Research Article

Metasurface-based non-orthogonal tri-channel polarization multiplexing for optical encryption [Invited]

YU LIU,^{1,†} XING-YUAN HUO,^{1,†} YU-TONG XIAO,¹ RUWEN PENG,^{1,2} AND MU WANG^{1,3}

¹National Laboratory of Solid State Microstructures, School of Physics, and Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, China ²rwpeng@nju.edu.cn ³muwang@nju.edu.cn

[†]These authors contributed equally.

Abstract: Orthogonal polarization multiplexing is typically required to avoid crosstalk between channels. However, for practical applications in optical information encryption, orthogonal polarization channels are vulnerable to decoding. Using non-orthogonal polarization channels can enhance information security. Here, we extend the conventional Jones matrix approach to achieve non-orthogonal tri-channel polarization multiplexing metasurfaces for optical encryption via optical holography. Using a supercell configuration with two pairs of α -Si meta-atoms, we experimentally demonstrate metasurface-based multiplexing under three linear polarization channels, including copolarized and non-copolarized channels. This design strategy is further extended to circular and elliptical polarization channels, which exhibits minimum crosstalk. As a proof-of-concept demonstration, we implement two optical encryption applications, i.e., image encryption and character encryption, based on non-orthogonal polarization-multiplexed metasurfaces. For image encryption, encrypted images are generated only in the correct polarization channels. While using seven different statuses of metasurface under various polarization channels, we also present a character encryption scheme. We envision that the non-orthogonal polarization multiplexing metasurface platform will open new possibilities in optical communication, optical encoding, and information security.

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1. Introduction

Metasurfaces, composed of artificial meta-atoms at subwavelength scales, have emerged as a promising platform for controlling the amplitude, phase, and polarization of light [1-3]. Leveraging their powerful light-manipulation capabilities, metasurfaces have enabled the development of various polarization devices [4], including polarization imaging [5–7], vectorial holography [8-11], and complex beam generation [12,13]. In polarization multiplexing, due to the fact that the polarization-dependent optical response of metasurfaces can be described by a 2×2 Jones matrix, most metasurface-based devices are restricted to orthogonal polarization channels [14–23]. However, this limitation impedes advancements in information security. Recently, considerable efforts have been dedicated to developing non-orthogonal polarization multiplexing devices [24–32]. For instance, Malus-assisted metasurface can simultaneously record a grayscale image and two binary-patterns in three non-orthogonal linear polarization channels. By introducing a vectorial compound metapixel design, two arbitrary non-orthogonal linear polarization multiplexing of independent grayscale images is demonstrated [26]. In optical holography displays, independent control over two arbitrary non-orthogonal polarization channels has been achieved by cascading two single-layer metasurfaces [27]. More recently, Xiong et al. have advanced this field by introducing engineered noise, enabling up to 11 non-orthogonal linear polarization

channels and breaking the fundamental limit of metasurface-polarization multiplexing capacity [29]. Additionally, non-orthogonal polarization multiplexing for holography in the infrared region has been demonstrated by fusing a controllable eigen-polarization engineering mechanism with a vectorial diffraction neural network [32]. However, to date, non-orthogonal polarization multiplexing remains less explored in optical encryption applications.

In this work, we extend the conventional Jones matrix approach to achieve three-channel non-orthogonal arbitrary polarization multiplexing for optical holography by relying on a metasurface. Using this design strategy, we experimentally demonstrate three-channel linear, circular and elliptical polarization multiplexing metasurfaces. Three distinct holographic images are reconstructed under three polarization channels by a single-layer dielectric metasurface. In addition, as a proof-of-concept demonstration, the designed metasurface is employed for two optical information encryption applications: image encryption and character encryption. We expect that the non-orthogonal polarization multiplexing metasurface platform may facilitate the development of applications in optical communications, optical encoding and information security.

