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PERSPECTIVE

Soft Matter Photonics: Interplay of Soft Matter and Light

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Cite This: *ACS Nano* 2025, 19, 11501−11516

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ABSTRACT: **The light−soft matter interaction and its applications form the foundation of Soft Matter Photonics, here termed "Soft Mattonics", positioning it as fertile ground for developing next-generation photonic technologies. Over the past few decades, this rapidly evolving field has achieved significant advancements, leading to successful applications across a wide range of disciplines, including optoelectronics, photonics, information technology, material science, robotics, biomedicine, and astronomy. In this Perspective, we provide an overview of Soft Mattonics, highlighting recent developments in light-controlled soft matter and their applications in light field manipulating. Additionally, we offer insights into future research directions for Soft Mattonics, with an emphasis on both foundational research and practical applications that will drive continued growth and innovation in this field.**

KEYWORDS: *light-matter interaction, soft matter, microstructure, liquid crystals, photonics*

Soft Matter Photonics, referred to here as "Soft Mattonics", is an emerging and rapidly evolving field that has garnered significant attention in recent years.[1−3] This interdisciplinary area explores the intricate interplay between light and soft matter, opening up new avenues for innovation in optical communication, sensing, energy harvesting, and beyond. On one hand, light serves as a potent tool to manipulate the soft matter. It can trigger molecular configuration transitions at the nanoscale, guide the self-assembly of functional microstructures, and even drive macroscopic shape morphing, facilitating an efficient, precise, remote, and multilevel control over these systems across various scales.[4−9] On the other hand, soft matter, with their finely tuned nano- and microscale architectures, interact with light in ways that allow for the manipulation of multiple degrees of freedom of light, including amplitude, polarization, phase, orbit angular momentum, frequency, and wave vector (Figure 1). This intersection of soft matter and photonics—to be both controlled by soft matter (light) and to control soft matter (light)—forms the foundation of Soft Mattonics, making it fertile ground for developing next-generation photonic technologies.

In this Perspective, we begin by introducing the concept of Soft Mattonics, which represents a synergistic integration of soft matter and photonics. Then we present recent developments in light-controlled soft matter and their implementation in light field manipulating, focusing primarily on optically anisotropic LCs as a representative case study of soft matter while also incorporating discussions of other representative soft matter. Subsequently, we consider the issues that need to be addressed further. In addition, we provide an outlook on the future development of Soft Mattonics in both practical application and fundamental research.

WHY SOFT MATTONICS?

The study of materials science encompasses a broad spectrum of materials with diverse properties and applications, which holds profound significance across various scientific, technological, and industrial domains. Among these, hard materials and soft matter represent two fundamental categories that, while distinct in their physical characteristics, complement each other in their roles within both natural and engineered systems.

Hard materials are distinguished by their significant resistance to deformation when subjected to forces, such as scratching, indentation, or mechanical wear. This characteristic hardness stems from specific bonding orientations, strong interatomic bond energies, typically ranging from 1 to 10 eV, and saturated bonding capacity, together leading to a stable and rigid structure. However, these materials are also

Received: February 10, 2025
Revised: March 11, 2025
Accepted: March 12, 2025
Published: March 20, 2025

https://doi.org/10.1021/acsnano.5c02465
ACS Nano 2025, 19, 11501−11516

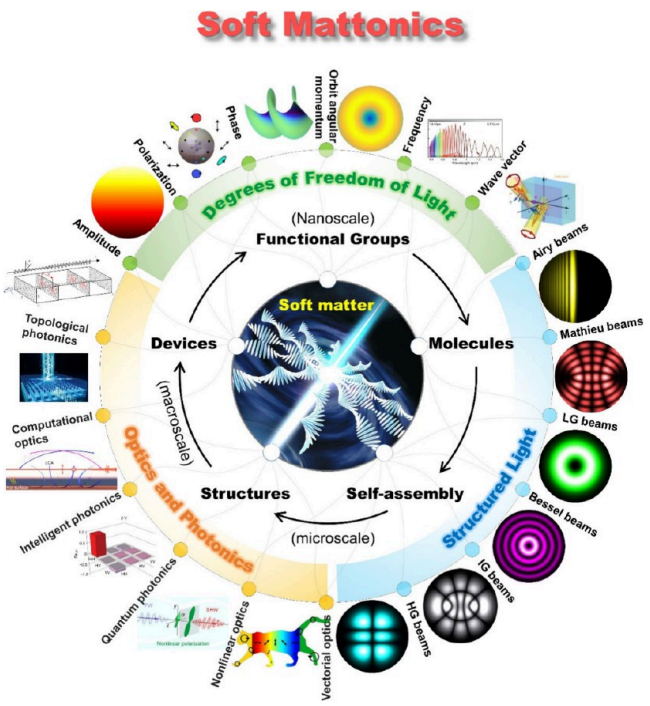

Figure 1. Soft Mattonics. The attributes, hierarchies, and distinctive features of soft matter (inner circle), ranging from nano- to macroscale. (Reprinted in part with permission from ref 5. Copyright 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.) Representative diagrams of degrees of freedom of light including amplitude, polarization, phase (Reprinted in part with permission under a Creative Commons CC BY License from ref 10. Copyright 2022 Springer Nature.), orbit angular momentum, frequency (Reprinted in part with permission from ref 11. Copyright 2022 Wiley-VCH GmbH.), and wave vector (Reprinted in part with permission from ref 12. Copyright 2015 Springer Nature Limited.) (outer circle, green part). Representative diagrams of structured light including airy beams, Mathieu beams, Laguerre-Gaussian (LG) beams, Bessel beams, Ince-Gaussian (IG) beams, and Hermite-Gaussian (HG) beams (Reprinted in part with permission from ref 13. Copyright 2021 Springer Nature Limited.) (outer circle, blue part). Soft matter photonics encompasses vectorial optics (Reprinted in part with permission under a Creative Commons Attribution 4.0 International License from ref 14. Copyright 2024 Springer Nature.), nonlinear optics, quantum photonics (Reprinted in part with permission under a Creative Commons CC BY License from ref 15. Copyright 2024 Springer Nature.), intelligent photonics (Reprinted in part with permission from ref 7. Copyright 2023 Wiley-VCH GmbH.), computational optics (Reprinted in part with permission under a Creative Commons CC BY License from ref 16. Copyright 2022 Springer Nature.), and topological photonics (Reprinted in part with permission under a Creative Commons CC BY License from ref 17. Copyright 2021 National Academy of Sciences.) (outer circle, yellow part).

constrained by spatial and point group symmetries, which limit their modulation and ability to resist localized plastic deformation.

In contrast, soft matter is characterized by weak intermolecular interactions, typically ranging from 10 to 100 meV. Unlike hard materials, these interactions have no directionality and saturability in bonding, granting soft matter a high degree of mobility, deformability, and flexibility. As a result, soft matter exhibits a rich diversity of phases and a wide variety of configurations across nano-, micro-, and macroscale (Figure 2), particularly in the form of topological defects, within the mesoscopic scale (approximately 10 to 10,000 nm). These unique properties, along with their "weak stimulus, strong response" behavior under various external fields, lead to complex dynamic systems with fascinating physical properties, and a broad range of applications.

The concept of "soft matter" was first introduced by Pierre-Gilles de Gennes during his Nobel Prize acceptance speech in 1991. He used the term to describe complex materials that exist in a state between liquids and ideal solids, such as LCs, polymers, colloids, complex fluids, foams, biological tissues, gels, and active matter (Figure 1).[4,6−9] These materials form the fundamental building blocks of living systems in nature largely due to their ability to spontaneously self-assemble into functional structures and their exceptional capacity to sense, respond to, and adapt to various environmental stimuli (usually nonlinear responses). Besides well-known stimuli-responsive LC materials, a prime example of soft matter is the cell membrane in living organisms, which is composed primarily of phospholipids arranged in a bilayer nanostructure.[25] The flexible, dynamic arrangement allows the cell membrane to perform essential functions, such as regulating the exchange of substances, maintaining cellular integrity, and facilitating communication between cells. The cell membrane's ability to adapt its structure in response to changes in the environment is crucial for maintaining vital biological functions such as homeostasis. Other important biological entities, such as DNA, cells, bodily fluids, and proteins, are also classified as soft matter. Moreover, recent studies have shown that the ultrafine size of inorganic nanostructures, such as nanowires, imparts them with flexibility and macromolecule-like self-assembly properties, while the inorganic backbone provides unique characteristics not found in traditional macromolecules, which further emphasizing the critical role of soft matter in both biological and technological contexts.[26,27]

From the above, we can see that the distinction between hard and soft matter is not only structural but also deeply functional. While hard materials construct the physical framework of the world, it is the soft matter that imbues it with life, adaptability, and harmony. These differences in form and function dictate the dynamics of systems at all scales—from the microscopic to the mesoscopic and ultimately to the macroscopic world. Therefore, soft matter is not just complementary to hard materials but is essential to the very essence of life and the complex operations of nature.

