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Fast response time of fringe-field switching liquid crystal mode devices with reactive mesogens in a planar alignment layer

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Abstract

We report the response time of fringe-field switching (FFS) liquid crystal (LC) mode devices using an ultraviolet-curable reactive mesogen (RM) mixed in a planar alignment layer. The RM polymers within the alignment layer increase the surface azimuthal anchoring energy and the order parameter of the LC molecules. As a result, the falling time and the rising time in the FFS mode are improved by the enhanced azimuthal anchoring energy and the increased dielectric torque induced by higher order parameter of LCs.

(Some figures may appear in colour only in the online journal)

1. Introduction

Liquid crystal displays (LCDs) have long been used for various display applications such as mobile phones, monitors and televisions because of their excellent display performance. In general, the LC modes, which are organized by initial alignment of LC molecules, and electrode structures govern the display performance characteristics such as transmittance, response time and viewing angle. Many kinds of LC mode devices have been developed such as twist nematic (TN), patterned vertical alignment (PVA), in-plane switching (IPS) and fringe-field switching (FFS) mode devices [1–6]. Of these types, the FFS mode has been favoured because of the high transmittance and wide viewing angle qualities. However, the response times of devices using this mode are not sufficiently fast for real moving pictures. Many researchers have worked to improve the response time of FFS mode devices by designing cell structures such as electrode configurations, cell gaps and rubbing angles as well as by improving LC material parameters such as viscosity, birefringence and elastic constants.

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Recently, a polymer-stabilized IPS mode was proposed to allow fast response time by adopting a UV-curable reactive mesogen (RM) mixed in with the LCs [7]. In their system, the polymer networks, formed by polymerized RMs, provide volume stabilization of the LC molecules and increase their anchoring energy. However, the polymer network structures caused by increasing the operating voltages and rising times are very slow at low grey levels. In our previous works, we reported improvements in response time using a polymerized RM layer on top of a planar alignment layer, which increased the surface azimuthal anchoring energy [8].

In this paper, we report the response time of FFS mode devices using a planar alignment layer mixed with UV-curable RMs. The mixed alignment layer increased the azimuthal anchoring energy and thus a fast falling time was obtained in the FFS mode. In such a situation, we also achieved the improvement of the rising time, which originated from the enhanced dielectric torque. We theoretically derived the enhancement of the dielectric torque using the LC director distribution, corresponding to the LC order parameter, and experimentally confirmed the enhancement of the LC order parameter by introducing the RMs into the alignment layer.

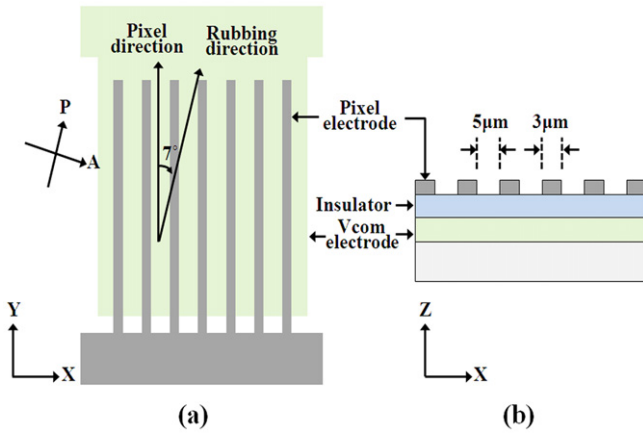


Figure 1. Schematic diagram of the FFS mode device structure: (a) *xy* plane and (b) *xz* plane.

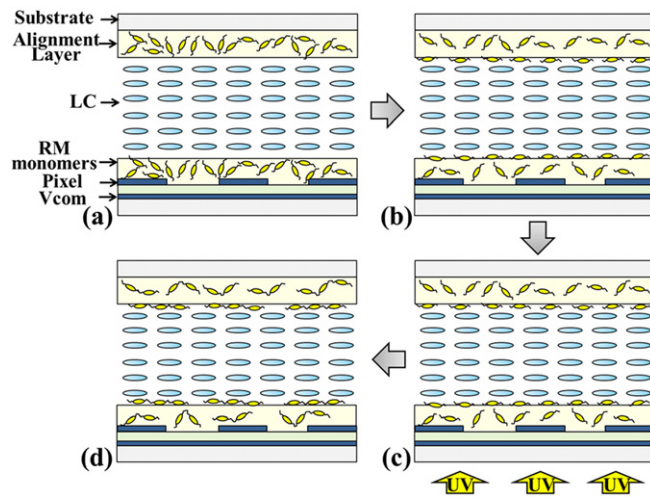


Figure 2. Schematic diagram detailing the process step in the fabrication of the proposed FFS mode device.

