



OPEN A simple pathway for complete polarization vision

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This paper introduces a novel method for achieving complete polarization vision through a full-Stokes polarization camera. Our technique employs a homogeneous dispersive retarder placed before a polarization sensor to harness wavelength-dependent retardation, enabling the differentiation of polarization states across the sensor's color channels. Assuming weak wavelength dependence of polarization for incoming light, this method facilitates the real-time, simultaneous measurement of the complete Stokes vector of incident light. This method provides a streamlined, versatile, and practical solution with broad potential applications in imaging, remote sensing, and augmented reality.

Keywords Polarization, Stokes vector, Circular polarization, Vision

The human visual system is attuned to the intensity and wavelength of visible light but largely indifferent to its polarization. While the manipulation and understanding of polarization were achieved more than two centuries ago, realizing simple and effective methods for complete polarization vision has remained a formidable challenge. Although polarized light is ubiquitous in nature, with numerous studies demonstrating varying degrees of sensitivity to polarization in the vision of many species, the ability to perceive circular polarization remains a notable exception, with only a few selected species, such as certain stomatopod crustaceans, possessing this capability^{1–3}.

In parallel with advances in microfabrication techniques, good-quality polarization camera systems have emerged, facilitating the detection of linear polarization properties such as the degree of linear polarization and its angle of polarization^{4,5}. However, existing systems typically fall short of providing comprehensive information regarding the ellipticity and handedness of incoming light. Current approaches aimed at simultaneously imaging the full Stokes vector using cameras often rely on complex and costly setups involving multiple polarization elements and detectors^{6–9}. Two primary methodologies have been established: the Division of Amplitude (DoA) and the Division of Focal Plane (DoFP). The DoA imaging approach entails the utilization of multiple cameras, each equipped with its own polarization element, to partition incident light into distinct channels using beam splitters. When employing polarization cameras as detectors, at least two cameras, one of which is furnished with a retarder, are requisite to capture the necessary polarization states^{10,11}. Despite its prevalence in the literature, this method necessitates the synchronization of more than one sensor to acquire comprehensive polarization information concurrently, thereby imposing inherent limitations^{6,12,13}.

Commercially available polarization sensors use the DoFP strategy, distributing incident light across an array of polarizers in the sensor's focal plane. However, existing commercial sensors are incapable of measuring the complete Stokes vector. Two proposed methodologies seek to address this shortfall: by utilization of microretarder arrays, which involves the fabrication of a layer comprising microretarders placed atop a polarizer array to enable the measurement of all four Stokes parameters^{14,15}. However, the fabrication of microretarder arrays, typically composed of birefringent reactive mesogens or liquid crystal polymers, is intricate and costly¹⁶. Moreover, precise alignment with the camera's photodiodes is imperative to minimize pixel crosstalk, presenting additional challenges. Polarization arrays based on metasurfaces offer an alternative approach by employing metasurfaces sensitive to polarization to direct light to different pixels on an image sensor according to various polarization bases^{17–20}. Nevertheless, the fabrication of metasurfaces is still challenging and expensive, and certain metamaterials can present large inherent losses that significantly impact detection signal-to-noise ratios.

This study presents a straightforward approach that unlocks complete polarization vision capabilities, extends beyond linear polarization, and is readily applicable to existing commercial technologies. The core of this strategy lies in incorporating a homogeneous dispersive retarder (waveplate) before a polarization sensor. This retarder introduces a wavelength-dependent retardance, or phase delay, between orthogonal linear polarization components, denoted as $\delta(\lambda)$. Here, “homogeneous” indicates a uniform distribution of retardance across the retarder's surface, while “dispersive” refers to the retardance varying with wavelength. This novel

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configuration enables the sensor's color channels to effectively discern distinct polarization states. This is based on the assumption that measured polarization states exhibit weak variation within the detection wavelengths. Consequently, the methodology facilitates the comprehensive measurement of the entire Stokes vector of incident polarized light. Essentially, this approach synthesizes principles from the DoFP method plane method with the color sensitivity already available in camera sensors.

Method

To elucidate the principles underlying our complete polarization vision method, we begin by establishing the mathematical framework. Consider incident polarized light with Stokes parameters S_0, S_1, S_2 , and S_3 where S_0 represents the total intensity of the light, S_1, S_2 are, respectively, the projection of linear polarization along the horizontal and 45° axes and S_3 represents the circular polarization component. A complete reconstruction of the Stokes vector requires a minimum of four measurements, using a technique commonly known as Stokes polarimetry. Its basic principle is to project the unknown polarized light onto different known analyzing polarization states and the resulting intensity can be used to calculate the Stokes vector.

