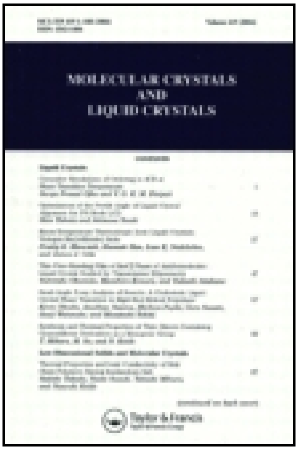

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Transient diffraction phenomena induced by external applied electric field to nematic liquid crystal (4-cyano-4'-n-pentylbiphenyl) cells have been investigated. Far-field ring diffraction pattern is observed and is caused by a quasiperiodic herringbone pattern, similar in appearance to the classical Williams domain, in the nematic liquid crystal cells. It is found that the electric-field and the temperature dependences of the diffraction transients have correlation with those of current transients due to the conduction of impurity ions. These findings are essentially the same for both homogeneously and homeotropically aligned nematic liquid crystal cells. It is concluded that the transient diffraction is attributable to the ion conduction via the formation of the herringbone texture.

Keywords: diffraction; Williams domains; transient current; impurity ions; nematic liquid crystal

INTRODUCTION

The influence of impurity ions in nematic liquid crystal (NLC) cells has been extensively studied[1] because of the fact that the impurity ions often degrade the device performance of NLC displays. To gain insight into the degradation, we have studied the transient ion transport[2], the ion generation[3], the electric double layer formed by the ions[4], and the ion adsorption onto and the ion desorption from alignment layers in NLC cells[5] by means of time-of-flight, dielectric, and ac conductivity measurements. For instance, from the time-of-flight measurements for the transient ion transport in 4-cyano-4′-n-pentylbiphenyl (5CB), we have found that the mobile charge carriers are positive ions and their drift mobility is 3.5×10^{-6} cm^2/Vs at 303 K[2]. In addition to these information, the transient light scattering study is also necessary to understand the influence of the impurity ions on the device performance. The reason for this is that the transient charge transport would affect the director orientation of NLC, which is likely to induce the transient light scattering.

In this paper, we study the transient light scattering from NLC cells induced by the transient ion transport, and find that the transient light scattering is due to diffraction from Williams-domain-like structures. The transient diffraction is observed for both homogeneously and homeotropically aligned NLC cells.

EXPERIMENT

The NLC used in the present experiment was 5CB with positive dielectric anisotropy ($\Delta\epsilon$ ~10). The 5CB was introduced between two pieces of glass with a transparent indium tin oxide (ITO) electrode, whose area was 2 cm^2. We prepared homogeneously and homeotropically aligned NLC cells using polyimide films coated on the ITO glass substrates. Alignment layers were prepared using PI-A for homogeneous alignment and RN-1204 for homeotropic alignment (both polyimides were obtained from Nissan Chemical Industries, Ltd.). For homogeneous alignment the surfaces of the polyimide films were unidirectionally rubbed. The thickness of the homogeneously and the homeotropically aligned NLC cells was 15 - 18 μm.

For the transient diffraction experiment, the light source used was a He-Ne laser which was normally incident onto the cells. The polarization of the incident beam was in the plane with the direction of the rubbing in the cells with homogeneous alignment. The diffracted light, in the orthogonal polarization through an analyzer, was focused on a photodetector by a collecting lens. The transient diffraction observed in this configuration was essentially the same when the cells were rotated around the incident beam for 90°. The transient diffraction from the cells with homeotropic alignment was observed with the same configuration. The far-field diffraction patterns were observed on a screen behind the cell without using the polarizer, the analyzer and the collecting lens, and the temporal development of the pattern after electric-field application was recorded on a video recorder. The cells were observed with a polarizing microscope (Nikon X2TP-11) under the same conditions for the observation of the far-field diffraction patterns.

For both transient current and transient diffraction measurements, polarity-reversal square-wave voltage (1 Hz) was applied to the NLC cells mounted in an Instec HS1-i hot stage, which kept the cell temperature in the nematic phase range of 5CB. The transient current of the NLC cells was measured with a digital oscilloscope at various applied voltages and temperatures.

RESULTS AND DISCUSSION

We found transient light scattering induced by the application of polarity-reversal voltage pulses to the NLC cells in the course of the study of influence of impurity ions on electro-optic properties of NLC. In what follows, we show that the transient light scattering is due to diffraction from quasiperiodic pattern in the NLC cells.

Figure 1 (a) shows the typical far-field pattern of the homeotropically aligned NLC cell induced by the application of polarity-reversal square-wave voltage (± 16 V, 1 Hz). A circular ring pattern is observed and in the center of the pattern, light scattering caused by orientational fluctuations is also observed because of the thermal fluctuations of molecular orientation.

