

Hyperspectral evaluation of an adaptive liquid-crystal spiral plate for tuning vortices in a broadband range

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Abstract. We show a hyperspectral procedure for evaluating phase-only liquid-crystal (LC) modulators, in particular, those with spatially varying retardance. The procedure is illustrated with an adaptive spiral phase plate (ASPP) based on a custom electrode design that produces spiral phases with variable phase depth, thus enabling the generation of vortex beams with tunable topological charge. By recording the spatially resolved spectrum of the device in a hyperspectral image, a comprehensive mapping of the optical retardance function to wavelength and applied voltage is obtained. This hyperspectral approach easily identifies the continuous variation in the topological charge introduced by the ASPP across the measured spectral range. Optical vortices with integer and semi-integer tunable topological charge are generated with monochromatic illumination at three different wavelengths, which validates the hyperspectral approach.

Keywords: liquid-crystal devices; spiral phase plates; hyperspectral imaging; vortex beams; phase modulation.

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1 Introduction

Liquid-crystal (LC) optoelectronics is a mature technology, mostly used in displays,¹ but also in spatial light modulators (SLMs)² and other nondisplay applications. Parallel-aligned (PAL) and vertically aligned (VAN) cells are standard configurations that behave as tunable linear retarders. As single-pixel elements, they are useful to precisely control the state of polarization in polarimetry or to operate as phase-only shifters in interferometry. Their dispersion properties also enable the design of tunable spectral filters, with applications in colorimetry,³ and spectral birefringent filters.⁴ Pixelated liquid-crystal-on-silicon (LCOS) phase-only SLMs⁵ have become key components for multiple applications. Based on custom electrode designs, other adaptive phase-only LC devices have been developed, such as tunable lenses,^{6,7} spiral diffractive lenses,⁸

axicons,^{9,10} and spiral phase plates.^{11,12} LC SLMs and LC custom devices have both become crucial elements in the field of structured light.¹³

In all cases, the correct use of LC retarders requires a precise evaluation of the modulation properties. One classical technique consists of placing the LC retarder between two linear polarizers, oriented at $\pm 45^\circ$ with respect to the LC director. In this situation, the intensity of the modulated beam follows a squared sinusoidal variation with respect to half the retardance.^{14,15} Because the retardance changes with both voltage and wavelength, two types of characterization methods are typically performed: (1) using monochromatic light to obtain the modulation as a function of voltage and (2) using a broadband light source and a spectrometer to obtain the spectral retardance function for a given voltage.¹⁶ In the first case, changes in the operating wavelength necessitate recalibration, whereas in the second case, any voltage modification requires a new spectral measurement.

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In the latter case, the spectral retardance function is typically fitted to a Cauchy-type relation.¹⁷ This approach is useful because the change of retardance with voltage can then be approximately described by a single voltage transfer function, valid over the considered wavelength range,^{18,19} thus leading to a full spectral-voltage determination of the retardance function. Another interesting feature of the spectral method is that it can reveal the presence of multiple reflections within the device.²⁰

Both characterization methods can be applied to LC retarders that exhibit spatial variations due to a nonuniform cell gap. However, this procedure can be time-consuming. In this context, an accurate and fast computational procedure for providing the spatial variations of LC retarders with planar alignment was recently reported.¹⁹ The method consists of measuring the spectral transmission at certain points and estimating its spatial dependency. In this work, we focus on LC devices with spatially varying retardance *per se*, i.e., not due to manufacturing difficulties, but where the device is designed to exhibit such spatial variations. This is the case of many LC custom devices.^{6–12} Here, hyperspectral imaging can be a very convenient tool as a characterization procedure.

Hyperspectral imaging (HSI) has undergone significant development. HSI provides spatially resolved spectroscopy, where the light spectrum is measured at each pixel of the image. Multiple scanning or snapshot HSI technologies are nowadays commercially available.²¹ Some of the scanning approaches rely on LC spectral filters to acquire images at different spectral bands,^{22,23} and LC devices have also been incorporated into recent neural-network-based spectral imaging architectures.²⁴

In this work, we take the opposite approach; instead of considering the LC device as an element of the HS technique itself, we propose the use of HSI for a fast quantitative characterization, in a broad spectral range, of LC phase-only devices with spatially varying retardance. The spectral calibration method¹⁸ is applied here to derive the spectral retardance function of an LC modulator in the absence of applied voltage. Then, by implementing a spatially varying voltage, the LC device exhibits a spatially varying retardance. Using an HS camera, a single-shot acquisition is enough to characterize the full wavelength-voltage modulation. Experimental results illustrating the technique are presented using an adaptive spiral $\Delta n = n_e - n_o$ is the birefringence (n_e and n_o are the extraordinary and ordinary refractive indices), phase plate (ASPP)²⁵ designed to generate vortex beams with tunable topological charge. This tunability of the topological charge is interesting for fiber-optic and free-space communications,²⁶ while the spectral sensitivity is useful in broadband optical sensing.²⁷

The paper is organized as follows. Section 2 describes the hyperspectral retardance characterization procedure, combining the spectral retrieval of the device retardance with its hyperspectral implementation on an adaptive LC spiral phase plate. Section 3 presents the results on the hyperspectral characterization of the spatially varying retardance and the retrieval of the wavelength-voltage modulation function. Then, it analyzes the operating conditions that lead to spiral retardance profiles with integer and fractional topological charges. The evolution of the topological charge with wavelength is shown in Videos 1–4. Section 4 discusses the validation of the characterization procedure through the experimental generation of vortex beams under different monochromatic illumination. A comparison against two established characterization methods is included in the [Supplementary Material](#). Finally, Sec. 5 draws the main conclusions and perspectives of this study.

2 Materials and Methods

The method is based on first describing the spectral retardance of an electrically-addressable LC layer and then exploiting the spatially-resolved information provided by HSI to extend the characterization to spatially-varying voltage distributions.

2.1 Spectral Characterization of LC Retarders

The retardance modulation of a voltage-addressable LC linear retarder can be measured by placing the device between two linear polarizers, with the input polarizer oriented at 45 deg with respect to the LC director axis, and the analyzer set either parallel or perpendicular to the input polarizer. In this configuration, the normalized transmission (t), defined as the ratio of the output light intensity normalized to the intensity impinging the LC retarder, is ideally given by¹⁴

$$t_{\parallel} = \cos^2\left(\frac{\phi}{2}\right), t_{\perp} = \sin^2\left(\frac{\phi}{2}\right), \quad (1)$$

where subscripts $\parallel$ and $\perp$ refer to the configuration with parallel or with crossed polarizers, respectively, and ϕ denotes the optical retardance. These relations assume an ideal retarder, which is a reasonable approximation for the LC device employed in this work. Under this assumption, additional polarimetric measurements required to determine possible diattenuation or depolarization effects are not considered.

