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Control of matter defects using optical phase singularities

Ivan Smalyukh, Paul Ackerman, Rahul P. Trivedi, and Taewoo Lee

Reversible, controlled creation of patterns of topological defects in liquid crystals is achieved using focused beams with optical phase singularities.

For many centuries, development of optical instruments and technologies has relied on the use of defect-free monocrystals. The notion that defects (also known as singularities) can be useful for photonic applications is relatively new but already broadly accepted.[1–3] Defects are typically points or lines at which the orientational or translational order of solid or liquid crystals is disrupted. Spontaneously occurring defects are often not desirable, since they can degrade performance of various electro-optic and display devices. On the other hand, dynamics of defects in metals permits easy plastic deformation, which is of pivotal importance for modern technology and our everyday life.

Optical phase singularities, in which the phase of light behaves discontinuously, enrich the properties of laser beams and find numerous applications including, imaging, enhanced laser trapping, and telecommunications. Defects in photonic crystals and photonic-crystal fibers allow for unprecedented control of the flow of light, similar to the control of electric current in electronic circuits.[1–3] Although many other important electro-optic, photonic, and all-optical applications of defects are possible, robust means for their control and generation in materials using low-intensity light is lacking. In liquid crystals, defects typically appear as a result of temperature quenching, symmetry-breaking phase transitions, and mechanical stresses.[4] These liquid-crystal defects can introduce well-defined spatial patterns of the molecular director (the optical axis for uniaxial liquid crystals) and corresponding refractive-index patterns. However, they commonly annihilate to minimize the elastic free energy[4] and have never been controlled or used for applications in a reliable way.

Noncontact control of structural organization in matter using light and, in turn, control of light by ordered materials are fascinating research themes that have revolutionized modern technologies, scientific instruments, and consumer devices. One of its most important goals is the development of means for control and patterning of defects in ordered materials and in the optical phase of laser beams.[5,6] Our work shows how

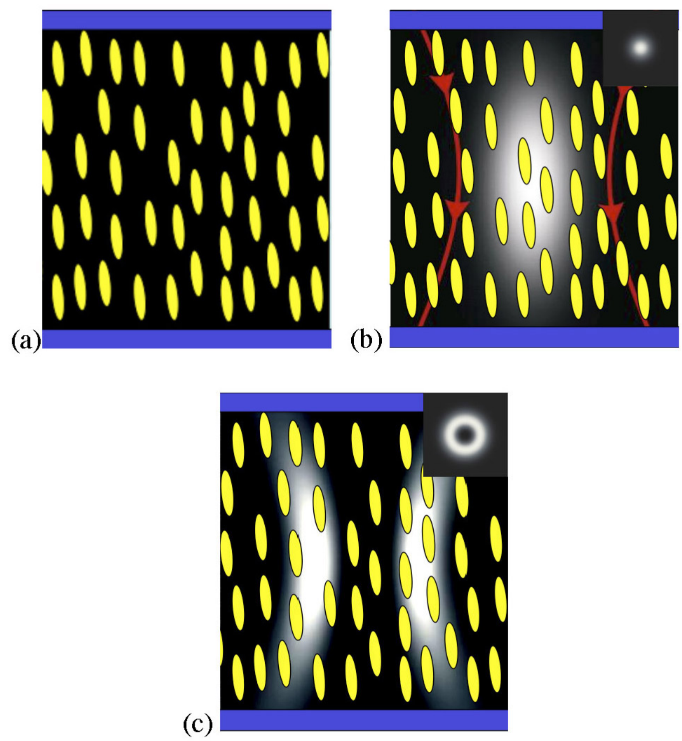

Figure 1. Focusing of Laguerre-Gaussian laser beams of different topological charge into a confinement-unwound, vertically aligned, chiral liquid crystal. (a) Schematic of vertical cross section of a cell with the uniformly aligned liquid crystal. (b) and (c) Vertical cross sections of cells overlaid with the patterns of laser-light intensity of tightly focused Laguerre-Gaussian beams with topological charge $l = 0$ and ± 5, respectively. The insets in (b) and (c) show the corresponding intensity distributions in the lateral plane of the IR beam.

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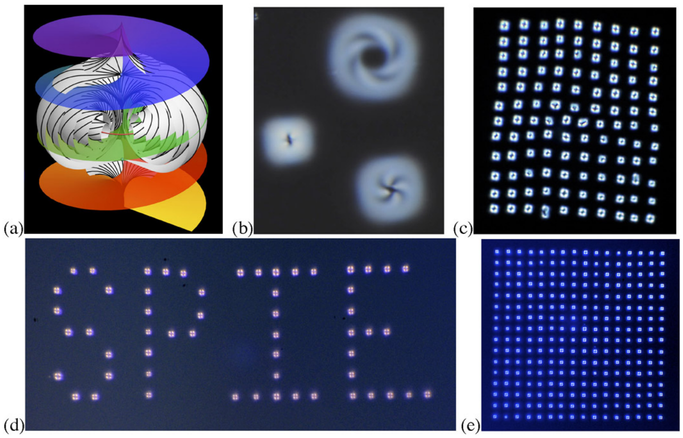

Figure 2. *Optical generation of arbitrary spatial patterns of Torons. (a) Schematic visualization of the optical generation of a Toron using a laser beam with optical phase singularity. (b) Different types of Toron structures formed by focusing Laguerre-Gaussian laser beams of different topological charge.[2] The largest Toron defect structure is approximately 15μm in diameter. (c) Optically generated periodic 2D pattern of Torons with a dislocation. Each Toron is $\sim$10μm in diameter. (d) Characters obtained by Toron generation, each approximately 5μm in diameter. (e) Square-periodic pattern of Torons generated in a liquid-crystal sample. The Torons are each $\sim$5μm in diameter.*

laser beams with optical phase singularities can be used to control topological singularities in ordered, liquid-crystalline materials,[6] potentially enabling a number of new applications.

