Vectorial wavefront holography based on a polarisation-insensitive hologram

Haoran Ren

School of Mathematical and Physical Sciences, MQ Photonics Research Centre, Macquarie University, Sydney, Australia

E-mail: haoran.ren@mq.edu.au

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Abstract
Polarisation holography generally demands polarisation-sensitive holograms for reconstructing either polarisation-multiplexed holographic images or polarisation-sensitive image channels. To date, polarisation holography is underpinned by the Jones matrix method that uses birefringent holograms, including ultrathin metasurface holograms, limiting the polarisation control to orthogonal polarisation states. Here I introduce a novel concept of vectorial wavefront holography by exploiting the wavefront shaping of a structured vector beam. I will show that a phase hologram can be used to tailor the polarisation interference of a vector beam in momentum space, creating arbitrary polarisation states that include but not limited to the linear, circular, azimuthal, and radial polarisations. This opens an unprecedented opportunity for the multiplexing generation of arbitrary polarisation distributions in a holographic image. The demonstrated vectorial wavefront holography offers flexible polarisation control without using birefringent optical materials, which may find applications in polarisation imaging, holographic encryption, holographic data storage, multi-view displays, holographic Stokesmeter, and polarimetry.

Keywords: polarisation holography, structured light, vectorial wavefront holography

(Some figures may appear in colour only in the online journal)

1. Introduction
Optical holography provides a disruptive technology that allows the use of a hologram to display 3D optical fields via the complex-amplitude modulation of an incident beam. In addition to the amplitude and phase degrees of freedom, light can also carry polarisation information—the oscillating direction of an electromagnetic light field. Conventional polarisation holograms have been optically recorded in birefringent media that have a polarisation-dependent sensitivity. Illuminating the birefringent media with two interfered orthogonal polarised fields allows the recording and reconstruction of polarisation-sensitive holographic images [1, 2]. As such, birefringent holograms open the door to polarisation holography that has the potential to increase the bandwidth and security of an optical hologram. However, a long exposure of polarised light into polarisation-sensitive media is required to induce sufficient birefringence, accompanied with an undesired high-temperature treatment [3]. These limitations have hindered the conventional polarisation holography for practical applications.

Recent development of metasurface technology has transformed the field of digital holography, opening the possibility to digitise polarisation-sensitive holograms using birefringent meta-atoms [4–14]. Birefringent metasurface holograms have recently been developed to either carry independent image channels for an improved hologram bandwidth [4, 6–8, 10–12, 15], or reconstruct and display a polarisation-multiplexed distribution [5, 9, 14]. However, birefringent metasurfaces underpinned from the Jones matrix method have obvious limitations: for instance, the polarisation access is typically limited to orthogonal polarisations [4, 6–8, 10]; detour [5, 14] or supercell meta-atoms [7, 11, 12] designed for the polarisation sensitivity sacrifice hologram resolution.
of an azimuthal polarisation. Unlike conventional optical beams with a homogeneous polarisation distribution, such as a Gaussian beam, an APVB, which belongs to a cylindrical beam, has spatially variant electric field vectors perpendicular to the cylindrical beam’s radial axis (figure 2(a)). Owing to its polarisation singularity, the APVB has a doughnut intensity distribution in the momentum space (e.g. on a Fourier plane) (figure 2(b)). Moreover, the Fourier transform of an APVB features a two-lobe intensity distribution in the electric field components of $E_r$ and $E_\phi$, as shown in figures 2(c) and (d), respectively. Since the azimuthal polarisation is immune to the depolarisation effect regardless how strong the Fourier lens focus is [16, 17], it is advantageous over other vector beams for pure polarisation manipulation (figure 2(c)). Nevertheless, other structured vector modes (e.g. arbitrary vector states on a generalised higher-order Poincaré sphere) can also be used for the vectorial wavefront holography.