2. Experiments

Figure 1 shows the cell and electrode structure of the FFS mode, which consists of two indium tin oxide (ITO) layers and an insulator layer of 40 nm and 400 nm thicknesses, respectively. On the bottom substrate, the upper and lower ITO layers were used as the pixel electrode with 3 μm width and 5 μm interval and the common electrode without pattern, respectively. The top substrate had no electrode layer. A mixture of the planar alignment material AL16470 (JSR, Japan), RM257 (Merck, Germany) and the photo-initiator IGGACURE 651 (Chiba chemical, Japan) was spin-coated on the substrates. The alignment layer was pre-baked at 100 °C for 10 min, followed by curing at 210 °C for 2 h. At this moment, the RM monomers are distributed randomly, as shown in figure 2(a). The surface was rubbed with 7° to the electrode direction for predetermining the switching direction. The cell thickness was maintained using glass spacers of 2.7 μm and then filled with LC materials ($\Delta\epsilon = 6.9$ and $\Delta n = 0.1023$, Merck) by capillary action at their isotropic phase temperature. Figure 2 shows a schematic of the fabrication process. At the initial state, the LC molecules were aligned along the

rubbing direction. The RM monomers then aligned along the LC molecules, as shown in figure 2(b). The RM monomers are easily dissolved in the LCs and movable due to the liquid crystalline property of RMs. For polymerizing the RM monomers, they were exposed to UV light (365 nm) for 30 min with 3.3 J cm⁻², then the RM monomers were polymerized along the direction of the LC molecules both on the surface and in the bulk of the alignment layer, as shown in figures 2(c) and (d).

The electro-optic properties were measured with a digitized oscilloscope (Tektronix, TDS754D) in a He–Ne laser system. The infrared linear dichroisms were recorded using a Fourier transform infrared spectrometer (Bruker, Hyperion 3000) equipped with a wire grid polarizer at room temperature to measure the LC order parameter. The sample was placed between two NaCl plates. The spacing between the plates was adjusted to approximately 4.0 μm with glass spacers and filled with LC materials.

3. Results and discussion

Figure 3 shows the response time of the proposed FFS LC cell with respect to RM monomer concentrations within the alignment material. When increasing the concentration of the RM monomer, the falling time and the rising time were improved over the whole applied electric field region.

First, the falling time of homogeneously aligned LCDs such as the IPS and FFS modes is generally dependent on the cell gap d , rotational viscosity γ and twist elastic constant K_{22} as follows [9]:

$$\tau_{\text{off}} = \frac{\gamma d^2}{K_{22}\pi^2}. \quad (1)$$

Equation (1) is derived using the assumption that the azimuthal anchoring energy (W) is very strong ($W \rightarrow \infty$). However, because W actually has a finite value, the falling time can be expressed as follows [10]:

$$\tau_{\text{off}} = \frac{\gamma}{K_{22}\pi^2} \left(d^2 + \frac{4dK_{22}}{W} \right). \quad (2)$$

From equation (2), it is clear that the falling time can be reduced by increasing the azimuthal anchoring energy. Figure 4(a) shows the measured azimuthal anchoring energy values as a function of RM concentrations within alignment materials using the torque balance method [11]. The azimuthal anchoring energy was increased to 1.29×10^{-4} J m⁻² (RM 0.5 wt%) and 1.63×10^{-4} J m⁻² (RM 1.0 wt%), compared with 9.61×10^{-5} J m⁻² (without RM). The azimuthal anchoring energy was enhanced because directionally polymerized RMs on the surface induce strong interactions with the LCs and increase the chain ordering of the alignment layer at the rubbing direction.

