From disorder to design: Exploring electrical tuning of branched flow in liquid crystal films

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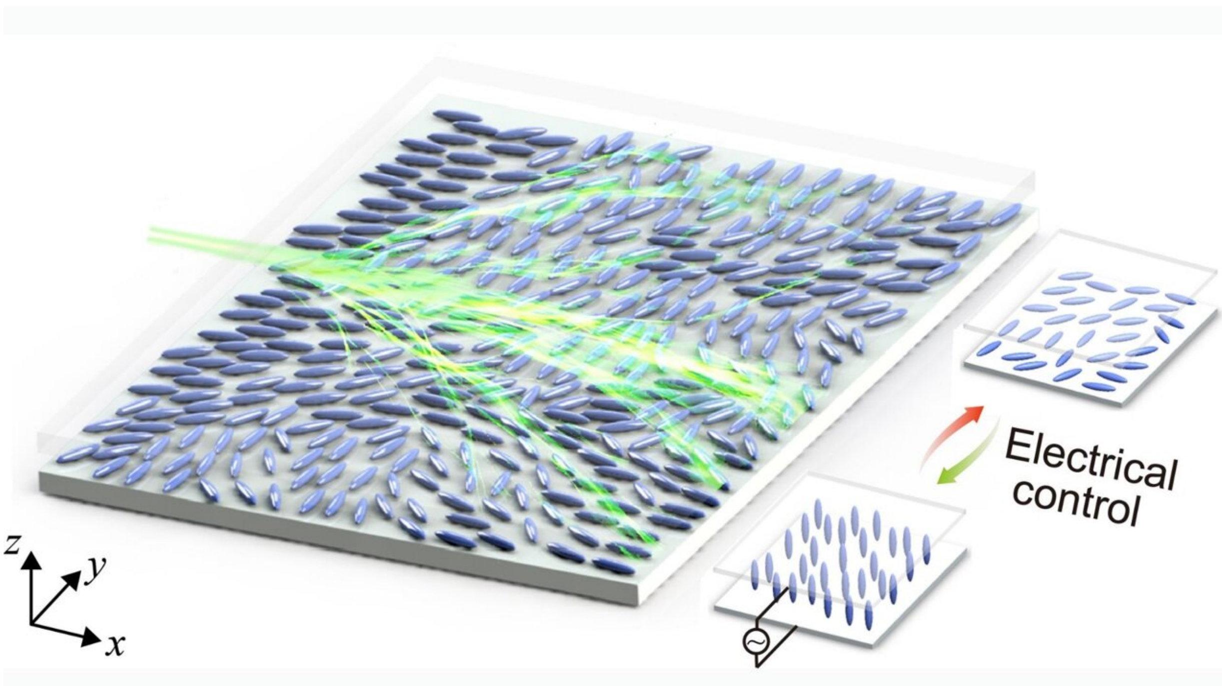

A schematic illustrating the branched flow of light in an NLC film. The random orientation of NLC molecules within a glass cell can be adjusted using an electrical voltage bias. Credit: Chang, Ss., Wu, KH., Liu, Sj. et al/ *Nature Communications*. 10.1038/s41467-023-44500-8.

A new study in *Nature Communications* investigates the electrical tuning of branched light flow in nematic liquid crystal (NLC) films, revealing controlled patterns and statistical characteristics with potential applications in optics and photonics.

Branched light flow manifests as intricate patterns in light waves navigating through a disordered medium, forming multiple branching pathways.

Positioned between ballistic and diffusive transport phenomena—where ballistic implies unhindered straight-line movement akin to a laser beam, and diffusive involves scattered, chaotic behavior—the phenomenon gains significance for its potential in controlling physical processes, particularly optics, and photonics.

Acting as a transitional state between ordered and disordered light propagation, it provides a platform for controlled and intricate light steering.

This manipulation becomes a focal point in a study conducted by Dr. Jin-hui Chen from Xiamen University in China and Dr. Jian-Hua Jiang from the University of Science and Technology of China, where they specifically explore the electrical tuning of branched light flow within NLC films.

"Owing to their erratic nature and rich behaviors, manipulation of branched flows in a controllable manner has never been realized in experiments. We find that disordered liquid crystal films with electro-optic effect provide an excellent platform for the generation and regulation of branched flow of light," Dr. Chen told Phys.org.

