Abstract
We demonstrated a fast liquid crystal (LC) display mode based on a nonchiral smectic C (NSC) LC with analog gray scales in a transverse electrode configuration and analyzed the display performances by means of two-dimensional numerical simulation; in this configuration, wide viewing properties were also achieved. The analog gray scales in the NSC LC mode are obtained in a dielectrically driving scheme as those in the nematic LC mode.

1. Introduction
Various approaches such as the in-plane switching (IPS) mode [1] and multi-domain alignment [2] have been utilized to improve viewing properties of liquid crystal displays (LCDs) based on nematic liquid crystals (NLCs). Except for the IPS mode, additional complex processes for alignment are often involved. From the viewpoint of fast response, a variety of display configurations using ferroelectric liquid crystals (FLCs) with spontaneous polarization, such as surface-stabilized (SS) and deformed-helix structures [3,4] have been extensively studied to obtain the dynamic image at a video-rate in large LCDs. For FLCs, however, it is difficult to obtain uniform alignment in large area since the polar nature of delicate interfacial interactions between treated substrates and the FLC molecules produce zigzag defects [3] and/or stripe domains. Moreover, SSFLC is bistable and thus no intrinsic gray scales are available unless a time- or space-averaging process is employed. A vertically aligned structure using a short pitch FLC was proposed to obtain the defect-free alignment and the analog gray scales [5]. A twisted structure of a FLC was also suggested to obtain a fast continuous electro-optic (EO) effect for optical communication applications [6].

Recently, a twisted structure [7] based on a nonchiral smectic C (NSC) LC has been theoretically studied and a transverse electrode structure [8] with the NSC LC layer has been experimentally studied to explore the probability of practical applications. Unlike FLC materials, analog optical modulation was achieved by means of the dielectric anisotropy (\(\Delta \varepsilon\)) as that in the NLC modes.

In this paper, we demonstrated experimentally an analog EO effect of NSC LC with fast response in a transverse electrode configuration and analyzed the device characteristics using numerical simulations based on a relaxation method [9] and the (extended) 2×2 Jones matrix method [10,11]. The NSC LC mode exhibits wide and symmetric viewing properties with no additional compensation films. For the NSC LC with positive dielectric anisotropy and a large tilt angle (about 45°), two domains, in which the configurations of the LC director are asymmetric, between interdigital electrodes enable to give excellent viewing properties under an external electric field. Furthermore, using a dielectrically driving scheme, as employed in the NLC mode, analog gray scales are naturally obtained.

2. Theoretical Model
2.1 Operation Principle
Figure 1 shows the operation principles of our NSC LC mode with positive dielectric anisotropy \(\Delta \varepsilon\). Consider a sample cell, containing an NSC LC with \(\Delta \varepsilon>0\), in which the NSC LC molecules are aligned antiparallel to glass substrates. The interdigital electrodes are patterned on only one of the substrates. The smectic layers are parallel to the electrodes on the substrate and the rubbing directions make an angle of the tilt angle in the smectic C phase with respect to the transverse electrodes.

As shown in Fig. 1 (a), in the absence of an electric field (dark state), the LC molecules are oriented parallel to the electrodes. When an external electric field is applied, the LC molecules align perpendicular to the electrodes, resulting in a bright state as shown in Fig. 1 (b).

Figure 1. The operation principles of the NSC LCD mode with positive dielectric anisotropy: (a) The absence of an external electric field (dark state) and (b) the presence of an electric field (bright state).
state), the director of the LC molecules is placed on the plane parallel to two glass substrates and is optically similar to that of a planar NLC. This structure of the NSC LC in the transverse electrode configuration corresponds exactly to a homogeneously aligned NLC structure except for the tilt of smectic layers. Therefore, a linearly polarized light, which is incident along the rubbing direction on one of the glass substrates, is blocked completely by the crossed analyzer.

On the other hand, when an electric field is applied (bright state), the LC molecules rotate on the induced smectic C cone since the cone structure is energetically favored. The director of the NSC LC with \( \Delta \epsilon > 0 \) tends to rotate parallel to the applied electric field and to reorient away from the rubbing direction as well as the substrate planes as shown in Fig. 1(b). With increasing the applied electric field, the two directors rotate oppositely on the induced smectic C cone in two half regions between interdigital electrodes and finally reach \( \pm 90^\circ \) of the azimuthal angle in each half region. This arises naturally from the curvature of the electric field in the transverse electrode configuration. In this situation, when a linearly polarized light is incident parallel to the rubbing direction, a pure phase modulation is achieved and thus optical transmission is produced.