2. Design principle

Figure 1 illustrates the schematic of non-orthogonal polarization-multiplexed metasurface for optical holography. When illuminated and analyzed under three non-orthogonal arbitrary polarization combinations, a single metasurface can generate three independent holographic images. Our design strategy extends the traditional Jones matrix method by introducing arbitrary polarization channels into the optical response equation of the metasurface. When all three polarization channels are considered simultaneously, a set of equations for three Jones matrix elements (J_{xx} , J_{xy} , and J_{yy}) is obtained, as follows:

$$\begin{vmatrix} E_1 \\ E_2 \\ E_3 \end{vmatrix} = \begin{vmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{vmatrix} \cdot \begin{vmatrix} J_{xx} \\ J_{xy} \\ J_{yy} \end{vmatrix},$$
(1)

where E_1 , E_2 , and E_3 are the optical responses under the three polarization channels. Each row of the square matrix A is determined by the combinations of corresponding input and output polarizations. In our design, for each channel, the required optical response is designed to generate a target holographic image in the far-field imaging plane. An iterative algorithm, Gerchberg-Saxton algorithm [33] is used to retrieve the near-field phase distribution provided by the metasurface. If the matrix $\{A_{ij}\}$ (here i, j = 1, 2, 3) is invertible, the equations can be solved precisely and the desired Jones matrices of metasurface can be acquired.

Subsequently, we need to design a metasurface that can implement desired Jones matrix. The meta-atoms are made of rectangular amorphous silicon (α -Si) nanopillars on an ITO coating glass substrate, as shown in Fig. 2(a). For the operation wavelength of 800 nm, the α -Si nanopillars are designed to have identical heights of H = 600 nm and located on a square array with a lattice constant of P = 360 nm. We have conducted full-wave simulations for the single rectangular amorphous silicon (α -Si) nanopillar by commercial software Lumerical FDTD Solutions. The 800nm-wavelength light source is x-polarized and incident along the z direction. Periodic boundary conditions are set in both x and y directions. Perfect matching layers are employed along the z-axis to absorb the outgoing waves. Figures 2(b) and (c) are the simulated transmission magnitude and phase shift as a function of the transverse dimensions of the single nanopillar at *x*-polarized incidence. To realize the symmetric Jones matrix with six degrees of freedom, we construct a supercell using two pairs of meta-atoms, as shown in Fig. 2(d). A modified genetic algorithm [29,34] is utilized to search for proper geometric parameters of nanopillars.



Fig. 1. Schematic of the non-orthogonal arbitrary polarization-multiplexed metasurface. When the metasurface is illuminated and analyzed by three non-orthogonal arbitrary polarization combinations, three different holographic images can be generated independently.

The desired real and imaginary parts of three Jones matrix elements are set as the six targets. The geometry parameters of nanoresonators inside the supercell are set as the input parameters, corresponding to a Jones matrix of the created supercell. The loss function is defined as the mean square error of those Jones matrix elements. The consistency of arbitrarily selected two Jones matrix targets and the FDTD simulation results of corresponding generated supercells are shown in Figs. 2(e) and (f).

3. Results

3.1. Linear polarization

Based on above strategy, we designed and further fabricated non-orthogonal linear polarization multiplexing metasurfaces for experimental characterization. We chose three non-orthogonal linear polarizations as 0°, 60° and 120° for the copolarized channels, which is defined as channels with identical input and output polarization. The target far-field holographic images are designed as letters "X", "Y" and "Z", consisting of 276×276 pixels. After solving the optical response equations and searching for the nanostructures pixel-by-pixel, the desired α -Si metasurface is obtained. Then, the α -Si metasurface is manufactured by means of electron beam lithography and inductively coupled plasma-reactive ion etching. Figure 3(b) shows the optical and scanning electron microscopy (SEM) micrographs of the fabricated sample with different magnifications. The optical setup shown in Fig. 3(a) is adopted to demonstrate polarization multiplexing holographic imaging functionalities. A laser beam irradiates normally onto the α -Si metasurface are collected with the objective lens, and subsequently analyzed by a polarizer. The holographic images are recorded by a charge coupled device (CCD) camera. In experiments, by

varying the orientation of input and output linear polarization from 0°, 60° to 120° simultaneously, three holographic images are captured at a distance of $z = 180 \,\mu\text{m}$ away from the metasurface plane. The measured results under such three linear copolarized channels are shown in Fig. 3(c), which are consistent with the simulated results. If we define the holographic efficiency as the ratio of total intensity of the holographic efficiencies are 29.92%, 25.68%, and 23.22%, corresponding to letters "X", "Y" and "Z", respectively. These results verify that the proposed metasurface can independently control the phase profiles for three non-orthogonal linearly copolarized channels.

