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Contrast ratio and switching of zigzag defect-free surface stabilized FLCD by photoinduced alignment

WON-SEOK KANG, HYUN-WUK KIM and JONG-DUK KIM*

Department of Chemical Engineering,
Korea Advanced Institute of Science and Technology, 373-1, Kusong-dong,
Yusong-gu, Daejeon, 305-701, Korea

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The contrast ratio and electro-optical switching behaviours of surface stabilized ferroelectric liquid crystal cells with alignment layers of a photodegradable polyimide prepared by polarized ultraviolet light irradiation have been investigated. The higher contrast ratio was obtained for a zigzag defect-free sample obtained by the photo-induced alignment method than by the rubbing method. The switching behaviours of the FLC, such as spontaneous polarization and response time, were measured. Higher spontaneous polarization and faster response times were obtained with cells prepared by the photoinduced alignment method. In addition, response times of the order of microseconds, which are fast enough to realize high quality moving images with video-frame rate, were obtained.

1. Introduction

The surface stabilized alignment of ferroelectric liquid crystals (FLCs) has been paid much attention in the field of liquid crystal displays (LCDs) because of their characteristics of fast response and intrinsic wide viewing angle [1]. Ferroelectric liquid crystals usually exist in a chiral smectic C phase (SmC*) with dipoles normal to the molecular long axis and form a layer structure between parallel plates. However, it is difficult to achieve a well-aligned situation for both the layers and the planar orientations of the molecules. Many attempts to align liquid crystals have been exercised such as applying gentle shearing [1], using a magnetic field [2] or an electric field [3], by the spacer edge method [4], the SiO film deposition method [5], the formation of a high surface pretilt together with a cross-rubbing treatment [6], and the temperature gradient method [7]. The photoinduced alignment method has also been applied with, for example, a polyimide (PI) film of azo-dye doped with a homeotropic surfactant [8], a hybrid alignment of a linearly photopolymerized liquid crystal polymer [9], a poly(vinyl alcohol) layer in combination with an azo-dye [10], and a poly(vinyl cinnamate) layer [11].

In this paper, we report the electro-optic performance of an LCD cell fabricated by the photoinduced alignment method [12]. The PI film was irradiated by polarized UV light (PUVL) and degraded to produce the zigzag defect-free alignment layer.

*Author for correspondence; e-mail: kjd@kaist.ac.kr

2. Experimental

A nematic liquid crystal mixture (E7, Merck) and an FLC mixture (ZLI-4654-100, Hoechst Co.) were used as purchased. A poly(amic) acid, the precursor of a polyimide (SE150, Nissan Co.), was used to prepare the alignment layers by PUVL, and this has been reported in a previous paper [12]. The intensity of the polarized UV light (250–340 nm) on the PI films was monitored using a UV detector (Ushio, UIT-150) and was about 5 mW cm^{-2}. The exposure energies were determined by the exposure time to the PUVL. Also, the rubbing alignment method was carried out to obtain cells for comparison and the rubbing strength was controlled in terms of the rubbing parameter (L) [13].

Two indium tin oxide (ITO) coated glass plates covered with PI films after surface treatment were assembled with parallel configurations, i.e. parallel rubbing directions or parallel polarization directions of the irradiating PUVL. The cell gaps were maintained by inserting poly(ethylene terephthalate) (PET) film with a thickness of 2, 12 or 100 μm as a spacer. Liquid crystals were filled into the cell in the isotropic phase by capillary forces and cooled to room temperature. The cooling rates were controlled with a heating stage (FP82, Mettler) and a temperature controller (FP80HT, Mettler).

The textures and contrast ratios were observed using optical microscopy with crossed polarizers. The spontaneous polarization of the FLC materials was measured by the triangular wave method [14] and the response times were measured by the field reversal method [15].

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3. Results and discussion

3.1. *Alignment of the layer structure in SSFLC*

The phase sequence of the FLC mixture is as follows: SmC*–(61°C)–SmA–(65°C)–N*–(74°C)–Isotropic. The uniformly bent chevron layer structure of the SmC* phase is required to obtain zigzag defect-free FLC cells. Figures 1 and 2 show the optical microscopic images of the FLC in cells made by the rubbing method and the PUVL alignment method. The thickness of the cells was 2 μm and the cooling rate was 1°C min^{-1}. Many zigzag defects were observed in every cell aligned unidirectionally with different rubbing strengths, while no zigzag defect was observed in cells made using PUVL irradiation for more than 40 min. If its cell is irradiated for less than 30 min, poorly-aligned textures with various domains are obtained, indicating different orientations of the molecular directors.

