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Selective reflection in ferroelectric liquid crystals distorted by an electric field

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Selective reflections were measured to study the elastic deformation of a ferroelectric chiral smectic C liquid crystal in a homeotropically aligned cell when a D.C. electric field was applied normal to the helical axis. The first, second and third order reflections which occur corresponding to the full pitch were detected very clearly. From the dependence of the pitch on the electric field, a torsional elastic constant for the deformation and a critical electric field to unwind the helix were evaluated.

1. Introduction

Ferroelectric chiral smectic C liquid crystals have been studied extensively by many authors because of the possibility of their application to high speed switching devices. One of the important things to achieve is an analysis of the static and dynamic elastic deformation. To study this problem theoretically, we must know the Frank elastic constants. The direct measurements of these and the critical electric field, E_c, needed to unwind the helix for 4-*n*-decyloxybenzylidene-4′-amino-2-methylbutyl cinnamate (DOBAMBC) have been studied by light scattering in freely suspended smectic C films [1–3] and by observing the pitch in homogeneously aligned cells [4–9], respectively. However, the pitch is easily influenced by surface anchoring in a homogeneously aligned cell, even for rather thick cells (about 200 μm) [10]. A typical example of the electric field dependence of the pitch is shown in [6] in which the pitch is almost constant for low fields and then increases steeply near E_c. Of course, the pitch increases steeply near E_c but the pitch should increase even in low electric fields.

To reduce the influence of surface anchoring, a homeotropically aligned cell is better than a homogeneously aligned cell. For measurement of the pitch we can then use the selective reflection in a homeotropically aligned cell. In fact, some experimental data on selective reflection without any external field have been published [11–13]. Moreover we have also reported in detail about this, especially the decrease in the selective reflection near the S_C^*–S_A transition [14]. It is therefore interesting to measure the selective reflection when a D.C. electric field is applied normal to the helical axis in a homeotropically aligned cell.

In this paper we report experiments on the electric field dependence of the selective reflection and then estimate a torsional elastic constant, by fitting the experimental results to theory, and also estimate E_c. The fitting was excellent even for low electric fields, and the experimental data were not noticeably influenced by the glass surface.

2. Experiment [14]

A ferroelectric chiral smectic C liquid crystal mixture, CS-1017 (Chisso Co., Ltd), which has an intrinsic helical pitch comparable with wavelengths in the near infrared

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region (0·8–2·5 μm) was used, because there are no molecular absorption bands or bands from the glass plate in this wavelength region. The sample was sandwiched between two soda-lime glass plates which were coated with a chrome complex after soaking them in a chromic acid mixture. Two stainless steel plates (7 mm × 20 mm) were used not only as spacers but also as electrodes. The thickness of the plates was 300 μm and they were set parallel, being separated by 285 μm. They were covered with evaporated SiO to avoid charge injection from them when an electric field was applied.

Homeotropic alignment was achieved by using a cooling rate of 0·1°C min^{-1} when passing through N* to S_A and S_A to S_C^*. We had to apply a D.C. electric field normal to the helical axis to obtain a homeotropically aligned monodomain sample when the temperature was lowered from the S_A into the S_C^* phase. The quality of the cell was excellent and this was checked by observing the birefringence colours under a polarizing microscope. We determined the transition temperature, $T_{S_C^*S_A}$, from S_C^* to S_A by observing the response to an applied D.C. electric field normal to the helical axis under the polarizing microscope. In our sample, $T_{S_C^*S_A}$ was about 55·3°C.

The monochromator used was Model CT-10 (Japan Spectroscopic Co., Ltd) which has a 0·7–2·6 μm wavelength region. The cell was mounted in a copper oven whose temperature was controlled with an accuracy of ±0·1°C and which was set perpendicular to the beam direction. The temperature of the cell was monitored by a copper–constantan thermocouple junction. We used a pair of lenses to increase the sensitivity, so that the incident angle is not exactly normal to the glass plates. However, this effect on the selective reflection is very weak. The transmittance spectra were measured in the S_C^* and S_A phases as a function of wavelength. The net transmittance in the S_C^* was obtained relative to S_A. We confirmed that the transmittance spectrum in the S_A phase was equal to that of the isotropic phase.

3. Results and discussion

The electric field dependences of the selective reflection of the first, second and third order reflection bands in the S_C^* phase at 37·3°C are shown in figures 1 (*a*), (*b*) and (*c*), respectively, as a function of wavelength. Some parts of the solid lines for fields over 302 kV m^{-1} in figure 1 (*b*) are cut off to make the figure clearer, but there are certain transmittances below the cutting point. When no electric field is applied, only the second order reflection appears and then the first and third order reflections appear as the electric field increases. The wavelengths, λ, of the selective reflection at each order satisfy the Bragg condition perfectly, where we have taken the wavelength at maximum dip as λ. This shows that the optical period of the structure without any electric field is half the pitch, but that in the electric field it is the full pitch.

