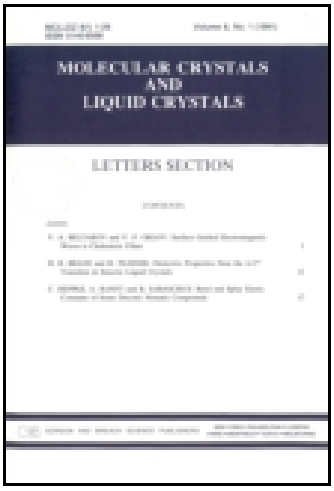

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Electrical Tuning of Optoelastic Interaction in Nematic Colloids

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We discuss the effect of electric field on the optoelastic trapping occurring when a micron size particle is dispersed in a nematic liquid crystal. It is shown that in case of homeotropic sample with dielectric positive anisotropy and radial anchoring of the director on the particle surface the applied voltage is able to control the strength and range of interaction. Excellent fit of experimental data is obtained by a theoretical model that considers the interaction due to the overlapping of the orientational distortion around the particle with the one in the focal spot.

Keywords Optical trapping; nematic colloids; optical reorientation

Introduction

Since the discovery of an optical trapping phenomenon occurring in liquid crystals (LCs) [1] when the refractive index of the particles n_p is lower than the ones of the surrounding medium n_m, the interest in understanding this unusual effect has attracted several scientists to investigate optical manipulation of microparticles dispersed in nematic LCs [2–4]. Firstly the interest was driven by the need of explaining a trapping mechanism different from the one based on strong optical gradient typical of optical tweezers occurring only if the particle refractive index is higher than the one of the surrounding medium. Secondly the large trapping range of this phenomenon provides an interesting tool for driving assembling of particles with potential applications in realization of novel structures with customized photonic properties.

Actually it has been pointed out that both conditions required for optical trapping originated by strong optical field gradient can be dropped using particles dispersed in liquid crystal. The first one is the mentioned requirement on refractive indices according to which the ratio $m = n_p/n_m$ must be > 1; the second is the requirement of high numerical aperture of the focusing system (usually N.A. > 0.7) needed to induce a high optical field gradient. Optical trapping in LC with limited N.A. has been demonstrated and exploited in recent works [4, 5]. As a consequence of these observations one must look for the origin of this phenomenon on physical mechanisms different from the one of conventional optical trapping. It is easy to recognize that in this case it must be driven by minimization of the

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elastic energy of the LC medium even if it may involve different processes as we will discuss in the next section. For this reason the effect can be denominated optoelastic trapping. Among the most interesting features of it is the wide trapping range as compared to the optical gradient trapping. In fact in optical tweezers the conventional trapping mechanism is efficient only very close to the optical trap, that is its trapping range is on the micron scale. On the contrary the LC long range orientational properties give to optoelastic trapping a much broader range, that, after the most recent results, can be envisaged to reach a macroscopic submillimetric dimension. On the other hand loosing the need of extremely strong focusing it may be possible to get optoelastic trapping using low light power in the submilliwatt range. These properties make the effect very promising for applications in driven self-assembling.

Since LC is very sensitive to applied field, it is obvious to investigate the effects of an applied electric field on the optoelastic interaction, with the aim of providing an additional tool to control the characteristics of this effect. Some aspects of the electric field effect on the unconventional optical trapping in LCs have been recently reported by us [5]. Here we review the main effects induced by the electric field on the optoelastic interaction in nematic LCs discussing the experimental results by using the proposed intuitive model.

Origin of the Optoelastic Interaction

The basic explanation accounting for the onset of attractive forces from the focal spot area to the silica bead is the long range elastic interaction caused by the light induced director reorientation occurring in the focal spot. In this view the origin of the optical trapping phenomenon is similar to the one responsible for the interaction between colloids dispersed in LCs. In these colloidal dispersions the elastic distortions of the host LC can mediate a long-range interaction between particles immersed in it [6], which is absent in usual colloidal dispersions with isotropic host fluids. The elastic distortions of the host LC arise from the anchoring of the mesogenic molecules on the surfaces of the dispersed particles resulting in an increase of the medium elastic energy that will be minimized if the two particles come closer. In a similar way we may have the onset of an attractive force between the optically reoriented area at the focal spot ("ghost colloid", GC) and a particle ("real colloid", RC): RC moves towards GC since in this way the overall LC deformation decreases lowering the elastic energy of the system. In spite of the parallelism of the mentioned cases (colloid-colloid interaction and RC-GC interaction), a strong difference between them is the dependence of the attractive force on the distance r, scaling as r^{-4} in case of two colloids while scaling as r^{-2} in case of the interaction RC-GC. This point has not been cleared yet, even if a qualitative explanation can be found in the different symmetry of the elastic distortion around a microparticle with respect to the one occurring as consequence of light-induced reorientation at the focal spot of the exciting beam.

