

# Electro-optic Control of Platelet Colloids in Nematic Liquid Crystals

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## Introduction

Liquid crystals are organic fluids that consist of rod-like molecules. The compound used in this study was pentylcyanobiphenol (5CB) a room temperature nematic liquid crystal (NLC). At high temperatures, above the nematic-isotropic transition temperature  $T_{NI}$ , the long axes of the liquid crystal molecules are randomly oriented, giving rise to isotropic properties. At lower temperatures, below  $T_{NI}$ , the molecules align parallel to each other. This is known as the nematic phase. This alignment is described as a function of space with a vector,  $\mathbf{n}(\mathbf{r})$ , referred to as the director field.

At surfaces or interfaces between a NLC and another material, there is a preferential alignment of liquid crystal molecules due to anisotropic molecular scale interactions. This is known as surface anchoring. For example, the macroscopic alignment direction of a NLC can be defined by a rubbed polymer surface. The director field at the polymer film is parallel with the grooves in the polymer. Imagine that glass plates are coated with rubbed polymer film and placed in parallel, with the rubbing direction of one plate rotated 90 degrees to the other. The liquid crystal molecules would anchor to the surface, aligned with the rubbing direction, causing the liquid crystal molecules within the cell to twist throughout the height of the cell. This twisting causes elastic distortion and costs elastic energy.

Now imagine a conductive layer, such as indium tin oxide, ITO, is coated on the glass plate as well as the polymer film. This would allow for a voltage to be applied to each plate, and an electric field to be induced perpendicular to the glass plates. In response to the electric field,

the liquid crystals will flip up, out of the planar alignment, and align with the electric field. This flipping, or ‘switching’ of the liquid crystal molecules by an electric field is the basis of the display industry. Technologies exist for controlling the liquid crystals in such applications as flat-panel, high definition, liquid crystal display televisions.

When non-spherical particles, such as squares, are placed in 5CB, they have a preferred alignment that minimizes the elastic distortion, with the diagonal aligned parallel with the director. The surface anchoring to the square particle is planar, meaning the molecules lie flat on the surface of the particle. This anchoring distorts the nematic liquid crystal alignment, costing elastic energy. This research focuses on the response of colloidal square particles to the electric field induced switching of the nematic liquid crystal.

## **Experimental Procedure**

Glass plates were first coated with a thin transparent conductive layer of indium tin oxide (ITO). They were then cleaned to remove all organic substances. The plates were ultra-sonicated in methanol and isopropanol, and then cleaned in a plasma cleaner. The plates were then spin-coated with a thin polyimide layer (PI-2555), which was subsequently rubbed to create uniform surface anchoring for 5CB parallel to the rubbing direction. 10  $\mu\text{m}$  thick sample cells with parallel rubbing directions were prepared by using spacers and uv-curable adhesive (Norland Optical Adhesive 61). The rubbing direction sets the far-field director  $\mathbf{n}_0$ . Using indium, leads were soldered to the ITO conductive layers on each glass plate allowing for a voltage to be applied across the gap of the sample cell. The cells were then filled with colloidal dispersions of square particles 5CB by capillary action and sealed with epoxy.

An electric field was induced by applying voltages of 1.5, 2, 3, 4, and 5 V. A function generator (Stanford Research Systems) was used to apply a sine wave at 1 kHz frequency. The switching motion was captured by video using an Olympus BX51 polarizing optical microscope.

The movies were captured using a SPOT CCD camera, 50x objective and a frame rate of 10 frames per second for a total of 160 frames.

## Results and Discussion

Individual frames of a video of the switching at an applied voltage of 2 are shown in **Figure 1**. The videos show a top view of the square particle in the liquid crystal cell. Notice the alignment of the square with its diagonal parallel to the director field,  $\mathbf{n}_0$ . The videos showed two time scales in the switching of the square particles. There is a shorter time scale, where the particle quickly flips out-of-plane, in response to the switching of the liquid crystals. This is shown in **Figure 1(a)**, with the time difference between frames being 0.2 seconds. The switching of the particle takes about 0.8 seconds, which is too fast for the employed CCD camera to capture.

This study focused on the longer time scale rotation, in which the upright particle rotates toward the director so that its long-axis is parallel to  $\mathbf{n}_0$ . This rotation takes about 3 seconds and is shown in the series of video frames in **Figure 1(b)**. The quick out of plane rotation (**Figure 1(a)**) leaves the square particle aligned nearly perpendicular to the director field. There is still some characteristic of the rubbing direction due to the surface anchored liquid crystals to the glass plates. Due to the presence of the director field along the rubbing direction, there is an elastic driving torque on the liquid crystal that will tend to rotate the particle toward the director. There is also a drag that tends to oppose this motion. We define the angle between the long axis of the flipped up square particle and the director as  $\phi$ . **Figure 1(c)** shows a side view of the sample cell and illustrates the rotation of the flipped square particle toward  $\mathbf{n}_0$  because of the small component of the director field (blue ellipses) along  $\mathbf{n}_0$  after the switch.

