

Simultaneous dynamic detection of phase and polarization topological charges of Poincaré beams

Xiangle Li, Junna Yao, Shuimei Wu, Qiwen Zhan and Anting Wang

Citation: Li XL, Yao JN, Wu SM, et al. Simultaneous dynamic detection of phase and polarization topological charges of Poincaré beams. *Opto-Electronics Plus* **2**, 260005(2026).

Received: 26 January 2026; Accepted: 19 March 2026; Published online: 31 March 2026

Related articles

Noncommutative metasurfaces enabled diverse quantum path entanglement of structured photons

Yan Wang, Yichang Shou, Jiawei Liu, Qiang Yang, Shizhen Chen, Weixing Shu, Shuangchun Wen, Hailu Luo

Opto-Electronic Science 2025, **4**(10): 250006 doi: [10.29026/oes.2025.250006](https://doi.org/10.29026/oes.2025.250006)

Research progress on generating perfect vortex beams based on metasurfaces

Xiujuan Liu, Manna Gu, Ying Tian, Mingfeng Zheng, Bo Fang, Zhi Hong, Chee Leong Tan, Xufeng Jing

Opto-Electronic Science 2025, **4**(11): 250007 doi: [10.29026/oes.2025.250007](https://doi.org/10.29026/oes.2025.250007)

Multi-resonance enhanced photothermal synergistic fiber-optic Tamm plasmon polariton tip for high-sensitivity and rapid hydrogen detection

Xinran Wei, Yuzhang Liang, Xuhui Zhang, Rui Li, Haonan Wei, Yijin He, Lanlan Shen, Yurui Fang, Ting Xu, Wei Peng

Opto-Electronic Science 2025, **4**(7): 240029 doi: [10.29026/oes.2025.240029](https://doi.org/10.29026/oes.2025.240029)

More related articles in Opto-Electronic Journals Group website 



Simultaneous dynamic detection of phase and polarization topological charges of Poincaré beams

Xiangle Li¹, Junna Yao¹, Shumei Wu¹, Qiwen Zhan² and Anting Wang^{1*}

Abstract: Poincaré beams (PBs), characterized by their entanglement between helical wavefronts and vectorial polarization, serve as high-dimensional information carriers in classical and quantum optics. The topological charge (TC) is the fundamental parameter governing their singularity structure; however, characterizing the phase and polarization TCs simultaneously remains a significant challenge. Conventional approaches are often limited to static measurements or decouple these parameters through complex, multi-step processes, failing to capture the real-time dynamics essential for modern optical communications. Here, we demonstrate a robust, single-shot detection system capable of simultaneously resolving phase and polarization TCs for arbitrary states on the hybrid-order Poincaré sphere (HyPS). By leveraging a pair of Pancharatnam-Berry optical elements (PBOEs), we implement a conformal mapping that transforms the full angular momentum eigenstates into spatially separated coordinates. This unique configuration allows for the direct readout of TCs through position encoding, effectively decoupling the spin and orbital angular momentum components. We experimentally validate this method by detecting the dynamic evolution of PBs across eight different HyPSs with component orders up to 20, confirming its capability to distinguish between scalar, vector, and hybrid modes in real-time. This work establishes a versatile framework for the dynamic decoding of structured light, holding profound implications for high-capacity optical communications and information encryption.

Keywords: Poincaré beams; vector vortex beams; optical conformal transformation; hybrid-order Poincaré sphere; light field manipulation

DOI: [10.67704/oep.2026.260005](https://doi.org/10.67704/oep.2026.260005)

Citation: Li XL, Yao JN, Wu SM et al. Simultaneous dynamic detection of phase and polarization topological charges of Poincaré beams. *Opto-Electron Plus* 2, 260005 (2026).

1 Introduction

Light possesses diverse degrees of freedom that can be harnessed to carry information. Beyond the spin angular momentum (SAM) associated with circular polarization¹, vortex beams endowed with helical phase structures carry orbital angular momentum (OAM) of $l\hbar$ per photon, where l denotes the topological charge (TC)^{2,3}. SAM is associated with the circular polarization state of light, while OAM is related to its phase distribution^{4–6}. Poincaré beams (PBs), as typical vector vortex beams, can be generated by the superposition of two orthogonally circularly polarized vortex beams with different phase TCs. Due to their rich spatial polarization variations and unique helical wavefronts,

PBs have found widespread applications in fields such as optical microscopy⁷, laser remote sensing⁸, and optical communications^{9–12}.

Recently, switchable PBs have been generated by rotating optical elements and all states on the hybrid-order Poincaré sphere (HyPS) can be obtained¹³. The HyPS serves as a geometric framework for PBs, generalizing both the high-order Poincaré sphere (HOPS) and the traditional Poincaré sphere (TPS)^{14–20}. Within this framework, PBs are uniquely characterized by two types of topological indices: the phase TC and the polarization TC^{21,22}. The phase TC describes the global helical wavefront and the overall OAM carried by the PBs, while the polarization TC governs the spatial distribution of the polarization vector^{23–25}. These two param-

Received: 26 January 2026

Accepted: 19 March 2026

Published online: 31 March 2026

¹State Key Laboratory of Opto-Electronic Information Acquisition and Protection Technology, School of Physical Sciences, University of Science and Technology of China, Hefei 230026, China; ²Zhejiang Key Laboratory of 3D Micro/Nano Fabrication and Characterization, Department of Electronic and Information Engineering, School of Engineering, Westlake University, Hangzhou 310030, China.

*Correspondence: AT Wang, Email: atwang@ustc.edu.cn

eters together determine the singularity structure and the high-dimensional information capacity of the structured light. Although the HyPS framework enables the description of polarization-phase evolution, current studies have primarily focused on total angular momentum or static polarization states, often neglecting the dynamic interplay between phase and polarization TCs^{26,27}.

Numerous breakthroughs have been achieved in the manipulation of structured light in recent years^{28–30}. The explosive growth of techniques for generating complex optical fields has led to an urgent demand for detecting and decoding phase and polarization TCs, particularly in practical applications such as optical communications and quantum information processing^{31,32}. Conventional detection methods, such as Stokes polarimetry, typically require sequential measurements and extensive post-processing, rendering them unsuitable for capturing rapid state evolutions^{33,34}. Since 2010, optical conformal transformation corresponding to the coordinate transformation of beams have promoted the development of separation and measurement for OAM beams carrying phase TC^{35–37}. Furthermore, the spin-dependent response of Pancharatnam-Berry optical elements (PBOEs) has been utilized to effectively measure the polarization TC of cylindrical vector beams^{38,39}. However, a unified approach that combines conformal mapping with PBOEs to simultaneously disentangle and measure both phase and polarization TCs during the dynamic evolution of orthogonal eigenstates remains elusive.

