Optical Trapping in Anisotropic Environment

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Preliminary remarks

Liquid Crystal (LC) is the ideal anisotropic fluid useful for studying and modeling the properties of optical trapping in anisotropic environment.

The investigation of optical trapping in LC environment only begin to be explored. Because of the richness of observed phenomena and fascinating experimental capabilities, optical trapping shows a great promise to become one of the mainstream techniques in the LC studies.

A different point of view is using LC droplets as particles to be trapped. This is subject provides very interesting effects such as transfer the optical angular momentum to the droplets and induce their rotation. This field is at least 10 years old and will not be covered by this lecture.
Preliminary remarks

Up to now studies of optical trapping in LC environment include:

- typical properties of optical trapping in anisotropic environment
- optical manipulation of colloidal particles immersed in LC to study colloidal interactions
- optical manipulation of trapped particles to study and manipulate LC defects and disclinations
- manipulation of line defects without using any trapped particle
- unconventional optical trapping of low index particles in high index environment
OUTLINE

1. Basic of Liquid Crystals
2. Optical Reorientation of LC
3. Optical Trapping of Particles immersed in LC
4. Optical manipulation of colloids and defects in LC
5. Unconventional trapping mechanisms in LC
Basic of Liquid Crystals

LCs are usually composed of anisotropic rod-like molecules with a rigid or quasi-rigid core and two terminal groups.

They flow like ordinary liquids, but present macroscopic anisotropies typical of solids.

For a given material the LC (mesomorphic) state appears changing one thermodynamical parameter such as temperature.

All LC exhibit long range orientational order which is responsible of their typical collective properties.
Basic of Liquid Crystals

A varying degrees of positional order, similar to solid crystals, may be present dependent on the material.

Nematic Liquid Crystals (NLC) have only orientational order and no positional order.

Smectic Liquid Crystals are characterized by a layered structure and have different types of positional order.

Cholesteric Liquid Crystals are NLC with a superimposed twist.

In the continuum approximation the average local orientation of the LC molecules is described by the director $n$. 
Basic of Liquid Crystals

Nematic

Smectic A

Smectic C
Basic of Liquid Crystals

In the continuum approximation the LC is an elastic medium with free energy given by:

\[ F = \left( \frac{K_1}{2} \right) (\text{grad } n)^2 + \left( \frac{K_2}{2} \right) (n \cdot \text{rot } n)^2 + \left( \frac{K_1}{2} \right) (n \times \text{rot } n)^2 \]

From the optical standpoint, an aligned LC is a uniaxial monocrystal with an optic axis along \( n \).

The large dielectric anisotropy \( \Delta \varepsilon = \varepsilon_{\text{par}} - \varepsilon_{\text{perp}} \) allows director reorientation by an applied electric field through the interaction energy

\[
U_E = -\frac{\Delta \varepsilon}{8\pi} \left( n \cdot E \right)^2
\]
Optical Reorientation of LC

Director reorientation similar to the one given by static low frequency fields are induced by the optical field of an e.m. wave.

The large optical anisotropy of these materials and the collective behaviour lead to a Giant Optical Nonlinearity.
Optical Reorientation of LC

The electric torque pulls the anisotropic polarization and hence the director \( \mathbf{n} \) toward the electric field direction.

\[
\tau_{em} = \langle \mathbf{P} \times \mathbf{E} \rangle = \varepsilon_0 \varepsilon_a (\mathbf{n} \cdot \mathbf{E}) (\mathbf{n} \times \mathbf{E})
\]

The rotation of \( \mathbf{n} \) corresponds to a local rotation of the optic axis and, as a consequence, to a variation of the refractive index of the extraordinary wave.
Optical Reorientation of LC

Janossy Effect
Anomalously large optical torque in dye-doped liquid crystals

\[ \tau_o = \eta \tau_{em} \]

The enhancement factor \( \eta \approx 100 \), for dye concentration 0.1% w/w

\[ n_2 \approx 10^{-3}-10^{-2} \text{ cm}^2/\text{W} \]

SINE Surface Induced Nonlinear Effect

From Supra - to Colossal Nonlinearity \( n_2 \approx 1-10^3 \text{ cm}^2/\text{W} \)
Optical Reorientation of LC

\[ n = n_0 + n_2 I \]