Figure 4(b) shows the measured pretilt angles (θ_0) as a function of RM concentrations. The pretilt angle was decreased to 1.94° (RM 0.5 wt%) and 1.69° (RM 1.0 wt%), compared with 2.19° (without RM). The reduction in the pretilt angle (θ_0) is also another evidence of an enhanced azimuthal anchoring energy parameter by introducing the RMs into the

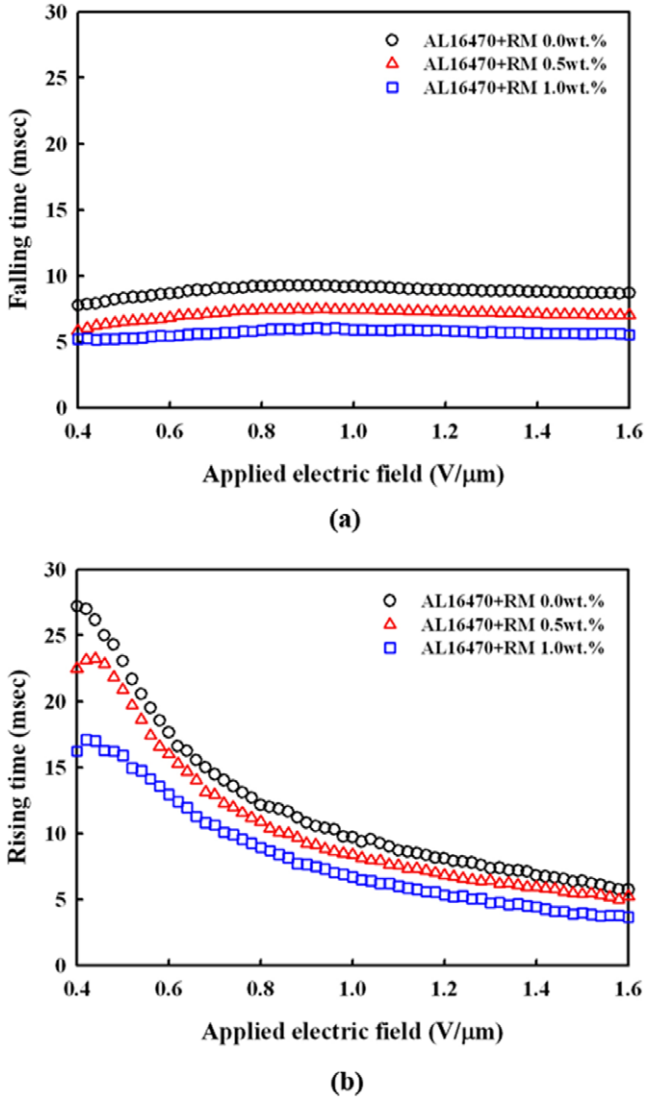


Figure 3. Response time of the FFS cells as a function of the applied electric field when the RM concentration mixed in the planar alignment layer is increased from 0.0 to 1.0 wt%: (a) falling time and (b) rising time.

alignment layer because the azimuthal anchoring energy tends to be proportional to $\cos \theta_0$ [12]. As known, the pretilt angle contributes to the response time in the splay configuration. However, in twist configurations such as the IPS and the FFS modes, the pretilt angle does not make an important contribution to the response time. As a result, the enhanced azimuthal anchoring energy gives rise to the improvement of the falling time in the FFS mode.

Next, we consider the rising time for homogeneously aligned LC cells. When the azimuthal anchoring energy is considered, the rising time can be expressed as [10]

$$\tau_{\text{on}} = \frac{\gamma}{|\varepsilon_0 |\Delta\varepsilon| E^2 - \beta^2 K_{22}} \quad (3)$$

where $\tan(\beta d) = \frac{2W/K_{22}\beta}{1 - (W/K_{22})^2}$.