In this work, we propose and experimentally demonstrate a compact optical system that bridges this gap. By combining switchable PBs and conformal transformation, we achieve the simultaneous characterization of total angular momentum eigenstates on the HyPSs via a single measurement. We utilize PBOEs to introduce conjugate spatial phase modulations, which reshape the donut-shaped PBs into two distinct linear patterns. The transverse displacements of these patterns directly correlate with the phase and polarization TCs, effectively separating the orthogonal eigenmodes to the encoding positions of the channels. Here we demonstrate the real-time detection of phase and polarization TCs during dynamic switching of PBs across 8 different HyPSs with component orders reaching up to 20. This work offers a solution to efficiently and dynamically analyze the TCs and orthogonal eigenstates of PBs and show whether the modes are pure scalar, pure vector, or hybrid, which may find applications in optical communications, information encryption, and quantum information science.

2 Methods

2.1 Switchable generation of PBs on HyPS

As shown in Fig. 1, the HyPS framework geometrically characterizes: i) the vector vortex beams with States A-D on the

equator and States G-H between the equator and the poles, ii) the right circularly polarized vortex beam such as State E is at the north pole, and the left circularly polarized vortex beam such as State F is at the south pole. Any state $|\psi_{m,n}\rangle$ on HyPS can be mapped to the space-variant polarization field of a light beam carrying OAM, which can be represented by a linear superposition of the two poles.

$$|\psi_{m,n}\rangle = \psi_R^m |R_m\rangle + \psi_L^n |L_n\rangle \quad (1)$$

where $\{|R_m\rangle, |L_n\rangle\}$ are the orthonormal circular polarization components that represent the right and left circularly polarized optical vortex with phase TC of m and n , $\{\psi_R^m, \psi_L^n\}$ are the coefficients. The components are defined as

$$\begin{cases} |R_m\rangle = \frac{\exp(im\varphi)}{\sqrt{2}} [1, i]^T, \\ |L_n\rangle = \frac{\exp(in\varphi)}{\sqrt{2}} [1, -i]^T, \end{cases} \quad (2)$$

where φ is the azimuthal angle. HyPS reduces to HOPS when $m = -n \neq 0$, and further degenerates to the typical TPS when $m = -n = 0$. The variations of all states are manifested both geometrically through $(2\theta, 2\varepsilon)$ coordinates and algebraically via superposition coefficients $\{\psi_R^m, \psi_L^n\}$.

Equation (1) can be further rewritten as

$$|\psi_{m,n}\rangle = \exp(iA\varphi) \cdot (\psi_R^m |R_{-B}\rangle + \psi_L^n |L_B\rangle), \quad (3)$$

where $A = (m + n)/2$ and $B = (n - m)/2$ are the topological indices of the PBs. Physically, A is defined as the phase TC, representing the global helical phase of the beam. Meanwhile, B is defined as the polarization TC, which dictates the local polarization rotation rate and the vector topological structure. Figure 1 shows how the HyPS represents the PBs when $m = 0$ and $n = 2$. In this case, both the phase and polarization TCs are 1, i.e., $A = B = 1$.

By comparing with Eq. (1), we see that an additional helical phase added to HOPS will evolve into HyPS. Therefore, VPs were used in our experiment to achieve this effect. The VP is essentially a half-wave retarder that produces either a vector polarized beam or a vortex beam, depending on the polarization state of the incident beam. The fast axis α of VP rotates continuously in the optical area:

$$\alpha = \frac{l\varphi}{2} + \alpha_0, \quad (4)$$

where l and α_0 are the order and initial orientation of the optical axis of the VP. Here we default the phase retardance of VP to π and α_0 to 0. The Jones matrix of VP is defined by

$$M_l = \begin{bmatrix} \cos(l\varphi) & \sin(l\varphi) \\ \sin(l\varphi) & -\cos(l\varphi) \end{bmatrix}. \quad (5)$$

The VP can introduce a geometric phase to modulate the wavefront of the incident beam. An arbitrary uniformly polarized vortex beam with the phase TC of l_1 passing

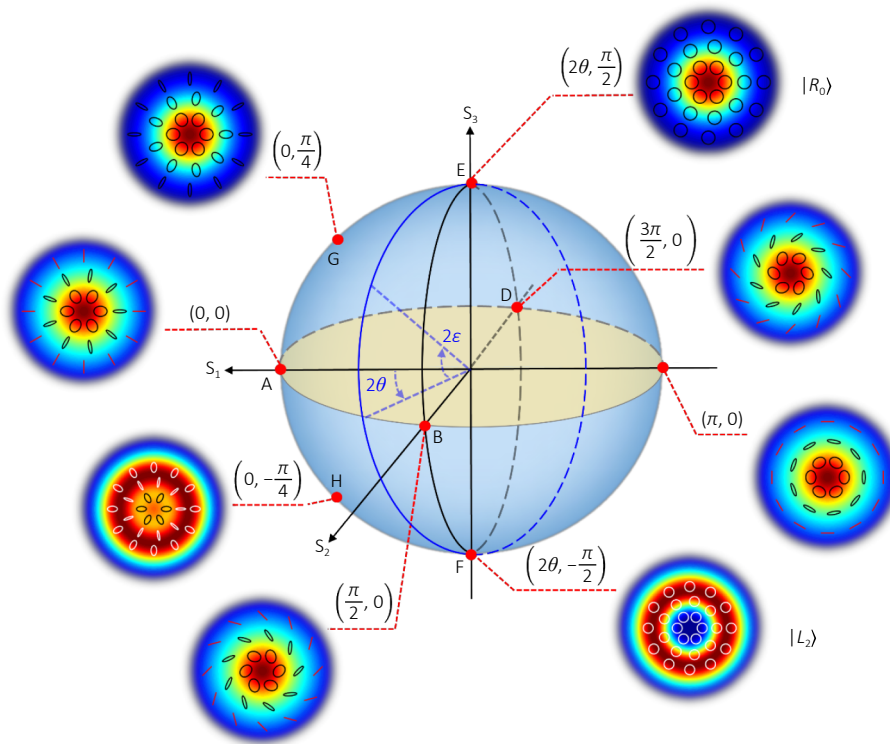


Fig. 1 | The geometric framework of the HyPS for $m = 0$ and $n = 2$ is defined by the Stokes parameters S_1, S_2 and S_3 as the primary axes. Points on the sphere are denoted by the coordinates $(2\theta, 2\varepsilon)$, where 2θ is equal to the initial phase difference between $|R_m\rangle$ and $|L_n\rangle$, and 2ε is determined by ψ_R^m and ψ_L^n . The inset shows the intensity and polarization distributions of States A–H on the sphere. Black circles, white circles, and red line segments represent the right circular polarization, the left circular polarization, and linear polarization, respectively.

