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Brief Communication

Effects of Carbon Nanotubes on Nematic Backflow in a Twisted Nematic Liquid-Crystal Cell

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Effects of carbon nanotubes (CNTs) on the nematic backflow in a twisted nematic liquid crystal cell have been investigated. It has been reported that CNTs suppress the nematic backflow and thus the switching time is improved in case of low CNT doping such that it does not change the driving voltage. However, according to our studies, the presence of CNTs does not play a role in suppressing the nematic backflow. [DOI: 10.1143/JJAP.46.7801]

KEYWORDS: carbon nanotube, liquid crystal, twisted nematic, backflow

In recent works,[1–3] effects of carbon nanotubes (CNTs) on the electro-optic characteristics such as hysteresis of voltage-dependent transmittance and the switching behavior have been demonstrated in a twisted nematic liquid crystal (LC) host. In the switching behavior, it is claimed that the CNTs in a rod-like nematic yielded a good guest–host effect, suppressing the nematic (back) flow[4,5] and as a consequence, a dramatic improvement of electro-optic responses to on/off switching time was achieved.

In this study, we investigated CNT effects on optical bounce during switching of twisted nematic LC cell, especially when the doping amount of CNTs is small enough not to disturb LC orientation in a microscopic level and not to disturb the driving voltage.

In general, the optical bounce during the switching originates from two factors: high cell retardation value over the first minimum and the nematic backflow that occurred when the mid-LC director tips over momentarily after the switch-off of a strong voltage. The former gives rise to the optimal bounce in the rising and decaying time, while the latter generates the optical bounce only in the decaying time. In addition, the optical bounce in the decaying time occurs as soon as the voltage is turned off in the latter case. On the other hand, it occurs whenever reorientation of the LC director matches Gooch–Tarry's minimum condition[5] before the LC fully relaxes to an original state in the former case.

In their fabricated cells, the LC 5CB or E7 (E7: a birefringence $\Delta n = 0.2255$ at a wavelength $\lambda = 589$ nm, dielectric anisotropy $\Delta\varepsilon = 14.1$), was used and the cell gap (d) was 5.7 µm. The optical transmittance was measured using a He–Ne laser operating at 633 nm. As a result, the cell retardation value ($d\Delta n$) with E7 is 1.254 µm, which is slightly higher than second minimum condition of the Gooch–Tarry's normally black (NB) twisted nematic (TN) cell.[6] This indicates that for their NB TN cell, the transmittance will increase first and then decrease, and again increase with increasing voltage, representing a bounce in a voltage-dependent transmittance (V–T) curve. Consequently, even the switching behavior which is time-dependent transmittance will show some bounce in the time-dependent transmittance curve when a low voltage is applied to the cell with its cell $d\Delta n$ which is located over the first minimum. According to the previous report,[1] both normally white (NW) and NB pure LC cells show the optical bounces during the decaying time. The small bounce in the NW cell and the second small bounce in the NB cell seem to be associated with the cell retardation value. However, a large optical bounce in the NB cell using E7 may arise from the nematic backflow, although it does not appear in the NW cell using 5CB unexpectedly.

In general, the optical bouncing phenomena depend strongly on the Oseen–Frank elastic constants, the six components of Leslie viscosity coefficients, as well as the birefringence, the dielectric anisotropy and the cell thickness. Moreover, the degree of the backflow strongly depends on the applied field, i.e., the higher the applied field, the larger the effect of the backflow.[5] In this paper, we investigated the effect of CNTs on the optical bounce during the switching of the twisted nematic LC cell, especially when the doping amount of CNTs is low enough not to disturb LC orientation in a microscopic level and not to disturb the driving voltage appreciably.

To confirm our assertion that the CNTs in LC do not contribute to the suppression of nematic backflow, two NB cells with a cell gap of 5.7 µm, C-1 (superfluorinated LC mixture MJ951160 from Merck with $\Delta n = 0.088$, $\Delta\varepsilon = 7.4$) and C-2 (E7) with their retardation values of 0.41 and 1.24 µm, respectively, were made and the optical transmittance was measured using a He–Ne laser operating at 633 nm, about the same conditions as previously reported.[1] Both V–T curves are almost identical for ac and dc voltage, indicating that both cells do not contain massive ions unlike the cells reported by Lee *et al.*[1] Due to the small amount of ions, the measured time-dependent transmittance by applying dc 3 V and ac 3 V shows the similar behavior, as shown in Figs. 1(a) and 1(b). The C-2 cell shows small optical bounces during the switching, as clearly indicated in the insets, whereas the C-1 cell does not exhibit the bounces at all, indicating that the bounce is clearly associated with $d\Delta n$ value. However, both cells do not reveal the optical bounce associated with the backflow at 3 V. It is well known that the TN cell should show the nematic backflow when the applied voltage is high enough. Therefore, in order to observe the optical bounce associated with the nematic backflow, ac 6 V with a square wave is applied to the cells. As indicated in Fig. 1(c), the optical bounce is observed only in the C-2 cell but not in the C-1 cell. Here the cell gap is the same with each

