Broadband decoupling of intensity and polarization with vectorial Fourier metasurfaces

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Intensity and polarization are two fundamental components of light. Independent control of them is of tremendous interest in many applications. In this paper, we propose a general vectorial encryption method, which enables arbitrary far-field light distribution with the local polarization, including orientations and ellipticities, decoupling intensity from polarization across a broad bandwidth using geometric phase metasurfaces. By revamping the well-known iterative Fourier transform algorithm, we propose "à la carte" design of far-field intensity and polarization distribution with vectorial Fourier metasurfaces. A series of non-conventional vectorial field distribution, mimicking cylindrical vector beams in the sense that they share the same intensity profile but with different polarization distribution and a speckled phase distribution, is demonstrated. Vectorial Fourier optical metasurfaces may enable important applications in the area of complex light beam generation, secure optical data storage, steganography and optical communications.
Optical waveform control plays a critical role in the optical systems for various applications. Among the different methods to address the electromagnetic field distribution in the far field, optical metasurfaces—artificial materials that consist of subwavelength structure arrays—are capable of tailoring the waveform of the electromagnetic waves with an unprecedented level of precision. In particular, due to the versatility of this approach, it is possible to engineer both amplitude and polarization information at will. Vectorial meta-holograms with arbitrary polarization have been developed using a diatomic reflective metasurface and a geometric phase-based metasurface. However, the generated polarization is limited by the multiplexing metasurface’s sub-pixels, which are not able to realize arbitrary spatially distributed polarization as yet. Some efforts have been made by using combining geometric phase and propagation phase, but it severely suffers from narrow bandwidth. A broadband waveform control that can decouple amplitude from polarization information has yet to be demonstrated.

One of the most important applications of meta-holograms is information security, which is important in many areas of the society, such as protecting individuals, industries, and military information from leaks and stealing. Among the different communication channels and information sharing techniques, photonics is the most efficient and effective way of carrying information across long distances. Optical waveforms possess many degrees of freedom, such as amplitude, phase, frequency, and polarization, and each can be used for data encoding. Moreover, optical encoding methods require specific professional equipment for data encoding, providing a more secure way towards high-security information encoding. Various optical encoding methods have been developed based on the intensity, such as spatial correlators, optical exclusive or (XOR) image encryption, phase-shifting interferometry, polarization-dependent imaging, Lippmann plates, and holograms. Many other efforts of optical encoding have been made by using multiplexing meta-hologram that can encode the optical information into multi-channels of holographic images.

The most common approach is based on polarization-dependent meta-hologram, which creates different holographic images using different polarizations of the incident beam. Chiral meta-holograms are also introduced for direction-dependent holographic encoding. Other encoding methods relying on incident wavelength, nonlinear effect, spatial frequency, orbital angular momentum, and tunable metasurface are also demonstrated. It is noteworthy that all of these proposed multiplexing meta-holograms encode information on the intensity of the holographic images.

In this study, we propose a vectorial Fourier metasurface for which amplitude and polarization information can be addressed independently one from the other. We utilize this specificity to encode intensity and the two polarization information channels, namely ellipticity and azimuth, to produce far-field images. The image refers to the spatial distribution of either total intensity, ellipticity, or azimuth information. The design of the metasurface is realized using a modified iterative Fourier transform (IFT) algorithm that does not only consider far-field intensity, but it severely suffers from narrow bandwidth. A broadband waveform control that can decouple amplitude from polarization information has yet to be demonstrated.