LC layers with homogeneous alignment exhibit LC director profiles that depend on the applied voltage and the characteristics of the material.²⁸ However, from the operational point of view, it can be considered as a linear retarder with tunable retardance. In the off-state, the LC retarder layer introduces a retardance between the extraordinary and ordinary components of the light beam given by

$$\phi_0 = \frac{2\pi d}{\lambda} \Delta n, \quad (2)$$

where $\Delta n = n_e - n_o$ is the birefringence (n_e and n_o are the extraordinary and ordinary refractive indices), and d denotes the LC layer thickness.

Equation (2) shows the explicit inverse wavelength-dependence of the retardance. In addition, the refractive indices $n_e(\lambda)$ and $n_o(\lambda)$, and therefore, the birefringence $\Delta n(\lambda)$ are also wavelength dependent. An empirical function widely applied to account for the wavelength-dependent refractive indices of LC materials is the Cauchy approximation.¹⁷ In this work, we consider the following expression for the spectral retardance of the LC layer:

$$\phi_0(\lambda) = \frac{A}{\lambda} + \left(\frac{B}{\lambda}\right)^3 + \left(\frac{C}{\lambda}\right)^5, \quad (3)$$

where A , B , and C are the fitting constants corresponding to the Cauchy approximation using solely the first three terms.^{29,30} Higher-order terms could be included, but they do not significantly improve the results in this case.

In a homogeneously aligned LC device, maximum retardance is achieved in the absence of applied voltage. This off-state retardance is denoted as $\phi_0(\lambda)$, and it is fitted following Eq. (3). Upon addressing a voltage to the device, the LC director tilts, thus reducing the effective retardance. A microscopic description

would require calculating the voltage-dependent director profile across the LC layer.²⁸ However, for calibration purposes, the device can be described by a voltage-dependent effective extraordinary index $n_{\text{eff}}(\lambda, V)$, thus leading to a voltage-dependent effective birefringence $\Delta n_{\text{eff}}(\lambda, V) = n_{\text{eff}}(\lambda, V) - n_o(\lambda)$. The change in n_{eff} depends on the tilt angle, which depends on the applied voltage.³⁰ A normalized birefringence function can be defined as

$$\frac{\Delta n_{\text{eff}}(\lambda, V)}{\Delta n(\lambda, 0)} = \frac{n_{\text{eff}}(\lambda, V) - n_o(\lambda)}{n_e(\lambda) - n_o(\lambda)}. \quad (4)$$

For practical purposes, this normalized function can be considered to depend only on the applied voltage (the tilt angle affects all wavelengths equally), thus defining a voltage transfer function $g(V)$ which accounts for the voltage-induced reduction of the birefringence as $\Delta n_{\text{eff}}(\lambda, V) \cong g(V)\Delta n(\lambda)$, whereas the wavelength dependence is contained in the off-state birefringence $\Delta n(\lambda)$. The monotonic function $g(V)$ takes values between one, corresponding to the off state, and zero, corresponding to the maximum applied voltage.³¹

Therefore, the retardance variation with voltage and wavelength can be approximated as

$$\phi(\lambda, V) = g(V)\phi_0(\lambda). \quad (5)$$

This separable expression should be regarded as an empirical calibration model valid over the measured spectral and voltage ranges. Such a voltage-transfer-function approach has been successfully applied by various researchers.^{18,19,31}

2.2 HSI Implementation on an Adaptive Spiral Phase Plate

Figures 1(a) and 1(c) show the experimental setup used in the HS characterization of the LC modulator. A standard halogen

lamp of broadband continuous spectrum covering the visible and NIR bands is employed as the light source. A diffuser is placed after the source to achieve uniform illumination on the LC modulator. A linear polarizer is placed before the LC modulator, with its transmission axis oriented at 45 deg with respect to the LC director, and a polarizer analyzer is placed before the camera objective. They are both Thorlabs LPNIRE100-B polarizers with a spectral band extending up to 1100 nm. The LC modulator is imaged with a Hinalea 4200 HS camera. This camera incorporates a Fabry-Pérot filter to scan the spectral bands and can measure the HS data cube with 400 bands in the range from 400 to 1000 nm, with a spectral maximum resolution of 4 nm and a spatial resolution of 968 pixel $\times$ 608 pixel.

As the LC modulator, we use an ASPP with a custom-designed electrode that drives a gradually varying voltage along the azimuthal coordinate, thus creating a spiral phase.²⁵ Figure 1(b) shows the electrode design that goes on top of the LC cell. It consists of a circular electrode that establishes a continuous azimuthal voltage gradient between two peripheral electrical contacts (control electrodes V_1 and V_2). This ring electrode is coupled to 100 pie-slice-shaped stubs, which act as voltage guides and evenly distribute the voltage across the aperture. As a result, this LC plate can generate optical vortices with around 95% conversion efficiency and tune their topological charge by varying one of the control voltages.²⁵

The device was fabricated by first preparing two ITO-coated glass substrates, one of which is patterned to form the structured electrode described above, whereas the other serves as a uniform ground electrode. Both substrates were then spin-coated with polyimide SE-130 (Nissan Chemical Industries) at 1.0 wt% in dimethylformamide (DMF). The films were dried at 70°C for 30 min and then cured at 180°C for 90 min. To ensure homogeneous alignment of the LC director, a unidirectional mechanical rubbing process was applied to both substrates using a fiber cloth mounted on a rotating roller. The ASPP cell gap was set to 50 μm by dispersing silica spacer beads in an adhesive epoxy

