Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

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Seung Ho Hong; Hyang Yul Kim; Myong-Hoon Lee; Seung Hee Lee

Online publication date: 11 November 2010

To cite this Article Hong, Seung Ho , Kim, Hyang Yul , Lee, Myong-Hoon and Lee, Seung Hee(2002) 'Viewing angle characteristics of a homogeneously aligned two-domain liquid crystal cell with an inter-digitated electrode', Liquid Crystals, 29: 2, 315 — 319

To link to this Article: DOI: 10.1080/02678290110101877

URL: http://dx.doi.org/10.1080/02678290110101877

LIQUID CRYSTALS, 2002, VOL. 29, NO. 2, 315–319

Viewing angle characteristics of a homogeneously aligned two-domain liquid crystal cell with an inter-digitated electrode

SEUNG HO HONG, HYANG YUL KIM

Cell Process Development Department, Hyundai Display Technology, San 136-1, Ami-ri, Bubal-eup, Ichon-si, Kyungki-do 467-701, Korea

MYONG-HOON LEE and SEUNG HEE LEE*

Department of Polymer Science & Technology, Chonbuk National University, Chonju-si, Chonbuk 561-756, Korea

(*Received 1 April 2001; in final form 18 September 2001; accepted 24 September 2001*)

The in-plane switching (IPS) mode in liquid crystal displays is known to exhibit a wide viewing angle. However, since the LC director rotates in one direction in the plane, devices with a single domain exhibit both a colour shift depending on the viewing angle, and grey-scale inversion at specific angles especially at low grey levels. This has been improved by wedge shaped electrodes so that fields in two directions exist inside a pixel, causing the LC molecules to rotate in opposite directions to compensate each other; this acts as a virtual two domains structure. Nevertheless, the colour shift still exists to some extent, especially at low grey levels. In this paper, we propose a realistic two-domain IPS mode that exhibits a minimized colour shift at all grey levels on changing the viewing direction. In this device, the LC molecules are initially aligned in two directions orthogonal to each other, and two field directions exist perpendicular to each other. We have performed device simulations with respect to viewing angle characteristics, and found that IPS devices with a real two-domain structure reduce the variation of the retardation more effectively, when the viewing direction changes.

1. Introduction

Recently, the image quality of liquid crystal displays (LCDs) using the thin film transistor as an operating switch has been improved greatly by several wide viewing angle technologies. In particular, in-plane field switching (IPS) [1–4] and fringe-field switching (FFS) [5–8] modes are typical examples of such approaches. In both modes, the LC molecules are homogeneously aligned with the optic axis coincident with one of the crossed polarizer axes in the dark state. In the bright state, the in-plane field and fringe-field modes drive the LC molecules to rotate in-plane and almost in-plane, respectively. Both modes show relatively good uniformity in transmittance, owing to the in-plane rotation of the LC director. However, both devices show a colour shift at off-normal directions, especially along directions perpendicular and parallel to the director in the on-state, since the director rotates in one direction. In order to overcome such a problem, a wedge-shaped electrode was suggested; that is, two different field directions are constructed inside a pixel so that with bias voltage the LC molecules rotate in two directions, clockwise and anti-clockwise imitating a virtual two-domain [9]. This approach compensates effectively for the variation of retardation of the cell only in the high grey level of the white state, because in that state two LC directors in a pixel are twisted perpendicular to each other. In other words, the light propagates parallel to the LC director in one half and perpendicular to it in the other half.

We have proposed a pixel structure and an LC alignment to minimize the viewing angle dependency of the retardation of the cell at all grey levels. In the pixel of the new device, the LC molecules are aligned in two directions separated by an angle of 90°, as are the field directions, and thus it has a real two-domain structure. On application of the bias voltage, the two LC directors rotate clockwise and anticlockwise with an angle of 90° difference to each other in all grey levels; that is, the asymmetry in the light transmission dependent on viewing direction is minimized. In this paper, we report simulation results on viewing angle characteristics for the IPS device with single domain (1-D), virtual 2-domain (V2-D) and real 2-domain (R2-D) structures.