Results of the image analysis of the rotation of the square particle toward the director field are shown in **Figure 2**. These plots show the angular rotation,  $\phi(t)$ , of the square particle.

**Figure 2(a)** shows the response of one square particle to an applied voltage of 2 V, switched four different times. The plots have been offset by 0.25 radians for clarity. The red lines show exponential fits to the data and give a time constant  $\tau_2 \approx 0.93 \pm 0.07$  sec.

We can understand this motion with a simple picture if we assume that the elastic driving torque is balanced by viscous drag, and is linear in  $\phi$  and the system is highly over damped (Reynold's number  $\ll 1$ ). The equation of motion is then represented by

$$-\mathcal{K}\phi = \mathcal{J} \frac{d\phi}{dt} \quad (1),$$

where the constant  $\mathcal{K} = KL$  ( $K$  is the average elastic constant of 5CB and  $L$  is a characteristic length) and  $\mathcal{J} = \eta L^3$  is the angular drag coefficient ( $\eta$  is a characteristic shear viscosity of 5CB).

The solution to Eq. (1) is an exponential:

$$\phi = \phi_0 \exp\left(-\frac{t}{\tau_2}\right) \quad (2)$$

with a time constant  $\tau_2 = \mathcal{J} / \mathcal{K}$ . Using dimensional analysis, the time constant can be estimated as

$$\tau_2 = \frac{\mathcal{J}}{\mathcal{K}} \sim \frac{\eta L^2}{K} \quad (3).$$

Taking the average elastic constant  $K \approx 7$  pN [1], and characteristic shear viscosity  $\eta \approx 0.075$  Pa⊙s for 5CB, as well as the side length  $L = 4.5$   $\mu\text{m}$  of the square particle, an estimate for  $\tau_2$  using Eq. (3) gives  $\sim 0.5$  seconds, which corresponds reasonably well to the time constant determined experimentally ( $\tau_2 \approx 0.93 \pm 0.07$  sec).

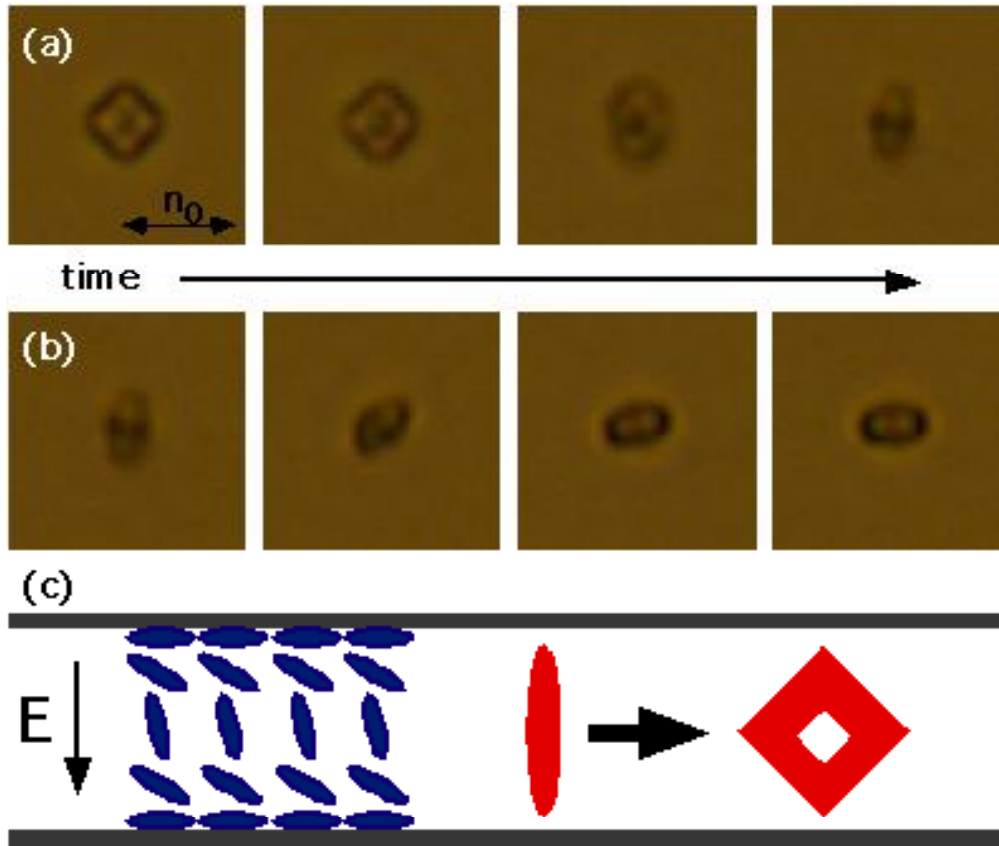
The voltage dependence of switching was also studied, switching the same square particle at four different voltages. The angle,  $\phi$ , increased with increasing voltage, as well as the saturation angle. This is shown in **Figure 2(b)**.