Soft matter physics has emerged as a widely recognized and significant field of study. This research area spans across physics, chemistry, and biology, and the advancement of soft matter physics is particularly critical, as it serves as a bridge between physical sciences and life sciences. Just as life depends on sunlight, light and soft matter share a profound and symbiotic relationship in the realms of materials science and optics. Soft matter, with its inherent flexibility, tunability, responsiveness, and self-assembly characteristics, offers unique opportunities for manipulating light in ways that hard materials cannot achieve. This close connection between light and soft matter is rooted in the latter's ability to undergo significant changes in structure, orientation, and properties in response to light, which in turn enables the development of advanced photonic devices and systems. This unique capability positions soft matter photonics as a critical trend in the evolution of condensed matter physics in the 21st century.

https://doi.org/10.1021/acsnano.5c02465
ACS Nano 2025, 19, 11501−11516

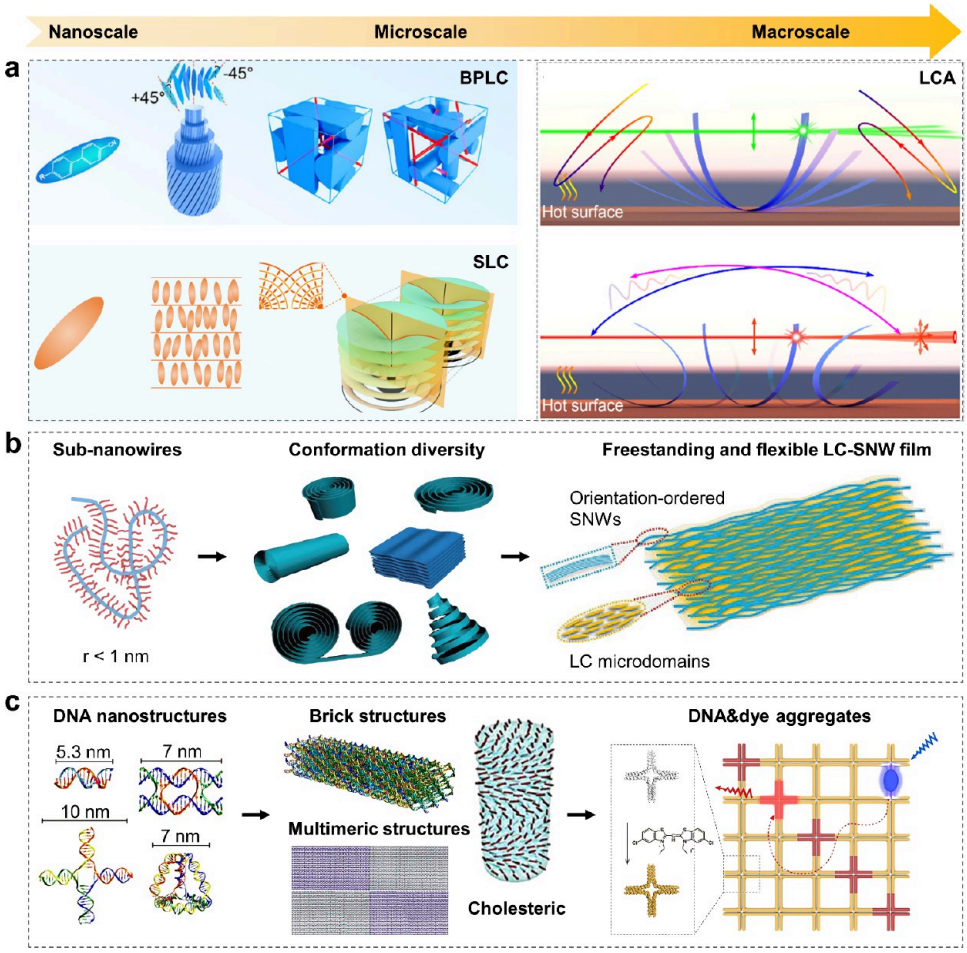

Figure 2. Cross-scale and multilevel structures in soft matter. Schematic diagrams of (a) LCs: nanoscale LC molecules, LC microstructures, and macroscopic LC actuators. BPLC and SLC denote blue phase LC and smectic LC (Reprinted in part with permission from ref 7. Copyright 2023 Wiley-VCH GmbH. Reprinted in part with permission from ref 18. Copyright 2024 Wiley-VCH GmbH. Reprinted in part with permission from ref 19. Copyright 2019 American Chemical Society.). (b) Inorganic subnanowires: from flexible subnanowire units to diverse assembly conformation, and macroscopic photonic application (Reprinted in part with permission from ref 20. Copyright 2013 American Chemical Society. Reprinted in part with permission from ref 21. Copyright 2024 Wiley-VCH GmbH.). (c) Biomass materials: from DNA nanostructures to diverse assembly structures and functional DNA+dye aggregates (Reprinted in part with permission under a Creative Commons Attribution 3.0 Unported License from ref 22. Copyright 2023 Royal Society of Chemistry. Reprinted in part with permission from ref 23. Copyright 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. Reprinted in part with permission from ref 24. Copyright 2022 Wiley-VCH GmbH.).

MANIPULATING SOFT MATTER BY LIGHT

The weak interactions inherent in soft matter create a delicate balance between entropic and enthalpic contributions to free energy, which facilitates the self-assembly of soft building blocks into cross-scale and multilevel structures (Figure 2) with high sensitivity to various stimuli, including light, electric fields, thermal fields, magnetic fields, mechanical forces, and pH. Among these stimuli, light is particularly advantageous due to its ability to provide untethered but efficient, selective but precise control capabilities of soft matter, allowing nanoscale, remote, noninvasive and highly targeted adjustments to their structure and behavior. The multiple degrees of freedom can also be harnessed. More recently, digital light emitted by commercial projectors has offered a flexible and convenient way for controlling soft matter in a pixelated manner. The ability to finely tune the response of soft matter by using light opens up new avenues for innovation, enabling the development of advanced photonic systems with broad applications across multiple fields.

Photoreactions in ordered media have been extensively studied.[28,29] LCs exemplify a quintessential class of soft matter with a unique combination of the anisotropic optical properties of crystals and the exceptional stimuli-responsiveness inherent in liquids.[30−33] When exposed to light, photoreactions trigger changes in the collective molecular orientation, which can be magnified across nano-, micro-, and even macroscale due to the strong cooperative change of the molecules.[30,34] Photochromic reactions have often been incorporated into soft matter due to their repeatability and effectiveness in controlling material properties. This approach has led to the development of various smart and light-responsive materials. These materials exhibit a range of phenomena, including surface-mediated photoalignment of LCs and incorporated anisotropic materials, photoinduced mechanical control of DNA polymer, photoinduced phase transitions, photoorientation of polymer thin films, photoinduced mass migrations, phototactic sliding motions, photodriven changes in monolayer morphology, and macroscopic photomechanical deformations, *etc.*