Results

Design method. The design principle of the vectorial Fourier metasurface is shown in Fig. 1. Each pixel of the metasurface consists of four lines of phase-gradient supercells as shown in Fig. 1a, in which the top two lines and bottom two lines of meta-structures are arranged counter-clockwise and clockwise, respectively, with the same orientation increment angle of \( \delta_{d} \). Each building block of the pixels, the pillar meta-structure, acts as a half-waveplate that converts the handedness of the incident CP beams and imposes a geometry phase (also called Pancharatnam–Berry (PB) phase) of \( \pm \delta_{d} \), where \( \delta \) is the orientation angle of each pillar (the signs “+” and “−” denote clockwise and counter-clockwise rotation, respectively), i.e., \( |+| \rightarrow e^{2\delta i} |−| \) and \( |−| \rightarrow e^{−2\delta i} |+| \), where \( |+| \) represents LCP and \( |−| \) represents RCP. Considering that the incident linear polarized (LP) light can be decomposed into LCP and RCP, the clockwise lines in a pixel deflect the LCP light to RCP light with a deflection angle of \( \theta_{1} = \arcsin(\frac{\delta_{d}}{P}) \) as shown in Fig. 1b, where \( k_{0} \) is the wavenumber in the free space and \( P \) is the period of the unit cell. The counter-clockwise lines in the same pixel deflect the RCP to LCP at the same angle of \( \theta_{1} \). The starting orientation angle of the four lines from top to bottom are \( \delta_{d}, \delta_{d} + \triangle \delta_{d}, \delta_{d} + \triangle \delta_{d}, \) and \( \delta_{d} + 2 \triangle \delta_{d} \), where \( \triangle \delta_{d} \) and \( \delta_{d} \) are respectively used to control the relative amplitude and phase between LCP and RCP. We ignore the co-polarization in the following text, simply because it is disfavored at the zero order and it does not interfere with the cross-polarized fields. The complex amplitude \( a^{m} \) in the metasurface plane is given by,

\[
a^{m}(x^{m}, y^{m}) = A^{m}(x^{m}, y^{m}) e^{i \varphi^{m}(x^{m}, y^{m})} + A^{m}(x^{m}, y^{m}) e^{i \varphi^{m}(x^{m}, y^{m})}
\]

where the superscript \( m \) represents the metasurface plane, \( x^{m} \) and \( y^{m} \) represent the pixel positions in the metasurface plane, and \( A^{m}(x^{m}, y^{m}) \) and \( \varphi^{m}(x^{m}, y^{m}) \) are the amplitude and phase of pixel \( (x^{m}, y^{m}) \) at the metasurface plane generated by the two CP of the light beam. For simplicity, in the following we ignore the notation...
of \((x^m, y^m)\). The amplitude \(A^m_i\) is controlled by the rotation angle difference of \(\Delta \theta_i\) due to the interference between two lines of LCP (or RCP) as,

\[
A^m_i = \left| e^{-i2\Delta \theta_i} + e^{-i2\Delta \theta_i} \right| / 2 = \sqrt{1 + \cos 2\Delta \theta_i} / 2
\]

(2)

where \(\sigma = +\) (or \(+1\)) represents LCP and \(\sigma = -\) (or \(-1\)) represents RCP. The phase \(\phi^m_i\) is generated by the rotation angle of \(\delta_i\), thanks to the geometric phase as,

\[
\phi^m_i = -2\alpha \delta_i
\]

(3)

Therefore, by varying the value of \(\delta_i\) and \(\Delta \delta_i\), arbitrary amplitude and phase information in the metasurface plane can be assigned to each pixel independently from the others, so as to control far-field amplitude and polarization information at will.

To decouple amplitude from far-field polarization information, we propose modifying the conventional Gerchberg–Saxton (GS) algorithm to a version working for vectorial fields. The GS utilizes IFT as shown in Fig. 2 (see more details in Supplementary Note 1)\(^{17,26,27}\), and in its vectorial version—instead of converting to a phase profile in the metasurface plane—we consider the phase profiles of two CP beams noted \(\phi_i\) realized by rotating the angle of \(\delta_i\) according to Eq. 3. In this implementation, the far-field polarization can be controlled over the entire profile, despite the fact that GS converges to designs with randomly distributed far-field phase profile. The condition for far-field polarization addressing requires that the phase retardation between orthogonal polarization channels is properly adjusted, i.e., the phase value for both polarization channels is randomly distributed on the transverse plane with a controllable phase retardation.