through a VP of order l_2 can be expressed as

$$\begin{aligned} |\psi\rangle &= M_{l_2} \cdot \left(\exp(i l_1 \varphi) \cdot |\psi_{0,0}\rangle \right) \\ &= \exp(i l_1 \varphi) \cdot |\psi_{-l_2, l_2}\rangle \\ &= |\psi_{l_1 - l_2, l_1 + l_2}\rangle, \end{aligned} \quad (6)$$

where $|\psi_{0,0}\rangle$ is the state on the TPS. Comparing Eqs. (1), (3) and (6), it can be found that using VPs of order l_1 and l_2 is able to generate PBs on HyPS of $m = l_1 - l_2, n = l_1 + l_2$. All states $|\psi_{m,n}\rangle$ on this HyPS can be obtained by changing the polarization state of the incident vortex beam.

2.2 Conformal transformation theory of PBOEs

PBOE is essentially a half-waveplate with two-dimensional orientation patterns, and its Jones matrix is as shown in Eq. (5):

$$T(x, y) = \begin{bmatrix} \cos 2\alpha(x, y) & \sin 2\alpha(x, y) \\ \sin 2\alpha(x, y) & -\cos 2\alpha(x, y) \end{bmatrix}, \quad (7)$$

here, $\alpha(x, y)$ denotes its optical axis distribution. For an incident field with circularly polarized components $\{|R\rangle, |L\rangle\}$, the PBOEs will introduce conjugate spatial

phase modulations of $-2\alpha(x, y)$ and $2\alpha(x, y)$, respectively, while the circularly polarized components of the output field are converted to $\{|L\rangle, |R\rangle\}$. Since PBOEs are pure phase optical elements that act independently on the two SAM eigenstates, we exploit this property to design a pair of PBOEs and construct a 4- f imaging system. This system enables the simultaneous separation of OAM and SAM of PBs, represented by their orthogonal eigenstates $\{|R_m\rangle, |L_n\rangle\}$. This process is achieved through a conformal mapping that transforms PBs from the initial Cartesian coordinates (x, y) to the final log-polar coordinates (u, v) . The Cartesian-to-log-polar coordinate transformation requires $u = -a \cdot \ln(\sqrt{x^2 + y^2}/b)$ and $v = a \cdot \arctan(y/x)$. PBOE1 performs the phase transformation from a donut-shaped beam to two relatively parallel rectangular beams, and its optical axis distribution $\alpha_1(x, y)$ can be derived through stationary phase approximation as^{40,41}

$$\alpha_1(x, y) = \frac{\pi a}{\lambda f} \left[y \cdot \arctan\left(\frac{y}{x}\right) - x \cdot \ln\left(\frac{\sqrt{x^2 + y^2}}{b}\right) + x \right], \quad (8)$$

where λ is the wavelength, f is the focal length of the lens between the two PBOEs, and a and b are used to adjust the beam size and position in the (u, v) plane. PBOE2 performs

phase correction to compensate for the phase. Similarly, $\alpha_2(u, v)$ can be derived as

$$\alpha_2(u, v) = \frac{\pi|u|}{\rho} + \frac{\pi ab}{\lambda f} \cdot \exp\left(-\frac{|u|}{a}\right) \cdot \cos\frac{v}{a}. \quad (9)$$

According to Fourier optics, a linear phase gradient on the plane is transformed by the lens into a spatial shift at the focal plane. As a tilt phase parameter, ρ is used to adjust the beam shift on the CCD3 plane. To achieve more accurate OAM spectra, we replace the spherical lens with a cylindrical lens (CL) after PBOE2, focusing the rectangular beams into narrow lines to preserve spatial information integrity⁴². The parameters of PBOEs are $a=1$ mm, $b=3$ mm, $\rho=1.5$ mm, and $f=100$ mm.

3 Results and discussions

The paraxial fundamental Gaussian beam at 532 nm from the LD is applied as the laser source. The experimental setup is composed of three functional parts as shown in Fig. 2: Beam Switcher, Phase Transformer, and Phase Corrector. For clearer description, these components in Fig. 2 are marked in yellow, pink, and cyan, respectively. The optical elements used in Beam Switcher include LPs, VPs, and QWPs, which can be used to switch PBs on the same HyPS or across different HyPSs. Phase Transformer consists of PBOE1 and a lens with a focal length of 100 mm, while Phase Corrector includes PBOE2 and CL with a focal length of 100 mm. The PBOEs are fabricated using the photo-alignment liquid-crystal in a thin film with a total pixel count of 1920×1920 and an individual pixel size of $5 \mu\text{m}$.

As shown in Fig. 3, the eight optical path configurations of Beam Switcher are listed, with the corresponding HyPSs labeled as Sphere 1 to Sphere 8. The orders of VP1 and VP2 are 2 and 4, respectively, and VPs are employed to generate

helical phases or inhomogeneous polarization distributions. In addition, the angles in the figure represent the transmission axis of LP or the fast axis of QWP relative to the x-axis. By rotating the optical elements in the setup, all states of the HyPSs can be obtained. These are categorized and described by color: the first four Spheres (Sphere 1 to Sphere 4, highlighted with a green background) represent specific HyPSs, while the latter four Spheres (Sphere 5 to Sphere 8, highlighted with a blue background) correspond to HOPSs.

Taking Sphere 1 as an example, LP and QWP1 are used to generate a right circularly polarized beam, which is converted to a left circularly polarized beam with an additional phase TC when passing through VP1. QWP2 and QWP3 transform it into an arbitrarily polarized vortex beam. Subsequently, VP2 is used to modulate the polarization distribution of the beam, which ultimately produces PBs on the HyPS with $m = -2$ and $n = 6$. Orthogonal optical axes in QWP4 and QWP5 create compensating phase differences, nullifying their effects on the polarization and phase distribution of the beam.