In addition to copolarized channels, this design strategy can be extended to non-copolarized channels. The output polarizations can be designed to be different from the input ones. As an experimental demonstration, the polarization channels of 0°-input/60°-output, 0°-input/120°-output and 60°-input/120°-output are chosen. Subsequently, we designed and fabricated the non-copolarization multiplexing sample. Figure 3(d) shows the optical microscopy and SEM images of the fabricated metasurface. The simulated and measured holographic images are shown in Fig. 3(e). As is can be seen, the experimental results agree well with the simulation results. The metasurface generates three independent holographic images of rainbow, moon and rain cloud under the three non-copolarized channels, with the efficiencies of 27.96%, 26.09%, and 22.16%, respectively.



Fig. 2. Metasurface design. (a) Schematic of the single α -Si nanopillar. Simulated transmission (b) magnitude and (c) phase shift of the nanopillar with *x*-polarized incidence. (d) Schematic of the designed supercell. (e, f) Jones matrix elements of two different supercells as examples. The blue and red symbols represent FDTD results and calculated results, respectively. The three different shaped symbols represent the three Jones matrix elements.



Fig. 3. Non-orthogonal linear polarization multiplexing metasurfaces. (a) The optical setup. (b) The optical and SEM micrographs of the copolarized multiplexing sample. The scale bars are 50 μ m, 400 nm, and 1 μ m, respectively. (c) Simulated and measured holographic images of the copolarized multiplexing sample. The scale bars are 25 μ m. (d) The optical and SEM images of the non-copolarized multiplexing sample. The scale bars are 50 μ m, 1 μ m, and 1 μ m, respectively. (e) Simulated and measured holographic images of the non-copolarized multiplexing sample. The scale bars are 50 μ m, 1 μ m, and 1 μ m, respectively. (e) Simulated and measured holographic images of the non-copolarized multiplexing sample. The scale bars are 25 μ m. The white arrows in the top right corner represent the corresponding input and out polarizations.

3.2. Circular polarization

Besides the linear polarization channels, three circular polarization channels can be also realized, as shown in Fig. 4. Two non-copolarized channels and one copolarized channel are selected, corresponding to three elements of Jones matrix under the circular polarization basis.

Figure 4(a) shows the optical and SEM micrographs of the fabricated metasurface. Figure 4(b) presents simulated and measured holographic images under three circular polarization channels, respectively. As can be seen, three different holographic images are generated, where the measured efficiency is 12.58% (RCP-RCP channel), 18.63% (RCP-LCP channel), and 37.41% (LCP-RCP channel), respectively. There is more background noise in the copolarized channel than the non-copolarized ones, which results from the presence of the unmodulated incident light.

3.3. Elliptical polarization

More generally, we extend the design to arbitrary elliptical polarization multiplexing. For the copolarization design, the 0° linear polarization and two elliptical polarization, *i.e.*, $\begin{bmatrix} 1/2 & \sqrt{3}i/2 \end{bmatrix}^T$ and $\begin{bmatrix} 1/2 & -\sqrt{3}i/2 \end{bmatrix}^T$ are selected. It is noted that the output polarization for elliptical copolarization channels is designed to be the conjugate state of the input one. Figure 5(a) shows the optical micrographs, SEM micrographs and measured holographic images under three elliptical



Fig. 4. Circular polarization multiplexing metasurfaces. (a) The optical and SEM micrographs of the sample. The scale bars are $50 \,\mu\text{m}$, $1 \,\mu\text{m}$, and $1 \,\mu\text{m}$, respectively. (b) Simulated and measured holographic images. The scale bars are $25 \,\mu\text{m}$.



Fig. 5. Non-orthogonal elliptical polarization multiplexing. The optical micrographs, SEM micrographs and measured holographic images of (a) the copolarized multiplexing and (c) the non-copolarized multiplexing sample. The scale bars are $50 \,\mu\text{m}$, $2 \,\mu\text{m}$, $50 \,\mu\text{m}$, and $10 \,\mu\text{m}$, respectively. The white arrows in the top right corner represent the corresponding incident and analyzed polarizations. Measured correlation coefficients matrix of (b) the copolarized multiplexing and (d) the non-copolarized multiplexing sample.



