

Soft Mattonics: harnessing light with liquid crystals

Wei Chen,^{1,2,†} Ze-Yu Wang,^{1,†} Xiao Yu,^{1,†} Jin-Tao Pan,^{1,†} Yang Wei,^{1,†} An-Zhuo Yu,^{1,†} Shen-Yi Yan,¹ Ling-Ling Ma,^{1,2,★} and Yan-Qing Lu^{1,2,★}

¹National Laboratory of Solid State Microstructures, Collaborative Innovation Center of Advanced Microstructures, College of Engineering and Applied Sciences, Nanjing University, Nanjing, China

²Key Laboratory of Intelligent Optical Sensing and Manipulation, Ministry of Education, Nanjing University, Nanjing, China

Abstract. We introduce Soft Mattonics—soft-matter photonics—as an emerging area dedicated to the comprehensive harnessing of light through programmable soft materials. Liquid crystals (LCs), with their directional molecular order and pronounced optical anisotropy, serve as a quintessential platform within this framework. This review presents a coherent narrative of how LCs have evolved from a scientific curiosity and display medium into a versatile, reconfigurable system for harnessing light. We articulate this progression along five interconnected frontiers: (i) from scalar to vectorial light manipulation, achieving independent control over polarization and phase; (ii) from free-space to in-plane device architectures, enabling integrated and flexible optical routing within soft materials; (iii) from linear to nonlinear regimes, unlocking second-harmonic generation and reconfigurable nonlinear geometric phases; (iv) from spatial to spatiotemporal modulation, allowing sculpting of complex structured wavepackets; and (v) from passive modulation to active emission, where self-assembled gain-anisotropy coupling yields tunable lasing and efficient luminescence. Together, these advances demonstrate that LCs can not only guide and modulate light but also generate it, establishing Soft Mattonics as a versatile, tunable, low-power, and information-centric photonic material platform. This platform is poised to advance adaptive optics, high-capacity communications, wearable and biomedical photonics, and quantum technologies.

Keywords: liquid crystal; light field manipulation; tunable optics.

Received Dec. 5, 2025; revised manuscript received Jan. 29, 2026; accepted Feb. 13, 2026; published online Mar. 27, 2026.

© The Authors. Published by CLP and SPIE under a Creative Commons Attribution 4.0 International License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.

[DOI: [10.3788/PI.2026.R03](https://doi.org/10.3788/PI.2026.R03)]

1 Introduction	3
2 From Scalar to Vectorial Light Manipulation	5
2.1 LCs as Programmable Media for Light Manipulation	5
2.1.1 Optical anisotropy and birefringence	5
2.1.2 Electrical and optical addressing	5
2.1.3 Light modulation in transmissive patterned LCs	6
2.1.4 One-dimensional soft photonic crystals: cholesteric LCs	6
2.1.5 Three-dimensional soft photonic crystals: blue phase LCs	7
2.2 Scalar LC Optics: Controlling Amplitude and Phase of Light	7
2.3 Vectorial LC Optics: Coordinated Control of Polarization and Phase	8

★Address all correspondence to Ling-Ling Ma, malingling@nju.edu.cn; Yan-Qing Lu, yqlu@nju.edu.cn

[†]These authors contributed equally to this work.

2.3.1 Planar LC devices for vector-field control	10
2.3.2 Generation of arbitrary vectorial wavefronts based on LCs	11
2.4 Emerging Frontiers and Representative Applications.	12
2.5 Discussion.	14
3 From Free-Space to In-Plane Light Steering	16
3.1 LC-Based In-Plane Waveguides for Guided Light Transport	16
3.1.1 Pure LC-based waveguides through in-plane alignment	16
3.1.2 Polymer-stabilized LC waveguides and ultrafast laser writing	16
3.2 In-Plane Self-Focusing Light Transport and Soliton Dynamics	17
3.2.1 From birefringent soft matter to a $\chi^{(3)}$ workbench	17
3.2.2 Experimental emergence of optical solitons	18
3.2.3 Steering of optical solitons	18
3.2.4 Functionalization of optical solitons through self-induced waveguides.	20
3.3 In-Plane Transformation Optics and Analog Cosmology	20
3.3.1 TO and ray tracing based on LC structures	20
3.3.2 In-plane observation and cosmic analogy	22
3.4 In-Plane Light Flow in Chiral Nematics and Beam-Driven Topological Matters	23
3.4.1 Chirality-enhanced in-plane nonlinear transport.	23
3.4.2 In-plane light-topological structure interactions	24
3.5 In-Plane Optical Branched Flow in Disordered LC Films	24
3.5.1 Branched flow phenomenon in diverse physical systems	24
3.5.2 Tailoring optical branched flow in LC films	24
3.6 Discussion.	25
3.6.1 Structured-light information processing	25
3.6.2 On-chip LC photonics and lasing	25
4 From Linear to Nonlinear Optical Processing	26
4.1 Linear Optical Modulation in LC Systems	26
4.2 Classical Nonlinear Optics in LCs.	27
4.3 Nonlinear Optical Limitations of LC Platforms	28
4.4 FNLC: Material Properties.	29
4.5 SHG Microscopy in FNLCs.	31
4.6 Nonlinear Geometric-Phase Modulation and Spin-Orbit Coupling in FNLCs	32
4.7 FNLCs Bridging Classical and Quantum Optical Regimes	34
4.8 Discussion.	35
5 From Spatial to Spatiotemporal Light Shaping.	36
5.1 Joint Manipulation of Spatial and Temporal Degrees of Freedom	36
5.2 STWPs Generated with LC-SLM-Based Pulse Shaper	37
5.3 Multidimensional Control of Structured ST Fields	43
5.4 Discussion.	46
6 From Passive to Active Light Emission	47
6.1 Evolution of Luminescent LC Architectures	48
6.1.1 Passive LC systems	48
6.1.2 Active luminescent LC systems	48
6.2 Photophysical Mechanisms in LLCs	50
6.2.1 Passive modulation mechanisms	50
6.2.2 Active luminescence mechanisms	50
6.2.3 Coupling mechanisms.	52
6.3 Stimuli-Responsive and Adaptive LLC Systems.	52
6.3.1 Photo-thermal response	52
6.3.2 Electromagnetic response	54
6.3.3 Stress response	54
6.4 Expanding the Dimensionality of Emission Control	54
6.4.1 Expansion in the polarization dimension	55
6.4.2 Spatial directionality and orientation control.	55

6.4.3 Regulation of luminescence dynamics	57
6.4.4 Multimodal coupling	57
6.5 Photonic and Optoelectronic Applications of LLC Systems	58
6.5.1 Display and lighting devices	58
6.5.2 Information encryption and anti-counterfeiting applications	58
6.5.3 Flexible optoelectronic devices	59
6.5.4 Photoinduced asymmetric synthesis	60
6.6 Discussion	61
7 Conclusion and Outlook	62
Acknowledgments	63
References	63

1 Introduction

Soft matter photonics, referred to here as “Soft Mattonics,” is an emerging and rapidly evolving interdisciplinary field, which not only encompasses the study of light–soft matter interactions but also extends beyond photonics to include a broader class of disciplines whose names end with “-onics,” such as soft matter electronics^[1–3]. This nomenclature reflects the inclusive and expansive nature of the field. Soft Mattonics explores the intricate interplay between light and soft materials, opening up new avenues for innovation in optical communication, sensing, energy harvesting, and beyond. On the one hand, light serves as a potent tool to manipulate soft materials, triggering molecular configuration transitions, guiding the self-assembly of functional microstructures, and even driving macroscopic shape morphing. This enables efficient, precise, remote, and multilevel control across various scales. On the other hand, soft materials, with their finely tuned nano- and microscale architectures, interact with light in ways that allow for the manipulation of multiple degrees of freedom, including amplitude, polarization, phase, orbital angular momentum, frequency, and wave vector. This bidirectional interaction, using soft matter to control light and light to control soft matter, forms the core of Soft Mattonics, establishing a fertile ground for next-generation optical and electronic technologies^[1–3].

Liquid crystals (LCs) represent a paradigmatic soft matter system within the Soft Mattonics framework. When liquids exhibiting crystalline behavior were first reported in the 1880s—Reinitzer’s observations of “double melting”^[4] and Lehmann’s mesophases^[5]—few could have imagined that such a soft, weakly ordered fluid would evolve into a programmable platform for photonics. Across successive generations of materials and devices, LCs have enabled application-driven advances in large-aperture, low-voltage modulation^[6,7]. Twisted-nematic cells, wave plates, and phase-only spatial light modulators (SLMs) were engineered to optimize either phase or amplitude^[8–10], providing robustness and manufacturability, while leaving polarization and other degrees of freedom only weakly coupled. Today, as alignment strategies and geometric-phase methods enter maturity^[11–15], control is undergoing a transition from single-parameter adjustment to coordinated, multi-degree-of-freedom design^[16–19]. The current emphasis is therefore shifting toward more comprehensive field control within a soft matter architecture where low-power, large-area formats, and reconfigurability are intrinsic^[20–22].

As scalar control yields to vectorial operation, patterned alignment and Pancharatnam–Berry (PB) geometric phase optics elevate polarization to parity with phase and amplitude^[20,23,24],

establishing LC-based vectorial manipulation in planar elements and in metasurface-integrated platforms^[25]. Spatially varying optic axes realized by photoalignment or anchoring engineering^[26–28] imprint spin-orbit coupling across the LC, producing polarization-dependent wavefronts and vector beams via digitalized geometric phases^[29] and vectorial LC holography^[30], as well as polarization-selective components compatible with wafer-scale processing and low bias^[27,28]. The geometric phase provides a broadband, wavelength-insensitive design handle^[20,31,32] that complements dynamic phase, enabling co-design of phase, polarization, and orbital angular momentum (OAM)^[31], with physics-constrained computer-generated holography further boosting performance without sacrificing device yield or efficiency^[30]. The result is a richer modal basis for beam shaping and multiplexed functionality suited to optical signal processing and high-throughput photonics, while retaining the advantages of a soft, low-power platform rooted in LC soft-matter architectures^[2] and bolstered by electrically controlled flat-optics hardware^[33,34] and mechanically/field-responsive LC systems across terahertz (THz)-visible bands^[35–37], together with planar LC singlets that unify imaging and spectrometry for scalable integration^[36].

The propagation geometry correspondingly extends from free space to in-plane photonics, where orientational order defines an effective refractive-index metric^[38–40]. Once light is coupled into the film, the director field delineates a dynamic scaffold for rewritable gradient index channels, voltage-switchable junctions, and defect guided conduits^[41–43]. Photoalignment sets templates for director landscapes^[43,44]; polymer stabilization and ultrafast laser inscription enable the fabrication of guiding, bending, and enabling transparent display while suppressing molecular fluctuations^[41,45,46]; voltage-induced reorientation adds an additional degree of freedom, offering rapid and energy-efficient reconfiguration of transporting pathways^[47,48]. The distinctive strength of in-plane LC optics lies in its role as a reconfigurable testbed, a laboratory for the fusion of multiple physical fields. Nonlocal elasticity supports milliwatt-level self-focusing and establishes optically written waveguides^[49–53] that can be steered, reflected, or driven to exhibit negative refraction under appropriate bias^[54–56]. Chirality further enriches this toolbox: cholesteric order enhances the effective reorientation amplitude and introduces a reflection band^[57–59], and intrinsic textures, skyrmions, torons, and twisted walls, act as readdressable photonic elements^[60]. Even weak disorder, often regarded as detrimental, can be harnessed by tuning the branched flow^[61–63]. In-plane LC photonics therefore emerges not merely as an extension of free-space optics, but as a uniquely reconfigurable landscape where geometry,

topology, and anisotropy converge to enable soft matter platforms for on-chip and free-space photonic processing.

Beyond linear transport and $\chi^{(1)}$ control, native $\chi^{(3)}$ nonlinearities enable self-phase modulation, cross-phase modulation, and Kerr-like guiding^[64–67], while the recent identification of ferroelectric nematic phases relaxes the long-standing bulk $\chi^{(2)}$ constraint^[68–70]. Spontaneous polarization, large permittivity, ultrafast electro-optic response, and high birefringence together yield a strong, multi-stimulus tunable $\chi^{(2)}$ in a fluid medium^[69–74]. This supports low-voltage second-harmonic and difference frequency generation^[75–78] and enables nonlinear geometric phase encoding to harness phase and OAM of harmonic fields^[79–82]. The same platform supports spontaneous parametric downconversion with programmable polarization^[83] and chiral, nonreciprocal pathways for an entangled photon pair source^[84], coupling amplitude, polarization, OAM, frequency, and time within a single reconfigurable material system for quantum and classical photonic information handling^[79,85,86].

The intrinsic tunability of LCs extends their functionality beyond spatial beam control toward full spatiotemporal (ST) optical field modulation. In $4f$ pulse-shaping architectures, LC modulators map the spectrum to space at the Fourier plane^[87–89], enabling pixel-resolved control of spectral phase and amplitude^[90–92] that reconstructs in the time domain. The convergence of these spatial and temporal developments has recently led to ST optical field control, and the resulting ST wavepackets (STWPs) exhibit prescribed axial dynamics^[93,94], tunable (including negative) group velocities^[93,95,96], and programmable polarization evolution within a single ultrafast light pulse^[97,98]. Building on this precise control over the ST properties of light, recent studies have further demonstrated that time-varying topological structures can be synthetically engineered. Therefore, time-dependent topology can be realized in ST optical vortices (STOVs)^[99–102], toroidal vortices^[103,104], and optical hopfions^[105], and the OAM content can vary across a pulse to form “light springs” via time-varying OAM or multi-comb synthesis^[106–108]. Furthermore, coupled with in-plane LC photonics and ferroelectric $\chi^{(2)}$ processes, these sources can be routed, frequency converted, and re-encoded within the same soft platform—e.g., second-harmonic generation (SHG) and high-order harmonic generation (HHG) of ST beams with OAM conservation—enabling dispersion-robust propagation and agile waveform control for optical computing tasks and high-dimensional encoding^[109–111].

LC systems are also advancing from passive optical regulation to active luminescence control^[3,112]. By incorporating organic luminescent materials^[113–115], rare-earth luminescent materials^[116,117], and quantum dot luminescent materials into ordered LC matrices^[118–120], it is possible to regulate aspects such as the spatial orientation of the luminescent materials, the polarization state of the emitted light, and the photoluminescence dynamics. Specifically, the oriented arrangement of LC molecules can induce uniform orientation of luminescent materials, achieving linearly polarized light emission^[116], while the optical bandgap of cholesteric LC (CLC) can induce circularly polarized light emission^[114]. The LC medium environment can further regulate the photoluminescence dynamics of the luminescent materials, enabling laser emission, chiral amplification of luminescence, and control of energy transfer processes^[121–123]. More importantly, the multi-stimulus responsivity of LC allows dynamic and reversible regulation of optical properties such as wavelength, lifetime, amplitude, polarization, and phase^[116,124,125], greatly expanding the dimensions of optical information control in LC systems and

making them ideal materials for next-generation optoelectronic information platforms.

Taken together, these developments reshape LCs as a powerful soft-matter platform that systematically broadens the controllable dimensions of the optical field. By unifying vectorial field control, in-plane guidance and steering, linear-nonlinear interactions, ST field sculpting, and active emission at low power and over large areas, LCs realize, within a soft, weakly ordered fluid, the kind of programmable photonics for optical information processing that few would have anticipated at their origins (Fig. 1). This review follows that trajectory, positioning LCs as a medium in which soft order can shape, guide, transform, and generate light across an integrated, high-dimensional

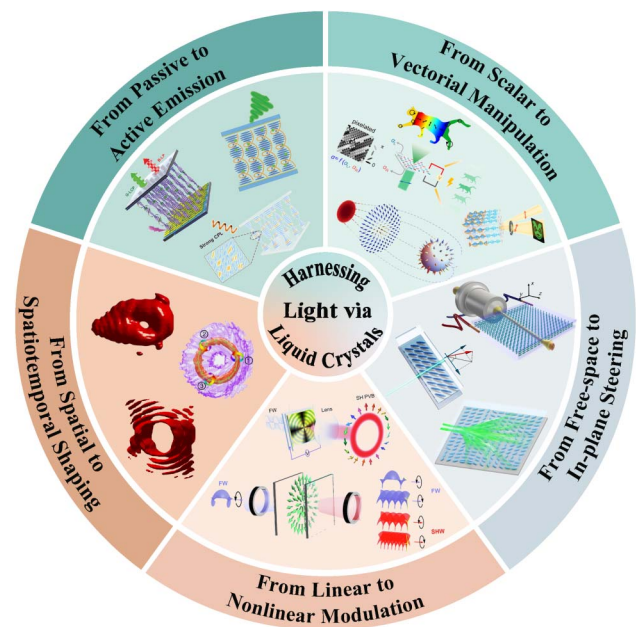


Fig. 1 Soft Mattonics with liquid crystals (LCs). Schematic overview of five converging directions: (i) scalar to vectorial manipulation. Reprinted with permission from Ref. [30], © Springer Nature (2024). Reprinted with permission from Ref. [126], © Springer Nature (2024). Reprinted with permission from Ref. [127], © Wiley-VCH GmbH (2023). (ii) Free-space to in-plane steering, Reprinted with permission from Ref. [48], © Springer Nature (2004). Reprinted with permission from Ref. [53], © Springer Nature (2018). Reprinted with permission from Ref. [62], © Wiley-VCH GmbH (2024). (iii) Linear to nonlinear modulation. Reprinted with permission from Ref. [79], © Springer Nature (2024). Reprinted with permission from Ref. [82], © Springer Nature (2025). (iv) Spatial to spatiotemporal (ST) shaping. Reprinted with permission from Ref. [99], © Springer Nature (2020). Reprinted with permission from Ref. [103], © Springer Nature (2022). Reprinted with permission from Ref. [104], © American Physical Society (2024). (v) Passive to active emission. Reprinted with permission from Ref. [114], © Wiley-VCH GmbH (2024). Reprinted with permission from Ref. [116], © Wiley-VCH GmbH (2022). Reprinted with permission from Ref. [128], © Wiley-VCH GmbH (2023). These directions collectively enable programmable, high-dimensional light harnessing within a single LC platform.

landscape tailored to next-generation optical information processing under the Soft Mattonics framework.

2 From Scalar to Vectorial Light Manipulation

2.1 LCs as Programmable Media for Light Manipulation

In the realm of Soft Mattonics, the evolution from scalar to vectorial manipulation of light using LCs marks a key advancement toward programmable, high-dimensional photonics. From an information-theoretic perspective, vectorial light fields inherently carry a far greater information capacity than their scalar counterparts. While scalar fields are described only by amplitude and phase, vectorial fields incorporate additional degrees of freedom such as polarization orientation, ellipticity, and spatially varying vectorial structures. Each of these dimensions can be independently encoded and multiplexed, substantially expanding the Hilbert space available for information representation.

In information theory, the entropy $H(X)$ of a discrete random variable X with possible values $\{x_1, x_2, \dots, x_n\}$ and probability mass function $P(X)$ is defined as

$$H(X) = - \sum_{i=1}^n P(x_i) \log P(x_i), \quad (2-1)$$

where $P(x_i)$ is the probability of the occurrence of event x_i . The logarithm is typically taken base 2, in which case the unit of entropy is bits. According to the entropy formula [Eq. (2-1)], this expansion directly leads to a corresponding increase in information entropy^[129]. Consequently, vectorial light fields enable higher-dimensional information channels that are particularly advantageous for applications in optical communication, imaging, encryption, and quantum information processing, where maximizing channel capacity and robustness against noise are of paramount importance.

The ability to manipulate optical fields with high precision lies at the heart of modern photonics^[130], enabling breakthroughs in imaging, communication, quantum information, and laser material processing. Among the diverse platforms for light control, LCs^[2] stand out due to their unique combination of large birefringence, reconfigurable molecular orientation, low driving power, and compatibility with mature device fabrication processes. From the earliest demonstrations of LC-based SLMs to the development of complex metasurface-like LC elements^[131], LC photonics has provided versatile tools for shaping both the scalar and vectorial properties of light^[132,133].

Historically, the first stage of LC-mediated optical control focused primarily on scalar fields, where modulation of amplitude and phase defined the frontier of beam shaping. LC-SLMs enabled dynamic holography, adaptive optics, and programmable diffractive optics, allowing researchers to synthesize propagation-invariant beams such as Bessel or Airy beams, as well as diffraction-limited focusing for microscopy and projection. These scalar approaches laid the foundation for practical applications in display technology, optical communication, and imaging systems, but they inherently neglected the vectorial degrees of freedom of light.

A natural progression emerged as researchers began exploiting the polarization-dependent response of LCs^[24]. The discovery and practical use of the PB geometric phase in patterned LC structures opened an entirely new avenue for vector beam

generation. Through spatially varying LC alignment, one can tailor local polarization transformations and thereby construct beams with spatially structured polarization states. This shift enabled the generation of radial and azimuthal vector beams, optical vortices carrying OAM^[134], and hybrid beams with complex coupling between amplitude, phase, and polarization. Such vectorial fields exhibit polarization singularities, enhanced focusing, and novel light-matter interaction mechanisms, marking a departure from purely scalar paradigms.

Today, the transition from scalar to vectorial control represents a cornerstone in the evolution of LC-based photonic devices. On one hand, scalar modulation continues to underpin high-efficiency holography, optical trapping, and display technologies. On the other hand, vectorial control has unlocked multidimensional encoding in optical communications, high-resolution polarization-sensitive microscopy, and versatile quantum state preparation. The convergence of these approaches has led to hybrid LC devices capable of simultaneously addressing amplitude, phase, and polarization, pointing toward a future of full-dimensional optical field control.

LCs occupy a unique position between solid and liquid phases, exhibiting long-range orientational order alongside fluidity. Their optical anisotropy and controllable molecular orientation provide a natural platform for photonic devices. Understanding the fundamental physics of LC-based light control is essential before addressing the progression from scalar to vectorial regimes.

2.1.1 Optical anisotropy and birefringence

At the microscopic level, LC molecules are elongated and tend to align along a preferred direction described by the director $\hat{n}$. Due to their anisotropic polarizability, light propagating through an LC experiences different refractive indices depending on its polarization relative to $\hat{n}$. This property, known as birefringence, can be expressed as

$$n(\theta) = \frac{n_o n_e}{\sqrt{n_o^2 \cos^2 \theta + n_e^2 \sin^2 \theta}}, \quad (2-2)$$

where n_o and n_e are the ordinary and extraordinary refractive indices, respectively. As shown in Fig. 2(a), θ is the angle between the optical field and the LC director. By controlling $\hat{n}$, one directly controls the effective optical path and thus the phase of transmitted light.

2.1.2 Electrical and optical addressing

The most common approach to controlling LC alignment is via external electric fields. Applying voltage across an LC cell induces dielectric torque that reorients the director. The corresponding optical phase modulation is given by

$$\Delta\varphi = \left(2\pi \frac{d}{\lambda}\right) (n_{\text{eff}} - n_o), \quad (2-3)$$

where d is the cell thickness, λ is the wavelength, and n_{eff} is the voltage-dependent effective refractive index. This principle underpins LC-SLMs and tunable retarders, as displayed in Fig. 2(b)^[131].

Alternatively, optical addressing methods employ photoalignment layers, often based on azo-dye molecules, to imprint spatially varying orientations by polarized light exposure. This

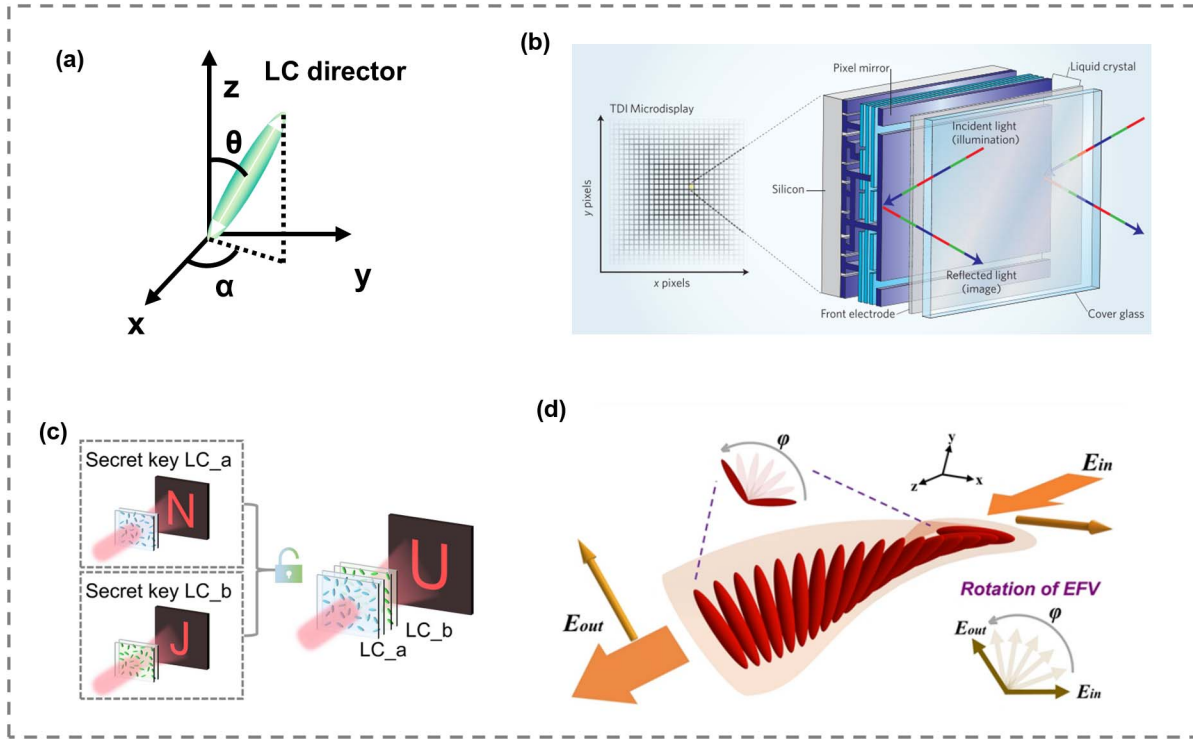


Fig. 2 Light field modulation via LCs. (a) The three-dimensional orientation of LC molecules imparts them with the capabilities of geometric phase modulation and propagation phase modulation. (b) LC SLM (LC-SLM). Reprinted with permission from Ref. [131], © Springer Nature (2010). (c) Geometric phase: planar LC device. Reprinted with permission from Ref. [135], © Optica Publishing Group (2023). (d) The optical rotation effect is achieved by TNLCs^[136].

technique allows fabrication of patterned LC devices with sub-micron precision, enabling more complex and static phase or polarization manipulations without electrical wiring.

2.1.3 Light modulation in transmissive patterned LCs

The transmission matrix for each LC domain can be written using the Jones matrix of $T(\alpha) = R(\alpha) \begin{bmatrix} e^{-i\frac{\Gamma}{2}} & 0 \\ 0 & e^{i\frac{\Gamma}{2}} \end{bmatrix} R(-\alpha)$, where α denotes the in-plane orientation angle of the LC director, as displayed in Fig. 2(a), $R(\alpha)$ represents the rotation matrix, and Γ is the phase retardation between an ordinary wave and an extraordinary wave.

The relation between incident and output electric fields of the LC can be written as $E_{out} = T(\alpha)E_{in}$; when circularly polarized light is incident, an additional phase associated with in-plane orientation α of the LC director is generated, and the expression of the transmission field is derived as

$$E_{out} = T(\alpha)E_{in} = T(\alpha) \begin{bmatrix} 1 \\ \pm i \end{bmatrix} = \left(\frac{e^{-i\frac{\Gamma}{2}} + e^{i\frac{\Gamma}{2}}}{2} \right) \begin{bmatrix} 1 \\ \pm i \end{bmatrix} + \left(\frac{e^{-i\frac{\Gamma}{2}} - e^{i\frac{\Gamma}{2}}}{2} \right) e^{i(\pm 2\alpha)} \begin{bmatrix} 1 \\ \mp i \end{bmatrix}. \quad (2-4)$$

It converts the incident CP light into the opposite helicity with imprinted geometric phases $e^{\pm i2\alpha}$ ($|\mathbf{R}\rangle \rightarrow e^{+i2\alpha}|\mathbf{L}\rangle$ and $|\mathbf{L}\rangle \rightarrow e^{-i2\alpha}|\mathbf{R}\rangle$, where $|\mathbf{L}\rangle$ and $|\mathbf{R}\rangle$ stand for the spin of light,

which enables a planar nematic LC (NLC) holography device [Fig. 2(c)]^[135]. The acquired geometric phases show a linear relation of twice α . The conversion efficiency depends on the wave plate transformation implemented by the LC, where $|\mathbf{L}\rangle = \frac{\sqrt{2}}{2} \begin{bmatrix} 1 \\ -i \end{bmatrix}$, $|\mathbf{R}\rangle = \frac{\sqrt{2}}{2} \begin{bmatrix} 1 \\ i \end{bmatrix}$. In addition, twisted nematic LCs (TNLCs) can also be used as polarization rotation devices and have been widely applied in LC displays [Fig. 2(d)]^[136]. In smectic LCs, special topological structures exist that enable simultaneous modulation of geometric phase and propagation phase^[137].

2.1.4 One-dimensional soft photonic crystals: cholesteric LCs

CLCs are characterized by a helical molecular arrangement^[138,139], where the director rotates with a periodicity defined by the pitch p . For light incident along the helix axis, as depicted in Fig. 3(a)^[27], CLCs exhibit Bragg reflection within the spectral window. Importantly, only circularly polarized light with the same handedness as the helix undergoes reflection, while the opposite handedness is transmitted. This selective reflection provides the foundation for polarization-dependent geometric phase control.

When circularly polarized light is Bragg-reflected by a CLC, the reflected optical phase is governed by the so-called helix phase ϕ , defined by the molecular orientation at the substrate surface. Owing to the head-tail symmetry of the director, the reflected phase shift equals 2ϕ ^[20]. Consequently, a π -rotation of the helix corresponds to a 2π change in the reflected phase. This mechanism constitutes the reflective PB phase, endowing CLC devices with nearly perfect circular polarization selectivity

and full $0-2\pi$ phase coverage. For linearly polarized (LP) light, a right-handed CLC reflects the right circular polarization (RCP) component and a reflective PB phase of $+2\alpha$ is imprinted, while left circular polarization (LCP) is transmitted without PB phase modulation^[31]. Conversely, a left-handed CLC reflects the LCP component with a -2α PB phase, while the RCP component is transmitted.

2.1.5 Three-dimensional soft photonic crystals: blue phase LCs

Blue phase LCs (BPLCs) represent a distinct class of soft mesocrystals formed by the self-assembly of double-twisted cylinders (DTCs) into three-dimensional cubic lattices, corresponding to body-centered cubic (BP I) and simple cubic (BP II) phases^[2,140,141]. This unique hierarchical order introduces three structural degrees of freedom—chirality, lattice constant, and cubic orientation—which establish one-to-one correspondence with the fundamental degrees of freedom of light.

BPLCs selectively reflect circularly polarized light with the same handedness as the helical twist of the DTCs, due to Bragg reflection. This feature enables spin-selective light modulation, in which left- and right-handed circular polarization states experience entirely different optical responses. The reflection band of BPLCs is directly related to the lattice constant (p). By controlling or tuning p , BPLCs provide sharp wavelength selectivity across the visible spectrum, enabling efficient full-color reflection and spectral light modulation. The azimuthal orientation of the cubic lattice determines the PB geometric phase imparted on reflected light. Spatial modulation of the lattice orientation allows for arbitrary two-dimensional phase engineering of wavefronts, including vortex generation, structured holography, and beam shaping.

Multi-Degree and Orthogonal Control. By simultaneously exploiting chirality (spin selectivity), lattice constant (wavelength selectivity), and cubic orientation (geometric phase), BPLCs enable multi-degree, orthogonal control of light. As shown in Fig. 3(b), this capacity allows for independent and predictable manipulation of polarization, wavelength, and phase, which is essential for advanced optical systems^[140].

2.2 Scalar LC Optics: Controlling Amplitude and Phase of Light

Light carries multiple degrees of freedom, including amplitude, phase, wavelength, and polarization^[142]. Early studies of light primarily focused on scalar optics, where LC-based photonic technologies—represented by LC-SLMs—have achieved remarkable progress. A representative milestone in this domain is holography^[143], which, owing to its arbitrariness in wavefront manipulation, has become a powerful tool for optical wavefront control^[143]. The integration of computational holography with LC-SLM has greatly accelerated the development of holographic imaging^[133,144]. More recently, the introduction of artificial intelligence techniques, such as neural networks^[145], has further elevated LC holography to unprecedented levels of performance. As illustrated in Fig. 4(a), Cao's research group reported a physics-constrained deep learning framework for propagation-adaptive computer-generated holography (CGH). By embedding diffraction physics into a spatial and Fourier neural operator (SFO-solver), the method generates phase-only holograms that can be directly uploaded to a high-resolution SLM. Unlike conventional CGH networks restricted to fixed distances, the proposed approach simultaneously takes the target image and propagation distance as inputs, enabling flexible depth-adaptive holographic reconstruction. Experimental demonstrations using a 4K SLM showcase high-quality 2D projections, dynamic refocusing, and multi-plane 3D displays. This study thus advances the use of SLM-based holographic displays. SLM has likewise been utilized in the production of structured light fields, encompassing Airy beams, vortex light, and lenses, among others^[23]. In recent years, the generation of OAM holograms has also been achieved based on SLM technology^[146] [Fig. 4(b)]. Furthermore, LCs can be synergistically integrated with other materials, such as metasurfaces^[33], to expand their functional capabilities. A research team from A*STAR (Singapore) has proposed the concept of an LC-modulated tunable dielectric metasurface^[34] [Fig. 4(c)]. By leveraging the dynamic tunability of LCs together with the subwavelength dimensions of metasurface elements, this approach enables adjustable phase modulation while simultaneously achieving miniaturization of the pixel size.

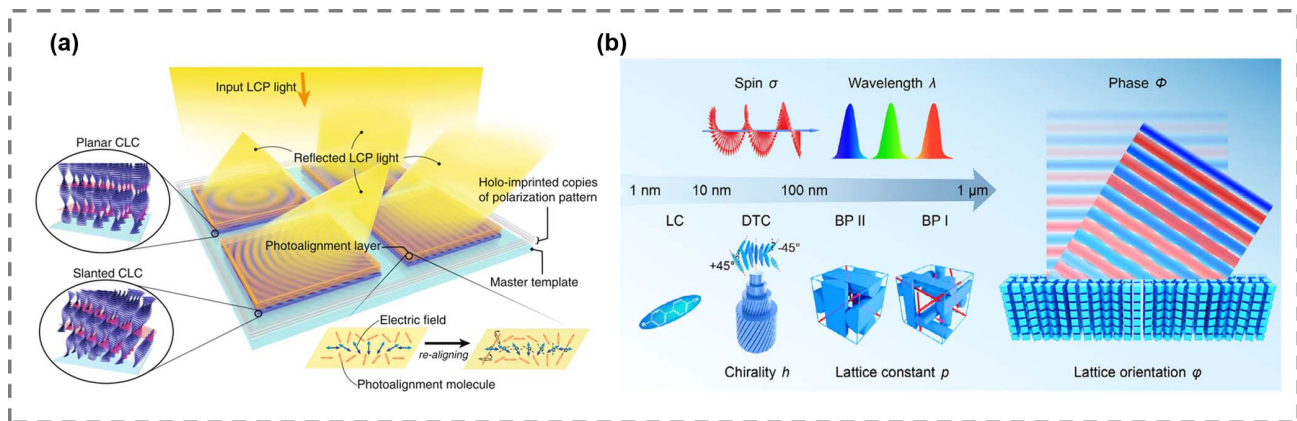


Fig. 3 LC photonic crystals. (a) One-dimensional soft photonic crystal with LCs^[27]. (b) Three-dimensional soft photonic crystal with LCs. Reprinted with permission from Ref. [140], © John Wiley and Sons (2024).

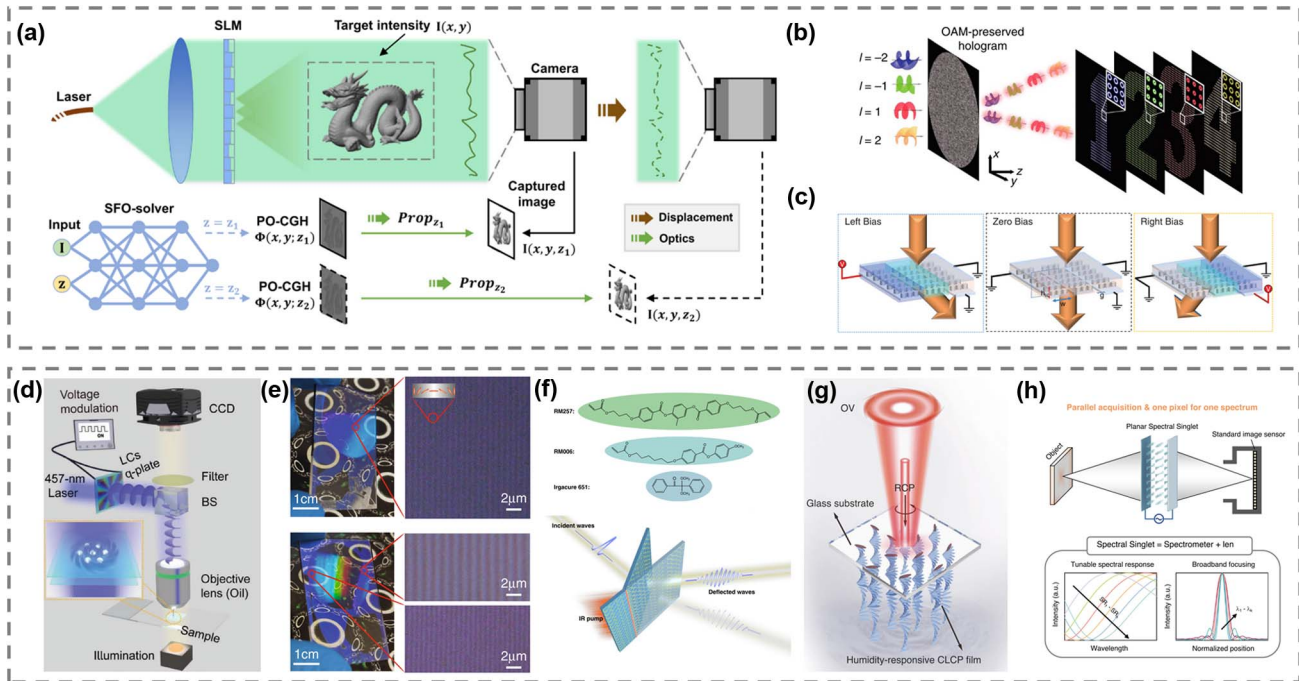


Fig. 4 Control of scalar light fields utilizing LCs. (a) Propagation-adaptive 4K computer-generated holography using physics-constrained spatial and Fourier neural operator^[150]. (b) OAM holography. Reprinted with permission from Ref. [146], © Springer Nature (2019). (c) Phase-only transmissive SLM based on tunable dielectric metasurface. Reprinted with permission from Ref. [34], © The American Association for the Advancement of Science (2019). (d) Optical tweezer manipulation via an LC *q*-plate based on jigsaw puzzles. Reprinted with permission from Ref. [149], © John Wiley and Sons (2023). (e) Holo-imprinting polarization optics with a reflective LC hologram template^[27]. (f) Active terahertz beam steering based on mechanical deformation of LC elastomer metasurface^[35]. (g) Geometric phase-encoded stimuli-responsive cholesteric LCs for visualizing real-time remote monitoring: humidity sensing as a proof of concept^[37]. (h) Electrically tunable planar LC singlets for simultaneous spectrometry and imaging^[36].

In recent years, with the rise of planar geometric-phase LC elements, extensive research and applications have been carried out in the field of light manipulation^[147,148]. Representative studies include the following advances. Wang *et al.* developed a programmable “optical jigsaw puzzle” strategy, where pixelated holographic surface reliefs direct LC orientation to realize reconfigurable phase distributions. This approach enables the generation of structured beams such as optical vortices and Airy beams, and they applied this approach to optical tweezers^[149] [Fig. 4(d)]. Xiong *et al.* introduced a holo-imprinting method, employing reflective LC holograms as templates to replicate high-quality polarization patterns. This non-contact, large-area fabrication technique paves the way for scalable production of transmissive and reflective LC polarization optics with applications in next-generation display and imaging systems^[27] [Fig. 4(e)]. Zhuang *et al.* demonstrated terahertz beam steering using mechanically deformable LC elastomer metasurfaces. By exploiting infrared- and heat-induced deformation, their device achieved broadband and reconfigurable terahertz wavefront control, highlighting the promise of LC-based metasurfaces in emerging THz communication and imaging technologies^[35] [Fig. 4(f)]. Li *et al.* reported a stimuli-responsive cholesteric LC polymer platform, where geometric phase encoding was harnessed to achieve real-time visual sensing. By encoding *q*-plate patterns into humidity-responsive

CLC films, the system produced vortex-beam-based readouts for remote humidity monitoring, thus demonstrating the potential of geometric-phase LC devices in environmental sensing^[37] [Fig. 4(g)]. Zhou *et al.* proposed electrically tunable planar LC singlets that unify imaging and spectrometry^[36]. Each LC unit cell functions simultaneously as a phase modulator and a tunable spectral filter, allowing compact hyperspectral cameras with high spatial resolution and spectral fidelity. This “two-in-one” framework resolves the traditional trade-off between imaging quality and spectral performance [Fig. 4(h)]. Together, these representative studies illustrate the rapid expansion of planar geometric-phase LC optics, from reconfigurable beam shaping and scalable fabrication to stimuli-responsive sensing, multifunctional imaging, and terahertz photonics.

2.3 Vectorial LC Optics: Coordinated Control of Polarization and Phase

Polarization, serving as a crucial dimension of light, constitutes one of its most fundamental characteristics^[142,151]. The basic principle of vector manipulation is to synthesize the desired vector by encoding the phase and amplitude of orthogonal polarization bases^[23]. Two common choices of orthogonal polarization bases are

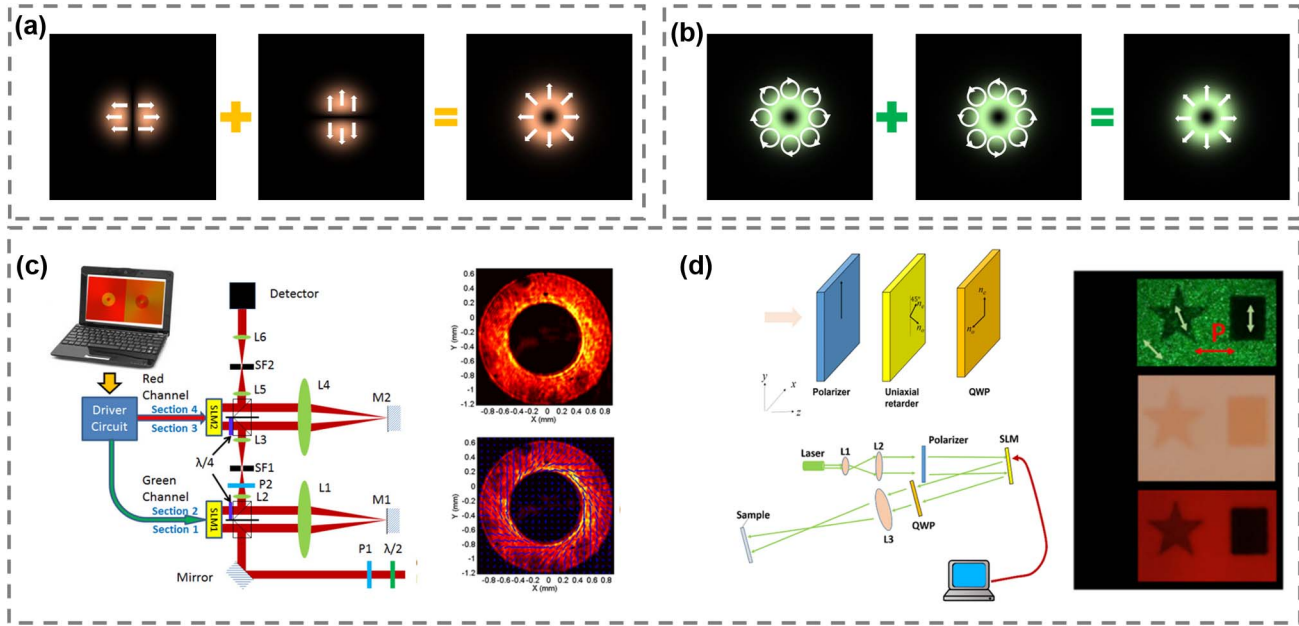


Fig. 5 Mechanism underlying optical vector synthesis. (a) Linear polarization basis for vector field control. (b) Circular polarization basis for vector field control. (c) Generating arbitrary vector light fields by SLM-based optical systems^[153]. (d) Single-step generation of vector light fields by SLM-based optical systems^[154].

$$\mathbf{E} = A_V e^{i\varphi_V} |\mathbf{V}\rangle + A_H e^{i\varphi_H} |\mathbf{H}\rangle = A_H e^{i\varphi_V} \left(\frac{A_V}{A_H} |\mathbf{V}\rangle + e^{i\Delta\varphi} |\mathbf{H}\rangle \right). \quad (2-5)$$

$|\mathbf{V}\rangle$ and $|\mathbf{H}\rangle$ denote the vertical and horizontal optical field vectors, respectively. Here, the amplitude ratio of $|\mathbf{V}\rangle$ and $|\mathbf{H}\rangle$ determines the azimuth of the synthesized vector, while the phase difference between $|\mathbf{V}\rangle$ and $|\mathbf{H}\rangle$ determines the ellipticity angle of the synthesized vector:

$$\mathbf{E} = A_R e^{i\varphi_R} |\mathbf{R}\rangle + A_L e^{i\varphi_L} |\mathbf{L}\rangle = A_L e^{i\varphi_R} \left(\frac{A_R}{A_L} |\mathbf{R}\rangle + e^{i\Delta\varphi} |\mathbf{L}\rangle \right). \quad (2-6)$$

Here, the amplitude ratio of $|\mathbf{R}\rangle$ and $|\mathbf{L}\rangle$ determines the ellipticity angle of the synthesized vector, while the phase difference between basis $|\mathbf{R}\rangle$ and $|\mathbf{L}\rangle$ determines its azimuthal angle. It can be noted that arbitrary polarization states of light can be synthesized regardless of whether orthogonal circular polarization bases or orthogonal linear polarization bases are chosen. As illustrated in Figs. 5(a) and 5(b), a radially polarized vector beam can be synthesized either from two Hermite–Gaussian beams with horizontal and vertical linear polarizations, or equivalently from two vortex beams with left- and right-handed circular polarizations. In selecting the basis, two factors are generally considered: on the one hand, the target polarization state for synthesis—whether it is linear, circular, elliptical, or any arbitrary state; on the other hand, the physical principle by which the device manipulates light—for example, geometric phase devices modulate the phase of circular polarization, while SLMs modulate the phase of linear polarization. Of course, through cascading multiple devices, both approaches can, to some extent, achieve equivalent functional outcomes.

As described above, LC devices have been widely applied in the field of scalar light field modulation and have achieved many significant results. When light field control entered the vectorial era, however, SLMs, which were highly successful in scalar modulation, appeared less adaptable to vectorial control, primarily because an SLM can only modulate the propagation phase of linearly polarized light aligned with a designated incident direction. This constraint limits its use in generating and manipulating vectorial light distributions.

Nevertheless, researchers have demonstrated that vectorial manipulation can be achieved by employing multiple SLMs or combining them with auxiliary optical components. For example, Tripathi *et al.* proposed a system for vector beam generation based on LC-SLMs^[152], where cascaded phase plates, SLMs, and quarter-wave plates were used to generate arbitrary vector beams corresponding to coordinates on the higher-order Poincaré sphere, with radial and azimuthal polarizations serving as the basis functions. Similarly, as shown in Fig. 5(c), Han *et al.* employed a cascaded system of four SLM modules assisted by quarter-wave plates and linear polarizers to realize the generation of light fields with controllable phase, amplitude, and polarization (ellipticity and azimuth)^[153]. They further characterized a variety of generated fields that contained phase, amplitude, and/or polarization modulations, confirming that SLM-based optical systems can achieve vectorial encoding of light fields.

Although these methods enable arbitrary encoding of vectorial light distributions, such systems are typically bulky and costly, and in many scenarios complete multiparameter control is unnecessary, as the modulation of only one parameter suffices. For instance, in the context of LC-based photoalignment techniques, it is often sufficient to encode only the azimuthal orientation of vectorial light fields, with amplitude and ellipticity remaining uniform. Addressing this scenario, Li *et al.*

proposed a vectorial modulation system based on a single SLM device that enables patternable control of the linear-polarization azimuth^[154]. Based on this approach, they realized arbitrary photoalignment of LC molecules, advancing the development of patterned LC photoalignment technology. As shown in Fig. 5(d), the core principle involves setting the incident linear polarization at a 45° offset from the SLM fast axis to encode a phase difference between orthogonal linear polarization bases, which is then converted into a phase-difference distribution between orthogonal circular polarization bases via a quarter-wave plate, ultimately enabling patternable control over the azimuthal distribution of linear polarization.

2.3.1 Planar LC devices for vector-field control

Planar LC elements have become the mainstream direction in the development of LC photonics in the post-display era, and their features of compactness, dynamic tunability^[155,156], patternable construction^[157,158], and geometric phase modulation^[32] introduce new avenues for vectorial control. As shown in Eq. (2-1) to Eq. (2-3), LC molecules can achieve polarization conversion of light fields^[159], while according to Eq. (2-2), they also possess electrically tunable characteristics, making them highly suitable for devices of dynamic polarization modulation. For example, as illustrated in Fig. 6(a), LCs have been applied as polarization

switching devices in non-Hermitian magneto-optical sensing^[160]. By inserting magneto-optical materials and LC elements into an optical cavity composed of two concave mirrors, the team constructed a non-Hermitian magneto-optical system with dissipation but no gain, successfully demonstrating the non-Hermitian magneto-optical effect and experimentally confirming the superior response and measurement sensitivity of non-Hermitian sensing compared to Hermitian sensing. As shown in Fig. 6(b), Ni *et al.* combined metasurfaces with LCs to demonstrate an electrically tunable near-infrared spectropolarimeter^[161], which reconstructed the full Stokes parameters and spectrum of incident light with high fidelity, offering a path to compact, low-cost vectorial spectropolarimeters with reduced size, weight, and complexity.

The advent of photoalignment techniques^[26] has enabled the patternable construction of LCs, which marks a new stage of applications for LC devices^[162,163]. Patterned planar LC devices allow pixelated modulation of polarization^[29,164]; for instance, as shown in Fig. 6(c), Wei *et al.* proposed a novel LC depolarizer with randomly arranged patterned nematic LCs. This disordered alignment enabled polarization-independent depolarization with a degree of polarization below 5%. On the other hand, by constructing specific alignment structures such as *q*-plates, patterned LCs can generate structured light fields such as vector beams while leveraging the material's intrinsic properties for unique functions. As shown

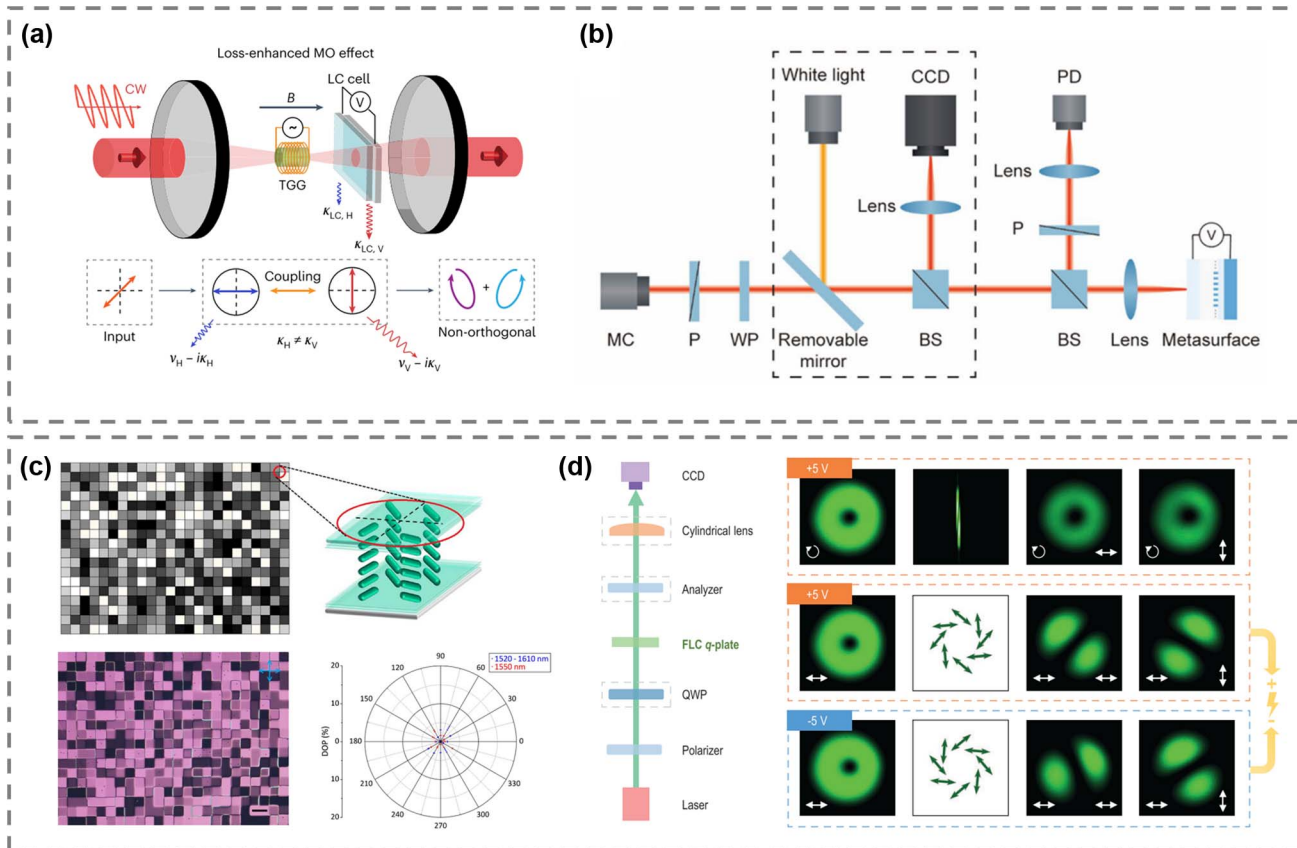


Fig. 6 Planar LC devices for vector-field control. (a) LC-enabled polarization modulation for the loss-enhanced magneto-optical effect^[160]. (b) Computational spectropolarimetry enabled by a tunable liquid crystal metasurface. Reprinted with permission from Ref. [161], © Springer Nature (2024). (c) LC depolarizer with randomly arranged patterned nematic LCs^[28]. (d) Fast vector beam switching with chiral LC superstructures^[165].

in Fig. 6(d), by fabricating a q -plate based on ferroelectric chiral smectic C (SmC*) LCs^[165], vector beams were generated, and thanks to the in-plane switching and ultrafast electro-optic response of ferroelectric LCs, rapid switching between orthogonally vector beams was successfully achieved.

