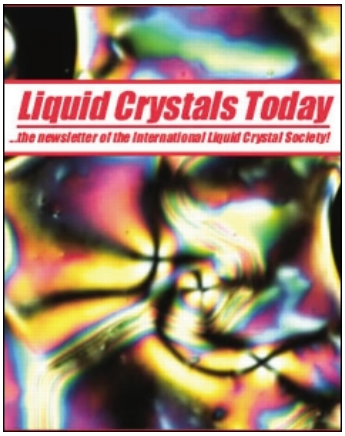

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Magnetic Field Induced Deformations in Nematic Liquid Crystals

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Liquid Crystals in Education

Magnetic Field Induced Deformations in Nematic Liquid Crystals

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Unlike most organic materials, liquid crystals respond readily to magnetic fields. This response originates in the anisotropic magnetic susceptibility of nematics, and the relative ease with which they undergo orientational deformations. Because of the large optical birefringence of liquid crystals, these orientational deformations are easy to observe. An interesting demonstration is to place a small rare earth magnet on a nematic cell between crossed polarizers which is illuminated from below. As the magnetic field reorients the liquid crystal, beautiful interference colours appear, indicating director deformations.

It is interesting to estimate the relevant physical quantities on the basis of first principles and dimensional arguments. In biphenyls, the susceptibility is due mainly to currents induced in the benzene rings. The molecular polarizability, having dimensions of volume, may be crudely approximated by area of the current loop ($\sim(2 \times 10^{-10}\text{m})^2$) times the classical electron radius ($\mu_o e^2/m = 3.4 \times 10^{-14}$m) to give $2 \times 10^{-33}\text{m}^3$. The susceptibility is the number density ($2 \times 10^{27}\text{m}^{-3}$) times the molecular polarizability, which gives 4×10^{-6}. If we assume the susceptibility in the orthogonal direction to be one half of this, we obtain the estimate for the susceptibility anisotropy $\Delta\chi = 2 \times 10^{-6}$, in reasonable agreement with measurements for 5CB [1].

Since the diamagnetic susceptibility is negative, for a field applied in the plane of the benzene rings the susceptibility is greater than in the normal direction, and the magnetic energy density $-(1/2\mu_o)\,\Delta\chi(\mathbf{B}\cdot\hat{\mathbf{n}})^2$ of the material in a magnetic field $\mathbf{B}$ is minimized if the director $\hat{\mathbf{n}}$ is parallel to the field.

Deformations of the director field in the nematic bulk are opposed by elastic torques; the average energy density associated with distortions of the wavelength λ and amplitude θ is $\frac{1}{4}K(2\pi\theta/\lambda)^2$ where K is an elastic constant with units of force. It has been argued [2] that for dimensional reasons $K \simeq kT_{NI}/\ell$, where $T_{NI} \simeq 300$K is the nematic–isotropic transition temperature and $\ell = 5 \times 10^{-10}$m is a molecular dimension; then $K \simeq 8 \times 10^{-10}$N, again, in reasonable agreement with experiment [3].

In a cell of thickness d, a magnetic field can induce a deformation (with wavelength $\lambda = 2d$) if the magnetic energy gain is greater than the elastic distortion energy cost, that is, if, $(1/4\mu_o)\,\Delta\chi B^2\theta^2 > \frac{1}{4}K(\pi\theta/d)^2$ or if the field $\mathbf{B}$ is greater than the critical field $\mathbf{B}_c = (\pi/d)\,(K\mu_o/\Delta\chi)^{1/2}$. Substituting the above values, we obtain $\mathbf{B}_c \simeq 0.07\text{T} = 700\,\text{G}$ for a 100 μm thick cell. A large variety of permanent magnets (ceramic, rare earth cobalt, alnico, alcomax, neodymium–iron–boron) are readily available today [4] with fields well in excess of this.

For our demonstration, we constructed a nematic cell, using 3 cm × 3 cm × 1 mm glass plates, with lecithin surface treatment to provide homeotropic director alignment. The 120 μm thick cell was filled with the liquid crystal 5CB. Adhesive polarizer sheets with orthogonal polarization were attached to the cell windows so that the cell normally appears dark. If the cell is placed on a light table or an overhead projector, and a small magnet with sufficiently strong $\mathbf{B}$ field is placed on top, the spatially varying field creates spatially varying distortions of the director field, and interference colours appear. A schematic of the cell and magnet is shown in figure 1. We used a small (5 mm × 5 mm × 5 mm) rare earth magnet with a 3 kG field at its surface. Figure 2 shows the observed pattern when the field is parallel to the cell walls.

