Characteristics of the process of reorientation of bipolar drops of a nematic with rigidly fixed poles

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The director configuration in a bipolar drop of a nematic with rigidly fixed poles is calculated as a function of the electric field directed perpendicular to the symmetry axis of the drop. It is shown that the reorientation of the drop is a dual process: a threshold process in the region where the initial director orientation is orthogonal to the electric field, and a nonthreshold process elsewhere in the drop. A relation for determining the critical field is obtained. Experimental investigations of the characteristics of scattered light for a film of polymer-encapsulated liquid crystals confirm the computational results. © *1998 American Institute of Physics.* [S0021-3640(98)01709-5]

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According to experimental and theoretical investigations[1–3] the reorientation of bipolar drops of a nematic liquid crystal (LC) under the action of an electric field directed perpendicular to the symmetry axis is a threshold, three-stage process. At low voltages no change was observed in the orientational structure of the drop. When the threshold field was reached, the poles of the drop started to move and the bipolar configuration of the director turned so that the symmetry axis was oriented along the field, if the dielectric-constant anisotropy of the LC is positive. Increasing the voltage further caused the director to line up with the field lines in the entire volume of the drop.[1,3] At the same time, the possibility that both poles of the drop become rigidly fixed was not ruled out in Ref. 1. As assumed in Ref. 1, this will make the reorientation of a drop with nucleation of a linear disclination at each pole a threshold process. Rigid fixing of both poles has been observed experimentally[4] in an ensemble of bipolar drops of the nematic liquid crystal 5CB which were dispersed in polyvinylbutyral. In the present letter a theoretical calculation of the orientational structure of such drops as a function of the electric field strength is performed. The computational results are analyzed in comparison with the experimentally measured characteristics of light scattered by a film of polymer-encapsulated liquid crystals (PELCs).

The configuration of the director in a nematic drop in an electric field was calculated by the standard procedure[3] of minimizing the free energy in the one-constant approximation:

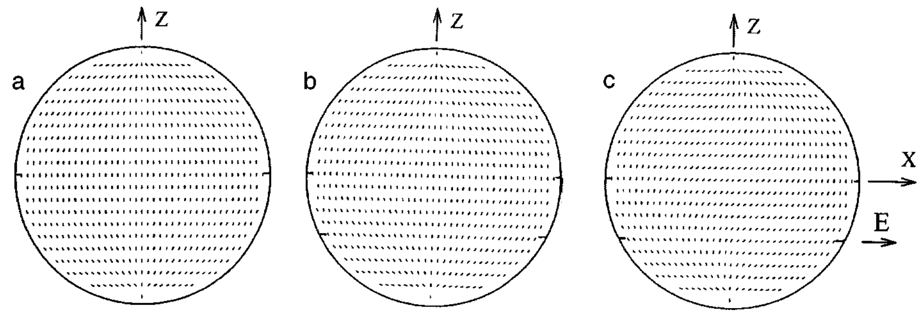

FIG. 1. Orientational structure of a bipolar drop of a nematic in the XZ plane with a) $E_n=0$, b) $E_n=3.2$, and c) $E_n=3.7$.

$$F=\frac{1}{2}\int \{K[(\nabla\cdot\mathbf{n})^2+(\nabla\times\mathbf{n})^2]-\epsilon_0\Delta\epsilon(\mathbf{n}\cdot\mathbf{E})^2\}dV, \tag{1}$$

where $\mathbf{n}$ is the director of the LC, K is the elastic modulus, $\Delta\epsilon=\epsilon_\parallel-\epsilon_\perp$, $\epsilon_\parallel$ and $\epsilon_\perp$ are the components of the dielectric constant, and $\mathbf{E}$ is the electric field vector. We assume the LC molecules to be rigidly anchored on the surface of the polymer matrix and the electric field inside the drop to be uniform. The director orientation at the interface is planar. Unline the case of Ref. 3, a homeotropic orientation of the director is imposed at two diametrically opposite points on the surface of the drop (on the Z axis, Fig. 1), and the vector $\mathbf{E}$ is assumed to be oriented in the direction of the X axis.