The capability of producing different polarisations through the use of a single phase-modulated APVB was explored in figures 3–6. To numerically simulate the interference of vector fields in momentum space, vectorial Debye diffraction theory was employed [17, 18]. Mathematically, the incident field $\mathbf{E}_i(\theta, \varphi)$ of an APVB carrying the azimuthal polarisation can be written as $\mathbf{E}_i(r, \theta) = A(r, \theta) e^{i\varphi(r, \theta)} \begin{bmatrix} \sin \theta \\ -\cos \theta \\ 0 \end{bmatrix}$, where $A(r, \theta)$ and $\varphi(r, \theta)$ represent the amplitude and phase components, $r$ is the radial coordinate, $\theta$ is the azimuthal angle in the transverse plane. For simplicity we consider the phase-only modulation on an APVB, which can be readily achieved from a diffractive optical element (e.g. spatial light modulator (SLM) or digital micromirror device) in the lab, and therefore we assume a uniform amplitude distribution $A = 1$ across the beam cross-section. To calculate the vector field diffraction in the Fourier plane, a Fourier lens with an aperture stop radius of $R$ and an effective numerical aperture (NA) was considered. In this case, the incident electric field $\mathbf{E}_i(r, \theta)$ can be rewritten as $\mathbf{E}_i(\theta, \varphi)$ through transforming the radial coordinate $r$ into the deflection angle defined as $\varphi = \tan^{-1} \left( \frac{y}{x} \right)$, where $n$ is the refractive index of medium behind the APVB. In addition, after passing through the Fourier lens, the incident polarisation is modified by on a polarisation transformation matrix $\mathbf{T}(\theta, \varphi)$, leading to a transmitted field (immediate after the Fourier lens) as $\mathbf{E}_t(\theta, \varphi) = \mathbf{T}(\theta, \varphi) \mathbf{E}_i(\theta, \varphi)$, where $\mathbf{T}(\theta, \varphi)$ is given as [17, 18]:

$$
\mathbf{T}(\theta, \varphi) = \begin{bmatrix}
1 + \cos(\theta - 1)\cos\varphi & (\cos(\theta - 1)\cos\varphi \sin\theta) & -\sin\theta \cos\varphi \\
(\cos(\theta - 1)\cos\varphi \sin\theta) & 1 + \sin(\theta - 1)\sin^2\varphi & -\sin\theta \cos\varphi \\
\sin\theta \cos\varphi & -\sin\theta \cos\varphi & \cos\theta
\end{bmatrix}.
$$

Here I demonstrate a new concept of vectorial wavefront holography through the phase manipulation of a structured vector beam. Breaking the rotational symmetry of an azimuthally polarised beam via a phase-only hologram allows flexible tailoring of the interference of vector fields in momentum space (the Fourier domain of a hologram), offering a new way for polarisation control. As such, vectorial wavefront holography alleviates the necessity of polarisation-sensitive materials for polarisation holography, making the polarisation control more flexible and robust. I will present the simultaneous reconstruction of different polarisation distributions that include the linear, circular, radial, and azimuthal polarisations in a holographic image. This was achieved from illuminating an azimuthally polarised vector beam (APVB) on a phase-only polarisation-multiplexing hologram (figure 1).

2. Design principle

The principle of creating arbitrary polarisation states based on the phase-only modulation of a structured vector beam is illustrated in this section. Here I show the creation of arbitrary polarisation states through the phase-only-modulation of an APVB. Unlike conventional optical beams with a homogeneous polarisation distribution, such as a Gaussian beam, an APVB, which belongs to a cylindrical beam, has spatially variant electric field vectors perpendicular to the cylindrical beam’s radial axis (figure 2(a)). Owing to its polarisation singularity, the APVB has a doughnut intensity distribution in the momentum space (e.g. on a Fourier plane) (figure 2(b)). Moreover, the Fourier transform of an APVB features a two-lobe intensity distribution in the electric field components of $E_r$ and $E_\phi$, as shown in figures 2(c) and (d), respectively. Since the azimuthal polarisation is immune to the depolarisation effect regardless how strong the Fourier lens focus is [16, 17], it is advantageous over other vector beams for pure polarisation manipulation (figure 2(c)). Nevertheless, other structured vector modes (e.g. arbitrary vector states on a generalised higher-order Poincaré sphere) can also be used for the vectorial wavefront holography.

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Here I demonstrate a new concept of vectorial wavefront holography through the phase manipulation of a structured vector beam. Breaking the rotational symmetry of an azimuthally polarised beam via a phase-only hologram allows flexible tailoring of the interference of vector fields in momentum space (the Fourier domain of a hologram), offering a new way for polarisation control. As such, vectorial wavefront holography alleviates the necessity of polarisation-sensitive materials for polarisation holography, making the polarisation control more flexible and robust. I will present the simultaneous reconstruction of different polarisation distributions that include the linear, circular, radial, and azimuthal polarisations in a holographic image. This was achieved from illuminating an azimuthally polarised vector beam (APVB) on a phase-only polarisation-multiplexing hologram (figure 1).