For a convenience purpose, we keep the amplitude in the metasurface plane \(A_i\) uniform for all pixels, i.e., \(\Delta \delta_i\) and \(\Delta \delta_i\) are two constant values for all pixels determined by the total intensity of two CP beams \(I_0\). The latter are calculated considering the intensity integral of all pixels in the image plane as:

\[
I_{0i} = I_0 = \sum_{x=1}^{N_x} \sum_{y=1}^{N_y} \left( a(x', y') \right)^2,
\]

where the superscript represents the far-field image plane, \((x', y')\) represent the pixel position in the far-field image plane, \(N_x \times N_y\) is the total pixel number, and \(a(x', y')\) are the amplitude of LCP and RCP light of each pixel \((x', y')\). It can be shown that the rotation angles \(\Delta \delta_i\) are given by (see more details in Supplementary Note 2),

\[
\begin{align*}
\Delta \delta_i &= 0, & \text{if } I_{0i} \geq I_{th} \quad (4) \\
\Delta \delta_i &= \arccos \left( \frac{\sum_{x=1}^{N_x} \sum_{y=1}^{N_y} \left( a(x', y') \right)^2}{\sum_{x=1}^{N_x} \sum_{y=1}^{N_y} \left( a(x', y') \right)^2} - 1 \right) / 2, & \text{if } I_{0i} < I_{th}
\end{align*}
\]

Equations (3) and (4) are then used to recover the orientation angles of each pixel of the metasurface.

The meta-structures are simulated using full-wave finite-difference time-domain (FDTD) and the simulation results are shown in Fig. 3. The top view and perspective view of one metasurface are shown in Fig. 3a, b, respectively. One-micrometer-tall GaN nanopillars, grown on low-index lattice-matched Sapphire substrate, are realized with rectangular cross-sections to induce structural birefringence. Both GaN and sapphire are
transient in the entire visible range, which are perfect candidates for the design of visible optical metasurfaces. The period of the nanostructure unit cell is \( P = 300 \) nm to avoid spurious diffraction effects in the substrate. The width is fixed to \( L_w = 120 \) nm. The CP conversion efficiency is shown in Fig. 3c with the long axis of the nanopillar swept from 160 to 260 nm and the wavelength \( \lambda \) swept from 450 to 700 nm. The dash line indicates the CP conversion at \( L_w = 210 \) nm, where the CP conversion efficiency is higher than 50% across almost the entire visible range. Figure 3d, e show the electric field distribution along short and long axis of the pillar, respectively, at the point of \( L_w = 120 \) nm and \( \lambda = 575 \) nm (the purple star in Fig. 3c). It is shown that there are 5.5 and 5 oscillations of electric field in \( E_x \) and \( E_y \) in the GaN nanopillar, i.e., a signature of half a wavelength retardation difference, which verifies that the meta-structure acts as a nanoscale half-waveplate for these structural parameters and operation wavelength. In addition, when the nanopillar is rotated with an angle of \( \delta \), a geometric phase of \( 2\delta \) is obtained on cross-CP as shown in Fig. 3f. The simulated geometric phase by using FDTD shown in blue stars agrees well with the theoretical one (\( \phi_{\text{GT}} = 2\delta \)) shown by the red curve. In addition, the CP conversion efficiency between LCP and RCP is, as expected, near unity as shown by the black curve.

