

Liquid-crystal modulators in optical phase-shifting interferometry and polarimetric imaging

Moduladores de cristal líquido en interferometría de desplazamiento de fase e imagen polarimétrica

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ABSTRACT:

This article summarizes the main scientific contributions of the doctoral thesis *Liquid-crystal modulators in optical phase-shifting interferometry and polarimetric imaging*. The thesis investigated liquid-crystal (LC) optical modulators as programmable devices for phase and polarization control in quantitative optical imaging. At the device level, two LC configurations were studied. First, a Mueller-matrix polarimetric framework was developed for twisted-nematic LC modulators, extending conventional Jones-matrix descriptions and enabling the determination of physical parameters from polarimetric measurements. Second, a special custom ferroelectric LC cell with a large in-plane switching angle was designed and experimentally validated for binary π -phase modulation ideally independent of the incident polarization state. At the system level, LC modulators were integrated into two quantitative imaging architectures. A pixelated parallel-aligned LC spatial light modulator was used for hologram generation and phase-shifting common-path interferometry, enabling phase retrieval of structured optical fields and tailored diffraction orders. In addition, single-pixel LC retarders were combined with a polarization camera to implement a programmable Mueller matrix imaging polarimeter with self-calibration capability and no moving polarization elements. Overall, the thesis demonstrates the use of LC modulators as compact, programmable, and metrological elements for phase-sensitive and polarization-sensitive optical imaging.

Key words: liquid-crystal modulators; Mueller matrix polarimetry; phase-shifting interferometry; spatial light modulators; structured light; polarization imaging.

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1. Introduction

Optical imaging techniques increasingly exploit properties of light beyond standard intensity modulation. In particular, the phase and polarization of an optical field provide quantitative information that cannot be obtained from irradiance measurements alone. Phase-sensitive methods are central to interferometry, wavefront analysis, holography, and structured-light characterization, while polarimetric methods describe how optical systems, materials, or samples transform the vectorial structure of incident light [1–3]. These approaches are therefore relevant to optical metrology, material characterization, biomedical imaging, and the analysis of structured optical components.

Liquid-crystal (LC) technology offers a versatile platform for implementing phase- and polarization-sensitive optical systems because LC devices behave as electrically tunable anisotropic elements. Their optical response is governed by the orientation of the molecular director and by the effective birefringence experienced by the incident light. By controlling the molecular orientation through an applied voltage, LC modulators can be used to modify intensity, phase, and polarization. They may be implemented as single-pixel devices, which apply a uniform optical transformation over the whole beam, or as pixelated spatial light modulators, which enable spatially varying phase or polarization patterns.

This article reviews the main scientific content of the doctoral thesis *Liquid-crystal modulators in optical phase-shifting interferometry and polarimetric imaging* developed at the Institute of Bioengineering of University of Miguel Hernández de Elche. The thesis was developed around two complementary directions: the device-level study of LC modulators and their system-level application in quantitative optical imaging. These contributions include the characterization and design of LC modulation devices, and their integration into interferometric and polarimetric imaging systems [4–8].

The article is organized as follows. Section 2 introduces the LC modulator technologies relevant to the thesis. Section 3 presents the device-level contributions, including the study of twisted-nematic and ferroelectric LC modulators. Section 4 describes the imaging-system applications in phase-shifting interferometry and Mueller matrix polarimetry. Finally, Section 5 summarizes the main results and conclusions.



2. Liquid-crystal modulators for phase and polarization control

Liquid-crystal (LC) modulators are electrically tunable anisotropic optical devices whose response is governed by the orientation of the LC molecules. The average molecular orientation is described by the director, which defines the local optical axis of the material. Because LC materials are birefringent, the refractive index experienced by an optical field depends on the orientation of the incident polarization with respect to this director. When an electric field is applied, the director distribution can be modified, changing the optical path difference accumulated by orthogonal polarization components. This electrically controlled birefringence is the basis for phase and polarization modulation in LC devices [9,10]. For a uniform retarder-like LC cell, the voltage-dependent retardance can be written as

$$\delta(V) = \frac{2\pi}{\lambda} \Delta n_{eff}(V) d \quad (1)$$

where $\delta(V)$ is the retardance, λ is the wavelength, d is the thickness of the LC layer, and Δn_{eff} is the voltage-dependent effective birefringence. This relation expresses the phase delay associated with the optical path difference ($\Delta n_{eff}(V)d$). Although it describes the basic operating principle of a tunable LC retarder, the complete modulation behaviour also depends on the LC phase, material parameters, boundary alignment, director distribution, and driving scheme.

