Antiferroelectric LCD with one polarizer in a reflective configuration

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Abstract — A reflective antiferroelectric liquid-crystal (AFLC) display with one polarizer is proposed. An optical retardation film was introduced into the reflective configuration to obtain enhanced electro-optic (EO) characteristics. Numerical simulations were carried out to optimize the cell parameters so that the EO switching between the black and white states could be easily achieved. The reflective AFLC display with optimized cell parameters was found to exhibit high contrast, excellent brightness, and fast response.

Keywords — Antiferroelectric liquid crystal, polarizers, reflective configuration.

1 Introduction

Reflective liquid-crystal displays (LCDs) have attracted much attention for low-power-consumption applications, such as portable information systems. In particular, various reflective LCDs consisting of a twisted-nematic (TN) mode with a single polarizer, such as TN electrically controlled birefringence (TN-ECB)\textsuperscript{1} and mixed TN (MTN)\textsuperscript{2}, have been recently proposed. These structures exhibit enhanced electro-optic (EO) characteristics that result in high brightness, enhanced contrast, and achromatic operation without requiring the use of a backlight. However, these reflective types exhibiting the TN mode still suffer from low contrast, narrow viewing angle, and slow-response characteristics. A potential solution to these problems is to use an antiferroelectric liquid crystal (AFLC) cell instead of a TN liquid-crystal cell.

In AFLCs, the pairing of the molecules plays an essential role in stabilizing the antiferroelectric structure.\textsuperscript{3} The pair formation of transverse dipole moments in adjacent smectic layers and the packing entropy due to the excluded volume effect are believed to be critical to the appearance of antiferroelectricity.\textsuperscript{3} In the presence of an external electric field, high enough to overcome the pairing energy, a field-induced transition may occur in such a way that an AF phase transforms into a ferroelectric (FO) phase through an intermediate ferrielectric (FI) phase.\textsuperscript{4}

In this paper, we propose a reflective AFLC display that is comprised of one polarizer and an optical retardation film. Numerical simulations were carried out to evaluate the resulting EO characteristics and to optimize the cell parameters. Based on the simulation results, the optimized AFLC cell was designed to experimentally demonstrate the novelty of such a device.

2 Experimental

The AFLC cell was made by using indium-tin-oxide (ITO) coated glass substrates. The polyimide (PI) (AL1051, Japan Synthetic Rubber Co.) was coated on the ITO-coated glass substrates to promote planar alignment. The PI layer on only one side of the substrates was unidirectionally rubbed to produce uniform planar alignment. The cell thickness was maintained by glass spacers with a thickness of about 2 μm. The AFLCs used (CS4001) were provided by Chisso Petrochemical Corp. The spontaneous polarization in the FO state and the molecular tilt angle were $-79.8$ nC/cm$^2$ and $24.9^\circ$, respectively.

As depicted in Fig. 1, a polarizer was attached to the front side of the AFLC cell while a metal reflector was attached to the rear side of the cell. An optically uniaxial retardation film was placed between the AFLC cell and the reflector. The polarizer was placed parallel to the optic axis of the AFLC layer. The optically uniaxial film with a phase retardation of 136 nm was used and its optic axis was oriented to be $\pi/4$ with respect to the polarizer. The AF-FO transition was produced by applying dc pulses with an alter-
3 Results and discussion

From an optics point of view, the mirror image of the reflective AFLC cell, with a cell thickness \( d \), one polarizer, and no retardation film, is identical to the transmissive type whose thickness is \( 2d \), composed of two parallel polarizers. If the angle \( \theta \) between the polarizer and the optical axis of the AFLC layer is \( 0^\circ \) under no field (AF-state), the bright state can be obtained in this reflective configuration. However, the dark state above the threshold field (FO-state) is not easily produced without optical compensation. To achieve a complete dark state, both the phase difference through the LC layer corresponding to a quarter-wave of the incident light and the molecular tilt angle \( \theta \) of the AFLC must be \( \pi/4 \) above the threshold field. However, AFLC materials with \( \theta = \pi/4 \) are not commercially available. If \( \theta \) is not equal to \( \pi/4 \), the reflected light is not extinguished in the dark state although the LC layer behaves as a quarter-wave plate. Consequently, the contrast ratio decreases considerably.

For high contrast, an intrinsically dark background is preferred in the configuration with a single polarizer and no retardation film. The dark state can be obtained at zero field with a polarizer rotation angle \( \theta = \pi/4 \). The value of \( d \Delta n \) for the AFLC cell should be adjusted to be a quarter-wave of the incident light. In this case, the contrast ratio becomes very high since a complete dark state can be obtained in the AF-state. However, the brightness would be fairly low when the tilt angle \( \theta \) is not exactly equal to \( \pi/4 \). This is because the optical axis of the LC layer in the FO-state is not parallel (or perpendicular) to the polarizer.