The ring pattern is clearly seen in the frequency range of applied voltage from 1 to 5 Hz, and a threshold voltage exists for the observation of the ring pattern and increases with increasing frequency of applied voltage. Below 1 Hz, it is easily recognized that the ring pattern is a

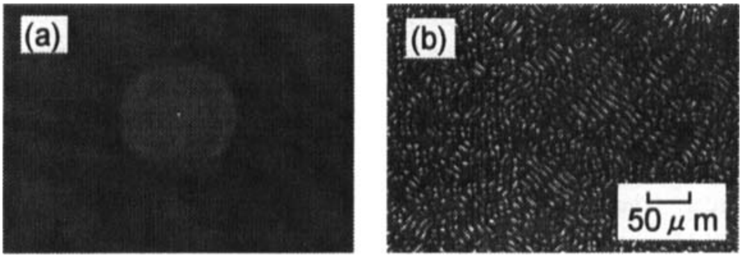

FIGURE 1 The far-field pattern (a) and the texture observed under crossed polarizers (b) in the homeotropically aligned NLC cell at 301 K . Square wave (±16 V, 1 Hz) was applied.

transient pattern; the ring pattern appears just after the rising of the square voltage pulses, and disappears within ~200 ms.

The photograph of Figure 1 (b) shows a quasiperiodic stable herringbone pattern, similar in appearance to the classic (hydrodynamic) Williams domains[6]. The photograph was taken under the same conditions of Figure 1 (a). The herringbone pattern is induced just after the rising of the voltage pulses and disappears soon below 1 Hz. We note that the spatial period of the pattern is roughly equal to the characteristic length calculated from the ring pattern in Figure 1 (a). It is therefore evident that the circular ring pattern in Figure 1 (a) is caused by the quasiperiodic herringbone pattern.

It is interesting to point out that the features of the domains shown in Figure 1 (b) are also similar to those of the Williams domain in the sense that the herringbone patterns can only be observed in the nematic phase, the spatial period of the herringbone patterns is approximately equal to the cell thickness, and the threshold voltage for the appearance of the herringbone pattern is increased with frequency of the applied voltage[6]. We thus speculate that the herringbone pattern shown in Figure 1 (b) is explained by the Car-Helfrich mechanism[7]. However, there is difference in the experimental features between the present observation and the Williams domains: the Williams domains have been observed in the frequency range of 3∼100 Hz while the present herringbone pattern can be observed in the frequency range of 0.001∼5 Hz (in the frequency range below 1 Hz the herringbone pattern appears transiently, and can probably be observed below 0.001 Hz). It is known that electrohydrodynamic instability has been extensively studied in NLCs with negative dielectric anisotropy such as *n*-*p*-methoxybenzylidene-*p*-butylaniline because spectacular patterns have been found in the materials. On the other hand, little attention has been given to the instability in NLCs with positive dielectric anisotropy[8,9].

The same results were obtained in the homogeneously aligned NLC cell, except for the observation that the diffraction pattern is a superposition of the both ring pattern and stripe-like pattern that runs perpendicular to the rubbing direction (accordingly, the pattern observed with a polarizing microscope was a more oriented pattern than that in Figure 1 (b); the stripes of the most domains are perpendicular to the rubbing direction).

Next, we examine a relation between the transient diffraction and the transient ion transport. Figures 2 (a) and 2 (b) show the waveforms of the transient current and the transient diffraction at 303 K, for the

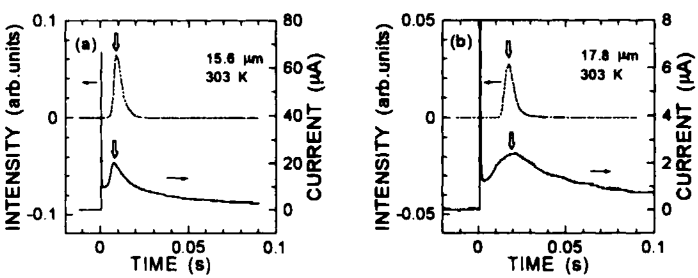

FIGURE 2 The current transient and diffraction transient of (a) homogeneously and (b) homeotropically aligned NLC cells at 303 K. The transient diffraction in the homogeneously and the homeotropically aligned NLC cells was measured with the analyzer and polarizer crossed. Square wave (±16 V, 1 Hz) was applied.

homogeneously and the homeotropically aligned NLC cells, respectively. We applied a square wave voltage ($\pm$16 V, 1 Hz) to the NLC cell. In both cells, the drift mobility calculated from the time at a prominent peak in the transient current, highlighted by the arrows in Figure 2, corresponds to the drift mobility parallel to the director.

