Geometric phase-encoded liquid crystal optical sensing

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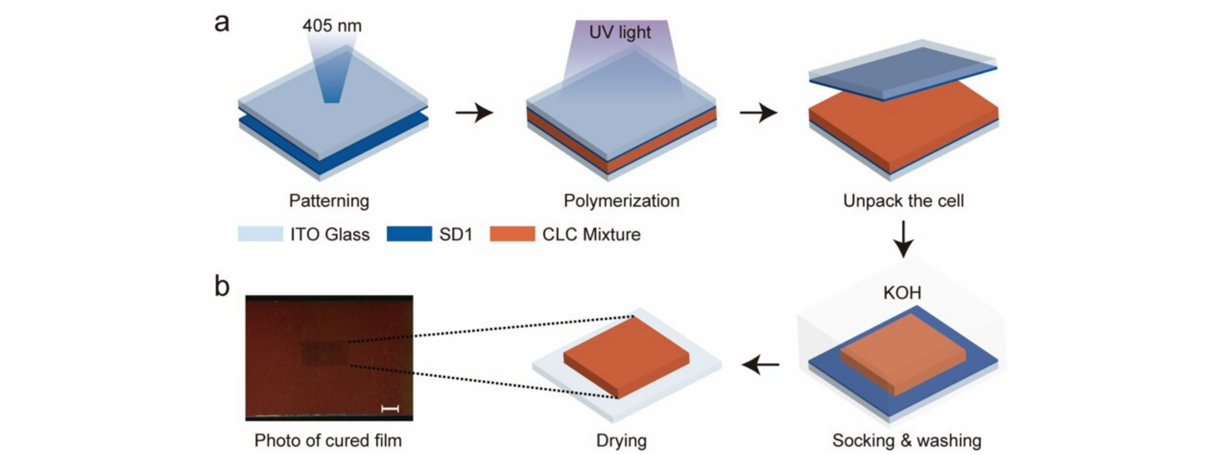

Fig. 1. a, fabrication process of humidity-responsive CLCP films with geometric phase encoding. b, Photo of the films cured at 65℃. The scale bar is 1 mm. Credit: Shi-Long Li, Zhao-Yi Chen, Peng Chen, Wei Hu, Chaohong Huang, Sen-Sen Li, Xuejia Hu, Yan-Qing Lu and Lu-Jian Chen

Sensing technology, integral to environmental monitoring, data acquisition, and precision data processing, is evolving rapidly. Researchers are at the forefront of developing swift, accessible, and cost-effective sensors. Among these innovations, cholesteric liquid crystals (CLCs) in stimulus-responsive photonic crystals exhibit exceptional promise.

Their unique helical structure and photonic properties enable the production of vivid, power-independent structural colors, paving the way for advanced visual analysis tools. However, a significant challenge hinders CLC's broader application in optical sensing: Although they visibly alter color in response to stimuli, accurately gauging these changes necessitates costly spectroscopic equipment, constraining their practical deployment.

Responding to the growing need for compact and planar optical elements, researchers have investigated Pancharatnam-Berry geometric phases, derived from light's spin-orbit interactions. Recent developments include integrating the geometric phase into reflected light via CLC helical superstructures, leading to novel photonic applications.

In CLC planar optics, this phase encoding alters the reflected light field across different wavebands, creating distinct visual patterns. This method surpasses traditional PBG wavelength/frequency sensing techniques. Additionally, the use of optical vortices (OV), which provide orbital angular momentum (OAM), has become pivotal in exploring tunable wavelength and OAM in vortex beams (VB).

To enhance sensing signal visualization, a team of researchers from Xiamen University and Nanjing University in China developed a cholesteric phase liquid crystal polymer (CLCP) visual sensing platform utilizing geometric phase coding.

This platform uniquely generates image-based sensing signals through real-time visual patterns, offering a more intuitive and readable alternative to conventional wavelength/frequency-based methods. The research is published in the journal *Light: Science & Applications*.

