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M. Oh-e [a], M. Ohta [a] & K. Kondo [b]
[a] Electron Tube & Devices Division, Hitachi, Ltd., 3300 Hayano, Mobara-shi, Chiba-ken, 297, Japan
[b] Hitachi Research Laboratory, Hitachi, Ltd., 7-1-1 Ohmika-cho, Hitachi-shi, Ibaraki-ken, 319-12, Japan

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PHYSICAL BEHAVIOR OF NEMATIC LIQUID CRYSTALS USING THE IN-PLANE SWITCHING MODE

MASAHITO OH-E[†], MASUYUKI OHTA[†] AND KATSUMI KONDO[††]
† Electron Tube & Devices Division, Hitachi, Ltd., 3300 Hayano, Mobara-shi, Chiba-ken, 297 Japan
††Hitachi Research Laboratory, Hitachi, Ltd., 7-1-1 Ohmika-cho, Hitachi-shi, Ibaraki-ken, 319-12 Japan

Abstract We have investigated the switching and response mechanism of the in-plane switching (IPS) mode which is a novel technique for wide viewing-angle liquid crystal displays. In the IPS mode, an in-plane electric field is applied to the liquid crystals along the direction parallel to the plane of the substrates. First, it was made clear that it was the electric field and not the voltage that drove the liquid crystals in the IPS mode. An inversely proportional relationship between the threshold voltage and the cell gap was found to hold. Second, the relaxation time of the liquid crystals when removing the electric field was described as a proportional relationship to the square of cell gap. A thinner cell gap also proved to be effective to obtain fast response time in the IPS mode. In contrast, the electric field strength governed the switching-on time when applying the in-plane electric field.

INTRODUCTION

Recently liquid crystal displays (LCDs) have made great progress in quality and are now under development for use in larger display areas. However, limited viewing-angle characteristics are still a serious problem for large display areas. Under these circumstances, an in-plane switching (IPS) mode showed up as a breakthrough for extremely wide viewing-angle LCDs.[1-4] Although the IPS mode has already been investigated by some researchers with interdigital electrodes,[5, 6] detailed studies have not been completed. Many of the physical behaviors of the liquid crystals have not been clarified when an in-plane electric filed is applied to the liquid crystals. However, G. Baur originally suggested that the IPS mode is promising for improving viewing-angle quality.[7-10] In 1995, we succeeded in developing actively addressed in-plane switching LCDs which have extremely wide viewing-angle characteristics with the IPS mode.[2, 3] Detailed studies are under investigation and many of the points concerning the switching principle of the liquid crystals have to be made clearer.

ELECTRO-OPTICAL PRINCIPLE

A schematic diagram in figure 1 shows the principle of the dark and bright states in the IPS mode. Liquid crystals are initially aligned homogeneously between the substrates

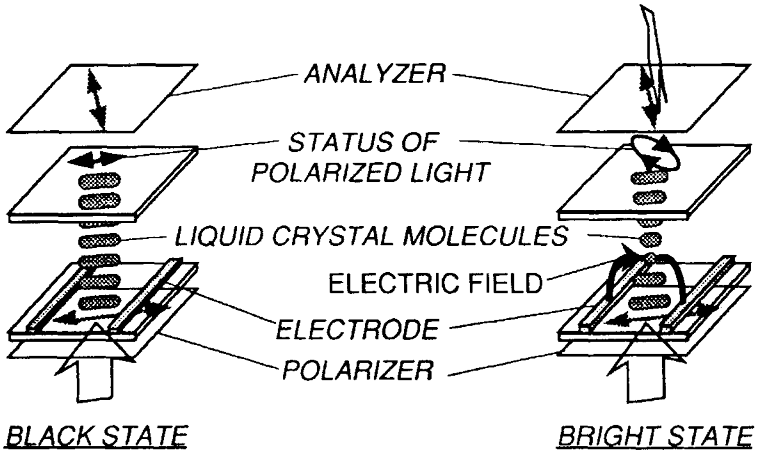

FIGURE 1 Electro-optical principle of the in-plane switching mode.

Basically, the liquid crystals respond to an in-plane electric field by retaining the plane of the substrates. The optical axis direction of the homogeneously aligned liquid crystals is in good agreement with the polarization axis of a polarizer at the initial stage. The polarizer and analyzer are set at right angles from each other on the axes. This configuration functions as forming a pure black state without the electric field. A pure modulation is achieved because the light behaves as an extraordinary ray. Accordingly, the electric field which is parallel to the plane of the substrates, is applied to the liquid crystal layer, and this makes the optical axis deviate from the polarization axis. As a result, light transmission is gradually increased because phase retardation occurs due to the different propagating speeds of the extraordinary and ordinary rays in the liquid crystal medium. The 45 degree deviation of the liquid crystal optical axis from the polarization axis leads to maximum transmittance. It is necessary to set the optical difference of the liquid crystal layer, $d \cdot \Delta n$, to half a wavelength to obtain a brighter outgoing beam, higher contrast ratio and insensitivity to wavelength of the incident light.

