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Novel optofluidic concepts enabled by topological microfluidics -INVITED

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Abstract. The coupling between flow and director orientation of liquid crystals (LCs) has been long utilized to devise wide-ranging applications spanning modern displays, medical and environmental solutions, and bio-inspired designs and applications. LC-based optofluidic platforms offer a non-invasive handle to modulate light and material fields, both locally and dynamically. The flow-driven reorientation of the LC molecules can tailor distinct optical and mechanical responses in microfluidic confinements, and harness the coupling therein. Yet the synergy between traditional optofluidics with isotropic fluids and LC microfluidics remains at its infancy. Here, we discuss emerging optofluidic concepts based on *Topological Microfluidics*, leveraging microfluidic control of topological defects and defect landscapes. With a specific focus on the role of surface anchoring and microfluidic geometry, we present recent and ongoing works that harness flow-controlled director and defect configurations to modulate optical fields. The flow-induced optical attributes, and the corresponding feedback, is enhanced in the vicinity of the topological defects which geenerate distinct isotropic opto-material properties within an anisotropic matrix. By harnessing the rich interplay of confining geometry, anchoring and micro-scale nematodynamics, *topological microfluidics* offers a promising platform to ideate the next generation of optofluidic and optomechnical concepts.

1 Optofluidics

Optofluidics–the exciting interface of optics and microscale fluid dynamics–occupies a conspicuous niche in today's world of cross-disciplinary research. Despite its relatively recent introduction spanning little over a decade, optofluidic investigations, both fundamental and applied, have seen a steady growth, allowing it to pervade into various domains of contemporary research. From microfabrication and on-chip innovations, non-invasive actuation and optical control, to precise sensing platforms, optofluidics has contributed significantly to the fields of physics, biology, engineering, and analytical instrumentation [1, 2].

The steady expansion and acceptance of optofluidics as a mainstream technology was possible due to the compact, integrated and miniaturized devices, rapid and dynamic response times, and the reconfigurability of the optical systems. Its growing presence in practically all fields of fundamental and applied research suggests a promising future over the years to come. Engineering suitable optofluidic systems involves design and optimization of microfluidic geometries, selection of appropriate fluidic interfaces (or fluid-solid interfaces) and detection of signals as optical or electronic readouts. By varying one, or a combination therein, several ground breaking discoveries have been realized including nonlinear alteration of the refractive indices due to thermocapillary effects [3], adaptive optics for biomedical imaging via high-order wavefront modulation [4], and three-dimensional manipulation of sub-100-nm objects [5], allowing incorporation of optofluidics for medical sensing and diagnosis. More recently, nanofluidic waveguides [6], and liquid-core waveguide chips [7] were used for rapid detection of the SARS-CoV-2 virus and infection with single molecule sensitivity.

Optofluidic specs and performance have improved considerably due to the concomitant progress in the design and fabrication techniques, thanks to the advancement of microfabrication processes, including soft lithography based microfluidic fabrication, laser cutting and micro-milling, and 3D printing techniques [8]. Altering the fluidic properties through external fields (e.g., thermal effects) has further contributed to diversification of optofluidic applications [9]. Despite the phenomenal advancement, majority of the initial studies was carried out with isotropic fluids, leaving out many promising complex anisotropic fluids unexplored until recently [10, 11]. Liquid crystals (LCs)–owing to their anisotropic viscous, elastics, and crucially, optical properties [12]–is a key example of complex anisotropic fluid, which offer a multi-variate handle to precisely tune the specs and performance of optofluidic systems. In addition to the exotic and emergent dynamical attributes of anisotropic fluids [13, 14], LCs furnish topological defects due to spontaneous symmetry breaking [15, 16]: such defects offer strong prospects as labile and reconfigurable optofluidic elements [17, 18]. Conflicting

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boundary conditions, in combination with geometric constraints and appropriate external fields (for instance hydrodynamic), allow tailored generation of topological defects in microfluidic environments [19-21], thus paving the way for the next generation of dynamic, flow-stabilized, defect-based optofluidic platforms [22].