The most common structure of a Stokes polarimeter consists of a fixed linear polarizer and a rotating linear retarder²¹. This time-modulated configuration is described using the Stokes-Mueller matrix formalism as follows:

$$S_{out} = M_P M_C S_{in}, \quad (1)$$

where S_{in} and S_{out} represent the Stokes vector of incident light and outgoing light, respectively. M_P represents the Mueller matrix of a polarizer, M_C is a linear retarder (sometimes also known as compensator) with a time varying azimuth angle as described in²². In this type of Stokes polarimeter, M_C dynamically changes with time, causing the measured intensity (the first element of S_{out}) also change, $I(t)$. These varying intensities can be assembled into a vector:

$$I = \begin{bmatrix} I(t_1) \\ I(t_2) \\ \vdots \\ I(t_n) \end{bmatrix} = W S_{in} \quad (2)$$

where W is a matrix consisting of the first row of $M_P M_C$ and describes the polarization states that are analyzed during measurement. When the magnitude of retardation is optimal, the projection of the polarization state of W matrix draws a curved "8" on the Poincaré sphere and if four polarization states are used for measurement can form a tetrahedron in Fig. 1(a)²¹. S_{in} can be extracted by inverting or pseudoinverting the W matrix.

$$S_{in} = W^+ I \quad (3)$$

The metric used to quantify the effectiveness of polarimetric data reduction is the condition number:

$$\kappa_2(W) = \|W\|_2 \cdot \|W^+\|_2, \quad (4)$$

where $\|W\|_2$ is the 2-norm of the matrix W and $\|W^+\|_2$ is the 2-norm of the inverted or pseudoinverted W .

Although time-modulated Stokes polarimeters have been largely popular, they result in a temporal sequence impractical for real-time imaging measurements. Commercially available polarization cameras use the DoFP strategy. They are capable of providing simultaneously the intensities of polarized light in four polarization directions $0^\circ, 90^\circ, 45^\circ, 135^\circ$ integrated into the sensor. These states of polarization respectively are $(1, 1, 0, 0)^T$, $(1, -1, 0, 0)^T$, $(1, 0, 1, 0)^T$, and $(1, 0, -1, 0)^T$ and they lie in the equatorial plane of the Poincaré sphere, as shown in Fig. 1(b). The W matrix formed by these states is

$$I = \begin{bmatrix} I_{0^\circ} \\ I_{90^\circ} \\ I_{45^\circ} \\ I_{135^\circ} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (5)$$

This form of W is not invertible, as the four states analyzed do not encompass any volume. Consequently, such cameras can provide the first three Stokes parameters related to linear polarization, but not the last parameter related to circular polarization.

Placing a static linear retarder before the micropolarizer array can rotate the four analyzed polarization states and can make the polarization camera sensitive to circular polarization. This case gives the following relation

$$I = \begin{bmatrix} I_{0^\circ} \\ I_{90^\circ} \\ I_{45^\circ} \\ I_{135^\circ} \end{bmatrix} = \begin{bmatrix} 1 & C_{2\theta}^2 + S_{2\theta}^2 C_\delta & C_{2\theta} S_{2\theta} (1 - C_\delta) & S_{2\theta} S_\delta \\ 1 & -C_{2\theta}^2 - S_{2\theta}^2 C_\delta & -C_{2\theta} S_{2\theta} (1 - C_\delta) & -S_{2\theta} S_\delta \\ 1 & C_{2\theta} S_{2\theta} (1 - C_\delta) & S_{2\theta}^2 + C_{2\theta}^2 C_\delta & -C_{2\theta} S_\delta \\ 1 & -C_{2\theta} S_{2\theta} (1 - C_\delta) & -S_{2\theta}^2 - C_{2\theta}^2 C_\delta & C_{2\theta} S_\delta \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (6)$$

where we have employed the short notation $S_X \equiv \sin(X)$ and $C_X \equiv \cos(X)$. θ is the azimuth angle and δ is the retardation of the retarder. This W is generated from the first row of the matrix multiplication $M_P M_C$, where M_P and M_C are respectively the Mueller matrices of the polarizers integrated into the micropolarizer array and the linear retarder placed on top of the sensor. In this case, W remains non-invertible since the four