We employed a computer-controlled, phase-only, spatial-light modulator (SLM, Boulder Nonlinear Systems) to generate holograms and convert an IR Gaussian beam into doughnut-shaped Laguerre-Gaussian laser beams of different topological charge (defining the number of twists that the phase of the light makes in one wavelength).[6] We then focused the beams into the bulk of the untwisted chiral liquid crystal confined between thin glass plates: see Figure 1(a)–(c). These chiral liquid crystals have a strong preference for molecular twisting, but can be untwisted by external fields and confinement, as shown in Figure 1(a). Using focused Gaussian and Laguerre-Gaussian vortex laser beams with different optical phase singularities—see Figure 1(b) and (c)—we generated topological liquid-crystal defect architectures containing both point and line singularities: see Figure 2(a).[6] The defects are bound to each other by twisted interdefect regions, forming stable or metastable 3D configurations. In chiral nematic liquid crystals that are confined into sandwich-like cells with vertical boundary conditions, these laser-generated topological defects embed the localized 3D twist into the uniform background of the director field. They are untwisted because of confinement, forming distinct localized chiro-elastic particle-like excitations of different types: see Figure 2(a) and (b).[6] These defect structures—dubbed 'Torons'[6]—can be generated at a desired location in the sample and their internal structures can then be controlled by varying the topological charge of the Laguerre-Gaussian laser beam. The resultant Torons are comprised of topological point- and ring-shaped defects of opposite topological charge, such that the overall charge is conserved: see Figure 2(a) and (b).[6]

We also find that vortex laser beams of power 10–100mW with screw-dislocation defects in the optical phase allow for control of the topological defects and internal configurations of Torons at a desired spatial location, enabling formation of desired long-term-stable defect superstructures. We show three examples of such superstructures containing Torons of different kinds, a square-periodic lattice with a dislocation in Figure 2(c), a structure in the form of the characters 'SPIE' in Figure 2(d), and a regular periodic pattern: see Figure 2(e). Using both single-beam steering and holographic laser-intensity patterning,[7] the periodic crystal lattices of Torons can be generated and tailored by tuning their periodicity, reorienting their crystallographic axes, introducing dislocation defects in the periodic patterns, etc. These periodic lattices can be dynamically modified, erased, and then recreated, depending on the need of the relevant application. Periodicity of these optically induced structures depends on the equilibrium pitch of the chiral nematic liquid crystal, and it can be tuned from several hundreds of nanometers to hundreds of microns by varying the pitch and using different structure-generation schemes.

The key advantage of our approach is the robustness with which the periodic patterns of liquid-crystal defects can be generated and switched between multiple distinct states.[6] The unprecedented control over organization of the defects offers promise for a wide range of applications, such as optical-data storage, light/voltage-controlled information displays, and tunable photonic crystals. Our preliminary results show that they can be used as efficient optically reconfigurable diffraction gratings. The structural multistability as well as low-voltage and low-laser-power switching may lead to powerless and low-power multimodal operation of electro-optic, all-optical, and information display devices. Our future work will be directed at realizing these applications, so that the optically controlled defects in liquid crystals may find use in controlling the properties of light.

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Author Information

Ivan Smalyukh
University of Colorado at Boulder
Boulder, CO

Ivan Smalyukh is an assistant professor of physics, a founding fellow of the Renewable and Sustainable Energy Institute, and a senior investigator of the Liquid Crystal Materials Research Center. His research interests are at the interface of optics/photonics, soft-condensed-matter physics, nanoscience, and renewable energy.

Paul Ackerman, Rahul P. Trivedi, and Taewoo Lee
Department of Physics
University of Colorado at Boulder
Boulder, CO

Paul Ackerman is an undergraduate research assistant in Smalyukh's research group. His research interests include liquid crystals, laser trapping and manipulation, and tunable diffraction gratings.

Rahul Trivedi is a PhD student and a research assistant in Smalyukh's group. His research interests include laser trapping and manipulation, nonlinear optical microscopy, liquid-crystal defects, optical generation of topological defects and structures, and electro-optics of liquid crystals.

Taewoo Lee is a postdoctoral research associate. His research interests focus on the development of novel optical-imaging techniques, such as coherent anti-Stokes Raman-scattering polarizing microscopy, multiphoton-excitation fluorescence microscopy, second-harmonic-generation polarizing microscopy, and imaging of liquid crystals, polymers, colloids, and biomolecular materials.

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