From X-ray measurements, a complicated smectic layer, called a chevron structure with a kink in the middle of the cell has been recognized and is usually formed in most surface stabilized FLCD (SSFLCD), giving defects. In a parallel rubbed cell, the two opposite layers are bent nearly parallel to the layer normals and are described in terms of the C1 and C2 layer orientations. If the layer bend direction is the same as the rubbing direction, it is called the C2 orientation, while, if it is opposite, it is called the C1 orientation. Any misarrangements in the layer bend directions occur along the domain boundaries; called the ‘zigzag defect’, this causes image irregularities and flickering and extremely impairs the display quality. It is important to remove the zigzag defects and improve the electro-optic performance.

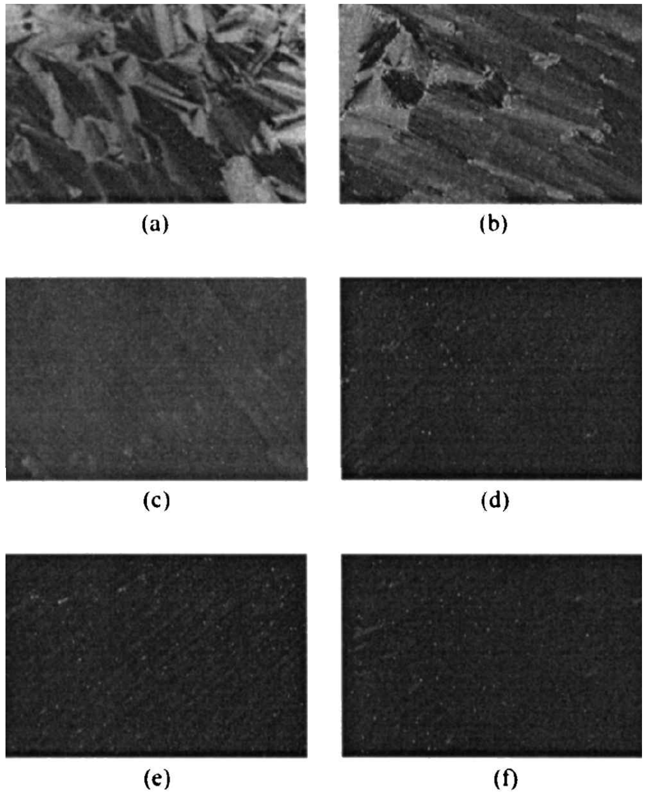

Figure 2. Optical microscopic images of the FLC in cells with various PUVL exposure times: (*a*) 20 min, (*b*) 30 min, (*c*) 40 min, (*d*) 50 min, (*e*) 60 min, (*f*) 90 min (cooling rate 1°C min^{-1}).

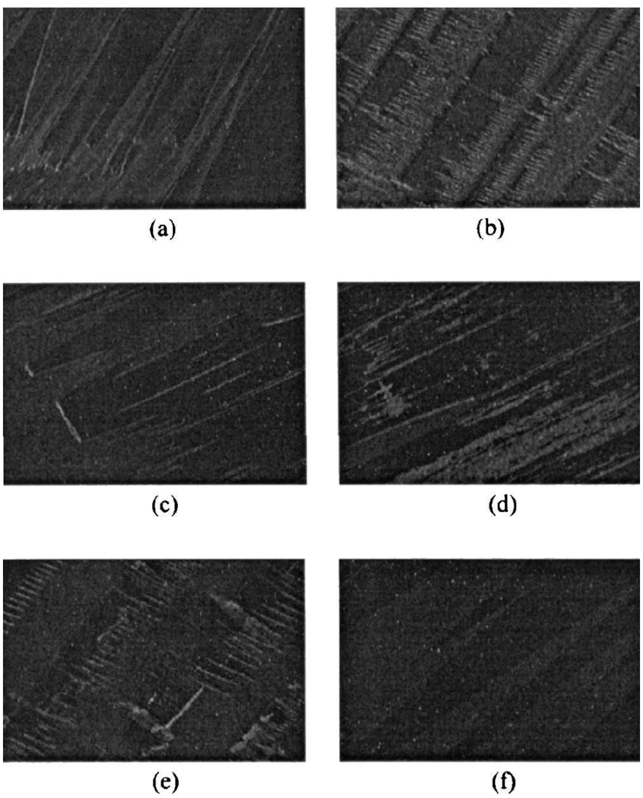

Figure 1. Optical microscopic images of rubbed cells of the FLC: (*a*) rubbing parameter $L=25$, (*b*) $L=50$, (*c*) $L=100$, (*d*) $L=150$, (*e*) $L=200$, (*f*) $L=250$ (cooling rate 1°C min^{-1}).