Figure 4(a) and (b) show the generation of PBs on Sphere 1 and Sphere 5, respectively, by comparing States A, E, and F. Each row displays the intensity profiles of the beams before and after passing through different polarization analyzers, with the transmission axes of the analyzers labeled above the figures. The number of lobes in the images after the polarization analyzers is twice the absolute value of the order of VP2. In Fig. 4(a), it can be observed that the right and left circularly polarized vortex beams of State A on Sphere 1 have different central dark spot sizes, which proves that the beam is formed by the superposition of components with different TCs. This is further validated by the images before and after the polarization analyzers for States E and F, where the north pole State E is a right circularly polarized optical vortex with phase TC of -2 , and the

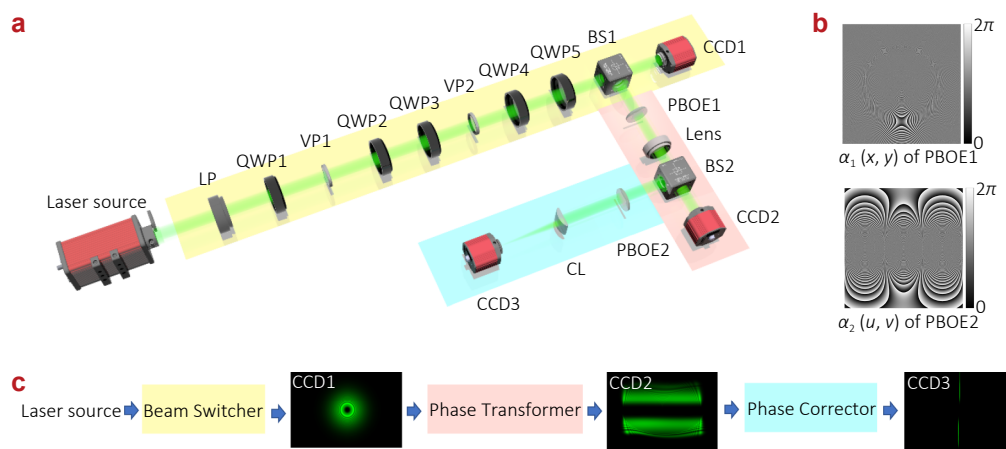


Fig. 2 | (a) Schematic of the experimental setup for generating switchable PBs and detecting TCs. (b) The angle functions $\alpha_1(x, y)$ of PBOE1 and $\alpha_2(u, v)$ of PBOE2 are on the right side of the schematic. (c) PBs are generated using Beam Switcher (yellow), then mapped through Phase Transformer (pink) and Phase Corrector (cyan). LP: linear polarizer; QWP: quarter wave plate; VP: vortex plate; BS: beam splitter; CL: cylindrical lens; CCD: charge-coupled device.

Elements Spheres	(LP, QWP1)	Order of VP1	(QWP2, QWP3)	Order of VP2	(QWP4, QWP5)	(<i>m</i> , <i>n</i>)
1	(0°, 45°)	2	varied	4	(0°, 90°)	(-2, 6)
2	(0°, -45°)		varied		(0°, 90°)	(-6, 2)
3	(0°, 45°)		varied		(0°, 0°)	(6, -2)
4	(0°, -45°)		varied		(0°, 0°)	(2, -6)
5	varied	2	(0°, 0°)	4	(0°, 90°)	(-6, 6)
6	varied		(0°, 90°)		(0°, 90°)	(-2, 2)
7	varied		(0°, 0°)		(0°, 0°)	(6, -6)
8	varied		(0°, 90°)		(0°, 0°)	(2, -2)

Fig. 3 | HyPSs obtained corresponding to different optical path settings. Elements are the devices used in the Beam Switcher, Spheres 1-4 are HyPSs (green), and Spheres 5-8 are HOPSS (blue). *m* and *n* are TCs of the north and south poles, respectively.

south pole State F is a left circularly polarized optical vortex with phase TC of 6 (i.e., $\{|R_{-2}\rangle, |L_6\rangle\}$). In contrast, Fig. 4(b) shows that the central dark spots of the right and left circularly polarized components of State A on Sphere 5 are of the same size, as State E is a right circularly polarized optical vortex with phase TC of -6, and State F is a left circularly polarized optical vortex with phase TC of 6 (i.e., $\{|R_{-6}\rangle, |L_6\rangle\}$).

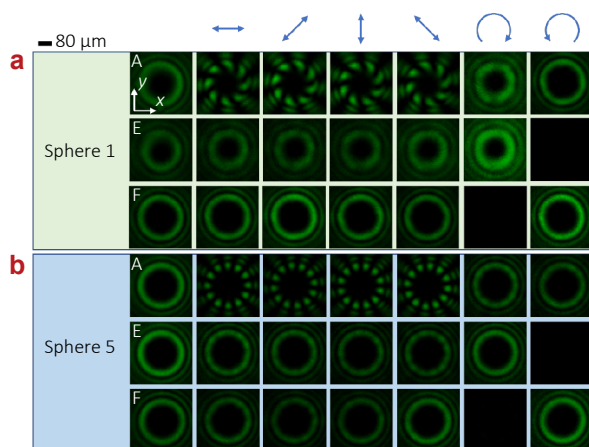


Fig. 4 | Generation of PBs on Sphere 1 and Sphere 5. (a) States A, E and F on Sphere 1. (b) States A, E and F on Sphere 5. Intensity profiles show pre- and post-analysis states, with analyzer orientations indicated above columns.