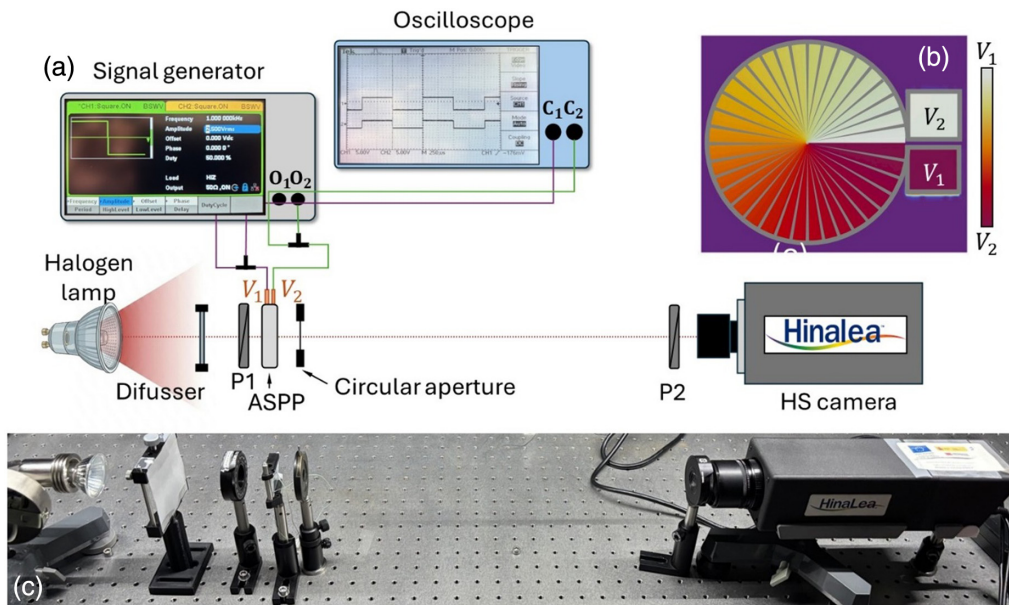


Fig. 1 (a) Scheme of the experimental setup. P1 and P2 are linear polarizers. ASPP is the LC adaptive spiral phase plate. (b) Diagram of the electrodes in the ASPP. (c) Photograph of the experimental system.

(NOA 68) and then dispensing the mixture onto the perimeter of one substrate. The two substrates were assembled in antiparallel rubbing directions to create a completely uniform, defect-free, and symmetric tilt across the thickness of the ASPP when a voltage is applied. Finally, the cell gap was filled with nematic LC HTD028200-200³² via capillary effect. This liquid crystal has birefringence $\Delta n = 0.27$ at $\lambda = 633$ nm, dielectric permittivities $\epsilon_{\perp} = 3.8$ and $\epsilon_{\parallel} = 11.7$ at 1 kHz frequency, and a viscosity of 27 mPa·s at 20°C.

Synchronized 1 kHz DC balanced square signals with RMS voltages V_1 and V_2 were applied to the two control electrodes of the modulator using a Siglent SDG1032X Plus signal generator, which provides two synchronized output channels. By adjusting the voltages V_1 and V_2 , the ASPP successfully generates a spiral phase, allowing the topological charge to be tuned.

Note that this ASPP, which exhibits an azimuthally varying retardance, differs from q-plate devices, which feature a spatially-uniform retardance but an azimuthal orientation of the LC director. Q-plates have been extensively studied because they couple the spin angular momentum (SAM) and orbital angular momentum (OAM) of light. They generate vortex beams for input circularly polarized light, with the OAM sign controlled by the input polarization helicity, and they transform input linear polarization into vector beams.³³ By contrast, phase-only spiral LC plates produce vortex beams for input light linearly polarized parallel to the LC director.^{34,35} The ASPP used here belongs to this second class of devices. We recently demonstrated that it can also be employed to generate vector beams by cascading it with a second ASPP in the orthogonal orientation, with the notable ability to tune the vector beam order.³⁶

3 Results

3.1 Spectral-Voltage Retardance Variation

The retardance model described in the previous section is here applied to analyze the HSI measurements of the ASPP. The key point is that the azimuthal voltage distribution maps the angular coordinate θ onto an effective voltage coordinate, whereas the HS camera records the spectral response at each position. Therefore, a single-shot HS acquisition contains the information required to retrieve the wavelength and voltage-dependent retardance modulation of the device.

When applying different control voltages V_1 and V_2 , a voltage distribution is generated along the azimuthal coordinate, thus producing an angular variation of the retardance with θ . Standard LC devices use cell gaps of 5 to 10 μm to operate as low-order retarders over a limited spectral range. By contrast, our $d = 50$ μm -thick cell behaves as a multi-order retarder, providing a much larger total phase delay. This increased optical path difference enhances sensitivity to voltage-induced refractive-index changes, enables multiple 2π phase modulation over a broad wavelength range, and allows the generation of high-order phase profiles without requiring extreme driving voltages. The difference $V_2 - V_1$ must be kept within the voltage range over which the LC layer's phase response is approximately linear.²⁵

This is illustrated in Figs. 2(a) and 2(b), which show two pseudo-colored RGB images generated from the HS data cube captured with the HS camera. These images are generated by assigning the RGB channels to the spectral bands centered

at wavelengths 650, 550, and 490 nm, respectively. In this way, they mimic what can be observed with the naked eye. In Fig. 2(a), the applied voltages are $V_1 = 1.00$ V and $V_2 = 8.00$ V. The image features the characteristic birefringence colours along the azimuthal coordinate θ , with a clear nonlinear variation. In the lower part of the image (low values of θ) the fringes vary rapidly, indicating very large retardance values, as expected in a multiple-order retarder. On the contrary, the fringes in the upper part of the image vary slowly, revealing a smaller retardance.¹⁶

By contrast, the case in Fig. 2(b), where $V_1 = 1.50$ V and $V_2 = 2.50$ V, shows a quite distinct linear variation of the color fringes along θ , thus indicating a linear angular variation of the retardance. Figure 2(c) presents several spectral bands selected from the HS data cube, evidencing how the number of angular fringes decreases for longer wavelengths, as expected from the retardance reduction with wavelength.

Figures 2(d) and 2(e) show the spectral transmittance for crossed polarizers in the spectral range from 500 to 1000 nm corresponding to the cases in Figs. 2(a) and 2(b), respectively. The spectra were obtained by averaging the signal along the radial lines at different angles $\theta = 5, 90, 180, 270$, and 350 deg, as indicated in Fig. 2(a). Because the retardance is approximately constant along the radial lines but varies azimuthally, these spectral transmittance curves oscillate with wavelength: the larger the retardance, the faster the oscillations.¹⁶ Note how the number of oscillations decreases as the angle θ increases, indicating the angular reduction of the retardance caused by the voltage variation from V_1 to V_2 . Figure 2(d) exhibits only two oscillations for $\theta = 350$ deg, where the voltage nearly reaches 8 V.

