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ABSTRACT

Featuring a nontrivial coupling between the orbital angular momentum of light and spatially inhomogeneous polarization, hybrid-order Poincaré sphere (HyOPS) beams have recently triggered numerous curiosities, especially in classical and quantum informatics. Despite much effort devoted to creating single HyOPS beam, it is still a formidable challenge to simultaneously harness multichannel and diverse HyOPS beams in a simple and efficient manner. Here, we propose a digitalized geometric phase optical element via photo-induced liquid crystal microstructures and demonstrate flexible and spin-controlled massive channels of HyOPS beams. By tuning the incident polarization, any state on up to 24 diverse HyOPSs is simultaneously mapped from common Poincaré sphere in high efficiency and good energy uniformity. All experimental results match well with the theoretical predictions of such a planar multifunctional device. This adds an extra spatial degree of freedom to advanced light tailoring and may facilitate parallel optical trapping, high-capacity communication, and high-dimensional quantum entanglement.

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Vector vortex beam (VVB), characterized by helicoidal transverse polarization and a spiral phase structure, has attracted ever-increasing interest. Compared with the optical vortex of homogeneous polarization and vector beam of flat wave-front, VVB carries both spin and orbital angular momentum (SAM/OAM) of light simultaneously, offering a much higher degree of freedom in light–matter interaction,1–4 high-resolution imaging,5 and optical communication.6 In particular, the inherently hyper-entanglement between its polarization and spatial degree of freedom makes VVB a versatile protocol for quantum information processing.7,8 Referring to the well-known Poincaré sphere, the theoretical framework of hybrid-order Poincaré sphere (HyOPS) has recently been proposed to describe complex polarization states of VVBs. For instance, a HyOPS with the topological charge \( m = +3 \) and \( l = +1 \) is illustrated in Fig. 1(a). North/south pole represents the right/left circularly polarized optical vortex carrying a SAM of \( -h/\pm h \) and an OAM of \( ml/\pm l \).9 Any other point on the HyOPS is the linear superposition of two such eigenstates. The equator denotes VVBs with both spatially variant polarization and phase, resulting in the dark central and partly separated lobes after passing through an analyzer. In the case of \( m = -l \), the HyOPS reduces to the so-called higher-order Poincaré sphere,11,12 whose equator indicates cylindrical vector beams with only one central polarization singularity and transforms to disconnected lobes accordingly.

On-demand engineering of HyOPS beams lies in the heart of their fundamental research and cutting-edge applications. Generally, generation strategies can be divided into two major types. One is independently manipulating and then combining two eigenstates of the desired HyOPS. Spatial light modulators (SLMs) are usually employed with the collaboration of an interferometer or prism.13–15 The other is based on the geometric phase originating from the spin–orbit interaction of light.15–18 Inhomogeneous anisotropic media are indispensable, among which metasurface-based spin-controlled light manipulation has been extensively studied.19–21 Despite the impressive progress aimed at single HyOPS using cascaded liquid crystal (LC) devices22,23 and modified metasurfaces24–26 only limited works27–29 involve the simultaneous acquisition of multichannel HyOPS beams while also facing challenging issues in system complexity, optical efficiency, and channel scale. Driven by promising opportunities in multiple optical tweezers,30 parallel laser manufacturing,31 and high-dimensional...
classical/quantum informatics, a compact, effective, and flexible scheme to harness massive HyOPS channels is highly desirable.

In this work, a special LC geometric phase element is proposed by digitalizing the conventional spiral phase with the Dammann vortex grating (DVG), and massive channels of HyOPS beams are achieved directly. Via such a single planar device, a large beam lattice with each order corresponding to a different HyOPS is obtained in good quality and relatively uniform energy distribution. The merit of spin dependence enables the simultaneous mapping from common Poincaré sphere to multiple diverse HyOPSs. Moreover, to extend the channel scale, the designed structure is further optimized and a 24-channel HyOPS beam is demonstrated. This supplies a robust and convenient method for large-scale manipulation of VVBs and other structured light.