After generating switchable PBs using Beam Switcher, the beam sequentially passes through Phase Transformer and Phase Corrector. Figure 5(a) numerically simulates the evolution of the intensity distribution of State A on Sphere 1. Initially, a donut shape ($z = 0$, at the PBOE1 plane which is also the CCD1 plane) transforms into two parallel rectangles ($z = 200$ mm, at the PBOE2 plane which is also the

CCD2 plane), which further evolve into two straight lines through focusing by CL ($z = 400$ mm at CCD3 plane). Additionally, the optical elements encountered by the beam at different propagation distances are labeled along the z -axis. It can be found that the two circularly polarized components are unfolded in different ways after passing through PBOE1, with $|R\rangle$ above and $|L\rangle$ below. The unique optical axis distribution of PBOE2 allows for distinct phase corrections on the two rectangles, enabling the beam to propagate in parallel. As shown in Fig. 5(b), we divide the image plane into four quadrants along the white dashed lines at $x = 0$ and $y = 0$, which can intuitively characterize the full angular momentum eigenstates of switchable PBs. The right circularly polarized components $|R\rangle$ appears in the $+y$ regions and $|L\rangle$ in the $-y$, while $|R_{m>0}\rangle$ and $|L_{n<0}\rangle$ are focused on the $+x$ side, and $|R_{m<0}\rangle$ and $|L_{n>0}\rangle$ are focused on the $-x$ side. It is precisely due to the unique properties and phase distribution of PBOEs that act like a diffraction grating, effectively separating $\{|R_m\rangle, |L_n\rangle\}$ and sorting them by their signs.

As shown in Fig. 6, the experimental and simulated results of the optical conformal transformation for State A on Sphere 1 and Sphere 5 (as illustrated in Fig. 4) are presented. The image captured by CCD3 is similarly divided into four quadrants like in Fig. 5(b). By comparing the experimental results with the simulation results, two main differences can be found. First, PBs emitted from the Beam Switcher are visible at the center of the experimental images, which is because the optical elements used are all transmissive, and the conversion efficiency of the phase elements is not 100%; second, some side lobes are generated around the central components at the CCD3 plane, which is because the rectangular plane wave exhibits as an amplitude profile of a sinc function in the Fourier plane.

As shown in Fig. 6(b) and (f), the two circularly polarized components $\{|R_{-2}\rangle, |L_6\rangle\}$ of State A on Sphere 1 are located on opposite sides in the y -direction and are offset in

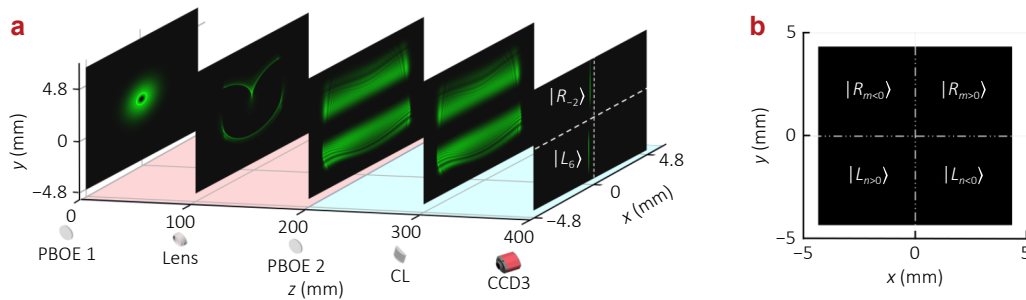


Fig. 5 | Simulation of the propagation of State A on Sphere 1. (a) The intensity profiles of PBs as it propagates through Phase transformer and Phase corrector sequentially. Pink and cyan are used on the x-z propagation plane to differentiate between the two parts. (b) The four quadrants of the image plane represent different PB eigenstates.

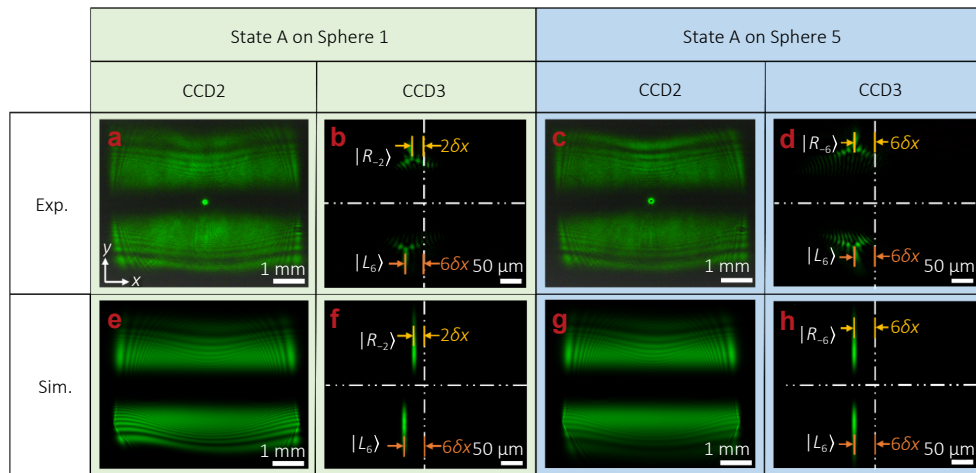


Fig. 6 | Intensity distributions of optical conformal transformation of State A on Sphere 1 (a, b, e, f) and Sphere 5 (c, d, g, h). (a–d) are the experimental results recorded by CCD2 or CCD3, while (e–h) are the corresponding simulation results.

the x-direction. In contrast, as shown in Fig. 6(d) and (h), the two circularly polarized components $\{|R_{-6}\rangle, |L_6\rangle\}$ of State A on Sphere 5 lie on a straight line in the x-direction. According to the theory of optical conformal transformation, the displacement of the focused lines in the x-direction is determined by TC. For $|R\rangle$, the sign of the displacement matches the sign of TC, while for $|L\rangle$, the sign of the displacement is opposite to that of TC. Moreover, their relationship is linear³⁵, with the spacing between adjacent TCs for both components being $\delta x = \lambda f / 2\pi a$. Calculations show that the distance in the x-direction between $\{|R_{-2}\rangle, |L_6\rangle\}$ is $\Delta = 4\delta x \approx 33.9 \mu\text{m}$, which is close to the experimentally measured distance $\Delta' = 33.6 \mu\text{m}$ in Fig. 6(b). Therefore, arbitrary PBs with unknown TCs can still be regarded as a superposition of two orthogonal circularly polarized components after undergoing geometric transformation. The designed PBOEs remain effective in separating and sorting these components according to their OAM signs. By directly identifying the mode orders m and n from the output intensity distribution, the phase TC $A = (m + n)/2$ and the polarization TC $B = (n - m)/2$ can be rapidly calculated.