2.2 Numerical Simulations

In the equilibrium state of the LC director under a constant potential \( V \), the Gibbs free energy is minimized [12]. In general, the Gibbs free energy consists of elastic terms associated with the deformations of the director and external field terms. The Frank-Oseen elastic free energy is widely used for the elastic terms [13]. In the nonchiral smectic C phase with no spontaneous polarization, the only external field term needed is a dielectric contribution like that in the NLC case.

In a simple director model with one-dimensional (1-D) deformation, in which case the LC director varies only in one direction and is independent of the others, the director configuration and the optical transmission cannot be calculated in the cell structure with patterned electrodes that generate nonuniform fields. In our transverse electrode configuration, the variation of the LC director along the direction of electrodes, denoted by \( y \)-axis, is ignored.

When the anchoring energy on the surface is assumed to be sufficiently strong in most LCDs, the Frank-Oseen elastic free energy density is expressed as

\[
f_{\text{elas}} = \frac{1}{2} K_{11} (\nabla \cdot \mathbf{n})^2 + \frac{1}{2} K_{22} (\mathbf{n} \times \nabla \times \mathbf{n})^2 + \frac{1}{2} K_{33} (\mathbf{n} \times \nabla \times \mathbf{n})^2,
\]

where \( \mathbf{n} \) is the LC director and \( K_{11}, K_{22}, \) and \( K_{33} \) are the splay, twist, and bend elastic constants, respectively. The dielectric free energy density is given by

\[
f_{\text{ele}} = \frac{1}{2} \varepsilon \cdot \mathbf{E} \cdot \mathbf{E},
\]

where \( \mathbf{E} \) is an electric field described as \( -\nabla V \) and \( \varepsilon \) is the dielectric tensor of LC in the frame of laboratory coordinate system, in which the normal direction to the smectic layers, the direction of the electrodes, and the normal direction to the substrates are denoted by the \( x \), \( y \), and \( z \)-axes, respectively. In the coordinate system, the LC director with a constant tilt angle \( \theta \) from the \( x \)-axis is expressed as \( \mathbf{n} = (\cos \theta, \sin \theta, \cos \phi, \sin \theta, \sin \phi) \), where \( \theta \) is an azimuthal angle in the \( xy \)-plane and depends on \( x \) and \( z \). The total free energy \( f_{\text{tot}} \) is obtained by integrating the Gibbs free energy density, \( f_{\text{tot}} = f_{\text{elas}} + f_{\text{ele}} \), over the volume.

In the equilibrium state of the director, the stationary condition leads to the Euler-Lagrange equations for the director profiles as follows:

\[
0 = -\frac{\partial f_{\text{elas}}}{\partial \phi} + \frac{d}{dx} \frac{\partial f_{\text{elas}}}{\partial \phi_x} + \frac{d}{dy} \frac{\partial f_{\text{elas}}}{\partial \phi_y} + \frac{d}{dz} \frac{\partial f_{\text{elas}}}{\partial \phi_z},
\]

\[
0 = -\frac{\partial f_{\text{ele}}}{\partial \phi} + \frac{d}{dx} \frac{\partial f_{\text{ele}}}{\partial \phi_x} + \frac{d}{dy} \frac{\partial f_{\text{ele}}}{\partial \phi_y} + \frac{d}{dz} \frac{\partial f_{\text{ele}}}{\partial \phi_z}.
\]

where the subscripts in \( \phi \)'s and \( V \)'s denote the partial derivatives of each variable along its direction. Since the variations of \( \phi \) and \( V \) along the \( y \)-direction are negligible, both the potential distribution and the director configuration can be calculated in 2-D. Using a relaxation method [9] based on the dynamic equation of the director, the equilibrium state will be found from the torque following balance.

\[
\gamma \frac{\partial \phi}{\partial t} = -\frac{\partial f_{\text{elas}}}{\partial \phi} + \frac{d}{dx} \frac{\partial f_{\text{elas}}}{\partial \phi_x} + \frac{d}{dy} \frac{\partial f_{\text{elas}}}{\partial \phi_y} + \frac{d}{dz} \frac{\partial f_{\text{elas}}}{\partial \phi_z},
\]

where \( \gamma \) is the relevant viscosity. From the discrete versions of Eqs. (3) and (4) and the iteration procedure for the director at each time step [14], the equilibrium director profiles can be found by the convergence criteria.

Figure 2 shows 2-D simulation results for the azimuthal angle \( \phi \). The distance across the transverse electrode and the cell thickness are along the \( x \) and \( z \)-axes, respectively. As shown in Fig. 2, the configuration of \( \phi \) in one side of the electrode is asymmetric with respect to the other side of the electrode, represented as a hatched region, at a given electric potential. Figure 2(b) shows the configuration of \( \phi \) in the mid-layer, denoted by a solid line in (a), at various applied voltages. With increasing the applied voltage,
the azimuthal angle reaches ±90° near the electrode as mentioned above.