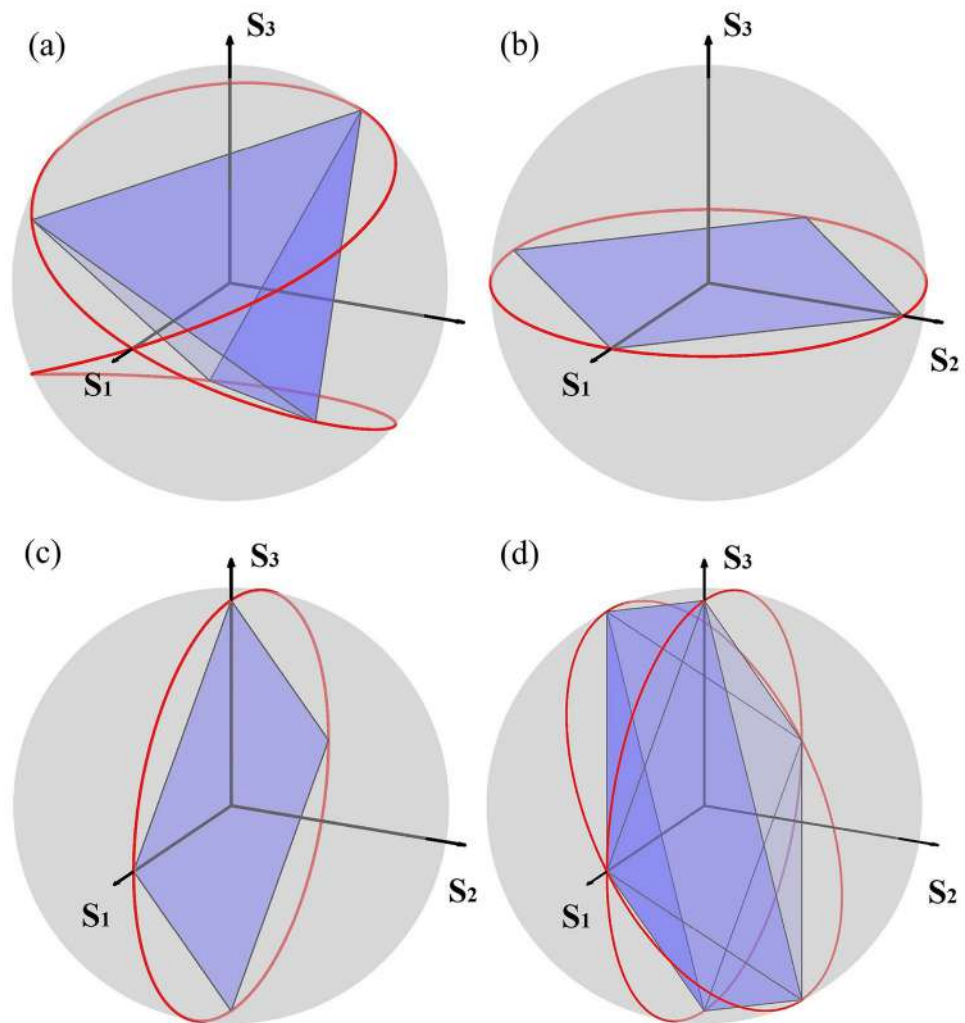


Fig. 1. Representation of accessible polarization states on the Poincaré sphere corresponding to different configurations used in Stokes polarimetry: **(a)** Time-modulation with a rotating $\sim 132^\circ$ linear retarder, the four chosen polarization states can form a tetrahedron; **(b)** Standard polarization camera, the four polarization states form a square centered in the equator of the sphere; **(c)** Polarization camera with a quarter-wave linear retarder, the plane including the polarization states is rotated 90° along the S_1 axis; **(d)** Polarization camera using two color channels in combination with a dispersive linear retarder providing $\Delta\delta \simeq 30^\circ$, an octahedron enclosing a certain volume is generated.

analyzed states will still lie in a plane (this is illustrated in Fig. 1(c)). Therefore, this configuration can neither extract the full Stokes vector.

The approach proposed in this work takes advantage of a color polarization camera with multiple wavelength channels. We employ a fixed linear retarder, using the natural wavelength-dependent dispersion of retardance found in all crystals or transparent polymers ($\delta = 2\pi\Delta n/\lambda$). The dispersive linear retarder facilitates the differentiation of polarization states across the sensor's color channels. As incident light traverses the dispersive retarder, the sensor's color channels discern polarization states with varying retardations (i.e. varying amounts of rotation in the Poincaré sphere), which makes that the retardance values for the wavelengths of interest, denoted as λ_1 and λ_2 , differ [$\delta(\lambda_1) \neq \delta(\lambda_2)$]. As a result, as light passes through this retarder, different wavelengths or color channels undergo varying phase retardances. If the polarization of the incoming light does not change substantially within the considered wavelengths, this method enables the simultaneous measurement of all Stokes parameters.

Considering two wavelengths (identified as 1 and 2) corresponding to two color channels of a polarization camera using a dispersive retarder on top of the array of four micro-polarizers, Eq. (6) can be rewritten as

$$I = \begin{bmatrix} I_{0^\circ}^1 \\ I_{90^\circ}^1 \\ I_{45^\circ}^1 \\ I_{135^\circ}^1 \\ I_{0^\circ}^2 \\ I_{90^\circ}^2 \\ I_{45^\circ}^2 \\ I_{135^\circ}^2 \end{bmatrix} = \begin{bmatrix} 1 & C_{2\theta}^2 + S_{2\theta}^2 C_{\delta_1} & C_{2\theta} S_{2\theta} (1 - C_{\delta_1}) & S_{2\theta} S_{\delta_1} \\ 1 & -C_{2\theta}^2 - S_{2\theta}^2 C_{\delta_1} & -C_{2\theta} S_{2\theta} (1 - C_{\delta_1}) & -S_{2\theta} S_{\delta_1} \\ 1 & C_{2\theta} S_{2\theta} (1 - C_{\delta_1}) & S_{2\theta}^2 + C_{2\theta}^2 C_{\delta_1} & -C_{2\theta} S_{\delta_1} \\ 1 & -C_{2\theta} S_{2\theta} (1 - C_{\delta_1}) & -S_{2\theta}^2 - C_{2\theta}^2 C_{\delta_1} & C_{2\theta} S_{\delta_1} \\ 1 & C_{2\theta}^2 + S_{2\theta}^2 C_{\delta_2} & C_{2\theta} S_{2\theta} (1 - C_{\delta_2}) & S_{2\theta} S_{\delta_2} \\ 1 & -C_{2\theta}^2 - S_{2\theta}^2 C_{\delta_2} & -C_{2\theta} S_{2\theta} (1 - C_{\delta_2}) & -S_{2\theta} S_{\delta_2} \\ 1 & C_{2\theta} S_{2\theta} (1 - C_{\delta_2}) & S_{2\theta}^2 + C_{2\theta}^2 C_{\delta_2} & -C_{2\theta} S_{\delta_2} \\ 1 & -C_{2\theta} S_{2\theta} (1 - C_{\delta_2}) & -S_{2\theta}^2 - C_{2\theta}^2 C_{\delta_2} & C_{2\theta} S_{\delta_2} \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (7)$$

where I^1 and I^2 are the intensities at two different color channels in which the dispersive linear retarder respectively has δ_1 and δ_2 retardances. θ is the azimuth angle of the linear retarder, which is the same for both colors. In principle, the optimal configuration (lowest condition number in Eq. (4)) is achieved when the difference between the two retardances $\Delta\delta = |\delta_1 - \delta_2|$ is 90° because it maximizes the determinant of the W matrix so that the analyzing states on the Poincaré sphere would form a regular octahedron (when the fast axis of the retarder coincides with one of the directions in the polarizer array). Other values of $\Delta\delta$ will result in a non-regular octahedron, as shown in Fig. 1(d), but will still be sufficient for calculating the full Stokes vector.

