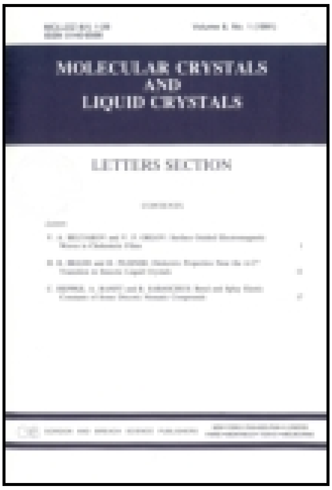

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Technologies for Sub-millisecond Response Time of Nematic Liquid Crystals

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In this paper, we introduce technologies for fast switching of nematic liquid crystals (LCs) using three-terminal electrodes. Fast switching of LCs can be achieved by employing a vertical trigger pulse, by applying a vertical bias field, and by random alignment of LCs.

Keywords Fast response; liquid crystal displays; nemaic liquid crystals.

1. Introduction

Following the improvement in the performance of liquid crystal displays (LCDs), LCDs have become widely used in small and large display applications such as in smart phones, monitors, tablet PCs, and TVs. LCDs exhibit high performance in terms of high contrast ratio, wide viewing angle, and low power consumption [1–4]. However, LCDs still suffer from a slow response time [5, 6]. Although the turn-on time can be reduced by overdrive schemes [7], the turn-off time remains slow because of the slow relaxation of the liquid crystals (LCs). A rapid response time is needed to reduce motion blur, obtain high image quality, and improve low-temperature operation. In particular, a rapid response time enables field sequential color (FSC) displays by which we can triple the optical efficiency and resolution density of a display system [8, 9]. To avoid color break-up in an FSC system, technologies for a three times faster switching of LCs must be developed.

Many different approaches have been studied in attempts to improve the response time. Most of these efforts use a thin cell gap [10], overdrive schemes [7], optimization of the LC materials [6], or new switching modes [11]. Another approach used to improve the switching speed is to incorporate nematic LCs into the polymer matrices. However, these technologies have only delivered a limited improvement in switching times. Recently, active studies on blue-phase LCs with a sub-millisecond response time have been conducted [12]. However, display devices using blue-phase LCs have not been commercialized yet because several problems still remain, such as a low transmittance, a narrow operating temperature range, and a high driving voltage of over 50 V [13].

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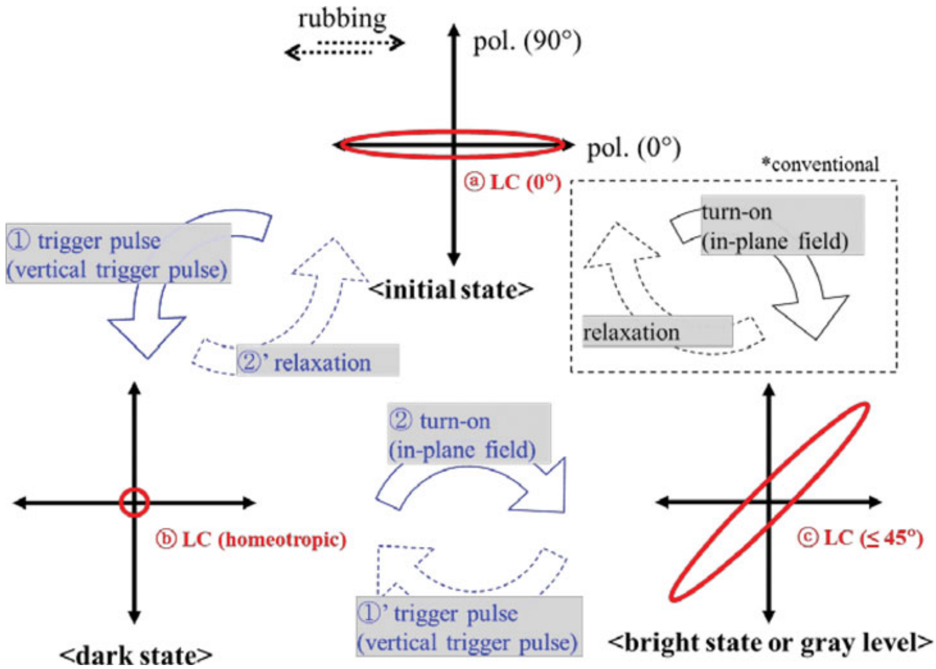

Figure 1. Operating principle of a homogeneously aligned 3T cell.