LC modulator technologies are commonly distinguished by the LC phase and by the director alignment imposed by the cell substrates. In nematic LCs, the molecules exhibit long-range orientational order without positional layering, and the director can generally be reoriented continuously by an applied electric field. Electrically controlled birefringence modulators exploit this effect and behave as voltage-tunable retarders; common geometries include parallel-aligned nematic cells and vertically aligned nematic cells. Twisted-nematic devices are also based on the nematic phase, but crossed substrate alignments produce a helical director distribution, usually with a 90° twist, so their response combines voltage-dependent retardance with polarization rotation [11–13]. In contrast, ferroelectric LC modulators are typically based on the chiral smectic C phase, where the molecules are arranged in layers and the director is tilted with respect to the layer normal. The presence of spontaneous polarization enables bistable switching between two stable orientations, commonly separated by an in-plane angle of about 45° in standard devices, making FLCs suitable for fast binary intensity or phase modulation [14].

These technologies may be implemented as single-pixel devices, which apply a uniform optical transformation over the beam aperture, or as pixelated devices, which impose spatially structured modulation. This distinction is central to the thesis: single-cell LC modulators were studied at the device level, whereas pixelated LC spatial light modulators and single-pixel LC retarders were integrated into interferometric and polarimetric imaging systems.

3. Device-level original contributions

The first part of the thesis focused on LC modulators as optical devices. Two single-cell configurations were investigated in detail: a twisted-nematic LC modulator and a ferroelectric LC modulator. In both cases, the aim was to go beyond the standard use of the device and to provide either a more complete characterization method or a special custom configuration with specific phase-modulation properties. The twisted-nematic device was studied through a Mueller-matrix polarimetric framework, whereas the ferroelectric device was designed and validated as a non-standard polarisation insensitive binary π -phase modulator.

3.1. Mueller-matrix characterization of twisted-nematic LC modulators

Twisted-nematic LC modulators are commonly described using Jones-matrix models, which are appropriate for fully polarized and coherent light. In these models, the optical response of the cell is related to physical parameters such as the twist angle α , the orientation ψ_D of the LC director at the input surface, and the voltage-dependent retardance of the LC layer. However, the experimental determination of these parameters is not always direct. Conventional characterization methods may require several polarization measurements, simultaneous fitting of multiple curves, multiwavelength measurements, or additional procedures to resolve ambiguities such as the sign of the twist angle and the identification of the fast and slow axes.

The original contribution of this work was to extend the physical description of a twisted-nematic LC modulator from the Jones formalism to the Mueller-Stokes formalism [4]. This is convenient since the Mueller-Stokes formalism is widely used in polarimetric imaging, where LC devices have become essential

devices. For a non-depolarizing optical element described by a Jones matrix $\mathbf{J}$, the associated Mueller matrix elements m_{ij} can be obtained from the corresponding Jones matrix [3]:

$$m_{ij} = \frac{1}{2} \text{Tr}(\mathbf{J} \sigma_i \mathbf{J}^\dagger \sigma_j) \quad (2)$$

where $\mathbf{J}^\dagger$ is the Hermitian conjugate of $\mathbf{J}$, σ_i and σ_j are the Pauli matrices, including the identity matrix.

Using this relation, the Jones-matrix model of the twisted-nematic LC cell was translated into the Mueller-matrix formalism for the relevant modulation regimes, including the general case, the adiabatic limit, the first pure polarization-rotator point, and the standard 90°-twist configuration. These theoretical descriptions are summarized in Table 1. This formulation is important because each regime provides specific information about the physical behaviour of the device. In particular, at the pure rotator point the TN-LC cell behaves as an optical polarization rotator, allowing direct determination of the twist angle α . The retardance vector and polarization eigenstates obtained from the Mueller matrix provide access to the effective retardance components and to the director orientation ψ_D .