To lowest order, the magnetic field is that of a dipole situated above the cell. If the dipole is normal to the cell walls, the pattern is nearly cylindrically symmetric. To compare the observed pattern with theory, we computed

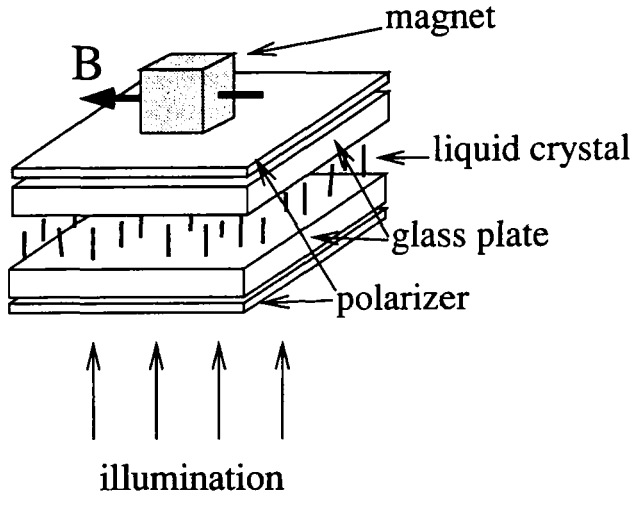

Figure 1. Cell configuration for demonstration of the magnetic Fréedericksz transition.

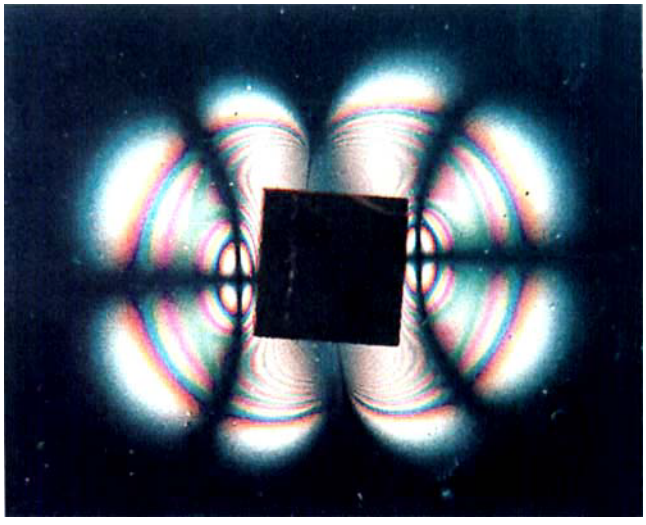

Figure 2. Photograph of projected image of cell.

the expected director configuration, assuming the magnet to be a dipole, and the transmitted light intensity. Our results are shown in figure 3. The director configuration was obtained using an averaging procedure which relies on a separation of length scales; the transmitted intensity was calculated for the three primary colours. The only adjustable parameter in the model is the magnitude of the dipole moment of the magnet. Details of the model and algorithm will be published elsewhere [5].

We note that the field of the magnet falls off rapidly with distance, approximately as $1/r^3$. For our small magnet even the 1 mm glass thickness results in a reduction in the magnetic field by a factor of ~ 1/3. The critical field depends inversely on sample thickness, and therefore thick samples enclosed between thin glass plates are ideal for the demonstration.

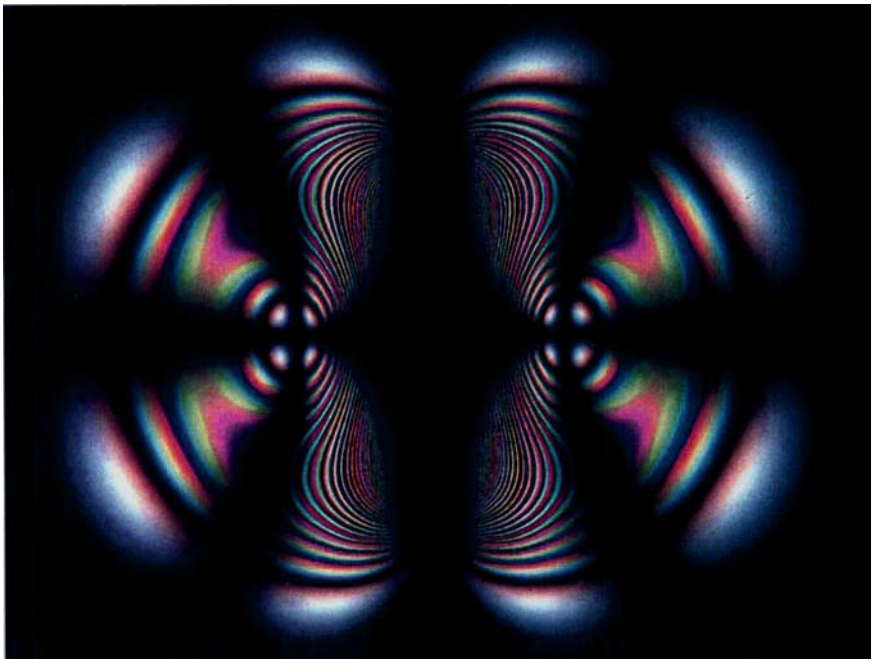

Figure 3. Computer simulation of the optical distortion induced by a centrally-placed magnetic dipole.

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5 FORTRAN source is available via the ILCS web server (http://alcom.kent.edu/ILCS).