In this paper, we introduce technologies for fast switching of nematic LCs using three-terminal (3T) electrodes. To reduce the response time of an LC cell, we rely on the applied electric field for both the turn-on and turn-off processes. Fast switching of LCs can be achieved by employing a vertical trigger pulse, by applying a vertical bias field, and by random alignment of LCs.

2. Homogeneously Aligned LCs

2.1 Switching Triggered by a Vertical Pulse

Fast switching of a homogeneously aligned LC cell can be achieved by applying a vertical trigger pulse [5]. The operating principle is schematically shown in Fig. 1. In contrast to the conventional switching methods, the switching process consists of two steps. Initially, the LCs are homogeneously aligned, which shows the dark state. At first, a vertical trigger pulse is applied temporarily to vertically align the LCs (step ① in Fig. 1). As soon as the trigger pulse is removed, an in-plane field is applied to obtain the bright state by rotating the LCs while they are tilted downward (step ② in Fig. 1). Because the vertical trigger pulse breaks the equilibrium in the first step, the LCs are in the transient state and easily respond to an applied in-plane field so that fast turn-on switching can be realized. For turn-off switching, a vertical trigger pulse is applied again to vertically align the LCs (step ①′ in Fig. 1). After several milliseconds, the vertical trigger pulse is removed, and the LCs relax to the initial state (step ②′ in Fig. 1). During the turn-off process, the cell is in the dark state as soon as the trigger pulse is applied because the rubbing direction and the optic axis of the polarizer are parallel to each other, resulting in an accelerated turn-off response

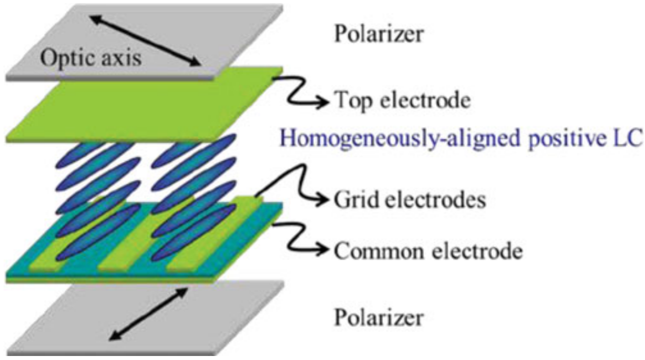

Figure 2. Structure of a 3T cell. An in-plane as well as a vertical electric field can be applied using the 3T electrodes.

time. To realize the proposed switching method, the 3T cell structure shown in Fig. 2 is used. An in-plane field is induced by applying an electric field between the grid and the common electrodes, whereas a vertical trigger pulse is induced by applying an electric field between the top and common electrodes.

To verify the electro-optical properties, we fabricated a unit cell by employing the structure shown in Fig. 2. The dielectric and optical anisotropies of the LC used in the fabrication were 7.1 and 0.1064, respectively. Both the width of the grid electrodes and the gap between them were 4 μm. The thickness of the LC layer was 3.8 μm. A homogeneous alignment layer was used, and the rubbing direction was set 5° with respect to the grid electrodes. For comparison, a unit cell with conventional two-terminal (2T) electrodes was also fabricated, whose parameters were the same as those used for the 3T cell. The 2T cell had a maximum transmittance of 27% at 4.4 V whereas the 3T cell exhibited the same maximum transmittance at 4.2 V [Fig. 3(a)].

To measure the turn-on and turn-off times of the 2T cell, we applied 4.4 V between the grid and the common electrodes for turn-on switching and then removed it after several milliseconds. The measured turn-on and turn-off times were 24 and 21 ms, respectively [Fig. 3(b)]. The measurement process for the response time of the 3T cell is described as follows. For turn-on switching, a vertical trigger pulse of 10 V was applied between the top and bottom electrodes for 1 ms. Then, 4.2 V was applied between the grid and the common electrodes. For turn-off switching, a vertical trigger pulse of 10 V was applied again for 1 ms. Then, the electric field was removed, and the LCs relaxed. By employing the proposed switching method, an accelerated turn-on time of 7.4 ms was observed. Notably, a very rapid turn-off time of 600 μs due to the vertical electric field that aligned the LCs was observed. We believe that the LCs vertically aligned temporarily by the in-plane field are much easier to rotate than those in the initial alignment state.