When W is sufficiently large (i.e. the azimuthal anchoring energy is strong), the right-hand side of equation (3)

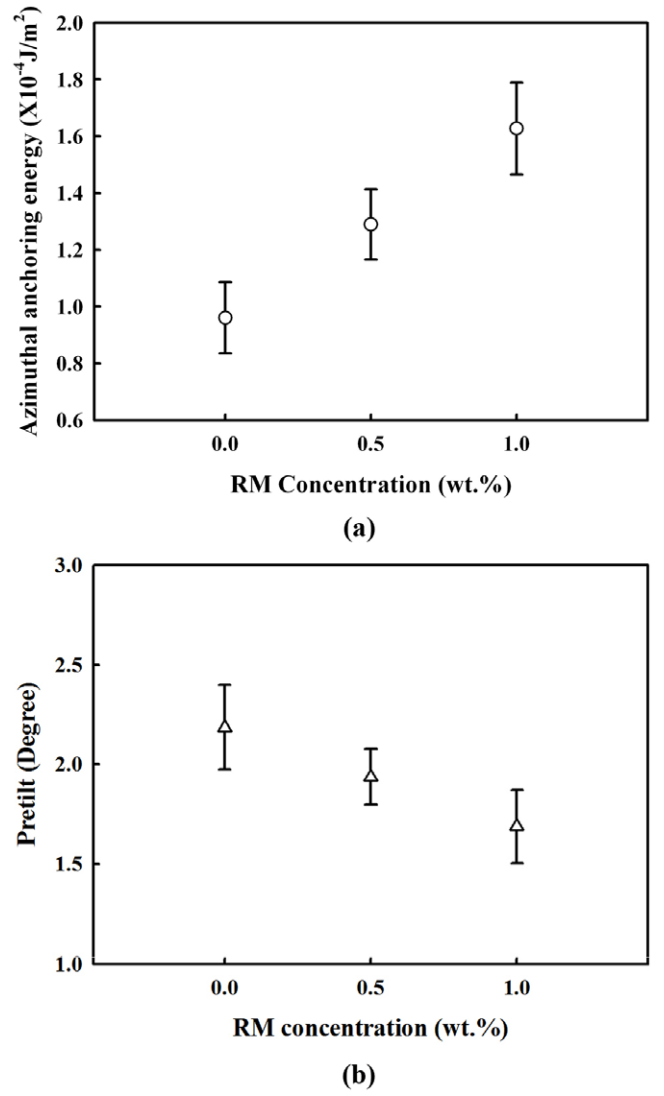


Figure 4. Azimuthal anchoring energies and pretilt angles as a function of mixed RM concentrations in the planar alignment layer.

approaches 0 from the negative side. Thus, we find $\beta = \pi/d$, and the rising time can be written, as is well known, by

$$\tau_{\text{on}} = \frac{\gamma}{|\varepsilon_0 |\Delta\varepsilon| E^2 - (\pi^2/d^2)K_{22}} \quad (4)$$

If $W \rightarrow 0$, $\tan(\beta d)$ is small and it can be approximated by βd . So, the rising time will simplify to the following expressions:

$$\tau_{\text{on}} = \frac{\gamma}{|\varepsilon_0 |\Delta\varepsilon| E^2 - \left(\frac{Wd}{K_{22}} + 2\right) \frac{W}{d}} \approx \frac{\gamma}{|\varepsilon_0 |\Delta\varepsilon| E^2 - \frac{2W}{d}} \quad (5)$$

In equation (5), it seems that the rising time should increase if the azimuthal anchoring energy increases. And, as is well known, the higher the anchoring energy, the longer is the rising time [13]. However, this theory includes the assumption that LC molecules have perfectly homogeneous alignment states for a given electric field. The ordering of LCs affects the dynamic behaviour of LCs when we apply an electric field. So, to fully explain the relation between the azimuthal anchoring

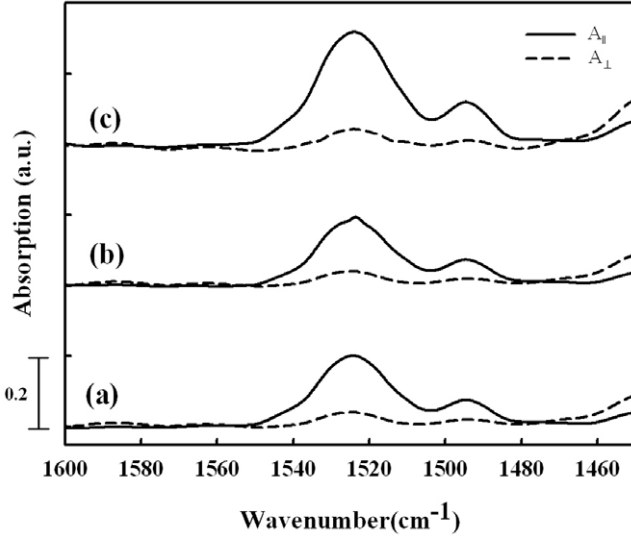


Figure 5. FT-IR spectra of a cell in the parallel (solid lines) and perpendicular (dashed lines) directions to the rubbing angle with different RM concentrations: (a) RM 0.0 wt%, (b) RM 0.5 wt% and (c) RM 1.0 wt%.

energy and the rising time, we should consider the ordering of the LC molecules.