Fig. 6. Polarization ellipses and Poincaré sphere representation for the polarization states used in the non-orthogonal polarization multiplexing design.

polarization channels. Three Greek letters are generated independently at different locations on the imaging plane. The measured holographic efficiencies are 21.75%, 18.50%, and 30.04%, corresponding to the Greek letters " α ", " β ", and " γ ", respectively. Furthermore, we obtained the correlation coefficient matrix based on measured holographic images. The correlation coefficient is defined as [29]

$$\rho(T,R) = \frac{\text{COV}(T,R)}{\sqrt{D(T) \cdot D(R)}},$$
(2)

where *T* and *R* are the intensity distribution of the target and measured images. COV(T, R) represent the covariance of *T* and *R*, D(T) and D(R) represent the variances of *T* and *R*, respectively. The correlation coefficient describes the degree of similarity between two images. As shown in Fig. 5(b), the diagonal elements of the matrix are all larger than 0.8, and the nondiagonal elements of the matrix are less than 0.1. We also demonstrate three non-copolarized elliptical polarization channels, as shown in Fig. 5(c) and 5(d). The output polarization is designed to be different from the input polarization. It can be seen that three independent holographic images are generated. The measured holographic efficiencies are 17.79%, 24.68%, and 26.28%, corresponding to the Greek letters " δ ", " θ ", and " λ ", respectively. These results indicate that three elliptical polarization channels with high quality and low crosstalk are achieved.

Figure 6 shows the Poincaré sphere representation for all input and output polarization states used in the above examples. The different colors of stars represent the linear, circular and elliptical polarization states for corresponding multiplexing metasurfaces, respectively. These polarization states are located at various positions on the Poincaré sphere, which suggests that our design method has less restrictions on the polarization states. Arbitrary polarization states can be employed in the non-orthogonal polarization multiplexing metasurfaces.

4. Optical encryption

4.1. Image encryption

The proposed non-orthogonal polarization multiplexing design can be employed for optical information encryption. As a proof-of-concept, we experimentally demonstrated image encryption scheme based on the linear non-copolarization multiplexing metasurface, as shown in Fig. 7. Under different polarization combinations of input and output light, the metasurface generates holographic images in the same spatial position. The designed images can only be recognized in the correct polarization channels, as schematically shown in Fig. 7(a). In the other polarization

channels, the image information cannot be revealed. Figure 7(b) shows the measured holographic images of metasurface under the corresponding input and output polarization combinations. The vertical and horizontal coordinates denote the corresponding input and output polarization states, respectively. As we can see, under the 120° -input and 60° -output polarization channel, the metasurface reconstruct an image of moon in the far-field. However, the reconstructed holographic image becomes a mixture of images of moon and rain cloud in the 120° -input and RCP-output channel. Similarly, the clear images of rainbow and rain cloud are only displayed in the 60° -input/0°-output and 120° -input/0°-output channels, which are marked by the dotted lines. Under the other polarization channels, the generated holographic images become the superposition images. The encrypted image information is hidden well.



Fig. 7. Proof-of-concept experimental demonstration of image encryption. (a) Schematic of image encryption based on the non-orthogonal polarization multiplexing design. The correct images are deciphered only if the input and output polarizations are the designed ones. Pseudocolors are used to distinguish between different polarization channels. (b) The measured holographic images of non-orthogonal linear polarization multiplexing sample under different combinations of input and output polarizations. The dotted lines outline the encrypted images.

4.2. Character encryption

Moreover, the character encryption scheme can also be achieved based on the non-orthogonal polarization multiplexing design. Here, we take the non-orthogonal elliptical polarization multiplexing metasurface as an example. As mentioned above, the metasurface can generate three independent holographic images of Greek letters " α ", " β " and " γ " in different in-plane positions under one linear and two elliptical copolarization channels. In addition, by applying other combinations of input and output polarizations, the three Greek letters in the holographic images can be controlled independently. Apart from the images of three distinct letters, the metasurface can also generate the combination images of three letters. As shown in Fig. 8(a), we eventually obtain seven distinguishable holographic images with minimum crosstalk under seven different non-orthogonal polarization channels. These holographic images include all the possible combinations of the three letters except for the null image. Hence, we can define different three-bit binary code based on the appearance and disappearance of each letter in the holographic image. Each letter corresponds to one bit, and its appearance and disappearance represent 1 and 0, respectively. As a result, with seven non-orthogonal polarization channels, seven different three-bit binary codes can be encoded by the metasurface. It is noted that the maximum number of channels that the current system can achieve is three, which limits the number of bits in the

binary codes. However, by introducing engineered noise [29] or optimization mechanisms like machine learning [32], it is possible to increase the number of channels (while maintaining minimal crosstalk) and further to expand the number of bits in the encoded system.