2.3.2 Generation of arbitrary vectorial wavefronts based on LCs

Vectorial holography, owing to its arbitrariness in manipulating the optical vector field, has become a powerful tool for vectorial light control and has attracted extensive attention due to its enormous potential in encryption, information storage, and optical communication. Metasurfaces, with their intrinsic multi-degree-of-freedom unit cells and versatile ability to manipulate light fields, have achieved remarkable success in this field^[166]. Capasso's team, by introducing Jones matrix holography and applying Jones calculus^[167], realized customized far-field holograms with arbitrary amplitude and polarization [Fig. 7(a)]. In addition, vectorial holography can also be achieved through the design of structural units or the development of new phase design algorithms^[168]. Huang's team demonstrated vectorial holography

based on a metasurface capable of encoding orthogonal linear polarization phases^[169], combined with phase optimization algorithms to encode polarization states corresponding to any point on the Poincaré sphere [Fig. 7(b)]. More recently, Xiong *et al.* broke the fundamental limitation of polarization multiplexing capacity imposed by the dimensional constraint of the Jones matrix through noise engineering^[170]. By employing different incident polarization states, they achieved as many as 11 independent holographic images, establishing a new paradigm of vectorial holography for applications in encryption and information storage.

Leveraging the dynamic tunability of LCs, dynamic vectorial holography can be realized by integrating LCs with metasurfaces^[171,172]. As shown in Figs. 7(c) and 7(d), Rho's team demonstrated dynamically reconfigurable polarization-dependent vectorial holography by coating uniform LCs onto metasurfaces^[25]. With the use of an analyzer, different holographic images could be switched under varying applied voltages, and when combined with structural color printing, the system achieved dual optical encryption, providing a novel method for information security and anti-counterfeiting applications.

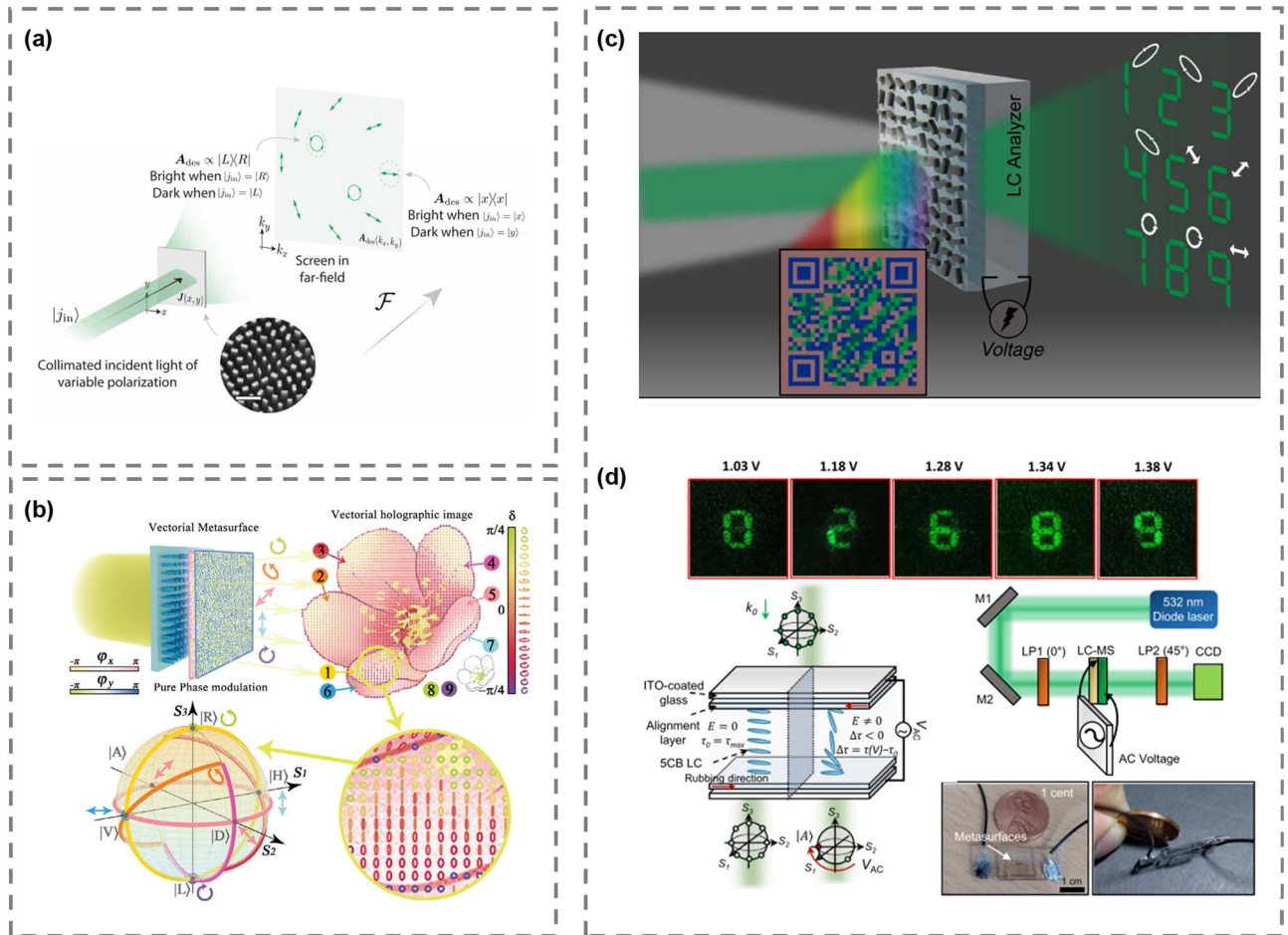


Fig. 7 Vectorial holography based on metasurfaces and metasurfaces integrated with LCs. (a) Jones matrix vectorial holography with metasurfaces. Reprinted with permission from Ref. [167], © The American Association for the Advancement of Science (2021). (b) Vectorial holography and polarization encryption based on birefringent metasurfaces. Reprinted with permission from Ref. [169], © John Wiley and Sons (2024). (c), (d) Dynamic vector holography and color printing driven by metasurface integrated LCs^[25].

Although metasurfaces have achieved remarkable success in the field of vectorial holography, they still suffer from limitations such as the lack of tunability, high fabrication costs, difficulties in large-area production, and complex processing requirements. By contrast, LCs possess the advantages of low cost, ease of fabrication, and dynamic tunability, thereby offering a promising new route for vectorial holography. Nevertheless, despite significant progress in structured light generation and polarization control based on LCs, conventional single-material LC devices cannot independently manipulate two orthogonal polarization states, which hampers their application in vectorial holography with higher degrees of freedom. This limitation highlights the urgent need for introducing new principles and techniques.

In 2024, Wang *et al.* proposed a vectorial holography approach based on nematic LCs^[30], in which a single-layer LC device enabled arbitrary vectorial encoding. By introducing a circular-polarization-multiplexed phase-difference encoding principle together with a dedicated LC vectorial holography algorithm, and by employing high-precision pixelated structuring techniques, they fabricated prototype devices that can encode arbitrary polarization states with dynamic tunability. As illustrated in Figs. 8(a) and 8(b), such devices can be applied to information encryption, data multiplexing, and dynamic holographic displays,

thereby providing a new and promising direction for vectorial holography.

On the other hand, Lu's group advanced the field by introducing chiral materials^[127], where a bilayer CLC device independently modulated the phases of orthogonal circular polarizations, enabling the synthesis of orthogonal linear polarizations. [Fig. 8(c)]. Combined with advanced vectorial holography algorithms, this approach allows for more arbitrary polarization encoding. Furthermore, as shown in Fig. 8(d), Luo's team explored cascaded LC-based devices to realize more complex functionalities in traditional information encryption and multiplexing^[173]. By integrating planar LC elements with SLMs into a cascaded system, they directly encoded vectorial information into reprogrammable vectorial inputs, which has pushed forward the further development and practical applications of LC-based vectorial holography.

2.4 Emerging Frontiers and Representative Applications

With the transition of optical field control from scalar to vectorial regimes, LC-based modulation has transcended the limits of scalar beam shaping and now offers powerful tools for new frontiers in photonics and cross-disciplinary applications. Nape *et al.* demonstrated the robustness of vectorial structured light propagating through complex channels^[174], showing that the

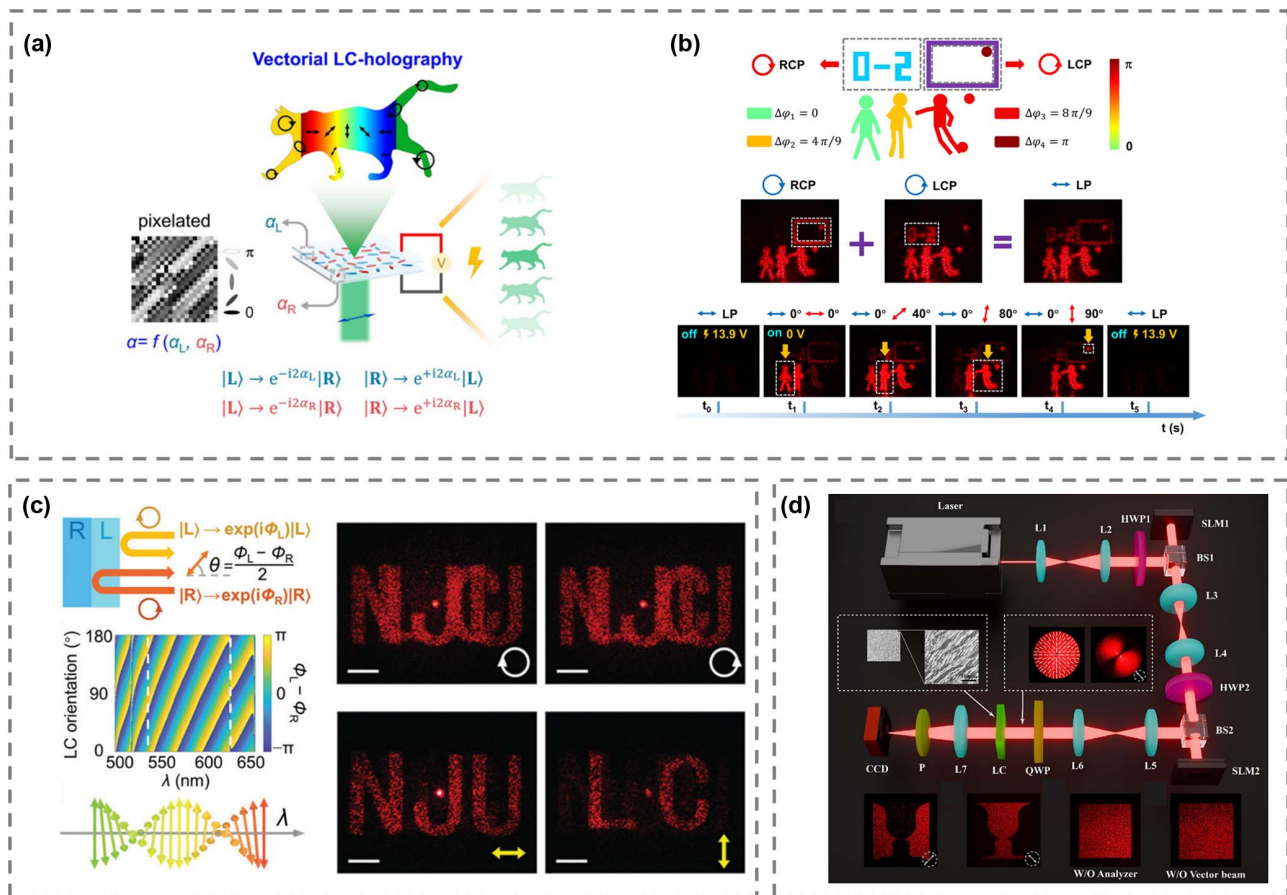


Fig. 8 Vectorial holography based on LCs. (a), (b) Vectorial LC holography^[30]. (c) Bi-chiral nanostructures featuring dynamic optical rotatory dispersion. Reprinted with permission from Ref. [127], © John Wiley and Sons (2023). (d) Vector optical field meets LC elements for enhanced security in holography. Reprinted with permission from Ref. [173], © John Wiley and Sons (2025).

polarization inhomogeneity defining vector beams remains invariant under unitary perturbations such as turbulence and aberrations, a finding crucial for imaging and secure optical communication in noisy environments [Fig. 9(a)]. Sit *et al.* realized high-dimensional quantum key distribution (QKD) in a turbulent intracity free-space link by encoding information in the combined spin and OAM degrees of freedom^[175], employing LC q -plates to generate four-dimensional quantum states, validating the practicality of high-dimensional secure communication [Fig. 9(b)].

Beyond their traditional role in scalar phase modulation, LC spatial light modulators have progressively evolved into versatile platforms for vectorial light control. By combining programmable phase retardation with polarization-selective addressing, LC-SLM-based systems enable not only intensity adaptive optics but also vectorial adaptive optics capable of simultaneously correcting phase and polarization aberrations^[176,177]. Such approaches further allow arbitrary vectorial state conversion through the coordinated modulation of orthogonal polarization bases, extending the functionality of SLMs from scalar

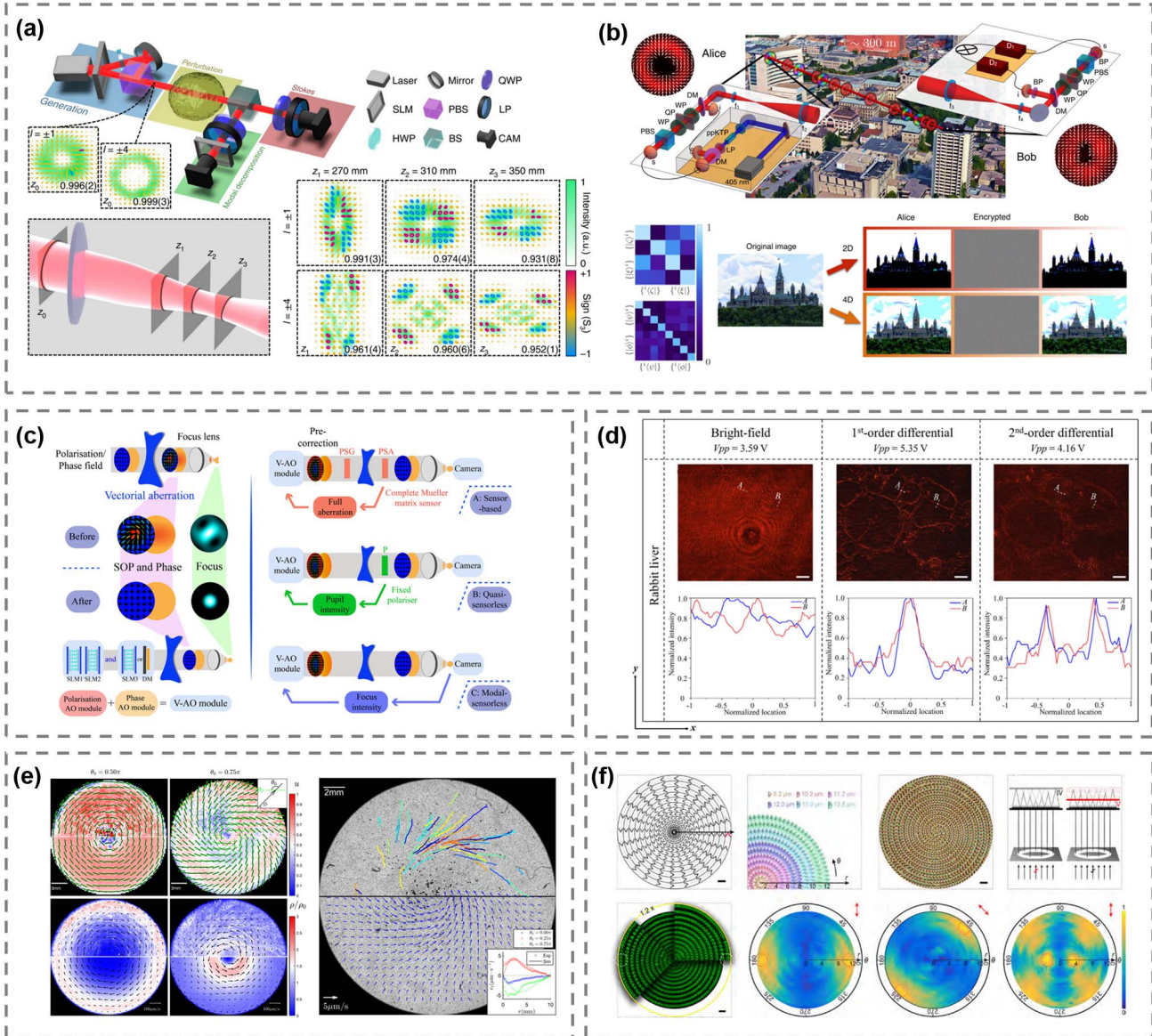


Fig. 9 Application of LC vector control. (a) Revealing the invariance of vectorial structured light in complex media. Reprinted with permission from Ref. [174], © Springer Nature (2022). (b) High-dimensional intracity quantum cryptography with structured photons^[175]. (c) Vectorial adaptive optics^[177]. (d) All-optical multi-order multiplexing differentiation based on dynamic LCs. Reprinted with permission from Ref. [178], © John Wiley and Sons (2024). (e) Controlling cell motion and microscale flow with polarized light fields. Reprinted with permission from Ref. [179], © American Physical Society (2021). (f) Self-assembled asymmetric microlenses for four-dimensional visual imaging. Reprinted with permission from Ref. [137], © American Chemical Society (2019).

wavefront shaping to full vector-field synthesis. These developments position LC-SLMs as a key technological bridge in the transition from scalar to vectorial photonics, particularly for advanced imaging systems operating in complex and aberrated environments. He *et al.* extended adaptive optics into the vectorial domain with vectorial adaptive optics (V-AO)^[177], incorporating LC SLMs to jointly correct phase and polarization aberrations, enabling high-fidelity vector-field control in microscopy and optical systems [Fig. 9(c)]. Liang *et al.* reported an all-optical multi-order multiplexing differentiator based on dynamic LCs^[178], achieving zeroth-, first-, and second-order differentiation under tunable voltages, offering a universal platform for broadband image processing and optical analog computing [Fig. 9(d)]. Yang *et al.* exploited polarized light fields to direct the collective motion of photoresponsive microalgae^[179], revealing that spatially varying polarization fields generated via LC optics can induce complex cell migration and microscale fluid flows, bridging biophotonics and active matter [Fig. 9(e)]. Finally, Ma *et al.* introduced self-assembled asymmetric LC microlenses capable of four-dimensional (3D space and polarization) visual imaging^[137], providing a compact route toward simultaneous depth and polarization information acquisition in a single snapshot [Fig. 9(f)]. Together, these works underscore how LC-enabled vector optics not only deepen the understanding of light–matter interactions but also open transformative avenues in secure communications, adaptive imaging, optical computing, and biophotonics.

Beyond serving as complex structured light states, optical skyrmions have emerged as fundamental topological and vectorial primitives within the framework of Soft Mattonics. Enabled by the continuous and reconfigurable nature of liquid crystal matter fields, these structures provide a robust platform for encoding high-density information through their intrinsic topological invariants. In recent years, remarkable advances have been made in the study of optical skyrmions enabled by LC-based light modulation^[180,181], where their topologically protected vectorial textures open new avenues for photonics^[181,182]. Shen *et al.* introduced the concept of tunable optical skyrmions^[183], proposing and experimentally realizing a generalized family of skyrmions—including Néel, Bloch, and anti skyrmion types—through parametric tuning of structured vector beams [Figs. 10(a) and 10(b)]. They further established a geometric Skyrme–Poincaré representation termed the “skyrmion torus,” enabling a comprehensive visualization of topological transitions, and demonstrated generation using SLMs with high fidelity to theory. Building upon this, Wang *et al.* rigorously analyzed the topological robustness of optical skyrmions in complex media^[184], revealing that their stability originates from boundary conditions of the polarization field [Figs. 10(c) and 10(d)]. Through both theoretical formalism and experiments employing cascaded LC-SLMs, they confirmed that skyrmion numbers remain conserved even under polarization aberrations, establishing a framework for exploiting skyrmions in high-density optical communications and computing.

At the quantum frontier, Ornelas *et al.* reported the first realization of non-local quantum skyrmions^[126], where entangled photon pairs exhibit skyrmionic topology [Figs. 10(f) and 10(g)]. By engineering OAM-polarization hybrid entanglement and employing LC-based modulation for state preparation and measurement, they demonstrated that skyrmion topology persists until entanglement vanishes, thereby introducing skyrmions as robust carriers

of quantum information and revealing a direct link between topology and entanglement classes. Together, these works establish LC-enabled optical skyrmions as a versatile platform, bridging classical structured light, topological protection in noisy media, and quantum information science. Recently, optical skyrmions have emerged as a promising candidate for photonic computing. By utilizing LC-SLMs to precisely manipulate the spatial polarization distribution of optical fields, He *et al.* demonstrated the first realization of perturbation-resilient integer arithmetic based on topologically robust optical skyrmions^[185]. Furthermore, the sensitivity of these topological textures to field distortions has led to their application as a “gold standard” for assessing the capabilities of vectorial adaptive optics in the presence of complex, non-unitary aberrations^[176].

The significance of LC-enabled optical skyrmions transcends individual demonstrations; they represent a broader paradigm shift toward topology-protected photonics within the framework of Soft Mattonics. A profound aspect of this platform is the topological isomorphism between the LC matter field and the optical light field. As a quintessential soft matter system, the LC director field itself can self-assemble into intricate topological textures, such as material skyrmions (this is discussed in Sec. 3). When used as a modulation medium, this structured matter field maps its internal topological order onto the electromagnetic field, thereby generating optical skyrmions. This dual capacity—where liquid crystals act both as the host for soft matter skyrmions and the generator for optical skyrmions—underscores the versatile role of LC-based “Soft Mattonics” in bridging material and optical topologies.

Beyond their diverse physical implementations, the above demonstrations can be understood within a unified functional framework enabled by Soft Mattonics. Specifically, LC-based vectorial light manipulation supports three fundamental roles in optical information systems. First, it enables high-dimensional encoding, where information is embedded across multiple vectorial degrees of freedom—including phase, polarization, orbital angular momentum, and topology—thereby significantly increasing information density. Second, it facilitates vectorial information processing, exemplified by vectorial adaptive optics, optical differentiation, and polarization-aware computation, in which both scalar and vectorial distortions are dynamically corrected or transformed. Third, Soft Mattonics provides a powerful route for light–matter transduction, whereby structured vector fields mediate interactions with complex media, or quantum states. Viewed from this perspective, Soft Mattonics does not represent a collection of isolated application cases, but rather a coherent platform for programmable, high-dimensional optical information processing across classical and quantum regimes.

2.5 Discussion

Within the Soft Mattonics paradigm, the evolution from scalar modulation of amplitude and phase to full vectorial control of light fields has established LCs as one of the most versatile and powerful media for optical field manipulation. Through the development of LC-SLM, planar LC elements, and hybrid LC–metasurface architectures, LC-based photonics now spans fundamental research and practical applications across imaging^[148], communication^[186], sensing^[37], light–matter interaction^[187], and quantum science^[188].

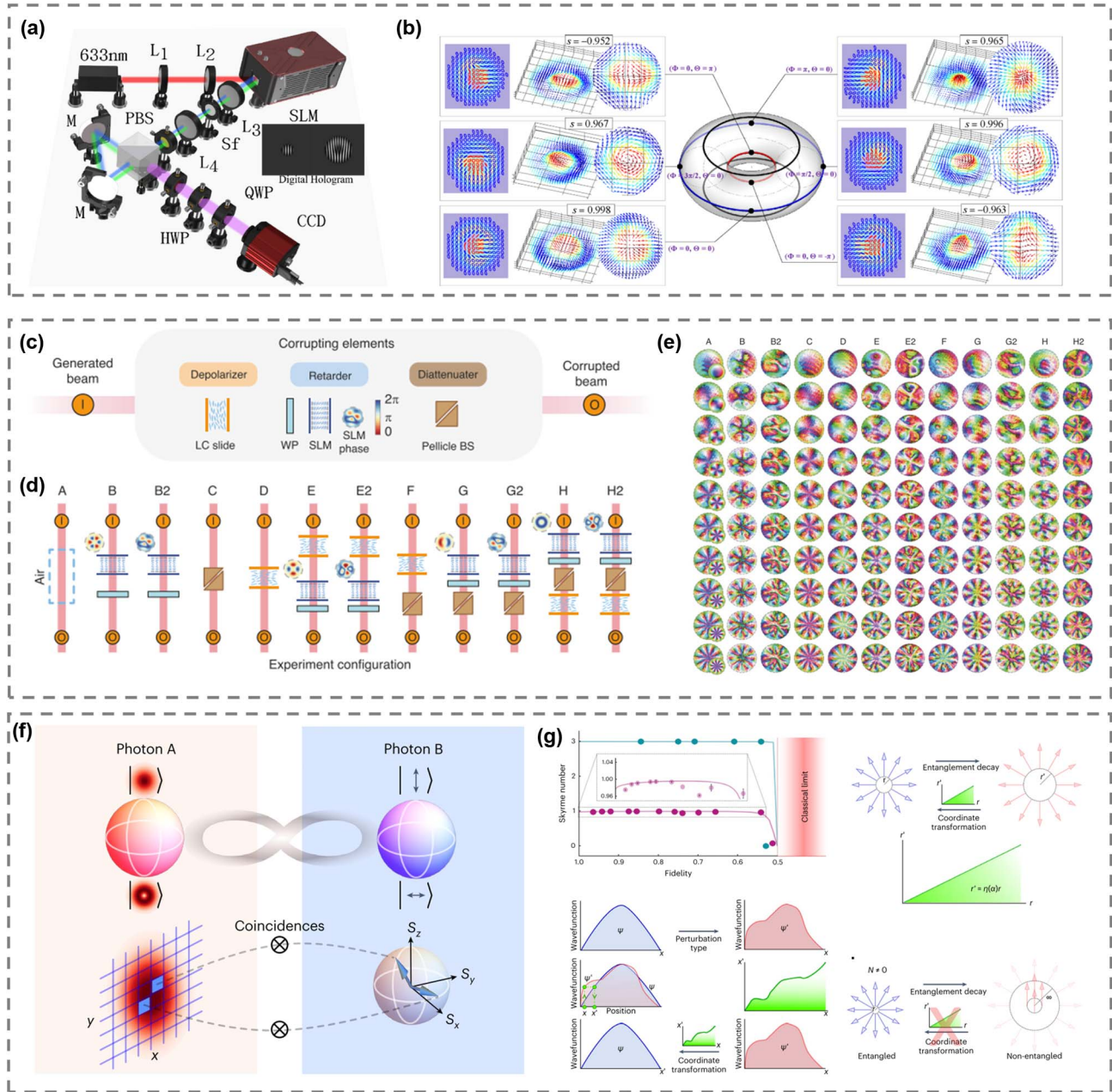


Fig. 10 Optical skyrmions enabled by LCs. (a), (b) Generation of optical skyrmions with tunable topological textures. Reprinted with permission from Ref. [183], © American Chemical Society (2022). (c)–(e) Topological protection of optical skyrmions through complex media^[184]. (f), (g) Non-local skyrmions as topologically resilient quantum entangled states of light. Reprinted with permission from Ref. [126], © Springer Nature (2024).

It is worth noting that vectorial light manipulation has also been extensively explored in static or quasi-static nanophotonic platforms, most notably metasurfaces, where polarization-dependent optical responses are encoded into fixed subwavelength structures. In such systems, vectorial control is primarily realized through carefully designed boundary conditions that prescribe local phase retardation and polarization transformation. In contrast, vectorial manipulation in Soft Mattonics—and particularly in LC-based systems—originates from field-responsive and continuously distributed material anisotropy. Rather than being permanently defined by nanostructure geometry, the vectorial degrees of

freedom are dynamically coupled to the underlying orientational order of the soft medium. As a representative soft material, LCs exhibit a rich diversity of phases and structural organizations, which makes them an ideal platform for vectorial manipulation with additional functionalities such as flexibility, reconfigurability, three-dimensional structuring, dynamic tunability, and responsiveness to multiple external stimuli. From this perspective, Soft Mattonics does not simply offer an alternative implementation of vectorial light manipulation, but instead represents a complementary material paradigm, especially suited for adaptive, reconfigurable, and high-dimensional vectorial control.

The material richness of LCs is still being continuously explored; for example, the recent discovery of ferroelectric nematic LC (FNLC) introduces optical nonlinearity and ultrafast response, further expanding their functional scope. Beyond the free-space vectorial control in the transverse (x - y) plane discussed above, LCs can also act as transmission media to achieve vectorial control along the longitudinal z -direction. This unique capability positions LCs as an ideal future-oriented platform for vectorial manipulation in increasingly complex scenarios and advanced applications. As research continues to push the boundaries with new materials, integration strategies, and computational approaches, LC-enabled light manipulation will remain at the forefront of both fundamental photonics and technological innovation.

3 From Free-Space to In-Plane Light Steering

Within the Soft Mattonics paradigm, LCs have long been established as powerful planar devices for free-space beam modulation, offering exceptional tunability and reconfigurability across scalar and vector light fields. The previous section outlined the advances of LC photonics in free-space geometries, where the manipulation of the in-plane director field largely governs the out-of-plane modulation of optical beams. By breaking through the studying framework, when optical beams are coupled into the LC layer itself, in-plane structuring of the director field provides a direct means to guide, trap, and deflect light inside the medium. This framework—termed in-plane optical steering—marks a conceptual transition from LC displays toward on-chip soft photonics, where LC films act not only as modulators of external light but as guiding substrates in their own right.

Importantly, the uniqueness of LC-based in-plane guiding lies in its programmable softness: the director field can be designed, reconfigured, and coupled with external fields to emulate diverse physical environments. This “god’s-eye view” enables researchers to use LC platforms as model systems for nonlinear wave transport, transformation optics, and topological interactions. In this section, we review the development of LC-based in-plane steering, from demonstrations of obvious soft waveguides to advanced schemes for soliton steering, cosmological analogies, light-topological structure interactions, and transport in weakly disordered films.

3.1 LC-Based In-Plane Waveguides for Guided Light Transport

The most direct entry point into in-plane LC photonics is the realization of waveguides. Historically, waveguides have been the backbone of integrated photonics, constructed from materials such as silica, silicon, or lithium niobate. LC photonics delivers a clear message: much of what rigid platforms achieve can be realized in soft matter—with added flexibility, tunability, and polarization sensitivity.

Early demonstrations combined LCs with conventional optical fiber or silicon platforms^[189–192]. At the Fraunhofer IPMS, researchers realized electro-optically induced LC waveguides directly integrated with fiber networks, enabling fast optical switching and tunable power splitting. These devices exploited the electro-optic Kerr response of nematic mixtures, achieving sub-microsecond switching and polarization-independent transmission around the telecom band (1550 nm). Such hybrid approaches established LCs as cost-effective, reconfigurable

complements to existing integrated photonics, particularly where polarization dependence is an asset rather than a limitation.

3.1.1 Pure LC-based waveguides through in-plane alignment

More fundamentally, LCs themselves can form stand-alone guiding structures. In 2020, Wei *et al.* reported that in-plane alignment of nematic directors can define graded-index channels that confine light beams within planar LC films^[41]. By programming straight, bent, and even closed-loop (ring resonator) geometries, they demonstrated that soft LC layers can mimic conventional dielectric waveguides, but with the added feature of voltage-controlled reconfigurability [Fig. 11(a)]. The concept was further extended to three dimensions. In 2024, Zheng *et al.* reported programmable wall defects in bulk nematic samples, fabricated via photoalignment and controllable with external electric fields [Fig. 11(b)]. These defects act as 3D refractive-index channels, enabling wide-angle reconfigurable guiding that can be erased and rewritten optically^[42]. Similarly, the 2025 work by Neyts *et al.* demonstrated that domain-wall engineering in nematic LCs can form robust guiding channels with enhanced stability against director fluctuations, paving the way for flexible, reconfigurable soft optical interconnects^[43]. Chiral nematics (cholesterics) offer a naturally three-dimensional director structure. In 2016, Zumer *et al.* showed that the fingerprint textures of cholesterics, with periodic director twists, act as self-assembled waveguiding grooves^[193]. Later work in 2020 expanded this approach, demonstrating how such cholesteric defects provide robust in-plane light guiding^[194]. These studies underscored the versatility of LC phases: by exploiting intrinsic chirality, one can achieve guiding geometries without external patterning, simply through molecular self-assembly.

3.1.2 Polymer-stabilized LC waveguides and ultrafast laser writing

To overcome molecular fluctuations and enhance device stability, LC monomers have been polymerized into polymer-stabilized LC networks. Wei’s 2020 work demonstrated that such LC–polymer hybrids suppress director noise while maintaining electro-optic tunability^[41]. More recently, Chen *et al.* reported that two-photon laser writing combined with UV polymerization can inscribe free-standing LC waveguides^[45]. These structures [Fig. 11(c)] exhibited low propagation losses (−0.2 dB/mm) and mechanical flexibility, even functioning when bent, pointing toward wearable and bio-integrated photonic applications.

Another important line of research focuses on transparent displays^[46,147,195]. In 2024, Yang’s group introduced dual-sided transparent LC displays that use waveguiding and scattering within polymer-stabilized LCs to achieve active-matrix control with ~65% transparency^[46]. Combined with their earlier edge-lit polymer stabilized LC (PSLC) waveguide displays^[195], this work shows that LCs can simultaneously perform guiding, modulation, and display, bridging optical communications with emerging augmented-reality platforms.

Taken together, these works establish that LCs can act as both complementary and independent waveguide platforms. These advances set the stage for the following sections, where the value of LC platforms transcends waveguiding, enabling explorations of soliton steering, transformation optics, and topological photonics.

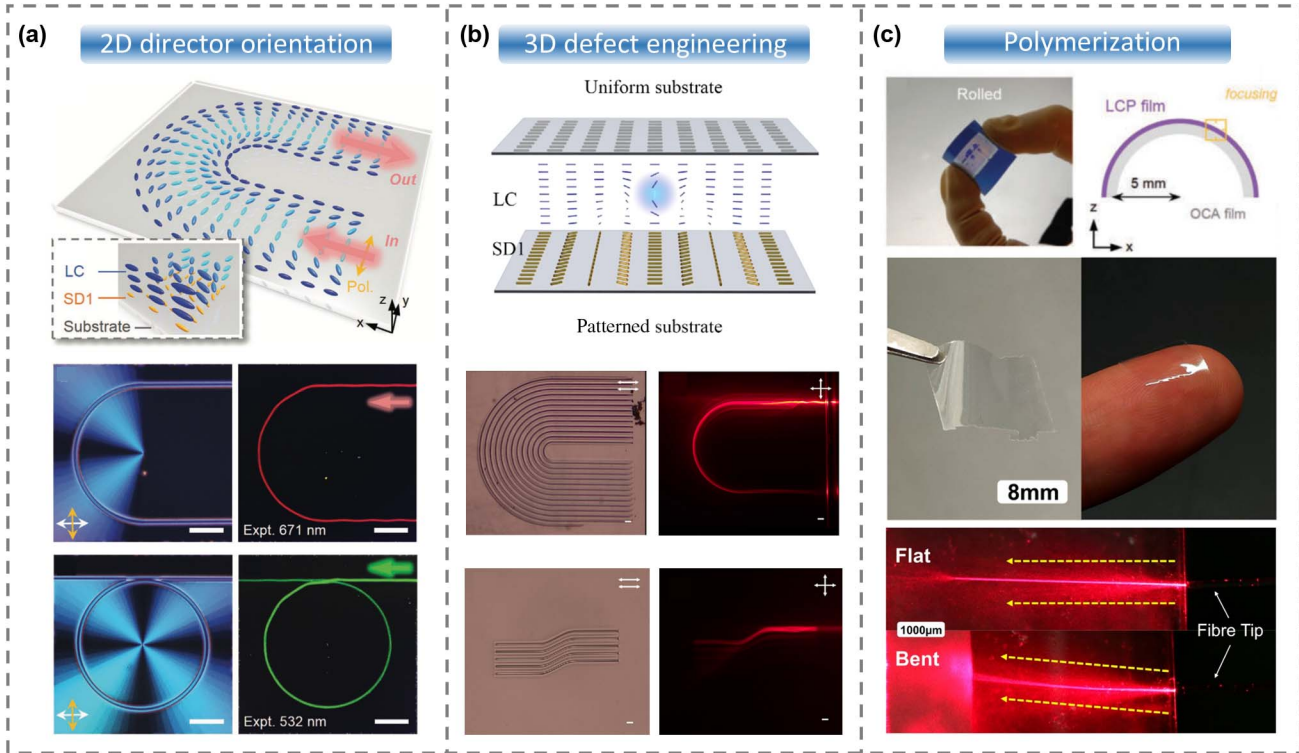


Fig. 11 LC-based in-plane waveguides. (a)–(c) In-plane optical waveguides realized through director engineering: (a) two-dimensional director rotation. [Adapted with permission from Ref. [41], © Wiley-VCH (2020)], (b) three-dimensional wall defect [Adapted with permission from Ref. [42], © Wiley-VCH (2024)], and (c) polymer-stabilized LC waveguides^[41,45].

3.2 In-Plane Self-Focusing Light Transport and Soliton Dynamics

Exploring nonlinear optical transport in LCs marked the inception of open-type in-plane LC optics, where optical beams propagate through a broad LC film without transverse confinement [Fig. 12(a)]. This development laid the groundwork for subsequent advances in topological photonics and transformation optics. The field-induced molecular reconfiguration allows propagating beams to self-modulate the refractive index of the host medium, leading to phenomena such as optical self-focusing and the formation of spatial solitons. Over the past two decades, this field evolved from proof-of-concept demonstrations of light confinement in soft matter to systematic studies of soliton interactions, steering, and interface dynamics, progressively shaping the notion of reconfigurable and functional soft photonics.

3.2.1 From birefringent soft matter to a $\chi^{(3)}$ workbench

NLCs combine long-range molecular order with strong optical birefringence, giving rise to extraordinarily large, non-resonant third-order nonlinearities. Unlike the instantaneous electronic Kerr effect in conventional dielectrics, the dominant $\chi^{(3)}$ response in NLCs originates from light-induced molecular reorientation. When an extraordinarily polarized beam propagates through an aligned NLC layer, the electric field couples to the director $\hat{n}$, exerting a dielectric torque of the form^[48]

$$\tau = \varepsilon_0 \Delta \varepsilon (n \cdot E) \hat{n} \times E, \quad (3-1)$$

where $\Delta \varepsilon = n_{\parallel}^2 - n_{\perp}^2$ is the dielectric anisotropy. This torque competes with the Frank–Oseen elastic restoring force, and their balance determines the steady-state director reorientation. A change in the local azimuthal angle θ modifies the effective extraordinary refractive-index n_{eff} according to Eq. (2-2)^[49], where a small optically induced reorientation produces a positive Δn_{eff} , forming a self-induced waveguide that counteracts diffraction.

The strength of this reorientational $\chi^{(3)}$ effect is typically expressed in terms of the nonlinear refractive-index coefficient

$$n_2 \approx \frac{\Delta n_{\text{eff}}}{I}, \quad (3-2)$$

with I being the beam intensity. For typical nematics such as E7 or 5CB, where $\Delta n \sim 0.2$, $\Delta \varepsilon \sim 10$, and the elastic constant $K \sim 10^{-11}$ N, the effective reorientational nonlinear coefficient reaches values of $n_2 \sim 10^{-11}$ – 10^{-9} cm²/W, corresponding to $|\chi^{(3)}| \sim 10^{-18}$ – 10^{-16} m²/V²^[48,49]. These values exceed those of silica fibers ($n_2 \sim 3 \times 10^{-16}$ cm²/W) by three to six orders of magnitude^[196], which explains why nematics can form at milliwatt powers over millimeter-scale distances, in stark contrast to the kilowatt peak powers required in optical fibers.

In the planar (in-plane) geometry, the optic axis is defined by the director orientation, with $n_{\parallel}$ along $\hat{n}$ and $n_{\perp}$ in the orthogonal plane. Light entering the NLC cell induces reorientation and thus modifies the effective extraordinary index, establishing the physical basis for in-plane beam self-confinement [Figs. 12(a)–12(c)]. This $\chi^{(3)}$ mechanism provides the foundation for the emergence

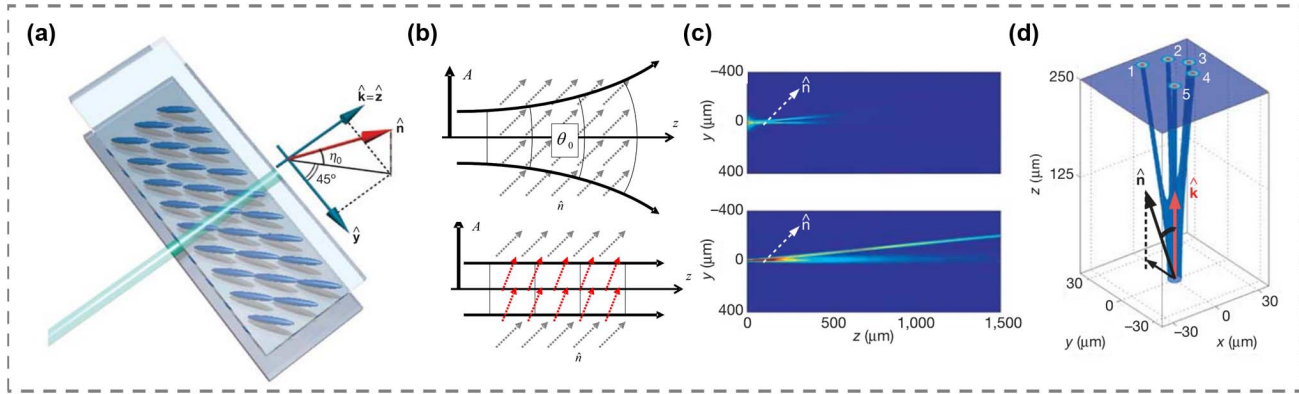


Fig. 12 Emergence of optical solitons in NLC films. (a) Experimental configuration for in-plane beam propagation in a planar-aligned NLC cell. (b) Schematic illustration of light-induced director reorientation and the resulting self-focusing of an extraordinarily polarized beam. Adapted with permission from Ref. [49], © Elsevier B.V (2012). (c) Propagation dynamics of the extraordinary wave under low input power (top) and high input power (bottom), demonstrating the transition from diffraction to soliton formation. (d) Voltage-controlled rerouting of nematons within the NLC film, highlighting the tunability of soliton trajectories under increasing bias. Panels (a), (c), and (d) are adapted with permission from Ref. [48], © Springer Nature (2004).

of nematons and their subsequent functionalization in Soft Mattonics.

3.2.2 Experimental emergence of optical solitons

The experimental realization of nematons—self-trapped optical spatial solitons—marked a decisive breakthrough in soft matter photonics. Before 2000, soliton formation in NLCs typically required dye-doping, where resonant absorption enhanced the nonlinear response and lowered thresholds but introduced thermal contributions that obscured the pure reorientational effect^[197–199]. The central challenges, therefore, were (i) reducing thermal artifacts, and (ii) achieving self-focusing at lower optical powers.

In their landmark 2000 demonstration^[47], Peccianti *et al.* reported dye-free nematons in uniformly aligned planar cells. Exploiting the intrinsic $\chi^{(3)}$ reorientational nonlinearity, they launched extraordinarily polarized beams that induced local director reorientation, producing a positive index change and self-focusing channel [Fig. 12(b)]. A key element was using a low-frequency bias to pre-tilt the director, thereby lowering the Fréedericksz threshold. This alignment strategy suppressed resonant absorption, minimized heating, and enabled stable soliton formation at milliwatt power levels (~ 4 mW) sustained over millimeter-scale propagation distances.

This achievement proved that nematons could be generated in pure nematic media, establishing them as robust, reconfigurable self-guided beams. Shortly after, experiments extended nematons to incoherent light beams, showing that the slow, non-instantaneous nonlinearity was sufficiently robust to preserve soliton stability even under partial spatial or temporal coherence^[50]. Together, these results transformed nematons from a laboratory curiosity into a practical platform for all-optical beam control and signal processing in soft matter.

3.2.3 Steering of optical solitons

Once nematons were firmly established as stable self-trapped beams in NLCs, attention rapidly turned to their interactions

with interfaces and external potentials, where new forms of beam control emerged. Unlike solitons in isotropic Kerr media, nematons inherently experience anisotropy and walk-off, so their response at interfaces is governed not by geometric optics but by the Poynting vector trajectory. Over the past two decades, experiments and theory have revealed refraction, reflection, tunneling-like escape from potentials, and even power-dependent negative refraction, establishing nematons as reconfigurable carriers for soft matter photonics.

3.2.3.1 Controllable routing: early demonstrations. Beyond nonlocality, a defining feature of nematons dynamics is the walk-off effect. Due to birefringence, the Poynting vector deviates from the wave vector, resulting in a transverse drift. The walk-off angle is given by

$$\tan |\delta(\theta)| = \frac{|\Delta\epsilon \cdot \sin(2\theta)|}{2(n_{\perp}^2 \sin^2(\theta) + n_{\parallel}^2 \cos^2(\theta))}. \quad (3-3)$$

This parameter governs not only the soliton trajectory and steering but also the stability under varying bias^[48].

With the theory and experimental techniques in place, the next step was to demonstrate controllable routing of nematons. In 2004, Peccianti *et al.* demonstrated the first controllable routing and interaction of nematons, using voltage-controlled reorientation of the director field [Figs. 12(c) and 12(d)]^[48]. By tuning the applied voltage, they reconfigured the director field, guiding nematons along curved trajectories. Crucially, these beams preserved their solitonic robustness: two nematons could collide, cross, and continue propagating without annihilation, exemplifying elastic interactions in soft matter. The ability to manipulate the trajectory of nematons led to the development of vector nematons. In 2006, Alberucci *et al.* demonstrated the formation of two-color vector nematons in which beams at different wavelengths shared a single nonlocal director-induced index well^[200]. This result showed that nematons could mutually trap each other and propagate stably as a vector soliton. Walk-off again

played a crucial role here: beams with different wavelengths have slightly different walk-off angles, allowing them to mutually interact and stabilize.

3.2.3.2 Interface-induced deflection of solitons: refraction, reflection, and negative refraction. The landmark demonstration by Piccardi *et al.* in 2006 showed that nematicons incident on engineered interfaces between voltage-controlled nematic domains undergo nonlinear refraction and total internal reflection (TIR)^[54]. Unlike plane waves, nematicons refracted non-specularly, with incident and transmitted angles determined by the walk-off of the Poynting vector. The experiments revealed angular shifts up to $\sim 18^\circ$ for refraction and $\sim 22^\circ$ for reflection [Fig. 13(a)], tunable by electrode bias. Importantly, this

was the first observation of soliton TIR in a cubically nonlinear medium, highlighting that nematicons propagate as quasi-particles subject to effective boundary conditions.

A particularly striking manifestation of nonlinear beam transport in nematicons was revealed in 2014, when Piccardi *et al.* demonstrated a power-controlled transition between positive and negative refraction in nematic cells [Fig. 13(b)]^[55]. Unlike conventional metamaterials or photonic crystals, this effect emerged purely from the self-action of light in a reorientational soft medium, where the walk-off angle between phase and energy flow could be optically tuned. Alberucci *et al.* provided the theoretical framework for this phenomenon^[56]. They showed that negative refraction arises when reorientation drives a sign inversion of the Poynting vector deflection, and derived scaling

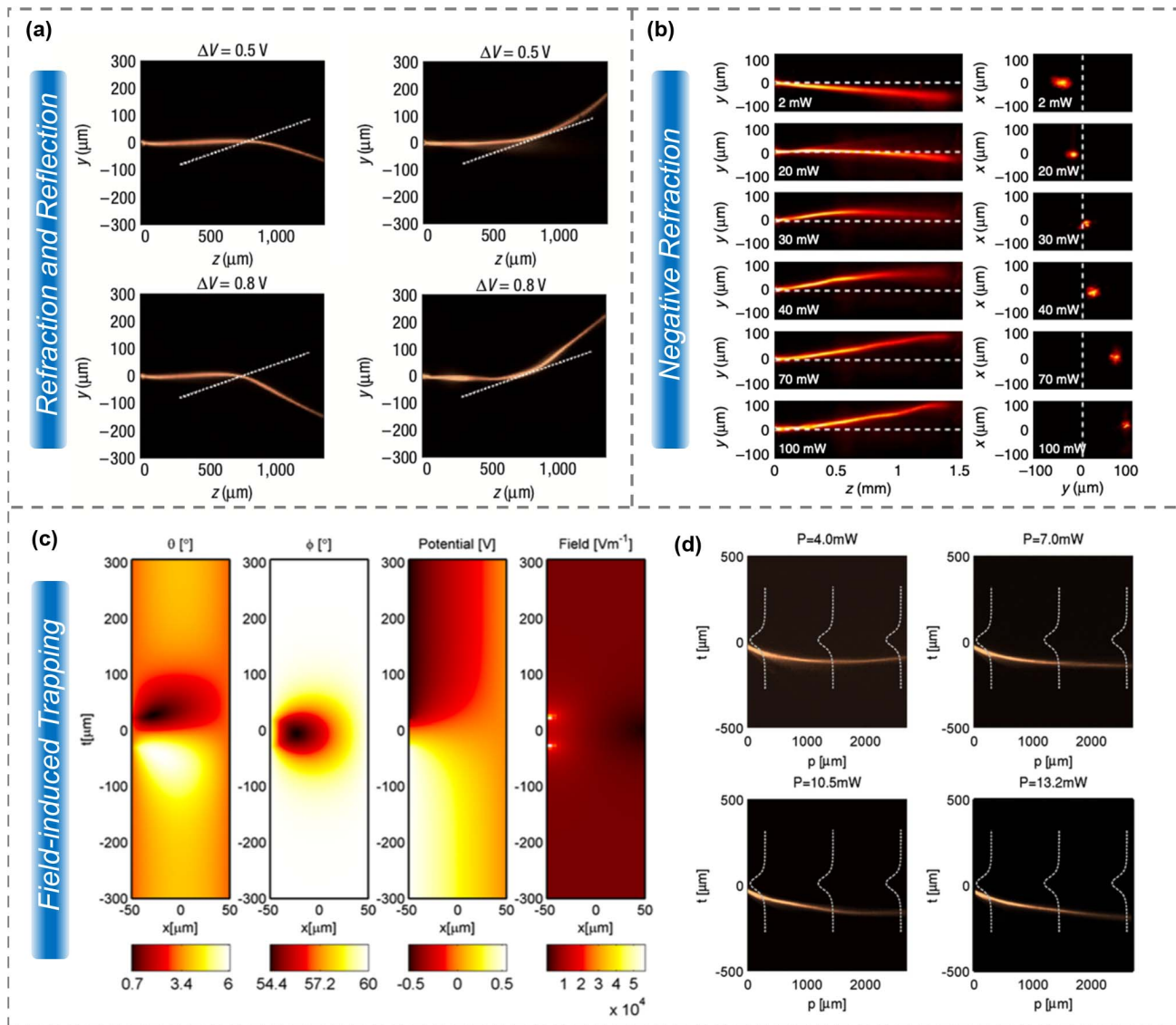


Fig. 13 Nematicon transport control via interfaces and potential engineering. (a) Electrically driven refraction of nematicons at the interface between two LC regions biased with different voltages^[54]. Adapted with permission from Ref.^[54], © Springer Nature (2006). (b) Electrically driven TIR at the interface^[55]. Adapted with permission from Ref.^[55], © Springer Nature (2014). (c) Creation of refractive-index trapping potentials by applying patterned electrode voltages^[203]. Adapted with permission from Ref.^[204], © American Physical Society (2008). (d) Micrographs of soliton trajectories illustrating trapping and escape of nematicons within bias-induced potentials^[203].

laws linking threshold power to beam waist, incidence angle, and cell thickness. Importantly, they confirmed that the process involves only forward-propagating waves, distinguishing LC negative refraction from backward-wave metamaterials while ensuring robustness for integrated photonics.