It is also worth noting that the amplitude of the oscillations is very small in some spectral regions, especially for the off-state curve at the edges of the measured spectral range. This effect can be attributed to a combination of the very fast spectral oscillations associated with large retardance values and the finite spectral resolution and spectral response of the HS imaging system.¹⁶

The black curve in Figs. 2(d) and 2(e) is obtained with the LC modulator in the off-state. In this situation, the modulator image appears uniform, and the spectrum exhibits the largest number of oscillations, as expected for the maximum retardance state. This curve is taken as a reference to fit the spectral retardance $\phi_0(\lambda)$ in Eq. (3). The resulting fitted function is obtained after minimizing the mean square error between the experimental data (black curve in Figs. 2(d) and 2(e) and the corresponding numerical data [black curve in Fig. 2(f)] and is shown in Fig. 3(a). This best fit is obtained for Eq. (3) with numerical constants $A = 89780$ nm, $B = 1601$ nm, and $C = -875$ nm. Note how this function $\phi_0(\lambda)$ varies from about 20π for $\lambda = 1000$ nm to over 60π for $\lambda = 500$ nm. This multiple-order retardance is consistent with the large thickness of the LC layer. Assuming the thickness $d = 50$ μm defined by the spacers, the LC birefringence Δn can be retrieved from $\phi_0(\lambda)$ using Eq. (2), resulting in the spectral variation shown in Fig. 3(b), which is in good agreement with previous measurements.³²

Once the function $\phi_0(\lambda)$ is determined, the spectra in Figs. 2(d) and 2(e) (obtained for different angles θ in the HS image) are fitted according to Eq. (5) with the voltage transfer function $g(V)$. The experimental data in Fig. 2(e) provide a more accurate result in the low-voltage region, up to 2.5 V, whereas the data in Fig. 2(d) provide the characterization at

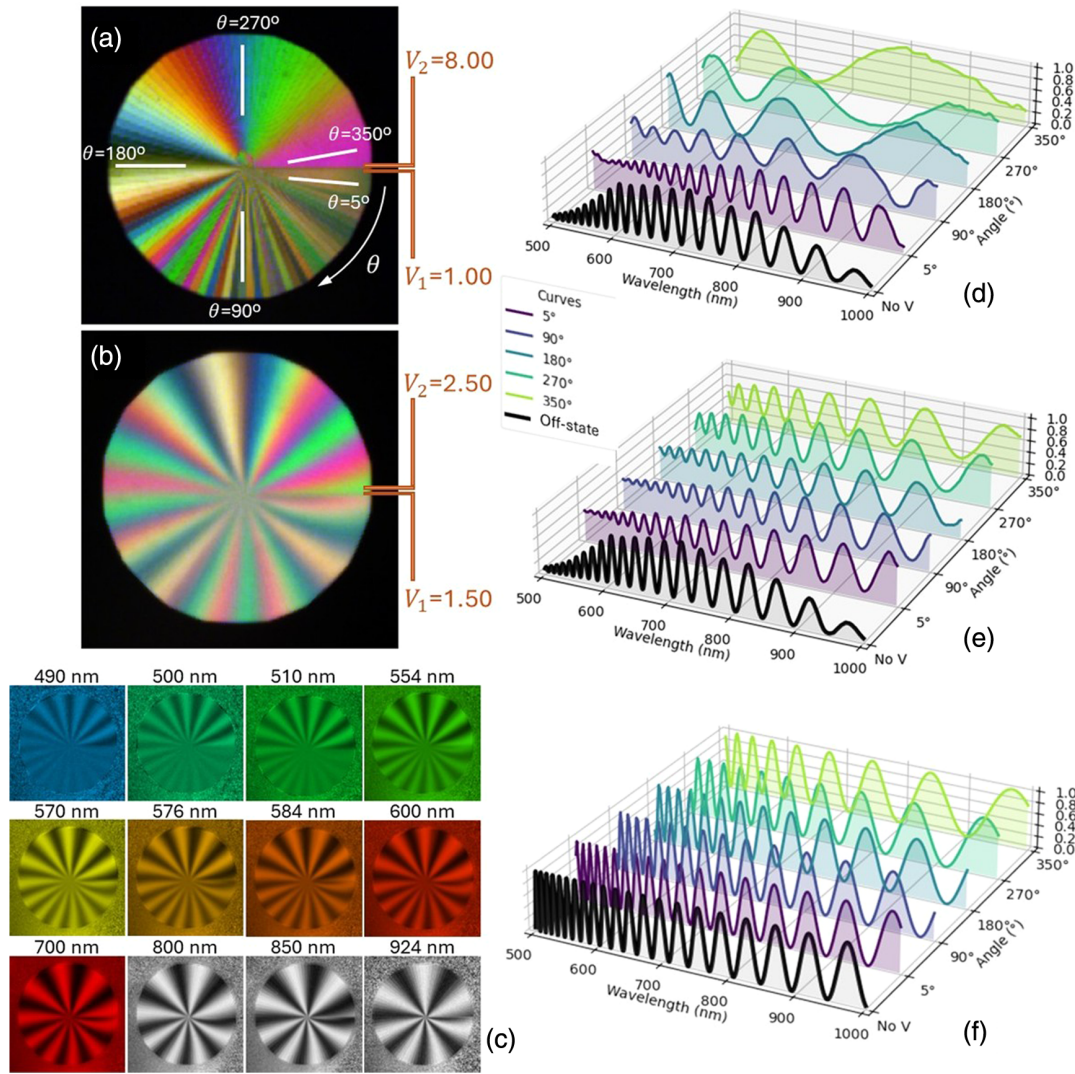


Fig. 2 Pseudocolored images of the ASPP with applied RMS voltages (a) $V_1 = 1.00$ V, $V_2 = 8.00$ V and (b) $V_1 = 1.50$ V, $V_2 = 2.50$ V. (c) Images of case (b) at different wavelengths. (d), (e) Experimental normalized transmittance spectra for cases (a), (b) measured at different angular directions $\theta = 5, 90, 180, 270$, and 350 deg. (f) Best fit of curves in case (e) using the retardance Cauchy model in Eq. (3) (Video 1, MP4, 2.41 MB [URI: <https://doi.org/10.1117/1.APN.5.6.066015.s1>]; Video 2, MP4, 2.24 MB [URI: <https://doi.org/10.1117/1.APN.5.6.066015.s2>]).

higher values reaching up to 8 V. For each selected value of θ , the applied voltage was calculated through the linear relation $V(\theta) = V_1 + (V_2 - V_1)\theta/360$ deg and $g(V)$ was adjusted to provide the best fit to the spectrum measured at this particular angle. For instance, Fig. 2(f) shows the normalized transmission that best fits the experimental data in Fig. 2(e), for angles $\theta = 5, 90, 180, 270$, and 350 deg. Additional angles were selected to obtain the voltage transfer function $g(V)$ plotted in Fig. 3(c), where the dots are experimental data. This transfer function clearly shows the threshold value around 1.3 V. A numerical interpolation was applied above the threshold voltage to obtain a continuous function versus V . Figure S1 in the [Supplementary Material](#) presents equivalent results to those in Fig. 2, but obtained with a point spectrometer.