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Figure 1. Schematic illustration of vectorial wavefront holography based on the phase-only modulation of an APVB. Based on the illumination of an APVB, a phase-only polarisation-multiplexing hologram can tailor the polarisation interference and reconstruct different polarisation distributions in a holographic image, including both the linear and circular polarisations.

Figure 1. Schematic illustration of vectorial wavefront holography based on the phase-only modulation of an APVB. Based on the illumination of an APVB, a phase-only polarisation-multiplexing hologram can tailor the polarisation interference and reconstruct different polarisation distributions in a holographic image, including both the linear and circular polarisations.
Due to the fact that the azimuthal polarisation is depolarisation free, giving rise to the transmitted electric field as
\[
E_{\theta}(\theta, \varphi) = e^{i\varphi} \begin{pmatrix} \sin \theta \\ -\cos \theta \\ 0 \end{pmatrix}. \]
According to the vectorial Debye theory, the electric field in the Fourier plane can then be described as the Fourier transform of the transmitted electric field \(E_{\theta}(\theta, \varphi)\) [19]:
\[
E_f = -\frac{f}{\lambda^2 \lambda_0^2} \mathcal{F} \left( \frac{E_{\theta}(\theta, \varphi) e^{-ik_z z}}{\cos \theta} \right),
\]
where \(f\) is the focal distance of the Fourier lens, \(\lambda\) is the wavelength of incident light, \(k_0\) is the free-space wavenumber, \(k_z\) is the wavenumber along the propagation \(z\)-axis.

In the simulation, an APVB has a transverse cross-section of 8 mm and an incident wavelength of 532 nm. A low NA Fourier lens with a focal length of 200 mm was considered. Without loss of generality, four different phase maps \(\varphi\) were imparted on an APVB for the generation of \(x\)-linear polarisation (figure 3), \(y\)-linear polarisation (figure 4), left-handed circular polarisation (LCP) (figure 5) and right-handed circular polarisation (RCP) (figure 6). Specifically, to create linear polarisation, a \(\pi\)-phase-step map was used to break the rotational symmetry of the APVB in the transverse cross-section plane. This allows the electric field vectors aligned with the phase-step line to be constructively interfere in the momentum space, leading to the generation of an arbitrary linear polarisation with a different polarisation axis. The polarisation axis can be controlled by the \(\pi\)-phase-step line (figures 3 and 4). It should be mentioned that the white defect lines observed in the polarisation distribution maps are due to the exact out-of-phase cancellation of the electric fields along the \(\pi\)-phase-step lines.

In addition, helical phase maps \(\varphi = \pm 2\pi \theta\) with topological charges of \(-1\) and \(+1\) can be imparted on an APVB to create LCP and RCP polarisations, respectively (figures 5 and 6). In this case, the electric field components \(E_x\) and \(E_y\) have an equal intensity but distinctive shapes, of which the central lobes are elongated along the \(x\)-axis and \(y\)-axis, respectively (figures 5(c), 5(d), 6(c) and 6(d)). With the use of different phase modulation maps, it is possible to extend the generated polarisation into arbitrary elliptical polarisation or even radial polarisation. It is obvious to see that the created polarisation distributions are not uniform in the Fourier plane, which has highly pure (near-unity) on-axis polarisation accompanied with orthogonal polarisations on the side lobes (about 30% intensity) [20]. However, as demonstrated in my previous work [16], a phase-modulated APVB has advantageous over homogenous polarisation incidence for
Figure 5. Simulated generation of the LCP through focusing a helical phase-modulated azimuthal polarisation, with a topological charge of $-1$. (a) Polarisation distribution across the incident beam. (b) Total intensity distribution of the helical phase-modulated azimuthal polarisation state in the Fourier plane. The simulation conditions are same as in figure 2. (c)–(e) Intensity distributions of the electric field components of $E_x$ (c), $E_y$ (d) and $E_z$ (e).