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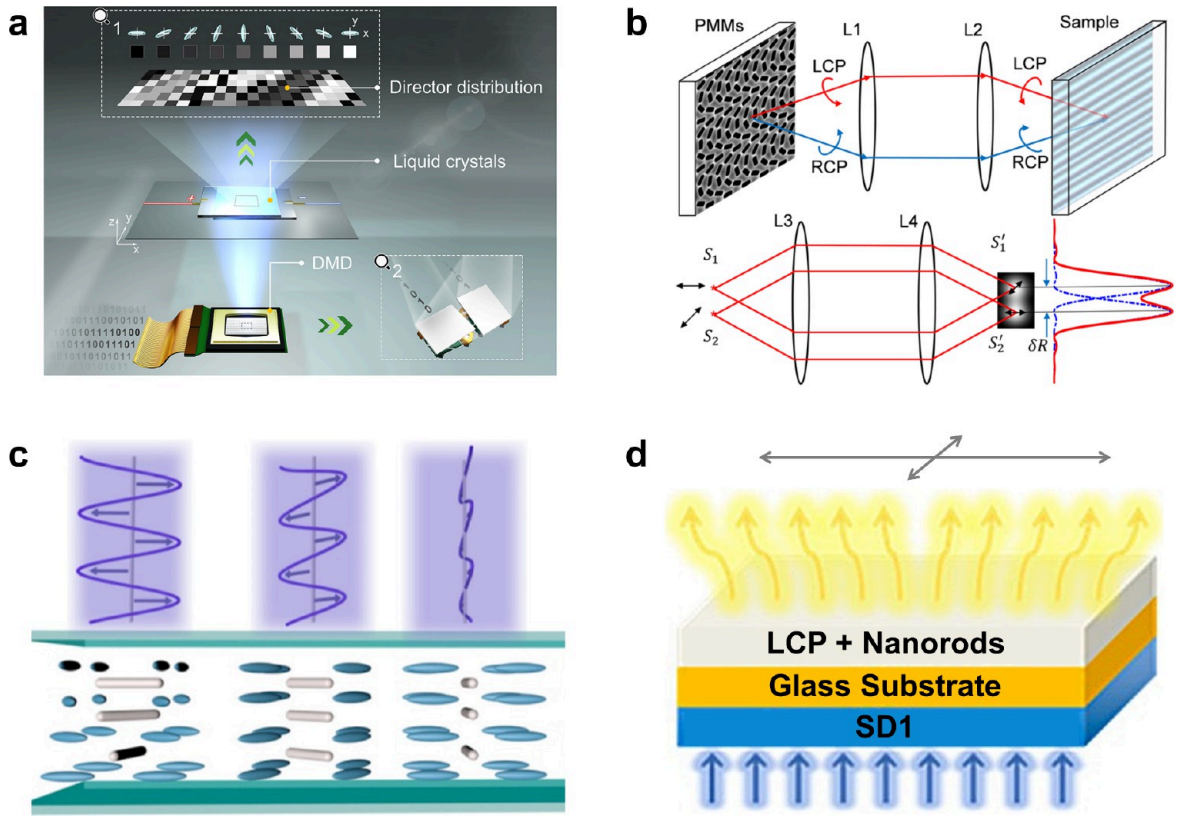

Figure 3. Photoalignment. (a) DMD based photopatterning system (Reprinted in part with permission under a Creative Commons CC BY 4.0 License from ref 14. Copyright 2024 Springer Nature.). (b) Plasmonic-metamask-based photopatterning system (Reprinted in part with permission from ref 35. Copyright 2024 Optica Publishing Group.). (c) Photoinduced colloidal silver nanowires in LC host with long-range order (Reprinted in part with permission from ref 36. Copyright 2024 American Chemical Society). (d) Photoalignment of nanorods in LC films. (Reprinted in part with permission from ref 37. Copyright 2015 American Chemical Society.).

Photoalignment. One of the most prominent examples of light control over LCs is the photoalignment,[38] which has become a prevailing technology for fabricating targeted LC nanostructures, microstructures, and even superstructures. The photoalignment process relies on photosensitive materials, such as azo-dyes, coated on substrates. When exposed to linearly polarized light (in most cases), these photoactive molecules orient their long molecular axes (or electric dipoles) perpendicular to light polarization. The LCs then align according to the director patterns created by molecular interactions with the photoalignment layer. Spatially variant director patterns can be achieved through multiple exposures to a focused laser beam in a pixel-by-pixel manner or to intensity patterns generated by digital micromirror devices (DMD) in a pattern-by-pattern manner (Figure 3a).[14] In these processes, the light is linearly polarized with its orientation adjusted for each exposure step. Alternatively, a single exposure to a light field with spatially variant polarization orientations—generated by either plasmonic metamasks or spatial light modulators—can also produce spatially variant director patterns. With the ongoing refinement of photoalignment techniques, both fundamental mechanisms and experimental precision have seen significant advancements. The smallest pixel sizes reported in the literature include 2 μm by direct laser writing,[39] 1 ∼ 2 μm by DMD-based photopatterning.[14] The smallest period achieved by a plasmonic-metamask-based photopatterning system (Figure 3b) is 1.5 μm.[35,40] Notably, unprecedented high spatial resolutions with minimal grating periods of 1 μm have been experimentally demonstrated.[35,41] The minimal core size in photopatterned singular topological defects is found to be smaller than 1 μm. Researchers are now capable of fine-tuning not only in-plane alignments but also out-of-plane architectures of LCs,[42] as well as achieving erasing and rewriting of alignment patterns.[43] Till now, photoalignment has been demonstrated to be valid in various LC phases (e.g., nematic LCs, lamellar smectic LCs,[44,45] helical cholesteric LCs,[5,46] double-twisted blue phase LCs,[47] lyotropic chromonic LCs,[48] liquid crystalline conjugated polymer[49]). These advancements are crucial for a wide range of applications where precise and versatile control over LC alignment is essential.

Thanks to the LCs light-controlled alignment technology and the excellent material compatibility of LCs systems, a variety of anisotropic exogenous functional nanomaterials, such as nanorods, nanowires, and nanoplatelets, can be introduced into the LCs matrix. This approach not only enables multifunctional integration but also, more importantly, allows for long-range orientation of the functional nanounits based on the molecular interactions between LCs molecules and anisotropic functional units. For example, micrometer-long colloidal nanowires can be dispersed in a nematic LCs host, resulting in the nanowires aligning parallel or perpendicular to the LCs director, depending on the interaction between surface ligands and surrounding LCs molecules (Figure 3c). Additionally, the self-assembly of colloidal nanowires into microdomains with different orientations can be achieved using photoalignment technology, enhancing the electronic properties and reducing the response time of LCs devices. Similarly,

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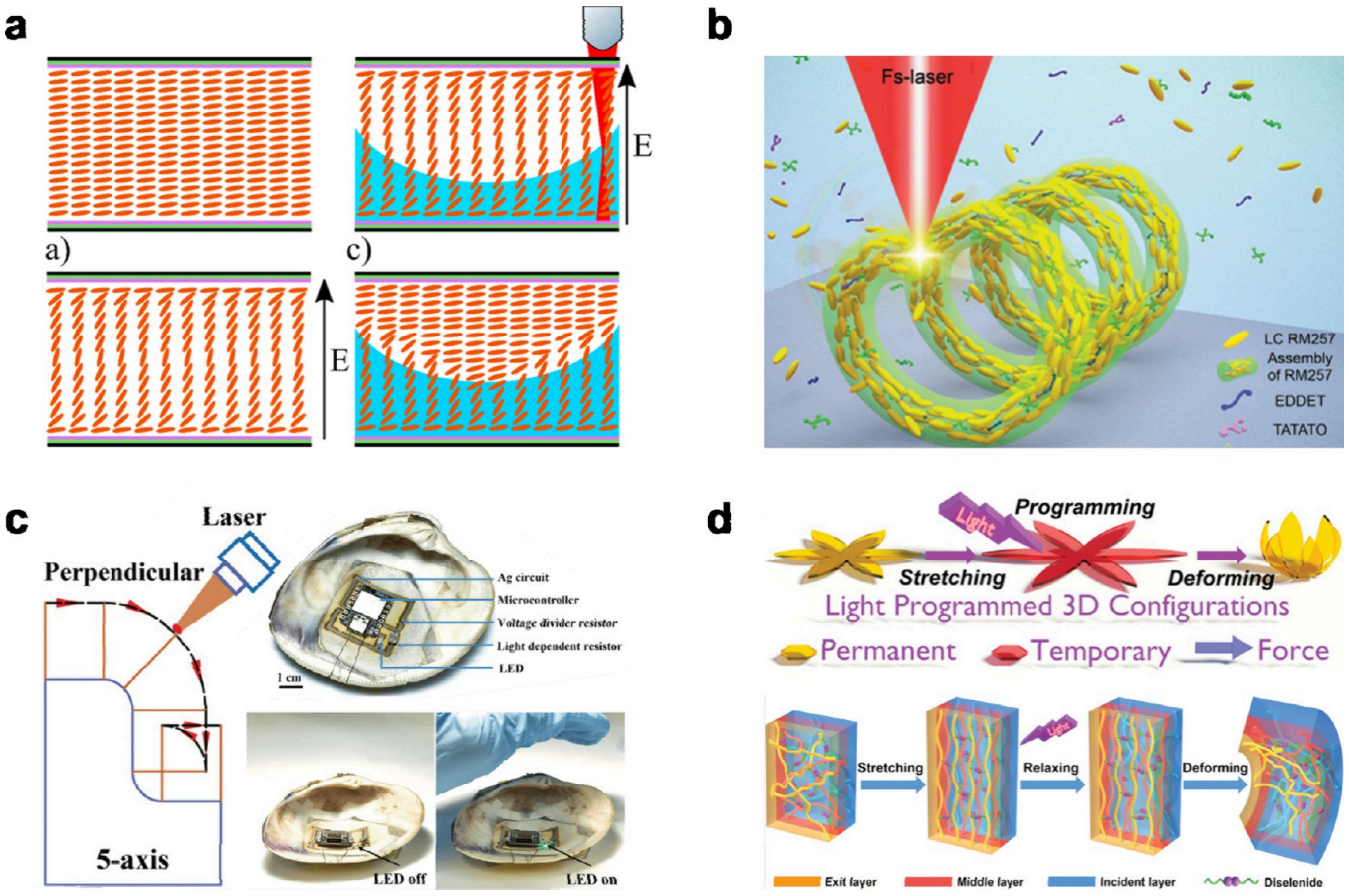