Using the configuration of the azimuthal angle obtained in Fig. 2, the optical transmittance averaged over an active region except for the region blocked by the Cr electrode is obtained using the 2×2 Jones matrix method [10]. The calculated transmittance was shown in Fig. 3 as a function of the applied voltage. As shown in Fig. 3, the EO transmittance increases monotonically with increasing the applied voltage above a certain threshold [15].

The viewing properties was calculated from using extended 2×2 Jones matrix method [11]. For simplicity, from the transmittance averaged at the distance of 5 and 15 in Fig. 2 for obliquely incident light the iso-contrast map was constructed as shown in Fig. 4. The horizontal axis (x-axis) represents the direction of the applied voltage. It was observed that the viewing property along the vertical axis was somewhat narrower than that along x-axis (see the contour lines with low contrast ratio) since the molecular tilt angles at two positions appeared asymmetrically. Along the directions of the crossed polarizers, the contrast ratio diverges because of the singular nature of calculation.

3. Experimental Results

The transverse electrode configuration was achieved using glass substrates, on one of which interdigital electrodes were prepared. The parallel electrodes were made by etching the Cr layer in an oppositely overlapped comb pattern and the separation between two electrodes was about 10 µm.

The alignment layer of Nylon 6 (Aldrich Chemical Company Inc.) was coated on the inner surface of the substrate and rubbed unidirectionally to promote homogeneous alignment. The cell was assembled such that the rubbing direction on the one surface was parallel to one of the crossed polarizers and made an angle of 45° with respect to the transverse electrodes. Note that the rubbing directions on the two substrates were antiparallel to each other. The sample cell thickness was maintained using glass spacers of 2 µm.

The NSC LC material used in this work is IS-5512 with positive dielectric anisotropy (Δε = 0.49) of Merck Co. Ltd. It has the following phase sequence: isotropic → (46.2 °C) → nematic → (38.0 °C) → smectic C → (26.0 °C) → crystal. The tilt angle of IS-5512 in the smectic C phase is about 45° with respect to the normal direction to the smectic layers. The LC was filled in the isotropic phase and cooled down into the smectic C phase.

Using the NSC LC cell, we measured the EO transmittance, the dynamic EO response, and the viewing properties as a function of the voltage of a bipolar square waveform at 30 and 50 Hz, respectively. For the measurements of the EO transmittance and dynamic EO response, a He-Ne laser of 632.8 nm and a digitizing oscilloscope (TDS 420, Tektronix) were used. The viewing properties of the sample cell were obtained using a LCD characterizing system (DMS 501, Autronics). All the measurements were carried out in the smectic C phase of IS-5512.

In Fig. 5, continuous gray scales of the NSC LC cell were shown as a function of the applied electric field of a bipolar square waveform at 30 Hz. With increasing the applied field above a certain threshold [15] of 3.8 V/µm, the EO transmittance increases monotonically as expected from the numerical simulations in Fig. 3.
Figure 6 shows the dynamic EO response of the NSC LC cell to the applied field at 50 Hz. It should be noted that the NSC LC cell can be operated with a bipolar square waveform by means of the dielectric anisotropy like the conventional NLC case. In the dielectrically driving scheme, the measured rising and falling times were 3.2 and 13.8 ms, respectively. The switching times on the order of 10 ms would be suitable for display applications at a video-rate.

Figure 7 shows the iso-contrast map of the NSC LC cell with no compensation film. The vertical axis (y-axis) represents the direction of the transverse electrodes. Since the horizontal axis (x-axis) is parallel to the direction of the applied electric field, the LC molecules with positive dielectric anisotropy rotate parallel to the x-axis and reorient away from the rubbing direction as well as the substrate planes. In the transverse electrode configuration, the curvature of the applied field induces the asymmetric distortions of the LC director in two half regions between interdigital electrodes. This makes the viewing properties along the x-axis be somewhat wider than that along the y-axis as shown in Fig. 4. No contrast inversion is seen in the range of the viewing angle (up to 80°) we measured.

4. Concluding Remarks
We have theoretically and experimentally demonstrated a fast analog EO effect of the NSC LC in a transverse electrode configuration. The rising and falling times were found to be 3.2 and 13.8 ms, respectively. The analog gray scales were obtained in the dielectrically driving scheme as in the NLC mode. Moreover, the intrinsic nature of two-domain structure between interdigital electrodes provides wide viewing properties. Although the further studies such as the effect of bending smectic layers near electrodes remain to be carried out, the NSC LC mode is expected to provide a viable technology to produce next-generation LCDs suitable for processing the dynamic image at a video-rate.

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6. References