More recently, continuous soliton steering has been achieved by constructing programmable director landscapes. In 2018, Laudyn *et al.* demonstrated curved soliton trajectories guided by predesigned director patterns fabricated via photoalignment^[201]. Zhang *et al.* realized nematicon deflection and routing using an orientation-programmable LC array with comb electrodes. By tuning applied voltages, the electrode pattern generated spatially periodic director distributions that produced controllable beam deflections up to $\sim 26^\circ$, as well as TIR at designed interfaces. Furthermore, nematicon pairs exhibited voltage-tunable deflection combinations, paving the way toward programmable soliton routing networks^[202].

3.2.3.3 Field-induced trapping of solitons. Building on this interface picture, Peccianti *et al.* introduced refractive-index trapping potentials by spatially modulating electrode voltages [Fig. 13(c)]^[203]. Nematicons confined in such channels oscillated inside the potential well but escaped when their “kinetic energy” exceeded a critical threshold, a behavior directly analogous to particles overcoming a trapping barrier [Fig. 13(d)]. Using an Ehrenfest-like theorem applied to the nonlinear Schrödinger model, the authors provided a quantitative description of nematicon trajectories. These escape dynamics not only reinforce the particle analogy for nematicons but also offer a strategy for switchable confinement and release of guided beams, with direct relevance to reconfigurable photonic circuits.

A natural extension was achieved in 2010 by Assanto and collaborators, who replaced static electrodes with light-induced refractive potentials^[204]. In dye-doped nematics, an auxiliary control beam reoriented the director locally, creating dynamic index gradients that deflected nematicon trajectories. The experiments demonstrated precise steering, including both positive and negative deflections, while theory showed that the trajectory depends only on the potential landscape, not on details of the soliton profile. Later developments broadened these strategies by incorporating additional external fields. For example, Assanto *et al.* demonstrated thermo-optic steering of nematicons, where heating effects—either externally controlled or beam-induced—altered the director configuration and effectively re-routed soliton trajectories^[205].

These discoveries not only expanded the functional scope of nematicons but also underscored their ability to emulate exotic wave phenomena with a simplicity unmatched by structured media.

3.2.4 Functionalization of optical solitons through self-induced waveguides

The recognition of nematicons as self-induced waveguides naturally opened the path from fundamental nonlinear dynamics to functional photonic applications. Once a beam not only self-traps but also establishes a reconfigurable guiding channel, it can serve as a platform for transporting, processing, and enhancing light in soft matter systems.

The functionalization of nematicons advanced further with the demonstration of external-field routing of light-induced channels, realized in both fluidic nematics^[51] and polymer-stabilized configurations^[52,53,206]. In 2017, Izdebskaya *et al.* reported a scheme

for three-dimensional steering of nematicon waveguides using external magnetic fields [Figs. 14(a) and 14(b)]^[52]. Unlike traditional planar cells, where director alignment is fixed by boundaries, bulk NLC samples free from lateral anchoring allowed unprecedented freedom. By applying a moderate magnetic field, the threshold power, molecular director orientation—and hence the nematicon trajectory—was reoriented in three dimensions [Fig. 14(c)]. Such demonstrations underscored the potential of nematicons as reconfigurable, steerable interconnects, directly controlled by external fields.

Perhaps the most striking application emerged in 2018, when Perumbilavil *et al.* combined nematicons with random lasing in dye-doped NLCs [Fig. 14(d)]^[53]. Random lasers, which rely on scattering for feedback, typically suffer from poor directionality and unstable profiles. By launching a near-infrared nematicon alongside the optical pump, the self-induced waveguide captured and steered the emission, resulting in directional, smooth, and efficient random lasing [Figs. 14(e)–14(g)]. Later work expanded this concept to examine the spatio-spectral properties of soliton-assisted random lasers^[206], showing that nematicons can merge multiple random lasing resonances into guided emission with enhanced stability and bidirectional control. This approach transforms nematicons from passive guiding structures into active elements for laser control, offering a unique synergy between nonlinear waveguiding and random lasing in soft photonics.

3.3 In-Plane Transformation Optics and Analog Cosmology

Transformation optics (TO) provides a general framework to manipulate electromagnetic waves by tailoring the spatial distribution of permittivity and permeability. It relies on the form-invariance of Maxwell’s equations under coordinate transformations: a mapping of space corresponds to engineered constitutive parameters that bend or reshape trajectories as if waves propagated in a curved geometry^[207]. Since its inception, TO has inspired a host of breakthroughs, including cloaking^[208,209], illusion optics^[210], on-chip nonlinear optics^[211], and cosmological analogy^[212]. Yet, the practical realization of TO remains nontrivial. TO prescriptions often require strongly anisotropic, inhomogeneous media, particularly at optical frequencies, demanding subwavelength metamaterials with graded properties that are challenging to fabricate lithographically. By contrast, LCs offer self-assembled anisotropy and reconfigurability, allowing TO-inspired metrics to be realized without nanofabrication^[38,39]. When light is launched in-plane, the director orientation defines an effective optical metric, making LC films a uniquely direct and experimentally accessible TO platform.

3.3.1 TO and ray tracing based on LC structures

Employing LCs for TO builds on the recognition that optic-axis distributions act as effective spatially varying metrics. Sátiro and Moraes provided some of the earliest theoretical predictions, showing that nematic disclinations can bend and focus extraordinary rays in a manner directly analogous to gravitational lensing [Fig. 15(a)]^[40,213]. Their models cast the director-induced refractive-index profile as a curved-space geometry, predicting deflection angles akin to light rays skirting cosmic strings. These early works established the principle that LC defects act as effective TO elements, shaping beams through orientational geometry rather than material density. The systematic potential

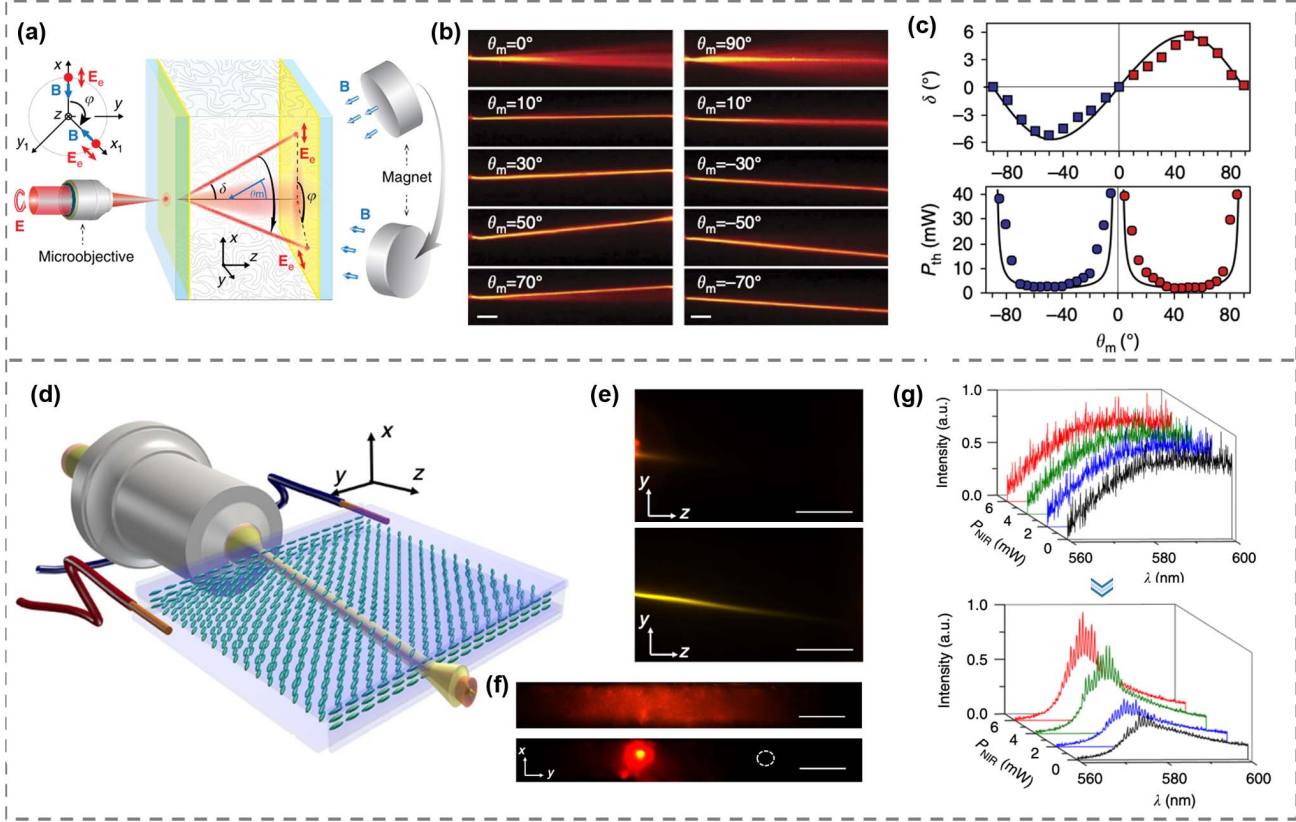


Fig. 14 Soliton-induced optical waveguides and functionalization. (a) Configuration for magnetic-field routing of nematicon waveguides^[52]. (b) Micrographs of soliton trajectories showing alternating walk-off controlled by the applied magnetic field^[52]. (c) Measured walk-off amplitude and threshold power as functions of the magnetic polar angle^[52]. (d) Experimental setup of a nematicon-assisted random laser, with coaxial incidence of a near-infrared beam for nematicon generation and a green pulsed laser for dye excitation^[53]. (e) Top-view images of random-laser emission without (top) and with (bottom) nematicon generation. (f) Random-laser emission recorded at the output facet of the LC cell^[53]. (g) Emission spectra in the presence of nematicons for different pump pulse energies (0.4 μ J, upper, and 0.55 μ J, lower)^[53].

of LCs for TO was first articulated by Lavrentovich, who outlined how director distributions could serve as self-assembled transformation media, implementing gradient anisotropies without resorting to nanofabrication^[38,39].

The link between LCs and TO arises from their anisotropic dielectric properties. Within the TO framework, a coordinate transformation $x \rightarrow x'$ modifies the constitutive parameters according to^[39]

$$\epsilon' = \frac{A\epsilon A^T}{\det(A)}, \quad \mu' = \frac{A\mu A^T}{\det(A)}, \quad (3-4)$$

where $A = \partial x' / \partial x$ is the Jacobian matrix of the transformation. ϵ is the local permittivity tensor of nematics. In practice, the director field of an LC provides a “self-assembled” implementation of ϵ , generating the required anisotropy and gradient distributions. Thus, spatially varying director textures can be interpreted as effective coordinate transformations, enabling beam bending, concentration, and splitting analogous to TO prescriptions.

Later in 2015, Zhang *et al.* demonstrated how conical curvature singularities steer beams [Figs. 15(b) and 15(c)]^[214], while Barros *et al.* (2020) showed that a single conical LC-inspired

structure can concentrate, diverge, shift, or split light depending on orientation^[215]. These studies underscored the versatility of LC-based TO, where orientational fields replicate geometric curvature without artificial metamaterials.

Ray tracing in LCs formalizes this picture. The extraordinary ray path minimizes the optical length according to Fermat’s principle, equivalent to a geodesic in an effective metric:

$$\delta \int n(\mathbf{r}) ds = 0, \quad (3-5)$$

where $n(\mathbf{r})$ is the position-dependent extraordinary refractive index. Applying the Euler–Lagrange equations yields the geodesic equation for ray trajectories:

$$\frac{d^2 x^i}{ds^2} + \Gamma_{jk}^i \frac{dx^j}{ds} \frac{dx^k}{ds} = 0, \quad (3-6)$$

where Γ_{jk}^i are the Christoffel symbols associated with the effective metric tensor $g_{ij} = n^2(\mathbf{r})\delta_{ij}$ ^[216]. In practical nematic geometries, this reduces to coupled differential equations describing transverse beam deflection, as referred to in Refs. [40,214].

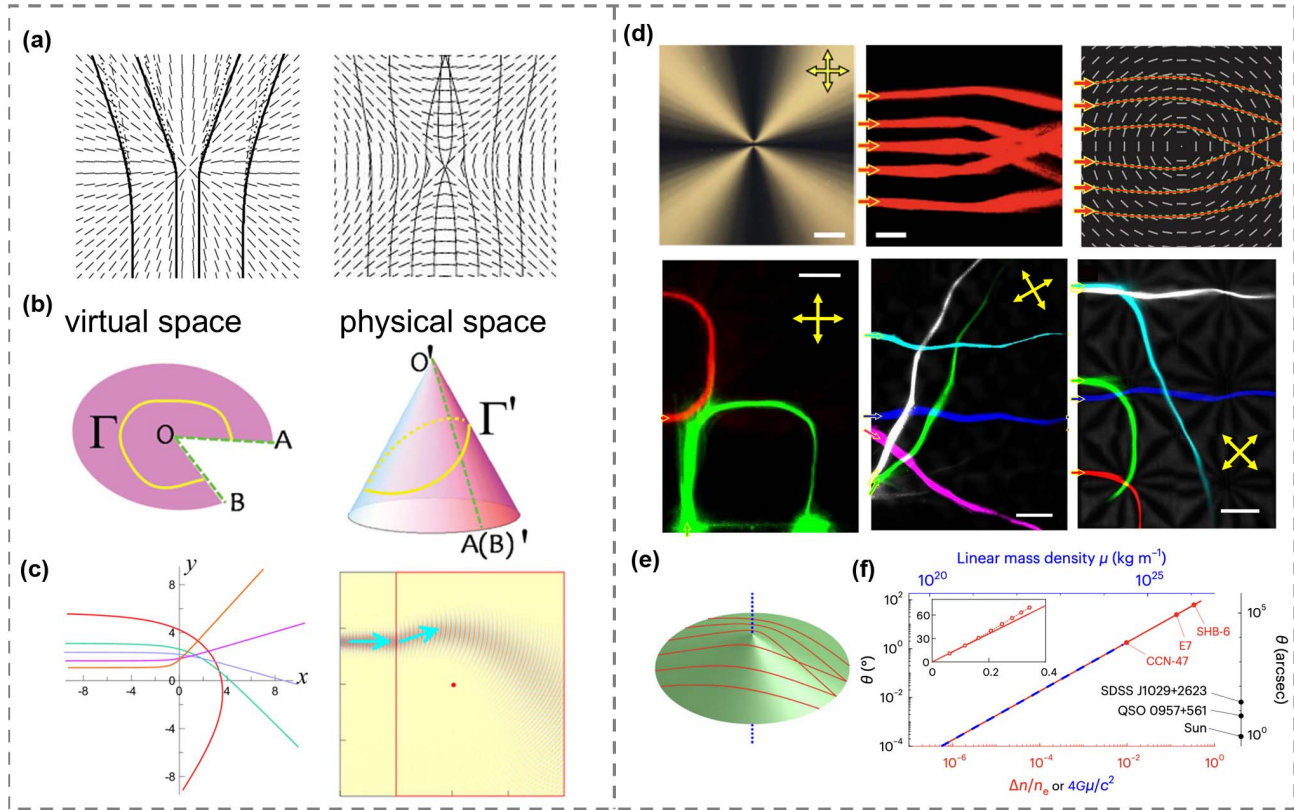


Fig. 15 In-plane TO and cosmic analogy. (a) Simulation of ray trajectories through LC topological defects. Adapted with permission from Refs. [40,213], © Springer Nature (2006 and 2008). (b) Schematic illustration of conical space construction via Volterra's cut-and-glue process. (c) Geodesics illustrating photon motion in the transformed medium, analogous to cosmic strings (left), and an example of a Gaussian beam propagation trajectory (right). Adapted with permission from Ref. [214], © Optical Society of America (2015). (d) Interaction of optical solitons with arrays of topological vortices, demonstrating trajectory bending. (e), (f) Cosmological analogy of light propagation near a cosmic string, emulated by nematicon-vortex interactions in NLC films. Adapted with permission from Ref. [44], © Springer Nature (2022).

Such equations, widely used in simulations of LC textures, capture how beams follow geodesics of a director-defined metric.

The TO paradigm in LCs has also been extended beyond optics. Barros and Pereira (2018) showed that the same LC textures can concurrently guide light and heat, establishing the concept of transformation thermodynamics in soft matter^[217]. Santos *et al.* (2018) further demonstrated rectification of both light and heat in cholesterics^[218]. These works highlight LCs as multi-physics TO platforms.

3.3.2 In-plane observation and cosmic analogy

The experimental validation of TO analogies in LCs culminated in the direct in-plane observation of beam steering by topological structures. In 2023, Meng *et al.* reported the first experimental demonstration of topological steering of nematicons by vortex-line director fields^[44]. By photo-patterning nematic vortices and launching self-focused solitons, they achieved nearly 360° beam deflections, with trajectories bending around defects in close analogy to light skirting cosmic strings. The experiments further demonstrated that solitons can trace closed loops and knot-like paths, providing a laboratory analog of curved spacetime geodesics [Fig. 15(d)].

Importantly, the steering dynamics were reconfigurable under external fields, illustrating that LCs afford tunable analog gravity experiments in real-time.

This landmark experiment built upon decades of theoretical predictions. Sátiro and Moraes' work had already proposed that nematic disclinations emulate cosmic string lensing^[40,213], while Figueiredo *et al.* (2017) drew explicit analogies between hyperbolic metamaterials and the Milne universe^[216]. These earlier studies framed the geometry-optics analogy that Meng *et al.* ultimately realized in the laboratory [Figs. 15(e) and 15(f)]. The advantage of the in-plane LC platform lies in its direct observability: unlike astrophysical phenomena or subwavelength metamaterials, here beams can be launched, steered, and imaged in real-time, offering a unique “god’s-eye view” of curved-space propagation.

Together, these studies underscore that the strength of LC in-plane optics lies in its ability to provide a reconfigurable, observable laboratory for TO and analog gravity. This positions LCs at the intersection of photonics and fundamental physics, where soft matter becomes a medium not just for light control, but for simulating the very fabric of spacetime. More importantly, the pronounced external-field responsiveness of liquid crystals enables dynamic, *in-situ* manipulation of in-plane light beams, thereby

distinguishing Soft-Mattonics-based TO from static or quasi-static nanophotonic platforms such as metasurfaces.

3.4 In-Plane Light Flow in Chiral Nematics and Beam-Driven Topological Matters

The next frontier extended beyond predesigned 2D director landscapes to intrinsic topological structures—fingers, skyrmions, and torons—that spontaneously arise in chiral nematic media (or cholesteric) phases (i.e., CLCs). The introduction of CLC opens a new dimension for in-plane LC optics. On the other hand, the CLCs characterized by intrinsic helical order with a tunable pitch significantly modify the elastic and optical landscapes. This helical symmetry alters the balance of torques governing director reorientation, thereby reshaping the nonlocal response to optical fields. As a result, CLC systems exhibit qualitatively new beam dynamics compared to their achiral nematic counterparts and diverse topological structures [Figs. 16(a) and 16(b)]^[57,219].

3.4.1 Chirality-enhanced in-plane nonlinear transport

In 2009, Laudyn *et al.* reported the formation of nematicons in CLC cells^[220]. They showed that, beyond sustaining stable spatial solitons at milliwatt powers, CLCs permit the creation of multiple independent nematicons across successive helical layers, each layer defined by the cholesteric pitch. Madani *et al.* revealed new nonlinear phenomena unique to chiral phases: self-splitting of nematicons into twin solitons under higher powers^[221]. They attributed this to saturation of the reorientational nonlinearity, where the helical geometry and nonlocal response redistribute the optical torque.

A decisive leap came in 2020, when Poy *et al.* reported chirality-enhanced periodic self-focusing in frustrated CLCs^[57]. In these unwound states, optical beams exhibited bouncing propagation patterns [Fig. 16(c)], repeatedly self-focusing and defocusing along the sample length. Simulations and tomographic imaging confirmed that chirality enhances the effective reorientation amplitude, nearly doubling the nonlinear index change compared with achiral systems. This periodic self-focusing

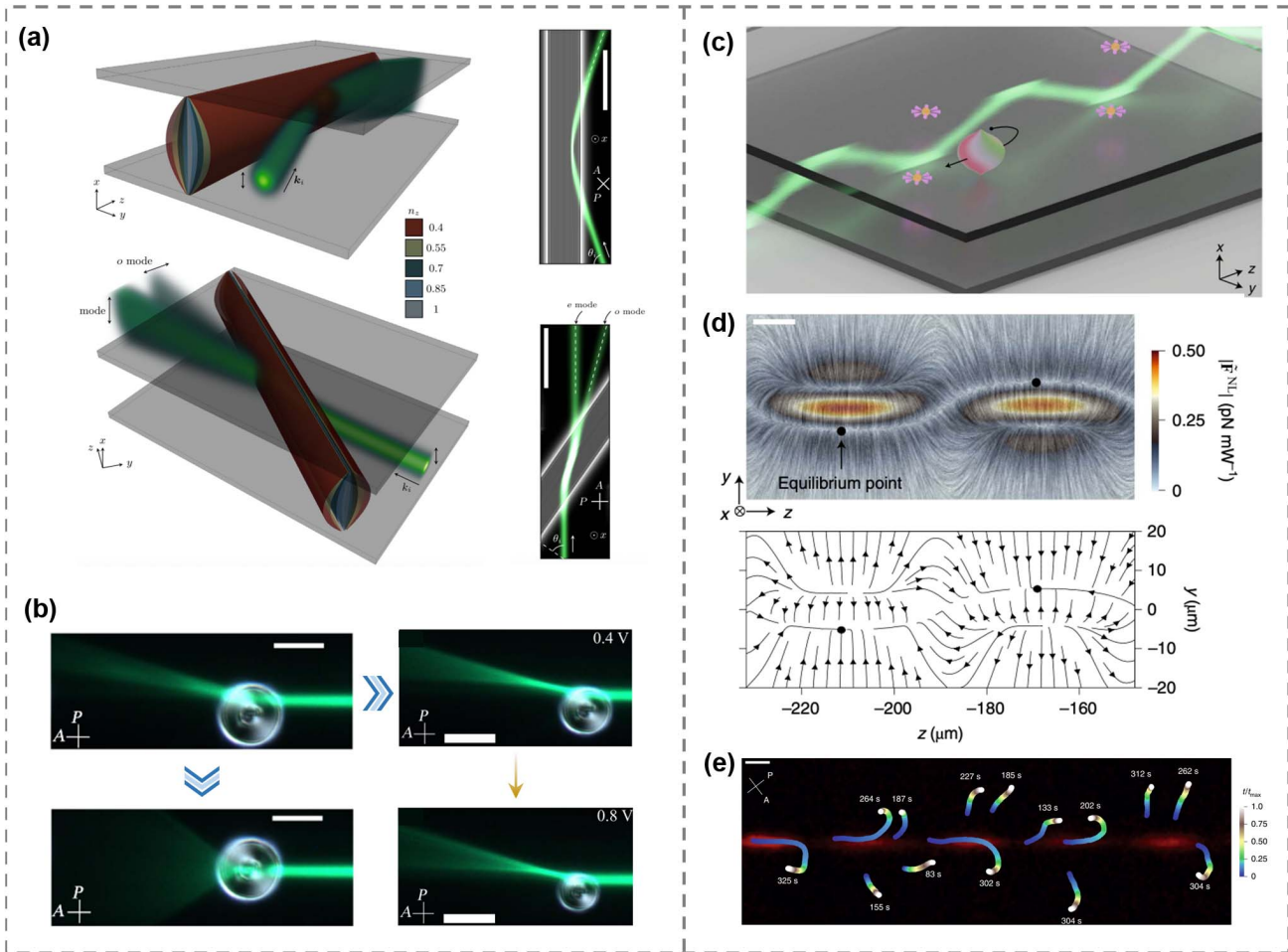


Fig. 16 Interactions between light and topological structures in LCs. (a) Beam interaction with a twisted-wall structure, resulting in optical deflection and refraction^[58]. (b) Beam deflection and lensing effects induced by a toron, with electrically tunable strength^[58]. (c) Schematic illustration of interactions between bouncing optical solitons and topological solitons. (d) Representation of the optical force field generated by a nematicon. (e) Direct comparison of experimentally observed toron trajectories with calculated force-field lines. Panels (c)–(e) are adapted with permission from Ref. [60], © Springer Nature (2022).

emerged directly from the coupling between the optical field and the spontaneous twist, which allows local release of elastic frustration and promotes three-dimensional director reorientation. As a result, chirality reduced the power thresholds for nonlinear guiding and introduced qualitatively new beam dynamics, offering prospects for low-power nonlinear lenses, adaptive routers, and interactions with topological solitons.

3.4.2 In-plane light-topological structure interactions

In a CLC system, the introduction of a spatially varying director along the z -direction enables the construction of 3D structures. The competition between elastic distortion, intrinsic chirality, and boundary anchoring stabilizes a hierarchy of topological textures—such as skyrmions, torons, and hopfions—characterized by nontrivial mappings of the director field onto the order-parameter manifold. These material solitons arise uniquely in chiral phases and constitute genuine topological excitations of soft matter.

Hess *et al.* (2020) investigated the linear interaction of Gaussian beams with twisted walls and skyrmions, demonstrating that such structures behave as localized refractive-index inhomogeneities [Figs. 16(a) and 16(b)]^[58]. Remarkably, the steering of beams by these solitons followed a generalized Snell's law, with deflections equivalent to refraction at a sharp interface, despite the medium being chemically uniform. This finding established that topological solitons act as reconfigurable optical elements—beam deflectors, lenses, and prisms—whose strength is tunable by electric fields and chirality. The framework connected light-defect interactions with Hamiltonian ray optics and effective geodesics, setting the stage for nonlinear extensions.

That nonlinear regime was realized by Poy *et al.* in 2022, who studied the interaction and co-assembly of optical nematicons with topological solitons such as skyrmions and torons [Fig. 16(c)]^[60]. They discovered that nematicons can attract, repel, or trap topological solitons, leading to rich collective behaviors. Optical beams acted as tractor forces [Fig. 16(d)], relocating skyrmions and even arranging them into one-dimensional arrays along the nematicon trajectory [Fig. 16(e)]. Conversely, skyrmions modulated nematicon dynamics, inducing bouncing and curved propagation modes. The interaction was elegantly modeled via an effective Langevin equation, combining local optical forces with nonlocal elastic couplings. This study revealed a new regime of mutual soliton-soliton assembly, in which light and matter solitons co-pattern and stabilize each other, marking a leap beyond passive beam steering into optomechanical synergy between nonlinear light and topological matter.

3.5 In-Plane Optical Branched Flow in Disordered LC Films

Previous studies of in-plane LC photonics have predominantly focused on orderly orientational environments, from nematicons stabilized in uniformly aligned nematics to light-topological structure interactions in engineered landscapes. These systems highlight the remarkable tunability of LCs under well-defined director fields, but they remain essentially ordered media. More recently, attention has shifted toward the contrasting regime of weakly disordered LC films, where multiple scattering events give rise to chaotic transport phenomena. In this regime, light propagates through random director fluctuations and

organizes into branched flow, thereby extending the informational complexity and dynamical richness of in-plane LC optics.

3.5.1 Branched flow phenomenon in diverse physical systems

Branched flow is a striking wave phenomenon in which coherent waves, instead of spreading uniformly or generating random speckles, evolve into tree-like caustic filaments when traversing a weakly disordered medium with a correlation length larger than the wavelength^[222]. First discovered in two-dimensional electron gases^[223] and later observed in water waves^[224], sound waves^[225], microwaves^[226], and light^[227], branched flow is now recognized as a universal signature of wave dynamics across scales.

The optical realization of branched flow was first reported in 2020, where smooth thickness variations in soap films acted as disordered potentials, producing caustic branching of light beams^[227]. Subsequent studies extended the phenomenon to incoherent illumination, confirming that branching persists even when interference is suppressed, though with altered statistics and blurred sidelobes^[58]. Theoretical advances emphasized the universality of branching and proposed wavefront shaping as a means to select individual branches^[228], highlighting the promise of photonic implementations. Together, these works established branched flow as an accessible regime for optics, yet still largely uncontrolled in conventional media. However, precisely because it depends sensitively on the underlying disorder potential, branched flow has been difficult to generate and manipulate on demand.

3.5.2 Tailoring optical branched flow in LC films

LCs, with their optical anisotropy, soft elasticity, and sensitivity to external fields, provide a unique solution. Their self-assembled textures naturally produce weak, correlated disorder, while electro-optic and photoalignment techniques allow tunability unmatched by other platforms. These properties position LC films as an ideal medium for exploring and controlling optical branched flow.

A breakthrough came in 2024, when Chang *et al.* demonstrated electrical tuning of branched flow in nematic LC films^[61]. The schlieren textures formed by intrinsic disclinations provided correlated disorder potentials, and applying a small voltage reoriented the molecules, modifying the correlation length and strength of the disorder [Fig. 17(a)]. This enabled reversible switching of branched flow on and off, as well as quantitative tuning of its branching density. Furthermore, due to birefringence, the branching pattern could also be tuned via input polarization. This was the first experimental realization of active, reversible control over branched flow in optics, achieved with millivolt-level voltages in a planar LC platform, and marked a key step toward integrating the phenomenon with reconfigurable photonics.

Yu *et al.* advanced the concept by coupling branched flow with the dynamics of topological defects in nematics. In 2024, they showed that applying AC fields drives time-dependent defect annihilation, altering the disorder potential from dense to sparse^[62]. Correspondingly, the optical response exhibited a continuous transition from branched flow to deterministic beam steering, effectively bridging random and ordered propagation regimes in one platform [Fig. 17(b)]. The work established a dynamical control mechanism, where branched flow is not a static response to frozen disorder but a tunable state in evolving LC architectures.

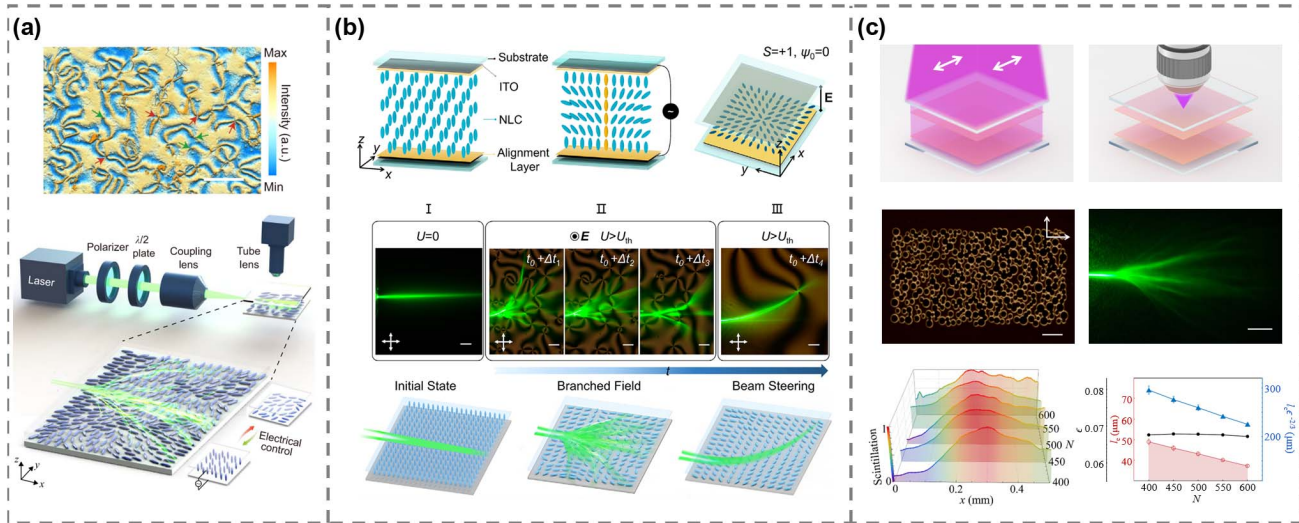


Fig. 17 In-plane manipulation of optical branched flow in LC layers. (a) Schematic illustration of branched-flow generation in an NLC film with spontaneously formed disordered textures^[61]. (b) Dynamic transition from branched flow to deterministic beam steering in evolving defect landscapes. Adapted with permission from Ref. [62], © Wiley-VCH (2024). (c) Tailoring of branched flow by engineering disordered optical potentials. Adapted with permission from Ref. [63], © Wiley-VCH (2025).

This enriches the physics of light–defect interactions and offers a route to adaptive optical elements.

Most recently, Yu *et al.* reported on-demand tailoring of branched flow using photoalignment-based domain engineering^[63]. By assembling nematic domains with designed orientations and controlled density, they crafted disordered potentials with adjustable correlation lengths [Fig. 17(c)]. This enabled precise localization of branching points and even unilateral branch formation at engineered boundaries, extending the conventional understanding of branched flow. Unlike earlier work limited to global electrical tuning, this approach provided microscale programmability of branching morphology, opening avenues toward diffractive optical computing and neural-inspired architectures.

3.6 Discussion

In recent years, in-plane LC optics has emerged as a versatile platform for probing light–soft matter interactions, spanning regimes from highly ordered director fields to weakly chaotic landscapes. By leveraging the intrinsic birefringence, elasticity, and self-assembly of LCs, this platform provides not only a testbed for multi-physics coupling—across electric, optical, and thermal fields—but also a uniquely reconfigurable medium for advanced optical control. These properties establish the foundation for multidimensional in-plane light information processing and the integration of LC-based on-chip photonic devices.

Looking ahead, the next frontier lies in exploiting structured-light formats, in which amplitude, phase, polarization, and OAM encode high-dimensional information. Incorporating such structured beams into in-plane LC architectures will expand the degrees of freedom for optical steering and interaction, transforming LCs into powerful carriers and processors of structured information. In parallel, advances in polymer stabilization and laser-writing techniques open opportunities for designing

subwavelength-scale photonic architectures directly within LC layers. Together with the recent demonstration of LC micro-lasers and reconfigurable waveguides, these developments point toward a new generation of adaptive soft matter photonic circuits.

3.6.1 Structured-light information processing

While most early demonstrations relied on Gaussian beams, recent progress has extended LC platforms to structured beams capable of encoding richer information^[229–231]. Airy beams, with their inherent self-acceleration and resilience, have been dynamically routed in metasurface-enabled LC cells [Fig. 18(a)]^[230]. Gradient director alignment imposed linear refractive-index potentials, allowing electrical control of curved trajectories without disturbing their diffraction-free nature [Figs. 18(b)–18(d)].

3.6.2 On-chip LC photonics and lasing

A parallel line of progress demonstrates that LCs can serve simultaneously as guiding media and active gain platforms. Very recently, the milestone achievement was reported by Mušević *et al.*, who realized the first LC-based on-chip laser system. By integrating dye-doped chiral LC microcavities with laser-printed polymer waveguides, they generated nanosecond pulses that could be actively switched via resonant depletion [Figs. 18(e)–18(g)]^[59]. This work established a proof-of-concept for all-optical control within a self-assembled platform. Smalyukh *et al.* emphasized the significance of this step: chiral LC assemblies offer a molecularly engineered alternative to costly microfabrication, with tunability and reconfigurability built in Ref. [232]. Earlier LC-based waveguides and displays foreshadowed this integration, but the emergence of LC micro-lasers signals the entry of soft matter into true on-chip photonic circuitry.

In sum, in-plane LC optics has established itself as an effective platform for physical modeling, spanning a broad range of

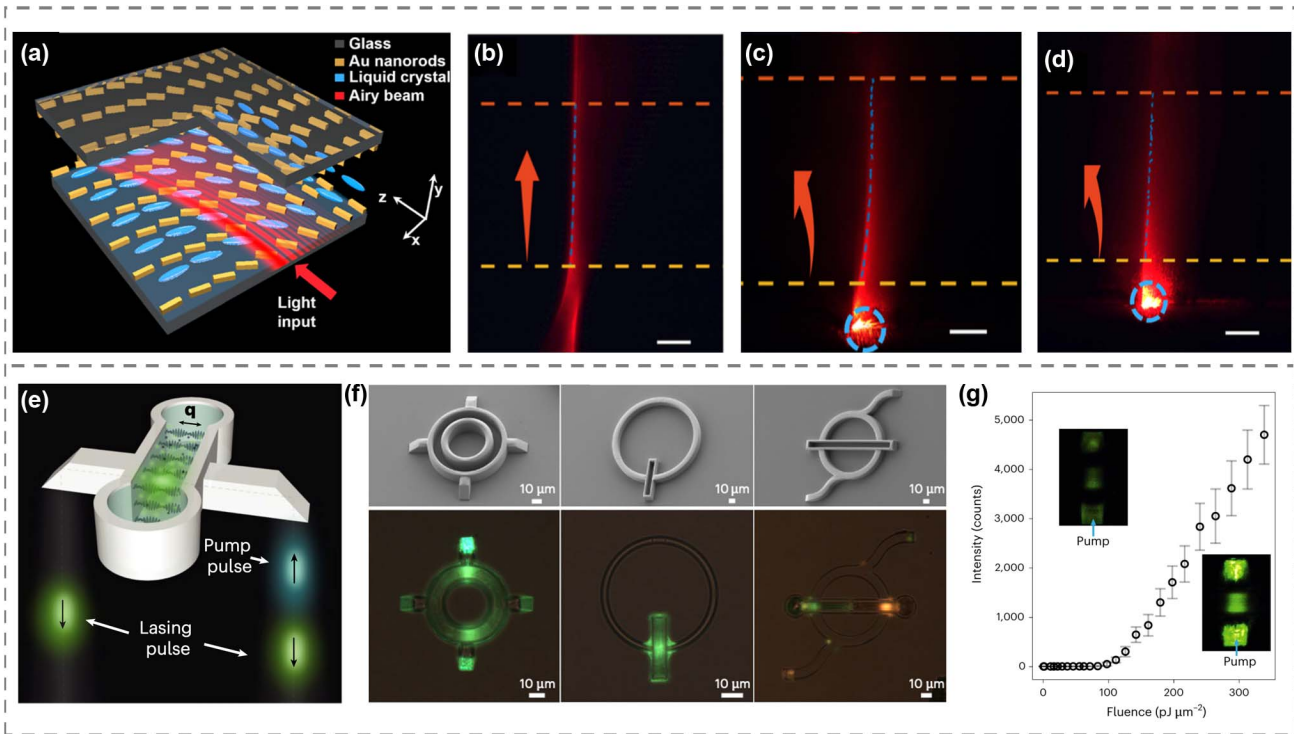


Fig. 18 In-plane structured-beam transformation and on-chip photonics. (a) Schematic setup for the in-plane transformation of an Airy beam^[230]. (b)–(d) Propagation of Airy beams in free space (b), an LC layer with a gradient refractive-index (c), and a uniform LC layer without a gradient (d)^[230]. (e), (f) Representative geometries and designs of CLC microlasers. (g) Optical intensity as a function of pump fluences, showing lasing threshold of an 8.2 μm microlaser^[59].

physical domains from optical transformation to microlasers. Owing to their intrinsic reconfigurability and self-assembly, LCs can host a rich variety of topological structures, providing a uniquely versatile platform for emulating diverse physical systems, ranging from chaotic dynamics to large-scale cosmological analogies, in a manner fundamentally distinct from solid-state nanophotonic materials. As a step forward, this study is poised to move beyond proof-of-concept demonstrations toward an era of informatization—where structured light and soft photonic devices converge into integrated systems for optical communication, computation, and fundamental physics simulations for the Soft Mattonics framework.

In a broader application perspective, the transition from free-space beam shaping to in-plane light steering fundamentally transcends the functional role of liquid crystals: rather than merely imprinting optical profiles at an interface, LC films enable propagation-based, on-chip information processing within a confined planar geometry. First, spatially engineered director landscapes act as programmable transport networks that support complex and even disorder-enabled trajectories. Phenomena such as branched flow and spontaneous pattern formation—originating from weak disorder and elastic interactions—provide physically reconfigurable scattering and multiplexing pathways, offering a natural platform for hardware-level information encryption and secure routing, where information is encoded in stochastic yet controllable in-plane paths. Second, the same geometry supports integrated linear and nonlinear processing, including beam steering, polarization-selective guidance, mode conversion, and soliton-mediated self-written waveguides,

allowing signals to be routed, switched, or reshaped during propagation; nonlinear responses further introduce intensity-dependent modulation and frequency conversion, expanding functionality beyond passive transport. Finally, embedded gain media and microcavities establish an on-chip transduction layer, where guided states are directly converted to lasing, electrical, or sensing outputs. Collectively, these capabilities position in-plane LC photonics not simply as a beam-control technique, but as a soft matter platform for integrated generation, processing, and readout of optical information on chip.

4 From Linear to Nonlinear Optical Processing

4.1 Linear Optical Modulation in LC Systems

In the context of Soft Mattonics, LCs offer a rich set of tools for linear optical modulation—from scalar to vector and from free-space to in-plane—where the material response is governed solely by the first-order polarization term. Here, “linear” refers to regimes where the material response is described by linear optics. From Maxwell’s equations, the optical response of any medium is given by its polarization vector, which can be written as a power series in the applied electric field, $\mathbf{P} = \mathbf{P}^L + \mathbf{P}^{NL}$. Here, $\mathbf{P}^L = \epsilon_0 \chi^{(1)} \mathbf{E}$ denotes the linear (first-order) polarization. In this expression, $\mathbf{E}$ is the applied electric field vector, and $\chi^{(1)}$ is the linear susceptibility tensor of the medium, which characterizes how the material responds linearly to the electric field. The remaining contribution $\mathbf{P}^{NL}$

encompasses all nonlinear polarization terms. This framework of linear polarization defines the domain of linear optics: the output field is proportional to the input and the photon energy is conserved. This restriction reflects not only an energetic conservation law but also a limit on information growth. From an information-theoretic point of view, such a system acts like a channel whose dimensionality is limited to the orthogonal modes supported within a single frequency. For a uniaxial nematic LC, the dielectric tensor originates from the linear susceptibility tensor^[233]. In the material's principal axis system, this tensor takes the diagonal form

$$\boldsymbol{\varepsilon} = \varepsilon_0(\mathbf{I} + \chi^{(1)}) = \begin{pmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}. \quad (4-1)$$

This diagonal form expresses optical anisotropy, which underlies birefringence in LCs. The two principal refractive indices, the ordinary index $n_o = \sqrt{\varepsilon_{xx}} = \sqrt{\varepsilon_{yy}} = \sqrt{\varepsilon_{\perp}}$ and the extraordinary index $n_e = \sqrt{\varepsilon_{zz}} = \sqrt{\varepsilon_{\parallel}}$, come directly from the diagonal elements of the dielectric tensor. The birefringence value is given by $\Delta n = n_e - n_o$, which governs the phase retardation between the ordinary and extraordinary waves and forms the physical basis for wave plate, polarization control, and phase modulation functionalities in LC optics. When an electric field is applied, the dielectric torque fights against the elastic torque. This threshold reorientation, first observed by Fréedericksz *et al.* in 1927, has since been referred to as the Fréedericksz transition^[234]. The change in retardance is linear in the induced angle for small excursions, forming the basis of LC phase modulators and display modes. The main ideas of this continuum elastic theory were set out by de Gennes *et al.*^[235] and later by Yeh *et al.*^[236]. These works explain how the director controls birefringence and phase retardation. Building upon this foundational electro-optic principle, the technology has evolved beyond its initial applications, forming the core of LC displays and enabling more sophisticated devices such as LCs on silicon SLMs. In these advanced systems, high-resolution pixel arrays provide spatially addressable control over the optical phase, amplitude, and polarization of light, facilitating precise wavefront shaping in addition to intensity modulation. This capability has positioned SLMs as indispensable tools in linear optical field modulation.

Furthermore, control of molecular orientation can also be patterned in space, with the classic application being the generation of geometric phase devices that convert spin into OAM. These PB phase elements highlight how the optical axis distribution, rather than just its uniform reorientation, can be used as an additional design parameter. Such patterned orientation expands the scope of LC linear optics from simple retarders and modulators to advanced devices for structured light generation and vector beam control. In 2006, Marrucci *et al.* reported the first clear experimental demonstration that an inhomogeneous anisotropic plate (*q*-plate) converts spin angular momentum into OAM, showing that patterned optic-axis orientation imprints a well-defined geometric phase on the output beam^[11]. Building on this principle, later work shifted focus to scalable and reconfigurable fabrication.

Then, high-resolution patterning of electrically tunable linear PB phase modulation devices was proposed. In 2014, Wei *et al.* employed a DMD-based microlithography with the rewritable azo-dye SD1 to fabricate photoaligned LC fork gratings capable of encoding arbitrary vortex charges^[237]. The devices combined high diffraction efficiency, broadband

operation, and polarization-insensitive performance, with the key advantage being electrical tunability: an applied voltage allows dynamic switching between Gaussian and vortex beam outputs while maintaining stable performance [Fig. 19(a)]. Later, multispectral management of photon OAM was achieved by combining electrically addressable “topological pixels” with self-organizing LC defects. As shown in Fig. 19(b), Nassiri *et al.* experimentally demonstrated independent OAM across multiple spectral channels using a topological LC SLM^[238]. This architecture enabled flexible spectral topological modulation and ST structuring of ultrashort pulses. By exploiting the defect-mediated geometric phase and electrically adjusting its orientation, the device circumvented the need for high-density photolithography while offering pixel-level programmability and multispectral flexibility.

In addition to electrically tunable approaches, another direction explores how to use alignment conditions of LCs to drive the self-assembly into complex optical diffractive structures. Ma *et al.* utilized preprogrammed photoalignment to induce smectic layer origami^[239]. By carefully designing the two-dimensional orientation pattern, the authors achieved deterministic control over the size, symmetry, and lattice arrangement of the templated focal-conic domains. These layered textures exhibit strong polarization-dependent diffraction, allowing the polarization state of the incident light to directly modulate the linear diffraction optical response [Fig. 19(c)].

Alongside photoalignment-driven self-assembly, mechanical stress has recently emerged as a versatile processing strategy. In 2024, Yu *et al.* reported a method to manipulate nematic topological defects through localized stress^[240], thereby enabling modulation of optical fields within the linear regime [Fig. 19(d)]. These mechanically induced structures expand the accessible director field configurations, allowing the electric field vector of light to span a full 2π range, thereby enabling the generation of vector beams with arbitrary polarization distributions.

4.2 Classical Nonlinear Optics in LCs

While the previous sections established the linear light field modulation provided by LCs, it is equally important to recognize that LCs have long been a fertile platform for nonlinear optics. From an information-theoretic viewpoint, linear optical media provide channels whose dimensionality grows only with the number of orthogonal modes one can address (frequency bins, spatial modes, and polarization states). Nonlinear optics, by contrast, creates new degrees of freedom: frequency conversion produces distinct spectral channels, multi-wave mixing couples otherwise independent modes, and parametric processes establish correlations that bind together spectral, temporal, and spatial degrees of freedom. In short, nonlinear interactions effect a kind of “channel multiplication” in which a given input stream can be mapped into an enlarged Hilbert space of outputs. This capability has direct implications for expanded bandwidth, mode-division multiplexing, and the generation or manipulation of entanglement in quantum photonics. LCs occupy a privileged place in this landscape because their mesoscopic order amplifies light–matter coupling in ways that differ qualitatively from both simple fluids and hard crystals. The orientational order (director field) couples strongly to applied fields and to optical torques; director reorientation, order-parameter changes, thermal effects, and space-charge formation provide multiple, often nonlocal, pathways by

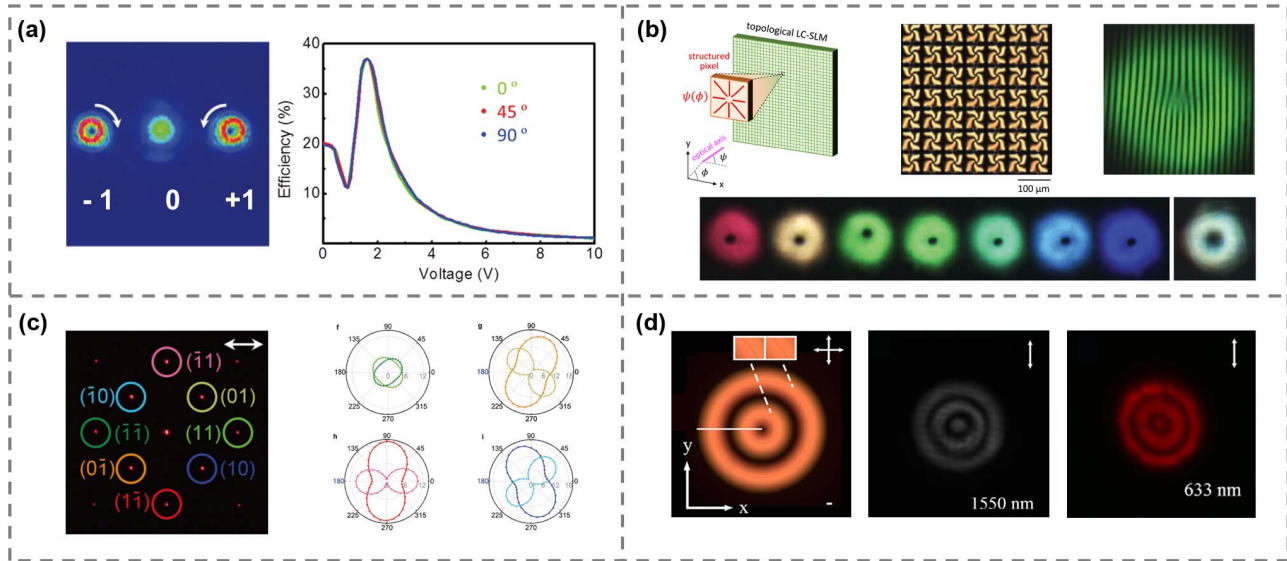


Fig. 19 LC-based linear optical modulation. (a) Electrically tunable photoaligned LC fork gratings. Reprinted with permission from Ref. [237], © Wiley-VCH GmbH (2014). (b) Electrically addressable “topological pixels” in LC SLMs. Reprinted with permission from Ref. [238], © American Chemical Society (2018). (c) Programmable “smectic layer origami”. Reprinted with permission from Ref. [239], © Wiley-VCH GmbH (2017). (d) Vector beam generator based on nematic disclination line control by mechanical stress. Reprinted with permission from Ref. [240], © Wiley-VCH GmbH (2024).

which an optical field can change the medium’s refractive-index and symmetry. This multiplicity of mechanisms means that almost every classical nonlinear optical phenomenon has been demonstrated in LC systems: Kerr-type nonlinearities^[64], self-focusing^[241,242], self-phase modulation^[65,243], multi-wave mixing^[66], spatial soliton^[67], field-induced SHG^[244,245], and interface second-order phenomena^[246]. The breadth of these phenomena is illustrated by a set of landmark studies covering self-action, harmonic generation, field-induced effects, dye-enhanced nonlinearities, and interfacial second-order signals.

One of the earliest and most striking demonstrations of nonlinear optics in LCs came from self-action effects. Braun, Fauchaux, and Libchaber reported strong self-focusing in nematic LCs, where the optical field itself drives director reorientation, producing an intensity-dependent lensing effect^[242] [Fig. 20(a)]. Closely related, Durbin *et al.* observed laser-induced diffraction rings in a nematic film, a direct manifestation of spatial self-phase modulation arising from the laser-induced Fréedericksz transition^[243], as shown in Fig. 20(b). Beyond self-action, LCs also support harmonic generation. A landmark result by Shelton *et al.* in 1970 demonstrated phase-matched third-harmonic generation in cholesteric LCs, exploiting the helical pitch as a natural quasi-phase-matching grating^[247] [Fig. 20(c)]. Later, Stolle *et al.* combined linear transmission and time-resolved SHG to disentangle director reorientation from induced dipole dynamics, demonstrating how bias fields can switch $\chi^{(2)}$ pathways on and off^[245], as outlined in Fig. 20(d). LCs also allow their nonlinear performance to be engineered and boosted through molecular design or compositional tuning. In 2004, Lucchetti *et al.* demonstrated colossal optical nonlinearity in dye-doped LCs, reporting a nonlinear refractive index as large as $10^3 \text{ cm}^2/\text{W}$ ^[248] [Fig. 20(e)]. Besides in bulk, SHG at interfaces has proven an especially sensitive

probe: Feller *et al.* used surface SHG to map alignment and broken inversion symmetry at LC boundaries, establishing interfacial $\chi^{(2)}$ as both a diagnostic and an exploitable nonlinear channel^[249], as shown in Fig. 20(f).

These landmark examples above illustrate both the breadth and the character of nonlinear optics in LCs. Yet these demonstrations also expose a persistent shortcoming for frequency-conversion applications: most LC nonlinearities are either effectively third-order (reorientational/Kerr-like), surface-localized, or require external electric field or dopants to produce even-order responses, so they do not provide a native, bulk $\chi^{(2)}$ pathway for efficient, device-level SHG. Therefore, in the next section, we investigate the fundamental origin of this limitation and show why the recently discovered polar/ferroelectric nematic phases (and domain engineering strategies) are crucial to overcoming it.

4.3 Nonlinear Optical Limitations of LC Platforms

Although classical studies have demonstrated a broad spectrum of nonlinear optical effects in LCs, the mechanisms behind these phenomena are usually third-order nonlinear optical processes or surface-localized second-order nonlinear optical processes. As a result, their efficiency and scalability remain limited when compared to bulk nonlinear crystals. This context clarifies a fundamental limitation of the linear-optical framework: conventional nematic phase lacks the ability to sustain a robust bulk $\chi^{(2)}$, and therefore cannot efficiently generate photons at new frequencies. Because linear responses conserve photon energy, devices in this regime can only manipulate amplitude, phase, and polarization SHG or on-chip entangled photon pair generation.