In this experiment we noticed that a certain electric field induced by impurity ions in the liquid crystal after applying the electric field. The induced electric field, E_i, remains until the next application and contributes to the next electric field as a negative field. Therefore, we have to take it into account when determining the net electric field. We measured it after this experiment by observing the change of transmitted light under a polarizing microscope after applying a high electric field. E_i was about 66 kV m^{-1} at this temperature. Therefore, all of the electric field strengths in figure 1 have been corrected for it. E_i was almost constant for electric fields over 175 kV m^{-1} but it seemed to be lower for fields below that. In consequence, the estimate of the net electric field may be too small for fields below 109 kV m^{-1}.

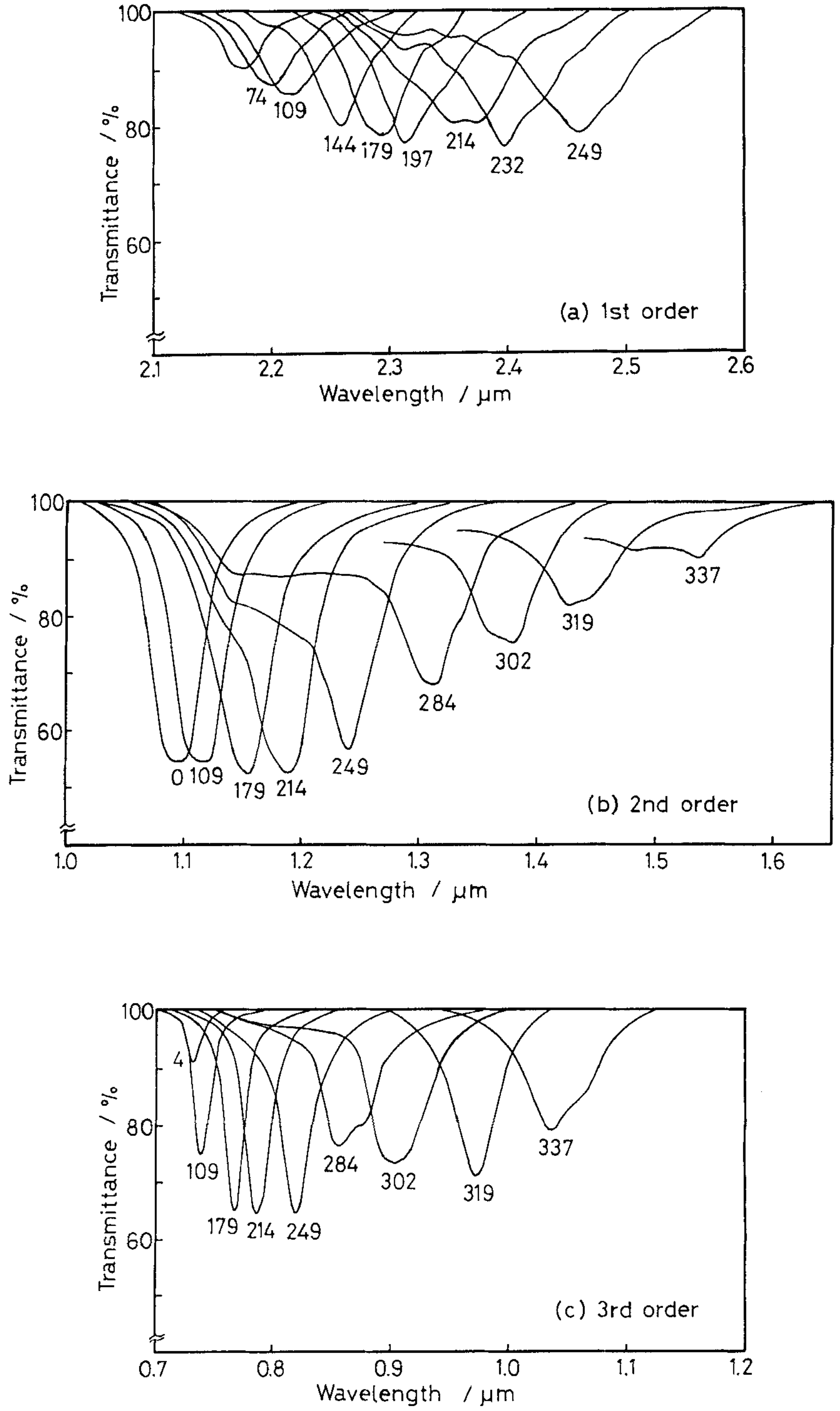

Figure 1. The electric field dependences of the selective reflection of each order as a function of wavelength; (*a*) first order, (*b*) second order, (*c*) third order. The numbers labelling each curve give the electric field strength in kV m^{-1}.