Note that efficiently creating a vortex beam requires a spiral phase that varies linearly with the azimuth angle. Otherwise,

a nonlinear phase variation along the azimuth creates a beam with multiple simultaneous OAM components.³⁷ Because the voltage of the ASPP varies linearly with θ , it is therefore necessary to operate the device within a voltage range ($V_2 - V_1$) where the retardance changes almost linearly with the applied voltage. As shown in Fig. 3(c), the range between 1.5 and 2.5 V fulfills this condition, which explains the fringe distribution in Figs. 2(b) and 2(c).

The functions $\phi_0(\lambda)$ in Fig. 3(a) and $g(V)$ in Fig. 3(c) provide a full predictive model through the function $\phi(\lambda, V) = g(V)\phi_0(\lambda)$ displayed in Fig. 3(d), which defines the retardance at any wavelength and any applied voltage within the measured ranges. Note that this full spectral-voltage information about the LC modulator is retrieved in a single-shot HSI acquisition since the spectral and spatial dimensions are recorded simultaneously. In practice, a second HSI capture was acquired for

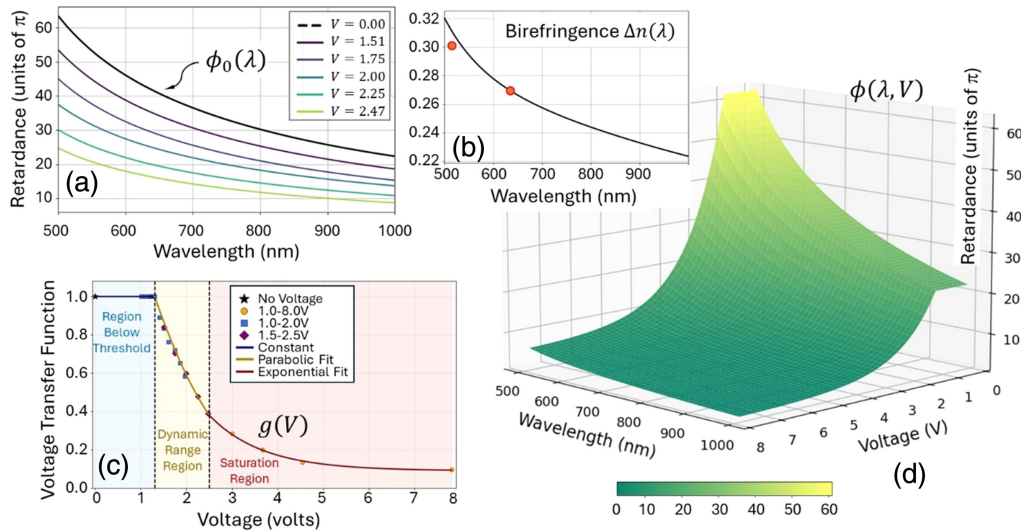


Fig. 3 Full spectral-voltage characterization results. (a) Spectral retardance function $\phi_0(\lambda)$ in the off-state ($V = 0$) and $\phi(\lambda)$ for different applied voltages. (b) LC spectral birefringence $\Delta n(\lambda)$; dots indicate the data in Ref. 32. (c) Voltage transfer function $g(V)$. (d) Full spectral retardance and voltage function $\phi(\lambda, V) = g(V)\phi_0(\lambda)$.

the orthogonal orientation of the analyzer to normalize the transmission spectra. The data were normalized with respect to the sum of the two polarization components,¹⁶ making them directly comparable to Eq. (1) and suitable for fitting the spectral retardance.

A transverse plane of the graph in Fig. 3(d) at a constant voltage yields the spectral retardance for that particular voltage. As an example, Fig. 3(a) presents the spectral retardance curves for azimuthal angles $\theta = 5, 90, 180, 270$, and 350 deg in Fig. 2(b), which correspond to voltages $V = 1.51, 1.75, 2.00, 2.25$, and 2.47 V, respectively. We can observe that the retardance progressively decreases as the voltage increases. Alternatively, a transverse plane of the graph in Fig. 3(d) at a constant wavelength gives the retardance modulation for that wavelength, i.e., the voltage transfer function $g(V)$ multiplied by the off-state retardance at the selected wavelength. In this way, Fig. 3(d) provides the full spectral-voltage information required to operate the spiral phase plate.

3.2 Wavelength Variation of the Topological Charge in the Spiral Phase Profile

The complete spectral-voltage retardance characterization allows the operating conditions of the ASPP to be properly selected. Figure 2(c) shows a discontinuity at the electrode location, in the right horizontal part of the images. This occurs because the retardance when approaching $\theta = 360$ deg does not match that when approaching $\theta = 0$ deg. This phase mismatch in the spiral phase profiles leads to vortex beams with fractional topological charge. Even though such beams have been known for decades,³⁸ integer topological charges have attracted most of the attention for practical applications. Nevertheless, vortex beams with fractional charges, the so-called fractional vortex beams,³⁹ have been applied in optical tweezers,⁴⁰ optical sensors,⁴¹ or quantum systems.⁴² Therefore, the capability of fine-tuning integer and fractional topological

charge values in the ASPP, for any desired operating wavelength and by means of a single-shot device characterization is a valuable advantage. Videos 1 and 2 show the continuous evolution of the topological charge with wavelength, from 500 to 1000 nm, for two specific voltage pairs: ($V_1 = 1.00$ V, $V_2 = 8.00$ V) and ($V_1 = 1.50$ V, $V_2 = 2.50$ V).