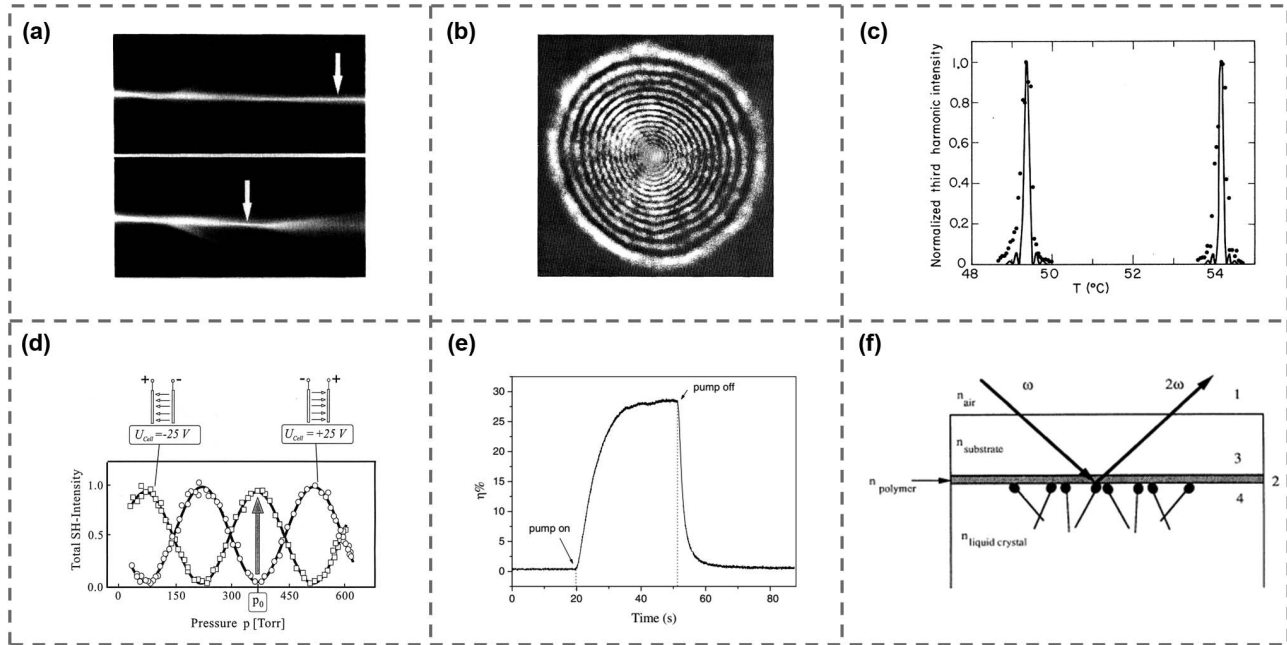


Fig. 20 Representative demonstrations of nonlinear optical phenomena in LC systems. (a) Strong self-focusing in nematic LCs. Reprinted with permission from Ref. [242], © American Chemical Society (1993). (b) Laser-induced diffraction rings from nematic films. Reprinted with permission from Ref. [243], © Optical Society of America (1981). (c) Phase-matched third-harmonic generation in CLCs. Reprinted with permission from Ref. [247], © American Chemical Society (1970). (d) Field-induced second-harmonic generation in nematic cells. Reprinted with permission from Ref. [245], © Optical Society of America (1997). (e) Colossal nonlinear refractive index in dye-doped LCs. Reprinted with permission from Ref. [248], © Elsevier B.V. (2004). (f) Surface-sensitive SHG probing of LC alignment. Reprinted with permission from Ref. [249], © Optical Society of America (1991).

To overcome this barrier and enable frequency conversion or electro-optic effects, a material must exhibit a strong nonlinear optical response. Such a response relies on a second-order nonlinear polarization tensor $\chi^{(2)}$, in contrast to the linear regime where light–matter interaction is governed by the dielectric tensor ϵ . In linear optics, the dielectric tensor dictates how the director orientation modulates birefringence, phase retardation, and polarization without altering photon energy. Nonlinear processes, however, require an effective $\chi^{(2)}$ to couple optical fields at different frequencies, thereby enabling effects such as the Pockels effect and efficient second-harmonic generation. Crucially, a finite $\chi^{(2)}$ demands the breaking of inversion symmetry, which stands in direct opposition to the centrosymmetric nature of conventional N phases [Fig. 21(a)]. In nematics, the apolar director ($\mathbf{n} \equiv -\mathbf{n}$) enforces centrosymmetry, thereby suppressing any even-order nonlinear optical processes.

The search for LC phases capable of breaking this symmetry has a long history. It can be traced back to a visionary prediction by Max Born in 1916^[250]. In his pioneering theoretical framework of LCs, Born introduced the concept of a “ferroelectric fluid” [Fig. 21(b)], which is a state of matter in which all molecular dipoles spontaneously align in the same direction, breaking inversion symmetry and enabling a second-order nonlinear susceptibility $\chi^{(2)}$. He believed his theory was not merely a prediction but an explanation of the then-mysterious “anisotropic fluids.” However, because no clear polar electro-optic response was experimentally observed at the time, and many

newly synthesized LCs were weakly polar or entirely nonpolar. Born’s proposed universal mechanism of ferroelectricity for LCs was ultimately dismissed.

4.4 FNLC: Material Properties

The situation remained unchanged for decades until breakthroughs in 2017, when two independent studies opened the door to the experimental realization of a new kind of polar nematic LC. That year, Mandle *et al.* synthesized a highly polar rod-like material that exhibited a conventional uniaxial N phase and a distinct low-temperature N phase of previously unknown structure^[68]. Simultaneously, Kikuchi *et al.* reported that a different material with a giant dipole moment of ~ 9.4 D exhibited an unusual phase with ferroelectric-like polar phase^[69]. These efforts culminated in the work of Chen *et al.*, who discovered that one of these polar compounds, known as RM734, forms a ferroelectric nematic phase (N_F) when cooled from a uniformly aligned nematic phase^[70]. Their study provided the first first-principles evidence of the long-hypothesized N_F phase, characterized by uniform spontaneous polarization P_s extending across macroscopic domains [Fig. 22(a)], thereby directly validating Born’s century-old theoretical vision. Owing to this polar order, FNLCs respond far more sensitively to external electric fields than conventional, nonpolar nematics. Fields as low as 10^2 V/m are sufficient to overcome the orientational elasticity of N_F and generate a strong restoring torque that reorients the polarization of FNLCs. This

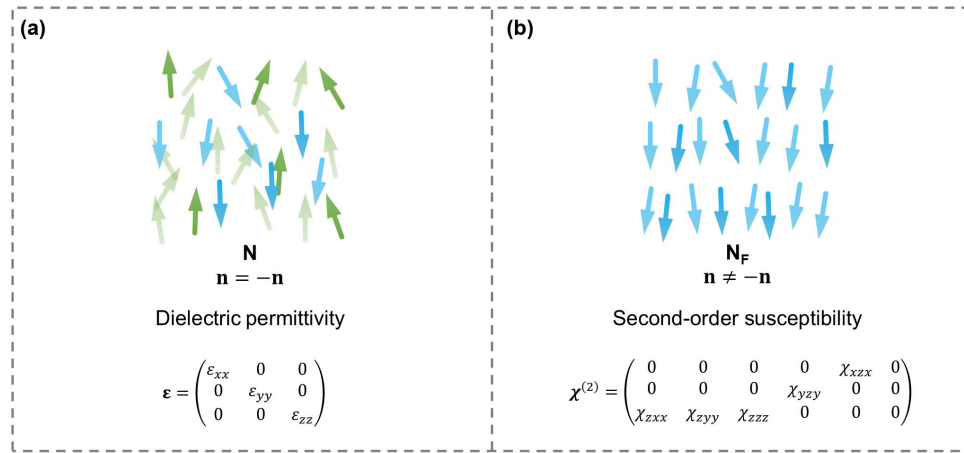


Fig. 21 Phase structures, director properties, and optical tensors of (a) traditional apolar LC: N and (b) emergent polar LC: N_F .

strong responsiveness stems from a polarization density as high as $P_s = 6 \times 10^{-2} \text{ C/m}^2$.

Besides its large spontaneous polarization, the N_F phase exhibits a distinctive set of electrical properties that further distinguish it from all known LC states. As shown in Fig. 22(b), Nishikawa *et al.* reported an anomalously large dielectric constant ($\varepsilon_{\parallel} \sim 10^4$), a value several orders of magnitude greater than that of conventional nematics, which drastically reduces the operating voltage required for director reorientation^[69]. Although the microscopic origin of this giant permittivity remains debated^[251,252], its practical significance lies in enabling low-power optical modulation. This strong dielectric response allows reorientation under very low electric fields, facilitating high-speed optical control without high operating voltages. Thus, irrespective of its microscopic mechanism, the N_F phase offers the requisite performance for high-speed, low-voltage photonic applications.

The direct coupling between the spontaneous polarization P_s and an external electric field enables an ultrafast electro-optic response^[71] [Fig. 22(c)]. In stark contrast to the viscous, millisecond-scale dynamics of conventional nematics, the collective reorientation of spontaneous polarization in the N_F phase can follow high-frequency AC fields ($\sim 200 \text{ kHz}$), exhibiting oscillations with a magnitude controlled by a balance of electric and viscous torques, rather than elastic forces. This ultrafast response has enabled device-level demonstrations, including GHz-rate optical phase modulation in silicon-integrated ferroelectric nematic platforms^[72], as well as an FNLC crystal-based silicon photonic modulator operating at 102 Gbit/s using PAM-4 modulation^[73].

In parallel to these exceptional electrical properties, the FNLC also exhibits superior nonlinear optical performance. Recently, by doping the prototypical FNLC RM734 with dispersed orange 3, Ortega *et al.* achieved a second-order susceptibility as high as 25 pm/V under resonance conditions, which is one of the highest values reported to date for LC materials^[75], as shown in Fig. 22(d). This result not only demonstrates significant enhancement over the pure RM734 host but also validates molecular doping as an effective strategy for optimizing nonlinear optical functionality in fluid ferroelectric systems. Moreover, the giant nonlinearity of FNLCs has recently been harnessed for tunable intracavity coherent upconversion^[76]. Beyond experimental demonstrations, recent advances have established a universal phase-matching mechanism

in helielectric polarization helices, which have been experimentally validated and further offer electric-field tunability^[77].

Recently developed FNLCs described by Song *et al.* exhibit remarkably high birefringence ($\Delta n \approx 0.4$), far exceeding that of conventional nematics^[74], as shown in Fig. 22(e). This high birefringence originates from the incorporation of rigid, conjugated molecular structures such as tolane-like units with triple bonds, which strongly enhance the electronic polarizability anisotropy of the mesogens. From the perspective of nonlinear optics, this synergy between birefringence and second-order nonlinear response is particularly advantageous for nonlinear field modulation, where efficient phase matching and strong light–matter coupling are essential. In FNLCs, the coexistence of fluid ferroelectricity with extreme optical anisotropy thus sets the stage for compact, low-voltage, and broadband nonlinear photonic devices.

Furthermore, recently discovered giant electroviscous effects in FNLCs provide new avenues for controlling fluid microstructure under electric fields^[253]. This, combined with its exceptional second-order nonlinearity, enables highly efficient SHG that can propagate over extended distances within mm-scale self-assembled fluid fiber architectures^[254]. Under confinement, FNLCs exhibit fluid superscreening, wherein the polarization smoothly adapts to curved microchannels^[255]. In unconstrained geometries, the ground state may adopt chirality through helicoidal polarization domains, even in the absence of molecular chirality^[256]. Moreover, at solid–ferroelectric interfaces, droplets undergo electro-mechanical instability upon entering the N_F phase, leading to fractal jetting and breakup^[257]. These diverse electrostatic phenomena enrich strategies for designing low-voltage nonlinear photonic devices, while also underscoring challenges related to interfacial stability.

A continuous stream of newly discovered ferroelectric phases complements the distinctive properties of FNLCs with surprising optical behavior. For example, Karcz *et al.* reported that the fluorinated compound MUT_JK103 led to the identification of a new ferroelectric phase, the helicoidal ferroelectric nematic (N_{TBF})^[258] [Fig. 22(f)]. Although the molecules are achiral, the system spontaneously breaks mirror symmetry through polar interactions, forming a helical structure with a pitch in the visible light range. Other recently identified polar phases include the helielectric nematic HN^* ^[259], and several smectic polar variants

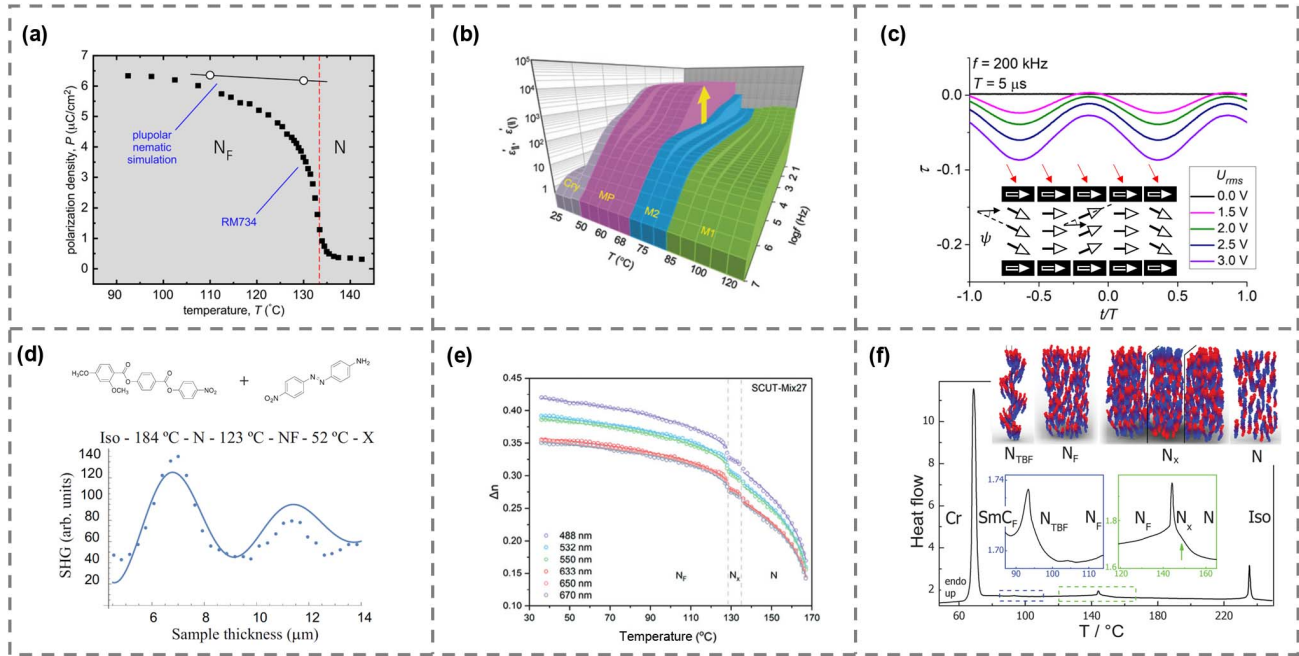


Fig. 22 Physical properties and emerging phases of FNLCs. (a) Macroscopic uniform spontaneous polarization^[70]. (b) High dielectric constant. Reprinted with permission from Ref. [69], © Wiley-VCH GmbH (2017). (c) Ultrafast electro-optic modulation^[71]. (d) Large second-order nonlinear susceptibility. Reprinted with permission from Ref. [75], © Taylor & Francis (2025). (e) High optical birefringence^[74]. (f) Emerging ferroelectric heliconical N_{TB} phase. Reprinted with permission from Ref. [258], © AAAS (2024).

(SmA_F ^[260], SmC_F ^[261], SmZ_A ^[262], and SmA_{AF} ^[263]). These emergent phases substantially broaden the optical functionality available in soft matter, enabling effects such as circular-polarization-selective reflection and electrically tunable photonic responses. This expanding landscape of molecular design and phase behavior offers a rich platform for developing next-generation photonic devices, including low-field-driven color reflectors^[264], circularly polarized multi-wavelength lasers^[265], and electric field modulated gratings^[266].

4.5 SHG Microscopy in FNLCs

As noted above, linear electro-optic control in FNLCs is governed by the dielectric tensor ϵ , second-order processes scale with the nonlinear polarization tensor $\chi^{(2)}$, providing a distinct pathway toward frequency conversion. The large second-order nonlinear susceptibility of FNLCs makes their nonlinear optical processes particularly efficient, which helps us better understand the interesting physical processes of FNLCs^[78]. Second-harmonic generation microscopy has emerged as a powerful tool for visualizing polar structures in FNLCs^[263,267]. Unlike conventional polarizing microscopy, which is sensitive to birefringence and director orientation, SHG is inherently sensitive to non-centrosymmetric order and local polarity, making it an ideal probe for mapping polar domains and topological textures in FNLCs. The origin of this SHG sensitivity lies in the nonlinear polarization response of the medium. In Maxwell's framework, the induced polarization can be expanded as a power series in the electric field^[196]:

$$\mathbf{P}^{NL} = \epsilon_0[\chi^{(2)}\mathbf{E}^2 + \chi^{(3)}\mathbf{E}^3 + \dots], \quad (4-2)$$

where $\chi^{(n)}$ are the rank- $(n + 1)$ susceptibility tensors. A central symmetry rule is that bulk second-order susceptibility $\chi^{(2)}$ vanishes in centrosymmetric media; $\chi^{(3)}$ is permitted. In typical apolar nematics, bulk $\chi^{(2)} = 0$ and effective $\chi^{(3)}$ arise via reorientational nonlinearity. For frequency conversion (e.g., SHG), the essential relation is

$$P_i(2\omega) = \epsilon_0 \sum_{j,k} \chi_{ijk}^{(2)} E_j(\omega) E_k(\omega), \quad (4-3)$$

where the dominant component of the effective nonlinear susceptibility coefficients is the $\chi_{zzz}^{(2)}$ ^[78], which is parallel to the local director $\mathbf{n}$ and the spontaneous polarization direction. This property makes SHG microscopy an indispensable tool for visualizing and characterizing the abundant spontaneous topological defects^[268,269] and photoaligned domain structures^[270,271] in FNLCs.

In the study by Yang *et al.*, SHG microscopy was employed to investigate polar topological textures in confined N_F droplets^[272]; see Fig. 23(a). The authors observed spontaneous chiral symmetry breaking in achiral N_F systems, leading to the formation of meron-like textures with divergent or convergent polarization fields. SHG confocal polarizing microscopy provided high-contrast images of these textures, revealing their intricate spatial distribution. However, conventional SHG techniques alone cannot distinguish the head-tail orientation of polarization vectors. To overcome this limitation, the authors utilized SHG interferometry, which captures phase information and enables full vectorial reconstruction of polarization fields. This approach mapped four distinct types of polarization merons, characterized by combinations of handedness and divergence.

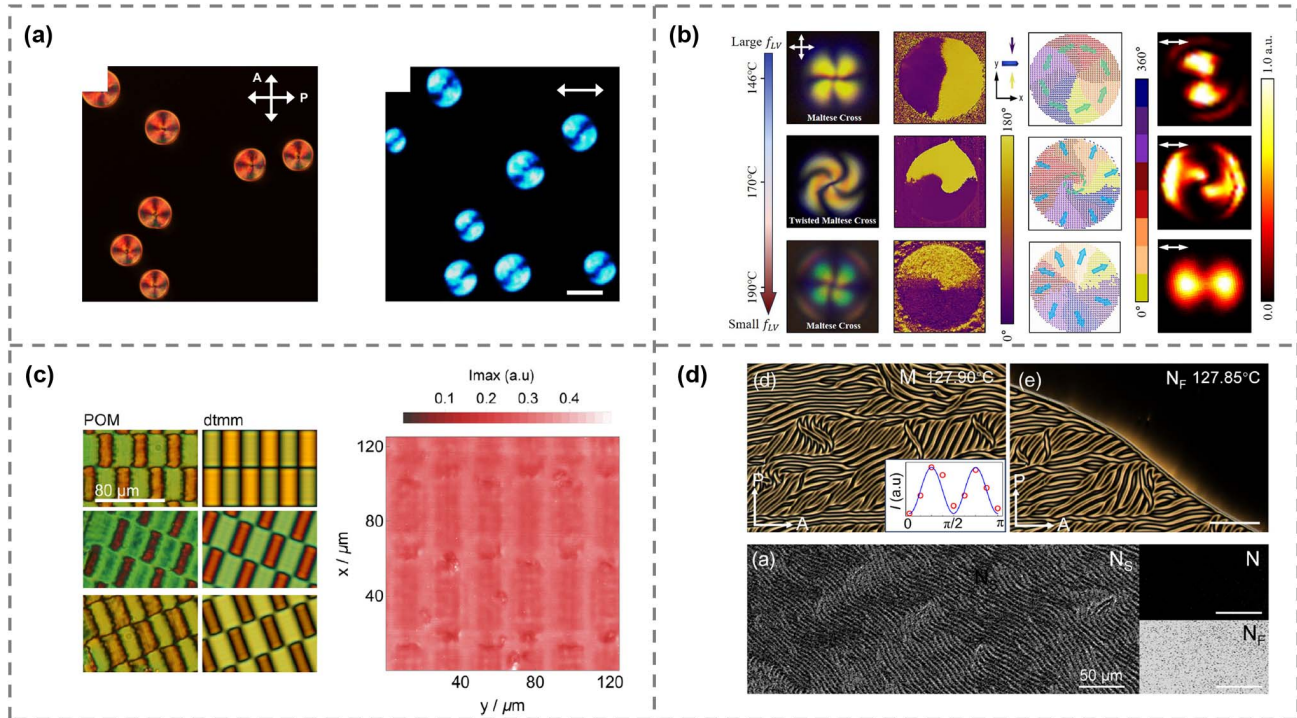


Fig. 23 SHG microscopy applications for polarization structures in FNLCS. (a) Spontaneous meron-like polarization textures in N_F droplets^[272]. (b) Vortices and divergent topological structures in N_F droplets. Reprinted with permission from Ref. [273], © Wiley-VCH GmbH (2025). (c) Two-dimensional photoalignment arrays in FNLCS^[274]. (d) Double-splay nematic order of N_F phase transition. Reprinted with permission from Ref. [275], © American Chemical Society (2025).

Recently, Xu *et al.* exploited the existence of vortices, centrifugal vortices, and centrally divergent topological structures by the SHG and piezoresponse force microscopy^[273], as shown in Fig. 23(b). The SHG signal is highly sensitive to the molecular dipole orientation, with its signal intensity proportional to the polarization component of light parallel to the incident ray. The SHG results are highly consistent with the results of angle-resolved piezoresponse force microscopy. In addition to the natural topological polar structures in the N_F phase, Lovšin *et al.* created and characterized two-dimensional SHG-active arrays using a photoalignment technique^[274] [Fig. 23(c)]. By photopatterning surfaces with spatially modulated splay and bend deformations, the authors induce complex director and polarization fields, which are then probed using polarization-resolved SHG microscopy and interferometry. The SHG signals reveal detailed information about the local polar order, domain walls, and twist structures across different FNLCS material systems.

SHG imaging is not limited to probing the N_F phase and its associated structures; it also plays a key role in detecting phase transition. The study by Ma *et al.* characterized the double splay nematic order in the first-order transition of ion-doped RM734^[275], as shown in Fig. 23(d). Under circularly polarized excitation, the SHG images clearly revealed periodic intensity modulation within the modulated phase, in contrast to the uniform signal observed in the homogeneous N_F phase. This periodic SHG intensity modulation confirms the presence of a non-centrosymmetric, polarization-modulated structure, consistent with the predicted double splay nematic order wherein splay deformations alternate along two orthogonal directions.

In short, these studies demonstrate that SHG microscopy and interferometry provide not only structural imaging of polar textures in FNLCS, but also a versatile toolkit for externally controlled patterning and real-time monitoring of phase transitions.

4.6 Nonlinear Geometric-Phase Modulation and Spin-Orbit Coupling in FNLCS

While SHG microscopy has established FNLCS as a powerful platform for probing polar textures, recent advances have taken it a step further by exploiting nonlinear processes themselves as functional degrees of freedom. By spatially patterning the local molecular orientation, it is possible to directly encode and dynamically manipulate the phase, OAM, and amplitude of harmonic light fields. The underlying mechanism is the nonlinear geometric phase: local rotations of the second-order nonlinear susceptibility tensor $\chi^{(2)}(\theta)$ accumulate geometric phase. This approach parallels nonlinear metasurfaces, where subwavelength unit engineering enables precise harmonic-phase control^[276–278]. FNLCS offer the additional advantages of intrinsic fluidity, tunability, and large $\chi^{(2)}$, enabling dynamically reconfigurable nonlinear photonic functionality.

Since the SH polarization in Eq. (4-2) is determined by $\chi^{(2)}$, its effective form under local director rotation can be obtained via the tensor transformation. Mathematically, for a local rotation $R(\theta)$ about the propagation axis z , the nonlinear tensor transforms as^[79,279]

$$\chi'_{ijk}(\theta) = \sum_{l,m,n} R_{il}(\theta) R_{jm}(-\theta) R_{kn}(-\theta) \chi_{lmn}. \quad (4-4)$$

It is convenient to express vectors and tensors in the circular polarization basis

$$\mathbf{e}_\sigma = (\hat{\mathbf{x}} + i\sigma\hat{\mathbf{y}})/\sqrt{2}, \quad \sigma = \pm 1, \quad (4-5)$$

where $\sigma = +1$ and $\sigma = -1$ refer to right/left-handed polarization. A planar rotation by θ acts diagonally on this basis:

$$R(\theta)\mathbf{e}_\sigma = e^{-i\sigma\theta}\mathbf{e}_\sigma. \quad (4-6)$$

Denoting the $\chi^{(2)}$ components as $\chi_{\sigma_{\text{out}}\sigma_{\text{in}}\sigma_{\text{in}}}$ (output circular polarization state σ_{out} , input polarization states $\sigma_{\text{in}}, \sigma_{\text{in}}$), a local rotation θ transforms them as

$$\chi'_{\sigma_1\sigma_2\sigma_3} = e^{i(2\sigma_{\text{in}} - \sigma_{\text{out}})\theta} \chi_{\sigma_1\sigma_2\sigma_3}. \quad (4-7)$$

The resulting nonlinear geometric phase imprinted on the generated harmonic is thus

$$\phi_{\text{NL}} = (2\sigma_{\text{in}} - \sigma_{\text{out}})\theta, \quad (4-8)$$

where the sign depends on the rotation convention. This relation shows that the phase depends only on the spin difference between input and output photons and the local director rotation. For instance, when $\sigma_{\text{in}} = +1$, one obtains

$$\begin{cases} \phi_{\text{NL}} = \theta, & \sigma_{\text{out}} = \sigma_{\text{in}} \\ \phi_{\text{NL}} = 3\theta, & \sigma_{\text{out}} = -\sigma_{\text{in}} \end{cases}. \quad (4-9)$$

More generally, for n -photon upconversion, the phase factor generalizes to

$$\phi_{\text{NL}} = (n\sigma_{\text{in}} - \sigma_{\text{out}})\theta. \quad (4-10)$$

From an angular-momentum perspective, this is intuitive: n input photons each carry spin σ_{in} , giving a total spin of $n\sigma_{\text{in}}$; the output photon spin σ_{out} differs by $2\sigma_{\text{in}} - \sigma_{\text{out}}$ (for $n = 2$), with the spatially varying orientation $\theta(x, y)$ supplying the corresponding OAM to conserve total angular momentum. For an azimuthal pattern $\theta = q\varphi$ (a “ q -plate”), the second-harmonic orbital topological charge becomes

$$\ell_{2\omega} = 2\ell_\omega + q(2\sigma_{\text{in}} - \sigma_{\text{out}}), \quad (4-11)$$

where ℓ_ω is the input OAM of each photon. Spatially patterning $\theta(x, y)$ thus generates multiple SHG wavefronts with distinct phases and orbital angular momenta, enabling vortex generation, nonlinear holography, and complex amplitude shaping. The general principle of nonlinear geometric phase derived above suggests that a patterned nonlinear medium can map spin angular momentum into OAM in the harmonic generation process, with phase factors that scale predictably with the nonlinear order. FNLCs provide an ideal physical platform to realize this concept in practice.

Recently, Pan *et al.* introduced the concept of nonlinear geometric phase in FNLC and designed corresponding nonlinear optical devices^[79]. As shown in Fig. 23(a), by pumping the RM734 molecule with a circularly polarized fundamental wave, the generated second-harmonic waves (SHWs) contain the components with both co- and cross-circular polarization components relative

to the fundamental wave. Under RCP pumping, the nonlinear geometric phases corresponding to the RCP and LCP components in the SHW are θ and 3θ , respectively.

Importantly, this framework also explains why the OAM states remain robust in a cascaded linear-nonlinear spin-orbit interaction process. After transmission through the q -plate, the fundamental wave of σ_{in} and OAM ℓ_ω contains both the unconverted mode

$$E_{\sigma_{\text{in}}}(\omega) \propto e^{i\ell_\omega\varphi}\mathbf{e}_{\sigma_{\text{in}}} \quad (4-12)$$

and the converted mode

$$E_{-\sigma_{\text{in}}}(\omega) \propto e^{i(\ell_\omega + 2\sigma_{\text{in}}q)\varphi}\mathbf{e}_{-\sigma_{\text{in}}}. \quad (4-13)$$

When these fields undergo SHG in the FNLC, the nonlinear geometric phase dictates that the co- and cross-circular SH components acquire azimuthal phase factors of $e^{-i\sigma_{\text{in}}q\varphi}$ and $e^{-3i\sigma_{\text{in}}q\varphi}$, leading to

$$\begin{aligned} P_{\sigma_{\text{in}}}(2\omega) &\propto e^{i(2\ell_\omega + \sigma_{\text{in}}q)\varphi}\mathbf{e}_{\sigma_{\text{in}}}, \\ P_{-\sigma_{\text{in}}}(2\omega) &\propto e^{i(2\ell_\omega + 3\sigma_{\text{in}}q)\varphi}\mathbf{e}_{-\sigma_{\text{in}}}. \end{aligned} \quad (4-14)$$

Repeating the analysis for the converted fundamental wave yields the same pair of SH states, because the additional linear phase $2\sigma_{\text{in}}q$ is exactly compensated for by the spin reversal in the nonlinear step. As a result, the cascaded spin-orbit interaction produces SH vortices with topological charges $2\ell_\omega + \sigma_{\text{in}}q$ and $2\ell_\omega + 3\sigma_{\text{in}}q$, independent of the fundamental wave conversion ratio. For the case of $q = 1$, and $\ell_\omega = 0$, this directly explains why the cascaded process consistently produces the robust pair of SH vortices with OAM charges of $+1$ (RCP) and $+3$ (LCP), as reported in Fig. 24(a).

In addition to demonstrating the nonlinear geometric phase control, Pan *et al.* further showed that the FNLC q -plate has remarkable dynamic tunability. By exploiting the soft matter nature of the FNLC, the device parameters can be tuned thermally and electrically. Notably, they reported a nonlinear circular dichroism as high as 0.86, evidencing a strong chiral selectivity in the SH response. This level of tunability highlights the unique advantage of FNLC-based nonlinear photonic devices: the same patterned medium can not only implement geometric-phase-driven spin-orbit conversion but also be reconfigured in situ by external stimuli. Notably, similar nonlinear spin-orbit coupling effects have also been observed in spontaneously self-assembled ferroelectric spherulites with vortex-like domain structures of FNLCs^[85,86].

Building on this demonstration, Chen *et al.* demonstrated a reconfigurable nonlinear PB platform by photopatterning ion-doped FNLCs [Fig. 24(b)], in which a space-varying nonlinear geometric phase was encoded for SHG^[81]. By analyzing the cascaded linear and nonlinear spin-orbit interactions, they demonstrated that distinct diffraction orders with tailored polarization states can be dynamically engineered. Electrical modulation of the splay angle enabled continuous tuning of both the intensity and polarization of SH diffraction orders, while ion doping ensured smooth and repeatable switching, highlighting the practical potential of reconfigurable nonlinear PB devices.

Recently, Zhang *et al.* extended the scope to material innovations, unveiling the mesophase as a new avenue for defect-free nonlinear vectorial optics, as shown in Fig. 24(c). In the phase

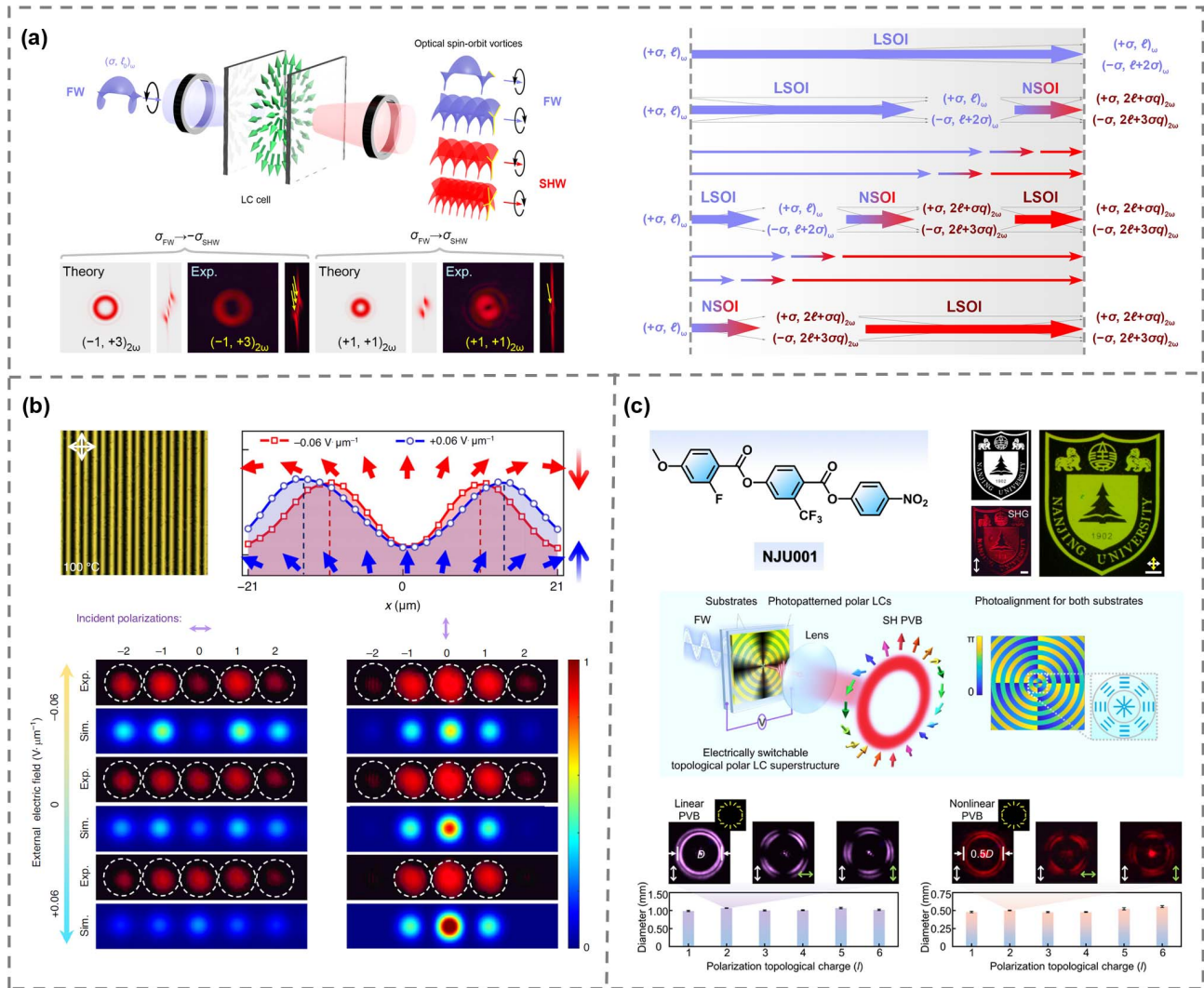


Fig. 24 Nonlinear geometric phase-encoded nonlinear optical modulation in FNLCs. (a) Nonlinear geometric phase coded tunable SH optical vortices in an FNLC q -plate^[79]. (b) Reconfigurable nonlinear PB diffractive FNLC grating^[81]. (c) Second-harmonic perfect vortex generation in the N_x phase^[82].

transition region of FNLCs, they identified a new polar meso-phase (the N_x phase) featuring periodically modulated unipolar and bipolar orders, which permitted large-area, in-plane polar patterning without defects, thereby offering a compact route toward nonlinear vectorial optics^[82]. Through material design (NJU001), they reveal that stripe-like polar superstructures with syn-parallel or anti-parallel local polarity produce spatially modulated SH signals. Through deliberate design of the patterned FNLC medium, the OAM states carried by the fundamental wave and SHW exhibit well-defined radial intensity distributions and phase singularities that are characteristic of perfect vortices and are independent of the beam waist.

4.7 FNLCs Bridging Classical and Quantum Optical Regimes

The demonstrated ability of FNLCs to manipulate nonlinear light fields lays a robust foundation for emerging applications in quantum optics. In particular, their outstanding electro-tunability has

recently driven breakthrough progress in reconfigurable quantum light sources. Sultanov *et al.* reported the first observation of spontaneous parametric downconversion (SPDC) in a fluid system, demonstrating electrically controlled generation of polarization-entangled photon pairs with efficiencies comparable to those of conventional nonlinear crystals^[83] [Fig. 25]. By leveraging the field-responsive molecular orientation of FNLCs, the polarization state of emitted photon pairs can be dynamically switched using voltages as low as only 2 V, enabling real-time selection between horizontal, vertical, or superposition states. By engineering predefined molecular twist geometries along the sample (e.g., 0 , $\pi/2$, or π twists), the effective nonlinear phase matching can in principle be spatially modulated, facilitating the generation of various entangled states within a single device. This unprecedented level of *in-situ* control over quantum light properties, combined with the material's fluid self-assembly and compatibility with industrial fabrication processes, positions FNLCs as a promising platform for tunable multi-pixel quantum light sources.

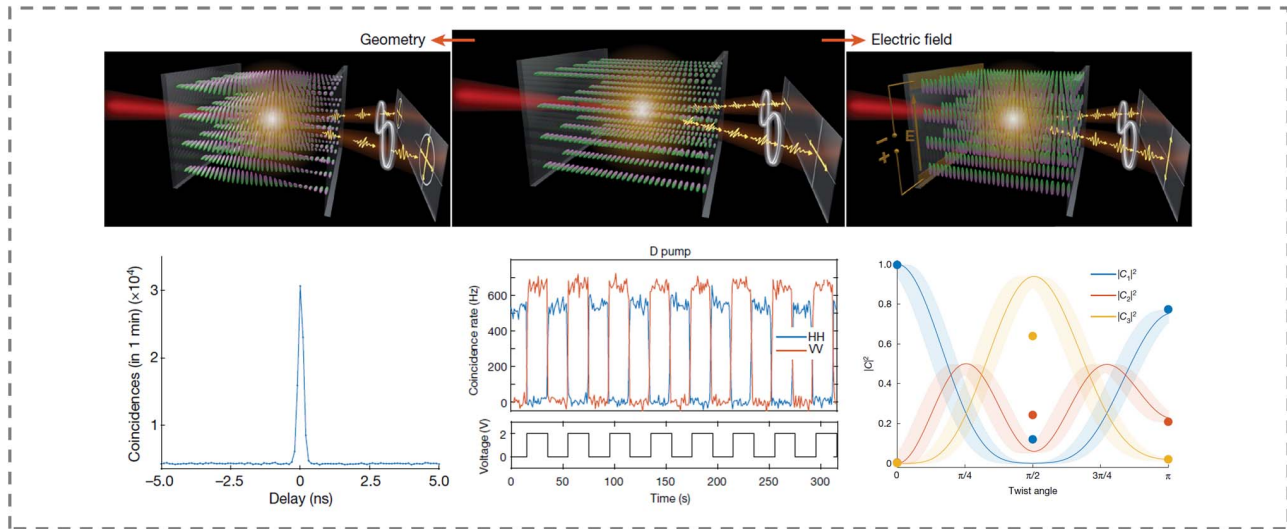


Fig. 25 Electrically and geometrically tunable quantum LC photon-pair sources^[83].

For the first time, FNLCs uniquely combine large intrinsic second-order nonlinearity with programmable molecular orientation in a single soft matter system, offering a new platform for optically controlling light by nonlinear optical processes. Unlike conventional nonlinear crystals whose susceptibility is fixed during growth or poling, the nonlinear response of FNLCs can be dynamically and spatially reconfigured via optical, electrical, or thermal stimuli, as well as through photopatterning. This allows a thin FNLC layer to function simultaneously as a nonlinear light generator (SHG, SPDC, etc.) and as a programmable wavefront shaper that controls phase and polarization. Such dual functionality facilitates highly compact device architectures where both light generation and beam shaping occur within the same medium.

This optical control follows directly from exceptional material properties: macroscopic spontaneous polarization and high dielectric constant enable strong electro-optic responses at modest fields; ultrafast modulation supports real-time tuning of nonlinear interactions; and large $\chi^{(2)}$ together with high birefringence permits efficient frequency conversion and flexible phase matching. These features allow FNLCs to support parametric processes while giving unprecedented control over spectral, polarization, OAM, and spatial degrees of freedom.

4.8 Discussion

In a broader context, these results point to a shift from using liquid crystals merely for linear wavefront control to employing them as a programmable medium for nonlinear optical processing, where frequency conversion and field structuring happen simultaneously within the same device. This perspective effectively turns the previous discussion into a clear, application-driven message: by combining nonlinear response with orientational programmability and geometric-phase design, we can produce frequency-converting elements that deliver tailored wavefronts and polarization states without the need to cascade separate linear and nonlinear components. It also points to immediate practical uses that stem directly from these material benefits, such as reconfigurable structured-light sources at harmonic wavelengths, electrically switchable converters for

compact photonic links, and sensing elements that encode wavefront information directly into the generated signal; with this context set, the outlook naturally shifts toward expanding these nonlinear processing capabilities and translating them into compact, integrated photonic platforms.

FNLCs offer a complementary route to representative planar nonlinear metasurfaces, which rely on subwavelength nanoresonators to shape harmonic wavefronts but typically result in a fixed response after fabrication. From a practical application standpoint, while metasurfaces are excellent for precise phase control in ultrathin designs, they often hit a wall with tunability, forcing a difficult trade-off between efficiency and bandwidth. FNLCs address this by leveraging a continuous, field-responsive medium to encode the geometric phase, allowing for active electrical or optical reconfiguration without sacrificing the strong intrinsic nonlinearity and birefringence necessary for flexible phase matching.

Looking ahead, FNLCs open several promising directions. Combining optical rectification with nonlinear geometric phase control offers a pathway to compact, electrically tunable terahertz sources whose amplitude and phase can be engineered on demand. Many other nonlinear processes remain underexplored in FNLCs, such as sum-frequency generation, difference-frequency generation, and four-wave mixing. These processes can broaden accessible frequency ranges, enable multi-wavelength processing, and realize high-dimensional entanglement. Therefore, systematic studies of these multi-wave interactions are crucial. Another compelling opportunity lies in leveraging in-plane nonlinear optical processes, such as those stimulated and confined in photopatterned structures or integrated waveguide structures. This planar nonlinear optical platform could enhance light-matter interaction, improve conversion efficiency, and facilitate on-chip signal routing and modulation.

Realizing this promise requires overcoming materials and fabrication challenges. Patterning and alignment steps must minimize domain walls, disclinations, and scattering centers that disrupt designed nonlinear geometric phase profiles. Ionic contamination and mobile charges must be controlled to avoid screening, bias drift, and polarization relaxation under sustained fields. Practical remedies include improved photoalignment and anchoring chemistries, ion-control strategies,

low-loss claddings and hermetic encapsulation, and hybrid integration with resonant cavities or dispersion-engineered waveguides to shorten interaction lengths. With progress along these lines, FNLCs can bridge fluidic reconfigurability and device-grade integration, transforming static nonlinear optics into rewritable photonic circuitry within the Soft Mattonics paradigm.

5 From Spatial to Spatiotemporal Light Shaping

5.1 Joint Manipulation of Spatial and Temporal Degrees of Freedom

As discussed in previous sections, LCs have played a key role throughout the evolution of programmable light-field control, building on the Soft Mattonics framework. With their electrically induced birefringence and pixel-level addressability, LC devices provide a unified platform bridging static and dynamic wavefront modulation [see also Figs. 2–4]^[280]. However, early applications were focused on purely spatial shaping, including adaptive aberration correction, phase-only holography, and the generation of structured beams. These approaches were intrinsically limited to the transverse spatial dimensions and offered little access to temporal degrees of freedom.

On the temporal shaping side, LCs have also been employed for pulse compression and stretching [Fig. 26(a)]^[281–285]. In cholesteric LC systems, the interplay of strong Bragg-edge dispersion and ultrafast intrinsic nonlinearities enables direct femtosecond compression as well as stretching–recompression sequences. In contrast, nematic-LC-filled photonic crystal fibers exploit long-range nonlinear propagation to achieve high-ratio pulse compression driven by soliton dynamics. Nevertheless, LC electro-optic switching is fundamentally constrained by

intrinsic response times spanning from milliseconds to nanoseconds [Fig. 26(b)]^[286–296]. This response-time spectrum dictates the temporal scales over which LCs can effectively operate: milliseconds for slow spatial modulation, microsecond–nanosecond regimes for fast switching and intermediate pulse control, but still insufficient for directly sculpting femtosecond–picosecond fields. To reach ultrafast precision, $4f$ pulse shaping architectures incorporating electro-optic or acousto-optic modulators have become standard, offering programmable spectral-domain phase and amplitude control [Fig. 26(c)]^[87–92,297]. Yet such purely temporal strategies form the basis of ultrafast optics and high-speed communication, but lack concurrent access to spatial degrees of freedom.

Recently, the convergence of these developments has led to ST optical-field control. Implemented most prominently via $4f$ pulse shaping, where a diffraction grating and lens spatially disperse spectral components that are then directly modulated by an LC-SLM in the Fourier plane, this approach enables the joint engineering of spatial and temporal degrees of freedom [Fig. 26(d)]. In this configuration, a diffraction grating first disperses the spectral components of an ultrashort pulse along one transverse axis, which are then collimated by a cylindrical lens such that different frequencies are spatially separated at the Fourier plane. An LC-SLM placed at this plane acts directly on individual frequency components, imposing programmable phase or amplitude masks. A second cylindrical lens and grating subsequently recombine the spectrum, yielding a reshaped pulse whose temporal envelope and spectral phase are precisely engineered. In this way, the $4f$ system effectively performs a Fourier transform into the frequency domain, applies targeted modulation, and then transforms back into the time domain. This arrangement provides a powerful means for arbitrary pulse shaping, enabling not only spectral

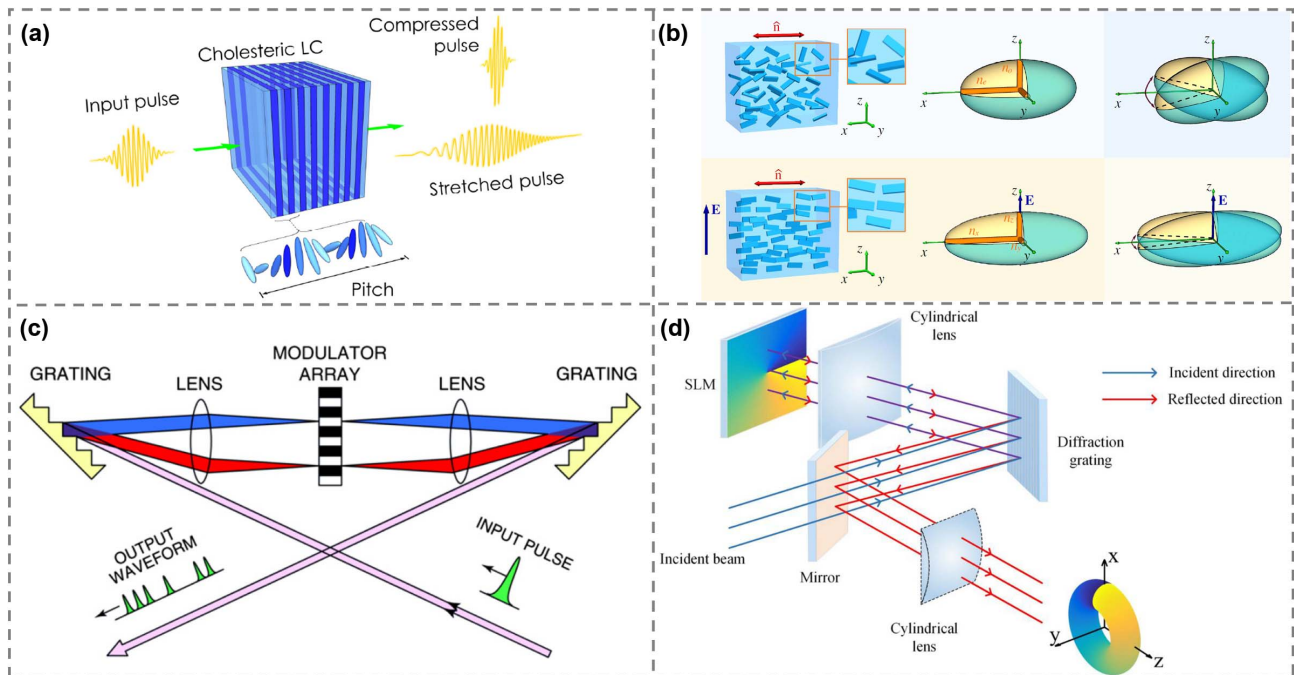


Fig. 26 (a) LC used to compress or stretch pulses^[283]. (b) Schematic illustration of field-induced effects for submicrosecond electro-optical switching^[286]. (c) The canonical $4f$ pulse-shaping arrangement. Reprinted with permission from Ref. [297], © Elsevier B.V. (2011). (d) ST beam synthesis with an LC-SLM. Reprinted with permission from Ref. [99], © Springer Nature Limited (2020).

phase compensation and dispersion control but also the synthesis of complex STWPs when combined with spatial modulation. This transition from independent spatial or temporal modulation to ST joint control marks a major shift, unlocking the synthesis of STWPs and opening new opportunities in optical communication, quantum information, and ultrafast light–matter interaction.

5.2 STWPs Generated with LC-SLM-Based Pulse Shaper

Having established why LC-SLMs provide a uniquely programmable interface to both spatial and temporal degrees of freedom, we now turn to the canonical LC-SLM-based STWPs. Building on the idea of coupling space and time, Abouraddy's group introduced a strict one-to-one correspondence between the temporal frequency ω and transverse spatial frequency (e.g., k_x) in the ST spectral domain. Implemented by placing an LC-SLM at the Fourier plane so that each temporal frequency component is programmably modulated as shown in Fig. 27(a), this construction yielded a class of diffraction-free STWPs—space–time light sheets—that propagate rigidly in free space^[298–301]. Geometrically, these fields are defined by spectral conic-section trajectories (elliptic, parabolic, or hyperbolic) between the light cone:

$$k_x^2 + k_z^2 = \left(\frac{\omega}{c}\right)^2, \quad (5-1)$$

where k_x and k_z are the transverse and axial wavenumbers, respectively, and k_y is set to zero due to no modulation along the y -axis. The tilted ST spectral planes are $k_z = k_0 + (\frac{\omega}{c} - k_0) \tan \varphi$. Varying the plane's tilt angle φ selects different propagation-invariant families with their corresponding group-velocity characteristics. This framework, anchored by the non-separable ST spectral mapping in the geometrical physical intuition, establishes the common conceptual foundation on which the later taxonomy, tunable-velocity beams, accelerating or trajectory-engineered packets, and application-oriented studies were built^[298–302].

With the conic trajectory on the light cone and one-to-one ST spectral mapping in hand, the next step is to formalize which spectral-plane intersections are admissible and how they translate into measurable propagation laws. Yessenov *et al.* gave a systematic classification of 10 propagation-invariant space–time light sheet families by where and how the spectral plane cuts the light cone. Crucially, in this taxonomy, the group velocity v_g , including its sign and magnitude, is determined by the tilt angle of the spectral plane^[93]. One noticeable example then demonstrated the signature capability of the platform: continuous, precise tuning of group velocity in free space, from subluminal to superluminal and even negative v_g , purely by sculpting the ST spectrum rather than relying on material dispersion, thereby elevating group velocity control to a free-space beam-engineering problem [Fig. 27(b)]^[95]. Furthermore, by engineering the ST spectrum such that different spatial bandwidths are assigned to different temporal frequencies, one can realize accelerating or decelerating STWPs whose group velocity varies continuously along the propagation axis, yielding a controlled axial profile of $v_g(z)$ [Fig. 27(c)]^[96,303]. Recent studies extended tunable-velocity beams to arbitrary prescribed trajectories in free space. Using an inverse-design method based on catastrophe optics and the stationary phase, STWPs were synthesized to follow complex S- or U-shaped

paths with possible velocity reversal, while retaining high localization and stability. This result demonstrates the broader versatility of spectral-phase engineering in programming light's motion^[304]. In parallel, it was shown that applying Lorentz boosts to the ST spectrum of an ST Airy wavepacket produces an acceleration-free ST Airy wavepacket that propagates rigidly in a straight line, in contrast to the conventional transverse acceleration of Airy beams, highlighting the relativistic underpinnings of ST spectral correlations^[305].

Whereas the demonstrations above chiefly employed continuous ST spectra, introducing a discretized (comb-like) spectrum adds qualitatively new behavior. The veiled Talbot effect revealed that imposing tight ST spectral correlations freezes all axial self-imaging in physical space, while Talbot revivals persist only in time-resolved measurements [Fig. 28(a)]^[306]. While the foregoing results establish free-space dynamics governed by conic spectra, a complementary question is what changes once material dispersion is introduced. In dispersive media, Hall *et al.* observed optical de Broglie–Mackinnon wavepackets: O-shaped space–time profiles that remain dispersion-free in a dispersive medium under anomalous group velocity dispersion [Fig. 28(b)]^[307]. In this case, the presence of dispersion reshapes the light cone itself, so that the tangent between the modified cone and the ST spectral plane yields a closed-ring-shaped spectrum. This construction realizes the long-predicted de Broglie–Mackinnon dispersion-free packets in optics, enabled by the ring-shaped spectrum that arises from the tangent of the modified light cone and spectral plane. More details about space–time light sheet families could be seen in Ref. [302].