Figure 4. Manipulating from 2D to 4D. (a,b) 3D laser direct writing (Reprinted with permission under a Creative Commons CC BY 4.0 License from ref 53. Copyright 2023 American Chemical Society; Reprinted in part with permission from ref 54. Copyright 2024 Wiley-VCH GmbH.). (c) Freeform laser induction methods for the fabrication of 3D conformable electronics (Reprinted in part with permission from ref 55. Copyright 2023 Wiley-VCH GmbH.). (d) Unconstrained 3D shape programming with a light-induced stress gradient (Reprinted in part with permission from ref 56. Copyright 2021 Wiley-VCH GmbH.).

by preparing composite films of nanowires and LC polymers (LCP), not only can the mechanical properties of the films be improved, but the nanowires/LCP films can also be further programmed through micro-multidomain photoalignment, making them suitable for flexible and wearable devices.[36,50] Furthermore, the local alignment of luminescent nanorods can be achieved by combining photoalignment external forces with the self-assembly of the nanorods, where the interactions between the nanorod ligands and the LCP matrix play a crucial role in transferring optical torque from the alignment layer to the nanorods (Figure 3d). This leads to the achievement of polarized emission with a high degree of polarization, offering great potential for modern photonic and display devices.[37]

Even in non-LC systems, light can be used to induce the directional alignment of soft matter. For example, nanowire yarns and films composed of aligned semiconducting nanowires can be constructed through a light-induced nanowire assembly. When photoexcited nanowires are exposed to an external electric field, they form large asymmetric charge distributions along their length, which can be exploited to align and assemble them. As only photoexcited nanowires are easily aligned, selective excitation can be used to assemble specific nanowires from a complex mixture, facilitating the creation of nanowire heterostructures. This, in turn, allows the resulting yarns to retain the unique optical and electrical properties of the constituent nanowires.[51] Interestingly, similar light-controlled alignment effects can be achieved in DNA systems. For instance, by combining photopolymerizing monomers with hydrogen bonding capability and DNA-functionalized gold nanorods as cross-linkers that act as photothermal heat generators, a light-mediated photothermal process can induce the delinking of the hydrogen-bonded hydrogel matrix and DNA duplexes. This leads to temperature-controlled reconfiguration of gold nanorod orientation, holding potential for light-programmable orientational control of anisotropic nanoparticles and reconfigurable plasmonic responses.[52]

Manipulating from 2D to 4D. The control dimensions of soft matter have evolved significantly, extending from two-dimensional (2D) to three-dimensional (3D) and now to four-dimensional (4D) frameworks. This progression is largely due to the integration of advanced alignment methods with photopolymerization technologies, which enable the precise 3D assembly of soft building blocks with micrometer-level accuracy. Direct laser writing (DLW) has revolutionized the fabrication of high-resolution polymer structures. By combining LCs with a monomer and photoinitiator, selective 3D polymerization can be achieved using a femtosecond laser through a two-photon absorption process with high spatial resolution (Figure 4a).[53] The orientation of the LC director is precontrolled by applying an electric field during the writing process, ensuring accurate alignment. Recent breakthroughs have demonstrated the ability to perform arbitrary 3D, precise,

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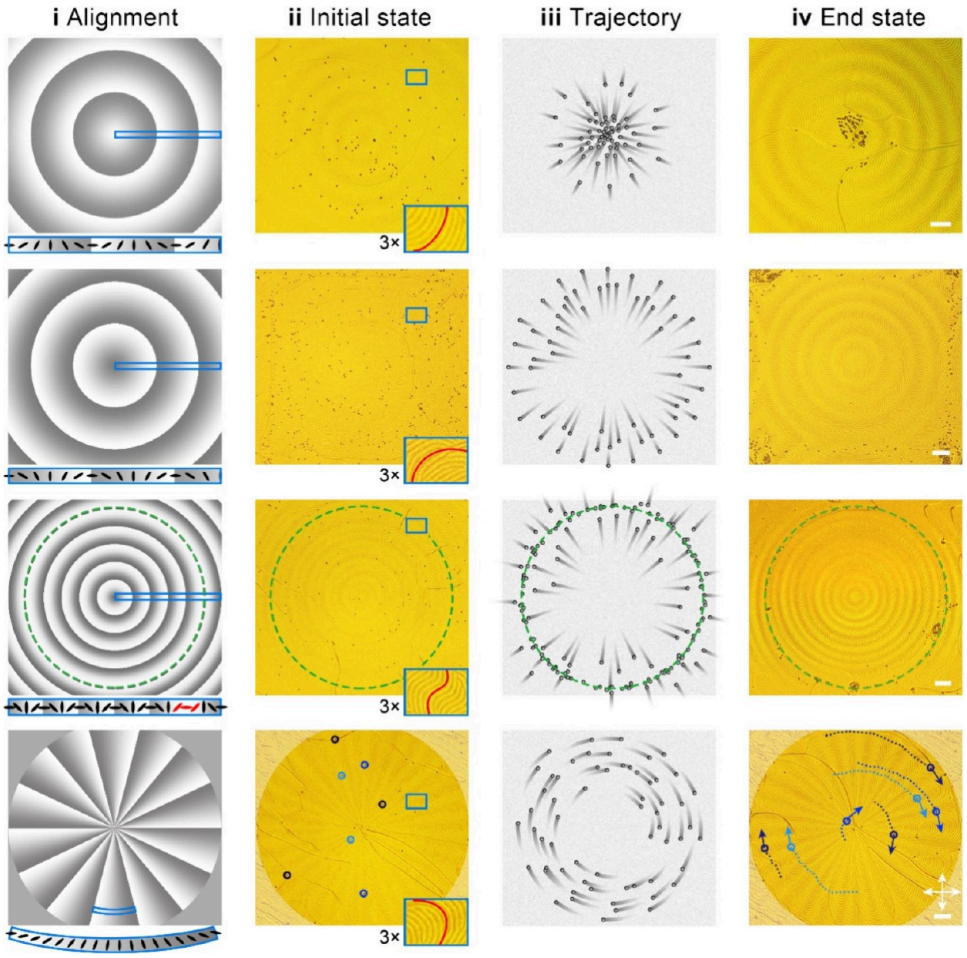

Figure 5. Programmable self-propelling actuators driven by light. (i) Photoalignment conditions, (ii) initial states, (iii) trajectories, and (iv) end states of dispersed microspheres for motions of converging, diverging, aggregating, and orbiting (Reprinted with permission from ref 65. Copyright 2021 The American Association for the Advancement of Science.).

programmable, and single-step directional assembly of LC molecules via femtosecond laser direct writing (Figure 4b).[54] This nanoscale high-precision assembly is achieved by defining the laser scanning pathway, which induces a directional shear flow effect. The transition from the liquid to solid phase during the polymerization process further enhances this shear effect, resulting in highly controlled molecular organization. Additionally, laser tweezers have been employed to manipulate and control the assembly of well-ordered 3D colloidal crystals within a bulk nematic LC.[8] Recently, light has emerged as a pivotal tool for 4D printing. Through spatiotemporal light control, light-regulated soliton dynamics has been reported in LCs.[57] It is also possible to manipulate the degree of curing, utilizing the intrinsic light attenuation in the through-plane direction to create mesogen alignment for reversible bending actions.[58] This spatially defined material heterogeneity allows a cured 2D film to morph into a 3D structure over time, introducing time as the fourth dimension. This innovation presents an attractive option for designing functionally diverse soft machines and expanding the potential applications of soft matter photonics.