Figure 1 shows the computational results for the orientational structure of a spherical drop of a nematic in the section ZX for three values of the normalized electric field:

$$E_n=E/E_0; \quad E_0=\frac{1}{R}\sqrt{\frac{K}{\epsilon_0\Delta\epsilon}}. \tag{2}$$

Here R is the radius of the drop. For $E=0$ (Fig. 1a), just as in Ref. 3, a bipolar director configuration with the symmetry axis directed along the Z axis is realized. Point defects (boojums[5]) occur at points of homeotropic orientation of the director.

When a field is applied, the director configuration starts to change. First, the orientation is observed to change only in the regions where the vectors $\mathbf{E}$ and $\mathbf{n}$ are not orthogonal, and the ordering symmetry of the director in the XZ plane remains the same as before, but the angle of inclination of $\mathbf{n}$ with respect to the Z axis increases (Fig. 1b). The director of the LC at points located on the Z axis and in the XY plane remains stationary. This process is elucidated in Fig. 2 for the central point of the drop and for a point shifted rightward and upward from the center by $R/2$ along the Z and X coordinate axes.

The situation changes substantially for $E_n>3.3$ (Figs. 1c and 2). At the center of the drop and at other points on the Z axis and in the XY plane the director starts to turn. The lines of the director assume a characteristic S shape. Rotation is equally likely to start in one or the other direction, and the resulting patterns will be mirror symmetric with

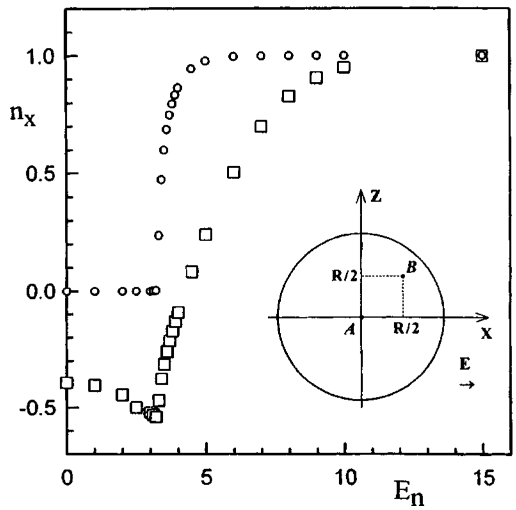

FIG. 2. Projection of the director of the LC on the *X* axis versus the electric field strength for the points *A* (○) and *B* (□) whose location inside the drop is shown in the inset.

respect to the *XY* plane. Further increasing the field will produce increasingly more uniform orientation of the director in the direction of the field in the volume of the drop. The field

$$E_c = 3.3\,\frac{1}{R}\sqrt{\frac{K}{\epsilon_0 \Delta\epsilon}} \tag{3}$$

is the critical value for the entire volume of the drop. For points where the vectors **E** and **n** are initially orthogonal to one another this has the meaning of a threshold field; elsewhere in the drop it appears as a sharp kink in the curve of the director orientation versus the field strength (Fig. 2).

The experimentally investigated PELC samples prepared as in Ref. 4 consisted of a 15 μm thick polyvinylbutyral film in which drops of the nematic liquid crystal 5CB were dispersed. The round LC drops had a maximum diameter of 19 μm in the film plane and were located in the same layer, making it possible to perform visual observations of the reorientation process using a polarization microscope. In the absence of a field the drops manifested in crossed polarizers a texture that is characteristic for a bipolar director configuration,[5] poles being arranged so that in all drops the axes joining the poles lay in the film plane. The sample was placed between two glass substrates with transparent electrodes on the interior sides. Thus the electric field in the experiment was perpendicular to the initial symmetry axis of the drops. The intensity of the light scattered by the PELC film at an angle α with respect to the direction of the helium–neon laser beam, incident normally, was recorded as a function of the applied voltage using a X–Y plotter.

According to a theoretical geometrical-optics analysis[6] of the characteristics of light scattering by an ensemble of LC drops with size greater than the wavelength of the light, the ray passing along the *X* axis through the center of the drop makes the main contribution to the intensity of the radiation passing straight through the drop. Therefore in our