Instrumentation and calibration

A waveplate (sapphire crystal plate with R-plane cut and with an approximate thickness of $170 \mu\text{m}$) is positioned in front of the color polarization sensor, as illustrated in Fig. 2(a). The fast axis or azimuth θ of the waveplate can be oriented randomly since its orientation can be determined through calibration and the condition number of the system (the metric used to quantify the effectiveness of polarimetric data reduction) does not depend on this angle. The waveplate must have uniform thickness to ensure constant retardation values across the entire camera sensor. Thus, a single retardance and an azimuth angle can represent the waveplate utilized here. For simplicity, we aligned the waveplate's fast axis roughly parallel to the edge of the photodetector, so approximately parallel to one of the polarizers in the array. After collection by the imaging lens, light passes through the waveplate, which introduces varying retardance across different color channels. The light then sequentially passes through the polarizer array and color channels before being collected by the photodiode, as shown in Fig. 2(b). Before mounting the waveplate onto the camera, it was spectroscopically characterized using a homemade Mueller matrix ellipsometer in transmission²³ (black line in Fig. 2(c)).

A commercial polarized color camera (FLIR Blackfly S) with the Sony IMX250MYR polarized sensor was employed (Fig. 2(d)). It features a resolution of 2448×2048 pixels with 8-bit depth for each image color channel.

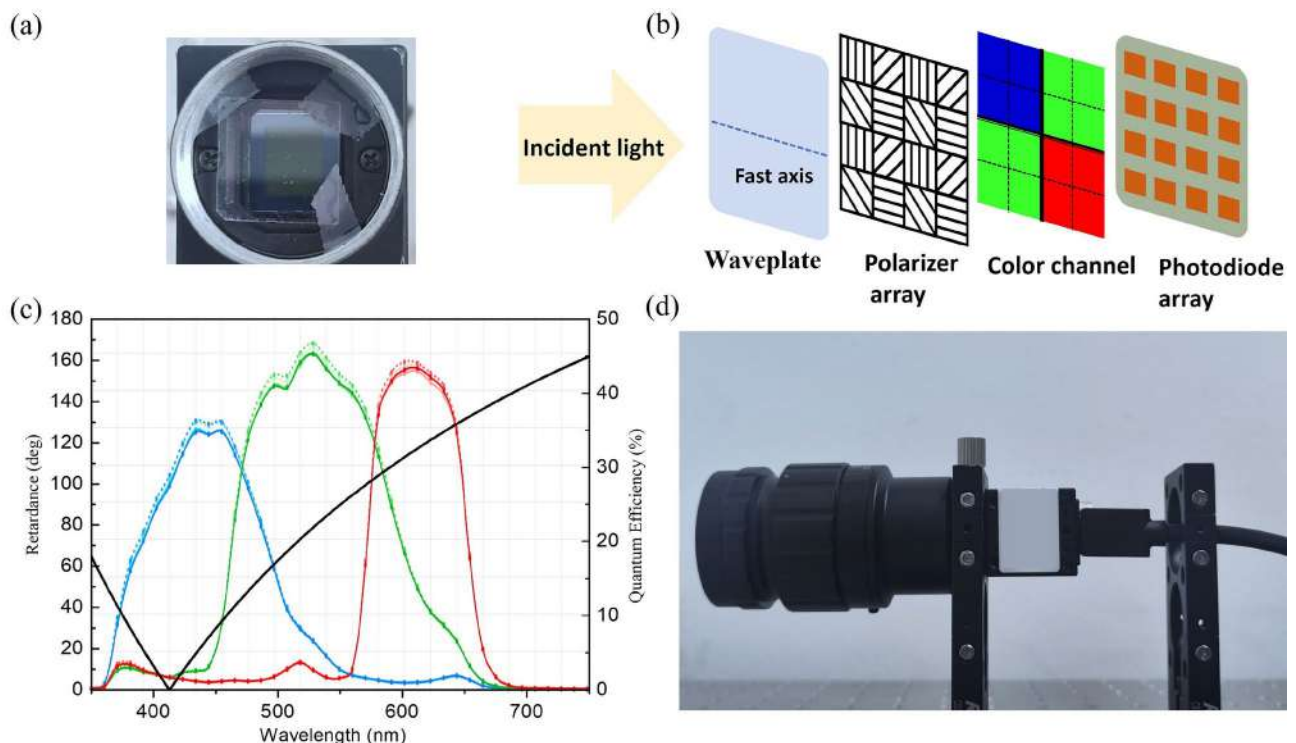


Fig. 2. Complete polarization vision configuration: (a) A linear retarder is placed in front of the color polarization camera sensor; (b) Light passes through the waveplate, polarizer array, and color channels in sequence; (c) Retardance of the waveplate and quantum efficiency of the color polarization camera sensor for different color channels; (d) Photo of the full-Stokes polarization camera setup with objective lens.