Let us discuss the tuning of integer charge values. Because the retardance varies continuously with wavelength, it is possible to identify those for which the accumulated spiral phase corresponds to an integer topological charge. Thus, following the previous characterization with applied voltages $V_1 = 1.50$ V and $V_2 = 2.50$ V, integer charges are identified by seeking the continuity of the fringes in the region where the electrodes are located ($\theta = 0$). Figure 4(a) shows images from the HS data cube corresponding to wavelengths 520, 547, 564, 590, 638, 678, 734, 800, and 910 nm. As in Fig. 2(c), the quite equispaced fringe distribution reflects an approximately linear variation of the retardance with the azimuthal angle. This behavior is clearly illustrated in Fig. 4(b), where the normalized transmission between crossed polarizers is represented as a function of the azimuth angle θ . A region of interest (ROI) was defined for every image in Fig. 4(a). It consists of an annular ring around the center of the image, such as the region delimited by the two dashed circles in the capture at 638 nm. The normalized transmission was averaged within this ROI for each angle θ and represented in Fig. 4(b) for the nine selected wavelengths. The resulting transmission profiles exhibit a sinusoidal variation with the azimuth and an approximately constant period, indicating that the retardance varies linearly with θ . The number of fringes reveals the topological charge ℓ of the encoded spiral phase. Note how it decreases with wavelength, changing from $\ell = 15$ at $\lambda = 520$ nm down to only $\ell = 7$ at $\lambda = 910$ nm.

To further prove the voltage control of the topological charge, Fig. 5 presents results aimed at achieving lower topological charges. This was obtained by reducing the voltage difference

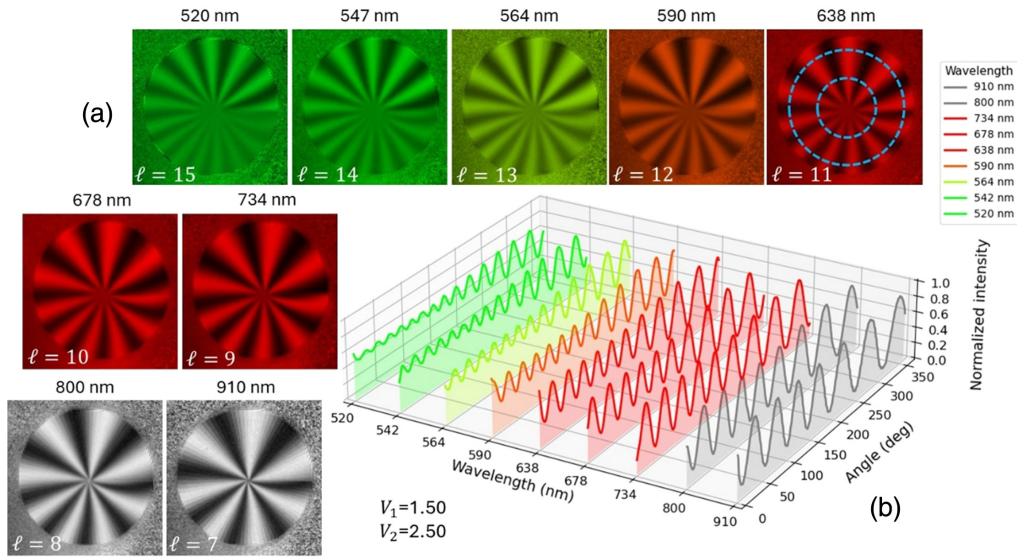


Fig. 4 (a) Images of the spiral phase plate for wavelengths exhibiting integer topological charge obtained when applying voltages $V_1 = 1.50$ V, $V_2 = 2.50$ V. (b) Normalized transmission between crossed polarizers versus the azimuthal angle for these images (Video 3, MP4, 3.03 MB [URI: <https://doi.org/10.1117/1.APN.5.6.066015.s3>]).