A very important characteristic of the optoelastic interaction driven by this orientational mechanism is the strong anisotropy of the trajectories of the RC when approaching the GC. In fact the curve in the plane of the focus (x-y) is strongly dependent on the direction of the line connecting the initial position of the RC with respect to the GC, having a spiral- like behavior except for the direction parallel to the light polarization, following in this case a straight line trajectory.

Another mechanism that can originate the trapping phenomenon in LCs has been also pointed out [7, 8]: tight focusing typical of an optical tweezers apparatus may increase the

local temperature of LC by few degrees due to the high local light intensity. The consequence is a thermal gradient leading to an order parameter gradient. At the focal spot one gets a local decrease of the average elastic constant of the LC with respect to the elastic constant far from it. In this way a particle is attracted to move to the focal point since in this way the elastic deformation around it will decrease its energy. However, in order to observe these attractive forces induced by order parameter gradient, it is necessary to use thin samples with boundary glasses coated by a layer, that produces the necessary absorption, e.g. ITO (Indium Tin Oxide). Unlike the optoelastic interaction driven by orientational effects this order parameter driven interaction leads to nearly isotropic trajectories around the focal spot. Another difference is the need of tight focusing (high NA) when using light power in the range of tens of milliwatt, that is not required for orientational driven trapping.

Finally we expect in the first case the optoelastic interaction to be strongly affected by external fields, being almost insensitive to them in the second case. In fact one can easily think of affecting the elastic interaction between the two orientational defects by applying an electric field to the LC sample, thus providing an additional parameter to control the trapping mechanism. With the aim of investigating how the electric field affects the unusual optical trapping occurring in LCs and to use it to control strength and range of trapping we have chosen experimental conditions where the optical gradient trapping is forbidden not only by the refractive indices condition but also by the limited numerical aperture (NA) of the focusing objective having an effective NA = 0.08 very far from the minimum necessary for tweezing effects [4]. By this choice of NA and working at light power of 10 mW in thick samples (50 μm) we have also made negligible the order parameter gradient effect. In fact, by comparing our experimental conditions to the ones used in ref. [7] we can evaluate in our case a local intensity at the focal spot about two order of magnitude lower thus producing a negligible thermal gradient.

Experimental Data and Discussion

In our experiments we have used 40-npentyl-4-cyanobiphenyl (5CB) nematic LC sandwiched between two ITO coated glass substrates. They were covered by dimethyloctadecyl[3-(trimethoxysilyl) propyl]ammonium chloride (DMOAP, from FLUKA), which ensures strong homeotropic anchoring. Silica spheres (from Bang Laboratories Inc.) with 2.5 μm radius and refractive index $n_s = 1.37$, were dispersed in the LC before filling the cells by capillarity. The silica spheres were also covered by DMOAP to get radial director orientation on their surface.

The extraordinary and ordinary refractive indices of 5CB at the used wavelength are ne = 1.71 and no = 1.54. The trapping light source is a linearly polarized Argon laser beam at 532 nm wavelength with Gaussian spatial profile. It is focused at normal incidence with an effective numerical aperture onto the sample NA = 0.08, hence preventing gradient force optical trapping as quantitatively demonstrated in a previous work [4]. A CCD video camera recorded in real-time the dynamics of the RC, exploiting a white light illumination from the opposite side with respect to the incident laser beam.