2.2 Vertical Bias Field

A response time of less than 1 ms is essential in implementing the FSC technology. The optically compensated bend mode, ferroelectric LC mode, and blue-phase LCs can be employed to realize FSC LCDs. However, they all exhibit problems such as a non-uniform bend transition, a low yield in the manufacturing process, difficulties in achieving

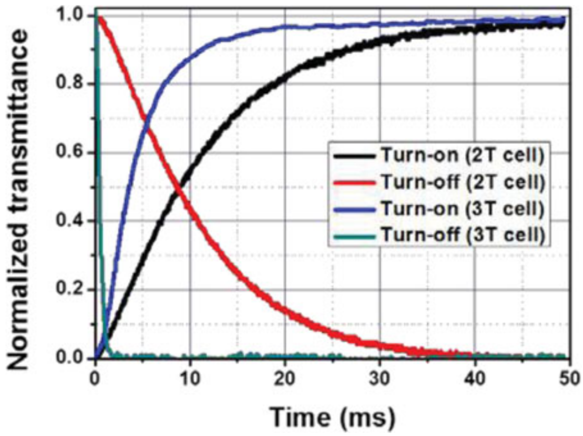

Figure 3. Measured response times of the fabricated LC cells.

high- quality alignment without defects, a low transmittance, and a narrow operating temperature range.

In this section, we propose a method for switching a 3T cell in less than 1 ms by applying a vertical bias field. The 3T cell structure shown in Fig. 2 is employed. The operating principle is schematically shown in Fig. 4. Initially, the LCs are homogeneously aligned. A vertical bias field is applied so that the LCs are vertically aligned, which shows the dark state (step ① in Fig. 4). An in-plane field is applied to align the LCs homogeneously for the bright state (step ② in Fig. 4). The LCs are switched on by the strong in-plane field, resulting in a fast response. When we remove the in-plane field, the LCs are vertically aligned again by the vertical bias field (step ①′ in Fig. 4).

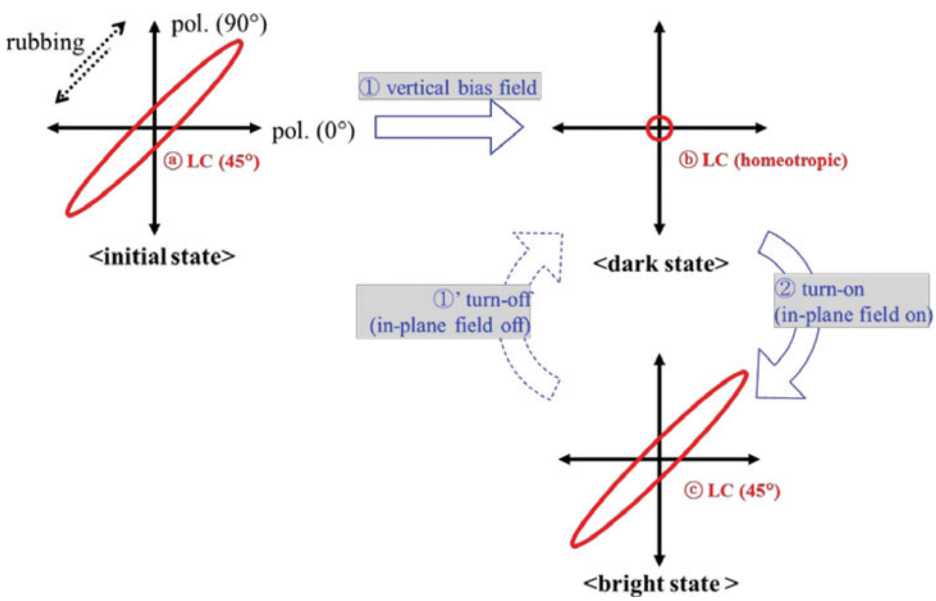

Figure 4. Operating principle of a 3T cell biased by a vertical electric field.

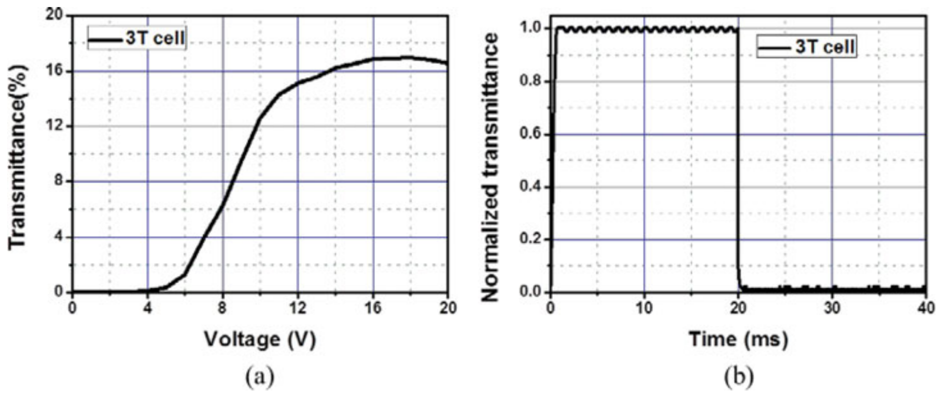

Figure 5. Electro-optical properties of a 3T cell biased by a vertical electric field. (a) Voltage–transmittance curves. (b) Response times.