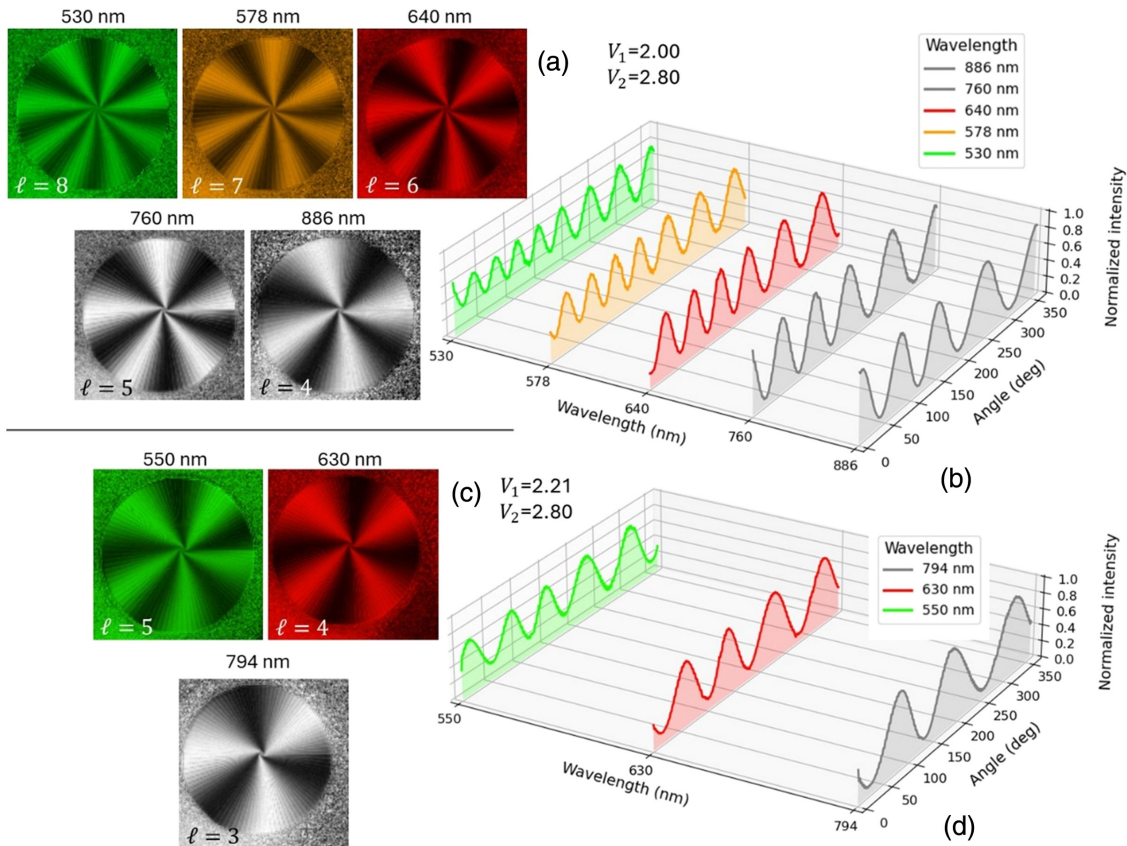


Fig. 5 Results obtained for voltages (a), (b) $V_1 = 2.00$ V, $V_2 = 2.80$ V and (c), (d) $V_1 = 2.21$ V, $V_2 = 2.80$ V. (a), (c) Images of the spiral phase plate at wavelengths exhibiting integer topological charges in each case. (b), (d) Corresponding normalized transmission versus the azimuthal angle for these images (Video 4, MP4, 2.87 MB [URI: <https://doi.org/10.1117/1.APN.5.6.066015.s4>]).

between the two electrodes. In Fig. 5(a), we selected $V_1 = 2.00$ V and $V_2 = 2.80$ V. In this voltage range, the retardance does not exhibit the fast variation observed in the region below 2 V. The HS data cube was captured again with the HS camera, and its evolution with wavelength is visualized in Video 3. Now the number of fringes along the azimuth is lower than that in Fig. 4. Five wavelengths can be identified: 530, 578, 640, 760, and 886 nm, for which integer topological charges from $\ell = 8$ to $\ell = 4$ are obtained. The corresponding angular profiles of the normalized transmission are shown in Fig. 5(b). Equivalent results to those in Fig. 5 have been obtained with baseline methods, as shown in Figs. S2 and S3 in the [Supplementary Material](#), obtained respectively with a point spectrometer and with monochromatic illumination.

Finally, Fig. 5(c) shows results with an even smaller voltage difference, corresponding to $V_1 = 2.21$ V and $V_2 = 2.80$ V. In this case, only three wavelengths (550, 630, and 794 nm) yield integer topological charges: $\ell = 5$, 4, and 3, respectively. The corresponding angular profiles of the normalized transmission are illustrated in Fig. 5(d). Note that in all cases the profile is continuous at the angular origin ($\theta = 0$). Video 4 visualizes the wavelength evolution for these voltages.

4 Discussion—Vortex Beams with Integer and Semi-Integer Topological Charge

To validate the predictive capability of the spectral-voltage retardance characterization, we performed an additional experiment using monochromatic laser illumination and verified the vortex beam generation at three different wavelengths. We illuminated the adaptive spiral plate with a Nd:YAG laser of 532 nm wavelength, a He-Ne laser of 633 nm wavelength, and a 780-nm diode laser. In each case, the laser beam was expanded and collimated, having a diameter of ~ 5 mm to illuminate the complete active area of the adaptive spiral plate. An input polarizer ensured that the beam was linearly polarized, and a half-wave retarder was used to rotate the polarization, so it was aligned parallel to the LC director of the ASPP. A standard color camera (Basler scA1390-17fc, with a $1/2''$ active area, 1390×1038 square pixels of $4.65 \mu\text{m}$ size) captured the field at ~ 500 mm from the spiral plate. A second monochrome camera with higher sensitivity in the NIR spectrum (Basler acA1300-200um, with a $1/2''$ active area and 1280×1024 square pixels of $4.8 \mu\text{m}$ size) was employed when illuminating with the 780-nm diode laser.

Figures 6(a)–6(c) show the results obtained for wavelengths 532, 633, and 780 nm, respectively. Voltage $V_1 = 2.50$ V is kept at one electrode, whereas V_2 , initially set at 2.50 V, is progressively reduced at the other electrode. In this way, the phase depth of the spiral phase increases with the voltage difference $\Delta V = V_1 - V_2$. The results demonstrate the generation of vortex beams with a central dark core corresponding to the phase singularity, whose diameter increases with the topological charge. At $\lambda = 532$ nm and $\lambda = 633$ nm, Figs. 6(a) and 6(b) show the topological charges tuned from values $\ell = 1$ up to $\ell = 11$. As expected, the shorter the wavelength, the smaller the voltage difference required to achieve the same topological charge. At a 780 nm wavelength, topological charges from $\ell = 1$ up to only $\ell = 8$ are obtained when V_2 decreases from 2.50 to 1.50 V.

Figure 6 also shows results for intermediate voltages not leading to integer topological charges. In these situations, there is a phase mismatch at $\theta = 0$, where the two electrodes are located. The phase continuity at this angle is lost, and a dark horizontal line appears. The contrast of this dark fringe is maximum when the phase difference is an odd multiple of 180° ,³⁸ thus leading to semi-integer values of the topological charge. Figure 6 illustrates such cases for charge values from $\ell = 1.5$ to $\ell = 4.5$.

Figure 6(d) shows the topological charge as a function of the voltage difference $\Delta V = V_1 - V_2 = 2.50 - V_2$. The dots indicate the experimental voltage values applied to achieve the images in Figs. 6(a)–6(c), whereas the lines describe the expected variation of the topological charge, as derived from the retardance characterization in Fig. 3. The experimental and prediction curves show very good agreement. The experimental dots follow well the predicted trend, although small discrepancies can be found, attributed to small changes in temperature, because the large thickness of the LC layer makes this device much more sensitive to temperature changes.

These results demonstrate the capability of the ASPP to tune the topological charge at different wavelengths within the measured spectral range.

5 Conclusion

In summary, we have presented a novel hyperspectral imaging technique for characterizing phase-only LC modulators with spatially varying retardance profiles. The technique has been illustrated using an ASPP LC device with custom-shaped electrodes designed to generate a voltage variation along the azimuthal angle, thus creating spiral phase profiles with variable phase depth. This LC device has proven useful for generating standard vortex beams with tunable topological charge when illuminated with a plane wave and could be combined with other phase holographic elements to generate more advanced vortex beams, such as the recently proposed steady optical vortex beam.⁴³

The technique makes use of the data cube from an HS image of the LC modulator placed between two linear polarizers to experimentally determine the spectral retardance function. In a first step, the off-state spectral retardance $\phi_0(\lambda)$ is obtained when no voltage is applied to the device. The experimental data are fitted to a Cauchy-type approximation of the spectral retardance function. Then, a full spectral-voltage retardance characterization is performed by applying a voltage difference between the two control electrodes of the device, which generates a spiral variation of the retardance. The HS data cube of the LC modulator in the on-state (with applied voltage) provides the information required to retrieve the voltage transfer function $g(V)$ that describes the retardance reduction induced by the applied voltage.