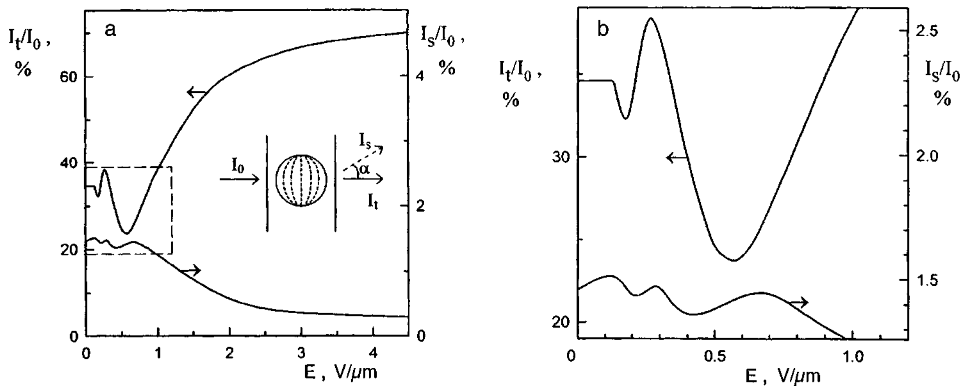

FIG. 3. a) Intensity I_t of the directly transmitted radiation and intensity I_s of the radiation scattered by an angle $\alpha\approx 7°$ versus the applied field. b) Enlargement of the outlined fragment in part a.

case the dependence of the intensity of the radiation passing straight through the drop on the applied field should be of a threshold character. The ray trajectories passing through the side regions of the drop curve as a result of the index gradient at the polymer–LC interface and the continuous variation of the index inside the drop.[6] Therefore the light scattered at an angle $\alpha\neq 0$ carries information about the director orientation in the side regions of the drop and the field dependence of its intensity should be of a nonthreshold form.

The experimental data (Fig. 3) confirm these conclusions. Here the intensity of the transmitted radiation was measured in the range of angles $0\leqslant\alpha\leqslant 0.5°$ and the intensity of the radiation separated by a ring-shaped diaphragm was measured in the range of scattering angles $6.8\leqslant\alpha\leqslant 8.5°$. The oscillations on the curves of the directly transmitted radiation above threshold had been observed and discussed earlier in Ref. 4. As one can see, the light-scattering curve has a nonthreshold character and oscillates.

The measured value of the critical field E_c for the experimental sample was equal to 0.13 V/μm. An estimate using Eq. (3) and the parameters $K=(K_{11}+K_{22}+K_{33})/3$, $K_{11}=6.2\times 10^{-12}$ N, $K_{22}=3.1\times 10^{-12}$ N, $K_{33}=8.3\times 10^{-12}$ N (Ref. 7), $\Delta\epsilon=11.8$ (Ref. 8), and $R=9.5$ μm gives the critical field $E_c=0.08$ V/μm. The radius of drops of maximum size was used in the calculations. Since the threshold field for such drops is minimum, they determine the value of E_c for an ensemble of drops of different size. The discrepancy between the computed and experimentally measured values of E_c is mainly due to two factors. First, the real shape of an LC drop in such samples is an ellipsoid, flattened in the film plane, with a ratio of axes equal to about 1.7 (Ref. 9). This makes it necessary to modify the computational model in order to take into account the ellipsoidal nature of the drop. It is obvious that decreasing the size of the drop along at least one of the coordinates will increase the computed value of E_c. The second factor is the redistribution of the applied electric field in the polymer–LC structure. Since the dielectric constant of the LC 5CB is higher than that of the polyvinylbutyral matrix ($\epsilon_\perp/\epsilon_p=1.46$ (Ref. 4)), the critical value of the field inside the drop will be less than the applied field $E_c=0.13$ V/μm.

In summary, the results of this work show that the process leading to the reorientation of bipolar drops of a nematic is in general a nonthreshold process. This result should also be true for drops with mobile poles. One can talk about a threshold only with respect to separate aspects of the process: onset of motion of the poles of the drop in the case when the poles are not rigidly fixed, or onset of local rotation of a region of a drop where the vectors **E** and **n** are orthogonal to one another in the case when the poles are rigidly fixed. The possibility of a combination of the two types of reorientation of bipolar drops, when the configuration of the director initially changes as shown in Fig. 1 and pole motion starts with a further increase in the field, cannot be ruled out. Apparently, the onset of changes in the configuration of the director (Figs. 1a and 1b) could not be observed by visually[1,2,4] because the deflections of **n** are small and the eye is too insensitive. It should be noted that contrary to the assumption in Ref. 1, the onset of rotation in the central part of the drop (Fig. 1c) is not accompanied by the formation of linear disclinations.

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