By rotating QWP2 and QWP3 in Beam Switcher, States

A-H shown in Fig. 1 can be obtained on Sphere 1. Different eigenmode compositions of switchable PBs are observed in the image plane of CL. Figure 7(a–h) show experimental results, while Fig. 7(a1–h1) present simulations, both aligned with States A–H. As mentioned earlier, the latitude 2ε of PBs on the sphere determines the superposition coefficients of the orthogonal circularly polarized components at the poles. The relative intensities of the focused lines on either side of the y-axis in the image plane of CL directly reflect the relative magnitudes of the two components, i.e., their contributions to the total field of PBs. As a state approaches the north pole, the right circularly polarized component $|R\rangle$ contributes increasingly to the total field, with its proportion rising until only $|R\rangle$ remains at the pole, while the left circularly polarized component $|L\rangle$ diminishes to zero. Similarly, the opposite occurs at the south pole, where $|L\rangle$ dominates and $|R\rangle$ vanishes. Figure 7(a–d) and 7(a1–d1) correspond to States A–D on the equator of the HyPS, where both components have equal intensity. Figure 7(e) and 7(e1) represent the north pole State E, where only $|R\rangle$ exists, and $|L\rangle$ is absent. Figure 7(f) and 7(f1) correspond to the south pole State F, where only $|L\rangle$ exists, and $|R\rangle$ is absent.

Figure 7(g) and 7(g1) show State G at latitude $2\varepsilon = \pi/4$, where $|R\rangle$ has a larger proportion and higher intensity, appearing brighter. Conversely, Fig. 7(h) and 7(h1) show the inverse scenario. It can be observed that the experimental results are in good agreement with the numerical simulations. Figure 7(i) depicts the normalized intensity profiles of the orthogonal circularly polarized components $\{|R_{-2}\rangle, |L_6\rangle\}$ of State A on Sphere 1 along the horizontal cut. Here, the horizontal axis represents the detected TCs, while the vertical axis represents the normalized intensities of $|R\rangle$ (red) and $|L\rangle$ (blue) respectively. The normalized intensity is the power of the detected TC accounting for the total power of all channels in their respective eigenmodes. As mentioned above, some light will leak into adjacent regions. Therefore, the crosstalk ratio can be quantitatively defined as the proportion of optical energy leaking from the target state into adjacent detection regions. This implies that the side lobes generated by the sinc function may lead to crosstalk and overlap between neighboring TCs⁴³. However, in our work, due to the inherent properties of the PBs and the designed PBOEs, the output intensity of $|R\rangle$ appears above $x = 0$, while that of $|L\rangle$ lies below $x = 0$. This natural separation effectively avoids central intensity competition between the two modes, thus ensuring high accuracy and reliability of the detection results.

By changing the orders of VP1 and VP2 in the optical setup in Fig. 2 to 4 and 16, respectively, we can generate PBs on the HyPS with $m = -12$ and $n = 20$. Its two orthogonal circularly polarized components are $\{|R_{-12}\rangle, |L_{20}\rangle\}$. Experimental results and numerical simulations of State A on this sphere are shown in Fig. 8, where Fig. 8(a,b) and 8(e,f) are the images captured by CCD1. The white arrows at the bottom right of the images are the directions of the transmission axis of the polarizer. Fig. 8(b) and (f) display the images after passing through a polarizer in the x-direction, with the number of lobes in the images being 32. Figure 8(c) and (g) are the images captured by CCD2, compared with the unfolded PBs on the previous spheres, it can be observed

that the two rectangular beams not only have bigger left-right misalignment in the x-direction but also exhibit increased curvature due to the higher TC. Figure 8(d) and (h) are CCD3 images, in which the distances between the two circularly polarized components and the white dashed line at $x=0$ are labeled. Here, $|L_{20}\rangle$ exhibits greater x-directional displacement and deformation than $|R_{-12}\rangle$, making it more prone to crosstalk in TC channels, as evidenced by both experimental and simulated data.

Building on this, we explored the evolution of the orthogonal eigenstates during the PBs switching process. Video 1 demonstrates continuous state transformation ($E \rightarrow A \rightarrow F$) on Sphere 1 (see Visualization 1), whereas Video 2 illustrates transformation between spheres: E (Sphere 6) $\rightarrow A$ (Sphere 1) $\rightarrow F$ (Sphere 5) (see Visualization 2). The former illustrates the evolution of different states on the same sphere, while the latter describes the evolution of different states across different spheres. The switching of PBs is not only reflected in the central dark spot of the CCD1 images but also can be observed through the relative positions and intensities of the dual rectangular beams or eigenmode composition. We believe that the discrepancies between the experimental results and numerical simulations are primarily due to imperfections in the fabrication of our PBOEs and the optical misalignment introduced during the modulation process of the whole system, which lead to incomplete phase transformation and correction. Nevertheless, we can still detect the prominent central components of the two orthogonal eigenstates in the image plane. Compared with the widely used interferometry for detecting the phase TC or Stokes parameter analysis for detecting the polarization TC, our proposed system requires neither a stable reference beam nor frequent adjustments of optical components, making it simpler for the dynamic detection of both phase and polarization TCs in a single measurement. Furthermore, in practical applications, CCD1 and CCD2 can be omitted, and CCD3 is needed to accomplish single-shot measurement of the PBs. In addition, CCD3 can also be replaced by a 1D line-scan CMOS sensor. This hardware simplification

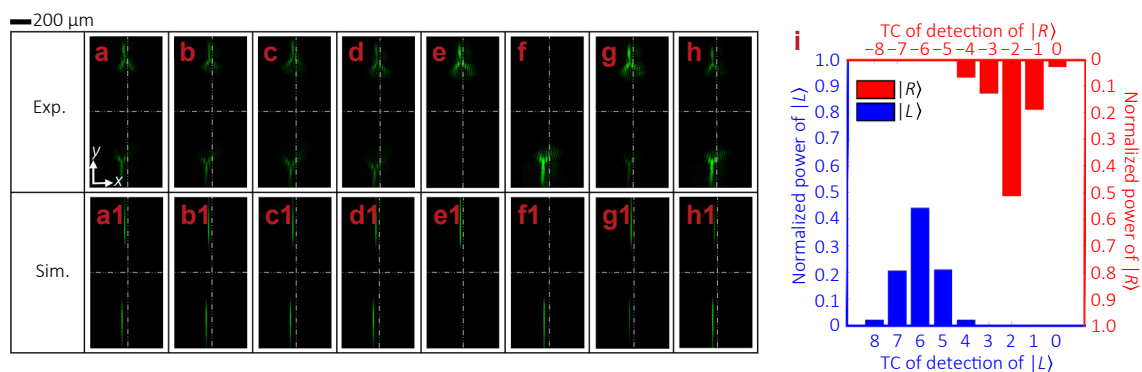


Fig. 7 | Intensity profiles of the components of States A-H on Sphere 1. (a-h) are the experimental records, while (a1-h1) are the corresponding simulation results. (i) normalized intensity profiles along a horizontal cut of $|R\rangle$ (red) and $|L\rangle$ (blue) of State A on Sphere 1.