## Conclusions and Future Work

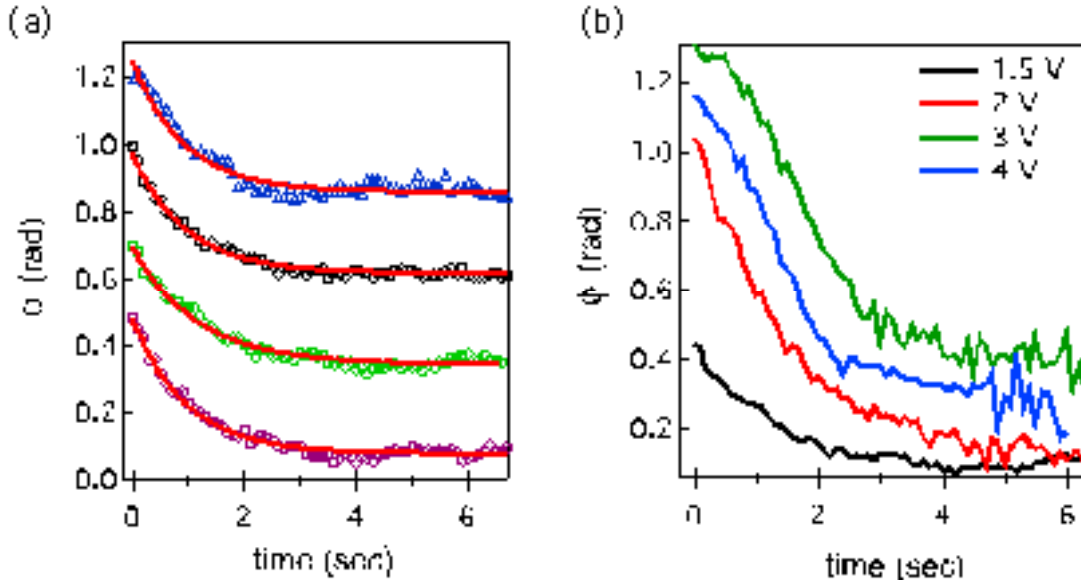
I have found that we can control the orientation of plate-like colloids in nematic liquid crystals efficiently and reversibly using electric fields. Not only can the particles be flipped and rotated in an electric field, they will also relax back to their original orientation when the electric field is in the off-state due to the elasticity of the NLC. In the future, switching of different shapes of colloidal particles, such as triangles and hexagons, will be studied. The switching motions are anticipated to be quite different between the different shapes due to the differences in alignment and elastic deformations of the director field.

I have also found that there are two different time scales in the switching motion. There is a shorter time scale of less than a second, where the particle quickly flips up, out of plane, in response to the fast ( $\sim 10$  msec) switching of the liquid crystal molecules. In future studies, a high-speed camera will be used to better investigate the properties of this quick flipping. There is also a longer time scale of about 3 seconds, where the square particle slowly rotates toward the director field. It was found that the flipping motion is exponential, and with an increasing voltage, the angle between the long axis of the particle and the director increases.

## Figures



**Figure 1.** Sequence of images showing the flipping and rotation of the square particle in response to an applied voltage of 2 V at 1 kHz frequency, from a top view of the liquid crystal cell. **(a)** The quick out-of-plane flipping of the particle in response to the upward flip of the liquid crystals. The time elapsed between frames is 0.2 seconds. **(b)** The late-time, slower rotation of the upright square particle toward the far-field director field,  $\mathbf{n}_0$ . The elapsed time between frames is 1 second. **(c)** A cartoon of the side view of a liquid crystal cell with the electric field in the ‘on state.’ With the applied electric field, the liquid crystals in the mid-plane of the cell rotate upwards and align parallel to the applied field and perpendicular to the glass plates (gray). The liquid crystal molecules near the top and bottom surfaces however are anchored parallel to the plates giving a significant component of  $n(r)$  parallel to  $\mathbf{n}_0$  at the top and bottom of the cell. The square particle, represented in red, first flips out of plane, then is rotated toward the director field, due to an elastic driving torque.



**Figure 2.** (a) Response of a square particle to an applied voltage of 2 V, switched four different times. This shows the angular rotation of the flipped square particle toward the director field. The plots have been offset by 0.25 rad for clarity. The red lines show exponential fits to the data. (b) The voltage dependence of switching of a square particle at four different voltages: 1.5, 2, 3, and 4 V. The initial angle  $\phi(t=0)$  increases with increasing applied voltage, as well as the saturation angle.

## References

- [1] L. M. Blinov, V. G. Chigrinov, *Electrooptic effects in liquid crystal materials* (Springer-Verlag, New York, 1996).