Table 1. Jones- and Mueller-matrix descriptions of the twisted-nematic LC cell for the main modulation regimes

Regime	Jones matrix $\mathbf{M}_{\text{TNLC}}$	Mueller submatrix $\tilde{\mathbf{m}}_{\text{TNLC}}$
General case	$e^{-i\beta} \mathbf{R}(-\alpha) \cdot \begin{bmatrix} X - iY & Z \\ -Z & X + iY \end{bmatrix}$	$\tilde{\mathbf{R}}(-\alpha) \cdot \begin{bmatrix} 1 - 2Z^2 & 2XZ & -2YZ \\ -2XZ & 2X^2 - 1 & -2XY \\ -2YZ & 2XY & 1 - 2Y^2 \end{bmatrix}$
Adiabatic limit ($\beta \gg \alpha$)	$e^{-i\beta} \mathbf{R}(-\alpha) \cdot \begin{bmatrix} \exp(-i\beta) & 0 \\ 0 & \exp(i\beta) \end{bmatrix}$	$\tilde{\mathbf{R}}(-\alpha) \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(2\beta) & -\sin(2\beta) \\ 0 & \sin(2\beta) & \cos(2\beta) \end{bmatrix}$
First pure rotator point ($\gamma = \pi$)	$e^{-i\beta} \cdot \begin{bmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{bmatrix}$	$\begin{bmatrix} \cos(2\alpha) & -\sin(2\alpha) & 0 \\ \sin(2\alpha) & \cos(2\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix}$
General case with standard twist ($\alpha = \pi/2$)	$e^{-i\beta} \cdot \begin{bmatrix} Z & -X - iY \\ X - iY & Z \end{bmatrix}$	$\begin{bmatrix} 2Z^2 - 1 & -2XZ & 2YZ \\ 2XZ & 1 - 2X^2 & 2XY \\ -2YZ & 2XY & 1 - 2Y^2 \end{bmatrix}$

Experimentally, the Mueller matrix elements of a single-pixel TN-LC modulator were measured as a function of the applied voltage. Figure 1(a) shows these measured elements together with the corresponding retarder matrix derived from the Lu–Chipman decomposition.

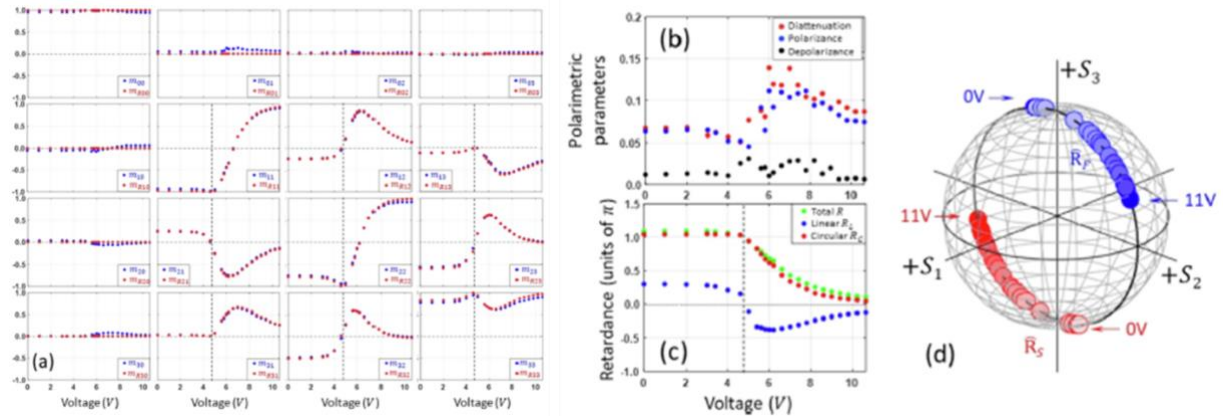


Fig. 1. Experimental Mueller-matrix characterization of the twisted-nematic LC modulator, showing the measured voltage-dependent response, the extracted retardance components, and the retarder eigenstates on the Poincaré sphere [4].

The associated diattenuation, polarizance, and depolarizance are shown in Fig. 1(b). Their small values confirmed that the measured response was dominated by the retarder contribution, allowing the voltage evolution of the matrix elements to be interpreted using the theoretical regimes summarized in Table 1.