The sensor includes an RGB Bayer (red, green, and blue colors) filter that creates distinct color channels. This configuration allows each pixel to capture both the color (or wavelength) and the polarization state of the incoming light. The raw color and polarization data (without implementation of any demosaicing algorithm) are used for the Stokes parameter calculation, resulting in a final effective image resolution of 612×512 pixels for each Stokes parameter. Higher-resolution images could be obtained using advanced demosaicing algorithms described for color polarization cameras^{24,25}.

In a Bayer color sensor, the green channel filters light with wavelengths between ~ 470 nm and 650 nm, while the red channel filters light between ~ 570 nm and 660 nm, as shown in Fig. 2(c), where the measured wavelength-dependent retardance of the waveplate is also presented. Due to the relatively broad nature of the RGB Bayer filters, there is some dispersion of the retardance within each color filter, causing the “effective” retardance to be an ensemble average. This effect can be understood as a depolarizing retarder where the magnitude of retardation varies within the detected wavelength while its orientation remains constant. The Mueller matrix of this dispersive retarder is

$$\overline{M}(\lambda) = \int w(\lambda) M_C(\delta_\lambda) d\lambda \quad (8)$$

where $w(\lambda)$ is the spectral bandwidth function normalized as $\int w(\lambda) d\lambda = 1$ and δ_λ is the wavelength-dependent retardation. The effective Mueller matrix of such depolarizing linear retarder, $M_{\text{dep}}(\delta_\lambda)$, when horizontally oriented is²⁶:

$$M_{\text{dep}}(\delta_\lambda) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & p \cos \delta_\lambda & -p \sin \delta_\lambda \\ 0 & 0 & p \sin \delta_\lambda & p \cos \delta_\lambda \end{bmatrix} \quad (9)$$

where p accounts for the depolarization effect caused by the spectral bandwidth of the color filters. This parameter can vary from 0 (fully depolarizing) to 1 (non-depolarizing). A simple model for p can be obtained with the following parameterization:

$$p = 1 - \frac{\Delta\delta\Delta\lambda_h}{2\pi\Delta\lambda_c}, \quad (10)$$

where $\Delta\delta$ represents the difference in retardance (or phase delay) between the two color channels that participate in the measurement ($\Delta\delta = |\delta_1 - \delta_2|$), and $\Delta\lambda_h$ is the bandwidth at half peak for each color channel. $\Delta\lambda_c$ is the separation between the mean wavelength of both colors. The value of $\Delta\delta$ and the ratio of $\Delta\lambda_h$ to $\Delta\lambda_c$ determine the robustness of the Stokes vector calculation. Assuming an ideal case where the bandwidth of the color channels is zero ($\Delta\lambda_h = 0$ ($p = 1$)), the condition number of the W matrix as a function of the phase delay is shown in Fig. 3 (red line). In this case, the optimal (in the sense of lowest condition number) phase delay, $\Delta\delta$, is found at 90° . In our system, however, $\Delta\lambda_h$ is ~ 130 nm for the green channel, and ~ 80 nm for the red channel. The condition number of the W matrix for this case is shown in Fig. 3 (blue line), revealing that the optimal $\Delta\delta$ shifts to $\sim 76^\circ$. As expected, this case has a condition number larger than the case with zero bandwidth. Additionally, if the bandwidth of the two color channels increases to approximately 240 nm, the optimal $\Delta\delta$ will decrease even further, as shown in Fig. 3 (yellow line).

Once p is taken into account, and if assuming for simplicity that $\theta = 0$, Eq. 7 should be modified as:

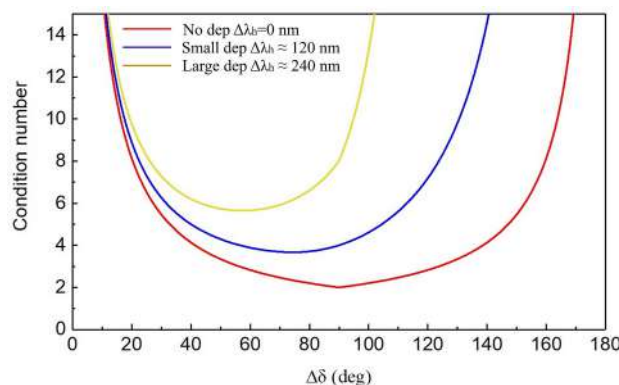


Fig. 3. Condition number of the W matrix as a function of the difference in retardance between two channels ($\Delta\delta$) when considering a depolarizing retarder according to Eqs. (9) and (10).

$$\begin{bmatrix} I_{0^\circ}^1 \\ I_{90^\circ}^1 \\ I_{45^\circ}^1 \\ I_{135^\circ}^1 \\ I_{0^\circ}^2 \\ I_{90^\circ}^2 \\ I_{45^\circ}^2 \\ I_{135^\circ}^2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 1 & 0 & p_1 C_{\delta_1} & -p_1 S_{\delta_1} \\ 1 & 0 & -p_1 C_{\delta_1} & p_1 S_{\delta_1} \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 1 & 0 & p_2 C_{\delta_2} & -p_2 S_{\delta_2} \\ 1 & 0 & -p_2 C_{\delta_2} & p_2 S_{\delta_2} \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (11)$$