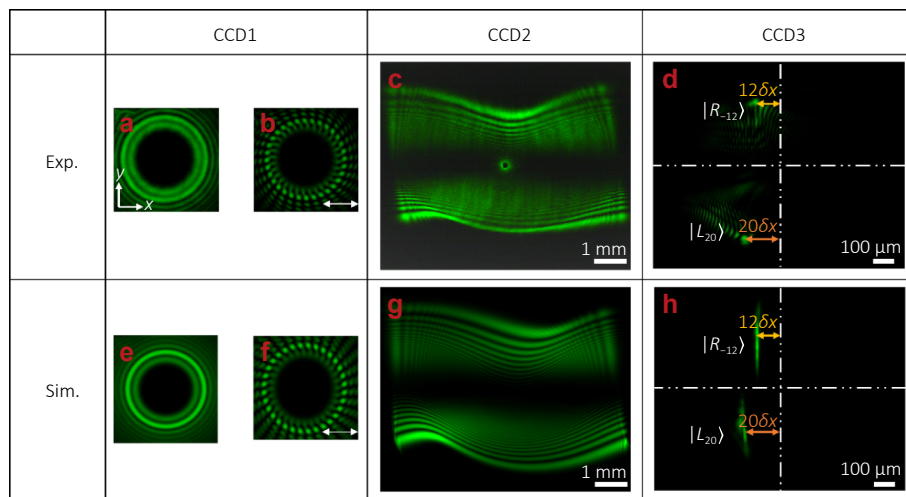


Fig. 8 | Intensity distributions over the entire light path of State A on HyPS with $m = -12$ and $n = 20$. (a)–(d) are the experimental records, while (e)–(h) are the corresponding simulation results.

drastically reduces both the overall cost and the system footprint, while effectively enabling real-time, high-speed decoding.

4 Conclusions

In this paper, we propose and experimentally demonstrate a system based on the optical conformal transform, which can not only detect the phase and polarization TC of PBs, but also be used to characterize eigenmode decomposition for switchable PBs with different TCs. By engineering the geometric phase through a pair of PBOEs, our system implements a polarization-selective mapping that unfolds the helical phase gradients of orthogonal eigenstates into spatially separated, linear coordinates. This approach overcomes the limitations of traditional methods by eliminating the need for iterative measurements, thereby allowing for the dynamic resolution of both isolated and coupled TCs. The experimental results, covering dynamic switching across various HyPSs, confirm that the system can intuitively visualize the eigenmode composition and evolution of complex vector beams. Even under the influence of turbulence or disturbances, the structured vector field is transformed through conformal mapping, which reduces it to a simple one-dimensional displacement. A single peak under crosstalk can still be easily detected. This greatly facilitates subsequent mode recognition and error compensation through integration with machine learning or detector arrays. Consequently, this technique serves not only as a robust characterization tool for researching vector field singularities but also as a high-speed decoder for switchable optical signals. We anticipate that this capability for instantaneous characterization will play a pivotal role in advancing technologies dependent on real-time mode analysis, including optical communications, high-dimensional quantum key distribution, and optical information security.

5 Experimental section

The light source is a continuous-wave solid-state laser (MW-GL-532) operating at a wavelength of $\lambda = 532$ nm. The intensity distributions at different propagation planes are captured by three identical Charge-Coupled Device cameras (Thorlabs DCC1240c). A pair of Pancharatnam-Berry optical elements are fabricated using the photo-alignment liquid-crystal in a thin film with a total pixel count of 1920×1920 and an individual pixel size of $5 \mu\text{m}$. The optical components such as the vortex plate (VPm-532), the quarter wave plate (QWP10-532B) and the beam splitter (MBS1455-A) were manufactured by LBTEK.

References

- Beth RA. Mechanical detection and measurement of the angular momentum of light. *Phys Rev* **50**, 115–125 (1936).
- Allen L, Beijersbergen MW, Spreeuw RJC et al. Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes. *Phys Rev A* **45**, 8185–8189 (1992).
- Chen RS, Wang JH, Zhang XQ et al. Fiber-based mode converter for generating optical vortex beams. *Opto-Electron Adv* **1**, 180003 (2018).
- Padgett MJ. Orbital angular momentum 25 years on [Invited]. *Opt Express* **25**, 11265–11274 (2017).
- Shen YJ, Wang XJ, Xie ZW et al. Optical vortices 30 years on: OAM manipulation from topological charge to multiple singularities. *Light Sci Appl* **8**, 90 (2019).
- Zhang Z, Li GY, Liu YL et al. Robust measurement of orbital angular momentum of a partially coherent vortex beam under amplitude and phase perturbations. *Opto-Electron Sci* **3**, 240001 (2024).
- Hao X, Kuang CF, Wang TT et al. Effects of polarization on the de-excitation dark focal spot in STED microscopy. *J Opt* **12**, 115707 (2010).
- Chen R, Agarwal K, Sheppard CJR et al. Imaging using cylindrical vector beams in a high-numerical-aperture microscopy system. *Opt Lett* **38**, 3111–3114 (2013).
- Parigi V, D'Ambrosio V, Arnold C et al. Storage and retrieval of vector beams of light in a multiple-degree-of-freedom quantum memory. *Nat Commun* **6**, 7706 (2015).