Conventional GON: \( n_2 \approx 10^{-5} \text{cm}^2/\text{W} \)
Dye enhancement (Janossy effect): \( n_2 \approx 10^{-3} \text{cm}^2/\text{W} \)
Photorefractive-like effect: \( n_2 \approx 10^{-3} \text{cm}^2/\text{W} \)
Methyl-Red doped 5CB: \( n_2 > 1-10^3 \text{cm}^2/\text{W} \)

\( \delta n = n_2 I \) can approach the LC birefringence!
Optical Trapping of Particles immersed in LC

Director configurations around particles and polarization dependence

A: tangential anchoring

B: perpendicular anchoring
thick sample

C: perpendicular anchoring
thin sample

D: weak anchoring
Optical Trapping of Particles immersed in LC

The unique trapping properties arise because:

- a linearly polarized beam propagating in the anisotropic fluid “sees” the local effective refractive index $n_{\text{eff}}$ that depends on the director $\mathbf{n}$ and the light polarization state

- a spherical particle in the LC with a uniform far-field director $\mathbf{n}_0$ causes local director distortions, which produce a refractive index “corona” (RIC), different from $n_{\text{eff}}$ index far from the sphere

- by controlling the particle’s surface characteristics, it is possible to generate well defined structures around the spheres and demonstrate that the angular pattern of trapping forces mimics that of the RIC
Optical Trapping of Particles immersed in LC

Trapping of the beads depends on the director structure, which can be changed by surface treatment of the particles or applying an external field.

The direction-sensitive trapping resembles that of objects with an anisotropic shape such as discs and rods.

Optical forces are varied by changing beam polarization, even up to an extreme situation when a particle is trapped at some polarizations, but repelled from the beam with other polarization states.
Optical Trapping of Particles immersed in LC

Particles with an index between the ordinary and extraordinary LC indices \((n_o < n_p < n_e)\) are either attracted to a stationary laser trap or repelled from it, depending on the beam’s polarization.

\[\text{LC} \quad n_e = 1.55, \quad n_o = 1.47\]

\[\text{Particle} \quad n_p \sim 1.51\]

Polarization parallel to \(n\):
Particle repelled

Polarization perpendicular to \(n\):
Particle trapped

*Bipolar bead* \((A,B,C)\)
*Quadrupolar bead* \((D,E)\)
Optical Trapping of Particles immersed in LC

The dynamics of a microsphere trapped in LC is strongly anisotropic

These results demonstrate that trapping forces in anisotropic fluids are in general anisotropic
Optical Trapping of Particles immersed in LC

Because of the RIC, the spherical beads exhibit trapping properties reminiscent of those of objects with an anisotropic shape, such as elongated cylinders and oblate discs.

Their trapping can be controlled by multiple means, such as:

- changing beam polarization
- modifying the particles’ surface treatment
- using different LCs
- using different sample thicknesses
- applying external fields to change RIC
Optical Trapping of Particles immersed in LC

Calculation of the trapping forces.
From the basic relation:

$$f(r) = \frac{\varepsilon_0}{2}(n_{\text{eff}}^2(\hat{P}) - n_p^2) \int_V \hat{E}(r, z)^2 dV,$$

The trapping forces and trap stiffness are obtained:

$$F_{t/\perp}(r) = \frac{2\omega^2 \alpha_{/\perp}}{l_{/\perp}} \exp \left[ -\frac{r^2}{2\omega^2} \right] \sinh \left[ \frac{rl_{/\perp}}{2\omega^2} \right]$$

$$\alpha_{/\perp} = 2l_{/\perp} \xi [n_p^2/n_{\text{eff}}^2(\hat{P}) - 1] \frac{W}{c\omega^2} \text{erf} \left[ \frac{l_{/\perp}}{2\sqrt{2}\omega} \right]$$

$$\text{erf} \left[ \frac{l_{/\perp}}{2\sqrt{2}\omega} \right] \exp \left[ -\frac{l_{/\perp}^2}{8\omega^2} \right],$$

$$\text{erf} \left[ \frac{l_{\perp}}{2\sqrt{2}\omega} \right] \exp \left[ \frac{-l_{\perp}^2}{8\omega^2} \right],$$
Optical Trapping of Particles immersed in LC

Then the trapping forces can be controlled by polarization between a maximum and a minimum value such that:

\[
\frac{F_{t_{\text{max}}} - F_{t_{\text{min}}}}{F_{t_{\text{max}}}} = \frac{n_p^2(n_o + n_e)\Delta n}{n_e^2(n_p^2 - n_o^2)}
\]
Optical manipulation of colloids and defects in LC

a) Forces between colloidal particles can be measured by optical trapping techniques

_Yada et al. PRL 92, 185501 (2004)_

Using the dual beam laser trap, two interacting particles were arranged in their initial positions, and then gradually reduced the laser power of one of the two beams until the particle started to be released.