Any two or more color channels can be used to calculate the full Stokes vector. In our design, the full Stokes vector camera utilizes the green and red channels, while the blue channel is only used in our software to generate a color image of S_0 . Five key parameters need to be calibrated: two retardances, δ_1 and δ_2 , two depolarization parameters, p_1 and p_2 , corresponding to the red and green channels, respectively, and the azimuth angle θ . The calibration method involves determining these parameters using light with a known polarization and a non-linear least-squares fitting procedure is implemented. Specifically, we collect intensity data from linearly polarized light at two different azimuths, as well as from left and right circularly polarized light. Achromatic optical elements are used to generate these calibration beams. For linearly polarized light, we apply the constraints $S_1^2 + S_2^2 = 1$ and $S_3 = 0$, while for circularly polarized light, the constraints are $S_1 = S_2 = 0$ and $S_3 = \pm 1$. Note that it is impossible to fully calibrate the five parameters using only linearly or only circularly polarized light, as δ_1 , p_1 , δ_2 , and p_2 only appear in the second and third columns of Eq. 11, making them independent of each other when using only one type of polarized light.

The homogeneous sapphire waveplate, spanning over the entire sensor, allows the calibration process to average all pixels of the same type across the polarization image, rather than performing a pixel-by-pixel calibration. After calibration, δ_1 and δ_2 are determined to be $90.3 \pm 0.2^\circ$ and $120.6 \pm 0.2^\circ$, respectively, and p_1 and p_2 are determined to be 0.91 ± 0.01 and 0.88 ± 0.01 , respectively. Additionally, the orientation angle of the retarder is calibrated to $\theta = 2.5 \pm 0.3^\circ$. These parameters are then applied to the incoming intensities of all pixels for the calculation in real time of the complete Stokes vector.

The phase delay $\Delta\delta$ between red and green channels in our system is approximately 30° , which is significantly less than the optimal value of 90° that we have previously indicated for optimal polarimetric conditioning of the system. Due to the broadband nature of the Bayer color filters, an increased phase delay between different color channels inevitably reduces the p values. Therefore, a compromise between phase delay and bandwidth of color channels is necessary as it was suggested by Fig. 3. While a phase delay closer to 90° would ideally enhance the system's polarimetric performance, it must be weighed against the resulting decrease in p , which can diminish the overall reliability of the polarization measurements. For an RGB-based system such as the one presented here, we estimate from Eq. (10) that optimal performance would be expected for $\Delta\delta \sim 70^\circ$. Nevertheless, our experimental configuration still ensures sufficiently robust conditioning.

Complete polarization vision

Our full-Stokes camera enables real-time complete polarization vision across a wide range of scenarios. It does not add bulk or increase power requirements compared to a standard camera, making it easily compatible with both in-lab and outdoor environments. Some illustrative experiments are provided in this section to demonstrate its capabilities.

A real-time measurement of the complete polarization image of various optical components is shown in Fig. 4 (multimedia available online). On the right side of the image, two perpendicular static linear polarizer polymer films (Edmund, XP42) generate horizontally and vertically polarized light, corresponding to polarization states $(1, 1, 0, 0)$ and $(1, -1, 0, 0)$, respectively. On the left side, a continuously rotating achromatic quarter-waveplate, preceded by a linear polarizer, dynamically alters the polarization state. An electronic watch with a liquid crystal display is included in the setup to provide a time reference. As time progresses, the continuously rotating quarter-waveplate modulates different states of polarized light, causing the S_3 parameter to continuously vary from 1 to -1 . To reduce random noise during the measurement process, the intensities used to calculate the Stokes vector are obtained by averaging three consecutive raw frames. While increasing the number of averaged frames can further suppress random noise, it comes at the cost of reducing the effective frame rate of the full-Stokes measurements. In this work, the camera used has a maximum frame rate of 75 frames per second. By averaging three consecutive frames, the frame rate for the Stokes parameters was maintained at a minimum of 24 frames per second, with an exposure time of 9 milliseconds. This configuration achieves a balance between real-time performance and noise reduction in polarization measurements.

Another illustration of our system is presented in Fig. 5 (multimedia available online), which shows the measurement of the last Stokes parameter, S_3 , while varying the stress applied to a glass microscope slide (BK7 glass) by pressing it with fingers. A laptop screen generating a horizontal linear polarization state serves as the background. In Fig. 5(a), the researchers' fingers are merely holding the glass in place with no pressure, and the S_3 parameter of the polarized light passing through the glass matches that of the background. However, when pressure is applied to the edge of the glass slide, stress is immediately induced, leading to birefringence due to the photoelastic effect. Figures 5(b) and 5(c) clearly illustrate the distribution of the circular polarization component resulting from this stress-induced birefringence. It should be noted that when using linearly polarized light as background, slight changes from stress-induced birefringence have almost negligible effect in S_1 and S_2 , but can be observed in S_3 . This can be demonstrated with the following calculation in which we assume that horizontal linear polarized light is used for illuminating the stressed material:

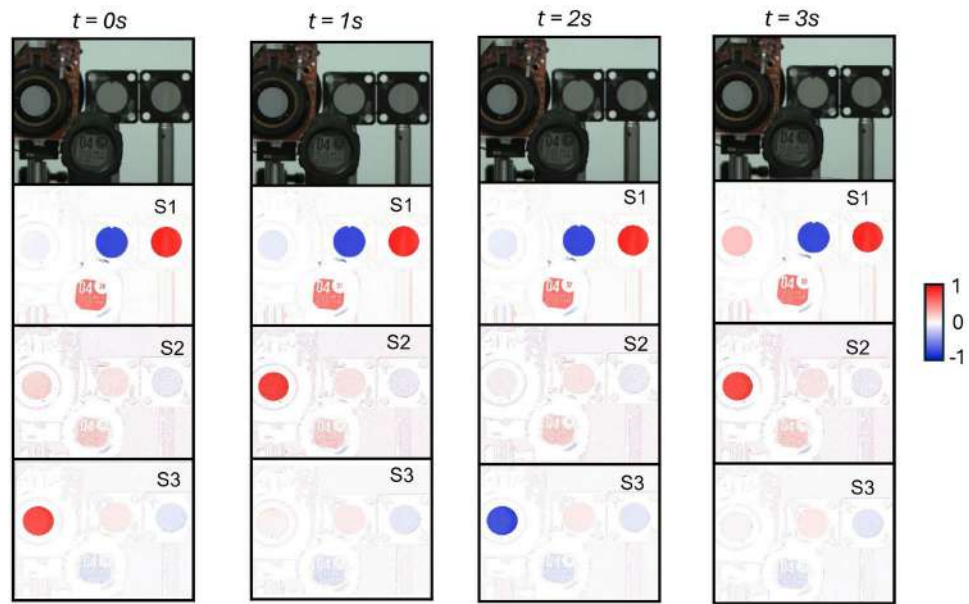


Fig. 4. Selected frames of a real-time Stokes vector imaging of a scene comprising of two perpendicular polarizers and a rotating achromatic waveplate in front of a linear polarizer. (Multimedia available online).

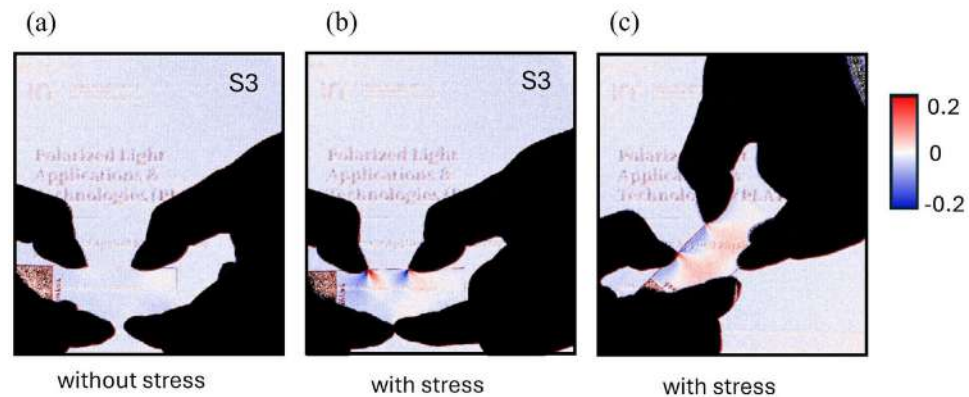


Fig. 5. Different frames showing the S_3 Stokes parameter imaging of a microscope glass substrate under finger-applied pressure. The scale is adjusted to ± 0.2 , instead of the usual ± 1 , to enhance the visibility of the effect. (Multimedia available online).

$$S_{out} = M_C S_{in} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_{2\theta} & S_{2\theta} & 0 \\ 0 & -S_{2\theta} & C_{2\theta} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & C_\delta & -S_\delta \\ 0 & 0 & S_\delta & C_\delta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_{2\theta} & -S_{2\theta} & 0 \\ 0 & S_{2\theta} & C_{2\theta} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} \quad (12)$$

$$= \begin{bmatrix} 1 \\ C_{2\theta}^2 + S_{2\theta}^2 C_\delta \\ C_{2\theta} S_{2\theta} (1 - C_\delta) \\ -S_{2\theta} S_\delta \end{bmatrix}$$

where we have assumed that the stressed material can be represented as a retarder with retardance δ and azimuth θ ²⁷. From this expression, it can be deduced that if the stress-induced retardation, δ , is weak ($S_\delta \simeq \delta$ and $C_\delta \simeq 1$), the resulting Stokes vector can be approximated to the first order as $[1, 1, 0, -\delta S_{2\theta}]^T$. In this weak stress case, a conventional polarization camera could not record any trace of stress.

Other configurations

We have demonstrated our approach to achieving complete polarization vision using a commercially available color-polarized camera with a simple modification. While our current implementation showcases the technique's viability, further refinement of polarimetric results could be achieved by employing a polarization sensor with

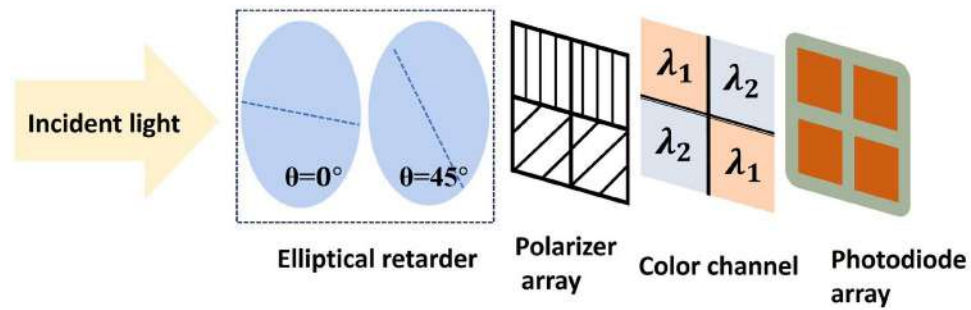


Fig. 6. Complete polarization vision configuration with an elliptical retarder composed of two identical cascaded linear retarders. Each superpixel comprises four unique combinations of polarizer orientations and wavelength filters, allowing the measurement of the complete Stokes vector from only four intensity measurements.