In a previous paper [12], we reported the fabrication of alignment layers that led to cells without zigzag defects, which usually form at the transition from C1 to C2, and without surface irregularities [16–18]. The smoother and flatter the surfaces were, the smaller was the occurrence of defects. The irradiation with PUVL produces no obvious changes of the surface morphology [19], while the rubbing method generates some scratches and microgrooves [20]. Although it is difficult to generate a high pretilt angle to avoid a reverse tilt disclination in a current TN-LCD, this method forms a uniformal selectively low pretilt angle to form the C2 orientation in a SSFLCD.

3.2. *Contrast ratio*

The contrast ratio may provide information about the alignment layer structure and is defined as the ratio of the maximum light transmission to the minimum light transmission through the sample set between crossed polarizers. Light leakage occurs in zigzag defects at an extinction position, and the contrast ratio becomes low as the number of defects increases. Figure 3 shows that the contrast ratio of FLC cells was lower for up to 30 min of irradiation than that given by rubbing, while the contrast ratios beyond 40 min of irradiation were higher than those for rubbed cells. Since the high contrast ratios are attributed to the defect-free alignment, it is possible to achieve a good dark state.

3.3. *Effect of cooling rates on photoinduced alignment*

The tilted SmC* has no unique optic axis. Molecules are aligned parallel to the surface due to surface force, and partially form polarization domains with different orientations. Thus, we need to align the precursor SmA phases which possess a unique axis, and then cool the sample into the required smectic phase [21]. It is well known that when the SmA phase is cooled to give SmC*, the layer structure of SmA is generally preserved with the molecules tilting with respect to the layer planes already formed in the smectic phase. Therefore, it is important to cool slowly to SmC* through the SmA phase. The cooling rate from the isotropic state to SmC* via SmA was varied at rates of 20, 10, 1 and 0.5°C min^{-1}; the optical microscopic textures showed the intrinsic focal-conic textures in the rapidly cooled cells for cooling rates of 20°C min^{-1} and 10°C min^{-1}, irrespective of irradiation time. The uniformly aligned domains became larger as the cooling rate became slower, and finally well aligned cells without zigzag defects were achieved when the cells were PUVL irradiated for more than 40 min and slowly cooled at rates of 1 and 0.5°C min^{-1}.

Figure 4 shows the contrast ratios for cells with different cooling rates. The more slowly the cells were cooled, the higher were the contrast ratios achieved. As we have already discussed, the molecules are poorly aligned at the different cooling rates up to 30 min of irradiation. After sufficient irradiation, the highest contrast ratio of about 23:1 was achieved at the cooling rate of 0.5°C min^{-1}.

3.4. *Electro-optic performance of ferroelectric liquid crystal cells*

The spontaneous polarization ($\mathbf{P}_s$) of each differently oriented domain in FLC cells represents the orientation of the FLC molecules, and therefore the FLC alignment states can be estimated by measuring the $\mathbf{P}_s$ switching current. Figure 5 shows the spontaneous polarization $\mathbf{P}_s$ of the FLC material in cells cooled at 1°C min^{-1} for the rubbed cell (*a*) and the PUVL irradiated cell (*b*). The $\mathbf{P}_s$ of the FLC in cells with PI films irradiated for more than 40 min is higher than that for cells made by rubbing,