To enable the parallel beam manipulating, the concept of Dammann grating is usually introduced.\(^{2,3,33}\) DVG is a binary-phase (0 and \(\pi\)) forked grating composed of a set of specific phase transition points. Here, we imprint the two-dimensional DVG into the \(q\)-plate \(^{35}\) by encoding the binary phase of DVG to traditional spiral geometric phase. Such a process can be an analogy with the computer binary system, so we call it "digitalizing," which denotes an integration of binary and space-variant geometric phases.\(^{2,3,33}\) Accordingly, a fancy digitalized geometric phase optical element is obtained, named as Dammann-vortex-\(q\)-plate (DVQP). The transmission function of a one-dimensional DVG with the phase profile \(\varphi_{x-DVG}(x)\) is expressed as\(^{33}\)

\[
T(x) = \exp\left(i\varphi_{x-DVG}(x)\right) = \sum_{p=-\infty}^{\infty} C_p \exp\left[ip \times (m_x \phi + \frac{2\pi x}{\Lambda_x})\right],
\]

where \(m_x\) is the topological charge of DVG, \(\phi = \arctan(y/x)\) is the azimuth angle, and \(\Lambda_x\) is the period. \(|C_p|^2\) is the power ratio of the \(p\)th diffraction order to the total. Through optimizing the number and values of phase transition points in the DVG, the incident light can be diffracted into \(N_x\) desired OAM modes with equal-energy distribution. As an example of \(N_x = 5\), normalized phase transition points can be selected as \(x_0 = 0\), \(x_1 = 0.03863\), \(x_2 = 0.39084\), \(x_3 = 0.65552\), and \(x_4 = 1\), respectively.\(^{32}\) By integrating two orthogonal one-dimensional DVG, a two-dimensional DVG is formed and further encoded into the \(q\)-plate. Accordingly, the optical axis orientation of such a DVQP can be formulated as

\[
\varphi = q \phi + \frac{1}{2} \varphi_{x-DVG} + \frac{1}{2} \varphi_{y-DVG},
\]

where \(q\) is the topological charge of the initial \(q\)-plate. For instance, Fig. 1(b) presents a DVQP with \(N_x = 5\), \(N_y = 2\), \(m_x = +1\), \(m_y = +2\), and \(q = 4.5\), whose space-variant optical axes are exhibited by gray color. The central region is enlarged and vividly depicted by green short sticks in Fig. 1(c).

As a convenient theoretical tool, the Jones matrix calculation\(^{36}\) is employed to derive the diffraction properties resulting from the spin–orbit interaction of light. Jones vectors of left and right circular polarization (LCP/RCP) are \(|L\rangle = [1 \quad i]/\sqrt{2}\) and \(|R\rangle = [1 \quad -i]/\sqrt{2}\), respectively. Thus, the incident light with arbitrary polarization state can be decomposed as

\[
|\psi_i\rangle = \cos \left(\frac{\Theta}{2}\right) e^{-i\Phi/2} |L\rangle + \sin \left(\frac{\Theta}{2}\right) e^{i\Phi/2} |R\rangle,
\]

where \((\Theta, \Phi)\) is the spherical coordinate on the conventional Poincaré sphere. Considering \(x\) in the half-wave condition, the Jones matrix of the DVQP can be described as

\[
J = \begin{bmatrix}
\cos(2x) & \sin(2x) \\
\sin(2x) & -\cos(2x)
\end{bmatrix}.
\]

Therefore, the output light follows...
corresponding to Figs. 1(b) and 1(c), while the forked net-like disclination in DVQP can be fabricated with a period of 48 μm flexibly controlled via the incident SAM.

As a natural birefringent material with controllable and stimuli-responsive self-assembly behavior, LCs have been witnessed with enormous advances in geometric phase planar optics. Here, the polarization-sensitive azo-dye SD138-based dynamic photo-patterning technology was adopted to imprint the designed optical axis orientation on the Poincaré sphere to the same point on the HyOPSs. Consequently, by precisely designing structure parameters (N, L, m, m, q) of the DVQP, the incident light can be equally diffracted into massive channels of diverse HyOPS beams, and the state of each channel can be flexibly controlled via the incident SAM.