The minimum laser power $I_{\text{min}}$ that is necessary to hold the particle, and the angular direction along which the particle started moving, were systematically examined to make a force map around the fixed particle.
Optical manipulation of colloids and defects in LC

Motions of polystyrene particles to a linear chain formation. (a) – (c): Optical microscope images, monitored after the release from the laser trap. z axis: the alignment direction of nematics far from the particles. (a’) and (c’) are predicted schemes of the director fields in (a) and (c), respectively.
Optical manipulation of colloids and defects in LC

Spatial distribution of the interparticle forces $F$, in case that a linear chain is formed
Optical manipulation of colloids and defects in LC

Motions of the particles having the defects to the different side along the \( z \) axis. (a) –(c): Optical microscope images, monitored after the release from the laser trap. (b’) and (c’) are predicted schemes of the director fields in (b) and (c), respectively.
Optical manipulation of colloids and defects in LC

b) study of colloidal interactions in quadrupolar nematic liquid crystal colloids, confined to a thin planar nematic cell

M. Skarabot et al. PR E 77, 031705 (2008)

Using the laser tweezers, the particles have been positioned in the vicinity of other colloidal particles and their interactions have been determined using particle tracking video microscopy.

1D and 2D spontaneous assembly of colloidal particles
Optical manipulation of colloids and defects in LC

c) laser manipulation of director structures in LCs when no foreign inclusions are present


The studied samples have homogeneous composition, but spatially-varying structures of molecular orientations

Since the LC’s effective refractive index depends on the LC director orientation and on the light polarization state, the spatially localized director structures usually have an effective refractive index different from that of the surrounding LC

This refractive index contrast allows the structures to be manipulated using polarization-controlled optical gradient forces that can be varied from attractive to repulsive.
Optical manipulation of colloids and defects in LC
Optical manipulation of colloids and defects in LC

Stretching of an optically trapped dislocation in a lamellar LC by moving the sample using a stage
Unconventional trapping mechanisms in LC

- Under the condition $n_p < n_o < n_e$ no trapping should be possible, but small colloidal silica particles are efficiently trapped into the laser focus in a birefringent liquid crystal.
  
  *I. Musevic et al. PRL 93, 187801 (2004)*
  *M. Skarabot et al. PR E 73, 021705 (2008)*

- This is against the basic trapping condition requiring the refractive index of the bead higher than the one of the surrounding medium.

- The phenomenon has been observed in the experiments using colloidal dispersions of micron-sized silica spheres (index of refraction 1.37) that could be laser trapped and manipulated in a nematic liquid crystal E12 (indices 1.52 and 1.74) and 5CB (indices 1.55 and 1.7).

- On the contrary, the particles have been expelled from the trap after heating the liquid crystal into the isotropic phase.
Unconventional trapping mechanisms in LC

Two different mechanisms are considered

- **Low Optical Power** ( < threshold for optical reorientation [OR])
  Trapping might be due to surface-induced distortion of the birefringent media around the particle, which creates a region of enhanced refractive index around the particle. The particle is therefore “dressed with high-index cloud” and behaves effectively as a high-index particle compared to surroundings.

- **High Optical Power** (> threshold for optical reorientation [OR])
  The second trapping mechanism includes optical induced distortion or local decrease (or even melting) of the order parameter of a birefringent fluid. This creates a “ghost” colloid at the laser spot that interacts via structural forces with the real colloid. The properties of this mechanism are regulated by the nonlinear optical response of LC.
Unconventional trapping mechanisms in LC

Low Power
The forbidden trapping has its origin in the anisotropic dielectric coupling of the electric field of the electromagnetic wave with the director field around the colloid.

The surface-induced distortion of the director field around the particle is accompanied by spatially varying direction of the eigenaxis of the dielectric tensor for optical frequencies.

For a particular polarization of the trapping beam, there are two energetically favourable locations of the beam waist, where the polarization is directed along the long axis of the molecules.

The colloid is, therefore, attracted into the laser focus until the favourable region of the distorted director field is in the most intense part of the optical trap.
Unconventional trapping mechanisms in LC

High Power
Above threshold for OR the highly localized EM wave creates a localized region of a liquid crystal, which is elastically distorted.