From the retarder matrix, the effective total, linear, and circular retardance components were obtained, Fig. 1(c), and the polarization eigenstates of the retarder were represented on the Poincaré sphere, Fig. 1(d). These quantities enabled the extraction of the physical parameters of the TN-LC cell. The pure polarization-rotator point was used to determine the twist angle, while the polarization eigenstates provided the orientation of the input LC director. Selected Mueller-matrix elements further allowed the voltage-dependent modulation functions and microscopic retardance parameters of the TN-LC model to be retrieved [4].

The main result was the demonstration that Mueller-matrix measurements can be used not only to describe the macroscopic polarimetric response of a twisted-nematic LC modulator, but also to infer the physical parameters that govern its operation. The analysis also resolved ambiguities in the sign of the twist angle, the sense of rotation of the LC director, and the identification of the fast and slow axes. This established Mueller-matrix polarimetry as a practical single-wavelength method for physical characterization and calibration of TN-LC modulators.

3.2. Ferroelectric LC modulator for polarization-independent binary π -phase modulation

The second device-level contribution focused on ferroelectric LC modulators. Unlike nematic LC devices, whose director can generally be reoriented continuously, ferroelectric LC cells exhibit bistable switching between two stable molecular orientations. This fast binary response makes them attractive for optical modulation. In standard FLC devices, the two stable states are commonly separated by an in-plane switching angle of about 45° . Such configurations are useful for binary intensity modulation, especially when combined with polarizers, but they are not generally suitable as polarization-independent binary phase modulators.

The original proposal of this work was a special custom ferroelectric LC configuration with a large in-plane switching angle [5]. The device was designed so that the director rotation between the two bistable states approached 90° , rather than the standard 45° switching angle. Under this condition, the two stable states can ideally behave as equivalent retarders that differ only by a global π phase shift. As a result, the device can operate as a binary π -phase modulator for arbitrary incident polarization states, while ideally preserving the common output state of polarization in both switching states.

The operating principle can be understood by considering the two FLC states as two half-wave retarders whose optical axes are separated by 90° . In Jones-matrix terms, these two states produce the same polarization transformation but differ by a sign in the output optical field. This sign change corresponds to a relative π phase shift between the two bistable states. Therefore, instead of using the FLC cell mainly as a polarization switch or intensity modulator, the proposed configuration exploits its bistability to produce a pure binary phase modulation.

The achievement was the design, fabrication, and experimental validation of this non-standard FLC modulator. The device was fabricated by collaborators at the Military University of Technology in Warsaw and was experimentally characterized by locating its two stable states, evaluating its spectral and temporal behaviour, and verifying the phase modulation interferometrically. The analysis confirmed that the large switching angle was essential to obtain the intended polarization-independent binary phase response.

The main result was the experimental demonstration of binary π -phase modulation for different incident states of polarization as shown in Fig.2. The output polarization states corresponding to the two bistable configurations were analysed on the Poincaré sphere, while interferometric measurements confirmed the phase shift between the two states. The results showed that the proposed FLC cell can provide binary π -phase modulation for arbitrary input polarization states, with the output polarization ideally preserved in both modulation states.

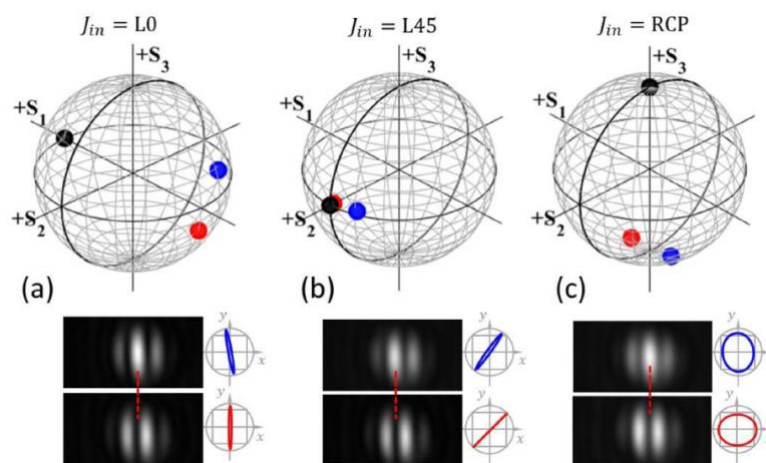


Fig. 2. Experimental validation of the special custom FLC modulator showing the output polarization states for different incident polarizations and the interferometric verification of the binary π phase shift between the two bistable states [5].