As capabilities matured, research branched toward applications and model diagnostics within a unified experimental framework. On the applications side, axial spectral encoding was introduced: by tailoring the ST spectrum so that the on-axis spectrum evolves along the z -axis while other degrees of freedom remain propagation-invariant, one can program red- or blue-shifts (and more elaborate axial codes) that persist under free-space transport, suggesting spectral “stamping” for ranging and remote sensing^[308]. The concept was subsequently demonstrated outdoors over hundreds of meters on an open-field laser range, highlighting both link robustness and distance-to-spectrum mapping with STWPs. Complementing these application-oriented results, interferometry with space–time light sheets showed enhanced passive phase stability in a Michelson configuration relative to Gaussian or Gaussian-like sheets, furnishing an empirical reliability baseline for metrology scenarios^[309].

Given that propagation-invariant space–time light sheets programmed with SLMs were established with non-separable ST spectra, the next step is to endow the field with topology rather than only geometry. STOVs are wavepackets whose phase winds in space–time^[99], producing a null at the vortex center and a circulatory Poynting flow in the x – t plane, thereby carrying transverse OAM^[100,101,310]. Unlike conventional spatial OAM beams (where the vortex lives in the x – y plane and the OAM is longitudinal), STOVs carry transverse OAM, tied to a helical phase factor $e^{i\ell\varphi_{x,t}}$ defined on the x – t coordinates; the integer ℓ sets the topological charge. On an SLM-based $4f$ platform, the winding is encoded by imposing a spiral phase across the frequency-resolved field at the Fourier plane, so that each spectral component acquires a phase offset consistent with the desired 2π circulation.

Given that STOVs have been realized by other synthesis methods^[311–314], Wan *et al.* realized STOVs by dispersing a pulse

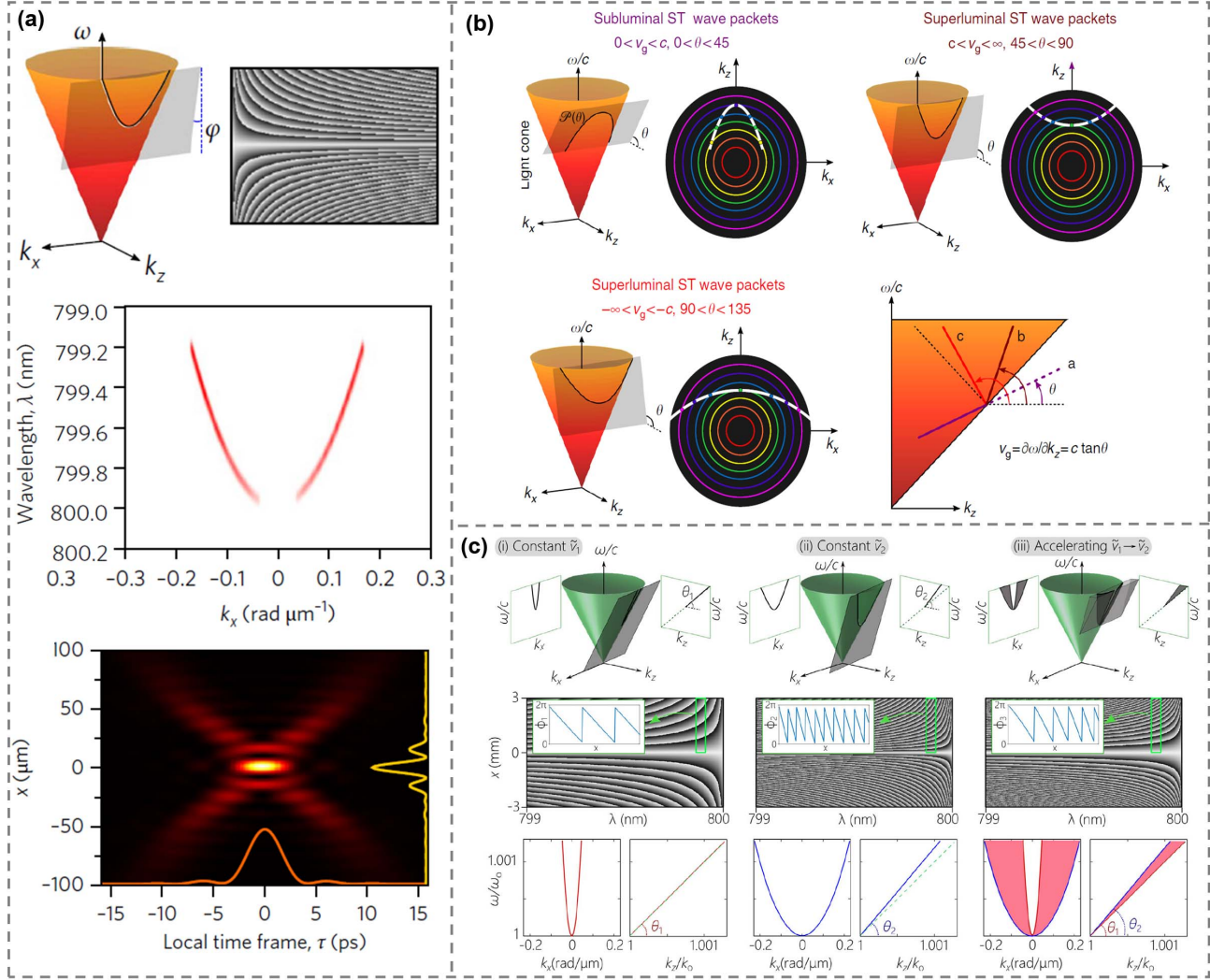


Fig. 27 (a) Basic construction of space-time light sheets: ST spectral locus defined by the intersection of a tilted spectral plane with the light cone, and corresponding experimental characterizations showing non-separable ST spectral mapping and localized wavepacket profiles. Reprinted with permission from Ref. [299], © Springer Nature (2017). (b) Classification of propagation-invariant ST families by spectral-plane tilt angles, which correspond to various group velocities^[95]. (c) Realization of tunable group velocity: spatial bandwidths of temporal frequencies determine the axial group velocity. Reprinted with permission from Ref. [96], © American Physical Society (2020).

in a $4f$ shaper and imprinting a helical phase across the frequency-resolved field, producing pulsed beams whose OAM is purely transverse and tunable [Fig. 29(a)]. This demonstrates that temporal frequency and transverse phase singularities can be co-programmed within a single ultrafast pulse and emphasized the scalability of the transverse OAM^[99,102]. To move beyond feasibility toward quantitative rules, Hancock *et al.* analyzed the mode structure and OAM transport of STOVs in free space and in dispersive media, showing that symmetric STOVs in vacuum can exhibit half-integer intrinsic OAM, whereas more general, asymmetric STOVs in dispersive media display integer quantization governed by symmetry and GVD [Fig. 29(b)], thereby establishing stability and quantization criteria for engineering robust transverse-OAM pulses^[101,315].

With feasibility and propagation mechanics clarified, the program turned to scaling the topological charge and expanding the

modal degrees of freedom. Addressing degeneracy and temporal spreading in earlier recipes, Chen *et al.* introduced time-diffraction-free transverse-OAM beams by reformulating the synthesis as immediate x - ω modulation at the Fourier plane, yielding ST Bessel vortices expressed by

$$E(\rho, \theta) = i^\ell e^{i\ell\theta} J_\ell(R_0\rho), \quad (5-2)$$

where $\rho = \sqrt{x^2 + \tau^2}$ and $\theta = \tan^{-1}(x/\tau)$ are the polar coordinates on the x - t plane, $\tau = t - z/v_g$ is the retarded time in the pulse frame, R_0 is the modulated radius, and J_ℓ is the ℓ -order Bessel function of the first kind, thereby retaining their temporal profile while carrying transverse OAM and thus enabling significantly higher topological charges without structural degradation [Fig. 29(c)]^[316]. In parallel, Liu *et al.* broadened the family to ST Laguerre–Gaussian (STLG) modes given by

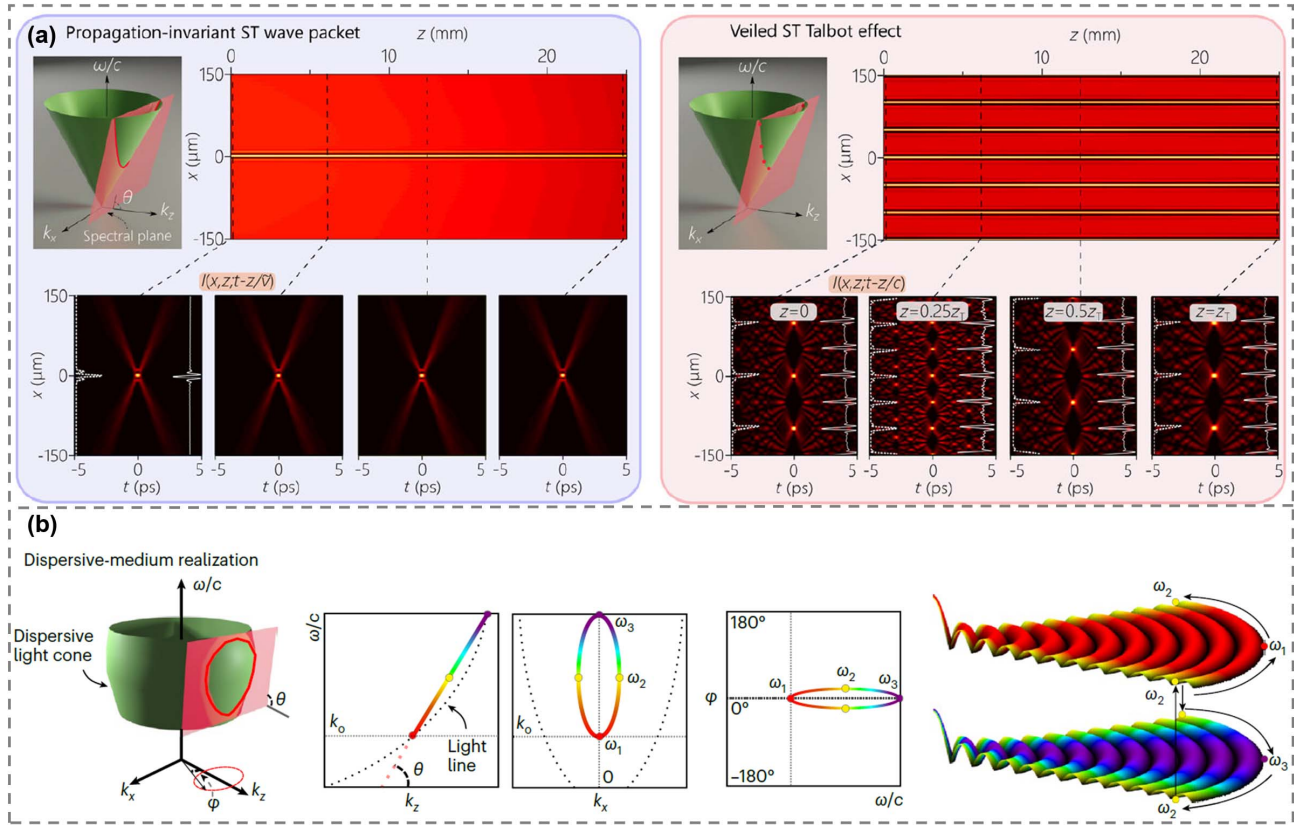


Fig. 28 (a) Veiled Talbot effect in space–time light sheets: while time-integrated measurements show frozen transverse profiles with no axial self-imaging, time-resolved detection uncovers hidden Talbot revivals. Reprinted with permission from Ref. [306], © American Physical Society (2020). (b) Optical de Broglie–Mackinnon wavepackets in dispersive media: anomalous group-velocity dispersion reshapes the light cone such that tangency with the spectral plane produces a closed ring spectrum, enabling dispersion-free propagation of O-shaped ST profiles. Reprinted with permission from Ref. [307], © Springer Nature (2023).

$$E(\rho, \theta) = \left(\frac{\sqrt{2}\rho}{w} \right)^{|\ell|} e^{\left(-\frac{\rho^2}{w^2} \right)} L_p^{|\ell|} \left(\frac{2\rho^2}{w^2} \right) e^{-i\ell\theta}, \quad (5-3)$$

where w is the radius and $L_p^{|\ell|}$ denotes the associated Laguerre polynomials of the orders p and ℓ with controllable radial and azimuthal quantum numbers. These pulses exhibit phase singularities and column-like edge dislocations in the x – t plane, form multi-ring topologies, carry a composite transverse OAM built from counter-directed components, can be interconverted with ST Hermite–Gaussian modes using strong ST astigmatism, and allow state identification via space–time intensity decoupling [Fig. 29(d)]^[317]. To provide a unified framework for systematically exploring ST beams, Chen *et al.* then proposed a 2D space–time duality framework by constituting the paraxial ST wave equation

$$\frac{\partial \psi(x, \zeta; z)}{\partial z} = \frac{i}{2\beta_0} \frac{\partial^2 \psi(x, \zeta; z)}{\partial x^2} + \frac{i}{2\beta_0} \frac{\partial^2 \psi(x, \zeta; z)}{\partial \zeta^2}, \quad (5-4)$$

where a length-scale parameter $\zeta = \frac{\tau}{\sqrt{-\beta_0\beta_2}}$ was introduced that quantifies the instantaneous spatial length scale of the ST beam in the z -direction, $\beta_0 = n(\omega_0)k_0$ is the propagation constant, and β_2 is the material dispersion, with a similar form to the spatial

paraxial wave equation. This framework maps scalar spatial beams to STWPs one-to-one, highlights the need to break the balance between paraxial diffraction and narrowband dispersion to steer ST dynamics, and prescribes complex-amplitude modulation for high-fidelity synthesis across various STOVs [Fig. 29(e)]^[94].

Having expanded control in free space, a natural question is whether charge-independent geometry can be achieved and verified. On the theory side, Ponomarenko *et al.* introduced perfect STOVs: under anomalous dispersion, the intensity profile becomes insensitive to topological charge over a practical range, effectively decoupling radius from the topological charge; an ST focusing route with conventional optics (an effective “ST lens”) was proposed to realize such profiles from suitable sources [Fig. 30(a)]^[318]. Experimentally, perfect STOVs with invariant ring radius and width and without sidelobes have been demonstrated, overcoming three persistent issues of prior STOVs—radius growth with charge, prominent high-order sidelobes, and non-circular cross-sections due to scale mismatch. Using spectral interferometry and 3D reconstruction, the study verified single-ring geometries that remain fixed during propagation, reported stable high-order realizations, and discussed practical limits (e.g., SLM aperture) [Figs. 30(b) and 30(c)]^[319,320]. Moreover, perfect STOVs allow programmable intensity shaping: by engineering the

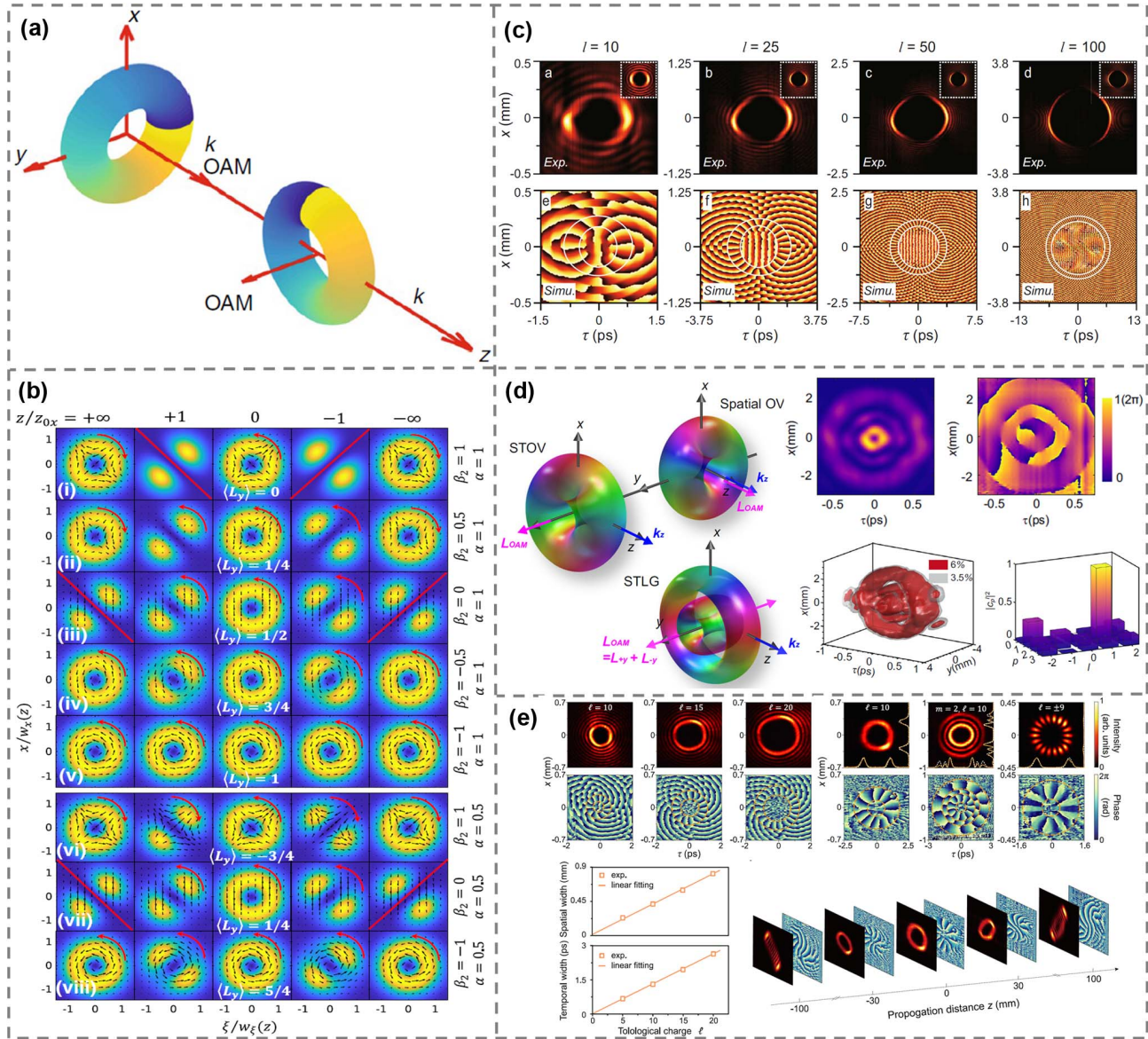


Fig. 29 STOVs: concepts, dynamics, and families. (a) Conceptual sketch of STOVs: a pulsed field whose phase winds in the x - t plane so that the OAM is transverse to the propagation direction k . Reprinted with permission from Ref. [99], © Springer Nature (2020). (b) Mode-structure and propagation behavior: calculated and measured ST intensity and phase maps illustrating how the vortex core and transverse-OAM quantization depend on symmetry and the group-velocity-dispersion parameter β_2 . Reprinted with permission from Ref. [101], © American Physical Society (2021). (c) STOVs with high topological charge: representative experimental x - t profiles for $\ell = 10, 25, 50$, and 100 [316]. (d) STL modes: schematics highlighting a single transverse-OAM vector for STOVs versus a composite transverse OAM for STLs (formed from counter-directed components) [317]. (e) High-fidelity STOVs generated based on 2D space-time duality theory [94].

spectral plane with digital axicons and helical phases, the ring can be flexibly tuned from circular to polygonal contours while remaining insensitive to ℓ [Fig. 30(d)]. The result is a sidelobe-free, scalable family of vortex beams whose geometry and size are robust, offering a versatile alphabet for applications in mode multiplexing, information encoding, and high-dimensional encryption [321]. More details about STOVs could be seen in Refs. [322–327].

Recent advances in ST structured light have expanded beyond single-vortex modes into richer families spanning orthogonal

bases, accelerating beams, non-paraxial solutions, and discrete lattices. A representative sequence includes the realization of ST Hermite–Gaussian (STHG) modes derived from STL beams, the generation of coupled Airy–Airy packets, the development of a 2D space–time duality framework encompassing ST Mathieu modes, and finally the creation of ST moiré lattice fields. Together, these works delineate a clear trajectory from mode diversity to programmable trajectories, to systematic theoretical frameworks, and ultimately to arbitrary spectrum engineering. The first step was the demonstration of STHG modes. By programming radial and

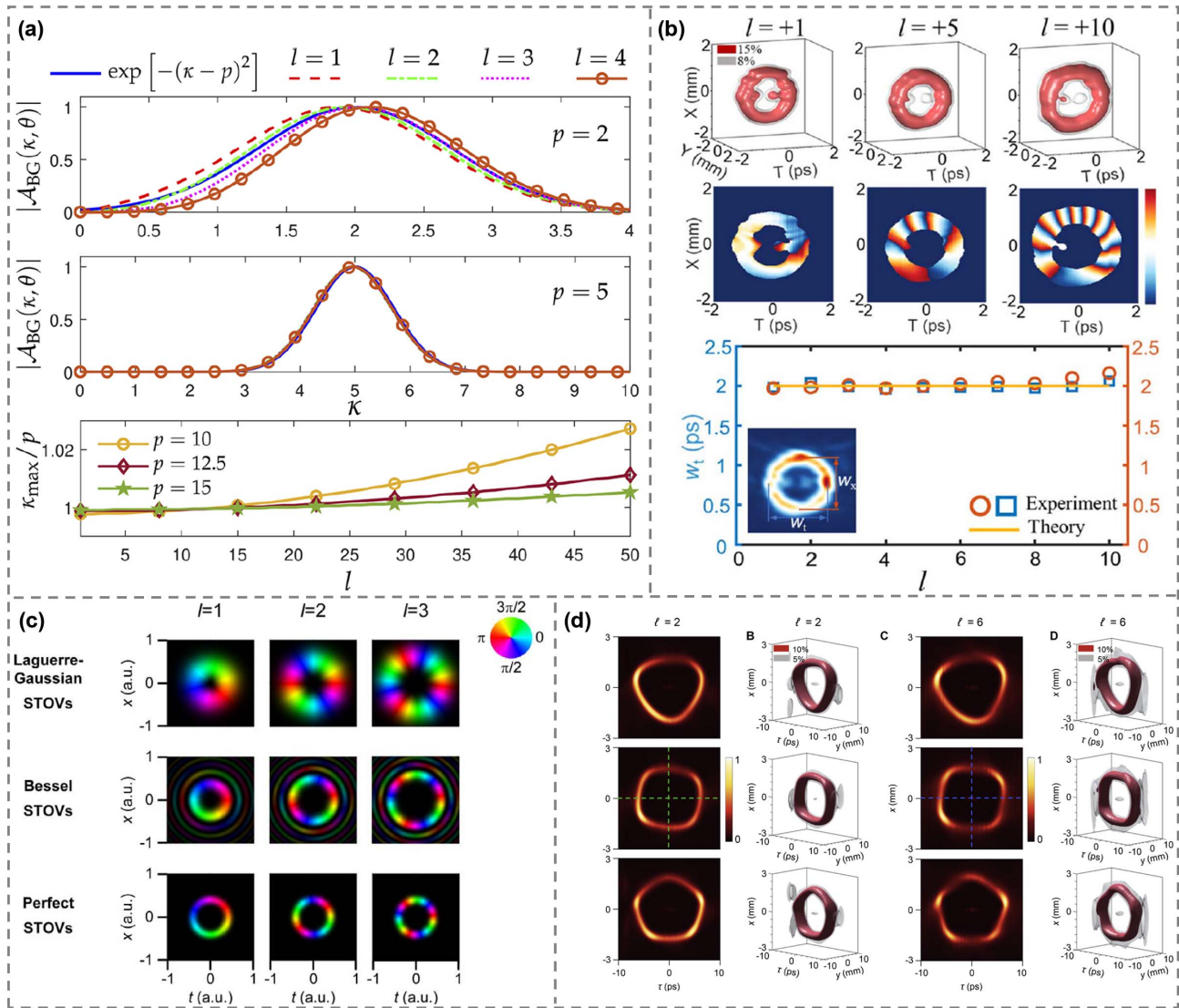


Fig. 30 Perfect STOVs. (a) Design and parameter maps used in perfect STOV synthesis: predicted ST intensity and phase distributions among topological charges^[318]. (b) Experimental verification of perfect STOVs: time-resolved $x-t$ distribution cuts and ring reconstructions for different l , and a radius-versus-charge plot confirming invariant ring radius and width. Reprinted with permission from Ref. [319], © Optica Publishing Group (2024). (c) Perfect STOVs with invariant radius and width compared with other sorts of STOVs. Reprinted with permission from Ref. [320], © Wiley-VCH GmbH (2025). (d) Perfect STOVs with controllable distributions^[321].

azimuthal quantum numbers with an LC-SLM, researchers generated STLG beams and then converted them to STHG modes via strong ST astigmatism [Fig. 31(a)]. Unlike STLGs, the STHGs exhibit Cartesian orthogonality and separable $x-t$ intensity profiles, enabling efficient state discrimination and classification^[317]. This established a convenient orthogonal basis that anchors comparisons with later non-parabolic solutions. Building on mode diversity, attention shifted to trajectory-engineered beams. By imprinting correlated cubic phases with adjustable rotation angles in the spectral plane, researchers realized coupled Airy–Airy packets that accelerate and self-heal simultaneously in space and time [Fig. 31(b)]. These beams preserved robustness over long propagation distances and highlighted the geometric mapping from spectral phase to axial dynamics, opening the door to programmable ST trajectories^[328].

To unify such developments, a 2D space–time duality framework was introduced. By deliberately breaking the balance between paraxial diffraction and narrowband dispersion, this approach established a one-to-one mapping between scalar spatial beams and STWPs. Within this framework, ST Mathieu–Gaussian and Ince–Gaussian modes were generated in elliptical coordinates, exhibiting quasi-diffraction-free propagation under dispersive conditions [Fig. 31(c)]. This provided a systematic pipeline for extending spatial families directly into the ST domain^[94]. Finally, discrete rotational symmetries were implemented through ST moiré lattices. By superposing two sets of N -fold discrete spectra with controlled relative rotation, experiments realized tunable sublattice scales and orientations, along with propagation-invariant time-integrated intensity patterns [Fig. 31(d)]. Adding spiral phases further produced arrays of ST vortices^[329]. These

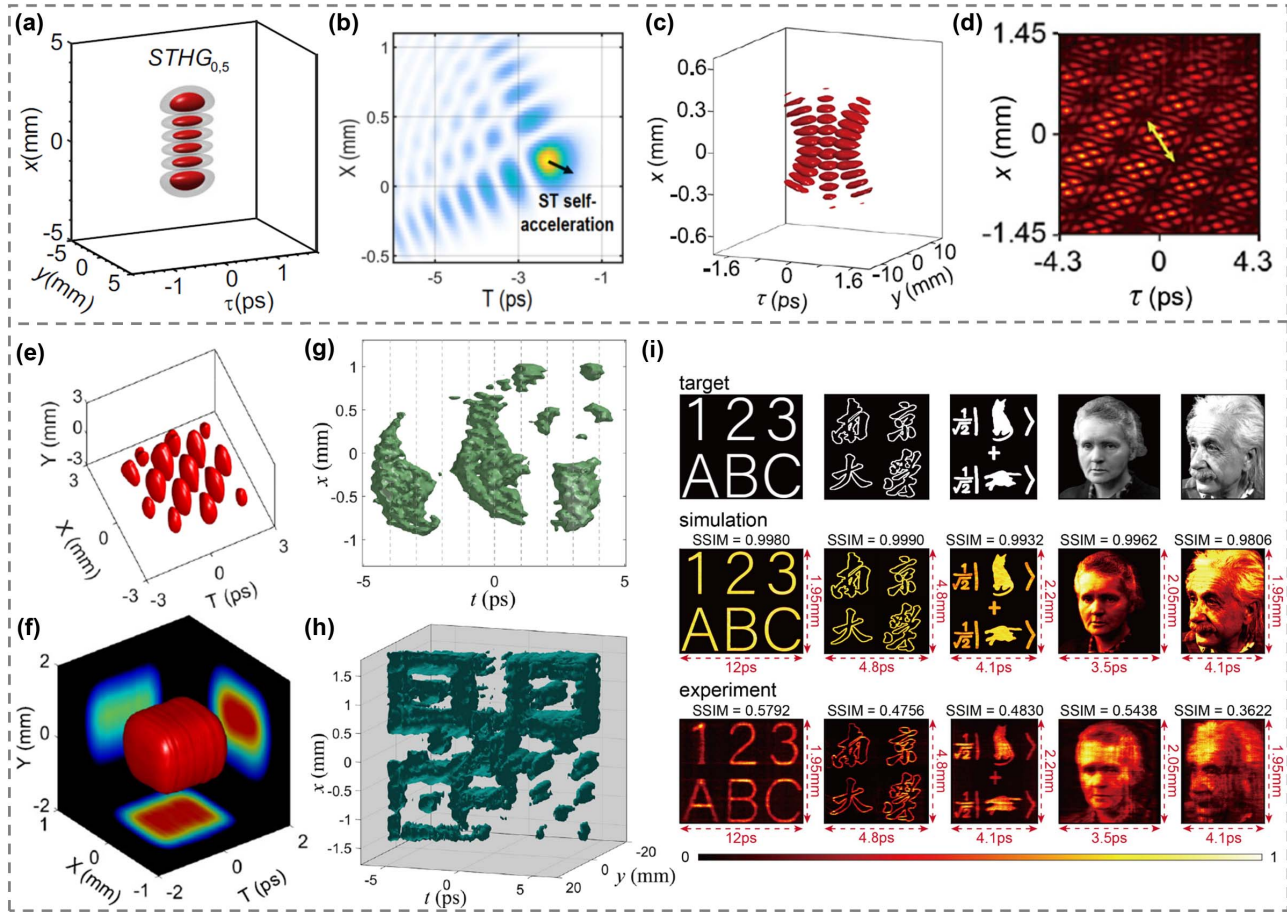


Fig. 31 Representative demonstrations of ST-structured beams and holography. (a) STHG mode, obtained from STLG beams via strong ST astigmatism, showing separable Cartesian intensity in the x - t plane^[317]. (b) Coupled ST Airy-Airy packet, exhibiting simultaneous ST acceleration along a tilted trajectory^[328]. (c) ST flat-top wavepacket, combining uniform spatial and temporal intensity within a single ultrafast pulse^[94]. (d) ST moiré lattice, generated by superimposing discrete rotational spectra with a relative angular offset, producing tunable lattice symmetries in the x - t domain^[329]. (e), (f) ST crystal and quasicrystal realized by complex-amplitude ST holography, displaying higher-order rotational symmetries (e.g., 4-, 5-, and 6-fold) and an ST flat-top beam, confirming invariant width and nearly constant ST envelope^[330]. (g), (h) ST holography of a panda image and quick response (QR) codes, reconstructed from a single ultrafast pulse to illustrate arbitrary target programmability. Reprinted with permission from Ref. [331], © Wiley-VCH GmbH (2025). (i) ST holography demonstrating high-fidelity reconstruction of a detailed grayscale image in the x - t domain^[94].

results mark a transition from single-beam topologies to programmable arrays and quasi-crystalline patterns, advancing ST structured light toward robust, application-ready platforms.

With rapid advances in ST holography and complex-amplitude control, increasingly sophisticated and functional ST structured beams have been realized within a single ultrafast pulse. The earliest demonstrations focused on ST crystals and quasicrystals, achieved in a $4f$ pulse shaper by loading arrays of apertures and spiral phases onto an LC-SLM. These fields exhibited 4-, 5-, and 6-fold rotational symmetries and even carried transverse OAM, thereby confirming that complex-amplitude holography can sculpt highly symmetric or quasiperiodic wavepackets [Fig. 31(e)]^[330]. This established the experimental platform for engineering entire families of STWPs. Building on this platform, researchers realized ST flat-top wavepackets, in which the spatial and temporal

dimensions simultaneously exhibited uniform intensity distributions. Unlike traditional flat-top beams that operate in a single domain, these ST flat-top fields combined spatial and temporal uniformity in one programmable packet [Fig. 31(f)]. Such beams are particularly relevant for ultrafast laser processing and optical computing, where uniform fluence and pulse shaping are critical. The shift from crystals and quasicrystals to flat-top profiles demonstrated the broad functionality of the same ST holographic approach.

Beyond analytic families, the method was extended to arbitrary target patterns via ST holography. Using an optimized LC-SLM configuration, single pulses were encoded to reconstruct 3D ST images of complex shapes such as a panda [Fig. 31(g)], quick response (QR) codes [Fig. 31(h)], and emblems. These results highlighted the generality of ST holography: not only capable of reproducing canonical wavepacket

families, but also capable of printing arbitrary images directly into the space–time domain^[331]. Finally, the approach was pushed further to reconstruct detailed and high-contrast images [Fig. 31(i)] that underscored the platform’s ability to reproduce intricate intensity and phase distributions with fidelities exceeding 90% (theory approaching 97%)^[94]. Taken together, these results chart a clear trajectory: from analytic wavepacket families such as ST crystals and flat-top beams to arbitrary programmable images including detailed portraits. This progression demonstrates both the universality and robustness of ST holography, establishing a closed loop that connects theoretical frameworks, experimental tools, and application scenarios in ultrafast programmable imaging and secure information encoding.

In sum, this section outlined a unified route to programmable ST fields using SLM–4f spectral engineering. A non-separable spectral mapping turns target propagation laws into phase and complex-amplitude masks, yielding propagation-invariant space–time light sheets with continuously tunable and even axially programmed group velocities. We then moved from geometry to topology with STOVs. Beyond first demonstrations and propagation rules, advances now include time-diffraction-free transverse-OAM beams (supporting very high charge), higher-dimensional modal control, and perfect STOVs that decouple radius and width from charge and suppress sidelobes, an engineering baseline for robust multiplexing and metrology. Finally, we broadened to ST structured beams and holography: orthogonal bases (e.g., STHG), trajectory-engineered packets (e.g., coupled Airy-type), and a 2D space–time duality that maps canonical spatial families into the ST domain with high fidelity. Full complex-amplitude ST holography delivers flat-top profiles, crystalline and quasi-crystalline symmetries, and arbitrary image reconstructions from a single ultrafast pulse, together pointing to scalable platforms for communications, precision sensing, and quantum control.

5.3 Multidimensional Control of Structured ST Fields

Research on STWPs has progressed from the foundational question of whether a pulse can remain localized over long distances to the broader challenge of programming multiple degrees of freedom—culminating in toroidal topology and chiral dynamics. The first step was to secure a robust linear carrier. By combining a temporal Airy waveform with a spatial Bessel profile through spectral engineering, Airy–Bessel wavepackets demonstrated 3D linear light bullets that preserve their envelope without relying on nonlinear self-focusing, thereby avoiding fragile balance conditions [Fig. 32(a)]^[332]. Building on this, ST Airy³ light bullets introduced space–time Airy constructs that exhibit self-healing, disturbance tolerance, and trajectory programmability in both the linear regime and at intensities where nonlinear effects emerge^[333]. Together, these works establish a portable, controllable ST platform on which more intricate phase and topology can be superimposed.

With a stable carrier in hand, the program naturally turned to making OAM orientation itself programmable. Zang *et al.* advanced the concept and then experiment of treating the OAM vector direction as an independent degree of freedom, no longer restricted to the propagation axis. A concrete implementation on STOVs followed: STOVs with arbitrary OAM orientation by astigmatic mode converters used astigmatic converters and cylindrical optics to continuously rotate the OAM vector to arbitrary 3D orientations while preserving the STWP quality

[Fig. 32(b)]^[334]. After clarifying how arbitrary-orientation STOVs can be generated, the concept of OAM orientation was elevated into a full 3D vector with tunable tilt. Wan *et al.* realized this by superimposing an STOV with a conventional spatial vortex within the same wavepacket [Fig. 32(c)]. Using astigmatic and cylindrical mode converters and 2D ST spectral modulation, they experimentally obtained OAM vectors pointing in arbitrary 3D orientations^[335]. Importantly, the average OAM per photon remains conserved during free-space propagation, while both the magnitude and orientation can be independently tuned via the topological charges and pulse dimensions of the two vortices. The authors further demonstrated embedding multiple STOVs together with spatial vortices into a single packet, temporally separable down to sub-100-fs scales.

Beyond tailoring the tilt direction of STOVs and exploring their superposition with other modes, recent efforts have shifted toward the synthesis of wavepackets that undergo multiple successive manipulations, producing ST beams with increasingly intricate structures and functionalities. Zhan’s group provided the first experimental observation of toroidal (smoke-ring-like) optical vortices [Fig. 32(d)], in which field and energy flows form closed loops in three dimensions—lifting vortex topology from point and line singularities to closed rings^[103]. A companion perspective clarified the physical picture and positioned toroidal vortices within the broader vortex and OAM landscape, supplying a common language and benchmarks for replication^[336]. Beyond toroidal vortices, the exploration of toroidal states was naturally extended to higher-order topologies: Wan *et al.* reported the first optical realization of scalar hopfions—wavepackets whose phase structure follows the Hopf fibration [Fig. 32(e)], giving rise to families of mutually linked closed loops^[105]. By coupling ST and spatial vortices to introduce both toroidal and poloidal twists, the authors generated hopfions with well-defined topological invariants, verified through interferometric measurements and 3D reconstructions. This result elevates vortex physics from simple closed rings to higher-order topological textures, bridging toroidal states and establishing a new platform for exploring topology and high-dimensional information encoding in optics.

Beyond hopfions, the study of toroidal vortices has revealed new chiral dynamics. Chen *et al.* observed that toroidal STOVs can undergo chiral symmetry breaking, leading to the emergence of asymmetric, helical wavepacket families termed photonic conchs [Fig. 32(f)]. These conch states manifest handedness-dependent propagation dynamics and mode conversion. This work not only demonstrates that chirality can spontaneously emerge within ST vortex platforms, but also establishes a new class of topological optical states that connect geometry, symmetry, and evolution in a unified picture^[104]. Another example combining the STWPs with chirality is the beams with time-varying OAM (or light springs)^[106–108,337–342]. The core idea of a light spring beam is to make the OAM within a single pulse evolve continuously in time: during spectral shaping, each frequency component ω is assigned a different topological charge $\ell(\omega)$ [Fig. 32(g)]. As a result, the instantaneous OAM becomes a programmable function of time (equivalently, of frequency), and the transverse intensity and phase pattern undergoes a deterministic rotation with a time-varying angular-momentum flow across the pulse. Naturally, a transverse light spring could be generated similarly via assigning each spatial frequency corresponding to ST OAM^[343]. This turns OAM from a static topological label into a time-domain degree of freedom, enabling

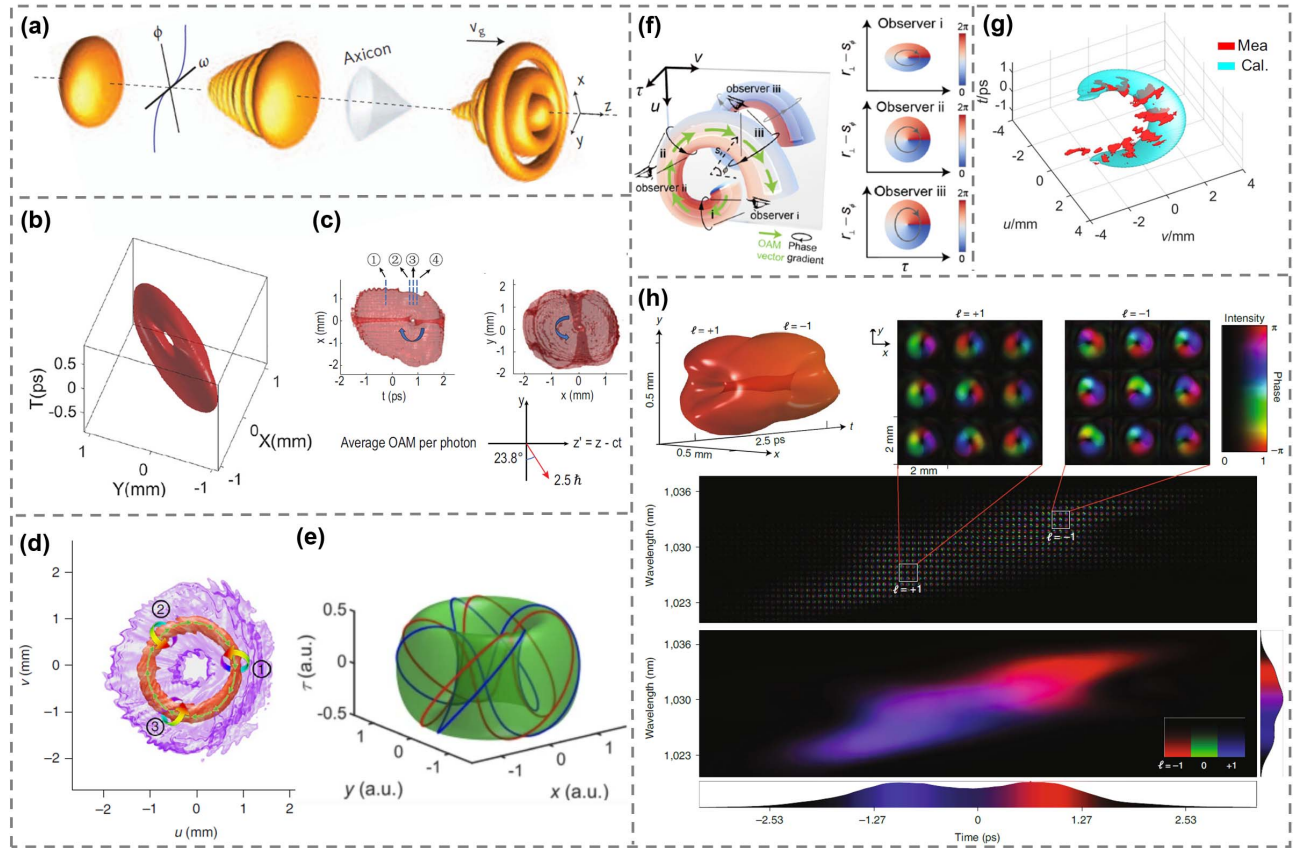


Fig. 32 Multidimensional control of STWPs. (a) Airy–Bessel linear ST bullet: produced by combining a temporal Airy profile with a spatial Bessel mode, achieving long-distance linear localization. Reprinted with permission from Ref. [332], © Springer Nature (2010). (b) Tilted STOV: an STOV whose transverse OAM vector is controllably inclined relative to the propagation axis^[334]. (c) Superposition of a tilted STOV with a spatial vortex: merging transverse and longitudinal OAM in a single pulse to realize arbitrary 3D OAM orientations^[335]. (d) Toroidal ST vortex: a “smoke-ring” type ST structure where phase and energy flow form closed loops in three dimensions^[103]. (e) Hopfion: higher-order topological wavepacket whose phase streamlines follow the Hopf fibration, producing mutually linked closed loops with both toroidal and poloidal twists^[105]. (f) Photonic conchs: helical families of states arising from chiral symmetry breaking in toroidal vortices. Reprinted with permission from Ref. [104], © American Physical Society (2024). (g) Time-varying OAM: generated by assigning a distinct topological charge $\ell(\omega)$ to each spectral component, yielding OAM that evolves continuously in time within a single pulse^[339]. (h) Multi-plane light conversion (MPLC) combined with $4f$ pulse shaping: a programmable platform for synthesizing ST wavepackets with time-varying OAM, validated through frequency- and time-resolved holographic reconstructions. Reprinted with permission from Ref. [344], © Springer Nature (2022).

ultrafast OAM–time encoding and controlled torque transfer to matter, and providing a practical route to study ST OAM coupling on picosecond–sub-picosecond scales.

Aiming to preserve and exploit ST correlations in complex media, a reconfigurable platform that combines $4f$ pulse shaping with multi-plane light conversion (MPLC) was demonstrated [Fig. 32(h)]. This architecture jointly programs the spectral phase and chirp and the transverse modal content to synthesize either separable or non-separable STWPs, including time-varying OAM evolving in an orderly fashion with time^[344,345]. The 3D amplitude–phase structure is retrieved via frequency- and time-resolved holographic tomography together with color-coded decomposition in the Laguerre–Gaussian basis, pointing to applications in multimode amplification, laser micromachining, and high-harmonic generation.

The multidimensional control of STWPs could also be expanded to vectorial STWPs, namely, STWPs with time-varying polarizations. Recent progress in vectorial STWPs charts a coherent progression from foundational methods and propagation-invariant carriers to precise temporal–polarization control, reconfigurable platform synthesis, and ultimately topological vector states. Zhan’s group establishes a common-path architecture (augmented with a quarter-wave plate) that linearly maps SLM phase to polarization rotation, enabling direct inscription of vector textures in the x – t volume [Fig. 33(a)]—e.g., spin gratings and temporally twisting polarizations—together with interferometric or tomographic diagnostics^[346]. Building on this engine, Abouraddy’s group realized 3D localized, propagation-invariant vector STWPs (including radial and azimuthal families) via spectral remapping with dispersive Bragg elements

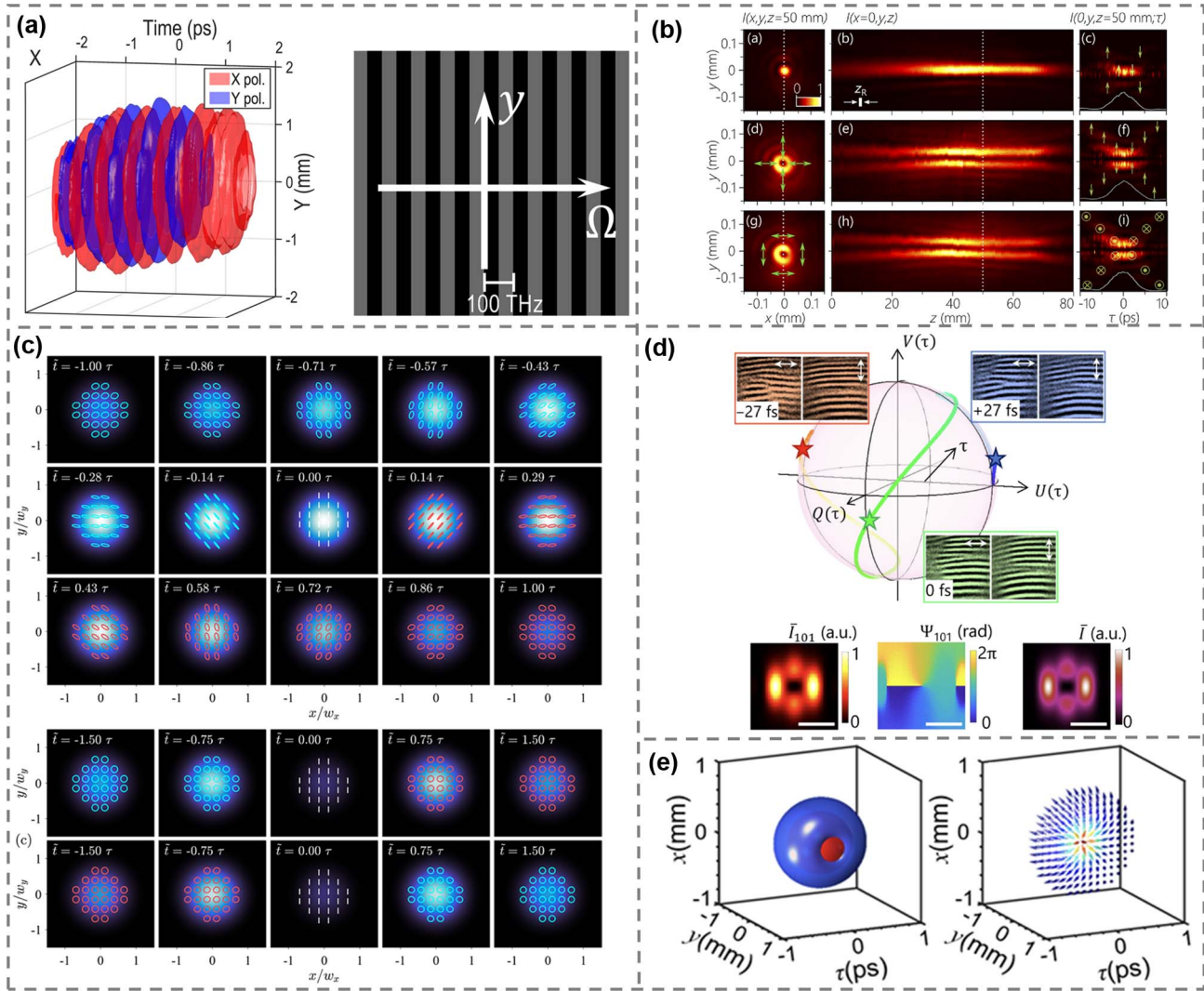


Fig. 33 Vector STWPs. (a) Vectorial sculpting engine: a common-path scheme writes programmable polarization textures in the x - t volume^[346]. (b) Propagation-invariant vector ST WPs: measured space-time intensity along the axis shows sustained localization over propagation, consistent with the designed vector spectra^[97]. (c) Programmable vector ST lattices and temporally twisting polarization: polarization ellipses evolve across normalized time, illustrating controlled ST polarization dynamics. Reprinted with permission from Ref. [98], © Optica Publishing Group (2024). (d) Temporally twisting polarization with analytic control: the time-dependent state traces a trajectory on the Poincaré sphere, enabling uniform azimuth rotation with adjustable ellipticity^[337]. (e) Optical ST skyrmions: x - t polarization textures that cover the full Poincaré sphere, visualized via 3D iso-surfaces and local polarization vectors, demonstrating robust vector topologies in ST fields^[347].

and an SLM, while retaining tunable group velocity and compatibility with OAM [Fig. 33(b)]^[97]. To refine the time degree of freedom, Jiang *et al.* provided an analytically tractable, experimentally validated scheme in a $4f$ pulse shaper whereby programmed group delay yields a uniform temporal rotation of the polarization azimuth with monotonic ellipticity control [Fig. 33(c)]; for larger delays, the pulse splits into two circularly polarized sub pulses of opposite handedness, furnishing a precise building block for ultrafast polarization control and coherent manipulation^[98].

Platform-level synthesis is achieved in the work of Chen *et al.*, which cascades metasurface-based $4f$ shaping with MPLC to generate separable and non-separable vectorial STWP trains and time-varying OAM, with full 3D field retrieval via frequency

and time-resolved holographic tomography and LG-basis color coding, tracing a trajectory on the Poincaré sphere, enabling uniform azimuth rotation with adjustable ellipticity; the architecture is compatible with multimode-fiber interfacing [Fig. 33(d)]^[337]. Finally, Teng *et al.* elevated vectorial ST structuring to a topological level: by coaxially superposing an STLG vortex pulse and a Gaussian pulse in orthogonal polarizations, the resulting x - t polarization textures cover the entire Poincaré sphere, forming ST skyrmions whose skyrmion tubes exhibit no out-of-plane twist [Fig. 33(e)], thereby enhancing robustness against distortions^[347]. Collectively, these works establish a reproducible and scalable pathway—from programmable vector writing and propagation-invariant 3D carriers, through analytically controlled temporal polarization, to a reconfigurable platform

synthesis and Poincaré-sphere-complete topological states—supporting advances in nonlinear optics, quantum information, precision metrology, and adaptive control in complex media.

This section traced a unified progression from linear ST bullets to programmable vortex topology, time-dependent angular momentum, and finally platform-level synthesis and vectorial control. Airy–Bessel bullets established a robust, fully linear combination of spatial and temporal control on which we introduced tilted STOVs and their arbitrary 3D OAM orientations, then closed the geometry into toroidal vortices and advanced to higher-order textures with hopfions; the observation of chiral symmetry breaking yielded the helical photonic conch families. Turning OAM from a static label into a time-domain degree of freedom, self-torque beams were realized by assigning $\ell(\omega)$ across the spectrum, and a reconfigurable MPLC combined with $4f$ pulse shaping architecture provided a practical route to synthesize and diagnose such ST fields in free space and fibers. Building on this foundation, we moved from scalar to vector ST beams: (i) a common-path engine inscribes programmable polarization textures in the x – t plane; (ii) propagation-invariant vector STWPs serve as 3D carriers with tunable v_g and OAM compatibility; (iii) temporally twisting polarization affords analytic, precise control of azimuth and ellipticity; and (iv) ST skyrmions realize Poincaré-sphere-complete topologies in (x, t) . Collectively, these results establish a reproducible pathway—from stable carriers to cascaded spectral–spatial engineering and full vector-topological programmability—positioning ST beams as a scalable toolset for nonlinear driving, quantum state preparation, high-capacity communications, precision metrology, and adaptive light–matter control in complex media.

5.4 Discussion

At present, the synthesis and control of STWPs rely primarily on LC-SLMs integrated in $4f$ pulse-shaping systems, where each spectral component is programmably addressed in the Fourier plane. Yet, these beams are still largely confined to free-space implementations, with the LC-SLM serving as the sole programmable element. Looking forward, a critical step is to move beyond free-space shaping and explore direct interaction of ST beams with LC platforms, where the intrinsic anisotropy, reconfigurability, and nonlinear response of LCs can complement SLM-based synthesis. In this context, one promising entry point is LC-based vectorial holography, which expands SLM modulation by extending it into the polarization domain and further enriches the toolbox of structured light synthesis. By exploiting the polarization sensitivity and pixel-level phase control of LC-based SLMs, arbitrary vector beams with spatially varying polarization states can be generated through vectorial holographic encoding. This approach extends conventional amplitude–phase holography into the vector domain, allowing simultaneous control of amplitude, phase, and polarization. When combined with ST modulation, LC vectorial holography offers a direct route to synthesizing vectorial ST fields, where spatial, temporal, and polarization degrees of freedom are jointly programmed. Such capabilities not only expand the dimensionality of optical field control but also open pathways toward high-capacity optical communication, multidimensional quantum state preparation, and adaptive light–matter interaction in complex media.