Similar to laser direct writing technology, a freeform laser induction (FLI) method facilitated by a 5-axis laser processing platform enables the direct fabrication of 3D flexible and conformable electronics on freeform surfaces with complex geometries. Furthermore, the integration of 3D printing with FLI in a multimaterial assembly process allows for the fabrication of various functional materials within 3D structures for photonic and electronic applications. For instance, flexible 3D wireless LEDs with excellent lighting performance and touchpads can be fabricated using flexible polymers (Figure 4c).[55,59] In addition, the light-induced 3D assembly of soft matter offers significant potential for diverse applications. For example, the reversible self-assembly of graphene oxide with stimuli-responsive polymers leads to the formation of a photo/thermally reversible supramolecular graphene/polymer composite hydrogel. This composite can be used to fabricate flexible and foldable all-solid-state supercapacitors with remarkable electrochemical performance.[60] Furthermore, light-programmed out-of-plane deformation of diselenide-containing shape-memory polymers (SMPs) can be achieved by incorporating diselenide bonds into the SMPs. When light penetrates the transparent sheet, an intensity gradient is generated along the thickness, resulting in a stress gradient that induces asymmetric contraction and out-of-plane deformation (Figure 4d). This strategy allows the programming of various 3D configurations, such as wavelike, flowerlike, and hand-like shapes, from a 2D polymer sheet. These 3D structures hold great potential for applications in soft robotics, smart actuators, and anticounterfeiting technologies.[56]

Actuations by Different Degrees of Freedom of Light. Manipulating of soft matter through the diverse degrees of

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ACS Nano 2025, 19, 11501−11516

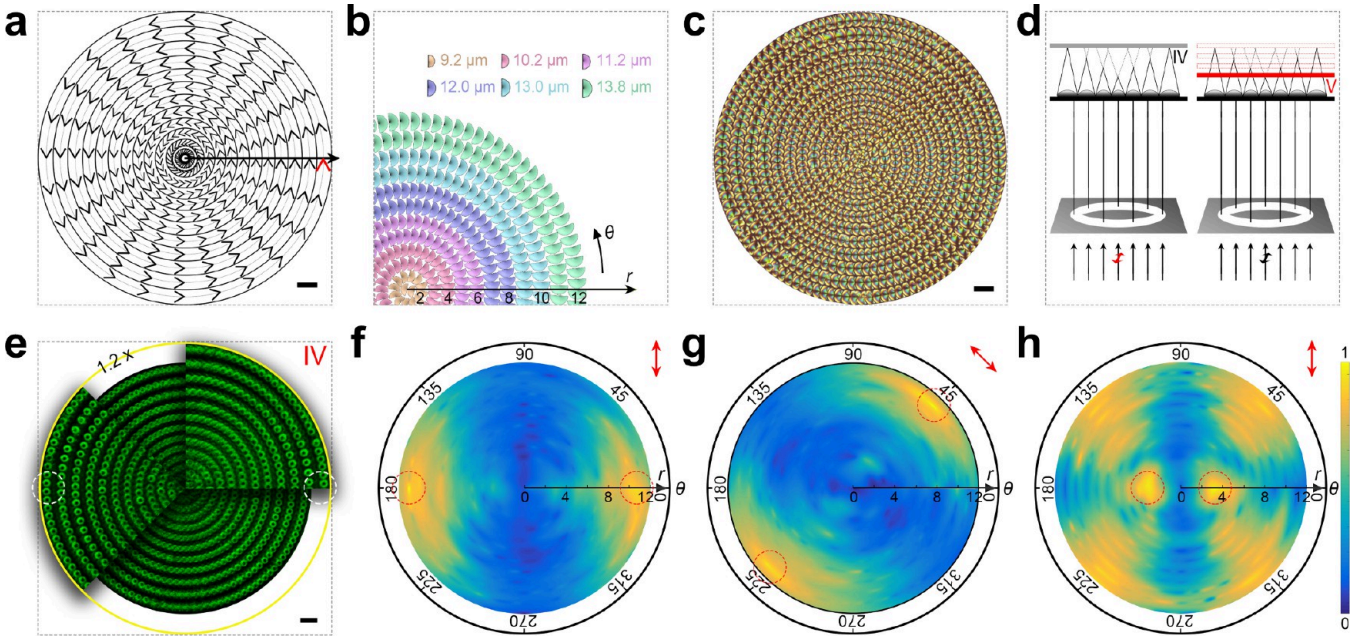

Figure 6. Extracting 4D information with multisize and orientation distorted toric focal conic domains. (a) Photoalignment pattern. (b) Schematic of well-arranged distorted toric focal conic domains. (c) Polarized optical microscope texture of the soft-matter sample. (d) Schematic illustration of polarization-selective and multifocal imaging with alterable components labeled in red. (e) Imaging pattern of a transmissive "O" mask for incident polarization of 90°. (f–h) Image definition maps (Reprinted with permission from ref 19. Copyright 2019 American Chemical Society.).

freedom offered by light reveals a vast range of possibilities and applications.[61] For instance, various winding and unwinding of self-assembled helical superstructures have been demonstrated under the light stimulation with different intensities and frequencies.[46,62−65] Programmable self-propelling actuators have been realized via a specific molecular assembly within a photoresponsive cholesteric medium, enabling parallel transports of microspheres in customized trajectories, including convergence, divergence, gathering, and orbital revolution (Figure 5).[65,66] By harnessing the spatial and temporal control of light intensity, various forms of underwater locomotion—including crawling, walking, jumping, and swimming—can be achieved through localized deformations induced by selective illumination.[67] Unique fluid slugs have been realized through the photoinduced asymmetric deformation of tubular microactuators, which generates light controlled capillary forces that allow for the direct manipulation of liquids.[68] A further advancement is seen in programmable LC elastomers, where anisotropy can be inscribed using linearly polarized light, based on the photoinduced cycloaddition reaction of chalcone mesogens.[69] Polarized light-driven LC elastomers actuators have also been developed,[70,71] where polarization serves as an extra degree of freedom for controlling actuators. These can be employed in devices such as oscillators, bionic structures like a dog's swinging tail, and even light-driven mills. Furthermore, interference holograms have been created using arbitrarily manipulated optical wavefronts.[39,72] A multistimuli-responsive soft actuator system that capable of performing not only multidirectional movement, but also different shape morphing modes has been reported by visible and infrared three-wavelength modulations.[34,73]

Beyond LCs, a variety of other soft matter—such as light-driven carbon-based actuators and light-actuated silk proteins[74]—are also increasingly being utilized in robotics, photonics, and biomedical applications. For example, polypyrrole@graphene-bacterial cellulose (PPy@G-BC) films have been proposed to construct multiresponsive, bilayer actuators integrated with multimodal, self-powered sensing functions. These PPy@G-BC films exhibit excellent photothermoelectric properties, along with good hydrophilicity and a high Young's modulus. As a result, they serve as the active layers in multiresponsive bilayer actuators that also incorporate self-powered sensing capabilities.[75] In addition to their ability to form light-driven actuators when combined with liquid crystals, carbon-based soft matter themselves are outstanding candidates for light-driven actuation.[76] For instance, the integration of an interconnected microtube graphene network into a poly(*N*-isopropylacrylamide) (PNIPAM) hydrogel matrix not only addresses limitations related to poroelasticity and skin layer formation in bulk PNIPAM, but also enables untethered, light-triggered actuation for soft actuators.[77] Regarding biomass-based soft matter, reversible shrinking and relaxation of a photoresponsive mechanical DNA polymer have been achieved through UV and visible light irradiation, which induces switching between the cis and trans states of azobenzene. When used as an extracellular matrix, this DNA polymer can reversibly regulate cellular morphology and induce cellular responses.[78] These developments underscore the immense potential of light as a tool for the precise and versatile manipulation of soft matter, opening new avenues for innovation in various scientific and technological domains.