In order to validate our approach to decouple intensity from polarization, we conceived a series of spatially variant far-field polarization profiles distributed on a donut far-field intensity profile (with the same radius), but having different azimuthal angle of the linear polarization defined by \( \psi(x, y) = \lambda \phi(x, y) + m \pi/2 \), where \( l \) is an integer number that represents the turns of the polarization rotation encircling the donut intensity profile, \( x \) and \( y \) are the coordinate of beam, \( \phi(x, y) = \tan^{-1}(\delta) \), \( m = 0 \) represents the radial mode, and \( m = 1 \) represents the azimuthal mode. We demonstrated four designs with different combinations of \( m \) and \( l \) (see more details in Supplementary Fig. 3). The scanning electron microscope images of the fabricated vectorial beam metasurfaces are shown in the first row of Fig. 4. The second row represents the designed intensity and polarization profiles. The measured total intensity profiles are shown in the third row, which agree well to the designed intensities. By placing a linear polarizer with different rotation angles in front of the vectorial beams, different patterns are observed from the fourth to the seventh rows. Interestingly, even if these beams resemble the well-known CVBs, we prove that they do not feature long-range spatial phase correlation. To do so, the amplitude and polarization information of the vectorial far-field patterns were also investigated by means of vectorial ptychography. This computational microscopy technique can indeed provide a quantitative map of the metasurface, thanks to the retrieval of its Jones matrix, mapped at a microscopic resolution of the whole sample area (see “Methods” and Supplementary Fig. 2b). This quantitative knowledge of the metasurface optical properties makes it possible to model totally the far-field pattern, by modeling a horizontally polarized illumination on the sample, followed by propagation (see Supplementary Fig. 2c). The resulting far-field complex amplitude distributions, either on a LP or on an RCP/LCP decomposition basis, as shown in Fig. 5, exhibit a short spatial phase correlation with a clear speckle pattern, while maintaining polarization over the whole intensity pattern. Indeed, with respect to CV beams that are vectorial solutions of Maxwell’s equations obeying axial symmetry in both amplitude and phase, our solution to produce spatially distributed amplitude and polarization field does not impose long-range spatial phase correlation. These fields could be beneficial for practical applications in laser machining, remote sensing, and so forth, or to decouple phase and polarization in singular optics. Using PB phase-tuning mechanisms, the polarization encoding is simply given by the rotation angle of the nanostructures, resulting in a broad operating bandwidth. It reveals that broad operating bandwidth is generally not achievable with a combination of propagation and PB phases. The characterization of the broadband properties is shown in Fig. 6. A CV beam with \( l = -2 \) and \( m = 0 \) is measured from \( \lambda = 475 \) nm to \( \lambda = 675 \) nm. A donut intensity profile is shown in the first row without polarizer. Subsequently, we insert a linear polarizer in front of the beam. The same pattern is observed for all of the wavelength with fixed transmission axis of polarizer as shown from the second to fifth rows, indicating that the metasurface could maintain polarization distribution properties over a broad wavelength range. The efficiency of the CV beam is in the range of \( 5 \sim 17\% \) across the entire visible range as shown in Supplementary Fig. 5, which is a bit low due to the fabrication errors and large pixel size. The latter is larger than the operating wavelength, resulting in higher-order images, which decreases the efficiency of the interested order.

After verification of the design approach with simple vectorial beams, we propose to encode optical information relying on the azimuth and ellipticity angles of the polarization information rather than encoding intensity profiles of conventional polarization.
states, realizing a sort of holographic polarization-only encoding technique. Two meta-holograms with the same intensity profile but different azimuth and ellipticity angles of the polarization are designed as shown in the Supplementary Fig. 6. The fabricated results of the two metasurfaces are shown in Supplementary Fig. 7. As the information is only encoded on the polarization properties, i.e., spatial distribution of the orientation and ellipticity, an additional retrieval method based on local Stokes polarimetry is required. Stokes parameters, which include the optical quantities of interest, are generally obtained using two sets of measurements, cascading a waveplate with the phase difference between fast axis and slow axis of $\phi$, and a linear polarizer with rotation angle of $\theta$ with respect to the $x$-axis in front of the image. The measured intensity profiles after the cascaded waveplate and linear polarizer are related to $\phi$ and $\theta$, which are denoted as $I(\theta, \phi)$. Therefore, the measured azimuth and ellipticity angles of the polarization are described as (see more details in Supplementary Note 3),

$$\psi = \frac{1}{2} \tan^{-1} \left( \frac{2I(45^\circ, 0^\circ) - I(0^\circ, 0^\circ) - I(90^\circ, 0^\circ)}{I(0^\circ, 0^\circ) - I(90^\circ, 0^\circ)} \right) \quad \left( -\frac{\pi}{2} < \psi \leq \frac{\pi}{2} \right)$$

(5)

$$\chi = \frac{1}{2} \sin^{-1} \left( \frac{I(0^\circ, 0^\circ) + I(90^\circ, 0^\circ) - 2I(45^\circ, 90^\circ)}{I(0^\circ, 0^\circ) + I(90^\circ, 0^\circ)} \right) \quad \left( -\frac{\pi}{4} < \chi \leq \frac{\pi}{4} \right)$$

(6)

In addition to these measurements, the total intensity profiles, i.e., with spatially varying polarization distribution, are measured directly, without any waveplate and/or polarizer. The measured results of the first metasurface are shown in Fig. 7a–c.