VIEWING-ANGLE CHARACTERISTICS

Figure 2 shows the viewing-angle characteristics of the IPS mode from the viewpoints of gray scale reversal and contrast ratio. These characteristics are strongly dependent on how the black state is created. In the TN mode, the black state is set where there is no birefringence effect along the direction nearly perpendicular to the substrates, which is strongly dependent on the viewing direction. Therefore the viewing direction affects the black state and the light leakage.

In contrast, the black state in the IPS mode is determined by the two crossed polarizers, because the optical direction of the liquid crystals is aligned with the polarization axis of the polarizer. The following expression describes the transmission in the uniaxial media with two crossed polarizers.

$$T = \sin^2(2\chi)\cdot\sin^2\left(\frac{\pi d\cdot\Delta n(\phi, \theta)}{\lambda}\right) \quad (1)$$

where χ is the angle between the optical axis of the liquid crystals and the polarization axis of incident light, and ϕ and θ are azimuthal and polar angles of the viewing direction. The birefringence Δn are strongly dependent on the viewing direction, ϕ and θ. However, when the dark state is selected, the first sine term is zero in equation (1). Thus the excellent viewing-angle characteristics in the IPS mode lie in the fact that the switching from the dark state to the bright state is achieved by the switching of the first sine term in equation (1).

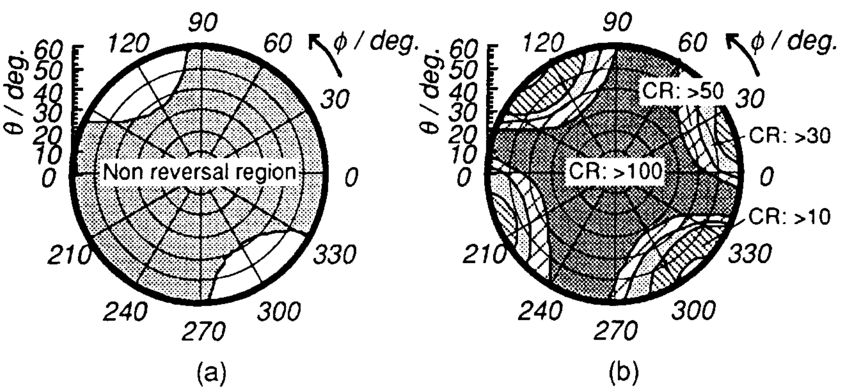

FIGURE 2 Viewing-angle characteristics of the IPS mode.
(a) Gray scale reversal, (b) Contrast ratio.

THRESHOLD CHARACTERISTICS

In order to analyze the threshold characteristics, the same procedure of applying the continuum elastic theory to the IPS mode as in the TN mode.[11, 12] During the derivation, it was assumed that the liquid crystals were homogeneously aligned and were strongly anchoring on the surface of alignment layer. In addition, it was also assumed that the in-plane electric field parallel to the substrates was applied along the direction perpendicular to the molecules. As a result, the threshold voltage V_c at which the twist angle ϕ of the liquid crystals just begins to change, can be reduced to:[11]

$$V_c = E_c \times \ell = \frac{\pi\ell}{d}\sqrt{\frac{K_2}{\varepsilon_0|\Delta\varepsilon|}} \quad (2)$$

where E_c is the critical field, d corresponds to the cell gap, K_2 is the twist elastic constant of the liquid crystals, $\Delta\varepsilon$ denotes the dielectric anisotropy, ε_0 is the vacuum dielectric constant and ℓ symbolizes the distance between electrodes. The obtained expression predicts that the electrode distance determines the threshold voltage. However, at the same time the cell gap influences the threshold behavior as well. Although an anomalous relationship can be derived in the TN mode, the dependence of electric field on the liquid crystal layer normal produces the threshold voltage as $V_c = E_c \cdot d$. This equation indicates that the threshold of the liquid crystals are not determined by the electric field but by the voltage. The direction in which the electric field is administered, parallel to the substrates, is independent of the liquid crystal layer normal in the IPS mode. Therefore, the threshold voltage in the IPS mode is changeable by the cell gap. It was experimentally confirmed that variation of the cell gap affects the threshold voltage. Furthermore, the reciprocal of the cell gap proved to be proportional to the voltage at maximum transmittance as presented in figure 3.