2 Liquid crystal optofluidics

LCs represent a rich system where an interplay between long-range order, spontaneous symmetry breaking and hydrodynamics elicits exotic effects distinct from those observed in isotropic fluids. The exotic properties are mediated by the anisotropic coupling in LC systems, which, traditionally, have been utilised to develop a range of liquid crystal based applications [23]. LCs offer an additional degree of freedom in manipulating the topology of the director field–the average molecular orientation of the LCs–by means of the anisotropic coupling of the director and an external field, for instance hydrodynamic field [14, 24]. Over the last decade, this intrinsic property of LCs has been leveraged toward developing the domain of *Topological Microfluidics*, that harnesses one or a combination of microfluidic geometry and architecture, surface anchoring conditions, and the strength and nature of the microscale flows (pressure-driven vs constant volume flows) to enable precise flow-governed director fields and programmable topological defect states [24-29]. This timely synergy between microfluidics and liquid crystals has led to basic and applied developments in LC-based lab-on-a-chip concepts, and demonstrated the unique role that flow-director coupling could play in triggering tractable emergent properties.

A local flow field can induce a change in the LC director field alignment, and, conversely, a local change of the LC orientation could trigger flows, also known as the backflow [30, 31]. The coupling between the flow and the LC director fields has been utilized to devise tunable optofluidic platforms that allow control of light intensity, polarization, and spectral composition within a microfluidic chip [32, 33]. Variation of the flow parameters leads to different LC orientational profiles: weak, medium, and strong, which can be further controlled by applying external fields including temperature or electromagnetic gradients [34, 35]. This forms the basis of tunable filters based on the micro-flow of nematic liquid crystals. When light passes through a flowing LC matrix, its wavelength-dependent birefringence can be tuned by modifying the flow, confinement or the surface anchoring conditions in the microfluidic chip, allowing for high spatio-temporal modulation of the light properties. Furthermore, upon integration of a dye-filled microchannel, one can measure the absorption spectrum of the dye, allowing for tunable optofluidic colour filters and spectroscope-on-a-chip.

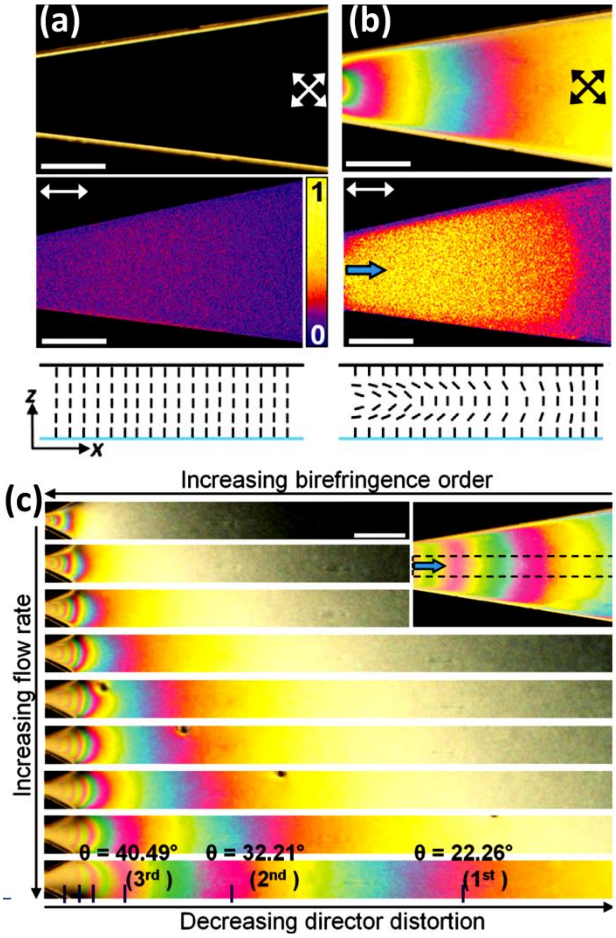

Fig. 1. Optofluidic velocimetry using nematic liquid crystal. (a) Polarized optical micrograph (top row) and fluorescence confocal polarized micrograph (middle row) of a channel filled with 5CB in absence of any flow. (b) At low flow rates, colourful birefringent domains appear, the corresponding fluorescent micrograph revealing the flow-induced director field. The laser is polarized along the flow direction. The bottom row schematically represents the molecular orientation in each case. Scale bar: 300 µm. (c) Polarized micrographs capture the evolution of the birefringent domains with gradual increase of the flow rate, as observed within the region marked in the inset. Adapted from Sengupta *et al.* [11].