As expected from the design, a uniform intensity profile is observed in Fig. 7a. However, both a “Blade” and a “Rocket” images are shown when looking at the polarization spatial distribution in the azimuth and ellipticity angles, respectively. Another design with the same uniform intensity profile but a “Tree” and a “Squirrel” polarization information is obtained in Fig. 7d–f. Besides, we also used vectorial ptychography to map both the amplitude and polarization information of the vectorial far-field patterns (see more details in “Methods” and Supplementary Fig. 2b). The Jones matrix maps of the metasurface as retrieved by vectorial ptychography are shown in Supplementary Fig. 8, whereas the far field is shown in Supplementary Fig. 9, including intensity and polarization information. As expected, a uniformly distributed intensity profile is observed in both designs of Supplementary Fig. 9a, d. Moreover, in the azimuth angle and ellipticity angle of polarization map, images of “Blade” and “Rocket” are respectively obtained in Supplementary Fig. 9b, c and images of “Tree” and “Squirrel” are observed in Supplementary Fig. 9e, f.

**Discussion**

In conclusion, we have demonstrated a general method to design vectorial Fourier metasurfaces, which decouple intensity from polarization information, such that spatially distributed full polarization profiles with arbitrary intensity distribution can be realized. The vectorial Fourier metasurfaces are conceived using a modified IFT algorithm that optimizes the transmission information properties to encode simultaneously both intensity and polarization far-field distribution. We produce an interesting series of far-field beam profile with donut-like intensity and spatially distributed polarization, resembling CVBs, but with
randomly distributed far-field phase distribution. To fully characterize the optical response of our Fourier metasurfaces, we retrieve the complete Jones matrix of the metasurface using vectorial ptychography and proved the short-range phase correlation in contrast to the long-range polarization distribution, indicating that both polarization channels have spatially correlated phase profiles. Furthermore, the proposed vectorial Fourier metasurfaces are able to encode complex polarization information onto uniform distributed intensity profiles. We demonstrated that a “Blade” (or “Tree”) and a “Rocket” (or “Squirrel”) images can be multiplexed and separately decrypted from the orientation angle and ellipticity angle of the polarization on a uniformly distributed intensity profile of a holographic image. Vectorial Fourier encoding could highly enhance the information security, having various promising applications in data encryption, optical ID tags for authentication and verification, and high-density optical data storage, but also for specific applications including optical trapping and laser machining.

Fig. 4 Fabricated results and optical measurement of the Stokes polarization parameters of the donut polarization-distributed field profile. Field distribution with a $l = 1, m = 0$; b $l = 1, m = 1$; c $l = -2, m = 0$; d $l = -4, m = 0$. Top row: fabricated results with the top view (top panels) and tilt view (bottom panels). The blue area shows one pixel of the meta-hologram. The red scale bar represents 1 μm. Second row: intensity profiles of the designed vectorial fields. The black arrow represents the local polarization. Third row: measured intensity profiles of the field distributions without linear polarizer. Fourth to seventh rows: measured intensity profiles of the field distributions with a linear polarizer. The white arrow represents the transmission axis of the linear polarizer.
Fig. 5 Complex amplitude and polarization information of far field as retrieved by the ptychographic measurement. Measured complex amplitude of a x-pol., b y-pol., c LCP, and d RCP components. The phase profiles for the four polarization components show typical speckle phase distributions. The inset figure in d is the color bar with phase encoded as hue and amplitude as brightness. Measured e azimuth angle and f ellipticity angle of polarization information.