While LC vectorial holography programs amplitude–phase–polarization at the source plane, in-plane LC photonics provides this complementary functionality, which supplies a

programmable 2D medium—via director patterning and field-tunable anisotropy—that supports self-written waveguides (nematicons), refractive and reflective routing, potential-well trapping and release, negative refraction, branched-flow transport, and topology-guided steering using defects and skyrmion and toron textures. These capabilities are well suited to post-processing ST sources: synthesize the ST wavepacket in free space with a $4f$ shaper, then couple it into the in-plane LC to realize on-chip routing, splitting, capture, and mode conversion while quantifying preservation, degradation, and recovery of ST correlations in a nonuniform, anisotropic medium. Theory further suggests that LC platforms that combine slow nonlocal reorientation with fast electronic Kerr response could support (3+1)D light bullets, but a systematic experimental validation of ST-correlation preservation in thin in-plane films remains an open target, guiding co-design of spectral encoding and LC landscapes.

Beyond linear transport and reconfigurable guiding, a natural next step is to endow LC platforms with nonlinear functionality. Integrating ST beams with the second-order nonlinearity of FNLCs extends programmable optics from wave shaping to frequency conversion. ST beams generated by SLM– $4f$ mapping provide pumps with tunable group velocity and structured topology, while FNLCs, endowed with spontaneous polarization, large $\chi^{(2)}$, and electrical tunability, support second-harmonic generation, nonlinear PB-phase encoding, and adjustable phase matching. This synergy enables transfer of ST-OAM structure into harmonic fields via nonlinear geometric phases, with external fields providing dynamic control. At the quantum level, ST correlations could be imprinted onto converted photons across space, time, polarization, and OAM, offering routes to programmable high-dimensional entanglement and reconfigurable light sources. In this way, FNLCs serve as a versatile nonlinear platform, pushing ST beams beyond shaping toward frequency conversion and information encoding, with implications for communications, imaging, and quantum photonics.

Extending the discussion from material integration to device-level implementations, LC-SLMs can be considered together with metasurfaces as complementary programmable photonic platforms. LC devices, particularly LC-SLMs, presently constitute one of the most versatile and scalable platforms for ST field synthesis. They offer large active apertures, mature and low-cost fabrication, and pixel-level electrical addressability, enabling dynamic and fully reconfigurable phase or amplitude modulation with micrometer-scale spatial resolution. Owing to their electrically tunable birefringence, LC devices also provide intrinsic polarization sensitivity, allowing simultaneous control of phase, amplitude, and polarization within a single platform. These attributes make LC-SLMs especially suitable for high-dimensional, adaptive, and cost-effective beam engineering in laboratory and system-level implementations.

By contrast, metasurfaces provide complementary strengths at the device level. Their subwavelength manipulation enables deterministic complex-amplitude and polarization control within an ultrathin setup, while offering high efficiency, broadband response, and compact integration without bulky $4f$ architectures. Rather than competing approaches, the two technologies are inherently synergistic: hybrid architectures that combine programmable LC encoding with metasurface-based fine or on-chip processing may therefore unify flexibility, efficiency, and integration, representing a practical route toward scalable ST photonic systems.

While LC platforms illustrate the diverse opportunities opened by combining ST beam synthesis with material responses, they also highlight a broader trend: SLM-based shaping is no longer limited to free-space demonstrations but increasingly converges with other programmable or functional materials. A particularly promising direction is the co-integration of LC-SLMs with heterogeneous material platforms: leveraging metasurfaces for subwavelength, locally addressable phase; phase-change materials for nonvolatile reconfigurability; LiNbO₃ and silicon photonics for high-speed electro-optic modulation^[348]; and acousto-optic and optomechanical hybrids to realize hybrid shapers that combine high bandwidths. Building on such hardware, the combination of 3D ST holography^[349], multi-spectral slicing, and MPLC—augmented by data-driven inverse design and closed-loop wavefront control—could extend today's 2D ST shaping to arbitrary-target synthesis and rapid reconstruction of four-dimensional fields (x, y, z, t). This would not only deliver on-demand optical fields for high-throughput nonlinear driving, quantum-state preparation, and multidimensional communications, but also provide general tools for high-fidelity light–matter interaction and adaptive control in complex media.

The convergence of LC devices, SLM-based synthesis, and hybrid integration with emerging functional materials is gradually shaping a more versatile framework for ST beam control under the Soft Mattonics umbrella. Rather than focusing on a single mechanism, these developments highlight complementarity and point toward increasingly flexible and scalable platforms. As these capabilities mature, attention naturally turns to the broader question of how such advances will support and transform the applications of ST beams. In nonlinear optics, ST beams can be engineered with tunable group velocities and phase-matching conditions that significantly enhance high-order harmonic generation^[109–111]. Their propagation-invariant or velocity-tailored envelopes enable efficient nonlinear processes, while also allowing tailored excitation of electronic or vibrational modes in matter. In quantum photonics, ST correlations extend the accessible Hilbert space by enabling photons with time-varying OAM or multimode entangled structures. This opens pathways for high-dimensional quantum encoding and more flexible architectures for quantum information processing. Meanwhile, their instantaneous angular momentum flow provides unprecedented control in particle manipulation, delivering a programmable optical trap at sub-picosecond scales, offering novel routes for micro- and nano-manipulation^[350]. In optical communications, ST beams bring dispersion-resilient propagation and additional multiplexing channels^[351], promising high-capacity, long-distance^[309], robust free-space, and fiber-based links. Beyond optics, the conceptual framework of ST correlations has already inspired analogues in acoustics^[352–354] and electron beams^[355,356], where similar space–time couplings can guide waves in engineered trajectories. Collectively, these applications illustrate how ST beams not only deepen our understanding of light–matter interactions but also pave the way for advanced technologies in ultrafast science, quantum information, and wave physics.

Taken together, these demonstrations—spanning adaptive optics, optical computation, imaging, sensing, communications, and particle manipulation—may appear application-specific at first glance, yet they share a common functional logic. At a more abstract level, LC- and ST-enabled platforms provide a unified means to encode high-dimensional information into multiple optical degrees of freedom, process this information through

programmable propagation and light–matter interactions, transduce it into measurable or communicable signals, and ultimately actuate matter via controlled transfer of energy, momentum, or angular momentum. Viewed through this lens, Soft Mattonics is not merely a collection of parallel application examples, but rather a general hardware framework that integrates information encoding, processing, readout, and physical actuation within a single reconfigurable photonic medium, thereby establishing a coherent paradigm for next-generation optical information processing and light–matter control.

6 From Passive to Active Light Emission

Building on the passive modulation capabilities highlighted in previous sections within the Soft Mattonics framework, this section explores the transition to active emission, where LCs evolve from modulating external light to generating and controlling their own optical signals. Owing to their anisotropy and tunable optical properties, LCs have long served as key media for optical modulation in displays and photonic devices. In the traditional sense, LC devices mainly work by the action of an external field to cause a change in molecular orientation, thereby achieving modulation of refractive index, phase delay, and polarization control. However, such devices are typically passive, depending on an external light source, and their functions are limited to “modulating incident light.” They still have shortcomings in the active generation of optical signals and the precise control of the emission state. With the continuous development of information photonics and functional materials, researchers have gradually expanded their perspective to the emerging field of “luminescent LCs (LLCs).” This is achieved by introducing luminescent units [including organic luminescent materials, rare-earth luminescent materials, and luminescent quantum dots (QDs)] into the LC matrix, so as to realize a leap from “passive optical control” to “active luminescence control.” Such composite systems can achieve programmable control in multiple dimensions, including luminescence peak position, intensity, polarization state, directionality, etc. They can also couple with external stimuli such as an electric field, optical field, thermal field, and magnetic field, thus showing a higher functional integration degree than traditional LC materials. They are gradually evolving into optoelectronic functional platforms with multiple degrees of freedom and cross-scale integration, which are of great importance for the development of new-generation optical information technologies. In particular, for the dynamic generation and control of circularly polarized light (CPL) and linearly polarized light (LPL), LC systems, due to their chiral amplification effect and controllable molecular orientation, have become important candidate materials for realizing active polarization-programmable luminescence.

To place this transition in context for a broad photonics readership, it is useful to contrast Soft Mattonics with static or quasi-static nanophotonic platforms such as metasurfaces. Metasurfaces predominantly encode optical functions into fixed subwavelength geometries (and, when combined with emitters, into predetermined resonant modes), offering compact and precise wavefront control but often limited post-fabrication adaptability. In luminescent LC systems, by contrast, optical functionality is encoded in a reconfigurable soft order parameter: alignment, chirality, and defect landscapes can be continuously and reversibly reprogrammed by weak external stimuli. As a result, the emission process and its manipulation can be co-programmed across multiple degrees of freedom including wavelength, directionality, and particularly the vectorial state of light (e.g., linear/circular

polarization and handedness switching). Moreover, the soft elastic energy landscape naturally supports nonlinearity and ST programmability, where textures can be written, erased, and driven in time to yield dynamic emission patterns and adaptive feedback (e.g., via LC photonic bandgaps). This perspective clarifies why active-emissive Soft Mattonics is complementary to metasurfaces: it prioritizes dynamical, multi-field reconfiguration and vectorial control, rather than relying solely on static geometrical encoding.

6.1 Evolution of Luminescent LC Architectures

6.1.1 Passive LC systems

According to the molecular arrangement and phase characteristics, LCs can be roughly divided into nematic, smectic, cholesteric, and some novel special phases. The nematic phase is the most common one. Its feature is that the molecules have long-range orientational order but no obvious layered structure, so the fluidity is similar to a liquid. In this phase, a common example is the positive nematic phase, which has a clear anisotropic refractive index and is easy to control with an electric field. The smectic phase forms a layered molecular arrangement on the basis of orientational order. The translational order of molecules increases, so the electro-optic response and elastic properties are different from those of the nematic phase. Smectic phases are suitable for electro-optic effect devices. CLCs are formed by chiral molecules or by doping chiral agents into achiral molecules. They have a twisted helical structure, and can selectively reflect specific CPL, thus possessing a natural photonic bandgap property. In addition to the traditional three categories, there are special phases such as blue phase LCs, ferroelectric LCs, and antiferroelectric LCs. Blue phase LCs, within certain temperature ranges, have a three-dimensional photonic crystal structure that exhibits Bragg reflection, and can be used for fast-response photonic devices. Ferroelectric and antiferroelectric LCs possess spontaneous polarization, and therefore have extremely fast response speeds, showing great potential for display and optical switching applications. Overall, different types of LCs, due to differences in molecular order and structure, exhibit unique electro-optic properties, optical selectivity, and response speeds. This provides a wide variety of material systems for the development of luminescent LC systems^[2,3].

6.1.2 Active luminescent LC systems

Compared with the “passive modulation” of traditional LC systems, in recent years, researchers have realized control of “active luminescence” by introducing luminescent functional materials into LCs. This change makes LCs able not only to adjust the parameters of incoming light, but also to control the light they emit themselves. Therefore, the research progress of luminescent LC systems is closely related to the diversity of luminescent dopant units. At first, doped systems based mainly on organic fluorescent dyes realized the basic function of photoluminescence. However, single organic molecules often have limitations such as low quantum yield and insufficient photostability. To overcome these problems, researchers have gradually introduced more diverse luminescent units, coupled with the LC matrix to form composite systems.

6.1.2.1 Organic luminescent materials and LCs. Organic luminescent materials have advantages such as flexible molecular structure design, strong tunability of function, low cost, and

easy processing. They have become an important topic in CPL research. Traditionally, it was believed that a high CPL dissymmetry factor (g_{lum}) requires introducing chiral fragments into the molecular skeleton. However, recent studies have shown that combining organic emitters with LC photonic systems can obtain significant chiral optical responses without relying on covalently introduced chirality^[357,358]. This provides a new strategy for organic CPL materials and promotes their applications in information encryption, anti-counterfeiting, and photonic devices.

For example, in polymer material systems, researchers have successfully constructed multimodal switchable CPL emitters. Zhao's group realized ultralong room-temperature phosphorescent CPL by combining organic phosphorescent polymers with chiral helical superstructures. The afterglow lifetime reached 735 ms and the g_{lum} value was as high as 1.49. This system maintained excellent stability after repeated light and heat cycles, and showed great application potential in optical multiplexed information encryption [Fig. 34(a)]^[114]. Ma's group proposed an “energy transfer-photonic coupling” strategy. By placing achiral luminescent units in the chiral environment of CLC polymers, the system realized multi-color circularly polarized afterglow from blue to red, while obtaining record g_{lum} values (up to 1.90) and superlong lifetimes (> 6 s). This study eliminated any orientational artifacts by LC photonic structure induction, and proved that high-level CPL can be achieved without introducing chiral elements at the molecular level^[359]. Deng's group used polymers containing chiral centers and coupled them with LC systems to achieve dual-mode modulation of CPL and chiral phosphorescent delayed emission^[360]. This system not only showed extremely high chiral signals, but also could switch modes under external stimuli, with potential applications in anti-counterfeiting labels and multiple information encryption. In addition, metal-organic composite systems constructed using the chiral ion-pair strategy have also promoted the development of organic CPL. Yu's group, by introducing a chiral anion as a “chiral induction source” into a non-chiral Pt(II) complex cation, achieved 71.5% quantum efficiency in an amorphous environment, and in CLCs, the g_{lum} value was amplified to -0.99 . Experimental results showed that when the Pt complex formed a crystalline state, chiral transfer was suppressed. But in polymer films or amorphous structures, the chiral anion could effectively induce cation self-assembly to achieve chiral transfer. This study provided a path for balancing processability and performance in organic-metal composite luminescent materials^[361].

In summary, the development of organic and polymer CPL materials has gradually eliminated dependence on internal molecular chirality, and instead has used LC photonic effects, energy transfer dynamics, and chiral environment induction strategies to achieve high-performance CPL. These materials are expected to play important roles in optical anti-counterfeiting, flexible information storage, and multidimensional optical communication in the future.

6.1.2.2 Rare-earth luminescent materials and LCs. Rare-earth ions, due to their unique electronic energy level structure and excited-state emission characteristics, have long been the focus of photoluminescence research^[362–364]. However, current research mainly focuses on controlling the intensity and wavelength of rare-earth luminescence, while neglecting research on the polarization state. The rich self-assembly characteristics

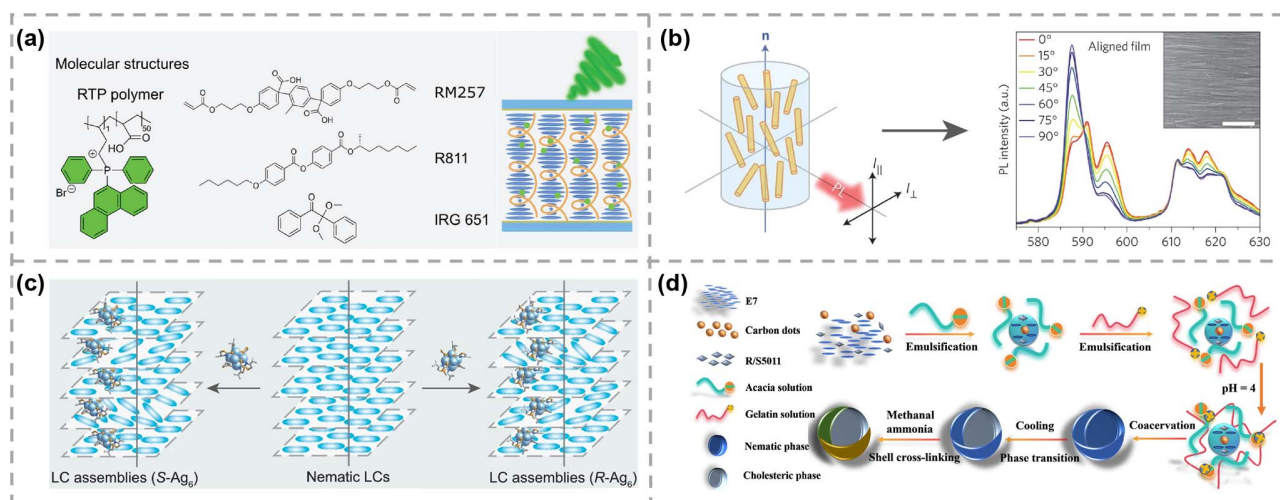


Fig. 34 Representative types of luminescent LC systems. (a) Schematic illustration of the room-temperature phosphorescence (RTP) polymer-doped chiral helical superstructure (RTP-CHS). Reprinted with permission from Ref. [114], © John Wiley and Sons (2023). (b) Schematic illustration of a preferential partial orientation of colloidal nanorods due to an external stimulus and their polarization-dependent luminescence spectra. Reprinted with permission from Ref. [365], © Springer Nature (2017). (c) Schematic illustration of the formation of the LC assemblies^[121]. (d) Schematic diagram of the preparation process of CDs-CPL. Reprinted with permission from Ref. [118], © The American Association for the Advancement of Science (2025).

of LCs provide an ideal environment for studying LPL and CPL properties of anisotropic rare-earth nanocrystals, whether as single particles or assemblies.

In the CPL field, rare-earth materials are valued mainly for their stable multi-band narrow emission, long lifetime, and strong resistance to photobleaching. These make them important candidates for high-precision photonics and anti-counterfeiting applications. However, rare-earth systems face challenges such as low absorption efficiency, low sensitivity, and difficulty in efficient matching with organic systems. In recent years, researchers have tried to combine rare-earths with ordered media such as LCs. This uses LC self-assembly and orientation to enhance their chiral luminescent performance.

For example, Gacoin's group dispersed rare-earth nanorods into an LC matrix. By orientation induction of the LCs, they realized LPL of Eu³⁺. This strategy emphasized the role of LCs as orientation templates [Fig. 34(b)]^[365]. For multilayer core-shell rare-earth materials, Duan's group embedded layered structures with different lanthanide ions into an LC matrix. They obtained multimode CPL covering the full visible spectrum. By rational hierarchical structure design, this system not only showed broadband emission, but also enhanced optical activity in the chiral LC environment, showing excellent potential in multi-channel optical anti-counterfeiting and encryption systems^[366]. Metal cluster systems have shown similar effects to rare-earth materials in some studies. Zang's group constructed hierarchical assemblies of metal clusters, successfully amplifying CPL signals and driving enantioselective photopolymerization [Fig. 34(c)]^[121]. Like rare-earth systems, they used multi-level assembly structures to enhance CPL signals, proving the universality of inorganic nano-assemblies in chiral photonics.

Overall, rare-earth luminescent materials combine high stability and sharp emission with robust LPL/CPL performance. Their main development direction is synergy with LCs or

ordered polymers to overcome low absorption efficiency and weak signal. In the future, these materials are expected to be used in multi-band information transmission and high-sensitivity photo-detector devices.

6.1.2.3 Luminescent quantum dots and LCs. QDs, as semiconductor nanocrystals with size-tunable optical properties, have become another hotspot in chiral luminescence research in recent years. They have advantages such as high photoluminescence quantum efficiency, tunable emission wavelength, and ease of solution processing, but they usually lack chirality. In CPL research, introducing QDs into LCs or chiral matrices to induce chirality has become the main approach to fully exploit their advantages.

For example, the composite system of QDs with CLC elastomers reported by Li's group is a typical case. This system achieved full-color CPL from blue to red, and through the responsive properties of LC elasticity, demonstrated dynamical and programmable CPL modulation. The study showed that such materials can be used not only for information storage and anti-counterfeiting encoding, but also in flexible wearable display devices^[123]. This direction emphasized the unique role of LC elastomers in achieving "active CPL signal modulation." Two-dimensional nanoplatelet (NPL) materials have also become an important representative extension of QDs-based systems. Osuji's group demonstrated stable dispersion of CdSe nanoplatelets in polymer LCs and their magnetic-field-induced orientation. Compared with commonly used one-dimensional or zero-dimensional emitters, two-dimensional NPLs in LC environments not only obtained highly anisotropic photoluminescence, but also achieved rapid and reversible control of emission direction through a magnetic field. This broke the previous barrier that two-dimensional semiconductor materials could not be stably dispersed in LC environments, and provided

a new approach for developing programmable, polarization-controllable photonic devices^[367].

In addition to traditional QDs, environmentally friendly green carbon dots (CDs) have also attracted widespread attention. Yuan's group used a confined helical co-assembly strategy to embed carbon dots into an LC matrix to create full-color CPL inks^[118]. This overcame the trade-off between quantum efficiency and chiral factor by achieving both high photoluminescence quantum yield (> 80%) and g_{lum} above 1.4. These materials not only broke previous performance limitations but also allowed pattern printing on flexible substrates for large-scale and controllable preparation. Thus, they greatly expanded the application scenarios of CPL materials in optical anti-counterfeiting, information encryption, and flexible displays [Fig. 34(d)].

In summary, the combination of QDs with LC systems shows promising prospects in CPL research due to their full-color modulation capability, high efficiency, and potential for flexible development. Traditional QDs with LC elastomers emphasize “dynamic modulation,” two-dimensional nanoplatelets in polymer LCs focus on “orientation and polarization modulation,” and green carbon dot systems highlight “environmental friendliness, low toxicity, and high processability.” These three types together lay a solid foundation for diversified future applications in luminescent display and information devices.

Combining the development trends of the three types of materials above, it can be seen that organic luminescent materials emphasize the synergy between structural design and the photonic environment, enabling multidimensional and high- g_{lum} performance breakthroughs. Rare-earth systems are characterized by stable narrow-band emission and long lifetimes, making them suitable for high-sensitivity and high-reliability applications. QDs combine a tunable spectrum with process flexibility, and when combined with LC systems, can achieve full-color and dynamically programmable CPL properties. Each material type has its own advantages and shortcomings, but all highlight the key role of the LC matrix in chiral transfer and signal amplification. Future development trends may focus on interdisciplinary coupling strategies, for example, by combining energy transfer, photonic bandgap control, ion-pair chirality induction, and LC self-assembly. This can further realize high-performance, multimodal, and environmentally friendly chiral luminescent material systems, supporting application blueprints in next-generation flexible displays, secure encryption, photonic communications, and chirality-driven chemical reactions.

6.2 Photophysical Mechanisms in LLCs

The reason that luminescent LC systems have attracted attention lies in the fact that their diverse optical responses do not rely on a single mechanism, but are instead the combined result of passive optical anisotropy, active luminescence processes, and the coupling between the two. In traditional LC physics, birefringence and orientation changes driven by external fields are the origin of phase modulation and polarization control. After luminescent units are introduced, the LC does not merely serve as an orientation template, but also becomes a critical environment that determines the arrangement of emission dipoles, the radiation mode, and the gain distribution. With the introduction of various materials, the physical mechanisms of LLCs can currently be divided into three levels: passive modulation mechanisms, active luminescence mechanisms, and coupling mechanisms between the two.

6.2.1 Passive modulation mechanisms

In optics, traditional LC materials mostly exist as “passive modulation layers.” Their physical mechanism mainly depends on the reorientation of LC molecules under external fields, which changes the birefringence and thereby allows modulation of light transmission, polarization state, and phase delay. For example, nematic or chiral nematic LCs can achieve selective reflection or optical rotation through adjustment of pitch and molecular alignment. In such situations, the LC does not emit light directly, but serves as an optical cavity or modulation medium. By tuning bandgap matching, energy transfer pathways, and optical field distribution, it provides the structural basis for subsequent active luminescence^[368,369].

6.2.2 Active luminescence mechanisms

In the field of LLCs, the LC is not only a light modulator but can also act as the luminescent unit itself or work in synergy with other emissive materials. The phase-ordered structure of the LC provides a favorable orientation environment for molecular emitters, thereby improving emission polarization, color purity, and effective lifetime. According to the excitation method and energy source, active luminescence can be divided into four main categories: photoluminescence, electroluminescence, mechanoluminescence, and laser emission.

6.2.2.1 Photoluminescence. Photoluminescence is the most common mode in luminescent LC systems. After external photons excite the doped molecules, electronic transitions occur, and photons are released during radiative relaxation. It is worth noting that the LC can provide an ordered environment that affects exciton recombination efficiency and dipole orientation. For example, rare-earth ions, due to their inner-shell electronic transitions, emit narrow and sharp spectral lines. When doped into an LC, their emission polarization state can be controlled by the LC orientation to produce linearly polarized or circularly polarized output.

At present, much research focuses on amplifying luminescence efficiency through the ordered arrangement of LCs and building functional polarized light sources. For example, Liu's group proposed a novel composite material system that, for the first time, realized efficient conversion from UCL to UC-CPL using a composite scheme of “oriented rare-earth luminescent nanorod film + CLC superhelix” [Fig. 35(a)]. This achieved the highest g_{lum} (1.92) so far in an upconversion luminescence system, and also allowed reversible switching between circular and linear polarization via an external electric field, further expanding the degree of control of devices^[116].

In addition, many studies have confirmed that the chiral superstructure of the LC can significantly enhance the circular polarization emission of emitters^[113,115,370]. By adjusting the LC phase state or the concentration of chiral dopants, the tunability of emission wavelength, intensity, and even polarization direction can be achieved. Furthermore, some systems have shown reversible switching between linear and circular polarization under stimuli such as temperature, electric fields, or light^[120,371,372], demonstrating the dynamic response advantages of photoluminescence in LC systems. Therefore, the photoluminescence mechanism not only lays the physical foundation for LLCs, but also provides possibilities for developing multicolor, multi-state, and intelligent CPL devices.

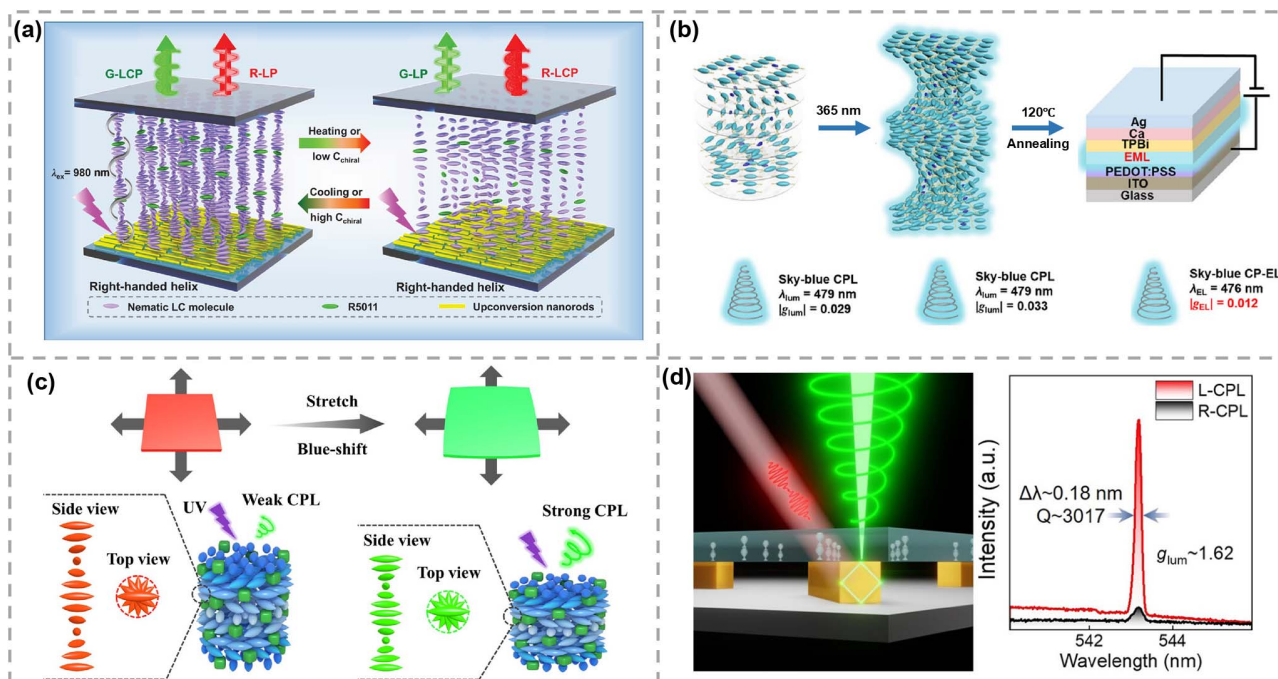


Fig. 35 Active luminescence mechanisms of luminescent LCs. (a) Structural schematic diagram and working principle of the right-handed CLC structure based on aligned UCNRs. Reprinted with permission from Ref. [116], © John Wiley and Sons (2022). (b) The fabrication process and device configuration of CP-OLEDs. Reprinted with permission from Ref. [373], © John Wiley and Sons (2025). (c) Schematic diagram of the effect of the biaxial stretching on CPL. Reprinted with permission from Ref. [372], © John Wiley and Sons (2024). (d) Schematic of the architecture used to achieve a chiral microlaser and measured CPL spectra of the composite device above threshold^[381].

6.2.2.2 Electroluminescence. Electroluminescence involves the injection, migration, and recombination of electrons and holes within a material, thereby generating photon emission. Although the LC itself is not a typical electroluminescent element, when electroluminescent molecules or polymers are incorporated, the ordered LC structures can be used to achieve electroluminescence.

For example, Cheng's group constructed a novel chiral co-assembled CLC polymer network (ChLC-PN) through a simple *in-situ* photopolymerization strategy, and used it as an emission layer to enhance CP-EL performance. The ChLC-PN is formed from a co-assembly of LC monomers (LCM) and chiral inducers (R/S-Cz). The final electroluminescent device produced sky-blue CP-EL with a maximum g_{lum} value of 0.012. This was the first report of using a chiral co-assembled CLC rigid polymer network to realize high-performance CP-OLEDs, demonstrating potential as a simple, stable, and scalable preparation platform [Fig. 35(b)]^[373].

Zhuang's group combined luminescent quantum dots with chiral LCs to develop a spiral full-color emission generator (SFEG). Based on its excellent tunable CPL performance, they fabricated a coating-type white light CPL device by coating the synthesized SFEG material on the surface of a commercial UV LED chip. With the combination of different narrow band-pass filters, they successfully prepared CPL devices with customizable colors, obtaining precise red (633 nm), green (540 nm), and blue (455 nm) emissions. They also built CP-EL devices based on an improved LC system by laminating a self-supporting,

highly asymmetric LC thin film on top of a multi-layer white QD LED. This design marked an important step toward realizing large-scale asymmetric CPL devices^[119]. The general physical mechanism of electroluminescence is similar to that in traditional OLEDs, involving exciton recombination and radiative transitions^[374,375], but in LC systems, this is further combined with chiral amplification and orientation control effects. This mechanism creates new possibilities for LLCs in display and lighting devices.

6.2.2.3 Mechanoluminescence. Mechanoluminescence is usually caused by external forces inducing changes in molecular or material structures, releasing energy and generating light. The unique feature of LC systems is that external forces can modulate the orientation of their ordered structures, and even change the helical pitch, thereby indirectly altering the radiation behavior of luminescent units. For traditional mechanoluminescent materials, mechanical perturbations often involve changes in molecular packing modes and reconstruction of local energy levels^[376,377]. The LC matrix may combine this mechanism with its orientation controllability, endowing LLCs with mechanically tunable luminescence. This offers unique advantages for flexible photonics and strain sensing, giving LLCs new functions in wearable sensing and adaptive photonics.

For example, applying mechanical stretching or compression to LC thin films can significantly change the emission intensity and circular polarization factor of doped dyes. Feng's group introduced specially designed photopolymerizable CsPbX₃ (X = Cl, Br, I) QD nanounits into an elastic polymer network

via LC-template-driven chiral self-assembly and *in-situ* covalent cross-linking, creating luminescent CLC elastomer films with both luminescence and structural color. Under biaxial stretching, this material could reversibly switch CPL, showing promising applications in flexible dynamic anti-counterfeiting labels [Fig. 35(c)]^[372].

It is worth noting that current research on mechanoluminescent LC systems is still limited to using external stress to affect the LC microstructure, and thereby control luminescence intensity and polarization state. This approach is effective but ignores the stress-responsive characteristics of the luminescent materials themselves: external stress can directly act on the emissive unit to induce and control its active luminescence. Therefore, future research should focus more on developing LC luminescent systems in which both the luminescent units and the LC units respond dynamically to external stress, achieving dual responses under a single stimulus and thus broadening the dimensionality of optical information control in LC systems.

6.2.2.4 Lasing emission. When the luminescent units embedded in the LC system reach the conditions for stimulated emission under optical pumping, laser output can be formed. The helical structure of the LC naturally builds a Bragg reflection cavity, which can provide optical feedback for lasing and produce circularly polarized laser emission. In recent years, composites of LCs with dye molecules, high-efficiency quantum dots, and perovskite nanocrystals have successfully achieved low-threshold, flexible, and stable CPL laser output^[378–382].

For example, Zussman's group used evaporation-induced self-assembly of cellulose nanocrystals (CNCs) with laser dyes to build an optical cavity with a chiral nematic structure, obtaining circularly polarized laser emission (CPLE). Further studies showed that the performance of the CNC chiral photonic structure could be controlled by tuning its helix pitch, thereby adjusting the laser emission wavelength. The fabricated CNC-based laser had a lasing threshold of 13 mJ/cm², and by choosing different dyes for assembly, it achieved a laser emission array covering a broad spectral range^[378].

Jiang's group reported a single-mode chiral microlaser constructed by combining CsPbCl_xBr_{3-x} perovskite micro-rods with a CLC layer. The perovskite micro-rods formed whispering gallery mode (WGM) cavities under optical pumping, providing gain and a high Q factor. The covering CLC layer, via its photonic bandgap (PBG) and Bragg reflection mechanisms, converted the original linearly polarized laser into a circularly polarized laser with chiral selectivity. Experimental results showed that this microlaser system could achieve wavelength-tunable chiral laser output across the visible range, with an extremely high dissymmetry factor of $g_{\text{lum}} = 1.62$ [Fig. 35(d)]^[381].

In addition, the excellent compatibility of LC materials allows them to be used as an ideal medium for studying the influence of noble metal nanoparticles on random laser performance. For example, Gu's group systematically compared, for the first time, the lasing enhancement effects of silver nanostructures with different shapes (wire, sphere, cube, and irregular particles) in dye-doped nematic LCs. They found that silver cubes exhibited the best performance due to their broad-spectrum absorption matching well with the absorption/emission of PM597 dye, along with local field enhancement and corner-induced charge separation effects, which made their lasing performance clearly superior to other structures^[382].

6.2.3 Coupling mechanisms

A core feature of luminescent LC systems is the mutual coupling and synergistic action of multiple mechanisms in the same system. On one hand, passive modulation by the LC and active luminescence processes are coupled, so that photoluminescence or electroluminescence outputs can be enhanced and optimized in emission direction, spectrum, and polarization degree^[116,122]. On the other hand, different luminescence modes can also cooperate with each other. For example, combining photoluminescence and mechanoluminescence allows LCs under external deformation to generate dynamically tunable photoluminescence signals, with potential applications in patterned display/encryption or optical sensing^[383]. In addition, multi-stimulus responsive LC systems can show complex multi-channel regulation under multiple external fields such as light, temperature, electricity, and force, embodying intelligent response and integrated function of the system^[120,383,384]. This multi-mechanism coupling not only expands the physical connotation of LLCs, but also provides rich designability and possibilities for applications in display, anti-counterfeiting, flexible photonics, and quantum communication.

In summary, the physical mechanisms of LLCs not only include photoluminescence, electroluminescence, mechanoluminescence, and laser emission, but also exhibit very unique coupling behaviors. These mechanisms essentially originate from the ordered orientation of LC molecules and their sensitivity to external fields. They not only determine the efficiency and polarization characteristics of the luminescence process, but also make possible the realization of multimodal interaction and intelligent functions. Future research directions will develop in several aspects: (i) further improve the stability and lifetime of LC luminescent systems through molecular design and self-assembly strategies; (ii) explore luminescence behavior under the combined action of multiple energy input channels (light, electricity, force, heat), to construct multimodal responsive platforms; and (iii) use advanced *in-situ* characterization and theoretical simulation to reveal the intrinsic coupling laws among molecular orientation, phase evolution, and luminescence behavior, thus providing a solid foundation for mechanism studies. With the gradual deepening of these works, LLCs are expected to move rapidly from experimental research to practical applications, and play a key role in new-generation optoelectronics, intelligent sensing, and green lighting.

6.3 Stimuli-Responsive and Adaptive LLC Systems

LLCs combine the ordered tunability of LCs with the molecular photoluminescence characteristics, and thus exhibit unique properties of being highly sensitive to external stimuli and responding through emission behavior. In recent years, numerous studies have focused on exploring the tunable behavior of luminescent units in LC systems under light, heat, electric, magnetic, and other stimuli, and a series of important progress has been made^[112,385].

6.3.1 Photo-thermal response

Light stimulus is currently the most deeply studied response mode. In this direction, researchers mainly introduce photochromic units, excitation-dependent dyes, and azobenzene compounds as photosensitive groups to give the system reversible regulation capability. For example, azobenzene derivatives in LC systems exhibit reversible trans/cis photoisomerization, which can trigger the switching of the luminescent chiral state

from left-handed to right-handed, and even realize extinction and regeneration of the luminescent signal.

Li's group, through molecular structure design, realized a class of photo-controllable azobenzene-based chiral molecular switches: Switch 1: (S, R, S)-configuration, containing an (R)-binaphthyl azobenzene group as the photosensitive chiral unit + two (S)- or (R)-binaphthyl fluorescent groups as emitters; Switch 2: (R, R, R)-configuration, serving as a control, having the same optically active structural units. Both molecules can undergo reversible trans/cis photoisomerization (365 nm UV light $\leftrightarrow$ 520 nm green light) in solution and in LC media, thereby regulating their chirality and CPL response in the CLC system. Based on this excitation-wavelength-controlled reversible CPL switch, the authors proposed concepts of a "dual optical information encryption system" and "CPL optical

Morse code" as proof-of-concept demonstrations, showing potential application value in multi-level steganography and light-responsive anti-counterfeiting fields [Fig. 36(a)]^[386].

In addition, some studies have utilized the characteristics of excitation-dependent dyes to achieve CPL inversion under different excitation wavelengths. Geng's group proposed a new mechanism of "dichroism competition between achiral dyes." Without changing the chirality of the CLC matrix and only relying on the excitation-dependent property of the dyes, they could achieve CPL inversion. Based on this excitation-dependent reversible CPL characteristic, they realized a quadruple digital anti-counterfeiting design^[125]. This system can provide high security and complexity for anti-counterfeiting and multi-level information encryption through excitation wavelength selection. It is worth noting that in recent years, there

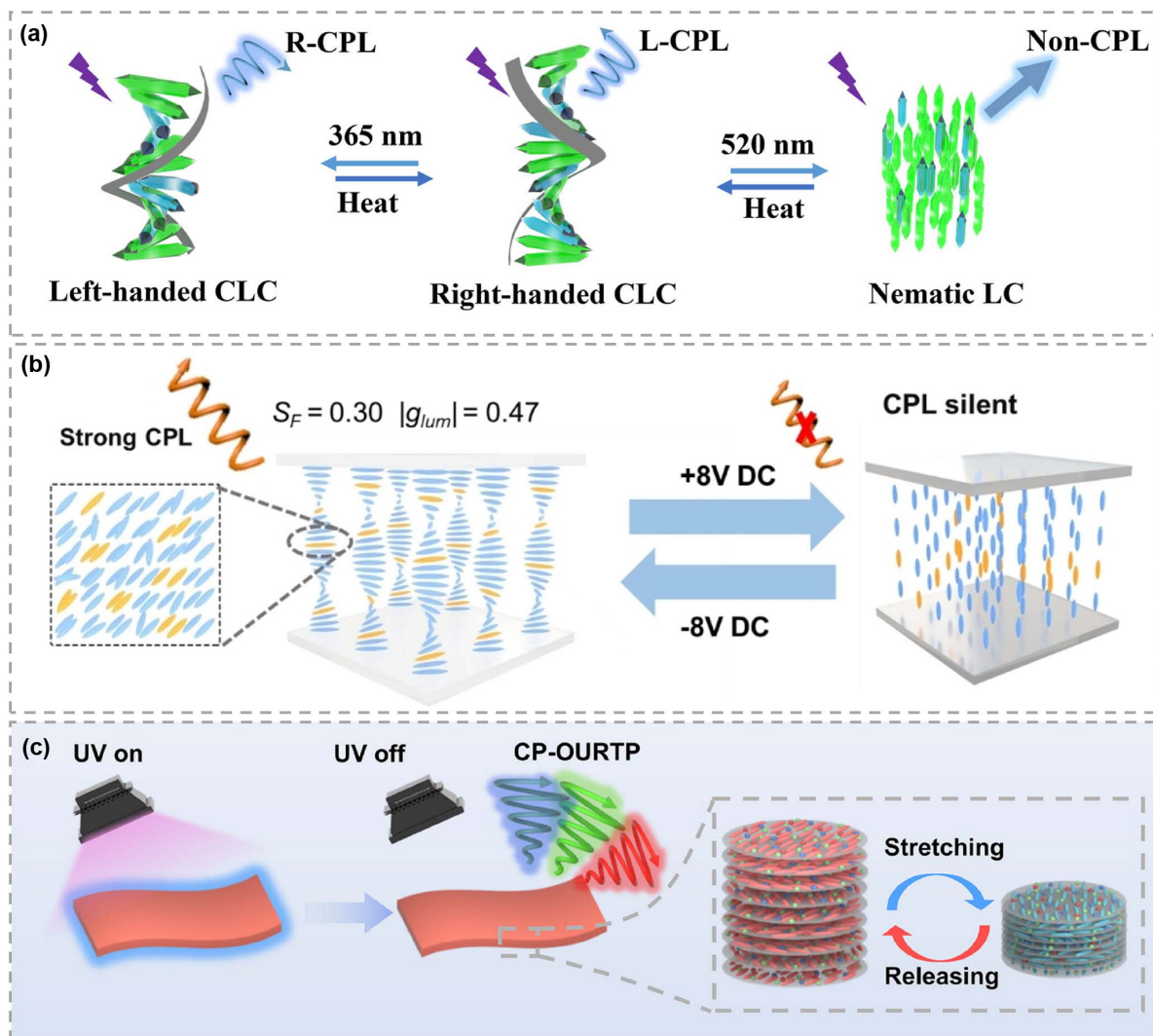


Fig. 36 Stimuli-responsiveness of luminescent LCs. (a) Helical handedness of the CLC system doped with the (S, R, S)-switch 1 under light irradiation. Reprinted with permission from Ref. [386], © John Wiley and Sons (2023). (b) The schematic diagram of the molecular alignment of PHECN CLC under "on-off" DC electric field. Reprinted with permission from Ref. [128], © John Wiley and Sons (2023). (c) Schematic illustration of the fabricated mechanically tunable CP-OURTP materials based on chiral superstructure elastomer (CSE)-RTP films. Reprinted with permission from Ref. [115], © John Wiley and Sons (2025).

have also been attempts to use CNCs as green chiral templates and to embed photochromic dopants to realize real-time alternation of CPL chirality triggered by light, while also possessing flexibility and degradability^[387]. These studies show that light stimulus can achieve remote, non-contact regulation, and also has reversibility and high timeliness, making it an important means to realize advanced information encryption, anti-counterfeiting, and dynamic photonics.

Thermal stimulus can regulate luminescence by inducing LC phase transitions, changing pitch, or molecular orientation. For example, in CLCs or LC-like systems, when the temperature rises, the material can undergo a transition from an ordered helical state to an isotropic state, causing changes in polarized luminescence intensity or even disappearance of CPL emission. During cooling, the structure recovers and the emission signal can also be reversibly converted^[370]. More importantly, when introducing light stimulus response, thermal processes are often used for “annealing” recovery, serving the role of self-repair and reset of the system. The above thermal response behavior provides an effective tool for erasable functions in optical displays and information encryption. For example, the CPL change in azobenzene dye LC systems triggered by UV/visible light can be restored to the initial emission state through heat treatment^[386]. In addition, thanks to the dynamic response characteristics of CLCs under thermal field driving, the change of helical twist energy leads to reversible changes in the optical bandgap of CLCs, thereby realizing selective emission of CPL of different wavelengths^[116]. Therefore, thermal response shows important values in stimulus-based reset, thermal-triggered dynamic encryption, and improvement of display stability.

6.3.2 Electromagnetic response

Electric-field regulation relies on the high sensitivity of LC molecular orientation to external electric fields. Luminescent molecules or nanomaterials doped in LCs can realign along with the LC orientation, thereby changing the luminescent properties. Cheng's group proposed a new regulation strategy—using the orientational order parameter of achiral dichroic dyes as a probe and regulation means to directly change the degree of ordered arrangement of the dyes in the CLC medium, thereby regulating CPL performance. The study showed that I-shaped phenothiazine (PHE) derivative PHECN dyes in CLCs have high orientational order. Therefore, under a DC electric field, they show significant CPL intensity enhancement and contrast improvement, while T-type molecules with poorer orientation show almost no response, indicating that molecular structure and orientational parameters are crucial to electrically responsive CPL [Fig. 36(b)]^[128].

In addition, Kang's group introduced anisotropic carbon QDs. By taking advantage of LC order, they realized macroscale uniaxial alignment of QDs and generated LPL. With a small voltage, they could change the orientation of QDs under surface anchoring and LC response, allowing LPL to be quickly and reversibly regulated, showing polarization-sensitive and electrically tunable switching luminescence. This type of electric-field-stimulated response has advantages of fast response speed and precise control, showing potential in electrically controlled anti-counterfeiting, switchable luminescent devices, and tunable optical components^[120].

Compared with light, heat, and electric stimulus modes, magnetic-field-response research is relatively scarce, but its non-contact nature and long-term stability provide unique means

for LC luminescence regulation. In some studies, an external magnetic field is used to change the orientation of luminescent molecules within LCs, thereby influencing the spiral structure and the polarization state of linearly or circularly polarized luminescence^[367,388]. Although related reports are still in the exploratory stage, magnetic-field control over large-scale ordered structures has unique advantages of being non-destructive and remote. It may show value in biomedical non-invasive imaging, external-field sensing, and non-contact optical switching in the future.

6.3.3 Stress response

In addition to the above main modes, mechanical stimulus is a key highlight. For example, Zhao's group used LC templates to self-assemble RTP polymers into chiral superstructured elastomers (CSEs), thereby obtaining multifunctional thin film materials with selective reflection color, dynamically tunable CP-OURTP, strong chiroptical response, and excellent processability. Mechanical deformation directly acts on the chiral helical arrangement, changing the direction and intensity of circularly polarized emission, thereby enabling dynamic reversible regulation of g_{lum} values [Fig. 36(c)]^[115].

Li's group doped red, green, and blue (RGB) QDs into reconfigurable blue-phase LC elastomers (BPLCEs) to achieve visually full-color CPL. Compared with traditional CLC elastomer (CLCE) systems, the three-dimensional chiral cubic superstructure of BPLCEs induced a CPL signal opposite to that of CLCE. The lattice structure of BPLCEs can be reversibly regulated through mechanical stretching, thereby inducing switching of CPL signals between “on/off” states. These changes can be further fixed through reversible reactions of dynamic disulfide bonds in BPLCEs. Based on this, the researchers constructed an intelligent polymer-based CPL system and demonstrated its potential application in anti-counterfeiting and information encryption^[123]. Feng's group prepared Lumin-CLCE flexible elastomer films, which showed on/off switching and intensity tunability of CPL signals under biaxial stretching, making them suitable as mechanically driven anti-counterfeiting labels or soft optical elements^[372].

In summary, luminescent LC systems exhibit rich tunability under external stimuli: light response is flexible and efficient, capable of achieving CPL inversion, extinction, and remote control; thermal response, based on phase transition and self-healing mechanisms, can serve as an auxiliary reset for light response; electric-field stimulus response is precise, reversible, and low-energy, most suited for integration with flexible devices; magnetic-field response, though limited in research, has great future potential in non-contact sensing; mechanical, chemical, and multimode stimulus methods greatly extend the application boundaries of LLCs. It can be seen that luminescent LC materials are evolving from single-response to multimodal intelligence, and are gradually moving toward the application frontiers of programmability, anti-counterfeiting, flexible sensing, and photonic devices, showing highly promising research and application value.

6.4 Expanding the Dimensionality of Emission Control

In conventional luminescent systems, modulation has largely been limited to two basic dimensions: intensity (brightness) and wavelength (color). This two-dimensional modulation has provided important support for basic photonic devices

and display technologies, but it has gradually become insufficient to meet the higher requirements of modern information technology and cutting-edge interdisciplinary fields for photonics. In recent years, with the rapid development of the coupling mechanisms between LCs and various luminescent units, LLC systems have demonstrated a series of multidimensional modulation capabilities far beyond the traditional framework. The new controllable dimensions include polarization state, directionality, coherence, and emission dynamics characteristics, as well as multimodal coupling responses. These expanded degrees of freedom not only provide a more three-dimensional research platform for revealing the fundamental laws of chiral optics and LC physics, but also open up completely new design ideas for applications such as information optics, security anti-counterfeiting, and flexible displays^[389].

6.4.1 Expansion in the polarization dimension

In LC composite systems with chiral units or nanomaterials, polarization has become the third core modulation dimension in addition to intensity and wavelength. Using the self-assembly and stimulus-responsive characteristics of LC microstructures, it is now possible for luminescent materials to expand their polarization dimension from non-polarized to linearly polarized and then to circularly polarized emission, and to achieve switching of polarized emission as well as reversible conversion between different polarization states.

First, chiral LC templates can be used to achieve the generation and modulation of CPL from luminescent units. For example, different from traditional strategies of introducing luminescent units by doping, Li's group proposed a supramolecular engineering strategy by co-assembling LLCs and chiral dopants to construct chiral nematic LC films with intrinsic luminescent properties. This not only achieved switching of an emission polarization state from non-polarized to circularly polarized, but also preserved the high fluorescence quantum efficiency of the luminescent units. This strategy solved the long-standing conflict between "polarization selectivity" and "luminescence intensity" in chiral optical materials, achieving a balanced improvement, and marked a key progress in the comprehensive performance of CPL materials [Fig. 37(a)]^[390]. Similarly, by using rubbing alignment or photo-alignment to control the directional arrangement of LC molecules, it is possible to induce the directional alignment of anisotropic luminescent units, thereby achieving LPL.

Second, the responsiveness of LC microstructures to external stimuli such as light, heat, electricity, magnetism, and humidity allows the emission polarization state of LLCs to be dynamically modulated under an external field, including light-responsive switching and CPL inversion. For example, Liu's group innovatively prepared uniaxially oriented upconversion nanorod (UCNR) films, which can provide high-intensity upconversion LPL and also serve as templates to induce the self-assembly of CLCs into a helical structure. Meanwhile, the match between the upconversion emission wavelength and the CLC optical bandgap achieved upconversion CPL output with a g_{lum} as high as 1.92. More importantly, under thermal stimulation, the pitch change of the CLC self-assembled helical structure causes a shift in the CLC photonic bandgap wavelength, thus realizing dynamic modulation of the upconversion CPL emission color. Under an applied voltage of 30 V, the arrangement of CLC molecules changes from the planar state to the focal conic state, resulting in a significant decrease in the degree of circular polarization of the upconversion CPL. When the voltage is

further increased to 130 V, the LC molecules reorient along the direction of the electric field, and the arrangement of CLC molecules changes from the focal conic state to the homeotropic state, achieving the conversion of upconversion luminescence polarization from circular to linear. This indicates that under an external electric field, the UCL of the composite system can be reversibly modulated between circular and linear polarization^[116].

On the other hand, combining LCs with one-dimensional materials (sub-nanowires, SNWs) or with ordered-oriented UCNRs provides a new path for the modulation of linear polarization and scattering polarization, obtaining high polarization degree, high haze, and multi-band control characteristics^[116,391,392]. For example, Wang's group prepared flexible and self-supporting LC/sub-nanowire composite films by a simple directional coating method. These films not only maintain stability in aqueous environments and under repeated temperature fluctuations, but also exhibit excellent polarization properties from visible to near-infrared wavelengths. In the range of 500–1200 nm, the average haze reached as high as 85%. This demonstrates their application potential in optical polarization materials, holographic projection imaging, and flexible optical devices. It can be said that the orderliness and responsiveness of LCs have brought polarization light modulation into the "programmable" stage, not only enabling the output of CPL carrying chiral information, but also realizing linear and scattering polarization signals spanning from the visible to near-infrared range, thus providing a broad space for optical encoding and polarization optical devices^[391].

6.4.2 Spatial directionality and orientation control

The orientational order of LCs endows luminescent units with unique spatial orientation modulation capability. Early studies showed that LC matrices can modulate the arrangement direction of luminescent molecules or aggregates, thereby influencing the orientation characteristics of optical output^[121,360,382]. In more frontier research, macroscopic ordered arrangements from the molecular scale to nanoparticles have been achieved through external field driving (electric field, shear field, and optical field) or template induction (chiral templates and nanoscale confinement)^[372,376,386,392,393].

For example, Liu's group demonstrated a highly ordered UCNR nematic phase formed under shear driving, with polarization-dependent emission at 657/661 nm. Subsequently, they used this technique to construct UCNR-oriented films, which serve both as active polarized emission sources for LLCs and as templates to guide LC molecule orientation^[116]. Tang's group, spanning from the nanoscale to the macroscopic bulk phase, systematically revealed the chiral amplification effect induced by chiral tetraphenylethylene (TPE) derivatives in LCs. AFM images directly showed that the TPE derivatives act as helical templates (sergeants) to stack into helical assemblies, whose gaps provide binding sites for LC molecules (5CB, soldiers), allowing LC molecules to arrange in a similar chiral manner (the "sergeant-soldier" rule) [Fig. 37(b)]. Theoretical calculations further clarified this mechanism and indicated that it is a fundamental law for chiral additives driving LC phases to form chiral nematic phases. This result provides important experimental evidence and theoretical support for the mechanism of chiral amplification and offers guidance for designing chiral LC supramolecular systems in the future^[394].