This optically induced distorted region interacts with the colloid and can lead to an anisotropic interaction between the laser focus and the colloid.

The mechanism of optical trapping is, therefore, accompanied by the elasticity-mediated interaction between two objects, the first object being the optically distorted region of a liquid crystal ("ghost colloid") and the second object is the particle
Unconventional trapping mechanisms in LC

In both cases, the colloid is attracted into the optical trap indirectly via the elasticity of LC while the direct interaction between the low-index colloid and the optical trap is repulsive.

The experiments have been performed using silica spheres of diameter $2a=0.97 \pm 0.05 \text{m}$ and the refractive index $n_s=1.43$ that were dispersed in NLC 5CB (refractive indices $n_o=1.52$ and $n_e=1.69$) or E12 (refractive indices $n_o=1.52$ and $n_e=1.74$)

The surface of the spheres was first covered with a monolayer of DMOAP that ensures very strong homeotropic surface anchoring of a NLC (perpendicular anchoring)
Unconventional trapping mechanisms in LC

a) Below OR threshold
b) Above OR threshold

Colloids could be found at different separations from the walls of the confining cell indicating a repulsion between the dipolar colloid and the homeotropic wall.
Unconventional trapping mechanisms in LC

Above OR threshold
Unconventional trapping mechanisms in LC

Above OR threshold

MOVIMENTI DA DESTRA

1,3,4 : laser già acceso a t=0
2 : laser acceso a t=0

MOVIMENTO BEAD IN 5CB DA DESTRA
(13-15 mW sul campione)
Unconventional trapping mechanisms in LC

a)

• The particle is attracted along the direction of polarization of the laser light. This is an indication that the particle is attracted into the laser trap via anisotropic dielectric interaction of the electric field of the EM and the inhomogeneous field of the dielectric tensor for optical frequencies.

• The region of enhanced refractive index is positioned symmetrically with respect to the center of the colloid and there are two energy minima very close to the surface of the colloid where the colloid is trapped.
Unconventional trapping mechanisms in LC

b)
- The bright spot indicating the “ghost colloid” is the evidence of the local distortion of the director field
- Two types of trajectories are observed in the trapping event depending on bipolar or quadrupolar symmetry of the director around the particle
- In the bipolar case the spiderlike trajectory can be rotated by rotation of the light polarization
Unconventional trapping mechanisms in LC

Dynamics and energy of trapping
Unconventional trapping mechanisms in LC

Transition from a) to b): strength of the trapping potential along the easy direction vs the optical power
Unconventional trapping mechanisms in LC

THEORY
The calculation is based on a numerical integration of the free energy density consisting of three contributions:

(i) elastic interaction due to deformed nematic director field around the colloid and the trap Frank’s elasticity,
(ii) the dielectric interaction of an inhomogeneous and anisotropic director field with an inhomogeneous electric field of the focused light,
(iii) the repulsive dielectric interaction of a colloid with a small refractive index with an inhomogeneous electric light field.

Free energy in one constant approximation

\[
F = -\frac{1}{2}K \int_{D_{LC}} \left( \frac{\partial n_i}{\partial x_j} \right) \left( \frac{\partial n_i}{\partial x_j} \right) dV - \frac{1}{2} \epsilon_a \epsilon_0 \int_{D_{LC}} [n(r) \cdot E(r)]^2 dV \\
+ \frac{1}{2} (\epsilon_{LC} - \epsilon_C) \epsilon_0 \int_{D_C} E(r)^2 dV,
\] (1)
Unconventional trapping mechanisms in LC

Scheme

a) Bipolar orientation around the bead

b) Quadrupolar orientation around the bead
Unconventional trapping mechanism in LC

The effective pair potential for the colloid in the vicinity of the laser trap above threshold for OR
Unconventional trapping mechanism in LC

The effective pair potential for the colloid in the vicinity of the laser trap below threshold for OR
Unconventional trapping mechanism in LC

Contributions of different Interactions to the total effective potential that acts on a colloidal particle

a) above threshold for OR

b) below threshold for OR.
SUMMARY

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PERSPECTIVES

This investigation is just at the beginning, a variety of different effects can be expected due to the variety of LC materials, anchoring conditions, nonlinear optical interaction, beam shape and beams combination.

Investigation on different (biological) anisotropic environment should also be considered.