Fig. 6 Broadband characterization of the vectorial metasurfaces designed for a field profiles with \( l = -2, m = 0 \). The measured intensity profiles at different wavelengths of a \( \lambda = 475 \text{ nm} \), b \( \lambda = 525 \text{ nm} \), c \( \lambda = 575 \text{ nm} \), d \( \lambda = 625 \text{ nm} \), e \( \lambda = 675 \text{ nm} \). Top row: measured intensity profiles without linear polarizer. Second to fifth rows: measured intensity profiles with a linear polarizer. The white arrow represents the transmission axis of the linear polarizer.
**Methods**

**Device fabrication.** A GaN thin film with 1 μm thickness is grown on a double-side polished c-plane sapphire substrate using molecular beam epitaxy RIBER system. Conventional electron beam lithography processes are used for the etching of GaN nanopillars. The poly (methyl methacrylate) resist (495A4) with ~180 nm is spin coated on the GaN and baked on a hot plate with temperature of 125 °C. It is exposed with designed patterns at 20 keV (Raith ElphyPlus, Zeiss Supra 40) and developed in 3 : 1 IPA : MIBK solution. Oxygen plasma etching (reactive ion etching (RIE), Oxford System) is used to clean the residual resist that is not completely removed during development. The sample is deposited with a 50 nm thickness of Nickel using E-beam evaporation and is immersed into acetone solution for lift-off process to obtain the Nickel hard mask. By using RIE (Oxford System) with a plasma composed of C2H2Ar gases, the pattern is transferred to the GaN. The residual nickel hard mask is removed by chemical etching with 1 : 1 H2O2:H2SO4 solution, revealing the GaN nanopillars. See more details of fabrication processes in Supplementary Fig. 1.

**Conventional optical setup.** The optical setup for characterizing the projected far-field is shown in Supplementary Fig. 2a. A laser beam propagates through a linear polarizer and a quarter wave plate (QWP). In order to avoid the birefringent effect of the sapphire substrate, we calibrate the polarization of the input light with a bare sapphire substrate to make sure the input light is LP in horizontal direction by controlling the rotation angle of the previous linear polarizer and QWP. After an achromatic lens with a focal length of 50 mm, the laser beam is weakly focused on the side polished c-plane sapphire substrate using molecular beam epitaxy RIBER meta-holograms. The vectorial far-field is obtained by modeling an LP illumination of the metasurface, followed by a propagation by fast Fourier transform of the vectorial exit field, as illustrated in Supplementary Fig. 2c. The spatial distribution of the propagation of the CV beams and two metasurface encryption are shown in Supplementary Movies 1–3.

**Data availability**

Psychography raw data and other data that support the findings are available upon request to the authors.

**Code availability**

The code used for the vectorial meta-hologram design is available in the Supplementary Note 4 and Supplementary Data 1.

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**Fig. 7 Measurement results of vectorial encoded images.** a–c Show the data obtained for the first metasurface design. d–f Correspond to the data for the second metasurface design. a–f Measurement results using conventional optical setup to image the Stokes parameters. a, d Measured intensity; b, e azimuth angle; c, f ellipticity angle of the polarization. Both interfaces encode a similar uniformly distributed intensity profile as shown in a and d. Color-coded images displaying the ellipticity and the orientation; images reveal a “Blade,” a “Rocket,” a “Tree,” and a “Squirrel” encoded polarization images as shown in b, c, e, and f, respectively.

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### Author contributions

Q.S. and P.G. conceived the idea and carried out the experiment. Q.S. performed the numerical simulation, calculation of meta-hologram, and optical characterization of meta-hologram. A.B. and P.F. performed the ptychography measurement, data processing, and analysis. Q.S., S.C., and V.B. contributed to the nano-fabrication. S.Y., B.D., and P.M. performed the G2N MBE growth. Q.S., P.C.W., S.K., P.F., and P.G. wrote the manuscript. P.G. supervised and coordinated the project. All the authors contributed and approved the manuscript.

### Competing interests

The authors declare no competing interests.

### Additional information

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