The resultant geometric phase ±2π from the DVQP contributes to an N × N beam channel determined by the Dammann phase transition points, where the diffraction order (p, q, sth) corresponds to a distinctive HyOPS with m = pm + sm + 2q and l = pm + sm − 2q. Moreover, the spin mapping is verified from the point (θ, φ) on the Poincaré sphere to the same point on the HyOPS. Consequently, by precisely designing structure parameters (N, L, m, m, q) of the DVQP, the incident light can be equally diffracted into massive channels of diverse HyOPS beams, and the state of each channel can be flexibly controlled via the incident SAM.

Figure 1(d) shows that the topological charge ranges l = −5 to l = +3, formulated as l = p + 2s − 1. The diffraction efficiency of each desired HyOPS order is measured as shown in Fig. 2(c), which matches well with the theoretical simulation in Fig. 2(b). The (+1st, −1st) order exhibits a bright central spot, indicating the Gaussian mode, based on the astigmatic transformation, a cylindrical lens (f = 100 mm) is placed between the DVQP and a charge-coupled device (CCD) to measure the topological charge distribution. Through the number and tilt direction of dark stripes, the converted pattern in Fig. 2(d) shows that the topological charge ranges from m = −3 to m = +5 and (p, q, sth) OAM order follows m = p + 2s + 1, consistent with Eq. (6). These channels correspond to eigenstates on the north poles of diverse HyOPSs. While for |ψ(a)| = |R⟩, the output turns to the respective south poles as simulated in Fig. 2(e) and recorded in Fig. 2(f), which looks centrosymmetric to that of |ψ(a)⟩ = |L⟩. The OAM detection result shown in Fig. 2(g) denotes a range from l = −5 to l = +3, formulated as l = p + 2s − 1. The diffraction efficiency of each desired HyOPS order is measured as an average value of 5.77% with a fluctuation within ±0.64%. The total efficiency approaches 58%, consistent with the theoretical value 62.72%. These indicate that a high efficiency together with a good energy uniformity is achieved, thanks to the LC mediated geometric phase. Accordingly, by alternating the incident spin, massive channels of OAM eigenstates on different HyOPSs can be dynamically switched.

In addition to polar eigenstates, VVBs on equators of multiple HyOPSs are also created. As a representative case, the horizontal linear polarization is incident to generate the equatorial point (π/2, 0) on the HyOPSs, where two orthogonal eigenstates are equally weighted. To reveal the polarization distributions of VVBs, another polarizer is used and the corresponding results are shown in Fig. 3. Three typical orders are selected as examples for clarification and illustrated on the respective HyOPSs. As a superposition of |R⟩ and |L⟩, order I corresponds to the HyOPS shown in Fig. 1(a). Order II, characterized by a bright center, is composed of a Gaussian mode and an OAM mode with l = −2. Order III is a standard cylindrical vector beam, located on the higher-order Poincaré sphere with m = −l = 1. The transmitted intensity profile of order III is observed as two disconnected lobes parallel to the analyzer orientation. In all, we obtain 10 different HyOPS channels in relatively equal energy distribution.
Although all transmitted orders have the similar shape featuring two main lobes, the intensity minima orient at different azimuthal directions, which could be attributed to the Gouy phase of the Laguerre–Gaussian mode. For horizontal polarizer and analyzer in Fig. 3(a), the intensity profile will find its minima at azimuth angles ϕ = (2k+1)π/m, where k is an integer from 1 to |m − l| and ζ = arctan(zl/πmω0). It is noteworthy that such a dependence on the Gouy phase during the propagation provides an additional degree of freedom to manipulating VVBs. All experimental results are consistent with theoretical simulations. Besides the high-quality generation of equatorial VVBs, any other states on diverse HyOPSs can be flexibly realized via an LC-mediated geometric phase element. By integrating a tunable LC wave-plate, electrical switching of multi-channel HyOPS is also achievable by further integrating a tunable LC wave-plate. This work advances the on-demand engineering of VVBs and provides more potentials in various fields, including optical manipulation, fabrication, and communication.

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DATA AVAILABILITY

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

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