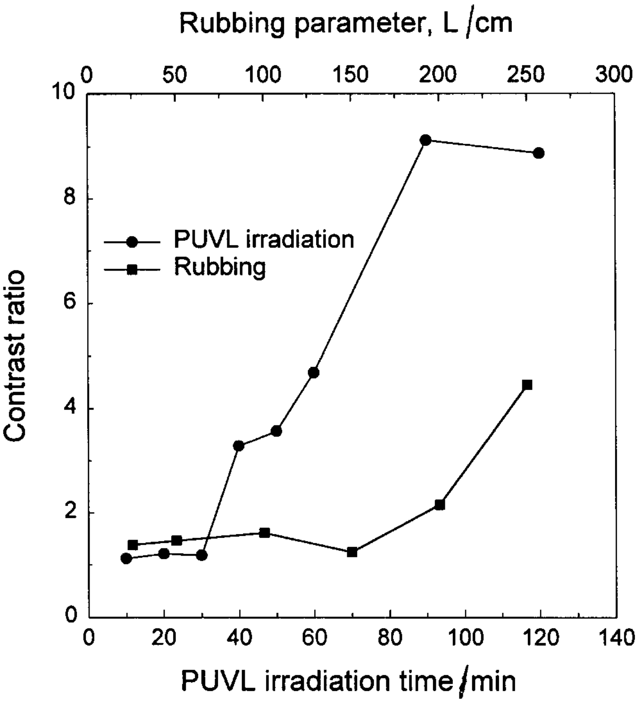

Figure 3. Contrast ratios of FLC cells prepared by ■ rubbing, and ● PUVL irradiation (cooling rate 1°C min^{-1}).

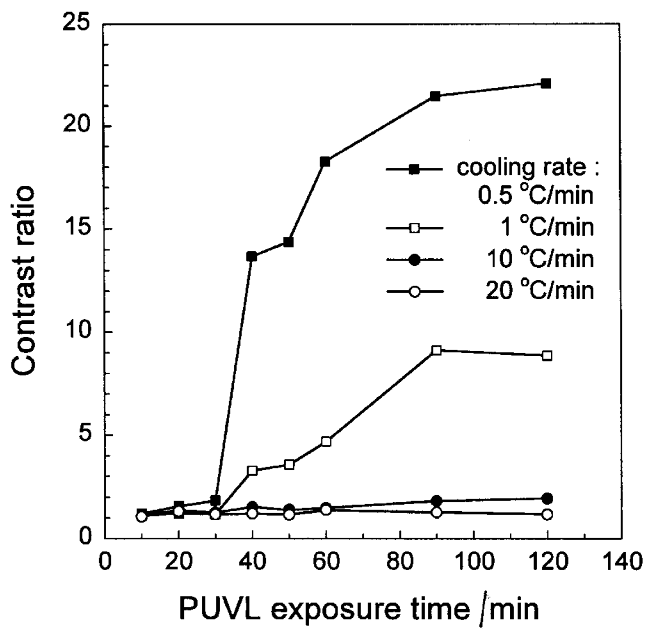

Figure 4. The effect of cooling rates on the contrast ratio of FLC cells (■ 0.5°C min^{-1}, □ 1°C min^{-1}, ● 10°C min^{-1}, ○ 20°C min^{-1}).