To verify the electro-optical properties of the proposed operation method, we fabricated a 3T cell whose parameters were the same as those used in the operation using the trigger pulse. The rubbing direction was set 45° with respect to the grid electrodes. The operating processes were as follows. First, a vertical bias voltage of 10 V was applied between the top and bottom electrodes. As we increased the magnitude of the in-plane field applied between the grid and bottom electrodes, the LCs were switched on along the rubbing direction parallel to the substrate. When an in-plane field of 20 V was applied, a maximum transmittance of 16.9% was obtained, as shown in Fig. 5(a). Both the turn-on and turn-off times were 300 μs, as shown in Fig. 5(b).

3. Randomly Aligned LCs

In this chapter, we use randomly aligned LCs to realize a fast response time [6]. The same 3T cell structure is employed (Fig. 2). However, the alignment layer is eliminated so that the LCs are initially randomly aligned, as shown in Fig. 6. We align the LCs not by using the alignment layer but by applying an electric field. The operating principle of the LC cell is shown in Fig. 7. The initial state is not used for switching. For the turn-on switching, an in- plane field is applied between the grid and bottom electrodes so that the LCs are

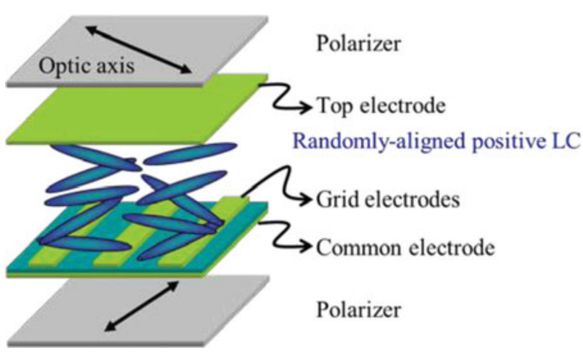

Figure 6. Structure of a 3T cell without alignment layers.

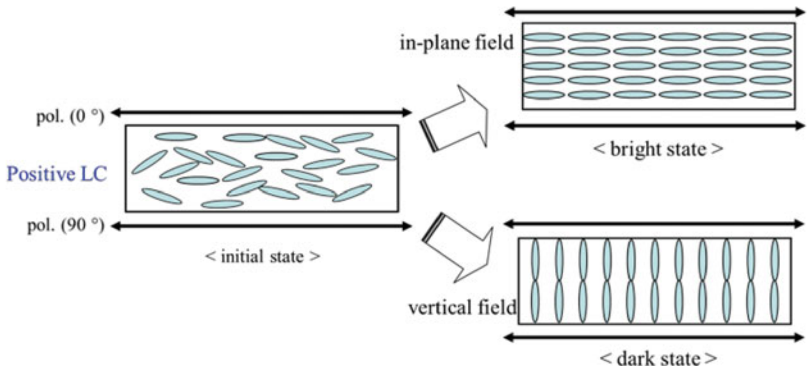

Figure 7. Operating principle of a 3T cell without alignment layers.

homogeneously aligned for the bright state. For turn-off switching, a vertical field is applied between the top and bottom electrodes so that the LCs are vertically aligned for the dark state. To confirm the electro-optical properties, we fabricated a 3T cell with non-rubbed homogeneous alignment layers and a 3T cell without alignment layers, and we compared them with a 2T cell with homogeneous alignment layers. The cell parameters were the same as those shown in Chapter 2, but the alignment layer was not used. Figure 8(b) shows the measured response times of the three types of LC cells. The 2T cell exhibited turn-on and turn-off times of 24 and 21 ms, respectively, at an applied in-plane field of 4.4 V. The 3T cell with non-rubbed homogeneous alignment layers exhibited a turn- on time of 10.3 ms at an applied in-plane field of 6 V and a turn-off time of 500 μs at an applied vertical field of 10 V. The 3T cell without alignment layers exhibited an accelerated turn-on time of 1.2 ms at an applied in-plane field of 5 V and a turn-off time of 500 μs at an applied vertical field of 10 V. From these results, we conclude that the response time can be accelerated by removing the alignment layers but not by removing the alignment process required to determine the alignment direction of LCs.