4. Applications in quantitative optical imaging systems

The second part of the thesis focused on the integration of LC modulators into quantitative optical imaging systems. After the device-level studies described in Section 3, LC technology was employed as an active element for phase and polarization control in two complementary imaging architectures. In interferometry, a pixelated parallel-aligned LC spatial light modulator was used for hologram generation and phase-shifting common-path interferometry. In polarimetry, single-pixel LC retarders were combined with a polarization camera to implement a programmable Mueller matrix imaging polarimeter.

4.1. Application in phase-shifting interferometry

Phase-shifting interferometry is a quantitative technique for retrieving the phase distribution of an optical field from a sequence of intensity measurements recorded with known phase shifts. In conventional interferometric arrangements, these phase shifts are introduced by mechanically or electronically modifying one arm of the interferometer. In the work reviewed here, the phase shifts were introduced electronically through a pixelated LC spatial light modulator, which also simultaneously generated the optical field to be characterized [6].

For the phase-shifting measurement, the intensity of the interference pattern can be written as

$$I(x, y) = I_0(x, y) \{1 + V(x, y) \cos[\alpha(x, y) + \varphi]\} \quad (3)$$

where $I_0(x, y)$ is the intensity term, $V(x, y)$ is the visibility of the interference fringes, $\alpha(x, y)$ is the phase distribution to be measured, φ is the reference phase shift, and (x, y) are the camera coordinates. A sequence of N interferograms, $I_n(x, y)$, is recorded by varying the constant phase term, $\varphi = \varphi_n$, with $n = 0, 1, \dots, N - 1$. In this implementation, the phase shifts were introduced electronically by adding constant phase offsets to the hologram displayed on the LC-SLM, allowing the phase distribution of the reconstructed field to be retrieved using phase-shifting interferometry algorithms.

The main achievement was the development of a compact common-path phase-shifting interferometric method in which the LC-SLM acted both as the beam-shaping element and as the phase-shifting element. This configuration reduced sensitivity to external mechanical instabilities because the interfering fields propagated along a common path. The method enabled the quantitative reconstruction of amplitude and phase distributions of holographically generated structured beams, including superpositions of Laguerre-Gaussian modes (LG) as shown in Fig 4 (e-h) [6].

The system (Fig.3) was based on a phase-only parallel-aligned LC spatial light modulator used to display computer-generated holograms. These holograms encoded diffractive optical elements for shaping the incident beam and generating structured light fields. By incorporating a diffractive lens into the displayed hologram, the Fourier transform of the diffracted field was formed at the back focal plane. A simple change in the polarization configuration converted this Fourier-transform holography arrangement into a common-path polarization self-interferometer, allowing the phase of the reconstructed field to be measured without adding an external interferometer [6].

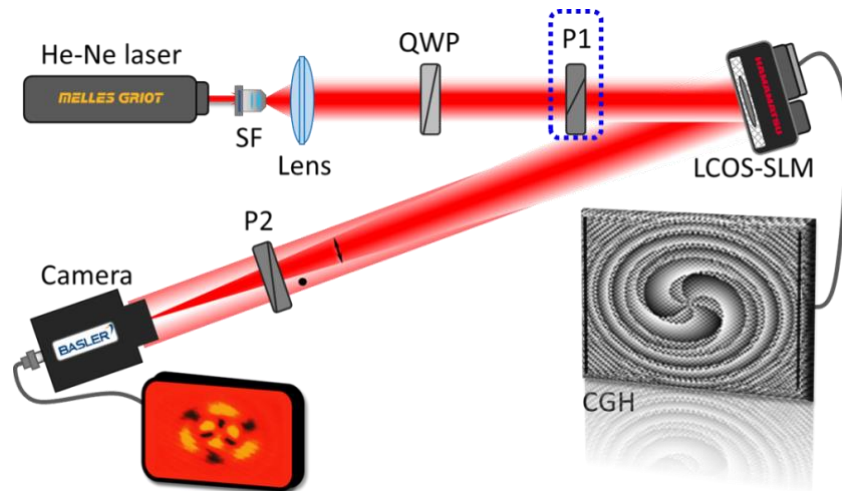


Fig. 3. Scheme of the optical system. SF: spatial filter, QWP: quarter-waveplate, P: linear polarizer, CGH: displayed phase-only computer-generated hologram [6].