Interestingly, the LC's capability to orient anisotropic luminescent units can also be used in reverse as a probe for

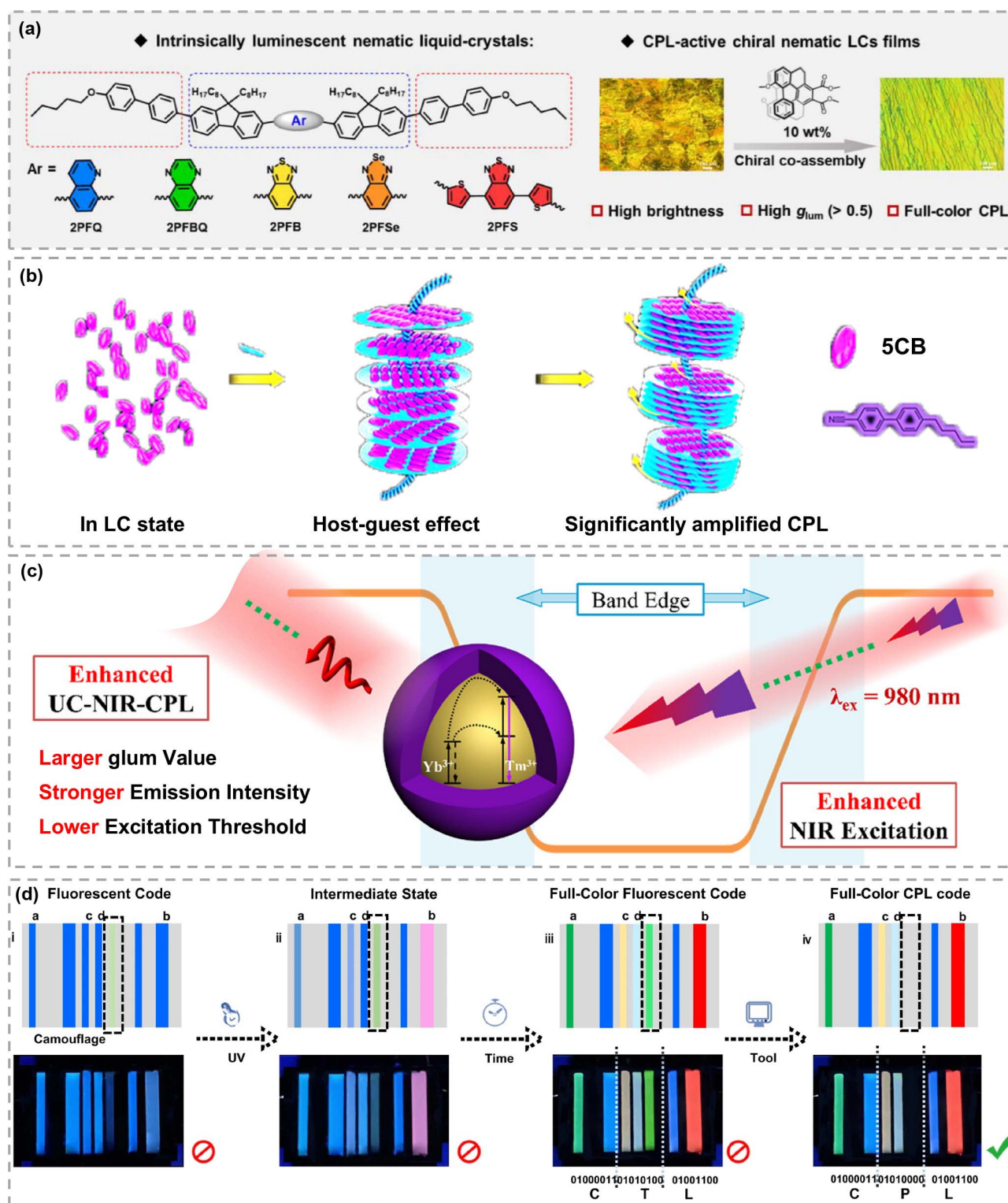


Fig. 37 Expansion of luminescence modulation dimensions. (a) Schematic illustration of the fabrication of intrinsically luminescent N*-LCs films with high-brightness full-color CPL. Reprinted with permission from Ref. [390], © John Wiley and Sons (2025). (b) Illustration of chiral amplification of TPE derivatives containing cholesteric attachments in LCs. Reprinted with permission from Ref. [394], © American Chemical Society (2021). (c) Schematics of the dual-band-edge enhancement effect on improving overall performance of UC-near-infrared-CPL. Reprinted with permission from Ref. [395], © American Chemical Society (2023). (d) Design and concept of 4D information encryption and decryption^[124].

monitoring the orientation of the fluid medium. Rare-earth luminescent materials exhibit unique polarized luminescence characteristics because the chemical environment and symmetry around the emission ions are anisotropic. However, to effectively utilize this property, it is necessary to precisely control and measure the overall orientation of the host particles. To solve this, Gacoin's group used an electric field to control Eu-doped LaPO_4 nanorods assembled in an LC phase, thereby enabling measurement of their photoluminescence polarization. They obtained Eu^{3+} emission spectra in three major optical configurations (σ , π , and α , depending on the observation direction and polarization axis), and used these as a benchmark for analyzing nanorod orientation. Since nanorods in a flow tend to align along the shear strain direction, researchers used this orientation analysis to measure the local shear rate in flowing liquids. By further optimizing the nanorod dimensions, this technique is expected to become a simple method for tomographic mapping and real-time monitoring in microfluidics and biofluidics, with the required high spatial resolution^[365]. Therefore, it can be seen that LCs act not only as a “flexible medium,” but also as spatial structuring templates to modulate the orientation of luminescent units at multiple scales, thus enabling optical functions with direction dependence.

6.4.3 Regulation of luminescence dynamics

In recent years, LLCs have shown unique advantages and broad prospects in the regulation of luminescence dynamics. Benefiting from the molecular orientation order and phase controllability of LCs, LLCs can effectively regulate the excited-state lifetime, radiative transition rate, and non-radiative relaxation pathways of luminescent molecules by altering molecular packing and local microenvironments.

For example, in CLCs, a photonic bandgap formed by the helical superstructure can provide selective feedback to the emission spectrum. When the emission wavelength lies at the edge of the bandgap, the Purcell effect and band-edge enhancement occur, resulting in a significant increase in the radiative rate and enabling dual control of fluorescence lifetime and emission intensity. At the same time, by tuning the bandgap position, it is possible to achieve cooperative coupling between excitation light and emission light. For example, Duan's group proposed a “dual band-edge enhancement effect” to address the problems of small g_{lum} values and insufficient emission intensity in traditional CPL emission systems [Fig. 37(c)]. Specifically, the team used lanthanide-doped upconversion nanoparticles (UCNPs) as the emission centers, providing 802 nm near-infrared emission, which is typically excited by 980 nm laser light. By tuning the position of the chiral LC bandgap so that the UCNPs' 802 nm emission wavelength and 980 nm excitation wavelength each lie at opposite edges of the same photonic bandgap, the system simultaneously achieves: 1) band-edge-enhanced excitation at 980 nm, and 2) band-edge-enhanced emission at 802 nm. This coupling leads to a stronger excitation process as well as stronger near-infrared emission intensity. Based on this design, the overall performance of upconversion CPL is significantly improved: including amplified g_{lum} values, dual enhancement of emission intensity, and reduced excitation threshold. Such upconversion CPL LLC materials with “dual band-edge enhancement effects” not only exhibit excellent chiral optical properties but also possess multi-level encryption capability, which can greatly improve information security in anti-counterfeiting materials^[395].

In addition to photonic bandgap effects, external-field stimuli are also important means of regulating LLC dynamics. Temperature variation can trigger LC phase transitions (such as nematic-to-isotropic), and thereby change molecular mobility and local viscosity, and directly affect the non-radiative relaxation rate of excited states. Electric fields can induce reorientation of LC molecules, thus adjusting the dipole orientation of emissive molecules to achieve dynamic and reversible regulation of lifetime and anisotropic emission behavior. Moreover, photoisomerizable LC molecules, such as azobenzene derivatives, can undergo trans-cis isomerization under UV/visible light irradiation, producing fluorescence on/off switching effects and enabling precise adjustment of excited-state lifetimes.

On the other hand, the donor-acceptor distance and orientation in LCs can be controlled, resulting in highly tunable Förster resonance energy transfer (FRET) efficiency and excited-state dynamics. Therefore, in LLC systems, not only the spectral output but also the coherence of the emission process and the energy transfer mechanisms can be deeply regulated. This expansion in control dimensionality indicates that LC systems could be used for low-power-consumption displays, coherent light source tuning, and even fundamental exploration of light-matter interactions.

6.4.4 Multimodal coupling

With increasingly diversified control methods, more and more research is focusing on multimodal superposition and information integration. For example, combining photoresponsive molecules with LCs can realize CPL chirality switching and bistable regulation^[371,383,396]. Cheng's group achieved reversible regulation of CPL signals in CLCs by introducing a photoresponsive achiral negative-dichroic dye (KG) and a static achiral positive-dichroic dye (Nile Red, NR), fully embodying the concept of multimodal integration. On the one hand, the system organically combines molecular photochemical processes (photoisomerization of KG) with LC photonic properties (selective reflection and ordered orientation of CLCs). Using light stimuli to trigger molecular-level configuration changes, it alters the dichroic response of the material. On the other hand, the research further introduced the positive dichroic molecule NR and utilized the complementarity of molecular dichroic effects to achieve CPL signal inversion while maintaining the stability of the macroscopic LC superstructure (pitch and helical direction). Through this novel fusion strategy of molecular photochemical regulation + photonic chiral structure + hybrid dye systems, the study endowed the material with flexible and reversible chiral optical regulation capability while ensuring its stability^[371].

Li's group demonstrated an innovative multimodal information integration approach by constructing light-tunable LC photonic microcapsules. The core idea is to organically integrate the time dimension, photonic structural dimension, color dimension, and polarization dimension, realizing the proof-of-concept of “4D information encryption” [Fig. 37(d)]. Based on this, the researchers proposed a multidimensional barcode system in which encrypted information comes from: monochromatic fluorescence (basic signal), time-dependent fluorescence/CPL (dynamic signal), full-color emission (color signal), and different polarization states (polarization signal). This multimodal integration strategy—photochemical regulation + chromophore energy transfer + photonic helical structure + capsule encapsulation—elevated the functionality of this work to the level of four-dimensional information encryption, providing a new

development pathway for intelligent photonic materials and high-security information storage^[124].

In summary, LLC systems have already demonstrated significant research value in the field of multimodal integration. With the continuous development of material design, encapsulation technologies, and interdisciplinary collaborative methods, LLCs, as a new generation of intelligent photonic materials, will undoubtedly open up broader application prospects in information security, flexible optoelectronic devices, advanced sensors, and life and health sciences.

With the gradual maturing of coupling mechanisms between LCs and luminescent units, LLC systems have already broken through the traditional “intensity + wavelength” two-dimensional regulation model, entering a new stage that includes polarization, directionality, luminescence dynamics, and multimodal information coupling. These multidimensional degrees of freedom not only offer more complex experimental controllability, facilitating the exploration of fundamental chiral optics and LC phase physics, but also directly drive innovative designs in fields such as information optics, photonic encryption, anti-counterfeiting displays, and flexible devices. It is foreseeable that the multidimensional regulation capabilities displayed by LLCs in the future will become an important cornerstone in interdisciplinary photonic material research, and may trigger a new wave of innovation in optical materials and devices.

6.5 Photonic and Optoelectronic Applications of LLC Systems

The research value of LLCs lies not only in the exploration of physical mechanisms, response behaviors, and modulation dimensions, but also in the fact that their unique material functions can be transformed into device integration at the application level. From single-molecule chirality amplification effects to programmable polarization output, from anisotropic emission to chiral lasers, the high degree of controllability exhibited by LLCs is gradually making them an important candidate platform for novel photonic devices^[397,398].

6.5.1 Display and lighting devices

LLCs have attracted wide attention in the fields of display and lighting. Their unique CPL characteristics offer a new approach for high-contrast display schemes without polarizers. Early research mostly focused on amplifying the photoluminescence of dyes or small molecules via chiral CLC phases to achieve polarized output^[123,390], thus laying the foundation for LC luminescent displays.

With the advancement of device fabrication, researchers have introduced chiral LCs into electroluminescent devices. Cheng's group first demonstrated high-efficiency CPL-OLEDs, achieving stable circularly polarized light output in organic electroluminescent devices, with the potential to significantly improve energy efficiency and display quality^[373]. Zhuang's group combined luminescent QDs with chiral LCs to develop an SFEG. Based on its excellent tunable CPL performance, they assembled a coating-type white CPL emission device by coating the synthesized SFEG material onto the surface of a commercial UV LED chip. By combining different narrow bandpass filters, they successfully produced CPL devices with customizable colors, achieving precise red (633 nm), green (540 nm), and blue (455 nm) emissions^[119]. They further constructed CP-EL devices based on an improved LC system by laminating a highly

asymmetric self-supporting LC thin film on top of the multilayer structure of a white quantum dot LED [Fig. 38(a)]. This design marked an important step toward large-scale asymmetric CPL devices.

On the other hand, Feringa's group introduced molecular machines into LC systems, using light-driven molecular motors as chiral dopants to reversibly invert LC chirality under light irradiation, thereby switching the chirality of CPL from embedded achiral dyes. This system not only achieved a high photoluminescence quantum yield of up to 0.75 and an excellent $|g_{lum}|$ value of 0.45, but also enabled spatially addressable CPL programming control, offering new possibilities for addressable pixelated displays and three-dimensional stereoscopic displays^[399]. These studies show that LC luminescent materials are crossing the critical stage from material modulation to practical device development, bringing new directions for future self-luminous display and lighting technologies^[119,373,400].

6.5.2 Information encryption and anti-counterfeiting applications

Information security and anti-counterfeiting are among the important application directions of LLCs, and their CPL output and external stimulus responsiveness present inherent advantages. For example, Lu's group proposed an optical anti-counterfeiting strategy combining LC near-infrared holography and rare-earth downshifting luminescence [Fig. 38(b)]. Based on a binary CLC, they achieved broadband dynamic reflection regulation. Through thermal regulation, the selective reflection band of the CLC system could be reversibly switched between 463 nm (visible) and 967 nm (near-infrared). Based on this characteristic, they developed a dynamically tunable LC holography technology in the visible–near-infrared range. The invisibility and encoding/decoding properties of LC near-infrared holography are inherently suitable for optical encryption development. The researchers further combined rare-earth nanomaterials with UV-excited downshifting luminescence, endowing the composite material with multi-wavelength excitation capabilities, thereby broadening the anti-counterfeiting dimension. This work provides a new concept and technical support for next-generation optical information encoding and anti-counterfeiting technology^[117].

Xie's group synthesized CPL optical waveguide materials based on room-temperature phosphorescent LC polymers (LCPs). Experimental results showed that these LCPs could stably exhibit a nematic phase and possess a phosphorescence lifetime of approximately 0.145 ms. The researchers further introduced chiral dopants to induce chiral arrangement in the LCPs, then fixed the chiral structure via a photochemical cross-linking reaction (photo-cycloaddition), and finally removed the chiral dopants via organic solvent washing. The resulting polymers exhibited stable solvent resistance and efficient circularly polarized phosphorescence, with chiral luminescence dissymmetry factors between 0.16 and 0.17. At the same time, these waveguide materials demonstrated efficient transmission of circularly polarized photon signals, with optical loss coefficients as low as ~ 0.175 dB/mm. Based on these properties, circularly polarized phosphorescent waveguide devices were further applied in information encryption/decryption and optical switching, providing a practical new solution for advanced photonics and optoelectronic devices^[401].

Gu's group further developed CLC-MOF composite systems, fixing chirality via [2+2] photocycloaddition to form thin

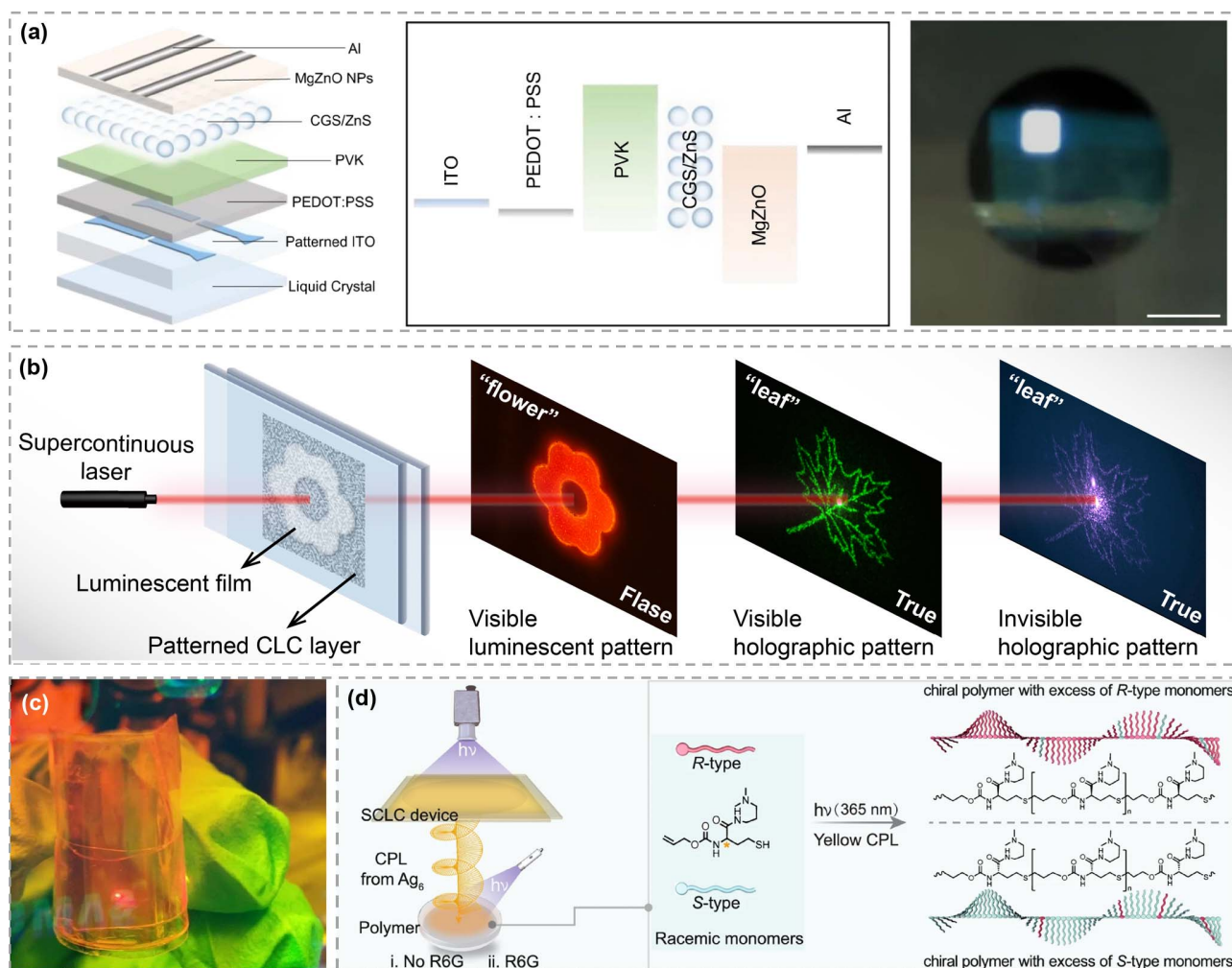


Fig. 38 Applications of luminescent LC systems. (a) Schematic of the electroluminescent CPL device and its optical performance^[19]. (b) Schematic of the optical encryption based on CLC scalar holography. Reprinted with permission from Ref. [117], © John Wiley and Sons (2025). (c) Photograph of a bent QDCLC laser on an adhesive film^[380]. (d) Schematic representation of the experimental setup for the photoinduced polymerization of DPAMOC and the production of an optically active polymer^[121].

films with strong CPL (maximum g_{lum} up to 0.4), capable of CPL inversion and spectral reconstruction under light and thermal stimulation^[384]. Such materials can produce visually recognizable patterns via filters, and also exhibit reversible CPL switching in patterned samples, showing great potential for applications in high-level anti-counterfeiting labels and information encryption storage.

In summary, the combination of LC dynamic responsiveness with luminescent properties greatly extends the optical information modulation dimensions of LLC systems, including amplitude, wavelength, lifetime, polarization, and phase. For example, introducing phosphorescent materials can bring temporal variations in emission intensity and wavelength, while LC-induced alignment of luminescent nanorods can bring polarization-dependent variations in emission intensity and wavelength. Therefore, the composite of LC units and luminescent units exhibits a “1 + 1 $\gg$ 2” capability in optical information modulation. This multidimensional, multifunctional, multiscale optical information regulation method provides a

solid material basis and technical means for next-generation high-level optical information storage and encryption.

6.5.3 Flexible optoelectronic devices

In recent years, with the rapid development of new electronic technologies such as wearable devices, smart displays, and flexible sensors, flexible optoelectronic devices have gradually become a focus of attention in both academia and industry. How to ensure excellent optoelectronic performance while maintaining flexibility and stability has become a key issue in the field. Among various candidate materials, LCs, due to their unique controllable molecular orientation, excellent optical anisotropy, and good processability, show great potential in the design and application of flexible optoelectronic devices. Therefore, systematically exploring LC research progress in this direction not only helps to further understand their advantages and challenges, but also provides valuable references for the future development of flexible optoelectronic technology.

For example, Hu's group first reported a self-supporting perovskite nanocrystal-CLC composite film in a Fabry-Pérot cavity structure to achieve CPL-amplified spontaneous emission (ASE) and lasing, with a g_{lum} as high as 1.4 [Fig. 38(c)]. The output chiral light signal could be continuously tuned in intensity and sign by excitation power. Furthermore, its ASE threshold was only $2.4 \mu\text{J cm}^{-2}$, and it maintained high stability after 100 bending cycles and 3 months of storage, making it suitable for wearable and complex deformation scenarios. This achievement not only demonstrated an all-solution process, flexible stability, and high tunability of the material system, but also provided a significant direction for wearable optoelectronic devices, 3D displays, optical encoding, anti-counterfeiting, soft robotics, and augmented reality, while showing great potential for future mass production and low-cost fabrication^[379].

Mohammadimasoudi's group first embedded QDs between polymerized CLC mirrors to construct a flexible QDs-CLC composite vertical-cavity surface-emitting laser, achieving stable CP lasing. This laser realized a free-standing flexible laser film that could operate stably in water and high-temperature environments. More importantly, its lasing wavelength exhibited multidimensional tunability (strain, temperature, pressure, and excitation site), effectively integrating the long-term gain stability of inorganic QDs with the high reflectivity and encapsulation of polymerized CLCs, thus opening a new platform for solution-processed, low-threshold, tunable CPL lasers^[380].

Combined with explorations of LC stress response and photoluminescence regulation^[114,117,119,402], it can be seen that LC systems, due to their fluidity and order, have a unique advantage in becoming flexible, tunable optoelectronic and laser systems. In short, LLCs show broad development prospects in flexible optoelectronic devices. First, due to the controllable orientation of LC molecules and unique photoluminescence mechanisms, LLCs in flexible displays and wearable displays have the advantages of high contrast, low energy consumption, and tunable color, and are expected to promote the development of next-generation foldable and rollable display technologies. Second, LC luminescent materials are easy to integrate with flexible transparent electrodes and polymer substrates, making them highly adaptable for flexible lighting, information storage, and bendable optical communication devices. Third, with the LC's responsiveness to external stimuli (such as electric fields, temperature, and mechanical strain), LLCs may be developed into multifunctional flexible devices that integrate display and sensing functions, for example, for health monitoring, smart wearable systems, and flexible optical sensing networks. Finally, with continuous advances in new LC luminescent molecule design, nanocomposite systems, and flexible encapsulation technology, LLCs are expected to achieve further breakthroughs in stability, efficiency, and device integration, thus forming an important platform with both fundamental research value and application potential in the field of flexible optoelectronics.

6.5.4 Photoinduced asymmetric synthesis

LLCs, combining the ordered orientation of LC phases with molecular luminescent units, can achieve optical anisotropy regulation while maintaining high emission efficiency, thereby becoming ideal sources of CPL. Compared with traditional polarization regulation methods relying on external wave plates or optical components, LLC materials can directly output a CPL signal with considerable intensity and reversible handedness at

the device level, having advantages of structural designability, controllability by external fields, and ease of integration. Therefore, they offer a more efficient and simpler chiral excitation method for photoinduced asymmetric synthesis than traditional light sources.

In recent years, researchers have successfully achieved various chiral polymerization reactions using CPL generated by LLCs [Fig. 38(d)]. First, in the photopolymerization system of diyne monomers, CPL from LLC devices was used to induce enantioselective photopolymerization of monomers such as 10,12-tricosadiynoic acid and 10,12-pentacosadiynoic acid, ultimately producing chiral polymers with distinct Cotton effects. Notably, the obtained polymers not only showed significant color changes during the reaction (e.g., from transparent to blue), but their circular dichroism (CD) signals also exhibited mirror inversion according to the handedness of CPL, directly proving the occurrence of light-matter chirality transfer. Unlike traditional methods requiring chiral auxiliaries or ligands, this strategy demonstrated the universality and simplicity of using CPL light sources to induce chirality construction at the monomer level^[119].

Second, in the asymmetric resolution polymerization system of racemic monomers, CPL from LLCs further demonstrated its unique catalytic substitution effect. For example, under the co-action of CPL and UV light, not only did efficient linear polymerization occur, but the resulting polymers exhibited an obvious chiral optical response (CD signals of mirror symmetry)^[121]. The study showed that this effect originated from the selectivity of radical intermediates induced by CPL light fields, which broke the symmetry of racemic monomers and achieved enantioselective resolution polymerization without metal catalysts. This result not only expands the scope of CPL in photoinduced asymmetric chemical reactions, but also provides a new route for sustainable synthesis under green chemistry conditions.

Looking forward, LLCs still have broad development space in the field of photoinduced asymmetric synthesis. On one hand, further optimization of molecular structure design and device construction is expected to simultaneously improve CPL emission intensity and chirality degree ($|g_{\text{lum}}|$ values), thus increasing the enantioselectivity of polymerization reactions. On the other hand, combining LLC light sources with flexible optoelectronic devices, information storage, and anti-counterfeiting technologies may promote the transition of chiral photochemistry from mechanism research to practical application. At the same time, leveraging the programmable responsiveness of LLCs, their deeper roles in simulating life processes related to chirality origin, developing intelligent photonics, and chiral functional materials can be explored. In summary, LLCs open a new research pathway for photoinduced asymmetric synthesis and will show greater potential in the cross fields of material science and life sciences in the future.

In summary, LLC applications are undergoing multidimensional expansion: in displays and lighting, progress has been made from dye systems to CPL-OLEDs and programmable 3D displays^[373,399]; in information security and anti-counterfeiting, reversible CPL switching and patterned coding demonstrations have been achieved^[384,401]; in flexible optoelectronics and laser applications, breakthroughs have been made in organic-inorganic composite wearable laser films^[379,380]. Moreover, an important future development direction for LLCs is toward integrated photonics and intelligent devices. For example, Xie's group realized optical communication capability through LC

waveguides, Gu's group demonstrated patterned encryption with MOF-CLC light/heat dual-stimulated CPL switching^[384], and Feringa's group demonstrated programmable pixel pattern output via light-driven molecular motors^[399]. These studies lay a solid foundation for applications of LLCs in integrated photonics and intelligent devices. Such intelligent responsive LC systems make CPL control no longer dependent on mechanical or electrical means, but achievable via multimode stimuli such as light/temperature/mechanics. At the same time, some early studies have provided proof-of-concept demonstrations in stress response, photorelaxation dynamic control, and multicolor CPL tuning, which have driven the development of LC materials toward multi-channel response and functional integration. With the accumulation of these researches, LLCs are expected to become a multifunctional photonic material platform that integrates "display–communication–sensing–anti-counterfeiting" in the future. These latest research works together outline the development path of LLCs from materials to applications, gradually advancing toward practical and multifunctional platformization.

6.6 Discussion

The development of LLCs has undergone a complete process from material discovery to mechanism investigation, and then to performance optimization and application exploration. Early studies mainly focused on achieving enhanced luminescence and chiral control through molecular design and LC phase self-assembly, gradually revealing the unique role of the LC matrix in structural ordering and chiral field amplification.

As material systems expand, researchers have achieved tunable fluorescence and phosphorescence, but have also realized multidimensional modulation and dynamic switching of luminescence through external stimuli. On the basis of these works, research on LLCs has gradually gone beyond mere demonstrations of materials at the laboratory level, and the direction of application has begun to extend to electroluminescent devices, flexible optoelectronics, information encryption and anti-counterfeiting identification, wearable lasers, as well as integrated photonics. These advancements have laid a solid foundation for the transition of this system from fundamental research toward practical applications.

Looking ahead, the development potential of LLCs systems is extremely broad. First, in the fields of display and lighting, LLCs are expected to be deeply integrated with electroluminescent devices to develop CPL displays and three-dimensional display platforms with high efficiency, low energy consumption, and dynamic controllability. Second, benefiting from their multi-stimulus responsiveness and programmability, LC materials will play an important role in information security and anti-counterfeiting, achieving reversible encryption and information storage through light, temperature, electric field, or mechanical force. Third, flexible and wearable optoelectronic devices will also become a research hotspot, and the combination of LLCs with novel luminescent units will drive their development in stretchable, portable, and biocompatible applications. Fourth, with the rise of integrated photonics and quantum information, LLC systems also have promising application prospects in miniaturized, low-loss waveguides, tunable lasers, and polarized light sources. Overall, this system is evolving from having a single material function toward being a multi-purpose, multi-platform intelligent photonic material, and is

expected to become a bridging material connecting fundamental science and practical applications in the future.

From an optical-field (and emissive-field) control standpoint, the seemingly diverse application directions share a common set of reconfigurable control primitives provided by the LC soft order. First, the LC photonic environment offers spectral selectivity via selective reflection bands, band-edge effects, and cavity feedback, which enables wavelength/color routing and reconstruction. Notably, this same spectral channel underlies both vivid displays/lighting and multi-level anti-counterfeiting readout. Second, chirality and molecular alignment program the polarization state of the emitted light, enabling handedness switching and high- g_{lum} CPL output without external optics. This polarization programmability supports CPL displays, patterned security labels, and chiral photonic sources for guided transmission. Third, spatially structured textures and defects provide addressable emission patterns (pixelated CPL programming and holography) and, when combined with stimuli responsiveness, enable reversible, multimodal switching in space and time. Finally, integrating gain media with LC photonic structures elevates these controls to coherent regimes (ASE and lasing), where mode selection, directionality, and robustness under deformation become accessible for flexible optoelectronic devices. Viewed through this unified "emissive-field engineering" lens, photoinduced asymmetric synthesis represents an extreme case in which the programmable optical chirality of the emitted field acts as an active reagent, translating field handedness into molecular handedness. In this way, different "applications" can be understood as different ways of selecting and combining the same optical/emissive degrees of freedom such as spectrum, polarization, spatial mode, temporal dynamics, and coherence within a single, stimuli-programmable soft material system.

Despite the significant progress, LLC systems still face several key issues that constrain their practical implementation. First, stability remains a bottleneck; many LC composite systems tend to degrade under humidity, illumination, or high temperature, which limits long-term reliable use. Second, the balance between high efficiency and large asymmetry factor (g_{lum}) has not yet been ideally solved, and it is often difficult to achieve both strong luminescence and pronounced chiral output simultaneously. Third, in terms of dynamic modulation, although multi-stimulus responsiveness has been realized, there are still problems such as relatively slow response speed, fatigue effects, and insufficient reversibility. At the same time, device integration and large-scale production are also practical challenges. At present, most achievements remain at laboratory-scale small-area samples. How to achieve compatibility with existing micro-nano optoelectronic fabrication, as well as low-cost large-scale preparation, are urgent technical issues to be addressed. Finally, the microscopic mechanisms of optical processes in LCs are still not fully understood, which, to some extent, constrains the precision of material design and the efficient development of new systems.

In summary, LLC systems have gradually shifted from material design and mechanism research toward functional modulation and application exploration, and they have shown great potential in multiple fields including displays, optical communications, anti-counterfeiting, and flexible electronics. Future development priorities should focus on performance enhancement, efficient and controllable external stimulus response, expansion toward flexibility and intelligence, as well as exploration of device integration and industrialization

pathways. At the same time, realistic challenges such as stability, efficiency balance, and large-scale fabrication must be addressed. We believe that with further interdisciplinary collaborative innovation within the Soft Mattonics framework, LLCs are expected to play an even more important role in the next generation of optoelectronic technologies and information-related fields.

7 Conclusion and Outlook

Within the Soft Mattonics paradigm, functional manipulation in photonic information systems is evolving beyond scalar amplitude or phase modulation toward the coordinated use of polarization, propagation direction, and temporal–spectral degrees of freedom. Acting in concert, these dimensions more effectively sculpt wavefronts, momentum, and temporal structure, enabling programmable light-field manipulation while preserving ST correlations across free-space and thin-film platforms^[302,325,327]. LCs, as a paradigmatic form of soft matter, provide a versatile route to this multidimensional integration. Their intrinsic anisotropy and programmable alignment bring geometric and dynamic phase control onto equal footing, enabling joint polarization-phase design. Their responsiveness to optical, electrical, thermal, magnetic, and mechanical stimuli supports transitions between linear and nonlinear operation, and between static and adaptive behaviors. Furthermore, their compatibility with photoalignment, digital light projection, and holographic or laser writing extends structural control from two to three spatial dimensions—and even time-varying configurations—allowing structure, function, and information to be co-optimized within a single materials platform^[2,13–16].

Central to Soft Mattonics is a self-reinforcing cycle: light shapes soft matter, and in return, soft matter manipulates light^[3]. Optical fields can induce orientation rearrangements, phase transitions, mass transport, and photomechanical deformation from the nano- to macroscale. In turn, programmable soft architectures selectively modulate phase, polarization, OAM, wave vector, and frequency^[17,20,22]. Compared with rigid materials and metasurfaces, soft matter tends to facilitate more accessible 3D/4D fabrication, enables multidimensional control within a single layer, and allows post-fabrication reconfigurability, complementing the bandwidth and stability of hard platforms and supporting embodied implementations of adaptive optics, programmable frequency conversion, and topological photonics. Bio-derived or stimuli-responsive LC superstructures further extend these advantages toward structural-color displays, environmental sensing, and wearable photonics^[32,36,37].

A promising direction is to integrate these dimensional controls into a coherent, experimentally testable framework that connects vectorial light generation, in-plane guidance and multiplexing, nonlinear interaction, and emissive outputs, with ST control embedded throughout. Vector LC holography and geometric-phase elements already realize co-designed phase–polarization–OAM fields and higher-order Poincaré beams^[11,12,15,16,29,30]. In thin films, programmable director metrics and defect-driven or chiral textures enable compact routing, multiplexing, and mode conversion^[2,20]. On the ST front, recent developments in space–time wavepackets and ST vortices provide robust, high-dimensional encoding and conversion across spatial, temporal, spin, and orbital domains, naturally interfacing with LC-based modulators and holograms^[94,302,327]. Furthermore, ST light control over soft matter may induce novel material phases characterized by dynamic ST

variations, potentially expanding the scope of “soft” matter to encompass these evolving systems in a broader dimension^[403–405].

From a broader perspective, these developments also suggest several entry points for newcomers to the field. Rather than approaching Soft Mattonics from a single functional dimension, a particularly fruitful strategy is to focus on how multiple optical degrees of freedom—such as polarization, spatial mode, topology, and ST structure—can be co-designed and dynamically coupled within one soft matter platform. Equally important is identifying problems where reconfigurability, defect tolerance, or embodied adaptivity provide clear advantages over rigid photonic architectures. For graduate students and early-career researchers, opportunities exist across multiple levels, from material synthesis and alignment chemistry, to device-level vectorial and ST control, and further to system-level integration with imaging, computation, and communication tasks. Developing intuitive design rules and predictive models that connect soft matter structure to high-dimensional optical functionality may be especially impactful in shaping the next phase of the field.

Particularly noteworthy is how FNLCs further expand this material palette by incorporating polar order and strong second-order nonlinearity, enabling nonlinear geometrical PB phase control. Building on the concept of nonlinear geometric phase in soft polar media^[79,80], photopatterned and ion-doped FNLCs have recently demonstrated reconfigurable nonlinear PB diffractive optics. By tailoring director distributions and electrically tuning splay, SH fields acquire spin-locked nonlinear PB phases that steer orthogonal polarizations into programmable diffraction orders, exhibiting continuous tuning of orders and intensities under low in-plane fields^[81]. The resulting grating behaves as a nonlinear Raman–Nath element, where transverse quasi-phase-matching is imposed by the patterned polarization texture—allowing dynamic nonlinear beam shaping without stringent longitudinal phase matching^[81]. These observations, consistent with theoretical models of cascaded linear–nonlinear spin-orbit coupling, establish FNLCs as a soft-matter platform for reconfigurable nonlinear beam steering, with potential impact in optical signal processing and quantum photonics^[81,83,84].

Despite rapid progress, several challenges remain. Ion screening, interfacial effects, and domain-wall motion can limit stability and uniformity in polar LCs. Nevertheless, FNLC research has advanced swiftly across materials discovery, electro-optic characterization, and nonlinear performance, including periodic-splay transitions, high birefringence, and enhanced SHG through dopants or helielectric ordering^[71,74,75,77,78]. Issues such as cross-scale uniformity, rewrite endurance, and the interplay between mechanical and optical degrees of freedom motivate continuing advances in photoalignment science and patterning throughput^[13]. Looking forward, predictive modeling frameworks that integrate anisotropic metrics, defects, nonlinearities, and noise—combined with fabrication-aware priors and closed-loop, physics-informed machine learning—are expected to accelerate quantitative structure–function mapping for LC holography and nonlinear PB devices^[2]. In summary, Soft Mattonics is rapidly evolving and reshaping LCs as a unified, information-centric photonics platform that integrates vectorial planar optics, in-plane steering, nonlinear geometric-phase control, ST sculpting, and active emission—turning high-dimensional encoding into practical capabilities for displays, adaptive optics, high-capacity communications, advanced imaging and sensing, and quantum photonics.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (Nos. 2022YFA1405000 and 2025YFE0114700), the National Natural Science Foundation of China (Nos. T2488302, 62375119, and 62305157), the Natural Science Foundation of Jiangsu Province, Major Project (No. BK20243067), the Basic Research Program of Jiangsu Province (Nos. BK20250164 and BK20232040), the Innovation Program for Quantum Science and Technology (No. 2021ZD0301500), the State Key Laboratory of Precision Measurement Technology and Instruments (No. Pilab2501), the Fundamental Research Funds for the Central Universities (Nos. 2024300360 and 2025300215), and the Open Research Fund of State Key Laboratory of Quantum Functional Materials (No. QFM2025KF006).

References

- Z. Zheng, W. Hu, and C. Peng, "Editorial for special issue on soft-matter photonics (Soft Mattonics)," *Chin. Opt. Lett.* **18**, 080001 (2020).
- L. L. Ma *et al.*, "Self-assembled liquid crystal architectures for soft matter photonics," *Light Sci. Appl.* **11**, 270 (2022).
- L. L. Ma *et al.*, "Soft matter photonics: interplay of soft matter and light," *ACS Nano* **19**, 11501 (2025).
- F. Reinitzer, "Beiträge zur kenntniss des cholesterins," *Monatshfte für Chemie* **9**, 421 (1888).
- O. Lehmann, "Über fließende Krystalle," *Zeitschrift für Physikalische Chemie* **4U**, 462 (1889).
- W. Helfrich, "Deformation of cholesteric liquid crystals with low threshold voltage," *Appl. Phys. Lett.* **17**, 531 (1970).
- M. Schadt and W. Helfrich, "Voltage-dependent optical activity of a twisted nematic liquid crystal," *Appl. Phys. Lett.* **18**, 127 (1971).
- P. Yeh, "Optics of liquid crystal displays," in *Conference on Lasers and Electro-Optics/Pacific Rim 2007* (Optica Publishing Group, 2007), p. ME2_1.
- S. T. Wu and D. K. Yang, *Reflective Liquid Crystal Displays* (Wiley, 2001).
- U. Efron, *Spatial Light Modulator Technology: Materials, Devices, and Applications* (Taylor & Francis, 1994).
- L. Marrucci, C. Manzo, and D. Paparo, "Optical spin-to-orbital angular momentum conversion in inhomogeneous anisotropic media," *Phys. Rev. Lett.* **96**, 163905 (2006).
- J. Kim *et al.*, "Fabrication of ideal geometric-phase holograms with arbitrary wavefronts," *Optica* **2**, 958 (2015).
- V. G. Chigrinov, V. M. Kozenkov, and H. S. U. Kwok, *Photoalignment of Liquid Crystalline Materials: Physics and Applications* (Wiley, 2008).
- Y. Guo *et al.*, "High-resolution and high-throughput plasmonic photopatterning of complex molecular orientations in liquid crystals," *Adv. Mater.* **28**, 2353 (2016).
- L. De Sio *et al.*, "Digital polarization holography advancing geometrical phase optics," *Opt. Express* **24**, 18297 (2016).
- P. Chen *et al.*, "Liquid-crystal-mediated geometric phase: from transmissive to broadband reflective planar optics," *Adv. Mater.* **32**, 1903665 (2020).
- S. Slussarenko *et al.*, "Guiding light via geometric phases," *Nat. Photonics* **10**, 571 (2016).
- H. Magallanes and E. Brasselet, "Macroscopic direct observation of optical spin-dependent lateral forces and left-handed torques," *Nat. Photonics* **12**, 461 (2018).
- D. Wen *et al.*, "Geometric metasurfaces for ultrathin optical devices," *Adv. Opt. Mater.* **6**, 1800348 (2018).
- J. Kobashi, H. Yoshida, and M. Ozaki, "Planar optics with patterned chiral liquid crystals," *Nat. Photonics* **10**, 389 (2016).
- M. Rafayelyan, G. Tkachenko, and E. Brasselet, "Reflective spin-orbit geometric phase from chiral anisotropic optical media," *Phys. Rev. Lett.* **116**, 253902 (2016).
- P. Chen *et al.*, "Chirality invertible superstructure mediated active planar optics," *Nat. Commun.* **10**, 2518 (2019).
- Q. Zhan, "Cylindrical vector beams: from mathematical concepts to applications," *Adv. Opt. Photonics* **1**, 1 (2009).
- J. Xiong and S.-T. Wu, "Planar liquid crystal polarization optics for augmented reality and virtual reality: from fundamentals to applications," *eLight* **1**, 3 (2021).
- I. Kim *et al.*, "Pixelated bifunctional metasurface-driven dynamic vectorial holographic color prints for photonic security platform," *Nat. Commun.* **12**, 3614 (2021).
- V. Chigrinov *et al.*, "Diffusion model of photoaligning in azo-dye layers," *Phys. Rev. E* **69**, 061713 (2004).
- J. Xiong *et al.*, "Holo-imprinting polarization optics with a reflective liquid crystal hologram template," *Light Sci. Appl.* **11**, 54 (2022).
- B.-Y. Wei *et al.*, "Liquid crystal depolarizer based on photoalignment technology," *Photonics Res.* **4**, 70 (2016).
- R. Xu *et al.*, "Perfect higher-order Poincaré sphere beams from digitalized geometric phases," *Phys. Rev. Appl.* **10**, 034061 (2018).
- Z.-Y. Wang *et al.*, "Vectorial liquid-crystal holography," *eLight* **4**, 5 (2024).
- L. Zhu *et al.*, "Pancharatnam-Berry phase reversal via opposite-chirality-coexisted superstructures," *Light Sci. Appl.* **11**, 135 (2022).
- H. Cao *et al.*, "Reflective optical vortex generators with ultra-broadband self-phase compensation," *Adv. Photonics Nexus* **2**, 026009 (2023).
- J. Li *et al.*, "Electrically-controlled digital metasurface device for light projection displays," *Nat. Commun.* **11**, 3574 (2020).
- S. Q. Li *et al.*, "Phase-only transmissive spatial light modulator based on tunable dielectric metasurface," *Science* **364**, 1087 (2019).
- X. Zhuang *et al.*, "Active terahertz beam steering based on mechanical deformation of liquid crystal elastomer metasurface," *Light Sci. Appl.* **12**, 14 (2023).
- Z. Zhou *et al.*, "Electrically tunable planar liquid-crystal singlets for simultaneous spectrometry and imaging," *Light Sci. Appl.* **13**, 242 (2024).
- S.-L. 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 Sci. Appl.* **13**, 27 (2024).
- O. D. Lavrentovich, "Liquid crystals, photonic crystals, metamaterials, and transformation optics," *Proc. Natl. Acad. Sci. USA* **108**, 5143 (2011).
- J. Xiang and O. D. Lavrentovich, "Liquid crystal structures for transformation optics," *Mol. Cryst. Liq. Cryst.* **559**, 106 (2012).
- C. Sátiro and F. Moraes, "Lensing effects in a nematic liquid crystal with topological defects," *Eur. Phys. J. E* **20**, 173 (2006).
- T. Wei *et al.*, "Liquid-crystal-mediated active waveguides toward programmable integrated optics," *Adv. Opt. Mater.* **8**, 1902033 (2020).
- H. Yu *et al.*, "Guiding light with programmable wall defects," *Laser Photonics Rev.* **18**, 2400266 (2024).
- P. Ropač *et al.*, "Liquid crystal 3D optical waveguides based on photoalignment," *Adv. Opt. Mater.* **13**, 2402174 (2025).
- C. Meng, J. S. Wu, and Smalyukh II, "Topological steering of light by nematic vortices and analogy to cosmic strings," *Nat. Mater.* **22**, 64 (2023).
- B. Chen *et al.*, "Ultrafast laser writing of liquid crystal waveguides," *Ultrafast Sci.* **4**, 0065 (2024).
- S. Halder *et al.*, "Dual-sided transparent display enabled by polymer stabilized liquid crystals for augmented reality," *Nat. Commun.* **15**, 9760 (2024).
- M. Peccianti *et al.*, "Electrically assisted self-confinement and waveguiding in planar nematic liquid crystal cells," *Appl. Phys. Lett.* **77**, 7 (2000).

48. M. Peccianti *et al.*, "Routing of anisotropic spatial solitons and modulational instability in liquid crystals," *Nature* **432**, 733 (2004).
49. M. Peccianti and G. Assanto, "Nematicons," *Phys. Rep.* **516**, 147 (2012).
50. M. Peccianti and G. Assanto, "Nematic liquid crystals: a suitable medium for self-confinement of coherent and incoherent light," *Phys. Rev. E* **65**, 035603 (2002).
51. N. Karimi *et al.*, "Molding optical waveguides with nematicons," *Adv. Opt. Mater.* **5**, 1700199 (2017).
52. Y. Izdebskaya *et al.*, "Magnetic routing of light-induced waveguides," *Nat. Commun.* **8**, 14452 (2017).
53. S. Perumbilavil *et al.*, "Beaming random lasers with soliton control," *Nat. Commun.* **9**, 3863 (2018).
54. M. Peccianti *et al.*, "Tunable refraction and reflection of self-confined light beams," *Nat. Phys.* **2**, 737 (2006).
55. A. Piccardi *et al.*, "Power-controlled transition from standard to negative refraction in reorientational soft matter," *Nat. Commun.* **5**, 5533 (2014).
56. A. Alberucci, C. P. Jisha, and G. Assanto, "Nonlinear negative refraction in reorientational soft matter," *Phys. Rev. A* **92**, 033835 (2015).
57. G. Poy *et al.*, "Chirality-enhanced periodic self-focusing of light in soft birefringent media," *Phys. Rev. Lett.* **125**, 077801 (2020).
58. A. J. Hess *et al.*, "Control of light by topological solitons in soft chiral birefringent media," *Phys. Rev. X* **10**, 031042 (2020).
59. M. Vellaichamy *et al.*, "Microscale generation and control of nanosecond light by light in a liquid crystal," *Nat. Photonics* **19**, 758 (2025).
60. G. Poy *et al.*, "Interaction and co-assembly of optical and topological solitons," *Nat. Photonics* **16**, 454 (2022).
61. S.-S. Chang *et al.*, "Electrical tuning of branched flow of light," *Nat. Commun.* **15**, 197 (2024).
62. X. Yu *et al.*, "Dynamic transition from branched flow of light to beam steering in disordered nematic liquid crystal," *Laser Photonics Rev.* **18**, 2400366 (2024).
63. X. Yu *et al.*, "On-demand tailoring of optical branched flow via soft matter domain engineering," *Laser Photonics Rev.* **19**, 2401717 (2025).
64. G. K. L. Wong and Y. R. Shen, "Study of pretransitional behavior of laser-field-induced molecular alignment in isotropic nematic substances," *Phys. Rev. A* **10**, 1277 (1974).
65. I. C. Khoo *et al.*, "Passive optical self-limiter using laser-induced axially asymmetric and symmetric transverse self-phase modulations in nematic liquid crystals," *Opt. Lett.* **11**, 227 (1986).
66. I. C. Khoo and T. H. Liu, "Theory and experiments on multi-wave-mixing-mediated probe-beam amplification," *Phys. Rev. A* **39**, 4036 (1989).
67. C. Conti, M. Peccianti, and G. Assanto, "Observation of optical spatial solitons in a highly nonlocal medium," *Phys. Rev. Lett.* **92**, 113902 (2004).
68. R. J. Mandle, S. J. Cowling, and J. W. Goodby, "A nematic to nematic transformation exhibited by a rod-like liquid crystal," *Phys. Chem. Chem. Phys.* **19**, 11429 (2017).
69. H. Nishikawa *et al.*, "A fluid liquid-crystal material with highly polar order," *Adv. Mater.* **29**, 1702354 (2017).
70. X. Chen *et al.*, "First-principles experimental demonstration of ferroelectricity in a thermotropic nematic liquid crystal: Polar domains and striking electro-optics," *Proc. Natl. Acad. Sci. USA* **117**, 14021 (2020).
71. B. Basnet *et al.*, "Periodic splay Fréedericksz transitions in a ferroelectric nematic," *Nat. Commun.* **16**, 1444 (2025).
72. I. Taghavi *et al.*, "GHz-rate optical phase shift in light matter interaction-engineered, silicon-ferroelectric nematic liquid crystals," arXiv:2405.08833 (2024).
73. L.-Y. Chiang *et al.*, "Ferroelectric nematic liquid crystal-based silicon photonic modulator demonstrated at 102 Gbit/s PAM-4," arXiv:2507.14724 (2025).
74. Y. Song *et al.*, "Ferroelectric nematic liquid crystals showing high birefringence," *Adv. Sci. (Weinh)* **12**, 2414317 (2025).
75. J. Ortega, C. L. Folcia, and T. Sierra, "High second harmonic generation in ferroelectric nematic liquid crystals by doping with optimally oriented chromophores," *Liq. Cryst.* **52**, 801 (2025).
76. D. Okada, H. Nishikawa, and F. Araoka, "Tunable intracavity coherent up-conversion with giant nonlinearity in a polar fluidic medium," *Adv. Sci. (Weinh)* **11**, 2405227 (2024).
77. X. Zhao *et al.*, "Nontrivial phase matching in helielectric polarization helices: Universal phase matching theory, validation, and electric switching," *Proc. Natl. Acad. Sci. USA* **119**, e2205636119 (2022).
78. C. L. Folcia *et al.*, "The ferroelectric nematic phase: An optimum liquid crystal candidate for nonlinear optics," *Liq. Cryst.* **49**, 899 (2022).
79. J.-T. Pan *et al.*, "Nonlinear geometric phase coded ferroelectric nematic fluids for nonlinear soft-matter photonics," *Nat. Commun.* **15**, 8732 (2024).
80. Z. Hu and G. Li, "Nonlinear geometric phase in optics: Fundamentals and applications," *Appl. Phys. Lett.* **126**, 100502 (2025).
81. H.-F. Chen *et al.*, "Reconfigurable nonlinear Pancharatnam-Berry diffractive optics with photopatterned ferroelectric nematics," *Light Sci. Appl.* **14**, 314 (2025).
82. G. Y. Zhang *et al.*, "Periodically-modulated unipolar and bipolar orders in nematic fluids towards miniaturized nonlinear vectorial optics," *Nat. Commun.* **16**, 9419 (2025).
83. V. Sultanov *et al.*, "Tunable entangled photon-pair generation in a liquid crystal," *Nature* **631**, 294 (2024).
84. J.-T. Pan *et al.*, "Nonreciprocal quantum photon-pair source with chiral ferroelectric nematics," arXiv:2503.11399 (2025).
85. Y. Liu *et al.*, "Broadband spin and orbital momentum modulator using self-assembled nanostructures," *Adv. Mater.* **36**, 2412007 (2024).
86. Y. Liu *et al.*, "Second order optical nonlinearity originated from ferroelectric spherulite with vortex domain," *Adv. Opt. Mater.* **13**, 2403095 (2025).
87. O. Martinez, "3000 times grating compressor with positive group velocity dispersion: Application to fiber compensation in 1.3–1.6 μm region," *IEEE J. Quantum Electron.* **23**, 59 (1987).
88. A. M. Weiner and D. E. Leaird, "Generation of terahertz-rate trains of femtosecond pulses by phase-only filtering," *Opt. Lett.* **15**, 51 (1990).
89. A. M. Weiner *et al.*, "Programmable shaping of femtosecond optical pulses by use of 128-element liquid crystal phase modulator," *IEEE J. Quantum Electron.* **28**, 908 (1992).
90. A. M. Weiner, "Femtosecond optical pulse shaping and processing," *Prog. Quantum Electron.* **19**, 161 (1995).
91. M. Fetterman *et al.*, "Ultrafast pulse shaping: amplification and characterization," *Opt. Express* **3**, 366 (1998).
92. A. M. Weiner, "Femtosecond pulse shaping using spatial light modulators," *Rev. Sci. Instrum.* **71**, 1929 (2000).
93. M. Yessenov *et al.*, "Classification of propagation-invariant space-time wave packets in free space: theory and experiments," *Phys. Rev. A* **99**, 023856 (2019).
94. W. Chen *et al.*, "Tailoring spatiotemporal wavepackets via two-dimensional space-time duality," *Nat. Commun.* **16**, 2818 (2025).
95. H. E. Kondakci and A. F. Abouraddy, "Optical space-time wave packets having arbitrary group velocities in free space," *Nat. Commun.* **10**, 929 (2019).
96. M. Yessenov and A. F. Abouraddy, "Accelerating and decelerating space-time optical wave packets in free space," *Phys. Rev. Lett.* **125**, 233901 (2020).
97. M. Yessenov *et al.*, "Vector space-time wave packets," *Opt. Lett.* **47**, 4131 (2022).