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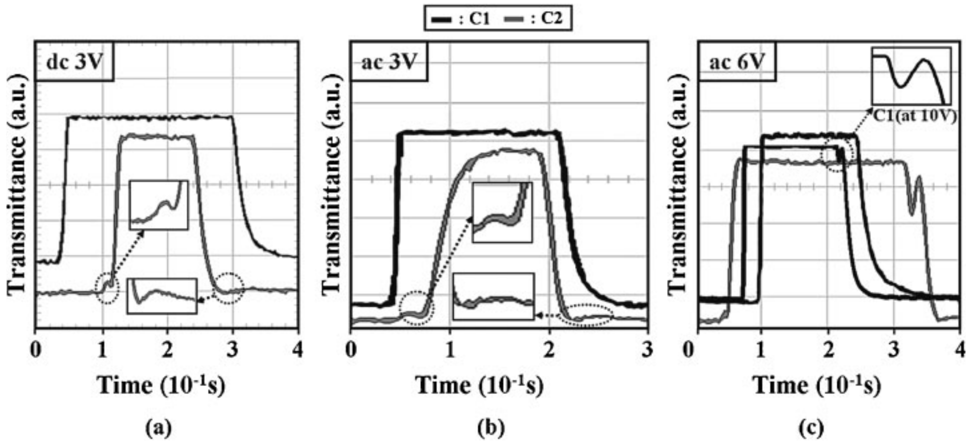

Fig. 1. The measured time-dependent transmittance when (a) dc 3 V and (b) ac 3 V are applied to to the NB TN cells. In (c), ac 6 V is applied to the cells C-1 and C-2 to observe the optical bounce associated with the nematic backflow. The C-1 cell shows the optical bounce with a bias voltage of ac 10 V as clearly indicated in the inset.

other so that the different behavior may originate from the difference in the dielectric toque, since $\Delta\varepsilon$ of E7 is about two times higher than that of MJ951160. Furthermore, ac 10 V is applied to the C-1 cell and the optical bounce is observed, as expected. From above experiments, we understand that the optical bounce is strongly related to the intensity of dielectric torque that governs the reorientation of the mid-director of LC, i.e., mainly the applied voltage and dielectric anisotropy of the LC. In addition, if the cell gap is increased with the same LC, giving rise to high $d\Delta n$, there is more probability of occurrence of the bounce, because the mid-LC director will have a higher tilt angle at the same voltage.

Now, to confirm the effect of CNTs on the switching time, we fabricated a CNT-doped NB TN cell by doping multi-walled CNTs of 5×10^{-3} wt % to the LC MJ951160 with $d\Delta n = 0.41\,\mu$m. The CNT-doped cell did not show any aggregates of CNTs at a microscopic level and the voltage-dependent transmittance curves showed that the driving voltage was almost the same with each other. Next, we observed the switching behavior by applying ac 10 V, as shown in Fig. 2. As clearly indicated, both pure and CNT-doped cells exhibit the clear optical bounces associated with the nematic backflow during switching-off, which means that the CNT does not play a role in suppressing the nematic backflow, at least at the mentioned CNT concentration.

Now, based on these observations, we could have two hypotheses that why the CNT-doped TN cell with E7 did not show the optical bounce. According to the previous work,[1] the operating voltage in the CNT-doped NW cell using 5CB is reduced by more than 2 V compared to the pure LC cell. Therefore, the first assumption is that disappearance of the optical bounce may originate from the difference in the applied voltage between two cells, i.e., the less voltage is applied to the CNT-doped cell. The second assumption is that the disappearance of the bounces in the CNT-doped cell with ~0.02 wt % may be attributed to the disturbance of the LC orientation by the existence of the CNT clusters from the initial state since both our observations[7–9] and others[2] exhibited the CNT clusters when the amount of CNTs exceeded 10^{-3} wt %.

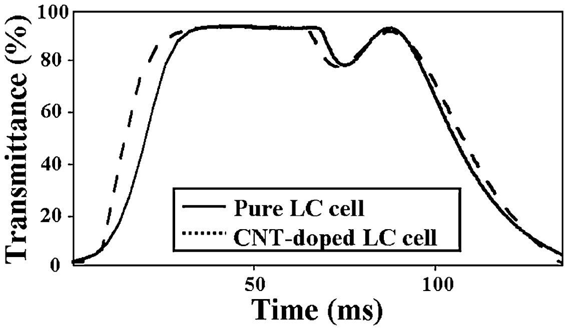

Fig. 2. The measured time-dependent transmittance when ac 10 V is applied in pure and CNT-doped NB TN cells.

In conclusion, the claim of the previous works that the CNT suppresses the nematic back flow and thus the switching time is improved needs to be reconsidered; in fact, the bounce in the TN cell during switching is strongly correlated with the cell retardation value and backflow associated with applied voltage. We observed clearly the optical bouncing associated with the backflow in decaying time for both CNT-doped and pure LC cells. This suggests that the CNT does not contribute to the optical bounce, at least at low CNT-doping concentration. Nevertheless, in a cell with massive ions, especially when the dc is applied, we admit that understanding the CNT effect on the switching time is rather too complex to confirm.

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