Generally, the rising time is inversely proportional to the square of the electric field from equation (5). In other words, a stronger electric field gives rise to a larger dielectric torque N because the dielectric torque N is given as follows [14]:

$$N = \left| \Delta\epsilon (\vec{n} \cdot \vec{E}) \vec{n} \times \vec{E} \right| = \frac{1}{2} \Delta\epsilon E^2 \sin 2\varphi_0 \quad (6)$$

where $\Delta\epsilon$, \vec{n} and φ_0 are the dielectric anisotropy of the LC, the LC director, and the angle between the rubbing and electric field directions, respectively. If we assume that θ has a normal Gaussian distribution form, the dielectric torque could be described as

$$N = \frac{1}{2} \Delta\epsilon E^2 \int_{-\infty}^{\infty} (\sin 2(\varphi_0 + \theta)) \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\theta^2}{2\sigma^2}\right) d\theta \quad (7)$$

where σ is the width of the Gaussian distribution function dependent on the LC order parameter. The dielectric torque is dependent on the electric field as well as the LC ordering. If the order parameters of the LC molecules can be increased (i.e. decreased σ), both the torque balance values and the rising time can be increased simultaneously. It has also been reported that enhancement of the azimuthal anchoring energy can increase the order parameter of LCs [15, 16]. To determine the LC order parameters, we evaluated the infrared linear dichroism of the LC cells with different RM concentrations within the alignment layer using FT-IR (Bruker, Hyperion 3000), as shown in figure 5. The order parameter of the LC was directly determined from the dichroic absorbance of the benzene ring's C=C stretching vibrational band at 1524 cm^{-1} , which is considered an indication of the orientation of the entire molecule [17]. The order parameter can be expressed by the following equation [18]:

$$S = \frac{R - 1}{R + 2} \quad \text{and} \quad R = A_{||}/A_{\perp} \quad (8)$$

Table 1. Order parameter as a function of RM concentrations in the planar alignment layer obtained from the absorbance dichroism of the benzene ring's C=C stretching vibrational band.

RM (wt%)	Wavenumber				
	(cm^{-1})	$A_{ }$	A_{\perp}	R	S
0.0	1524	0.200	0.041	4.88	0.564
0.5	1524	0.194	0.033	5.88	0.619
1.0	1524	0.317	0.043	7.37	0.680

where R is the dichroic ratio, and $A_{||}$ and A_{\perp} are the absorbance in the directions parallel and perpendicular to the rubbing angle, respectively.

Table 1 shows the LC order parameter as a function of different RM concentrations within the alignment layer. The order parameter of the cell with RMs was approximately 21% higher than that of the cell without RMs. It is clear that the ordering of the LC molecules is enhanced by the inclusion of RM into the alignment layer due to the increase in the azimuthal anchoring energy.

Now, we consider the relation between the order parameter and the dielectric torque, which affects the rising time. The LC order parameter is defined by considering the average value of the second-order Legendre polynomial as follows [19]:

$$S = \frac{1}{2} \langle 3\cos^2\theta - 1 \rangle = \int_0^{\pi} \frac{1}{2} (3\cos^2\theta - 1) f(\theta) \sin\theta d\theta / \int_0^{\pi} f(\theta) \sin\theta d\theta \quad (9)$$

$$f(\theta) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(\hat{a} - \vec{n})^2}{2\sigma^2}\right) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\theta^2}{2\sigma^2}\right) \quad (10)$$

where θ is the distribution angle between the LC director and the long axis (\vec{n}) of the individual LC molecules (\hat{a}), and $f(\theta)$ is the distribution function, which is expressed by the Gaussian distribution form of equation (10) [20]. The order parameter could be written as

$$S = \int_0^{\pi} \frac{1}{2} (3\cos^2\theta - 1) \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\theta^2}{2\sigma^2}\right) \sin\theta d\theta / \int_0^{\pi} \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\theta^2}{2\sigma^2}\right) \sin\theta d\theta. \quad (11)$$