In addition to flows, application of an external electric field provides a direct way of controlling the LC director, owing to the dipole moment of the LC system. Light-guided variation of the LC director and fluid actuation [36] are central to the modulation of the index of refraction, often leveraged in display technologies. However, the electric field by itself may trigger complex nonlinear responses. Taken together, the combined effect of hydrodynamic flow and an external electric field, could drive the emergence of a secondary axis in the anisotropic fluid. This was confirmed recently *in silico*, where a uniaxial NLC under equilibrium conditions produced an effective biaxiality under steady-state non-equilibrium conditions [13].

3 Topological defects as optical elements

Topological defects in liquid crystals have gained significant traction as optical vortex generators in recent years. The spin-orbit interaction of light, i.e., the coupling between the spin and the orbital angular momentum of light in anisotropic LCs has studied in thin films and droplets [37]. A key challenge therein lies in the generation of well-controlled orientation of the local optical axis at the microscale. Though micro-fabrication technology has been leveraged for devising high quality microscopic vortex beam generators, their passive characteristics limit the applicability. Liquid crystals offer highly efficient and tunable variants–as droplets or films embedding topological defects–realized by using electric field [38-40]. The operating wavelength and mode of such optical spin-orbit microscopic encoders can be controlled in real time using low-voltage electric fields. Complementing the field-induced topological defect generation in LC films and droplets, dispersions of NLCs in immiscible fluids and gels (like water or glycerin), have offered self-assembled alternatives [41]. These include microdroplets which have been utilized as tunable optical microresonators [42], 3D microlasers [43, 44] and Whispering-Gallery Mode (WGM) microlasers [45]. Such self-assembled fluidic structures have provided the impetus to employ NLC dispersions as basic photonic elements for soft-matter photonic circuits [46].

Despite our current understanding of topological defects in the context of *topological microfluidics*, and the unique potential of defects as optical elements, the two domains are yet to forge a meaningful synergy. Topological microfluidics has enabled programmable generation, stabilization, and guidance of defects and director topology, which taken together with droplet-based microfluidic techniques to generate dispersed phases like droplets and shells [47] offer an rich and exciting, albeit underexplored path ahead. Integrating microfluidic programming of the director and defect topology with optical manipulation offers a versatile potential for on-chip platform, with upstream opto-mechanical and opto-elastic components (actuators, valves and soft rails [26, 48]) that will enable downstream optofluidic manipulation and applications within the same microfluidic pipeline.

4 Toward novel optofluidic concepts enabled by topological microfluidics

Though the advent of *topological microfluidics* has propelled our understanding of the microscale LC flow behavior, the integration of optics–either to modulate the flow-driven LC director fields or to tune optical field via microflows–is still in its infancy. Optical fields have been extensively applied to modulate the fluidic properties of isotropic materials on-chip, yet replacing an isotropic fluid by anisotropic matrix remains grossly underexplored. Broadly, *topological microfluidics* will enable novel optofluidic and optomechanical concepts via two primary flow-mediated modes, as depicted in Figure 2: (i) non-singular LC director fields, *i.e.,* through continuous director fields and non-singular defect states; and (ii) singular LC director fields, *i.e.,* topological singular defects possessing different winding numbers. Both modes allow for dynamic programmability of the director and defect topology, thus offering a range of possibilities for optofluidic manipulations in the parameter space of microfluidic geometry, surface anchoring conditions, and the strength and nature of the imposed flow fields.