MANIPULATING LIGHT FIELDS BY SOFT MATTER

In today's information society, shaped by the rapid growth of big data and artificial intelligence, photonics offers a distinctive approach by using light as a crucial carrier of information. Unlike traditional electronics, photonics excels in its ability to encode information into various degrees of freedom of light ($A\mathbf{e}\rightharpoonup cos(kz + \omega t + \varphi)$, where A is amplitude, $\mathbf{e}\rightharpoonup$ denotes polarization, z represents space, ω is frequency, and φ indicates

https://doi.org/10.1021/acsnano.5c02465
ACS Nano 2025, 19, 11501−11516

phase), leading to foundational technologies across diverse fields such as medicine, astronomy, and material science.

Materials with the ability to manipulate the light field at such a fundamental level will have broad implications for the next generation of information systems from advanced data processing and transmission to innovative applications in artificial intelligence and sensing technologies. Among various materials, soft matter, such as LCs, polymers, and gels, are particularly well-suited for applications in photonics due to their programmable cross-scale architecture and dynamic tunability.[79−89] For example, LCs can reorganize their molecular arrangement in response to external stimuli, thereby altering their optical properties; Polymers can be manipulated to change their refractive index or absorbance when exposed to specific wavelengths of light,[90] making them ideal for use in waveguides, sensors, and other optical components. These capabilities are crucial in meeting the increasing requirements of data-storage capacity and information processing speed.

In the following discussion, we will focus on recent research that employs artificial LCs superstructures as a case study for achieving multidimensional light manipulation. Alongside this, we will also discuss representative studies of light manipulation in other soft matter.

Phase. Utilizing soft matter, particularly LCs, in wavefront control for optical applications offers numerous advantages such as high transparency, low cost, ease of fabrication, and fast switching speeds. Wavefront manipulating is typically achieved by adjusting the optical path length nL, which is defined for an optical medium as the product of the refractive index (n) and the physical propagation distance (L) through the material. This phase shift that results from such optical path length variations is called a dynamic-phase shift $2\pi nL/\lambda$), as these parameters directly affect the wave's propagation time through a medium. An example is the LC lens with a spatially varying optical path length caused by either a designed refractive index distribution[91] or a curved surface.[92] By delicately preprogramming the curving of smectic LC layers and tailoring the asymmetric phase profiles, distortion-controllable microlens arrays have been achieved, which help acquire high-dimensional information (3D in space and polarization) simultaneously on the basis of the locations of the clearest images in a single snapshot (Figure 6).[19]

Additionally, polymer waveguide thermo-optic phase modulators (TOPMs) demonstrate efficient phase modulation with low electrical power consumption, owing to their high thermo-optic (TO) effect and excellent heat isolation properties.[93] The combination of polymer and LCs, such as polymer-stabilized blue phase liquid crystals (PSBP-LC), enables electrical regulation of optical phase shifts due to the propagation of incident light along the optical axis of PSBP-LC, coupled with the birefringence induced by the Kerr effect.[94] Furthermore, colloidal nanomaterials such as CdSe quantum wells can modulate light phases using femtosecond interferometry. The excitonic properties of 2D materials enable broadband, ultrafast, and significant phase modulation, extending even into the near-infrared due to intraband transitions.[95]

Recently, the geometric phase shift, also referred to as "Pancharatnam−Berry phase", arises as a kind of "memory" of the evolution of a lightwave through an anisotropic parameter space.[96] Unlike the dynamic phase that arises from optical path differences, the geometric phase originates from the spin coupling effect of light with coordinate frame rotations[12] and describes the relationship between the phase change and the polarization conversion as light interacts with an anisotropic material. Its magnitude is directly proportional to the orientation of an effective optic axis (α) and has a spin-dependent sign (2α). In this context, the controllable anisotropic LC system and the geometric phase delivers a perfect match for advanced photonics.[97]

Orbital Angular Momentum. Based on the geometric phase associated with inhomogeneous transformation of optical polarization,[98] optical spin-to-orbital angular momentum conversion was experimentally demonstrated in an LC medium that is both optically inhomogeneous and anisotropic.[99] This conversion leads to the generation of optical vortices carrying orbital angular momentum, where the wavefront helicity is controlled by the input polarization. Additionally, self-assembled spherulite material, consisting of synthesized molecules with large dipole moments aligned azimuthally, forms a vortex polarity with spontaneously broken symmetry. These materials can be used to generate a family of optical vortex beams with various light polarization states and topological charges. This provides remarkable opportunities for the next generation of broadband spin and orbital angular momentum spatial light modulators, which can be applied in information processing technologies, classical and quantum communications, and beyond.[100,101] Moreover, the generation of both first- and higher-order perfect vortex beams, characterized by optical orbital angular momentum, can be achieved through a polymer-based phase plate using a maskless lithographic exposure technique.[102] Additionally, chiral helical poly-3-hexylthiophene (P3HT) nanowires, exhibiting strong orbital angular momentum, can be fabricated to study circularly polarized emission. The chiral compound interacts directly with the conjugated P3HT, affecting the $\pi-\pi$ interaction and promoting helical stacking, which induces orbital angular momentum. However, the orbital angular momentum in helical chiral nanowire structures can be suppressed by inhibiting electron transport along the helical path, thereby reducing circularly polarized light emission at room temperature.[103]

Until now, various forms of structured light have been reported, including vortex Airy beams,[104] Bessel vortex beams,[105] broadband multichannel optical vortices,[106] reflective polychromatic optical vortices,[107,108] and even 3D orbital angular momentum beams.[109] LC superstructures with specifically designed helicities can encode distinct phases onto two orthogonal spin states, unlocking the multifunctionality of advanced planar optics.[110] These developments hold great promise for enhancing existing devices in optical information technologies, positioning angular momentum control as a key component of future innovations in soft matter photonics.

Polarization. The essence of polarization control lies in precisely manipulating the phase retardation of light as it passes through a homogeneous anisotropic medium such as waveplates. In twisted nematic LCs, when the Mauguin condition is satisfied,[7,33] an important optical property of this structure is that it will rotate the plane of polarization of light transmitted through the film, following the LC director distribution at the rear surface.[112,113] By leveraging the sensitive response of LCs to electric fields, these two polarization control mechanisms have led to remarkable industrial achievement of LC displays. In addition to LCs, flexible subnanowires with polymer-like properties, intrinsic order, and multilevel interactions have garnered significant

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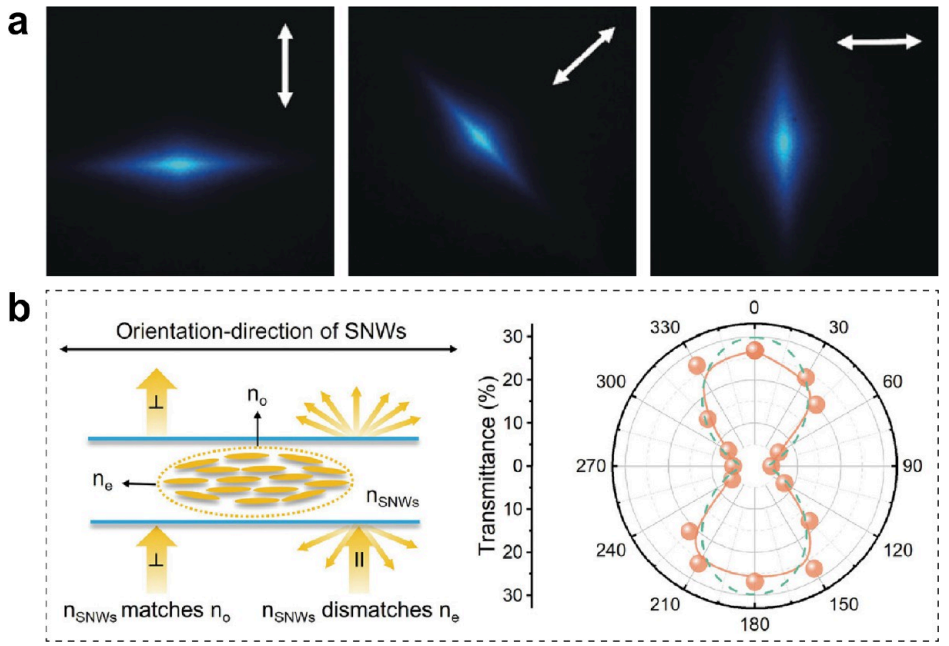