Figure 6 shows both the measured order parameter and the width of the Gaussian distribution (σ) calculated from equation (11) as functions of RM concentration. As S was increased by increasing the RM concentration, σ was decreased. Figure 7 shows the relationship between σ and the dielectric torque N as a function of the applied electric field calculated from equation (7). The dielectric torque was increased as the σ value decreased. These results reveal that the rising time can be decreased by increasing the order parameter of the LCs with a high surface anchoring energy due to a high concentration of RMs within the alignment layer.

As discussed previously, the falling time was improved by enhancing the azimuthal anchoring energy. The azimuthal anchoring energy increased in turn the LC order parameter. And then the rising time was also improved by a strong

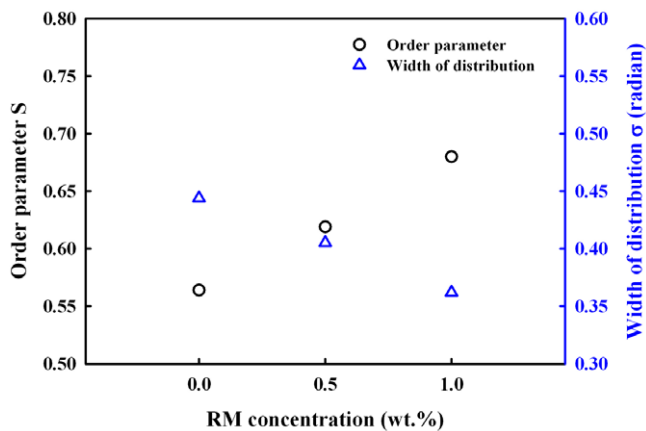


Figure 6. Order parameter of the LC layer (open circle) and the calculated width of Gaussian distribution (open triangle) with different RM concentrations.

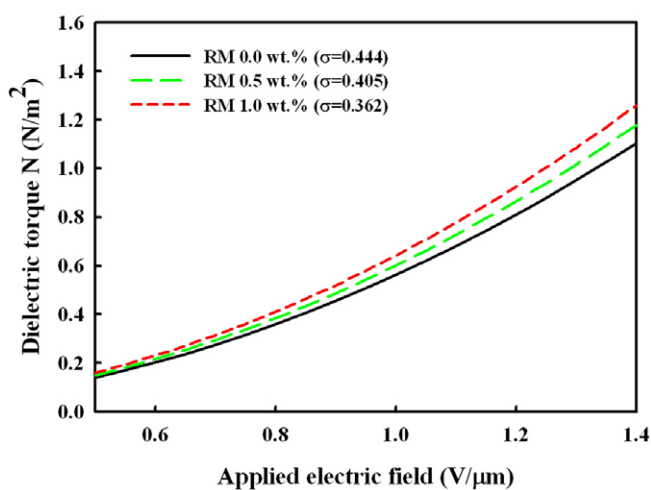


Figure 7. Calculated relationship between dielectric torque and applied electric field as a function of RM concentrations in the planar alignment layer.

dielectric torque, which is induced by the higher order parameter. The high azimuthal anchoring energy due to the inclusion of RM polymers in the planar alignment layer improved the falling time as well as the rising time in FFS mode devices.

4. Conclusions

We reported enhanced response time in FFS mode devices using UV-curable RMs within the planar alignment layer. The RM mixed alignment layer increased the azimuthal anchoring energy and thus a fast falling time was obtained in the FFS mode. Furthermore, we achieved an improvement of the

rising time in our FFS mode with the RM mixed alignment layer. By introducing the dielectric torque based on the LC order parameter, we successfully explained the improvement of rising time and experimentally confirmed that the LC order parameter in the RM mixed alignment layer is superior to that in the bare alignment layer. As a result, we were simultaneously able to achieve both fast falling time and rising time in FFS mode devices. We believe that this method could be adapted to various other LC mode devices using in-plane switching configurations.

Acknowledgments

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