In practice an isolated dipolar colloidal particle was firstly selected lying at an altitude z approximately in the middle of the cell. The laser beam was focused at the same altitude, in order to minimize the heating effects due to ITO absorption, and it was located on the sample at an initial distance d_0 from the particle. The particle motion was recorded for various values of d_0 and applied voltage V at 1 kHz frequency, with an incident laser power fixed at 10 mW. In all cases the quantitative data were retrieved from experimental conditions chosen to correspond to straight line trajectories. In fact it was checked the

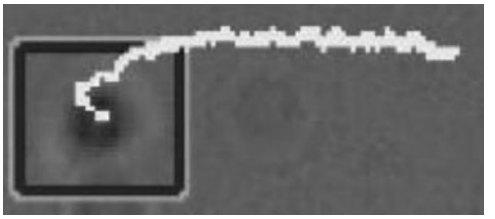

Figure 1. Trajectory of the RC towards the GC at the centre of the squared area, when the line connecting the initial position of RC and GC is not parallel to the light polarization.

anisotropic nature of the interaction by recording the images of trajectory originating from different locations in the x-y plane (taking the focal spot as the origin), showing the characteristic behavior already reported by other authors [2]. This observation confirms that in our experimental conditions elastic interaction is the dominant effect, since in case of thermal gradient trapping the anisotropy of the trajectories is only weakly observable [7].

An example of such anisotropic behavior is shown in Fig. 1 where it is reported a trajectory in the x-y plane when the line connecting the initial position of RC and GC is not correspondent to the direction of the laser beam linear polarization.

In Fig. 2 we report the experimental data related to r(t), being r the distance between the center of the RC and the center of GC. The curves correspond to different values of the applied voltage for a initial distance $d_0 = 23\ \mu$m at fixed power (P = 10 mW). As expected, since the applied voltage reduces the orientational distortion (it stabilizes the homeotropic orientation of the sample), the rise of the voltage slows down the trapping effect until a

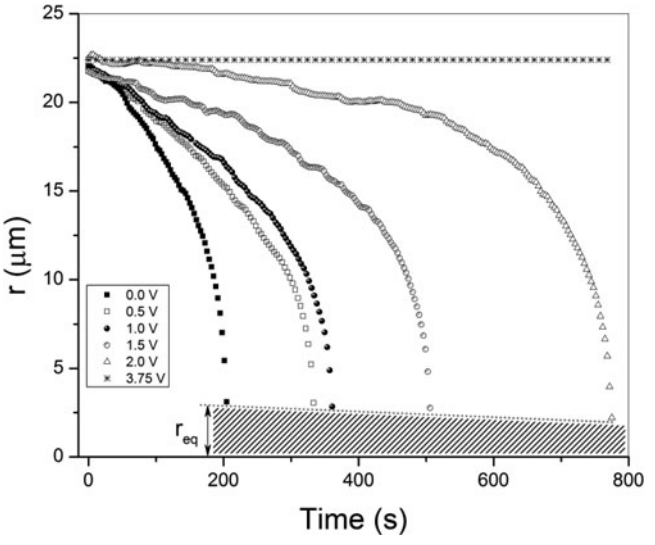

Figure 2. Position of the RC vs time during the optoelastic trapping for different values of the applied voltage. The initial position d_0 is 23 μm. The final value is the equilibrium distance r_{eq} from the centre of the trap.