Figure 7. Polarization manipulation by soft matter. (a) Anisotropic emergent light spots passing through the NW film. The major axis direction of the light spots turned as the NW film turned (Reprinted in part with permission from ref 111. Copyright 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.). (b) Schematic diagram of the polarization mechanism of the film and the polar plot of the transmission intensity at 600 nm as a function of the polarization angle (Reprinted in part with permission from ref 21. Copyright 2024 Wiley-VCH GmbH.).

attention as promising building blocks for polarizers (Figure 7a). For example, an all-inorganic colloidal nanocrystal flexible polarizer can be fabricated by wet-spinning GdOOH nanowires into films. These nanowires exhibit strong unidirectional alignment, resulting in a birefringence of 0.004 (comparable to quartz crystal and higher than many polymers) and polarization of UV light, providing a novel approach for fabricating nanowire wave plates and polarizers (Figure 7b).[111] Subnanowires can also be combined with luminogens to generate linearly polarized luminescence. For instance, by dispersing AIEgens in a subnanowire matrix, the superaligned subnanowires can induce parallel alignment of the AIEgens, resulting in linearly polarized luminescence with a polarization ratio of 0.44.[114] Moreover, the integration of subnanowires with liquid crystal materials can effectively combine the advantages of both systems (Figure 7c, d). For instance, the fabrication of freestanding and flexible LC-nanowires films not only demonstrates good stability under water and temperature fluctuations, but also exhibits excellent polarization performance for visible and near-infrared light, holding great potential for applications in polarizers, holographic projection imaging, and flexible optical devices.[21]

In recent years, the advancements in photopatterned LCs have allowed for the generation of cylindrical vector beams, characterized by hollow-shaped intensities and rotational-symmetric polarization distributions.[115] Interestingly, the arbitrarily generated vector beams can also be used in reverse to implement the alignment of LC molecules, enabling the creation of elements such as vector-photoaligned q-plates.[116] Another example of this synergy is the development of a digital method for controlling the polarization distribution at the pixel level using a spatial light modulator combined with a quarter-wave plate. Subsequently, such 2D linear polarization field is implemented in fabricating Pancharatnam−Berry devices with arbitrary wavefronts.[117] This reciprocal relationship, where advancements in photonics (soft matter) are driven by soft matter (or photonics), highlights the unique and compelling nature of this evolving field: soft matter photonics.

Amplitude. As a phase-only material, LCs cannot directly modulate the intensity of the light. The most straightforward method to achieve amplitude control involves incorporating dichroic dyes into the LC matrix, leveraging the guest−host effect. These dyes selectively absorb the component of light that is parallel to the long axis of the dye molecules while allowing the orthogonal component to pass through, thus enabling effective control over light intensity.[118,119] Another prominent example of amplitude control is polymer-dispersed LC, which can switch between scattering and high-transparency states under an electric field, thereby modulating the transmitted light intensity.[120] This effect can also be achieved by embedding ethylene glycol solution microdroplets into polydimethylsiloxane (PDMS) through a one-step emulsification process, which results in high transparency and bidirectional transparency-temperature response.[121] Submicrosecond electro-optical switching has also been demonstrated with soft matter.[4,122] Additionally, scalar LC holography offers a robust tool for controlling the intensity distribution of the holographic images (in the far field). More advanced schemes, such as cascaded LC holography, provide even more complex amplitude manipulation, enhancing capabilities in information processing and encryption.[123] Moreover, the amplitude of incident light can be regulated through energy conversion processes, such as photothermal and photoelectric conversion. These processes are vital for various light-based applications. For instance, flexible photothermal conversion films can be fabricated from materials like M_xWO_3 nanowires, single-walled carbon nanotubes, and graphene.[124−126] Similarly, flexible carbon nanotubes can be utilized to create photoelectric conversion films for efficient solar cells.[127]

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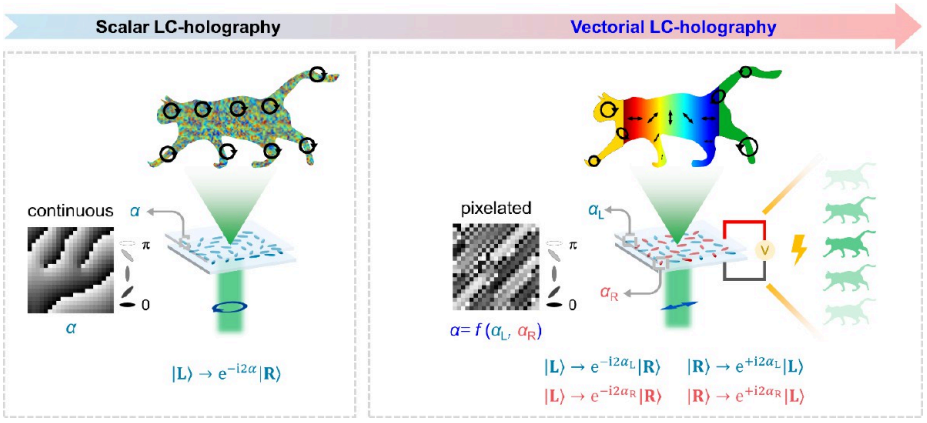

Figure 8. Schematic illustrations of scalar and vectorial LC-holography. Pixelated LC enables versatile and tunable vectorial holography, in which both the polarization and amplitude could be arbitrarily and independently controlled at varying spatial positions (Reprinted in part with permission under a Creative Commons CC BY 4.0 License from ref 14. Copyright 2024 Springer Nature.).

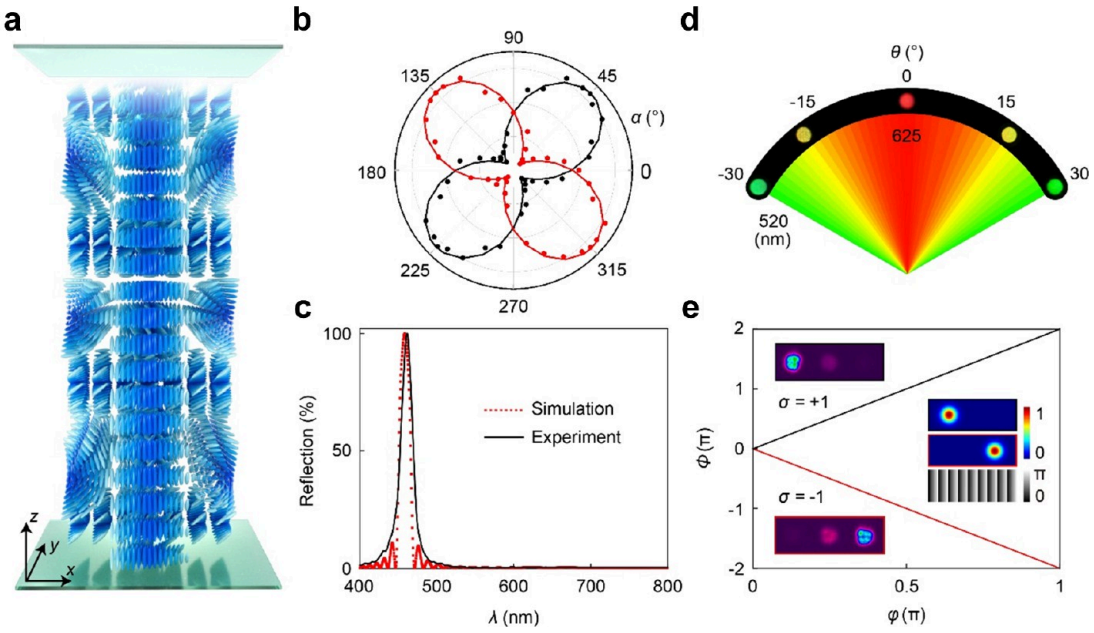

Figure 9. Mapping relationship between the freedom of light and the hierarchy of blue phase LC mesocrystals. (a) Schematic LC director distribution of blue phase LC. (b) Dependency of the spin of light on the chirality of double-twisted structure. (c) Simulated and experimental reflection spectra. (d) Dependency of wavelength on incident angle. (e) Dependency of phase on azimuthal orientation of lattice (Reprinted with permission from ref 18. Copyright 2024 Wiley-VCH GmbH.).