The diffraction transient is shown in Figure 2 and a prominent peak in the transient, highlighted by the arrows, is also observed. We note in Figure 2 that the time at the peak in the transient current coincides with that in the diffraction transient, for both of the homogeneously and the homeotropically aligned NLC cells. To examine the relationship between the peak times in the current transient and in the diffraction transient in detail, we show the temperature and the applied-electric-field dependences of both peak times for the homogeneously and the homeotropically aligned

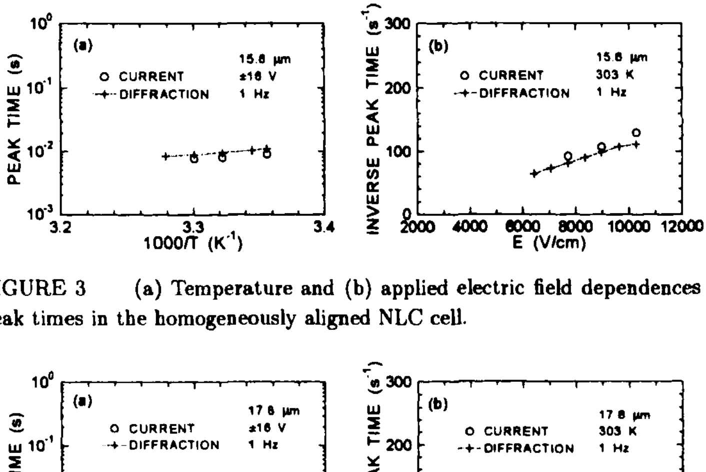

FIGURE 3 (a) Temperature and (b) applied electric field dependences of peak times in the homogeneously aligned NLC cell.

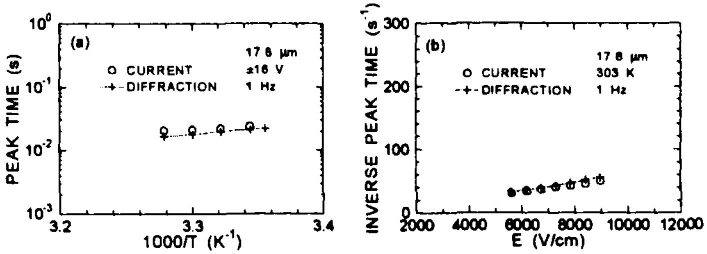

FIGURE 4 (a) Temperature and (b) applied electric field dependences of peak times in the homeotropically aligned NLC cell.

NLC cells. In Figure 3 (a), the temperature dependence of the peaks in the current transient and the diffraction transient is shown for temperatures in the nematic range. The peak time of the transient current in Figure 3 (a) exhibits thermally-activated behavior with the activation energy of 0.27 eV. In Figure 3 (b), the applied-electric-field dependence of the peak times is shown at 303 K. The transient current and the transient diffraction were measured for > 10 V. Inverse of the peak time in the current transient is proportional to applied electric field as $1/t_p = \mu E/0.78L$, where t_p is the time at the peak appeared in the transient current, μ is the drift mobility of ions, L is the thickness of the NLC cell, and E is applied-electric field. In case of the transient space-charge-limited current, $t_p \cong 0.78t_r$, where $t_r = L/\mu E$[2]. Hence, the drift mobility calculated from Figure 3 (b) is 1.8×10^{-5} cm^2/Vs.

We show the temperature and the applied-electric-field dependences of the peaks for the homeotropically aligned cell in Figure 4. The results obtained in this figure are essentially the same as those in Figure 3 but we found that the drift mobility calculated from Figure 4 (b) is slightly different from that calculated from Figure 3 (b) and is 7.2×10^{-6} cm^2/Vs. The difference in the drift mobility may be attributable to the different species of ions dissolved from the polyimides for homogeneous (Figure 3 (b)) and homeotropic alignments (Figure 4 (b))[10]. It is evident from Figures 3 and 4 that the peak times in the diffraction transients are in good agreement with those in the current transients.

We conclude from the experimental results mentioned above that the transient ion transport induces the transient diffraction, which would affect the performance of NLC display devices, via the formation of the quasiperiodic stable herringbone pattern. It is important to mention that the transient diffraction is not caused by the application of step voltage to the NLC cells, indicating that the transit of impurity ions from one electrode to the other electrode is a crucial condition for the observation of the transient diffraction.

CONCLUSIONS

We have studied the transient light diffraction induced by external applied electric field in 5CB cells. First, we have examined far-field patterns and textures in 5CB cells. It is found that the far-field pattern is a ring pattern and that the cells exhibit a quasiperiodic stable herringbone pattern, similar to classic (hydrodynamic) Williams domains. The experimental features of the herringbone pattern such as threshold voltages and their frequency dependence are also similar to those of the classic Williams domain. We show that the far-field ring pattern is caused by the herringbone pattern. Then, we have examined the temporal variation in diffraction and ion transport. The diffraction is found to be induced during the transit of impurity ions. From these findings, we demonstrate that the ion transit across the NLC cells induces the transient diffraction via the formation of the quasiperiodic pattern. The present experimental results are observed for both homogeneously and homeotropically aligned NLC cells.

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