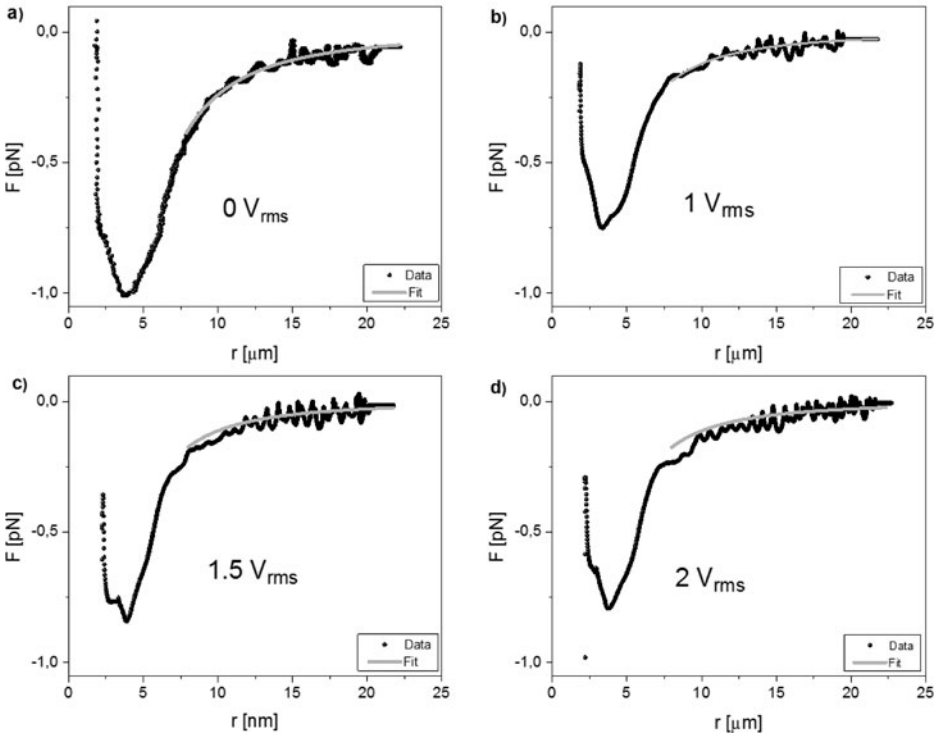

Figure 3. Trapping force F acting on the silica particle versus the distance r to the laser beam axis at a) 0 V_{rms}, b) 1 V_{rms}, c) 1.5 V_{rms}, d) 2 V_{rms}. The solid curve refers to the best Fit from the attractive part of the total force exerted on the particle, $F_A = -A/r_2$.

"quenching" voltage V_q is reached that quenches the interaction between GC and RC, thus r(t) becomes constant (in the case of Fig. 2 this happens at V = 3.75 V).

Since the interaction can be active when the orientational distortion around the RC "feels" the one of the GC it is expected the effect of the applied field be dependent on the initial position of the RC with respect to the GC. Due to the decreasing overlapping of two distorted area (the reoriented spot GC and around the RC) the long range attractive force can be controlled until trapping stop ($V = V_q$). This has been actually demonstrated showing that V_q decreases as d_0 increases [5].

From data of Fig. 2 one can retrieve the force acting on the RC to show that the control of the interaction range in optoelastic trapping is a direct consequence of the control of the strength of this interaction. This is clear by looking at Fig. 3 and Fig. 4. In Fig. 3 the curves F(r) are reported for different values of the external applied voltage, as calculated by the tracking experiment providing r(t). In fact by neglecting the inertia of the microparticle, the attracting force is calculated balancing it by the viscous drag force acting on the particle by the surrounding fluid. One can use the well known expression for the drag force $F_D = 6\pi R\eta v$, being R the Reynolds number, η the effective viscosity and v the speed of the particle.

The initial part of the F(r) dependence has been successfully fitted by $F_A = -A/r^2$ [2, 4] with $A > 0$, therefore the initial slopes of the curves at different voltage allow to get the dependence of the interaction parameter on it, expressed by A(V). In Fig. 3 the smooth

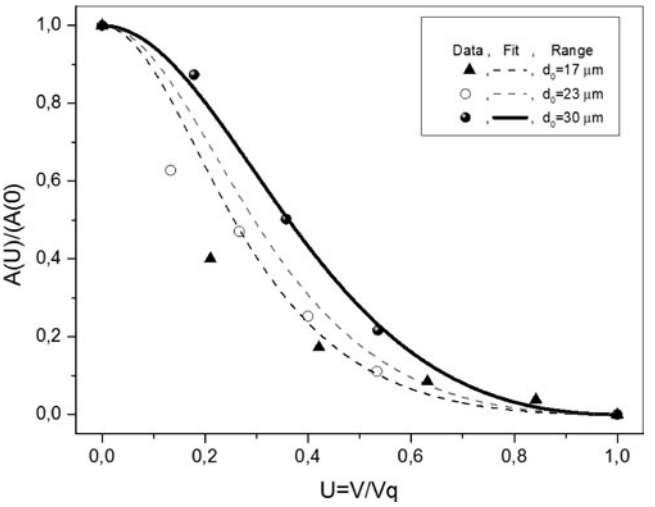

Figure 4. Dependence of parameter A(U) normalized to its max value A(0) vs the normalized applied voltage $U = V/V_q$ for three different starting point d_0 of the bead. The markers are the experimental data while the solid curve is the model.

lines represent the best results of the fitting procedure allowing to obtain the dependence of the attracting force A(V) on the applied voltage for various values of d_0. Those data summarize the effect of the electric field on the force strength.