Recently, the first prototype of vectorial LC-holography has been uncovered in which both the polarization and amplitude are arbitrarily controlled at varying positions (Figure 8). Particularly, such vectorial LC-holography strategy can achieve full utilization of polarization channels, including circular polarization, elliptical polarization, and linear polarization control. This novel approach advances the process from scalar to vectorial LC optics, revealing new opportunities for advanced cryptography, super-resolution imaging and many other tunable applications.[14]

Wavelength. Several schemes have been developed to tune the light wavelength using soft matter. One prominent method leverages the unique properties of chiral soft matter, i.e., Bragg reflection, which is associated with photonic band gaps.[4,74,128,129] In this mechanism, only circularly polarized light with a wavelength within the photonic band gap and matching the handedness of the cholesteric LC is reflected, while the opposite polarization is transmitted. This phenomenon has enabled the precise tuning of reflected light wavelengths,[130] leading to various innovative functionalities,[131] including programmable chromatic aberration,[132,133] optical orbital angular momentum processors,[134] and multimode modulable optical encryption.[74] Beyond LC systems, we present an all-biomass-based photonic crystal platform that hierarchically integrates chiral nematic and inverse opal structures through colloidal self-assembly, silk protein self-assembly, and chiral self-assembly of cellulose nanocrystals. This integration allows multiplex structural color manipulation in both 2D and 3D spaces.[74] Furthermore, the Stokes and anti-Stokes luminescence processes can also convert incident light wavelengths, offering promising applications in optical displays, anticounterfeiting, and information encryption based on soft matter. For example, by adjusting the composition of flexible all-inorganic perovskite nanowires, multicolor luminescence

https://doi.org/10.1021/acsnano.5c02465
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can be achieved under a single excitation wavelength, and multicolor polarized luminescent films can be prepared through the directional assembly of nanowires.[135] Similarly, thanks to the rich energy level structure of rare earth ions, optical films based on rare earth-based flexible nanowires can also achieve multiwavelength polarized luminescence.[20] The same principle applies to polymer materials: in addition to their intrinsic luminescent properties, fluorescent polymers can achieve multimode excitation, multiwavelength emission, and both linear and circular polarized luminescence through blending with fluorescent dyes or coupling with optically active ions (e.g., Eu^{3+}, Tb^{3+}, Cr^{3+}, Cu^{3+}, Zn^{2+}), providing a versatile strategy for developing full-color emissive soft matter.[136−138]

Recently, a mapping relationship has been established between the hierarchical superstructures in blue phase LCs (the lattice constant, helix chirality, and the azimuthal orientation of cubic lattices) and the optical properties (the wavelength, spin, and geometric phase of light) has been established (Figure 9).[18] This led to the experimental demonstration of light modulation across multiple degrees of freedom. Moreover, the ability to tune photonic band gaps has opened up possibilities for creating tunable lasers. Notable examples include DNA self-switchable microlasers[6] and soap bubble optofluidic lasers,[139] which offer advantages over traditional solid-state lasers, such as ease of fabrication, tunable wavelength, high sensitivity, and low cost. Additionally, the recent discovery of ferroelectric nematic LCs with strong nonlinear optical properties presents another promising platform for frequency conversion, further expanding the potential of soft matter in photonic applications.[140−142]

CONCLUSION AND PERSPECTIVE

It is important to recognize that humans rely on vision for approximately 80% of the information we perceive,[143] which is inherently dependent on the interaction between light and soft matter systems, as exemplified by our eyes. This natural reliance underscores the significance of Soft Mattonics.

The past few decades have witnessed the rapid development of photonics-based information technology. Notable advancements include the evolutions from scalar to vectorial liquid crystal (LC) holography,[14,144] from linear to nonlinear optics,[145] from stimulus-response to autonomous optical functionalities,[7,146,147] from classical to quantum optical systems,[148] from trivial to nontrivial topological lasers,[149] from single-layer to cascaded photonics,[123,133] and from steering to branched flow of light (Figure 1).[150,151] Moreover, the integration of soft matter such as DNA, silk proteins, colloidal nanomaterials, subnanowires, polymers, and hydrogels, *etc.*[152−154] in Soft Matter Photonics presents exciting new possibilities for the development of reconfigurable, adaptive, and responsive optical devices. Their ability to undergo dynamic changes in response to external stimuli, combined with their versatile optical properties, positions them as key enablers in advancing photonics—particularly in applications requiring flexibility, lightweight design, and multifunctionality.[155,156] These materials are central to emerging technologies in areas such as wearable optics, adaptive lenses, and high-performance sensing systems. Moreover, Soft Matter Photonics also offers new possibilities in the biomedical field for disease diagnosis, drug delivery, biological imaging, and opto-controlled phototherapy. For example, light-responsive soft matter can serve not only as platforms for real-time monitoring of enzyme activity and dynamic changes within cells, but can also be designed as drug carriers that enable precise control over the timing and location of drug release under light exposure.[157−159] Looking forward, the boundaries of Soft Mattonics will continue to expand.

(1) Potent capability of Soft Mattonics. The foundation of this field lies in the use of soft matter to construct desired structures, which can then be used to manipulate light fields on demand. Fortunately, soft matter stands as the most flexible and controllable material in the realm of optical materials. It offers a promising platform for producing a wide variety of complex microstructures that can be dynamically modified by external stimuli, particularly light fields, with the potential to reconfigure 3D structures postfabrication. Due to their sensitive responsiveness to external conditions, soft matter can adapt to and interact with the environment, enabling smart features through thoughtful design. Such capability is well-aligned with the demands of modern intelligent terminals, such as the Internet of Things and smart cities. With these potent capabilities, Soft Mattonics could pave the way for the development of compact, intelligent, and highly efficient optical systems that surpass traditional rigid photonic devices.

(2) Future trajectory of Soft Mattonics. Comparisons are often drawn between this field and the currently hot-spot metasurface-based photonics.[160−169] The unique advantage of soft matter photonics, particularly in liquid crystal-based photonic systems, lies in its ability to facilitate the fabrication of well-controlled 3D micro- and nanostructures with low cost, allowing for the simultaneous, independent, and dynamic manipulation of multiple degrees of freedom of light.[1,170] As we know, soft matter have proven track records in the industry, e.g., LC displays and LC-based spatial light modulator, with a well-established pathway from laboratory research to practical applications. The compatibility of soft matter with various rigid materials, including silicon substrate and metasurfaces,[171] makes them easy to integrate and empowers the development of photonic systems with multifunctionality, high capacity, and complex processability. As numerous applications of soft matter photonics have already been demonstrated, the future of Soft Mattonics is bright, especially in areas such as advanced displays, optical computing, optical interconnects, anticounterfeiting, optical encryption and storage.

More importantly, the combination of liquid crystal materials with other soft matter systems offers a range of outstanding properties. On one hand, such composites retain the inherent flexibility, stretchability, plasticity, and self-assembly characteristics of soft matter, which is essential for the development of future wearable smart interactive optoelectronic devices. On the other hand, this integration not only combines the optical properties of different material systems but also enables the realization of complementary functional characteristics. Furthermore, we emphasize that "Soft Mattonics" also implies beyond "Soft Matter Photonics". We believe that soft matter not only play an irreplaceable role in photonics but also hold immense potential in fields such as soft matter electronics, optoelectronics, and spintronics, *etc.* thanks to their controllable structural ordering, precise tunability, and intelligent feedback capabilities.

https://doi.org/10.1021/acsnano.5c02465
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However, some challenges persist. Despite the advanced control capabilities of soft matter, the arbitrary creation of 3D microstructures that can be tuned and reconfigured on demand remains complex and difficult to achieve. Currently, vectorial optics and nonlinear photonics based on soft matter are still in their nascent stages,[14,147] with many aspects yet to be thoroughly explored. In addition, the theoretical understanding of soft matter photonics is still evolving. Comprehensive models that can predict the behavior of soft photonic systems under different conditions are essential for guiding experimental work and accelerating the development of new applications. As an interdisciplinary field, Soft Matter Photonics requires the collaborative efforts of researchers from various domains to fully unlock its potential and address these challenges.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors sincerely thank Q. Chen (Southern University of Science and Technology) and H. Jiang (Nanjing University of Posts and Telecommunications) for their valuable assistance. This work is supported by the National Key Research and Development Program of China (No. 2022YFA1405000); National Natural Science Foundation of China (No. T2488302); National Natural Science Foundation of China (Nos. 62375119 and 62305157); National Key Research and Development Program of China (No. 2021YFA1202000); Natural Science Foundation of Jiangsu Province (No. BK20243067).

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https://doi.org/10.1021/acsnano.5c02465
ACS Nano 2025, 19, 11501−11516