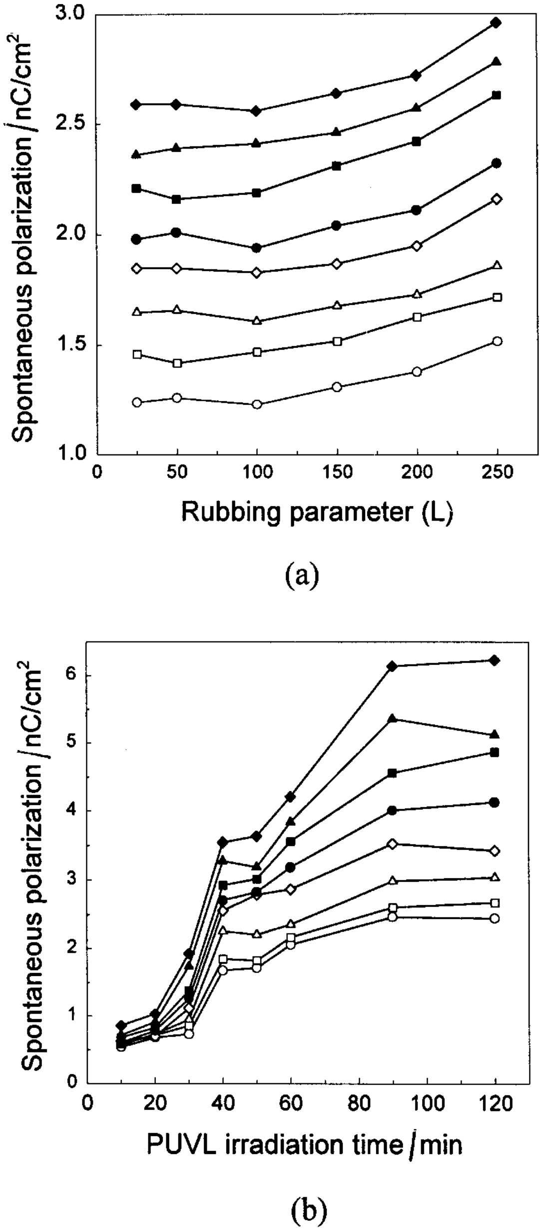

Figure 5. Spontaneous polarization of the FLC in cells with alignment layers prepared (*a*) by rubbing and (*b*) by PUVL irradiation during application of a 10 Hz triangular wave (cooling rate 1°C min^{-1}, ● 3 $V_{p\text{-}p}$, ■ 5 $V_{p\text{-}p}$, ▲ 7 $V_{p\text{-}p}$, ◆ 8 $V_{p\text{-}p}$, ○ 9 $V_{p\text{-}p}$, 10 $V_{p\text{-}p}$, △ 15 $V_{p\text{-}p}$, ◇ 20 $V_{p\text{-}p}$).

while the $\mathbf{P}_s$ for cells with PI films irradiated for less than 30 min is lower. The former cells have a well aligned state, but the latter have a poorly aligned state. In addition, the $\mathbf{P}_s$ increased as the rubbing strength and the PUVL irradiation time increased. This means that the alignment state is improved as the rubbing strength and the irradiation time increase. These results are consistent with the results on the cell textures and the contrast ratio. As the applied voltage increased, the $\mathbf{P}_s$ also increased. When a low field is applied, the FLC molecules may not be switched completely.

Figure 6 shows the response times of the FLC in cells with applied voltages at room temperature. The response time was fast in cells with a large $\mathbf{P}_s$, which is in agreement with the following equation

$$\tau^{-1} = \frac{\mathbf{P}_s \ \mathbf{E}}{\gamma} \tag{3}$$

where τ is the switching time, γ is the cone mode viscosity, and $\mathbf{E}$ is the electric field. The response time of the FLC in cells treated by PUVL irradiation for more than 40 min was faster than that for cells obtained by rubbing. The poorly aligned cells have slow response times, but as the degree of alignment increases, the response time is significantly reduced to 1 ms even at a low applied voltage. As the applied voltage increases to 9 V at 2 µm cell thickness, the response times are reduced until they saturate. Finally, we obtained a response time of the order of microseconds, which is fast enough to realize high quality moving images with video-frame rates.

4. Conclusions

The contrast ratio and switching performance of a FLC mixture were investigated for cells with PI films treated by polarized UV light irradiation at normal surface incidence. The alignment of the LC layer structure is very important for the control of zigzag defects in the photo-induced alignment method, and much higher contrast ratios were obtained than those obtained using the

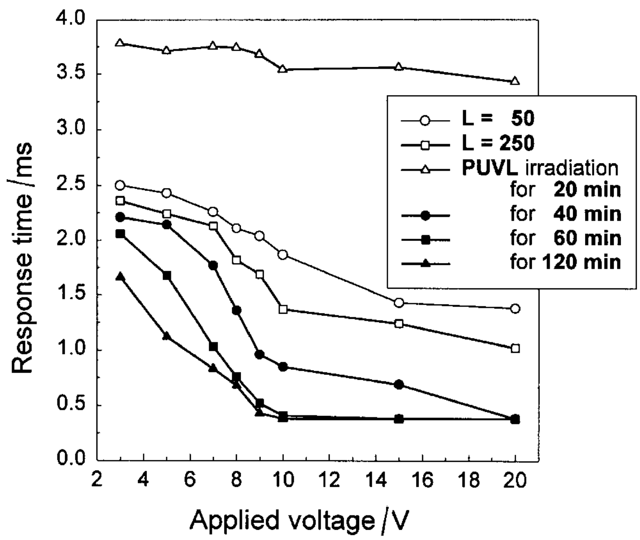

Figure 6. Response times for the various FLC cells, 2 µm, with voltage change at room temperature (cooling rate 1°C min^{-1}, 10 Hz square wave); ○ rubbing parameter, $L = 50$, $L = 250$; △ PUVL irradiated for 20 min, ● 40 min, ■ 60 min, ▲ 90 min.

rubbing method. Also, we report that for the alignment of the FLC, the cooling rates should be optimized. As the cooling rate becomes slower, the FLC alignment state is improved.

Switching behaviours were investigated by measuring the spontaneous polarization and the response time. The FLC on the PUVL irradiated PI films had a higher spontaneous polarization than on rubbed PI films. It has been reported that the $\mathbf{P}_s$ is directly related to the FLC alignment, and we could confirm that the better alignment state was achieved by the photoinduced alignment method. In addition, a fast response time in the order of microseconds could be realized for high quality moving images by using the photo-induced alignment method.

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