To analyze the cause of the fast response time, we measured the azimuthal anchoring energy of each cell and found that the measured anchoring energy of 1.0 × 10−6 J/m2 of

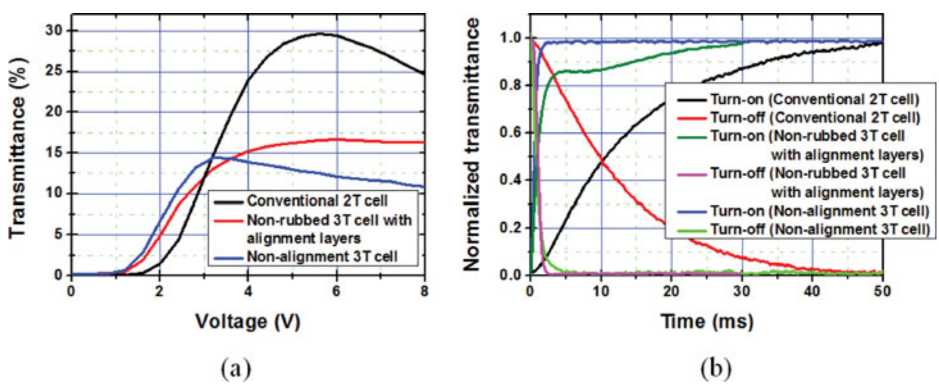

Figure 8. Electro-optical properties of a conventional 2T cell, a 3T cell with non-rubbed homogeneous alignment layers, and a 3T cell without alignment layers. (a) Voltage–transmittance curves. (b) Response times.

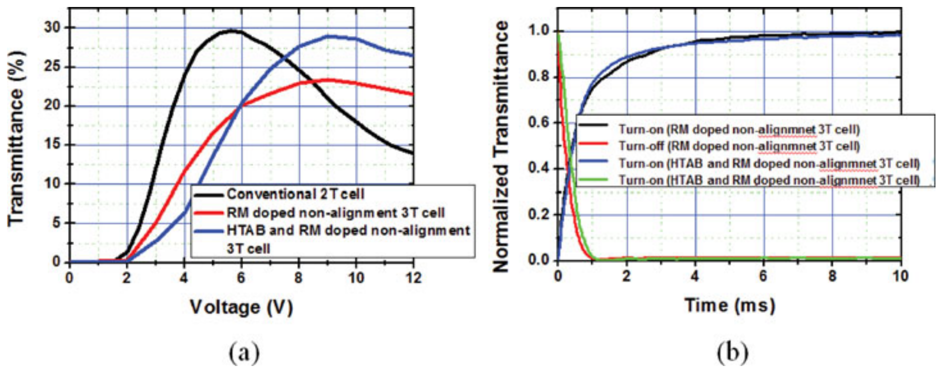

Figure 9. Electro-optical properties of 3T cells doped with an RM and with an RM and organic compound. (a) Voltage–transmittance curves. (b) Response times.

the LC cell without alignment layers is much lower than the anchoring energy of 6.9 × 10−5 J/m2 of the LC cell with alignment layers. We believe that the LC cell without alignment layers has a much faster response time than that with alignment layers because of the lower anchoring energy.

Although very fast response time could be achieved, the transmittance of the LC cell without alignment layers was very low, as shown in Fig. 8(a). To increase the transmittance, we mixed an organic compound and a reactive mesogen (RM) into the LCs. While the mixture was injected into an empty cell, an in-plane field was applied to uniformly align the LCs. Then, the cell was exposed to UV light as we apply an in-plane field to align the LCs in the bulk and surface regions. Fig. 9(a) shows the voltage–transmittance curves of the fabricated LC cells. When only the RM was doped into the LCs, the maximum transmittance increased to 23.1%. When both the organic compound and the RM were doped into the LCs, we obtained a maximum transmittance of 28.9%, which is almost identical to the transmittance of 29.1% of the 2T cell with homogeneous alignment layers. Fig. 9(b) shows the response times of the fabricated LC cells. The measured turn-on times were 2.3 and 2.2 ms. By doping with the organic compound and RM, we were able to simultaneously obtain high transmittance and fast response time.

4. Conclusions

In summary, we have presented our recent studies for rapid switching of nematic LCs. Various LC modes and driving schemes using the 3T electrode structure were introduced. We expect that the proposed fast-switching LC modes would be considered as excellent candidates for application in FSC LCDs.

Acknowledgments

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