narrower custom-designed wavelength filters. The spectral response of these filters could be adjusted to desired wavelengths and, if necessary, extend beyond the visible spectrum to include, for instance, the near-infrared. A sensor using narrower and custom-positioned spectral bands could improve the accuracy of polarization measurements and reduce the requirement of uniformity of incoming polarization states across different wavelengths.

An interesting alternative for a full-Stokes camera based on our method involves utilizing a color sensor equipped with a polarizer array that features only two orientations instead of the standard four. This configuration, coupled with an elliptical retarder (which can be created by superimposing two misaligned linear retarders), offers a unique advantage: it requires the minimum number of intensity measurements, four, to obtain the complete Stokes vector, thus eliminating the system's overdetermination. This approach would not only simplify the system but also allow for higher resolution in the final measured Stokes vector images. Notably, this implementation is only possible with an elliptical dispersive retarder and cannot be achieved with a single dispersive linear retarder.

When using a train of two identical linear retarders (i.e., having the same retardance δ) superimposed at any relative orientation, the resulting elliptical retarder can be described as follows:

$$M_{\text{ellip}} = M_{C1}(\delta, \theta_1) M_{C2}(\delta, \theta_2) \quad (13)$$

The Mueller matrix of this elliptical retarder will be determined by three parameters: the retardance δ and two angles of orientation θ_1, θ_2 . It is worth noting that M_{ellip} is also equivalent to a linear retarder followed by a rotator^{28,29}.

According to our optimization results, there are multiple optimal configurations for robust measurement. A specific, industrially feasible solution is recommended in Fig. 6. This solution includes a polarization array with two orientations: 0° and 45° in front of the photodiode array, with two wavelength filters also in place. In addition, an elliptical retarder composed of two identical homogeneous linear retarders (both made of the same material and having the same thickness) is placed to cover the entire sensor. The fast axes of these two linear retarders are oriented at an angle of 45° relative to with each other is placed to cover the entire sensor. Finally, the complete Stokes vector can be instantaneously calculated from four intensities in the superpixel $(I_{0^\circ}^1, I_{0^\circ}^2, I_{45^\circ}^1, I_{45^\circ}^2)$ which (once imposing $\theta_1 = 0^\circ$ and $\theta_2 = 45^\circ$) will be given by:

$$I = \begin{bmatrix} I_{0^\circ}^1 \\ I_{45^\circ}^1 \\ I_{0^\circ}^2 \\ I_{45^\circ}^2 \end{bmatrix} = \begin{bmatrix} 1 & C_{\delta_1} & S_{\delta_1}^2 & C_{\delta_1} S_{\delta_1} \\ 1 & 0 & C_{\delta_1} & -S_{\delta_1} \\ 1 & C_{\delta_2} & S_{\delta_2}^2 & C_{\delta_2} S_{\delta_2} \\ 1 & 0 & C_{\delta_2} & -S_{\delta_2} \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (14)$$

This W matrix can be inverted, and it has optimal polarimetric conditioning when the linear retardance corresponding to the two wavelength channels differs by $\sim 111^\circ$ (this value is obtained when ignoring wavelength bandwidth-induced depolarization).

Conclusions

In this work, we have demonstrated a novel approach to achieving complete polarized vision using a commercially available color polarization camera, without the need for specialized or custom-built equipment. Our method leverages the natural wavelength-dependent retardation of a crystal waveplate to differentiate polarization states across the sensor's color channels, thus enabling the simultaneous measurement of the complete Stokes vector of incident polarized light.

The method was demonstrated using a commercial color polarization camera equipped with a Sony IMX250MYR polarized sensor and a sapphire waveplate. Extraction of all Stokes parameters is achieved under the assumption that the measured polarization states exhibit weak variation with wavelength, a condition that holds true for a wide range of practical applications.

Our approach overcomes the complexities and high costs associated with other state-of-the-art methodologies, such as microretarder arrays and metasurface-based sensors, which require complex designs and intricate nanofabrication processes. Furthermore, the presented technique is not only limited to the visible spectrum but can be extended to other wavelength ranges, such as near-infrared and ultraviolet, by selecting appropriate wavelength filters and dispersive retarders. In conclusion, the proposed method provides a robust, efficient, and economically viable solution for complete polarization vision, opening new possibilities for enhanced imaging capabilities in various scientific and industrial applications.

Supporting Information

The supporting information files include real-time full-Stokes video recordings corresponding to the visualizations presented in Figs. 4 and 5.

Data availability

The data needed to evaluate the conclusions in the paper are described in the text. More experimental results can be provided upon reasonable request to the corresponding author (O.A.)

Received: 17 December 2024; Accepted: 3 March 2025

Published online: 14 March 2025

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Author contributions

S. B. conceived and conducted the experiments, O. A. conceived and conducted the experiments. Both authors contributed to the manuscript writing and revision.

Declarations

Competing interests

The authors declare that they have no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-025-92653-x>.

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