As a proof-of-concept demonstration, the combination of two three-bit binary numbers with seven different values can represent 49 different binary codes. The result in the first polarization channel forms the first three bits of the code, and the result in the second polarization channel forms the last three bits of the code, as shown in Fig. 8(b). Furthermore, such six-bit binary codes can be used to denote a series of characters including letters, numbers and marks based on a method similar to Base64 alphabet. For instance, we can obtain 011 and 100 sequentially under two corresponding polarization channels. Then we decipher the letter "R" represented as 011100 by looking up the alphabet. Similarly, we can also obtain 101 and 111 sequentially under two corresponding polarization channels and recognize the number "9" as 011100 in the Base64

(a)	Input		→ Ĵ	Ð	C	C	\longleftrightarrow	Ð
	Metasurf	ace						E E
	Outpu	ıt ←	→ ()	Ċ	Ð	Ċ	Î	C
		1	+ +	+	+	t -	` ∔	¥
	Code Ch	art	β	β	α	α	αβ	αβ
(b)		001	¥ 010	011	100	101	110	111 Y
(u)	last 3	$\leftrightarrow \leftrightarrow$	00	(උප	00	10	<+>↓	CC
	first 3	001	010	011	100	101	110	111
	$\leftrightarrow \leftrightarrow$	γγ	γβ	γ ^β γ	γ	γγγ	γ β	γ ^α βγ
	001	[A]	[B]	[C]	[D]	[E]	[F]	[G]
	00	βγ	ββ	ββγ	β	β αγ	β ^α β	β ^α β _γ
	010	[H]	[I]	[J]	[K]	[L]	[M]	[N]
	00	βγγ	β _γ β	βγβγ	βγα	βγγγ	β _γ ^α β	βγ ^α βγ
	011	[0]	[P]	[Q]	[R]	[S]	[T]	[U]
	CO	α γ	β	β _γ	αα	ααγ	αβ	α α β γ
	100	[V]	[W]	[X]	[Y]	[Z]	[1]	[2]
	90	α γ γ	α β	α βγ	α α γ	α α γ γ	α α β	${}^{\alpha} {}_{\gamma} {}^{\beta} {}_{\gamma}$
	101	[3]	[4]	[5]	[6]	[7]	[8]	[9]
	↔Ĵ	^α β γ	^α β β	^α β β _γ	βα	^α β ^α γ	^α β ^α β	^α β ^α β _γ
	110	[0]	[!]	[0]	[#]	[\$]	[%]	[^]
	CC	^α β _γ γ	^α β _γ β	^α β _γ β _γ	α _{βγ} α	^α β _γ ^α γ	^α βγ ^α β	$\alpha \beta_{\gamma} \beta_{\gamma}$
	111	[&]	[*]	[(]	[)]	[-]	[+]	[=]

Fig. 8. Proof-of-concept experimental demonstration of character encryption. (a) Holographic images under different non-orthogonal polarization channels are translated into three-bit codes. (b) A series of characters are decrypted as two polarization combinations including letters, numbers and marks based on a method similar to Base64 alphabet.

alphabet. In this way, the letters, numbers and marks can be encoded accordingly. Utilizing the fabricated metasurface, we can encode abundant information consisting of characters in non-orthogonal polarization channels.

5. Conclusion

In summary, we propose a design strategy that extends the traditional Jones matrix method. Using the design strategy, a single-layer dielectric metasurface can provide independent phase control for three non-orthogonal arbitrary polarization channels. As a proof-of-concept demonstration, we have designed, fabricated and characterized a series of metasurfaces for generating linear, circular and elliptical polarization-multiplexed far-field holographic images, respectively. Further, benefitting from the information security of non-orthogonal polarization channels, we have demonstrated optical encryption applications based on the non-orthogonal arbitrary polarization-multiplexed metasurfaces, including image encryption and character encryption schemes. This non-orthogonal polarization multiplexing metasurface platform may promote practical applications in optical communications, optical encoding and information security.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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