The same methodology was later applied to the phase characterization of diffraction orders generated by phase-only gratings with tailored continuous phase profile [7]. In this case, the phase retrieved by the common-path interferometer made it possible to measure and compensate the quadratic phase introduced when a diffractive lens and a grating were encoded in the same SLM plane.

After this correction, the relative phase shifts among diffraction orders could be determined experimentally with the relevant compensation as shown in Fig 4 (a-b).

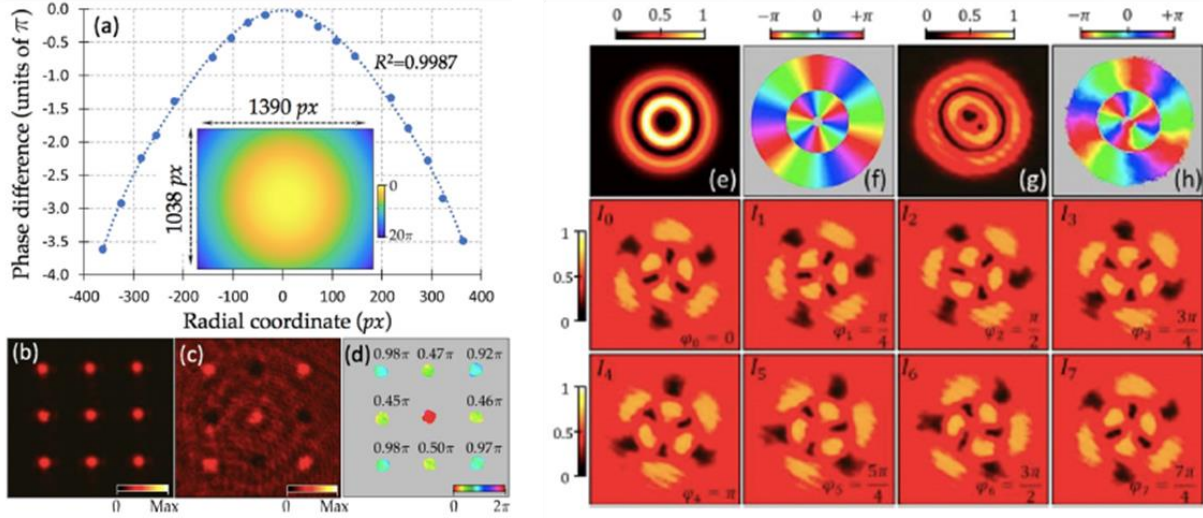


Fig. 4. (a) Experimental quadratic phase profile measured at the FT plane. The inset shows values at the complete area of the camera array. Nine diffraction orders generated by two crossed triplicators with a period of 12: (b) intensity, (c) interferogram, and (d) phase [7]. (e;g) theoretical and experimental intensity and (f;h) phase distributions of LG_{13} retrieved from the interferograms shown below with eight consecutive phase shifts of step $\Delta\phi = \pi/4$ [6].

4.2. Application in Mueller matrix imaging polarimetry

The second quantitative imaging application was the development of a complete Mueller matrix imaging polarimeter based on programmable LC retarders and a polarization camera [8]. While interferometry retrieves the phase distribution of an optical field, Mueller matrix polarimetry characterizes how a sample or optical component transforms the state of polarization of incident light. In an imaging implementation, this transformation is determined at each image pixel according to

$$S_{out}(x, y) = M(x, y) S_{in}(x, y) \quad (4)$$

where $S_{in}(x, y)$ and $S_{out}(x, y)$ are the incident and emerging Stokes vectors, respectively, and $M(x, y)$ is the spatially resolved Mueller matrix of the sample. From $M(x, y)$, polarimetric quantities such as retardance, diattenuation, polarizance and depolarization can be obtained.