Based on the idea described above, we performed numerical simulations. The reflected light intensity through the reflective AFLC cell can be readily computed by employing the \( 2 \times 2 \) Jones matrix method.\(^5\) It was assumed that \( \theta \) and \( \Delta n \) of the AFLC are \( 24.9^\circ \) and \( 0.088 \), respectively.\(^6\)

As can be seen in Fig. 2(a), the bright state is achieved in the AF-state (under no field) regardless of the cell thickness, and the minimum reflected light intensity is obtained at about \( d = 1.54 \mu m \) in the FO-state (above threshold field). Therefore, the cell thickness of the optimized AFLC cell in the reflective configuration with a polarizer and no retardation film is \( 1.54 \mu m \). Then, \( d \Delta n \) of the AFLC cell is \( 136 \) nm, nearly a quarter-wave of \( 543.5 \) nm, which is the wavelength of He–Ne laser. As predicted above, the complete dark state can not be obtained in the FO-state in spite of the fact that the AFLC cell behaves as a quarter-wave retardation film. The reason for this is that the angle \( \theta \) between the polarizer and the optical axis of the LC layer in the FO phase is \( 24.9^\circ \) (or \(-24.9^\circ \)), corresponding to the molecular tilt angle \( \theta \), so that the reflected light exists in the dark state to some extent. The contrast ratio is \( 2.4:1 \). Therefore, this configuration is not suitable for display applications.

Figure 2(b) shows the calculated intensity of the reflective AFLC cell without a retardation film when the angle \( \theta \) between the polarizer and the optical axis of the LC layer in the AF phase is \( \pi/4 \). The minimum intensities in both the AF-state and the FO-state are produced at the same thickness, \( d = 1.54 \mu m \). At this cell thickness, the difference between the reflective intensity in the AF-state and in the FO-state is maximum and the reflective intensity in the AF-state is zero. Therefore, the cell thickness of the optimized AFLC cell in a reflective configuration with a polarizer and no retardation film is \( 1.54 \mu m \). In other words, the value of \( d \Delta n \) for the AFLC cell is \( 136 \) nm, nearly a quarter-wave of \( 543.5 \) nm. In this case, the contrast ratio is very high since the complete dark state can be obtained in the AF-state. However, as expected, the brightness is still low because the molecular tilt angle \( \theta \) is not exactly equal to \( \pi/4 \) so that the angle \( \theta \) in the FO state is not \( 0 \) (or \( \pi/2 \)).

The other method of achieving a good dark state and higher brightness is to introduce an extra phase difference through an optically uniaxial retardation film that corresponds to a quarter-wave of the incident light as shown in Fig. 1. The optical retardation film placed between the AFLC cell and the reflector compensates for the phase difference experienced through the AFLC layer. In the AF-state, the AFLC layer with the optic axis parallel to the
polarizer does not change a linearly polarized state of the incident light irrespective of $d\Delta n$. The phase difference through the quarter-wave retardation film after being reflected from the mirror becomes a half-wave. While the light is transmitted through the LC layer in a similar fashion, the linearly polarized state of the light remains unchanged and the polarization direction is perpendicular to the input polarizer. Hence, the complete dark state is readily obtained. Moreover, if $d\Delta n$ of the AFLC layer is adjusted to be a quarter-wave of the incident light in the FO-state, the polarization of the reflected light rotates by an angle of $\pi$, and the polarization direction of the reflected light is parallel to the polarizer. Therefore, the reflected light passes through the AFLC cell.

In order to design an optimized AFLC cell in a reflective configuration, we computed the reflected light intensity through the reflective AFLC cell with a 136-nm uniaxial retardation film. The reflected intensities for both the AF-state and the FO-state were calculated. The reflected intensity of the AFLC cell was calculated as a function of the phase difference $\delta$ between the retardation film and the AFLC layer of thickness $d$ to obtain the best EO characteristics, i.e., $\delta$ and $d$ were treated as independent parameters. The simulated contour plots of the $\delta$-$d$ parameter space are shown in Fig. 3. Here, the angle between the polarizer axis and the optic axis of the retardation film is $\pi/4$. The numbers in the contours represent the reflectivity in steps of 0.1.