"During my visit to Prof. Chen at Xiamen University, he was researching the branched flow of light in liquid crystals. Recognizing the significance of topological defects in this context, I understood that their stability under electrical fields contributes to system stability, allowing the repeatable on-and-off switching of branched light flow," added Dr. Jiang.

Topological defects in NLCs

Liquid crystals display characteristics of both fluid and solid states. Their molecules can flow like a liquid while maintaining some degree of order akin to a solid. This distinctive behavior arises from the delicate balance between intermolecular forces and thermal energy.

The researchers focused on the behavior of NLC in particular. Nematic liquid crystals are characterized by the alignment of their molecules in a specific direction, creating a distinct order within the material. This alignment is sensitive to external factors, such as electrical fields.

The electrical tuning of branched light flow within NLC films involves manipulating the orientation of these liquid crystal molecules. When an electrical field is applied, it induces a reorientation of the molecules, altering the properties of the NLC film. This process is crucial for generating and regulating the intricate patterns of branched light flow.

Topological defects in the NLC film play a dual role in the phenomenon.

Dr. Chen explained, "Firstly, they contribute to the spontaneous formation of structured patterns called schlieren textures, resulting from disordered orientations of NLC molecules and uneven dielectric anisotropy. This acts as a weak disordered potential for propagating light."

"Secondly, under a small electrical voltage, the reorientation of liquid crystal molecules occurs without disrupting the schlieren textures. The robustness of topological defects, possibly pinned by surface forces at the interface, ensures good recoverability of the branched flow generated by light waves in the system."

Observing branched light flow in NLC films

The researchers employed a meticulous experimental setup to investigate the electrical tuning of branched light flow in NLC films. A high-precision three-dimensional translation stage allowed for precise tuning of the light coupling into the NLC film.

This involved manipulating a 532 nm laser's polarized field with a polarizer and a half-wave plate. Observations of the light flow were facilitated by a microscope with a 10x objective lens, and an optical camera collected intrinsic light scattering from the NLC film.

Additionally, the researchers used simulations to explore liquid crystal orientations in response to the gating (control) electrical field.

One of the most surprising findings by the researchers was the robustness of the topological defects that pinned the schlieren textures in the liquid crystal and, therefore, the light scattering patterns.

Dr. Jiang explained, "Even with a notable electrical voltage that tilts the orientation of liquid crystal molecules very much, after switching off the electrical voltage, the topological defects are recovered, and so are the schlieren textures."

"This enables the electrical tuning (switch on and off) of the scattering potentials, and the branched flow of light can be repeated many times. It is really out of expectation. It tells us how stable the topological defects in liquid crystals are."

A noteworthy observation was the variation in the scintillation index, a crucial statistical property of branched flow, with changes in input light polarization, noted Dr. Chen. This polarization dependency, previously unachievable in other platforms, added an extra layer of complexity and control to the branched light flow generated in the NLC film.

In addition to the topological defects and the relationship between the scintillation index and polarization, a third factor held importance: the correlation length of the disordered potential, a measure of how structured or ordered the disorder is within the material, in relation to the wavelength of propagating light.

The correlation length of the disordered potential must be larger than the wavelength of the propagating light for the appearance of branched flow. A larger correlation length implies a more extended and coherent pattern of disorder.

"Due to the robustness of the topological defects, the schlieren textures and the scattering potential are quite coherent. These factors make everything controllable and enable us to demonstrate the beautiful tuning of the branched flow of light," explained Dr. Jiang.

Optical neural networks and sensors

Explaining potential applications and future work, Dr. Chen said, "Liquid crystals can create programmable hierarchical superstructures for light-matter interactions, showing high sensitivity to external fields."

"Future research from our group will delve into the interaction of light with disordered liquid crystal systems, exploring in-plane and out-of-plane transport configurations with potential applications like optical neural networks."

From a technological perspective, Dr. Jiang pointed out that this phenomenon could be enhanced for manipulating light beams. "The electrical tuning is quite promising for device operations. For instance, it can be used as a switch for sensors or detectors when linked to the liquid crystal film," he concluded.

More information: Shan-shan Chang et al, Electrical tuning of branched flow of light, *Nature Communications* (2024). DOI: 10.1038/s41467-023-44500-8