Optical tweezers tie knots and links

Application Note

Introduction

Tying knots and linking microscopic loops of polymers, macromolecules, or defect lines in complex materials is a challenging task for material scientists. Knots are fascinating topological objects and have always played a prominent role in physical and life sciences. In physical chemistry knots are considered to be topology isomers, i.e. they have identical chemical composition but a different topology. Well known examples in chemistry are rotaxanes and catenanes, interconnected molecular rings which can not be separated without opening at least one covalent bond. In polymer chemistry crystallization and rheological parameters can be described. In biology molecular knots and links are of interest because the entanglement of DNA molecules plays a central role in important processes like replication, transcription and recombination. Knot-like topological defects have been observed in chiral nematic liquid crystal (NLC) but have remained unexplored because of the difficulty associated with control.

Fig. 1 Aresis Tweez250 optical tweezer mounted on Nikon Eclipse inverted microscope.

Optical Tweezer

All experiments have been carried out on an Aresis Tweez250 system. It utilizes a 1060 nm, 5 W fiber laser. Beam steering is controlled by a set of acousto-optic deflectors (AOD). This unique setup enables formation and sub-nanometer control of an arbitrary number of traps in a time sharing modus. This setup has been used for the formation of 2D nematic colloidal crystals consisting of more than 10x15 dipolar colloids.

Experiment

The group of Igor Musevic at the department of Condensed Matter Physics, University Ljubljana, Slovenia utilizes the optical tweezer system to study structure, properties and mechanism of the formation of knots and links. The tweezers were used to position colloids and assist their assembly into stable 2D structures.

The temporal position of the colloids was video-monitored by means of an optical microscope and image capture. Analysis of the colloidal trajectories allows to determine the separation dependence of the structural forces between colloids and the binding energy of colloids in colloidal assemblies. They have successfully demonstrated knotted and linked microscopic loops of topological defects of arbitrary complexity in chiral nematic colloids. The loops are responsible for the stabilization of the colloidal microparticle structures in a chiral NLC, thus forming an unusual soft matter. Knot and link manipulation was performed by cutting, fusing and reversibly reconnecting individual defect loops into knots and links of arbitrary complexity. The highly focused light of the laser tweezer gives full control over the knot and link formation.

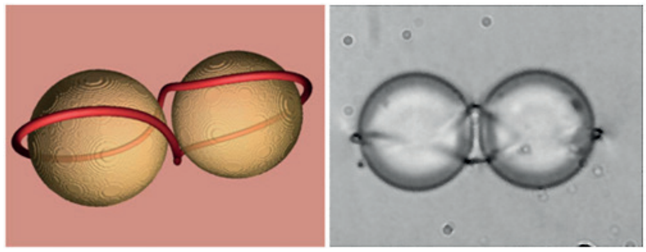

Fig. 2 Silica colloids inside liquid crystal. Colloidal dimers bound by topological defect loops can be created by locally thermally quenching a thin layer of the nematic liquid crystal around selected colloidal pairs by using laser tweezers. (theory: left, experiment: right)

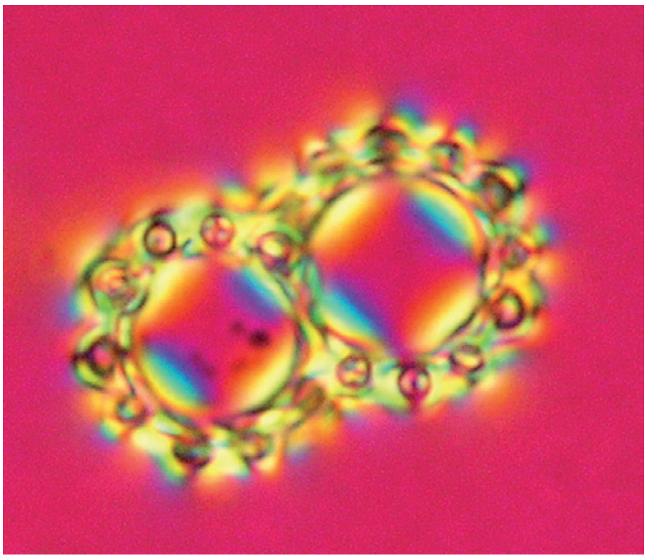

Fig. 3 Silica colloids inside liquid crystal. Smaller colloidal particles trapped into the topological defect loop, twisting around a larger colloidal pair. The microscopy image is aquired using birefringence, showing nematic distortion around the colloidal superstructure.

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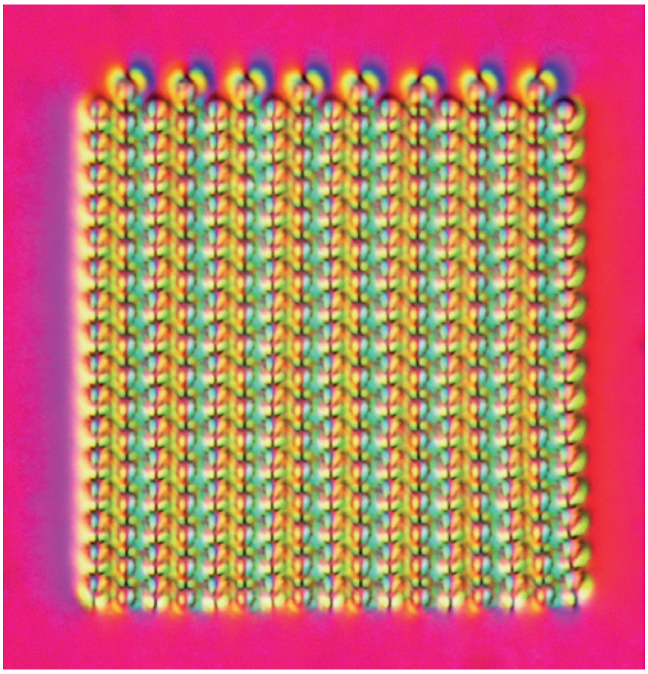

Fig.4 A 2D dipolar crystal formed by pairs of antiparallel dipolar chains of silica colloids. Different colors represent different orientations of the nematic molecules.

The work of the Musevic group has shown that chiral nematic colloids are stabilized by defect knots and links of fascinating complexity, which can be fully controlled and rewired by light. This unusual colloidal soft matter system provides a robust made-to-order assembly of an arbitrary knot or link on a microscopic scale and is a new route to the fabrication of soft matter with special topological features. This seems to be a promising route for a better understanding of the knotting of topologically nontrivial entities, such as DNA, skyrmion lattices in chiral magnets and confined blue phases, and entangled vortices in superconductors.

Further reading:

I. Musevic, M. Skarabot, U. Tkalec, M. Ravnik and S. Zumer, "Two-Dimensional Nematic Colloidal Crystals Self-Assembled by Topological Defects", Science, 2006, Vol.313, p.954ff

U. Tkalec, M. Ravnik, S. Copar, S. Zumar and I. Musevic, "Reconfigurable Knots and Links in Chiral Nematic Colloids", Science, 2011, Vol.233, p.62ff