Figure 3(a) shows the contour plots in the AF-state when the optic axis of the LC cell and the polarizer are parallel to each other. The solutions for zero reflection and total reflection in Fig. 3(a) correspond to the horizontal lines at $\delta = 135.9$ and 271.8 nm, corresponding to a quarter-wave and a half-wave at 543.5 nm, respectively. Figures 3(b) and 3(c) show the contour plots in two FO-states when the angle $\theta$ between the polarizer and the optical axes of the LC layer are 24.9° and $-24.9^\circ$, respectively. One interesting point is that Fig. 3(c) is just a mirror image of Fig. 3(b) with respect to the horizontal line at $\delta = 135.9$ nm. If no solution exists on the horizontal line at $\delta = 135.9$ nm, the reflectivities in two FO-states, governed by the field direction, are different. In a multiplexed driving scheme, the two FO-states can not be used alternatively for every frame. This is one of the difficult problems when using multiplex driving. As shown in Fig. 3, the solution for high contrast and brightness can be obtained by finding the point which corresponds to the largest difference in the reflectivity among the intersections of the horizontal lines in the AF-state [Fig. 3(a)] and the contour lines in the FO-states [Figs. 3(b) and 3(c)]. Within the range of the parameters used, there is only one solution for the best reflective configuration at $(d, \delta) = (2.3 \text{ nm}, 135.9 \text{ nm})$. At this point, the reflectivities in the AF- and the FO-states are 0 and 1, respectively. And the reflectivities in the two FO-states are equivalent to each other.

Figure 4 shows the experimental results together with numerical simulations for the reflective AFLC cell as a function of the applied field. The open circles and the solid line represent the experimental and calculated results, respectively. To calculate the field dependence of the reflected intensities through the reflective AFLC cell, the bilayer model, based on the electrostatic dipolar interactions between the two nearest-neighboring pair of dipoles at the molecular end, was adopted. In this bilayer model, the free energy is written as

$$F = f_{el} + f_{di} - \sum_i \mathbf{P}_i \cdot \mathbf{E} + \frac{1}{2} \sum_{i<j} \left( \frac{\Lambda}{r_{ij}} \right)^2 \left[ \mathbf{P}_i \cdot \mathbf{P}_j - 3(\hat{\mathbf{z}}_{ij} \cdot \mathbf{P}_i)(\hat{\mathbf{z}}_{ij} \cdot \mathbf{P}_j) \right],$$

where $f_{el}$ and $f_{di}$ represent the elastic and the dielectric energies, respectively. Here, $\hat{\mathbf{z}}_{ij} = (\mathbf{r}_i - \mathbf{r}_j)/|\mathbf{r}_i - \mathbf{r}_j|$ with $j = i \pm 1$, and $\mathbf{P}_i$ and $\mathbf{P}_j$ are the effective polarizations in the $i$-th and $j$-th layers, respectively. The measure of the range of the dipole–dipole coupling is represented by $\Lambda$. It is interesting to note that the fourth term, the dipole–dipole interactions,
is responsible for the appearance of antiferroelectricity. By minimizing the free energy in one elastic-constant approximation, the director profiles can be calculated. Surface anchoring is assumed to be very strong. The field dependence of the reflected light intensity is accordingly calculated from the director profiles using the $2 \times 2$ Jones matrix method.

In Fig. 4, the reflected light intensity increases slightly below the threshold (~9 V/µm), which is known as the pre-transitional effect. The reflectivity curve increases steeply at 9 V/µm. This is related to the ferrielectric-like intermediate ordering during the AF–FO transition. The bright state was achieved at above 10 V/µm. The field dependence of the measured reflected intensity is consistent with the simulated results. This tells us that the threshold behavior of the field-induced AF–FO transition is accurately described by the bilayer model. As expected, the AFLC cell in the reflective configuration exhibits excellent EO steepness, fast response, and high contrast. Depending upon the addressing scheme, the EO steepness is one of the important factors for devising a new type of reflective LCD. The degree of the steepness will determine the image quality and the amount of the information content.

As shown in Fig. 5, the rise and fall times were measured to be about 0.34 and 4.72 msec, respectively. This fast response, compared to the TN or super-TN case, makes the reflective AFLC configuration useful for video-rate applications.

The iso-contrast contours of the reflective AFLC cell are shown in Fig. 6. This result shows symmetric and wide-viewing characteristics. The maximum contrast ratio is about 5:1 (not calibrated) under a white-illuminating light source. The contrast ratio can be further enhanced by using the optimized cell parameters and better alignment.

### 4 Conclusion

We demonstrated a reflective-type AFLC display consisting of a single polarizer and a retardation film. In this type, the EO switching between the black and white states can be easily achieved. By using the optimized values of the material parameters, the reflective AFLC cell exhibits excellent EO characteristics, such as high contrast and fast response. This reflective-type AFLC display is expected to be useful for low-power-consumption applications.

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References

6 This value is determined from the birefringence measurement using the method described in Ref. 7.

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