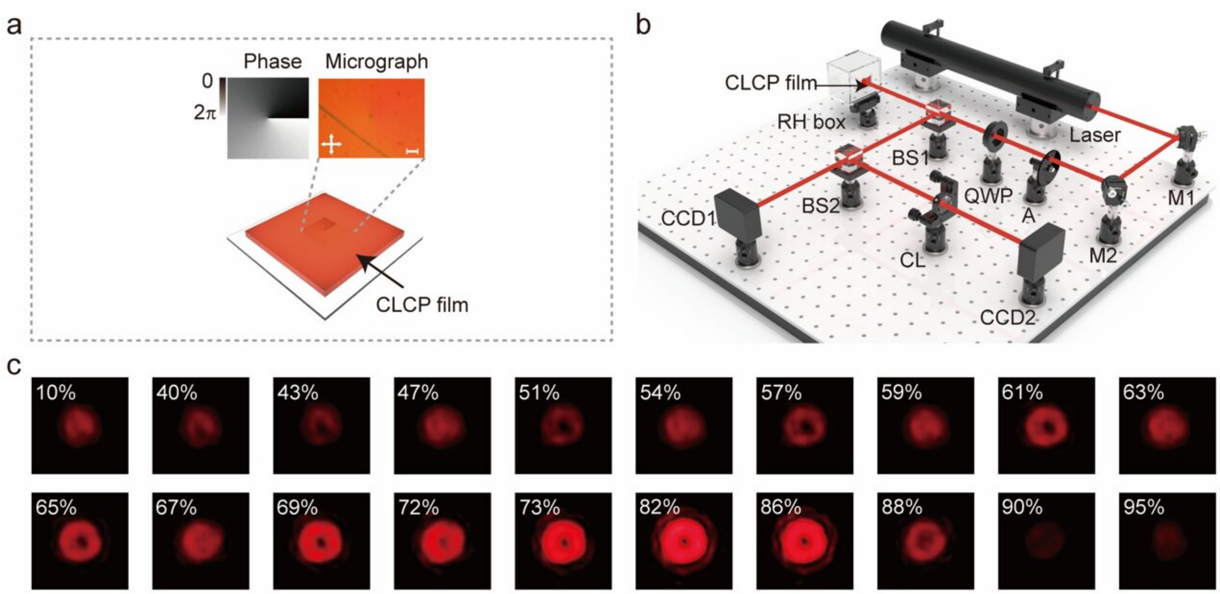

Fig. 2. a, schematic representation of a single q-plate encoded humidity-responsive CLCP film sample. The illustration shows a geometric phase pattern of the q-plate with a topological charge q = +0.5 (left), and micrograph of the encoded positions of humidity-responsive CLCP film cured at 65℃ (right). Orthogonal double-arrows indicate crossed polarizers. The scale bar is 100 µm. b, schematic diagram of the single-wavelength humidity monitoring system. Laser, 632.8 nm He-Ne laser, 15 mW/cm^2; M, mirror; A, attenuator; QWP, quarter waveplate; BS, beam splitter; CL, cylindrical lens; CCD, charge-coupled device. c, reflected diffraction patterns produced by a single q-plate encoded humidity-responsive CLCP film as the RH increases from 10% to 95%. Credit: Shi-Long Li, Zhao-Yi Chen, Peng Chen, Wei Hu, Chaohong Huang, Sen-Sen Li, Xuejia Hu, Yan-Qing Lu and Lu-Jian Chen

For proof-of-concept, the team demonstrated humidity detection using specially prepared CLCP films, composed of reactive liquid crystal monomers, photoinitiators, and chiral agents. As humidity increases, these films absorb water, expand, and undergo a pitch increase, leading to a reflective band's red-shift. This confirms CLCP's high humidity sensitivity, customizable response range, and excellent reversibility.

The team conducted an in-depth reflection diffraction analysis of humidity-responsive CLCP films, which encode a single q-plate, using a single-wavelength monitoring system. These experiments revealed that CLCP films can effectively translate changes in ambient humidity into visual signals. This finding underscores their suitability for real-time and long-range monitoring applications.

To broaden the humidity monitoring capabilities and detect trends, the researchers introduced two innovative approaches for studying the interaction between humidity and the geometrically phase-encoded CLCP films' reflected light (Fig. 3).