The optical architecture combined LC retarders in the polarization state generator and polarization state analyser with a polarization camera in the detection arm. Figure 5(a) shows a picture of the developed imaging polarimeter, operating in a transmission and in a reflective geometry. The LC retarders enabled computer-controlled generation and analysis of the required polarization states, avoiding mechanically rotating elements. The polarization camera, based on a pixelated micro-polarizer array, recorded four linear polarization components in a single acquisition. This configuration provided a compact and automated imaging polarimeter suitable for the characterization of spatially varying polarization elements.

A central contribution of this work was the self-calibration strategy. The polarization camera was used as an internal reference to estimate and compensate errors in the generated and analysed polarization states, avoiding the need for external calibration equipment. In addition, the use of multiwavelength LED illumination extended the spectral operation of the system and reduced coherent speckle-like artefacts.

The system was validated using structured optical components, including patterned polarizers and retarders, which impose spatially varying polarization transformations. The reconstructed Mueller matrices and derived polarimetric parameters confirmed the capability of the instrument to characterize structured-light components quantitatively. As an example, Fig 5(b) shows the Mueller matrix retrieved for a birefringent resolution test, and Fig 5(c) some derived polarimetric parameters. This work therefore

demonstrated a compact, cost-effective, and fully programmable Mueller matrix imaging polarimeter with no moving polarization elements.

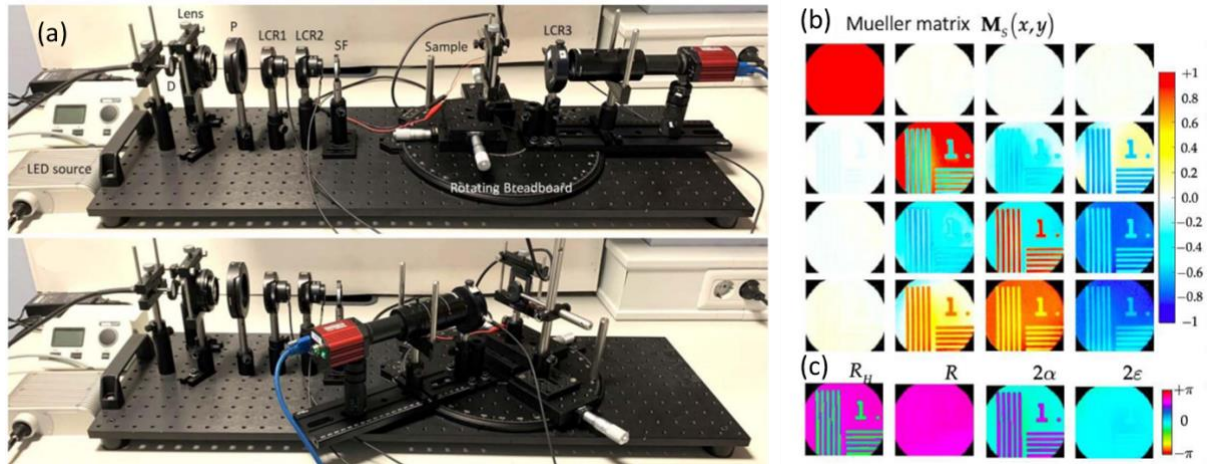


Fig. 5. (a) Scheme of the Mueller matrix imaging polarimeter (b) Experimental MM of the birefringent resolution test under red light channel illumination. (c) Retrieved horizontal linear retardance (R_L) and total retardance (R), and azimuth (α) and ellipticity (ϵ) of fast eigen states [8].

5. Conclusions

This article has reviewed the main contributions of the thesis to the use of LC modulators in quantitative optical imaging. At the device level, the work showed that the polarimetric response of twisted-nematic LC modulators can be linked to their physical parameters through a Mueller-matrix formulation, enabling single-wavelength characterization and resolving ambiguities in the determination of the twist angle, director orientation, and retardance properties. In addition, a special custom ferroelectric LC configuration was designed and experimentally validated for binary π -phase modulation for arbitrary incident polarization states.

At the system level, LC modulators were integrated into compact quantitative imaging architectures for phase and polarization measurement. A phase-only LC-SLM enabled common-path phase-shifting interferometry for the phase retrieval of structured optical fields and tailored diffraction gratings, while programmable LC retarders combined with a polarization camera enabled Mueller matrix imaging polarimetry without moving polarization elements. Overall, the thesis demonstrates the versatility of LC technology as a platform for compact, programmable, and metrological optical systems.

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