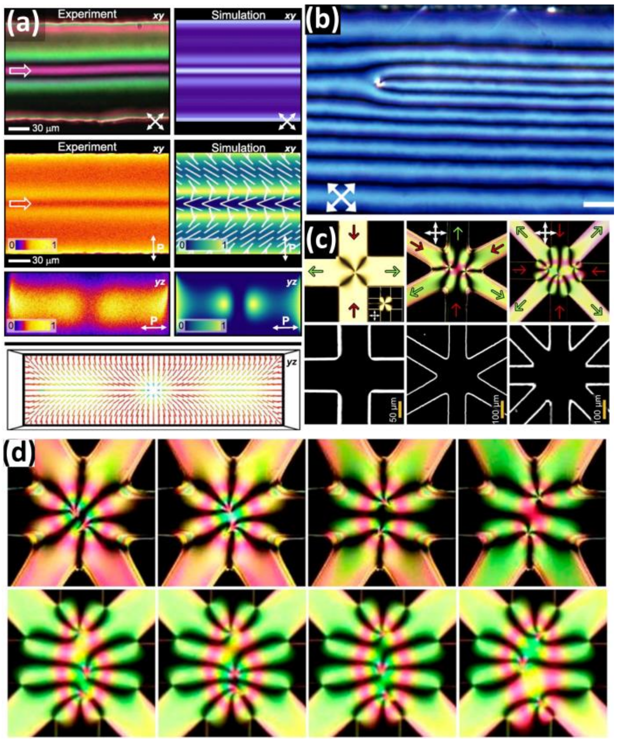

Fig. 2. Topological Microfluidics allows manipulation of director and defect topology toward novel optofluidic concepts. (a) Tunable complex flow-induced director field observed in microfluidic channels with homeotropic anchoring modulation, observed in both experiments and simulations. The topology of the director field can be modified by altering the microfluidic geometry, surface anchoring, and flow rates [34]. (b) Formation of a π-wall due to the nematic microflow in a channel with degenerate planar surface anchoring. The leading defect (bright spot) evolves spontaneously, which over time, reduces in length and stabilizes by aligning vertically within the channel [27]. (c) Microfluidic geometry can be harnessed to program the topology of nematic defects, shown here for generating effects of strength -1, -2 and -3 [19]. (d) Higher strength topological defects and lower multiples thereof (each with -1 strength) can be spatio-temporally manipulated by hydrodynamic flows [19]. The images are adapted from works of the author (Refs. [19,27,34]).

At a fundamental level, one could consider a fourth parameter, through the choice of the LC material. LC director field–in general–encounter short- and long-range elastic deformations in shear flows, depending on the order parameter and aligning (or tumbling) nature of the LCs. Four distinct regimes, spanning different

Deborah (*De*) and Ericksen (*Er*) numbers, are observed [14], of which the elastic-driven steady state corresponds to tumbling (or non-aligning) nematics and nematic elastomers, and the viscous-driven steady state corresponds to the flow-aligning behaviour at higher Er numbers. The two dimensionless numbers, *De* and *Er,* respectively capture the ratio of the viscous to short range elastic effect, and the ratio of the viscous effect to long-range elastic effect. Additionally, the intrinsic non-linearity in the system can be harnessed to drive the system into flow bifurcations, which promises novel parameter space for optofluidic applications. The synergy between *topological microfluidics* and optofluidics has already initiated, as evidenced by the recent progresses in several directions [49, 50]. For instance, the orientation of the nematic director is highly susceptible to electric or magnetic fields, thus the presence of additional fields would vastly expand the scope of LC-based optofluidic systems. Another novel direction would be the choice of chiral nematic phases for optofluidic applications: the chiral phase structure, known for versatile optical properties, can be integrated into the microfluidic pipeline for unique applications [50]. Finally, LC-based optofluidic platforms can be used to generate tailored light-environments at micron and sub-micron dimensions, with large dynamic range for tuning the intensity, wavelength and polarization of light waves. Such precision light fields which could be guided to a desired target, will allow simulated light conditions in different biological research systems (where specific light conditions are desired), for instance *in vitro* research on photosensitive microorganisms and plant cells.

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