Once the characterization and fitting of the experimental data have been completed, the resulting spectral-voltage function $\phi(\lambda, V)$ provides the information required to operate the device at any wavelength within the measured broad spectral range, from 400 to 1000 nm. This capability is demonstrated by operating the ASPP under different voltage conditions and tracking how the topological charge evolves with wavelength. This allows identification of the specific wavelengths at which the generated spiral phase yields integer or fractional topological charges. Finally, vortex beams with integer and semi-integer tunable topological charge are experimentally generated under

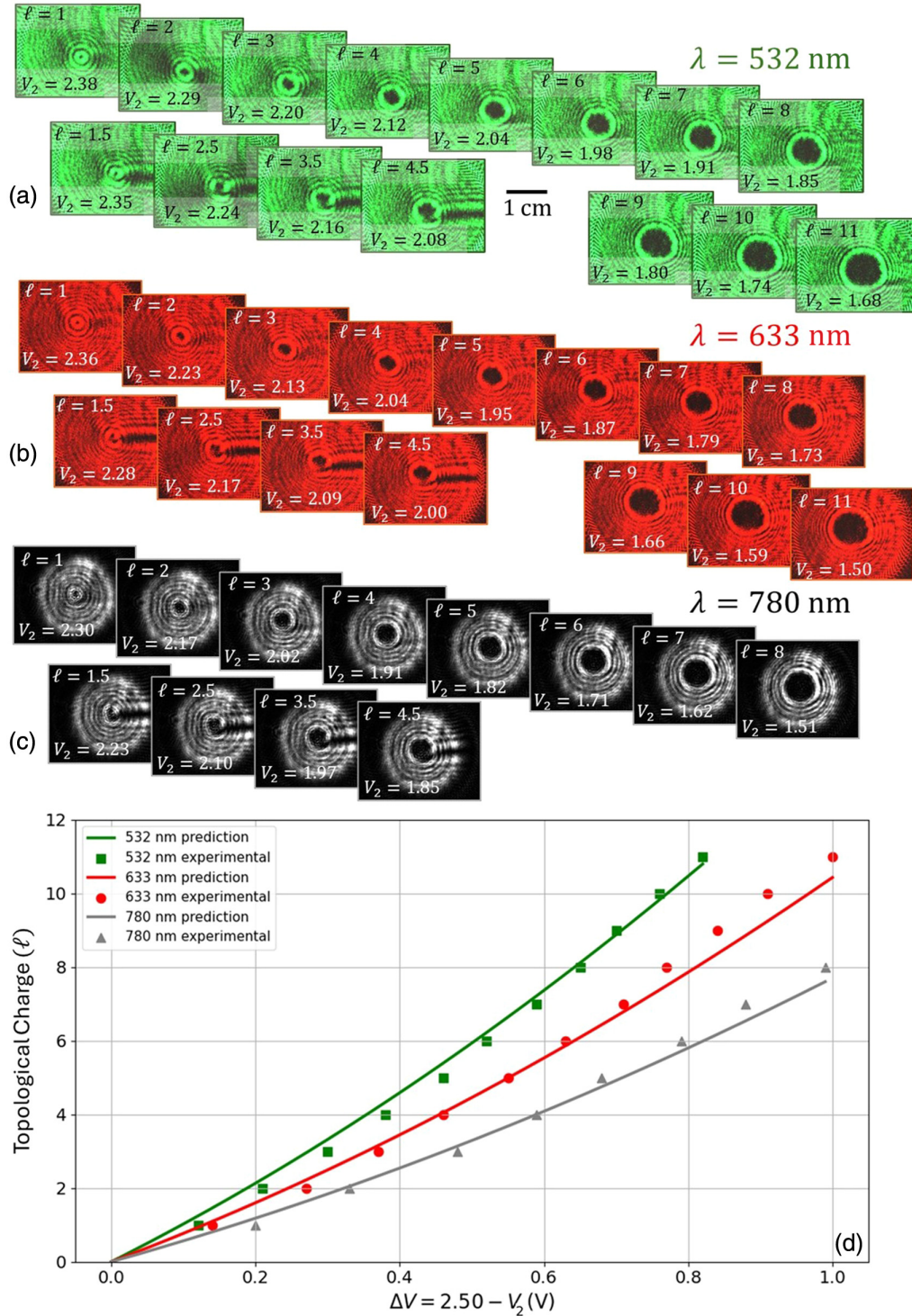


Fig. 6 Vortex beams generated at wavelengths (a) 532, (b) 633, and (c) 780 nm, after propagating 500 mm, showing different topological charges obtained when applying voltages $V_1 = 2.50$ V and different values of V_2 . (d) Topological charge versus voltage difference $\Delta V = 2.50 - V_2$. The unit of voltage is V.

monochromatic illumination at 532, 633, and 780 nm. The experimental results agree with the theoretical predictions based on the hyperspectral retardance characterization. These results support the advantage of the proposed technique as a practical tool for calibrating and operating adaptive LC phase devices over broad spectral ranges.

Furthermore, we would like to highlight that, using broadband achromatic circular polarizers as in Ref. 44, this hyperspectral technique can be useful to inspect other structured light devices, with both spatially variant retardance and optical axis distribution, such as modal q-plates⁴⁵ and meta-q-plates⁴⁶ that enhance the beam shaping capabilities with a single device.

Disclosures

The authors declare no conflicts of interest.

Code and Data Availability

Data underlying the results presented in this work may be obtained from the authors upon reasonable request.

Authors' Contribution

Sergio López-Rincón: investigation, methodology, software – programming, visualization – preparation, and writing – original draft.

Santiago Ríos-Álvarez: investigation, methodology, visualization – preparation, and writing – review & editing.

María del Mar Sánchez-López: formal analysis, supervision, and writing – review & editing.

Noureddine Bennis: formal analysis, methodology, and writing – review & editing.

Pascuala García-Martínez: formal analysis, funding acquisition, supervision, and writing – review & editing.

Ignacio Moreno: conceptualization, funding acquisition, supervision, and writing – original draft.

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