference of reconstructed images in far field. Utilizing only two sets of interleaved metasurfaces, two different holograms are independently encoded for the RCP and LCP light and a third extra vectorial holographic image is flexibly encrypted at the overlapping area of reconstructed holographic images. Through continuously controlling the

Figure 4. The broadband spectral property of the metasurface for optical illusions. A supercontinuum laser is used to characterize the optical illusions, with wavelengths of 40 nm bandwidth, ranging from 490 to 650 nm. At each wavelength, the linearly polarized light with two specific polarized states respectively illuminates on the metasurface.
phase difference between the incident RCP and LCP light, the x-polarized component of extra encrypted scenes are dynamically unveiled with high contrast at the overlapping area. Moreover, we verify that this method shows good performance in optical encryption and message transmission. Tremendous message can be encoded via the combinations of dark and bright states with high security. Importantly, our design strategy has no limit to the holographic images and flexible vectorial distributions can be easily encoded and encrypted at the overlapping area of reconstructed images with no further complexity of fabrication. If combined with wavelength, position, or angle multiplexing, it can be extremely extended and more information can be multiplexed, opening up new approaches for optical encryption, dynamic displays, anti-counterfeiting, high-density data storage, and many other fields.

5. Experimental Section

**Numerical Simulations:** The commercial COMSOL Multiphysics software was utilized to design and simulate the building blocks of silicon placed on sapphire substrate. Periodic boundary conditions and perfectly matched layers were employed along transverse and longitudinal corresponding to the propagation of the incident light. Port boundary conditions were used at both sides of the incidence and transmission to excite and measure the circularly polarized light. The refractive indexes of silicon and sapphire substrate were respectively set as 4.15 + 0.03i and 1.77 at 532 nm.

**Sample Fabrication:** The metasurfaces were fabricated with electron beam lithography technique followed by a lift-off process. First, 300 nm silicon sapphire substrate was cleaned in the ultrasound bath in acetone and isopropyl alcohol (IPA) for 10 min, respectively. Second, 80 nm PMMA film was spin-coated onto the silicon-coated sapphire substrate and the substrate was baked at 180 °C for an hour. After that, the PMMA resist was exposed to the electron beam (Raith E-line, 30 kV) and developed in MIBK/IPA solution for 60 s at 0 °C to form the PMMA nanostructures. Then the sample was transferred into an E-beam evaporator and directly coated with 25 nm Cr films (deposition rate 0.5 Å s⁻¹, base vacuum pressure 5 × 10⁻⁷ Torr). After immersing the sample in acetone for 8 h, the PMMA was removed and the nanostructures were well transferred to Cr. Then the silicon was etched away with reactive ion etch (RIE) performed in an Oxford Plasma System using CHF₃ and SF₆ gases. Finally, by immersing the sample into the chromium etchant for 10 min, Si metasurfaces were finally obtained.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Figure 5.** Experiment results for extra information encryption. a) Two images ("apple" and "strawberry") are designed for RCP and LCP, respectively. The encrypted word of "PKU" is located at the left side of overlapping areas. Their phase difference ΔΦ is set as π/4, −π/4, and π/4 respectively. The right part without encrypted information is for reference. b) Reconstructed images under the incident RCP, LCP, and LP lights, respectively. c) Decoding the encrypted information under the illumination of the linearly polarized light with four specific polarized states shown at the right corner. The encrypted letters are unveiled within the "heart."
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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

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

Keywords

hologram, metasurface, optical encryption, phase difference, vectorial holographic images

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