Figure 6. Simulated generation of the RCP through focusing a helical phase-modulated azimuthal polarisation, with a topological charge of $+1$. (a) Polarisation distribution across the incident beam. (b) Total intensity distribution of the helical phase-modulated azimuthal polarisation state in the Fourier plane. The simulation conditions are same as in figure 2. (c)–(e) Intensity distributions of the electric field components of $E_x$ (c), $E_y$ (d) and $E_z$ (e).

high-purity polarisation control in a tight focus, especially for a two-photon nonlinear process. Therefore, this approach offers great flexibility for arbitrary polarisation control by simply changing phase maps on a SLM.

Consequently, I experimentally verified the generation of four different polarisations through using a SLM to implement required phase maps on an APVB, showing quite consistent results with the simulation ones, as presented in figure 7.

The use of phase maps for the control of different polarisations provides an alternative approach to polarisation holography, capable of multiplexing generation of different polarisation distributions in a holographic image. The design of a polarisation-multiplexing hologram is illustrated in figure 8. According to Fourier optics, when a phase-modulated APVB is impinged onto a Fourier hologram, physical properties of incident light, including amplitude, phase, and polarisation, will be mathematically regarded as the impulse function of Fourier transform (FT) and convoluted to each spatial-frequency component of the hologram. Mathematically, the polarisation-multiplexing hologram can be regarded as superposition of complex-amplitude fields of different image channels encoded with distinctive phase and grating profiles,

$$
\varphi_j(r, \theta) = \varphi'_j(r, \theta) + \varphi'_p(r, \theta) + \varphi'_g(r, \theta),
$$

in the hologram plane: $E_{\text{mul}} = \sum_{j=1}^{M} e^{i\varphi_j(r, \theta)} \begin{pmatrix}
\sin \theta \\
\cos \theta \\
0
\end{pmatrix}$, wherein $\varphi'_j(r, \theta)$, $\varphi'_p(r, \theta)$ and $\varphi'_g(r, \theta)$ stand for the phase-retrieved hologram (third column in figure 8), polarisation-controlling phase (fourth column in figure 8) and grating phase (fifth column in figure 8) of each image channel; $i$ and $j$ represent the imaginary unit and the total number of multiplexing channels, respectively. Since the complex-amplitude hologram is Fourier-based, its
reconstructed optical fields in momentum space can be represented as
\[ \mathcal{F} \{ \mathbf{E}^{\text{mul}} \} = \sum_{j=1}^{M} \mathcal{F} \left( e^{i \varphi_j^l(r,\theta)} \begin{pmatrix} \sin \theta \\ -\cos \theta \\ 0 \end{pmatrix} \right) \]
\[ \otimes \mathcal{F} \left( e^{i \varphi_j^l(r,\theta)} \right) \mathcal{F} \left( e^{i \varphi_j^l(r,\theta)} \right) \]  
where \( \mathcal{F} \) denotes the FT operator, expressing multiplexing results as the superposition of a convolution of the phase-modulated APVB
\[ \mathbf{E}_j(r,\theta) = e^{i \varphi_j^l(r,\theta)} \begin{pmatrix} \sin \theta \\ -\cos \theta \\ 0 \end{pmatrix} \]  
used for creating a holographic image, and additional grating phase \( \varphi_j^l(r,\theta) \) used for shifting the image in the Fourier plane. Both the phase hologram and the grating phase have determined the spatial-frequency components of the polarisation-multiplexing hologram. Therefore, a phase-modulated APVB impinging onto the multiplexing hologram can be mathematically regarded as an impulse function of FT and its optical properties including amplitude, phase and polarisation are then convoluted to each spatial-frequency component of the multiplexing hologram. For the phase-only approximation, the final polarisation-multiplexing hologram was calculated as the argument of the above complex-amplitude superposition results: \( \arg(\mathbf{E}^{\text{mul}}) \).

Owing to the FT relation, spatial-frequency components of a Fourier hologram are simply represented by the pixels of the holographic image in momentum space [21–23]. To preserve the polarisation property in momentum space, spatial-frequency components of the hologram need to be sampled, equivalent to the sampling of holographic images by using a two-dimensional (2D) Dirac comb function (second column in figure 8). As long as the sampling period is larger than the diffraction-limited impulse response of the phase-modulated APVB in momentum space, the polarisation property of the incident beam can be well reversed in each pixel of the holographic image. This lays the physical foundation of a new concept of vectorial wavefront holography. It should be mentioned that to preserve the polarisation in multiple image channels, distinctive grating phase profiles (fifth column in figure 8) have been added to the phase holograms of image channels, otherwise the overlapped images will interfere and destroy the polarisation states in the Fourier plane. Consequently, I demonstrate the parallel generation of different polarisation distributions in a holographic image.