In summary the reported experimental results show how interaction range and strength can be easily controlled in case of electric field applied to a positive dielectric anisotropy LC and homeotropically aligned sample.

This behavior has been satisfactorily explained by a simple model [5] based on these main hypothesis:

a) the forces are originated by the mutual overlapping of the orientational distortions around RC and GC;
b) the interaction depends on the square of the length of such overlapping;
c) overlapping is defined by the region where the reorientation θ_{RC} around the RC and reorientation θ_{GC} around the GC overcome the one due to thermal fluctuations θ_T. In other words no interaction occurs (which corresponds to quenching by the applied field) if in the overlapping region $\theta_{RC} \leq \theta_T$ and $\theta_{GC} \leq \theta_T$.

The aim of the model is to propose an intuitive explanation of the experimental observations without describing the actual director profile in vicinity of neither of the ghost colloid nor around the real one.

Therefore by limiting the analysis to quite large distances between RC and GC, without considering the actual distortion at the particles site it is possible to keep the approximations of cylindrical symmetry and small reorientation in order to describe the tilt angle simply as $\vartheta(r, z) = \theta(r)\sin(\pi z/L)$ being L the sample thickness.

According to the listed points and keeping a cylindrical symmetry for the reorientation around the RC and in the GC, the Euler-Lagrange equations have been solved [5] and allow

to calculate the interaction parameter A(V):

$$\frac{A\left(\tilde{U}\right)}{A\left(0\right)} = \frac{1}{1+\tilde{U}^2\tilde{V}_q^2}\left(\frac{\sqrt{1+\tilde{V}_q^2}-\sqrt{1+\tilde{U}^2\tilde{V}_q^2}}{\sqrt{1+\tilde{V}_q^2}-1}\right)^2 \tag{1}$$

where

$$\tilde{V}_q = \sqrt{\left(\frac{d_0^*}{d_0}\right)^2 - 1} \tag{2}$$

with $d_0 \leq d_0^*$, being d_0^* the maximum distance where the RC feels the interaction at V = 0V.

The normalized quantities have been defined as:

$$\tilde{V} = \frac{V}{V_F} \text{ and } \tilde{U} = \frac{V}{V_q}$$

being V_F the Freedericksz threshold voltage $V_F = \Pi\sqrt{K_3/\varepsilon_0\varepsilon_a}$, with the usual meaning of the symbols.

This model provides an excellent agreement with experimental data as soon as the initial distance between RG and GC is not too small, that is the initial distortion overlap each other giving a negligible perturbation to the initial cylindrical symmetry. This is clear in Fig. 4 where the data obtained by experiments for $d_0 = 29$ μm fall on the theoretical curve, that is the continuous line calculated from eq. (4). On the contrary the long distance approximation becomes weaker as d_0 becomes smaller since the strong overlapping of the director distortion makes no more negligible the mutual perturbation. This is clear from the second and third curve (dashed line) shown in Fig. 4 related to data obtained in the same sample with $d_0 = 23$ and 17 μm. In this case the qualitative agreement is still satisfactory, but the same excellent fit is not achieved when the distortion is wider (i.e. when A is bigger). This is neither a surprise nor an analytical approach failure since the proposed simplified model, relies on the asymptotic description of the GC and NC reorientation profiles, ignoring the mutual interaction of the GC and NC reorientation regions.

However, a very important result of this model that has been reported [5] and confirmed by experimental data is the possibility of drawing a map in the plane V_q-d_0 where become clear the values for which a trapping force exists and the ones where the trapping force is zero.

It is of great interest also the result obtained from the theory for LC with negative dielectric anisotropy [5] where it is foreseen a divergence of the interaction range by increasing the applied voltage. The experimental demonstration of this effect is still under investigation. The interest lies in the possibility of getting a submillimetric interaction range controlled by electric field.

In conclusion we have briefly reviewed the main effects that has been observed when an electric field has been applied to a nematic liquid crystal sample during the occurrence of optoelastic trapping driven by reorientational effects. Data refers to homeotropic samples and particles with radial orientation of the director on the surface. Control of the strength and range of the interaction has been demonstrated for positive dielectric anisotropy and additional effects are foreseen for negative dielectric anisotropy. These results may provide novel protocols for self-assembling in liquid crystal environment to be investigated.

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