10. Ndagano B, Perez-Garcia B, Roux FS et al. Characterizing quantum channels with non-separable states of classical light. *Nat Phys* **13**, 397–402 (2017).
11. Liu J, Li SM, Zhu L et al. Direct fiber vector eigenmode multiplexing transmission seeded by integrated optical vortex emitters. *Light Sci Appl* **7**, 17148 (2018).
12. Willner AE. Vector-mode multiplexing brings an additional approach for capacity growth in optical fibers. *Light Sci Appl* **7**, 18002 (2018).
13. Yao JN, Li XL, Jiang XH et al. Switchable generation and dynamic evolution of vector vortex beams. *Opt Express* **32**, 39570–39578 (2024).
14. Milione G, Sztul HI, Nolan DA et al. Higher-order Poincaré sphere, Stokes parameters, and the angular momentum of light. *Phys Rev Lett* **107**, 053601 (2011).
15. Milione G, Evans S, Nolan DA et al. Higher order Pancharatnam-Berry phase and the angular momentum of light. *Phys Rev Lett* **108**, 190401 (2012).
16. Yi XN, Liu YC, Ling XH et al. Hybrid-order Poincaré sphere. *Phys Rev A* **91**, 023801 (2015).
17. Liu ZX, Liu YY, Ke YG et al. Generation of arbitrary vector vortex beams on hybrid-order Poincaré sphere. *Photonics Res* **5**, 15–21 (2017).
18. Liu S, Qi SX, Zhang Y et al. Highly efficient generation of arbitrary vector beams with tunable polarization, phase, and amplitude. *Photonics Res* **6**, 228–233 (2018).
19. Lou SZ, Zhou YQ, Yuan YD et al. Generation of arbitrary vector vortex beams on hybrid-order Poincaré sphere based on liquid crystal device. *Opt Express* **27**, 8596–8604 (2019).
20. Arora G, Ruchi, Senthilkumaran P. Hybrid order Poincaré spheres for Stokes singularities. *Opt Lett* **45**, 5136–5139 (2020).
21. Fu SY, Zhai YW, Zhang JQ et al. Universal orbital angular momentum spectrum analyzer for beams. *Photonix* **1**, 19 (2020).
22. Yao JN, Wu SM, Li XL et al. Generation of arbitrary vector vortex beam using a single Q-plate. *Laser Photonics Rev* **19**, 2402290 (2025).
23. Zheng SQ, Zeng XK, Shangguan HC et al. Improve polarization topological order sorting with the diffractive splitting method. *Opt Lett* **44**, 795–798 (2019).
24. Sakamoto M, Kaneko Y, Kakedo Y et al. Hybrid polarization grating for mode detection of vector beams. *Opt Express* **29**, 27071–27083 (2021).
25. Yao JN, Jiang XH, Li XL et al. Cascaded mode converter for generating high-order Poincaré sphere beams of multiple different orders. *Appl Phys Lett* **122**, 181103 (2023).
26. Pal SK, Rusch LA. Tailoring focal plane component intensities of polarization singular fields in a tight focusing system. *Sci Rep* **14**, 13565 (2024).
27. Yang H, Ou K, Liu Q et al. Metasurface higher-order Poincaré sphere polarization detection clock. *Light Sci Appl* **14**, 63 (2025).
28. Pu MB, Li X, Ma XL et al. Catenary optics for achromatic generation of perfect optical angular momentum. *Sci Adv* **1**, e1500396 (2015).
29. Nan T, Zhao H, Guo JY et al. Generation of structured light beams with polarization variation along arbitrary spatial trajectories using tri-layer metasurfaces. *Opto-Electron Sci* **3**, 230052 (2024).
30. Liu XJ, Gu MN, Tian Y et al. Research progress on generating perfect vortex beams based on metasurfaces. *Opto-Electron Sci* **4**, 250007 (2025).
31. Guo YH, Zhang SC, Pu MB et al. Spin-decoupled metasurface for simultaneous detection of spin and orbital angular momenta via momentum transformation. *Light Sci Appl* **10**, 63 (2021).
32. Li XY, Chen C, Guo YH et al. Monolithic spiral metalens for ultra-high-capacity and single-shot sorting of full angular momentum state. *Adv Funct Mater* **34**, 2311286 (2024).
33. Singh K, Dudley A. Digital toolbox for vector field characterization. *Nanophotonics* **11**, 753–761 (2022).
34. Yao JN, Jiang XH, Zhang JL et al. Quantitative detection of high-order Poincaré sphere beams and their polarization evolution. *Opt Express* **31**, 3017–3027 (2023).
35. Berkhout GCG, Lavery MPJ, Courtial J et al. Efficient sorting of orbital angular momentum states of light. *Phys Rev Lett* **105**, 153601 (2010).
36. Mirhosseini M, Malik M, Shi ZM et al. Efficient separation of the orbital angular momentum eigenstates of light. *Nat Commun* **4**, 2781 (2013).
37. Grillo V, Tavabi AH, Venturi F et al. Measuring the orbital angular momentum spectrum of an electron beam. *Nat Commun* **8**, 15536 (2017).
38. Fang JC, Xie ZW, Lei T et al. Spin-dependent optical geometric transformation for cylindrical vector beam multiplexing communication. *ACS Photonics* **5**, 3478–3484 (2018).
39. Wang J, Zeng QJ, Wu HS et al. Mode multiplication of cylindrical vector beam using raytracing control. *Chin Phys Lett* **41**, 094202 (2024).
40. Hossack WJ, Darling AM, Dahdouh A. Coordinate transformations with multiple computer-generated optical elements. *J Mod Opt* **34**, 1235–1250 (1987).
41. Ruffato G, Rotunno E, Giberti LMC et al. Arbitrary conformal transformations of wave functions. *Phys Rev Appl* **15**, 054028 (2021).
42. Lavery MPJ, Robertson DJ, Sponselli A et al. Efficient measurement of an optical orbital-angular-momentum spectrum comprising more than 50 states. *New J Phys* **15**, 013024 (2013).
43. Zheng SQ, Li Y, Lin QG et al. Experimental realization to efficiently sort vector beams by polarization topological charge via Pancharatnam-Berry phase modulation. *Photonics Res* **6**, 385–389 (2018).

Acknowledgements

We appreciate the financial support from the National Natural Science Foundation of China (62375251) and National Key Research and Development Program of China (2020YFB2205802).

Author contributions

Xiangle Li: Methodology, Validation, Writing – original draft, Writing – review & editing. Junna Yao: Investigation, Methodology. Shumei Wu: Investigation, Methodology. Qiwen Zhan: Methodology, Supervision, Writing – review & editing. Anting Wang: Funding acquisition; Methodology, Project administration, Supervision, Writing – review & editing (equal).

Competing interests

The authors declare no competing financial interests.

Supplementary information

The supplementary material includes two videos, which demonstrate the evolution of the orthogonal eigenstates during the PBs switching process.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons

license, and indicate if changes were made. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/> ©The Author(s) 2026.