3. Experimental results

To experimentally verify the vectorial wavefront holography concept, the designed polarisation-multiplexing hologram was experimentally implemented through a SLM. An azimuthal polarisation converter (APC) was used to convert an incident linear polarisation into an APVB. The schematic diagram of the optical setup is shown in figure 9(A). A Fourier lens with a focal distance of 200 mm was used to perform the Fourier holography, giving rise to a polarisation-multiplexed holographic image in momentum space, which was detected by a charge-coupled device (CCD). To verify different polarisation distributions, a linear polariser (LP) or the cascaded use of a quarter wave plate (QWP) and a LP have been utilised to distinguish either the linear or circular polarisations, respectively. As a result, the parallel reconstruction of four different polarisation distributions in a holographic image was experimentally verified (figure 9(B)). By passing the holographic image through a LP, polarisation image channels of ‘Sydney Opera House’ and ‘kangaroo’ were identified to possess x-linear (figure 9(C)) and y-linear (figure 9(D)) polarisations, respectively. In addition, passing the holographic image through the combination of a QWP and a LP, polarisation image channels of ‘The Great Wall’ and ‘panda’ were detected to carry LCP (figure 9(E)) and RCP (figure 9(F)), respectively. Therefore, vectorial wavefront holography allows the reconstruction of an arbitrary polarisation distribution, which is not limited to orthogonal polarisations, paving the way for advanced and flexible polarisation holography without using birefringent optical materials. Indeed, the position of the APC in the experimental setup is critical for the polarisation reconstruction, as this device was designed to be coaxially aligned with an incident beam at normal incidence. In the experiment, the APC was placed close to the SLM, so that the phase-modulated beam reflected from the SLM can fully go through the APC device with approximately normal incidence. This works because the Fourier hologram was designed to have a very small NA of 0.0216, which can deflect beam into very small angles. Alternatively, when the beam deflection angle

![Figure 8](image-url)
Figure 9. Experimental demonstration of vectorial wavefront holography. (A) A schematic diagram of the optical setup used for both implementation of vectorial wavefront holography and verification of different polarisation distributions in a reconstructed holographic image. SLM: spatial light modulator, APC: azimuthal polarisation converter, LP: linear polariser, QWP: quarter wave plate. (B) Experimental reconstruction of a polarisation-multiplexed holographic image captured by a CCD. (C)–(F) Polarisation filtered holographic images for distinguishing the $x$-linear (C), y-linear (D), LCP (E) and RCP (F) polarisations, respectively. The yellow dotted lines label out specific image channels with target polarisations.

from the SLM is large, one can place the APC in a conjugate plane of the SLM by using a 4f system that consists of two lenses.

4. Conclusions

In conclusion, I have introduced a new concept of vectorial wavefront holography based on the phase-only modulation of a structured vector beam. Parallel reconstruction of an arbitrary polarisation distribution (including non-orthogonal polarisations) in a holographic image has been numerically designed and experimentally verified. Instead of developing polarisation-sensitive birefringent optical materials for polarisation holography with a limited polarisation access, this paper applies simple phase maps for tailored polarisation interference of a structured vector beam in momentum space. This alleviates the necessity of polarisation-sensitive materials for polarisation holography. Despite the fact that azimuthal polarisation exhibits a high degree of polarisation purity for the momentum-space polarisation manipulation, vectorial wavefront holography can be realised from other structured vector beams. Indeed, the rich family of structured vector beams offers a tremendous resource and great flexibility for vectorial wavefront holography [24, 25]. Since the orbital angular momentum of light can be solely controlled by a helical phase [26–28], this work can be further extended to manipulate both the polarisation and orbital angular momentum distributions in a holographic image. Therefore, I believe this demonstration will advance holography technology and may find significant impacts on a multitude of photonic applications, such as polarisation imaging [29], holographic encryption [23], polarisation-encoded data storage [16], multi-view displays [30], holographic Stokesmeter [31], and polarimetry [32].

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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ORCID ID

Haoran Ren https://orcid.org/0000-0002-2885-875X

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