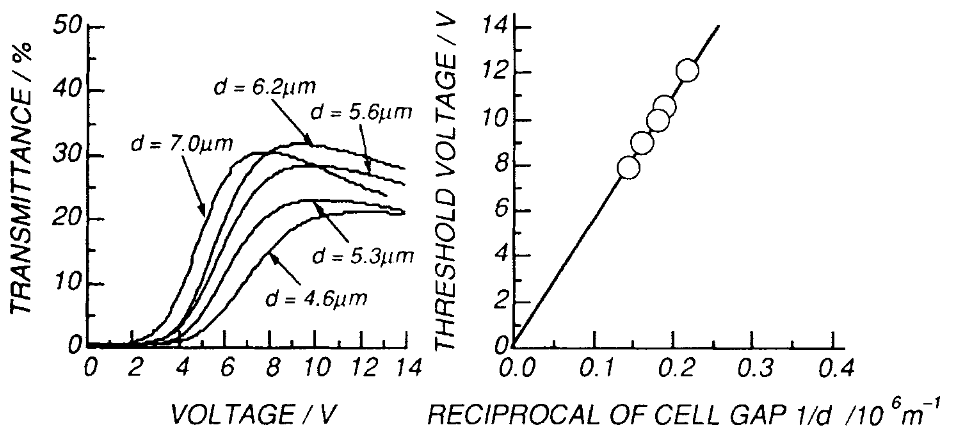

FIGURE 3 (a) Cell gap effect on voltage-dependent transmittance and (b) relationship between the threshold voltage and the square of cell gap.

DYNAMICAL BEHAVIOR

In dynamic responses, the viscous torque, which opposes the director rotation, should be considered.[12-14] Response time can be derived with an equilibrium equation in which the elastic, electric and viscous torques are expressed. The switching off and on times can be reduced to:[14]

$$\tau_{off} = \frac{\gamma_1 d^2}{\pi^2 K_2} = \frac{\gamma_1}{\varepsilon_0 |\Delta\varepsilon| E_c^2} \tag{3}$$

$$\tau_{on} = \frac{\gamma_1}{\varepsilon_0|\Delta\varepsilon|E^2 - \frac{\pi^2}{d^2}K_2} = \frac{\gamma_1}{\varepsilon_0|\Delta\varepsilon|(E^2 - E_c^2)} \quad (4)$$

where γ_1 denotes the viscous coefficient. Figure 4 (a) shows the cell gap dependence on relaxation time when removing the electric field. The linear relation is in accordance with the derived switching-off time. A larger elastic energy should exist in a thin liquid crystal layer than in a thick layer, if it is assumed that the same degree of twist deformation occurs in the layer. In order to confirm the effect of the field strength on the switching-on time, the relationship between $1/\tau_{on}$ and $(E^2-E_c^2)$ was analyzed. Figure 4 (b) shows the experimental results of the proportional relationship of the reciprocal of relaxation time τ_{on} in the switching-on process versus the difference between the square of the electric field strength and the square of the critical field $(E^2-E_c^2)$. In contrast to the switching-off process, the response time for the switching-on process is strongly dependent on the electric field strength.

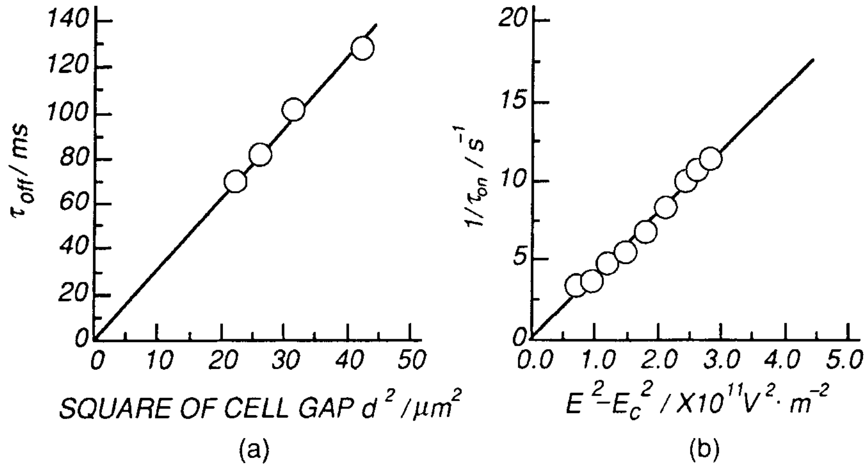

FIGURE 4 (a) Cell gap effect on switching-off time, and (b) electric field dependence of switching-on time.

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