98. X. Jiang *et al.*, "Controllable temporal twisting polarization within an ultrafast laser pulse," *Opt. Lett.* **49**, 6225 (2024).
99. A. Chong *et al.*, "Generation of spatiotemporal optical vortices with controllable transverse orbital angular momentum," *Nat. Photonics* **14**, 350 (2020).
100. K. Y. Bliokh, "Spatiotemporal vortex pulses: angular momenta and spin-orbit interaction," *Phys. Rev. Lett.* **126**, 243601 (2021).
101. S. W. Hancock, S. Zahedpour, and H. M. Milchberg, "Mode structure and orbital angular momentum of spatiotemporal optical vortex pulses," *Phys. Rev. Lett.* **127**, 193901 (2021).
102. Q. Cao *et al.*, "Non-spreading Bessel spatiotemporal optical vortices," *Sci. Bull.* **67**, 133 (2022).
103. C. Wan *et al.*, "Toroidal vortices of light," *Nat. Photonics* **16**, 519 (2022).
104. W. Chen *et al.*, "Observation of chiral symmetry breaking in toroidal vortices of light," *Phys. Rev. Lett.* **132**, 153801 (2024).
105. C. Wan *et al.*, "Scalar optical hopfions," *eLight* **2**, 22 (2022).
106. L. Rego *et al.*, "Generation of extreme-ultraviolet beams with time-varying orbital angular momentum," *Science* **364**, eaaw9486 (2019).
107. Z. Zhao *et al.*, "Dynamic spatiotemporal beams that combine two independent and controllable orbital-angular-momenta using multiple optical-frequency-comb lines," *Nat. Commun.* **11**, 4099 (2020).
108. M. Piccardo *et al.*, "Broadband control of topological-spectral correlations in space-time beams," *Nat. Photonics* **17**, 822 (2023).
109. G. Gui *et al.*, "Second-harmonic generation and the conservation of spatiotemporal orbital angular momentum of light," *Nat. Photonics* **15**, 608 (2021).
110. S. W. Hancock, S. Zahedpour, and H. M. Milchberg, "Second-harmonic generation of spatiotemporal optical vortices and conservation of orbital angular momentum," *Optica* **8**, 594 (2021).
111. R. Martín-Hernández *et al.*, "Extreme-ultraviolet spatiotemporal vortices via high harmonic generation," *Nat. Photonics* **19**, 817 (2025).
112. R. Zheng *et al.*, "Stimuli-responsive active materials for dynamic control of light field," *Responsive Mater.* **1**, e20230017 (2023).
113. J. Liu *et al.*, "Multi-color circularly polarized room-temperature phosphorescence from processable chiral photonic films," *Adv. Funct. Mater.* **35**, 2506911 (2025).
114. J. Liu *et al.*, "Circularly polarized organic ultralong room-temperature phosphorescence with a high dissymmetry factor in chiral helical superstructures," *Adv. Mater.* **36**, e2306834 (2024).
115. Z. P. Song *et al.*, "Mechanically-tunable and full-color circularly polarized long-lived phosphorescence in chiral superstructure elastomers," *Adv. Mater.* **37**, e2419640 (2025).
116. H. He *et al.*, "Cholesteric-superhelix-enabled reconfigurable circularly polarized luminescence from uniaxially aligned upconversion nanorod films," *Laser Photonics Rev.* **16**, 2200115 (2022).
117. Z. C. Yang *et al.*, "Thermally tunable reflective colors of cholesteric liquid crystal for near-infrared planar optics," *Adv. Opt. Mater.* **13**, 2500654 (2025).
118. J. Li *et al.*, "Helical coassembly enables full-color efficient circularly polarized light emission from carbon dots with high dissymmetry factors," *Sci. Adv.* **11**, eadt8219 (2025).
119. Y. Zhou *et al.*, "Helical-caging enables single-emitted large asymmetric full-color circularly polarized luminescence," *Nat. Commun.* **15**, 251 (2024).
120. S. Subedi *et al.*, "Electrically switchable anisometric carbon quantum dots exhibiting linearly polarized photoluminescence: syntheses, anisotropic properties, and facile control of uniaxial orientation," *ACS Nano* **16**, 6480 (2022).
121. C. Zhang *et al.*, "Maximized circularly polarized luminescence from metal clusters accelerates chiral photopolymerization," *Nat. Commun.* **16**, 6848 (2025).
122. H. Ji *et al.*, "Chiral dual-annihilator model for controllable photon upconversion and multi-dimensional optical modulation," *Nat. Commun.* **16**, 4952 (2025).
123. S. Li *et al.*, "When quantum dots meet blue phase liquid crystal elastomers: visualized full-color and mechanically-switchable circularly polarized luminescence," *Light Sci. Appl.* **13**, 140 (2024).
124. S. Lin *et al.*, "Photo-triggered full-color circularly polarized luminescence based on photonic capsules for multilevel information encryption," *Nat. Commun.* **14**, 3005 (2023).
125. K. Yao *et al.*, "Excitation-dependent circularly polarized luminescence inversion driven by dichroic competition of achiral dyes in cholesteric liquid crystals," *Angew. Chem. Int. Ed. Engl.* **64**, e202420290 (2025).
126. P. Ornelas *et al.*, "Non-local skyrmions as topologically resilient quantum entangled states of light," *Nat. Photonics* **18**, 258 (2024).
127. S. J. Liu *et al.*, "Bi-chiral nanostructures featuring dynamic optical rotatory dispersion for polychromatic light multiplexing," *Adv. Mater.* **35**, e2301714 (2023).
128. Y. Li *et al.*, "Achiral dichroic dyes-mediated circularly polarized emission regulated by orientational order parameter through cholesteric liquid crystals," *Angew. Chem. Int. Ed. Engl.* **62**, e202312159 (2023).
129. C. E. Shannon, "Communication theory of secrecy systems," *Bell Syst. Tech. J.* **28**, 656 (1949).
130. F. Ding, C. Meng, and S. I. Bozhevolnyi, "Electrically tunable optical metasurfaces," *Photonics Insights* **3**, R07 (2024).
131. D. Vettese, "Liquid crystal on silicon," *Nat. Photonics* **4**, 752 (2010).
132. Q. Zhang *et al.*, "Diffractive optical elements 75 years on: from micro-optics to metasurfaces," *Photonics Insights* **2**, R09 (2023).
133. G. Makey *et al.*, "Breaking crosstalk limits to dynamic holography using orthogonality of high-dimensional random vectors," *Nat. Photonics* **13**, 251 (2019).
134. P. Chen *et al.*, "Digitalizing self-assembled chiral superstructures for optical vortex processing," *Adv. Mater.* **30**, 1705865 (2018).
135. Z. Wang *et al.*, "Cascaded liquid crystal holography for optical encryption," *Chin. Opt. Lett.* **21**, 120003 (2023).
136. P. Sun *et al.*, "Tailoring ultra-broadband vector beams via programming the electric field vector of light," *Opt. Express* **30**, 28506 (2022).
137. L. L. Ma *et al.*, "Self-assembled asymmetric microlenses for four-dimensional visual imaging," *ACS Nano* **13**, 13709 (2019).
138. S. J. Liu *et al.*, "Multidimensional photopatterning of heterogeneous liquid-crystal superstructures toward higher-level information optics," *Adv. Mater.* **37**, e2506778 (2025).
139. L. L. Ma *et al.*, "Programmable self-propelling actuators enabled by a dynamic helical medium," *Sci. Adv.* **7**, eabh3505 (2021).
140. Q. Chen *et al.*, "Soft mesocrystal enabled multi-degree light modulation," *Laser Photonics Rev.* **18**, 2301283 (2024).
141. Z. Xie *et al.*, "Monochromatic wide-angle optical edge detection enabled by a three-dimensional soft photonic crystal," *Adv. Funct. Mater.* **35**, 2500920 (2025).
142. A. H. Dorrah and F. Capasso, "Tunable structured light with flat optics," *Science* **376**, eabi6860 (2022).
143. A. W. Lohmann, "Reconstruction of vectorial wavefronts," *Appl. Opt.* **4**, 1667 (1965).
144. A. H. Dorrah *et al.*, "Light sheets for continuous-depth holography and three-dimensional volumetric displays," *Nat. Photonics* **17**, 427 (2023).
145. W. Ma *et al.*, "Deep learning for the design of photonic structures," *Nat. Photonics* **15**, 77 (2020).
146. X. Fang, H. Ren, and M. Gu, "Orbital angular momentum holography for high-security encryption," *Nat. Photonics* **14**, 102 (2019).
147. D. Zhang *et al.*, "Colorless and unidirectional diffractive-type solar concentrators compatible with existing windows," *Photonix* **6**, 20 (2025).

148. Z. Shen *et al.*, “Liquid crystal integrated metalens with tunable chromatic aberration,” *Adv. Photonics* **2**, 1 (2020).
149. Y. Wang *et al.*, “Programmable Jigsaw puzzles of soft materials enabled by pixelated holographic surface reliefs,” *Adv. Mater.* **35**, e2211521 (2023).
150. N. Liu *et al.*, “Propagation-adaptive 4K computer-generated holography using physics-constrained spatial and Fourier neural operator,” *Nat. Commun.* **16**, 7761 (2025).
151. Y. Fan *et al.*, “Dispersion-assisted high-dimensional photodetector,” *Nature* **630**, 77 (2024).
152. S. Tripathi and K. C. Toussaint, Jr., “Versatile generation of optical vector fields and vector beams using a non-interferometric approach,” *Opt. Express* **20**, 10788 (2012).
153. W. Han *et al.*, “Vectorial optical field generator for the creation of arbitrarily complex fields,” *Opt. Express* **21**, 20692 (2013).
154. Y. Li *et al.*, “Single-exposure fabrication of tunable Pancharatnam-Berry devices using a dye-doped liquid crystal,” *Opt. Express* **27**, 9054 (2019).
155. C. W. Chen and I. C. Khoo, “Optical vector field rotation and switching with near-unity transmission by fully developed chiral photonic crystals,” *Proc Natl. Acad. Sci. USA* **118**, e2021304118 (2021).
156. C. Peng, C. Xu, and W. Hu, “Smart beam via electrically addressing the dye-doped and polymer-stabilized cholesteric liquid crystals,” *Chin. Opt. Lett.* **22**, 053301 (2024).
157. Q. Wang *et al.*, “Liquid crystal integrated dynamic terahertz metalenses,” *Laser Photonics Rev.* **18**, 2400869 (2024).
158. K. Chen *et al.*, “Multifunctional liquid crystal device for gray-scale pattern display and holography with tunable spectral-response,” *Laser Photonics Rev.* **16**, 2100591 (2022).
159. Y.-H. Zhang *et al.*, “Logical rotation of non-separable states via uniformly self-assembled chiral superstructures,” *Nat. Commun.* **15**, 1108 (2024).
160. Y.-P. Ruan *et al.*, “Observation of loss-enhanced magneto-optical effect,” *Nat. Photonics* **19**, 109 (2024).
161. Y. Ni *et al.*, “Computational spectropolarimetry with a tunable liquid crystal metasurface,” *eLight* **2**, 23 (2022).
162. G.-Y. Wang *et al.*, “All-liquid-crystal and full-visible-band tunable polarimetry,” *Adv. Photonics Nexus* **4**, 025001 (2025).
163. G.-Y. Wang *et al.*, “A tri-channel liquid crystal device for single-pixel-imaging encryption,” *Appl. Phys. Lett.* **123**, 091102 (2023).
164. D. Tang *et al.*, “Simultaneous surface display and holography enabled by flat liquid crystal elements,” *Laser Photonics Rev.* **16**, 2100491 (2022).
165. W. Chen *et al.*, “Fast selective edge-enhanced imaging with topological chiral lamellar superstructures,” *Natl. Sci. Rev.* **11**, nwae247 (2024).
166. T. Liu *et al.*, “High-efficiency vectorial holography based on ultra-thin metasurfaces,” *Adv. Photonics* **7**, 056004 (2025).
167. N. A. Rubin *et al.*, “Jones matrix holography with metasurfaces,” *Sci. Adv.* **7**, eabg7488 (2021).
168. R. Zhao *et al.*, “Multichannel vectorial holographic display and encryption,” *Light Sci. Appl.* **7**, 95 (2018).
169. X. Zhang *et al.*, “Spatial varying vectorial holography and polarization encryption based on birefringent metasurface,” *Adv. Funct. Mater.* **34**, 2404196 (2024).
170. B. Xiong *et al.*, “Breaking the limitation of polarization multiplexing in optical metasurfaces with engineered noise,” *Science* **379**, 294 (2023).
171. P. Yu, J. Li, and N. Liu, “Electrically tunable optical metasurfaces for dynamic polarization conversion,” *Nano Lett.* **21**, 6690 (2021).
172. Y. Hu *et al.*, “Electrically tunable multifunctional polarization-dependent metasurfaces integrated with liquid crystals in the visible region,” *Nano Lett.* **21**, 4554 (2021).
173. X. Xu *et al.*, “Reprogrammable vector optical field meets planar liquid crystal elements for enhanced security in holography,” *Laser Photonics Rev.* **19**, 2401962 (2025).
174. I. Nape *et al.*, “Revealing the invariance of vectorial structured light in complex media,” *Nat. Photonics* **16**, 538 (2022).
175. A. Sit *et al.*, “High-dimensional intracity quantum cryptography with structured photons,” *Optica* **4**, 1006 (2017).
176. Y. Ma *et al.*, “Using optical skyrmions to assess vectorial adaptive optics capabilities in the presence of complex aberrations,” *Sci. Adv.* **11**, eadv7904 (2025).
177. C. He, J. Antonello, and M. J. Booth, “Vectorial adaptive optics,” *eLight* **3**, 23 (2023).
178. X. Liang *et al.*, “All-optical multi-order multiplexing differentiation based on dynamic liquid crystals,” *Laser Photonics Rev.* **18**, 2400032 (2024).
179. S. Yang *et al.*, “Controlling cell motion and microscale flow with polarized light fields,” *Phys. Rev. Lett.* **126**, 058001 (2021).
180. H. Teng *et al.*, “Physical conversion and superposition of optical Skyrmion topologies,” *Photonics Res.* **11**, 2042 (2023).
181. C. He *et al.*, “A reconfigurable arbitrary retarder array as complex structured matter,” *Nat. Commun.* **16**, 4902 (2025).
182. Y. Shen *et al.*, “Optical skyrmions and other topological quasiparticles of light,” *Nat. Photonics* **18**, 15 (2023).
183. Y. Shen, E. C. Martínez, and C. Rosales-Guzmán, “Generation of optical Skyrmions with tunable topological textures,” *ACS Photonics* **9**, 296 (2022).
184. A. A. Wang *et al.*, “Topological protection of optical skyrmions through complex media,” *Light Sci. Appl.* **13**, 314 (2024).
185. A. A. Wang *et al.*, “Perturbation-resilient integer arithmetic using optical skyrmions,” *Nat. Photonics* **19**, 1367 (2025).
186. Y. Shen *et al.*, “Optical vortices 30 years on: OAM manipulation from topological charge to multiple singularities,” *Light Sci. Appl.* **8**, 90 (2019).
187. N. Bhebbhe *et al.*, “A vector holographic optical trap,” *Sci. Rep.* **8**, 17387 (2018).
188. S. Ye *et al.*, “Entanglement-controlled vectorial meta-holography,” *Light Sci. Appl.* **14**, 135 (2025).
189. B. Bellini and R. Beccherelli, “Modelling, design and analysis of liquid crystal waveguides in preferentially etched silicon grooves,” *J. Phys. D* **42**, 045111 (2009).
190. M. Notaros *et al.*, Integrated visible-light liquid-crystal phase modulator, in *Frontiers in Optics/Laser Science* (Optica Publishing Group, 2018), p. FW6B.5.
191. R. Chauhan, U. S. Tripathi, and V. Rastogi, “Liquid-crystal clad tunable wavelength de-multiplexer and coupler/filter in silicon nitride rib waveguide structure,” *Opt. Commun.* **556**, 130287 (2024).
192. R. Chauhan, U. S. Tripathi, and V. Rastogi, “Liquid crystal-based tunable coupler and filter for CWDM using parallel long-period waveguide gratings,” *J. Opt. Soc. Am. B* **42**, B1 (2025).
193. M. Cancula *et al.*, “Liquid microlenses and waveguides from bulk nematic birefringent profiles,” *Opt. Express* **24**, 22177 (2016).
194. G. Poy and S. Zumer, “Physics-based multistep beam propagation in inhomogeneous birefringent media,” *Opt. Express* **28**, 24327 (2020).
195. Y. Shin *et al.*, “Patterned waveguide liquid crystal displays,” *RSC Adv.* **10**, 41693 (2020).
196. R. W. Boyd, *Nonlinear Optics* (Academic Press, 2020).
197. S. Akhmanov, R. Khokhlov, and A. Sukhorukov, *Laser Handbook* (Amsterdam: North-Holland, 1972).
198. Y. R. Shen, “Self-focusing: experimental,” *Prog. Quantum Electron.* **4**, 1 (1975).
199. S. A. Akhmanov, A. P. Sukhorukov, and R. V. Khokhlov, “Self-focusing and diffraction of light in a nonlinear medium,” *Soviet Phys. Uspekhi* **10**, 609 (1968).
200. A. Alberucci *et al.*, “Two-color vector solitons in nonlocal media,” *Phys. Rev. Lett.* **97**, 153903 (2006).
201. U. A. Laudyn *et al.*, “Accelerated optical solitons in reorientational media with transverse invariance and longitudinally modulated birefringence,” *Phys. Rev. A* **98**, 023810 (2018).

202. S. Y. Zhang *et al.*, “Deflecting and routing nematicons via orientation programmable liquid crystal array,” *Opt. Express* **31**, 20955 (2023).
203. M. Peccianti *et al.*, “Escaping solitons from a trapping potential,” *Phys. Rev. Lett.* **101**, 153902 (2008).
204. G. Assanto, B. D. Skuse, and N. F. Smyth, “Solitary wave propagation and steering through light-induced refractive potentials,” *Phys. Rev. A* **81**, 063811 (2010).
205. G. Assanto *et al.*, “Temperature control of nematicon trajectories,” *Phys. Rev. E* **100**, 062702 (2019).
206. S. Perumbilavil, M. Kauranen, and G. Assanto, “Spatiospectral features of a soliton-assisted random laser in liquid crystals,” *Opt. Lett.* **44**, 3574 (2019).
207. J. B. Pendry, D. Schurig, and D. R. Smith, “Controlling electromagnetic fields,” *Science* **312**, 1780 (2006).
208. W. Cai *et al.*, “Optical cloaking with metamaterials,” *Nat. Photonics* **1**, 224 (2007).
209. H. Chen *et al.*, “Ray-optics cloaking devices for large objects in incoherent natural light,” *Nat. Commun.* **4**, 2652 (2013).
210. Y. Lai *et al.*, “Illusion optics: the optical transformation of an object into another object,” *Phys. Rev. Lett.* **102**, 253902 (2009).
211. C. Huang *et al.*, “A conformal mapping approach to broadband nonlinear optics on chip,” *Nat. Photonics* **18**, 471 (2024).
212. C. Sheng *et al.*, “Definite photon deflections of topological defects in metasurfaces and symmetry-breaking phase transitions with material loss,” *Nat. Commun.* **9**, 4271 (2018).
213. C. S  tiro and F. Moraes, “On the deflection of light by topological defects in nematic liquid crystals,” *Eur. Phys. J. E* **25**, 425 (2008).
214. Y. L. Zhang *et al.*, “Steering electromagnetic beams with conical curvature singularities,” *Opt. Lett.* **40**, 4783 (2015).
215. W. Barros *et al.*, “Concentrating, diverging, shifting, and splitting electromagnetic beams using a single conical structure,” *J. Appl. Phys.* **128**, 093105 (2020).
216. D. Figueiredo *et al.*, “Cosmology in the laboratory: An analogy between hyperbolic metamaterials and the Milne universe,” *Phys. Rev. D* **96**, 105012 (2017).
217. W. K. P. Barros and E. Pereira, “Concurrent guiding of light and heat by transformation optics and transformation thermodynamics via soft matter,” *Sci. Rep.* **8**, 11453 (2018).
218. S. J. Santos Jr., J. Andrade, and E. Pereira, “Simultaneous rectification of heat and light using liquid crystal,” *J. Appl. Phys.* **124**, 094501 (2018).
219. J. B. Tai and Smalyukh II, “Three-dimensional crystals of adaptive knots,” *Science* **365**, 1449 (2019).
220. U. A. Laudyn, M. Kwasny, and M. A. Karpierz, “Nematicons in chiral nematic liquid crystals,” *Appl. Phys. Lett.* **94**, 091110 (2009).
221. A. Madani, J. Beeckman, and K. Neytsc, “An experimental observation of a spatial optical soliton beam and self splitting of beam into two soliton beams in chiral nematic liquid crystal,” *Opt. Commun.* **298-299**, 222 (2013).
222. E. J. Heller, R. Fleischmann, and T. Kramer, “Branched flow,” *Phys. Today* **74**, 44 (2021).
223. M. A. Topinka *et al.*, “Coherent branched flow in a two-dimensional electron gas,” *Nature* **410**, 183 (2001).
224. H. Degueldre *et al.*, “Random focusing of tsunami waves,” *Nat. Phys.* **12**, 259 (2015).
225. M. A. Wolfson and S. Tomsovic, “On the stability of long-range sound propagation through a structured ocean,” *J. Acoust. Soc. Am.* **109**, 2693 (2001).
226. R. Hohmann *et al.*, “Freak waves in the linear regime: a microwave study,” *Phys. Rev. Lett.* **104**, 093901 (2010).
227. A. Patsyk *et al.*, “Observation of branched flow of light,” *Nature* **583**, 60 (2020).
228. A. Brandst  tter *et al.*, “Shaping the branched flow of light through disordered media,” *Proc. Natl. Acad. Sci. USA* **116**, 13260 (2019).
229. U. A. Laudyn *et al.*, “Vortex nematicons in planar cells,” *Opt. Express* **28**, 8282 (2020).
230. M. Gao *et al.*, “Dynamic propagation of an Airy beam in metasurface-enabled gradiently-aligned liquid crystals,” *Nanophotonics* **12**, 4205 (2023).
231. M. Kwasny *et al.*, “Optothermal vortex-solitons in liquid crystals,” *Opt. Lett.* **45**, 2451 (2020).
232. S. Takano, T. Asahi, and I. I. Smalyukh, “Chirality-assembled on-chip lasers,” *Nat. Photonics* **19**, 659 (2025).
233. D.-K. Yang and S.-T. Wu, *Fundamentals of liquid crystal devices* (John Wiley & Sons, 2014).
234. V. Fredericksz and A. Repiewa, “Theoretisches und Experimentelles zur Frage nach der Natur der anisotropen Fl  ssigkeiten,” *Zeitschrift f  r Physik* **42**, 532 (1927).
235. P.-G. De Gennes and J. Prost, *The Physics of Liquid Crystals* (Oxford University Press, 1993), p. 83.
236. P. Yeh and C. Gu, *Optics of Liquid Crystal Displays* (John Wiley & Sons, 2010).
237. B. Y. Wei *et al.*, “Generating switchable and reconfigurable optical vortices via photopatterning of liquid crystals,” *Adv. Mater.* **26**, 1590 (2014).
238. M. Ghadimi Nassiri and E. Brasselet, “Multispectral management of the photon orbital angular momentum,” *Phys. Rev. Lett.* **121**, 213901 (2018).
239. L.-L. Ma *et al.*, “Smectic layer origami via preprogrammed photoalignment,” *Adv. Mater.* **29**, 1606671 (2017).
240. H. Yu *et al.*, “Programmable liquid crystal defects and dynamically manipulation with mechanical stress,” *Laser Photonics Rev.* **18**, 2301220 (2024).
241. I. C. Khoo *et al.*, “Extremely nonlinear photosensitive liquid crystals for image sensing and sensor protection,” *Opt. Express* **4**, 432 (1999).
242. E. Braun, L. P. Faucheux, and A. Libchaber, “Strong self-focusing in nematic liquid crystals,” *Phys. Rev. A* **48**, 611 (1993).
243. S. D. Durbin, S. M. Arakelian, and Y. R. Shen, “Laser-induced diffraction rings from a nematic-liquid-crystal film,” *Opt. Lett.* **6**, 411 (1981).
244. S. K. Saha and G. K. Wong, “Investigation of nematic ordering using electric-field-induced second-harmonic generation,” *Appl. Phys. Lett.* **34**, 423 (1979).
245. R. Stolle, T. D  rr, and G. Marowsky, “Molecular motion analysis in nematic liquid-crystal cells using linear and nonlinear optical techniques,” *J. Opt. Soc. Am. B* **14**, 1583 (1997).
246. Y. R. Shen, “Optical second harmonic generation at interfaces,” *Annu. Rev. Phys. Chem.* **40**, 327 (1989).
247. J. W. Shelton and Y. R. Shen, “Phase-matched third-harmonic generation in cholesteric liquid crystals,” *Phys. Rev. Lett.* **25**, 23 (1970).
248. L. Lucchetti *et al.*, “Colossal optical nonlinearity in dye doped liquid crystals,” *Opt. Commun.* **233**, 417 (2004).
249. M. B. Feller, W. Chen, and Y. R. Shen, “Investigation of surface-induced alignment of liquid-crystal molecules by optical second-harmonic generation,” *Phys. Rev. A* **43**, 6778 (1991).
250. M. Born, “Ueber anisotrope Fl  ssigkeiten: Versuch einer Theorie der fl  ssigen Kristalle und des elektrischen Kerr-Effekts in Fl  ssigkeiten,” *Sitzungsber. Preuss. Akad. Wiss* **30**, 614 (1916).
251. N. Vaupti  c *et al.*, “Ferroelectric nematics: materials with high permittivity or low resistivity?” *Liq. Crys.* **1** (2025).
252. N. A. Clark *et al.*, “Dielectric spectroscopy of ferroelectric nematic liquid crystals: Measuring the capacitance of insulating interfacial layers,” *Phys. Rev. Res.* **6**, 013195 (2024).
253. M. P. Kumar *et al.*, “Giant electroviscous effects in a ferroelectric nematic liquid crystal,” *Phys. Rev. Appl.* **19**, 044082 (2023).
254. A. Jarosik *et al.*, “Fluid fibers in true 3D ferroelectric liquids,” *Proc. Natl. Acad. Sci. USA* **121**, e2313629121 (2024).
255. F. Caimi *et al.*, “Fluid superscreening and polarization following in confined ferroelectric nematics,” *Nat. Phys.* **19**, 1658 (2023).
256. P. Kumari *et al.*, “Chiral ground states of ferroelectric liquid crystals,” *Science* **383**, 1364 (2024).

257. R. Barboza *et al.*, “Explosive electrostatic instability of ferroelectric liquid droplets on ferroelectric solid surfaces,” *Proc Natl. Acad. Sci. USA* **119**, e2207858119 (2022).
258. J. Karcz *et al.*, “Spontaneous chiral symmetry breaking in polar fluid-heliconical ferroelectric nematic phase,” *Science* **384**, 1096 (2024).
259. X. Zhao *et al.*, “Spontaneous helielectric nematic liquid crystals: Electric analog to helimagnets,” *Proc Natl. Acad. Sci. USA* **118**, e2111101118 (2021).
260. H. Kikuchi *et al.*, “Fluid layered ferroelectrics with global C_{∞v} symmetry,” *Adv. Sci. (Weinh)* **9**, 2202048 (2022).
261. H. Kikuchi *et al.*, “Ferroelectric smectic c liquid crystal phase with spontaneous polarization in the direction of the director,” *Adv. Sci.* **11**, 2409827 (2024).
262. X. Chen *et al.*, “The smectic Z(A) phase: Antiferroelectric smectic order as a prelude to the ferroelectric nematic,” *Proc Natl. Acad. Sci. USA* **120**, e2217150120 (2023).
263. G. J. Strachan *et al.*, “Nematic and smectic phases with proper ferroelectric order,” *Adv. Sci. (Weinh)* **12**, 2409754 (2025).
264. M. S. H. Himel *et al.*, “Electrically tunable chiral ferroelectric nematic liquid crystal reflectors,” *Adv. Funct. Mater.* **35**, 2413674 (2025).
265. C. L. Folcia *et al.*, “Chiral ferroelectric nematic liquid crystals as materials for versatile laser devices,” *Giant* **19**, 100316 (2024).
266. F. Hassan *et al.*, “Optically induced holographic gratings in a ferroelectric nematic liquid crystal activated by an electric field,” *Opt. Lett.* **50**, 4038 (2025).
267. N. Sebastián *et al.*, “Electrooptics of mm-scale polar domains in the ferroelectric nematic phase,” *Liq. Crys.* **48**, 2055 (2021).
268. J. Yang *et al.*, “Flexoelectricity-driven toroidal polar topology in liquid-matter helielectrics,” *Nat. Phys.* **20**, 991 (2024).
269. S. Yi *et al.*, “Chiral pi domain walls composed of twin half-integer surface disclinations in ferroelectric nematic liquid crystals,” *Proc Natl. Acad. Sci. USA* **121**, e2413879121 (2024).
270. C. Y. Li *et al.*, “Domain engineering in ferroelectric nematics for nonlinear optical modulation,” *Sci. Adv.* **11**, eadu7362 (2025).
271. N. Sebastián *et al.*, “Polarization patterning in ferroelectric nematic liquids via flexoelectric coupling,” *Nat. Commun.* **14**, 3029 (2023).
272. J. Yang *et al.*, “Spontaneous electric-polarization topology in confined ferroelectric nematics,” *Nat. Commun.* **13**, 7806 (2022).
273. Z. Xu *et al.*, “Interface-engineered polar topological domains in ferroelectric nematic liquid crystals,” *Adv. Mater.* **37**, 2501395 (2025).
274. M. Lovšin *et al.*, “Patterning of 2D second harmonic generation active arrays in ferroelectric nematic fluids,” *Giant* **19**, 100315 (2024).
275. Z. Ma *et al.*, “Double splay nematic order in confined polar fluids,” *Phys. Rev. Lett.* **134**, 238101 (2025).
276. S. S. Kruk *et al.*, “Asymmetric parametric generation of images with nonlinear dielectric metasurfaces,” *Nat. Photonics* **16**, 561 (2022).
277. G. Li *et al.*, “Nonlinear metasurface for simultaneous control of spin and orbital angular momentum in second harmonic generation,” *Nano Lett.* **17**, 7974 (2017).
278. Z. Hao *et al.*, “Full complex-amplitude modulation of second harmonic generation with nonlinear metasurfaces,” *Laser Photonics Rev.* **15**, 2100207 (2021).
279. G. Li *et al.*, “Continuous control of the nonlinearity phase for harmonic generations,” *Nat. Mater.* **14**, 607 (2015).
280. T. Vipin and S. B. Nandan, *Holography* (IntechOpen, 2022), p. Ch. 1.
281. L. Song *et al.*, “Direct femtosecond pulse compression with miniature-sized Bragg cholesteric liquid crystal,” *Opt. Lett.* **38**, 5040 (2013).
282. R. A. Hussein, M. F. O. Hameed, and S. S. A. Obayya, “Ultrahigh soliton pulse compression through liquid crystal photonic crystal fiber,” *IEEE J. Sel. Top. Quantum Electron.* **22**, 302 (2016).
283. Y. Liu *et al.*, “Ultrafast pulse compression, stretching-and-recompression using cholesteric liquid crystals,” *Opt. Express* **24**, 10458 (2016).
284. Y. Liu, J. Zhou, and T.-H. Lin, “Blue-phase liquid crystals: synthesis and prospective applications in nonlinear image processing and self-action sensor protection,” *Proc. SPIE* **13587**, 135870B (2016).
285. I. C. Khoo, “Cholesteric and blue-phase liquid photonic crystals for nonlinear optics and ultrafast laser pulse modulations,” *Liq. Cryst. Rev.* **6**, 53 (2018).
286. L. Ma *et al.*, “Submicrosecond electro-optical switching of one-dimensional soft photonic crystals,” *Photonics Res.* **10**, 786 (2022).
287. V. Borshch, S. V. Shiyanovskii, and O. D. Lavrentovich, “Nanosecond electro-optic switching of a liquid crystal,” *Phys. Rev. Lett.* **111**, 107802 (2013).
288. V. Borshch *et al.*, “Nanosecond electro-optics of a nematic liquid crystal with negative dielectric anisotropy,” *Phys. Rev. E* **90**, 062504 (2014).
289. B.-X. Li *et al.*, “Electro-optic switching of dielectrically negative nematic through nanosecond electric modification of order parameter,” *Appl. Phys. Lett.* **104**, 201105 (2014).
290. B. X. Li, S. V. Shiyanovskii, and O. D. Lavrentovich, “Nanosecond switching of micrometer optical retardance by an electrically controlled nematic liquid crystal cell,” *Opt. Express* **24**, 29477 (2016).
291. B.-X. Li *et al.*, “Enhanced nanosecond electro-optic effect in isotropic and nematic phases of dielectrically negative nematics doped by strongly polar additive,” *J. Mol. Liq.* **267**, 450 (2018).
292. B.-X. Li *et al.*, “Microsecond electro-optic switching of nematic liquid crystals with giant dielectric anisotropy,” *Phys. Rev. Appl.* **12**, 024005 (2019).
293. B. X. Li *et al.*, “Dye-doped dual-frequency nematic cells as fast-switching polarization-independent shutters,” *Opt. Express* **27**, 3861 (2019).
294. J. Chen *et al.*, “Polymerization enabled reduction of the electrically induced birefringence change in nematic liquid crystals,” *Chin. Opt. Lett.* **20**, 023201 (2022).
295. K. Thapa, S. Paladugu, and O. D. Lavrentovich, “Microsecond electro-optic switching in the nematic phase of a ferroelectric nematic liquid crystal,” *Opt. Express* **32**, 40274 (2024).
296. K. Thapa, S. Paladugu, and O. D. Lavrentovich, “Submicrosecond electric switching of large birefringence in the isotropic phase of ferroelectric nematics,” *Adv. Opt. Mater.* **13**, e01338 (2025).
297. A. M. Weiner, “Ultrafast optical pulse shaping: a tutorial review,” *Opt. Commun.* **284**, 3669 (2011).
298. H. E. Kondakci and A. F. Abouraddy, “Diffraction-free pulsed optical beams via space-time correlations,” *Opt. Express* **24**, 28659 (2016).
299. H. E. Kondakci and A. F. Abouraddy, “Diffraction-free space-time light sheets,” *Nat. Photonics* **11**, 733 (2017).
300. M. A. Porras, “Nature, diffraction-free propagation via space-time correlations, and nonlinear generation of time-diffracting light beams,” *Phys. Rev. A* **97**, 063803 (2018).
301. R. Almeida *et al.*, “Universal structure of propagation-invariant optical pulses,” *Opt. Lett.* **50**, 3393 (2025).
302. M. Yessenov *et al.*, “Space-time wave packets,” *Adv. Opt. Photonics* **14**, 455 (2022).
303. L. A. Hall, M. Yessenov, and A. F. Abouraddy, “Arbitrarily accelerating space-time wave packets,” *Opt. Lett.* **47**, 694 (2022).
304. C. Wang *et al.*, “Spatiotemporal optical wave packets with arbitrary trajectories,” *Opt. Lett.* **50**, 4114 (2025).
305. H. E. Kondakci and A. F. Abouraddy, “Airy wave packets accelerating in space-time,” *Phys. Rev. Lett.* **120**, 163901 (2018).
306. M. Yessenov *et al.*, “Veiled Talbot effect,” *Phys. Rev. Lett.* **125**, 243901 (2020).

307. L. A. Hall and A. F. Abouraddy, "Observation of optical de Broglie-Mackinnon wave packets," *Nat. Phys.* **19**, 435 (2023).
308. A. M. A. Motz, M. Yessenov, and A. F. Abouraddy, "Axial spectral encoding of space-time wave packets," *Phys. Rev. Appl.* **15**, 024067 (2021).
309. L. A. Hall *et al.*, "Long-distance axial spectral encoding using space-time wave packets," *Opt. Lett.* **50**, 4698 (2025).
310. M. A. Porras, "Transverse orbital angular momentum of spatiotemporal optical vortices," *Prog. Electromagn. Res.* **177**, 95 (2023).
311. A. Sukhorukov and V. Yangirova, "Spatio-temporal vortices: properties, generation and recording," *Proc. SPIE* **5949**, 93 (2005).
312. M. Dallaire, N. McCarthy, and M. Piche, "Spatiotemporal Bessel beams: theory and experiments," *Opt. Express* **17**, 18148 (2009).
313. K. Y. Bliokh and F. Nori, "Spatiotemporal vortex beams and angular momentum," *Phys. Rev. A* **86**, 033824 (2012).
314. N. Jhajj *et al.*, "Spatiotemporal optical vortices," *Phys. Rev. X* **6**, 031037 (2016).
315. S. W. Hancock *et al.*, "Free-space propagation of spatiotemporal optical vortices," *Optica* **6**, 1547 (2019).
316. W. Chen *et al.*, "Time diffraction-free transverse orbital angular momentum beams," *Nat. Commun.* **13**, 4021 (2022).
317. X. Liu *et al.*, "Spatiotemporal optical vortices with controllable radial and azimuthal quantum numbers," *Nat. Commun.* **15**, 5435 (2024).
318. S. A. Ponomarenko and D. Hebri, "Perfect space-time vortices," *Opt. Lett.* **49**, 4322 (2024).
319. H. Fan, Q. Cao, X. Liu, A. Chong, and Q. Zhan, "Perfect spatiotemporal optical vortices," *Photonics Res.* **13**, 1776 (2025).
320. J. Cheng *et al.*, "Spatiotemporal optical vortices with invariant radius and width," *Laser Photonics Rev.* **19**, e00318 (2025).
321. S. Zhang *et al.*, "Controllable perfect spatiotemporal optical vortices," arXiv:2501.10055 (2025).
322. W. Chen, Y. Liu, and Y.-Q. Lu, "Spatiotemporal optical vortices: toward tailoring orbital angular momentum of light in full space-time," *ACS Photonics* **10**, 2011 (2023).
323. C. Wan, A. Chong, and Q. Zhan, "Optical spatiotemporal vortices," *eLight* **3**, 11 (2023).
324. F. Feng and X. Yuan, "A new member of the structured light family: optical spatiotemporal vortices," *Light Sci. Appl.* **12**, 236 (2023).
325. Y. Shen *et al.*, "Roadmap on spatiotemporal light fields," *J. Opt.* **25**, 093001 (2023).
326. A. Bekshaev, "Spatiotemporal optical vortices: Principles of description and basic properties," *APL Photonics* **9**, 110806 (2024).
327. X. Liu, Q. Cao, and Q. Zhan, "Spatiotemporal optical wavepackets: from concepts to applications," *Photonics Insights* **3**, R08 (2024).
328. Z. Huang *et al.*, "Observation of spatiotemporal coupled Airy-Airy wavepacket and its propagation dynamics," *Opt. Express* **33**, 31949 (2025).
329. A. Z. Yu *et al.*, "Spatiotemporal Moiré lattice light fields," *Nanophotonics* **14**, 707 (2025).
330. Q. Cao *et al.*, "Spatiotemporal hologram," *Nat. Commun.* **15**, 7821 (2024).
331. B. Wu *et al.*, "Single ultrafast pulses shaped to spatiotemporal images," *Laser Photonics Rev.* **19**, 2402238 (2025).
332. A. Chong *et al.*, "Airy-Bessel wave packets as versatile linear light bullets," *Nat. Photonics* **4**, 103 (2010).
333. D. Abdollahpour *et al.*, "Spatiotemporal airy light bullets in the linear and nonlinear regimes," *Phys. Rev. Lett.* **105**, 253901 (2010).
334. Y. Zang, A. Miranda, and A. Chong, "Spatiotemporal optical vortices with arbitrary orbital angular momentum orientation by astigmatic mode converters," *Nanophotonics* **11**, 745 (2022).
335. C. Wan *et al.*, "Photonic orbital angular momentum with controllable orientation," *Natl. Sci. Rev.* **9**, nwab149 (2021).
336. F. Cardano and L. Marrucci, "Smoke rings of light," *Nat. Photonics* **16**, 476 (2022).
337. L. Chen *et al.*, "Synthesizing ultrafast optical pulses with arbitrary spatiotemporal control," *Sci. Adv.* **8**, eabq8314 (2022).
338. B. Chen *et al.*, "Integrated optical vortex microcomb," *Nat. Photonics* **18**, 625 (2024).
339. Q. Lin *et al.*, "Direct space-time manipulation mechanism for spatio-temporal coupling of ultrafast light field," *Nat. Commun.* **15**, 2416 (2024).
340. Y. Liu *et al.*, "Integrated vortex soliton microcombs," *Nat. Photonics* **18**, 632 (2024).
341. S. Shi *et al.*, "Double-helix singularity and vortex-antivortex annihilation in space-time helical pulses," *Nanophotonics* **14**, 741 (2025).
342. X. Su *et al.*, "Space-time wave packets in multimode optical fibers with controlled dynamic motions and tunable group velocities," *Nat. Commun.* **16**, 2027 (2025).
343. F. Kong *et al.*, "Generation of transverse light spring," *Opt. Lett.* **50**, 2622 (2025).
344. D. Cruz-Delgado *et al.*, "Synthesis of ultrafast wavepackets with tailored spatiotemporal properties," *Nat. Photonics* **16**, 686 (2022).
345. D. Cruz-Delgado *et al.*, "Spatiotemporal control of ultrafast pulses in multimode optical fibers," *Nat. Commun.* **16**, 6081 (2025).
346. Q. Cao, P. Zheng, and Q. Zhan, "Vectorial sculpturing of spatiotemporal wavepackets," *APL Photonics* **7**, 096102 (2022).
347. H. Teng *et al.*, "Construction of optical spatiotemporal skyrmions," *Light Sci. Appl.* **14**, 324 (2025).
348. J. C. Yang *et al.*, "Nonlinear photon sieves for high-fidelity wavefront engineering," *Laser Photonics Rev.* **19**, e01117 (2025).
349. P. Béjot and B. Kibler, "Taming light in all dimensions," *Nat. Photonics* **16**, 671 (2022).
350. A. B. Stilgoe, T. A. Nieminen, and H. Rubinsztein-Dunlop, "Controlled transfer of transverse orbital angular momentum to optically trapped birefringent microparticles," *Nat. Photonics* **16**, 346 (2022).
351. S. Huang *et al.*, "Spatiotemporal vortex strings," *Sci. Adv.* **10**, eadn6206 (2024).
352. H. Ge *et al.*, "Spatiotemporal acoustic vortex beams with transverse orbital angular momentum," *Phys. Rev. Lett.* **131**, 014001 (2023).
353. H. Zhang *et al.*, "Topologically crafted spatiotemporal vortices in acoustics," *Nat. Commun.* **14**, 6238 (2023).
354. S. Liu *et al.*, "Generation of spatiotemporal acoustic vortices with arbitrarily oriented orbital angular momentum," *Nat. Commun.* **16**, 2823 (2025).
355. J. Verbeeck, H. Tian, and P. Schattschneider, "Production and application of electron vortex beams," *Nature* **467**, 301 (2010).
356. V. Grillo *et al.*, "Measuring the orbital angular momentum spectrum of an electron beam," *Nat. Commun.* **8**, 15536 (2017).
357. P. She *et al.*, "Photoactivated circularly polarized luminescent organic radicals in doped amorphous polymer," *Angew. Chem. Int. Ed. Engl.* **63**, e202403660 (2024).
358. J. Han *et al.*, "Recent progress on circularly polarized luminescent materials for organic optoelectronic devices," *Adv. Opt. Mater.* **6**, 1800538 (2018).
359. C. Yin *et al.*, "A universal strategy for multicolor organic circularly polarized afterglow materials with high dissymmetry factors," *Proc. Natl. Acad. Sci. USA* **122**, e2419481122 (2025).
360. X. Wang, B. Zhao, and J. Deng, "Liquid crystals doped with chiral fluorescent polymer: multi-color circularly polarized fluorescence and room-temperature phosphorescence with high dissymmetry factor and anti-counterfeiting application," *Adv. Mater.* **35**, e2304405 (2023).
361. S. Q. Qiu *et al.*, "Chiral luminescent ion pair (CLIP) strategy enables amorphous platinum complexes circularly polarized phosphorescence," *Angew. Chem. Int. Ed. Engl.* **64**, e202501011 (2025).
362. X. Cheng *et al.*, "Recent development in sensitizers for lanthanide-doped upconversion luminescence," *Chem. Rev.* **122**, 15998 (2022).

363. Y. Wei *et al.*, “Frenkel defect-modulated anti-thermal quenching luminescence in lanthanide-doped $\text{Sc}_2(\text{WO}_4)_3$,” *Angew. Chem. Int. Ed.* **62**, e202303482 (2023).
364. Y. Wei *et al.*, “Tunable anti-thermal quenching luminescence of Eu^{3+} -doped metal-organic framework and temperature-dependent photonic coding,” *Adv. Funct. Mater.* **34**, 2401664 (2024).
365. J. Kim *et al.*, “Monitoring the orientation of rare-earth-doped nanorods for flow shear tomography,” *Nat. Nanotechnol.* **12**, 914 (2017).
366. B. Yang *et al.*, “Upconversion/downshifting circularly polarized luminescence over 1200 nm in a single nanoparticle for optical anticounterfeiting and information encryption,” *Angew. Chem. Int. Ed. Engl.* **64**, e202417223 (2025).
367. D. Kim *et al.*, “Dynamic magnetic field alignment and polarized emission of semiconductor nanoplatelets in a liquid crystal polymer,” *Nat. Commun.* **13**, 2507 (2022).
368. H. Moon *et al.*, “Stability of quantum dots, quantum dot films, and quantum dot light-emitting diodes for display applications,” *Adv. Mater.* **31**, e1804294 (2019).
369. S. Chang *et al.*, “Mechanoluminescent functional devices: developments, applications and prospects,” *Nano Energy* **122**, 109325 (2024).
370. J. Liu *et al.*, “Dynamically modulating the dissymmetry factor of circularly polarized organic ultralong room-temperature phosphorescence from soft helical superstructures,” *Angew. Chem. Int. Ed. Engl.* **63**, e202319536 (2024).
371. Y. Li *et al.*, “Light-driven sign inversion of circularly polarized luminescence enabled by dichroism modulation in cholesteric liquid crystals,” *Adv. Mater.* **36**, e2312331 (2024).
372. X. Zhang *et al.*, “Mechanically tunable circularly polarized luminescence of liquid crystal-templated chiral perovskite quantum dots,” *Angew. Chem. Int. Ed. Engl.* **63**, e202404202 (2024).
373. C. Fu *et al.*, “Chiral co-assembled liquid crystal polymer network enabled by *in-situ* photopolymerization for high-performance CP-OLEDs,” *Angew. Chem. Int. Ed. Engl.* **64**, e202512257 (2025).
374. J. Chen *et al.*, “Efficient and bright white light-emitting diodes based on single-layer heterophase halide perovskites,” *Nat. Photonics* **15**, 238 (2020).
375. J. Sun *et al.*, “Exceptionally stable blue phosphorescent organic light-emitting diodes,” *Nat. Photonics* **16**, 212 (2022).
376. J. Guo *et al.*, “In-sensor computing with visual-tactile perception enabled by mechano-optical artificial synapse,” *Adv. Mater.* **37**, e2419405 (2025).
377. H. I. Jeong *et al.*, “Super elastic and negative triboelectric polymer matrix for high performance mechanoluminescent platforms,” *Nat. Commun.* **16**, 854 (2025).
378. D. Qu *et al.*, “Circularly polarized laser with chiral nematic cellulose nanocrystal cavity,” *ACS Nano* **15**, 8753 (2021).
379. W. Lin *et al.*, “Toward chiral lasing from all-solution-processed flexible perovskite-nanocrystal-liquid-crystal membranes,” *Adv. Mater.* **35**, e2301573 (2023).
380. M. Mohammadimasoudi *et al.*, “Quantum dot lasing from a waterproof and stretchable polymer film,” *Light Sci. Appl.* **11**, 275 (2022).
381. H. Gu *et al.*, “Color-tunable lead halide perovskite single-mode chiral microlasers with exceptionally high $g(\text{lum})$,” *Nano Lett.* **24**, 13333 (2024).
382. L. Ye *et al.*, “Controllable random lasers from dye-doped liquid crystal with plasmonic silver nanostructures,” *Opt. Mater.* **164**, 117038 (2025).
383. Y. He *et al.*, “Irradiation-wavelength directing circularly polarized luminescence in self-organized helical superstructures enabled by hydrogen-bonded chiral fluorescent molecular switches,” *Angew. Chem. Int. Ed. Engl.* **60**, 27158 (2021).
384. X. X. Yang *et al.*, “Chiral liquid crystalline metal-organic framework thin films for highly circularly polarized luminescence,” *J. Am. Chem. Soc.* **146**, 16213 (2024).
385. J. Liu *et al.*, “Circularly polarized luminescence in chiral orientationally ordered soft matter systems,” *Responsive Mater.* **1**, e20230005 (2023).
386. W. Kang *et al.*, “A photo- and thermo-driven azoarene-based circularly polarized luminescence molecular switch in a liquid crystal host,” *Angew. Chem. Int. Ed. Engl.* **62**, e202311486 (2023).
387. S. Kang *et al.*, “Bio-organic chiral nematic materials with adaptive light emission and on-demand handedness,” *Adv. Mater.* **33**, e2103329 (2021).
388. H. Munderoor *et al.*, “Hybrid molecular-colloidal liquid crystals,” *Science* **360**, 768 (2018).
389. H. Zhong *et al.*, “Matching Rule” for generation, modulation and amplification of circularly polarized luminescence,” *Acc. Chem. Res.* **57**, 1188 (2024).
390. Z. X. Yu *et al.*, “Intrinsically luminescent nematic liquid crystals enabling high-brightness full-color and white circularly polarized luminescence via chiral coassembly,” *Angew. Chem. Int. Ed. Engl.* **64**, e202507802 (2025).
391. S. Zhang *et al.*, “Freestanding scattering polarizer assembled with subnanowires and liquid crystals,” *Adv. Funct. Mater.* **34**, 2405243 (2024).
392. H. He *et al.*, “Linearly polarized emission from shear-induced nematic phase upconversion nanorods,” *Nano Lett.* **20**, 4204 (2020).
393. P. Zhao *et al.*, “High-performance white circularly polarized photoluminescence and electroluminescence from multi-emission enantiomers,” *Angew. Chem. Int. Ed. Engl.* **64**, e202424918 (2025).
394. Q. Xia *et al.*, “Direct visualization of chiral amplification of chiral aggregation induced emission molecules in nematic liquid crystals,” *ACS Nano* **15**, 4956 (2021).
395. X. Yang *et al.*, “Dual band-edge enhancing overall performance of upconverted near-infrared circularly polarized luminescence for anticounterfeiting,” *ACS Nano* **17**, 2661 (2023).
396. J. Liu *et al.*, “Light-dynamic chirality inversion of circularly polarized organic ultralong room-temperature phosphorescence enabled by soft helical superstructure,” *Adv. Opt. Mater.* **13**, 2403468 (2025).
397. J. Liu *et al.*, “Circularly polarized organic ultralong room-temperature phosphorescence: generation, enhancement, and application,” *Adv. Funct. Mater.* **35**, 2414086 (2024).
398. X. Zhang *et al.*, “Liquid crystal-templated chiral nanomaterials: from chiral plasmonics to circularly polarized luminescence,” *Light Sci. Appl.* **11**, 223 (2022).
399. J. Hou *et al.*, “Programming and dynamic control of the circular polarization of luminescence from an achiral fluorescent dye in a liquid crystal host by molecular motors,” *Angew. Chem. Int. Ed. Engl.* **61**, e202206310 (2022).
400. Y. Chen *et al.*, “Dynamic circularly polarized luminescence with tunable handedness and intensity enabled by achiral dichroic dyes in cholesteric liquid crystal medium,” *Adv. Mater.* **34**, e2202309 (2022).
401. J. Li *et al.*, “Phosphorescent liquid crystalline polymer-based circularly polarized luminescence optical waveguides for enhanced photonic signal processing and information encryption,” *Angew. Chem. Int. Ed. Engl.* **64**, e202423395 (2025).
402. Y. Shi *et al.*, “Recyclable soft photonic crystal film with overall improved circularly polarized luminescence,” *Nat. Commun.* **14**, 6123 (2023).
403. E. Galiffi *et al.*, “Photonics of time-varying media,” *Adv. Photonics* **4**, 014002 (2022).
404. S. Yin, E. Galiffi, and A. Alù, “Floquet metamaterials,” *eLight* **2**, 8 (2022).
405. N. Engheta, “Four-dimensional optics using time-varying metamaterials,” *Science* **379**, 1190 (2023).