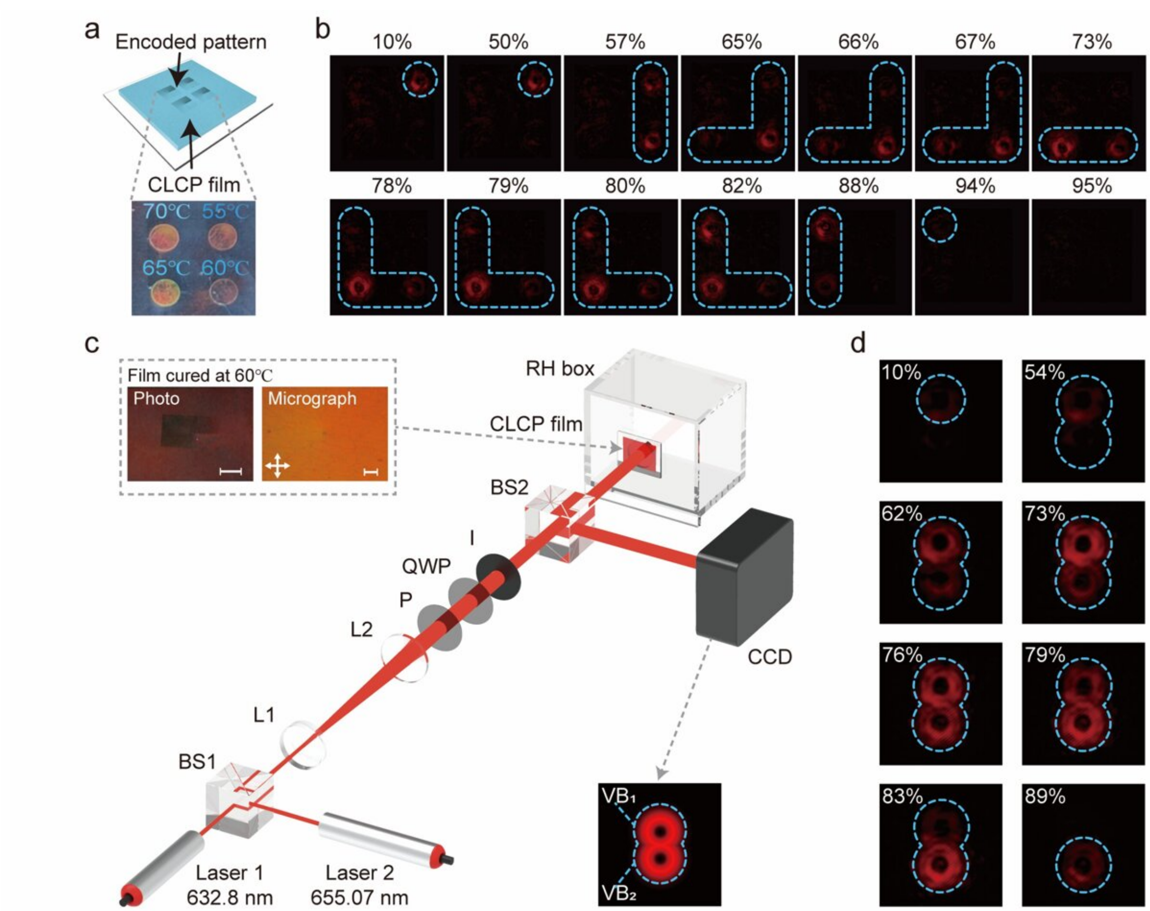

Fig. 3. a, schematic diagram of four-quadrant q-plate array encoded humidity-

responsive CLCP film sample (top). photograph of the film encoded with a four-quadrant q-plate array (bottom). b, reflected diffraction patterns of a CLCP film encoded with a four-quadrant q-plate, observed under a single-wavelength humidity monitoring system across varying RH levels. c, Schematic of the dual-wavelength humidity monitoring system. Insets: top left, photo (scale bar: 1 mm) and micrograph (scale bar: 100 μm) of the single q-plate encoded CLCP film, cured at 60℃; bottom right, diffracted light distribution. d, reflected diffraction patterns of a CLCP film encoded with a single q-plate, observed under a dual-wavelength humidity monitoring system across varying RH levels. Credit: Shi-Long Li, Zhao-Yi Chen, Peng Chen, Wei Hu, Chaohong Huang, Sen-Sen Li, Xuejia Hu, Yan-Qing Lu and Lu-Jian Chen

The first approach extended the monitoring range by incorporating a four-quadrant q-plate array onto the CLCP films. By UV curing each quadrant at different temperatures, distinct humidity ranges were achieved, correlating with variable VBs.

The second approach involved a dual-wavelength system, creating two VBs of different wavelengths. These VBs formed a dynamic "8" pattern, consisting of two "donut" shapes, responsive to humidity changes. These methods have proven effective in addressing the limitations of CLCP materials, enabling the monitoring of a broader humidity range and the detection of humidity trends.

This study introduces a novel CLCP optical sensing method using geometrical phase encoding, demonstrated through q-plate encoded humidity-responsive films. This technique allows for remote, non-contact humidity detection, creating VBs with clear "donut" patterns. It surpasses traditional liquid crystal sensing in accuracy, cost-efficiency, and commercial viability.

The approach is adaptable to various beam types, including Bessel and

Airy beams, offering potential for anti-jamming capabilities and customizable visual patterns. Integrating machine learning for image-based sensing, this technique promises significant advancements in sensor technology.

Future integration with fiber optic technology is anticipated, paving the way for innovative environmental monitoring in communication and energy networks.

More information: Shi-Long Li et al, Geometric phase-encoded stimuli-responsive cholesteric liquid crystals for visualizing real-time remote monitoring: humidity sensing as a proof of concept, *Light: Science & Applications* (2024). DOI: 10.1038/s41377-023-01360-7

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