As the electric field increases, the width of the peak becomes broader because of the inhomogeneity of the electric field near the glass surface. We had to cut the edge of the spacer to avoid concentration of the electric field, and so the field near the edge of the spacer would be a little weaker than that of the central part.

The reflectances of each order increase up to a certain electric field and then decrease, except in a few cases in figures 1 (*a*) and (*c*) due to the very low intensity of the spectrum of the light source in this wavelength region. As for the optical eigenmodes (two forward modes), the modes change from one reflective and one propagative mode to two reflective modes in each order as the electric field increases [15]. Therefore, if we calculate the reflectances of each order in a finite cell thickness, they should increase as the electric field increases. We can see the tendency in a relatively weak electric field. For high fields, however, it does not agree with the calculated results because of the disorder of the molecular orientation.

By dividing λ by λ_0 in figure 1 (*b*) we can determine the electric field dependence of the pitch normalized by the intrinsic pitch, where λ_0 is the wavelength of the selective reflection without any electric field. This is shown in figure 2, in which the experimental data are represented by closed circles. In addition to the data, theoretical results based on a nematic-like expression for the elastic free energy density [16] are also shown as the solid lines to evaluate the torsional elastic constant $\tilde{\kappa}$, where

$$\tilde{\kappa} = \sin^2\theta(K_2\sin^2\theta + K_3\cos^2\theta),$$

where K_2 and K_3 are the twist and bend elastic constants, respectively, and θ is the tilt angle. The parameters used are the spontaneous polarization, $P_s = 7{\cdot}1 \times 10^{-5}\,\mathrm{C\,m^{-2}}$ and the intrinsic pitch $P_0 = 0{\cdot}731\,\mu\mathrm{m}$; the dielectric anisotropy is ignored. P_s and P_0 were determined by measuring the induced current with a triangular wave and from λ_0/n_{av}, respectively, where n_{av} is the average refractive index and we have taken n_{av} to be 1·5 since the value of n_{av} was not available.

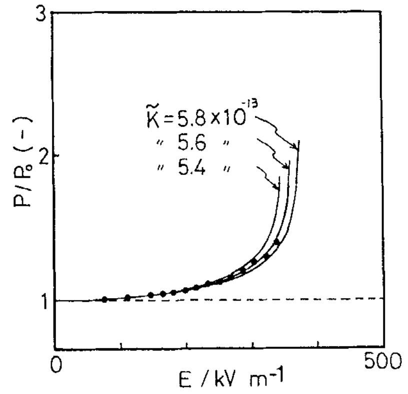

Figure 2. The electric field dependence of the helical pitch. The experimental data, which are determined by λ/λ_0 in figure 1 (*b*), are represented by closed circles. The full lines show the theoretical results for different values of $\tilde{\kappa}$.

As seen in figure 2, the fit between the experimental data and theory is best for $\tilde{\kappa} = 5{\cdot}6 \times 10^{-13}\,\mathrm{N}$ and is much better than that for a homogeneously aligned cell [6], especially in low electric fields. This shows that the pitch in a homogeneously aligned cell is strongly influenced by the glass surface, but the influence in a homeotropically aligned cell is very weak. In order to confirm the value of $\tilde{\kappa}$, measurements have been made on samples with a separation between the spacers of 320 μm and with a spacer thickness of 200 μm. The same results were obtained within experimental error of about $\pm 5\%$. We can therefore also estimate the critical electric field E_c $(=\pi^4\tilde{\kappa}/4P_sP_0^2)$ needed to unwind the helix; E_c was found to be about 372 kV m^{-1} at this temperature.

4. Conclusion

We have measured the selective reflections of a ferroelectric chiral smectic C liquid crystal mixture, CS-1017, in a homeotropically aligned cell when a D.C. electric field was applied normal to the helical axis. The selective reflections of first, second and third order were detected clearly and they satisfied the Bragg condition perfectly. From this experiment the electric field dependence of the pitch was determined and then the torsional elastic constant and the critical electric field needed to unwind the helix were also estimated by fitting the experimental data to theory. A certain electric field induced by impurity ions should be taken into account for the net electric field.

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