*Author for correspondence; e-mail: lsh1@moak.chonbuk.ac.kr

Liquid Crystals ISSN 0267-8292 print/ISSN 1366-5855 online © 2002 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/02678290110101877

2. Cell structure of the IPS device with 1-D, V2-D, and R2-D structures

In the IPS device the birefringent LC medium is under crossed polarizers, and the normalized light transmission is given by [9]:

$$T/T_0 = \sin^2(2\psi)\sin^2(\pi d\Delta n(\theta,\phi)/\lambda) = \sin^2(2\psi)\sin^2(\delta/2)$$

where ψ is the angle between the crossed polarizers and the LC director, d is a cell gap, Δn is the birefringence of the liquid crystal medium dependent on polar (θ) and azimuthal (ϕ) angles, λ is the wavelength of incident light, and δ is the retardation of the cell. Figure 1 shows a cross-section of the IPS cell structure with a configuration of the LC director in the OFF (dark) and ON (bright) states. In the device, the pixel and counter electrodes exist only on one substrate. In the OFF state, the LC molecules are homogeneously aligned with the optic axis coincident with one of the axes of the crossed polarizers so that the cell appears black. In the ON state, with increasing bias voltage, the horizontal field drives the LC molecules between the electrodes to rotate almost in plane such that ψ is increased, giving rise to transmission between the electrodes. In the fully bright state, the average degree of rotation of the LC director, ψ is 45°.

Figure 2 shows the structure of one pixel in the IPS device with a thin film transistor (TFT) and a configuration of the LC director in the initial state for the 1-D, V2-D, and R2-D arrangements. A LC with negative dielectric anisotropy is used, so that the LC molecules align perpendicular to the field direction. In the 1-D device, the pixel and counter electrodes are patterned in a slit form so that the horizontal field generated mainly in one direction, when a voltage is applied. In this case, the LC director is aligned using conventional rubbing or photoalignment techniques [10] and makes some angle with the field direction. In the V2-D device, the pixel and counter electrodes are patterned in a wedge form, so that the field directions in one pixel are different from each other. In this device, the LC molecules are aligned in the horizontal direction. In this way, on applying the bias voltage the LC molecules in the upper and bottom halves of one pixel rotate anticlockwise and clockwise, respectively. In the R2-D device, the pixel and counter electrodes are patterned in a form that can generate horizontal fields in vertical and horizontal directions inside a pixel; also the LC molecules in one pixel are aligned in two directions perpendicular to each other at some angle with the applied field. Such an alignment is possible using photoalignment techniques. In this device, the optic axes of the LC director in one pixel are always coincident with one of the transmission axes of the crossed polarizers such that it also gives a dark state in the OFF state. When a voltage is applied, the LC director rotates in only one direction, either clockwise or anticlockwise, dependent on the initial alignment of the LC molecules. In the case of figure 2(*c*), the LC molecules rotate counterclockwise.

Figure 3 describes the configurations of the LC director under crossed polarizers in the low, mid, and brightest grey (white) levels for the devices with 1-D, V2-D and R2-D structures. As indicated, in the low grey level the transmission is about 10%, and the LC directors deviate from one of the axes of the crossed polarizer by an average value of $\psi = 9.2°$. In these cases, the LC molecules rotate, respectively, in one direction, two directions symmetrically along the horizontal axis, and counterclockwise but orthogonal to each other for 1-D, V2-D, and R2-D. In the mid and the brightest grey levels, the LC directors deviate from the initial alignment by an average value $\psi = 22.5°$ and 45°, respectively in the same way as in the low grey level. Consequently, in the IPS

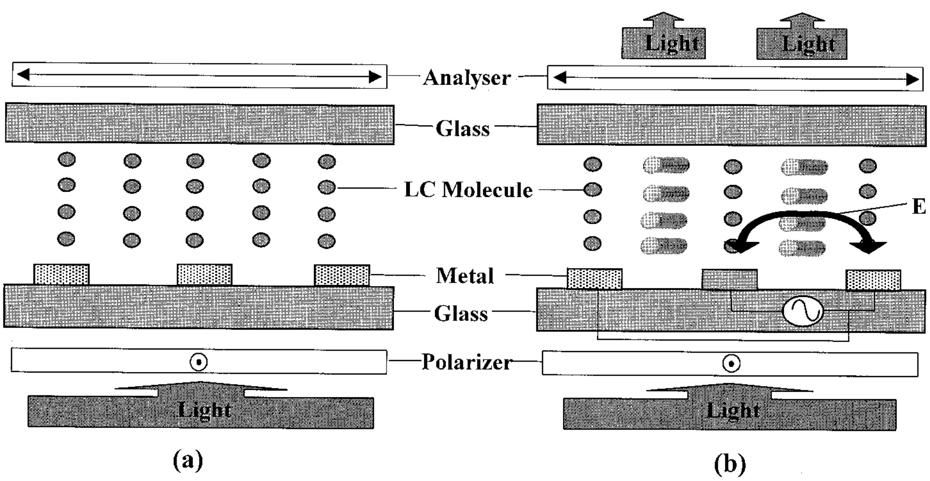

Figure 1. Cross-sectional view of the IPS cell structure with configuration of the LC molecules in the (*a*) OFF and (*b*) ON states.

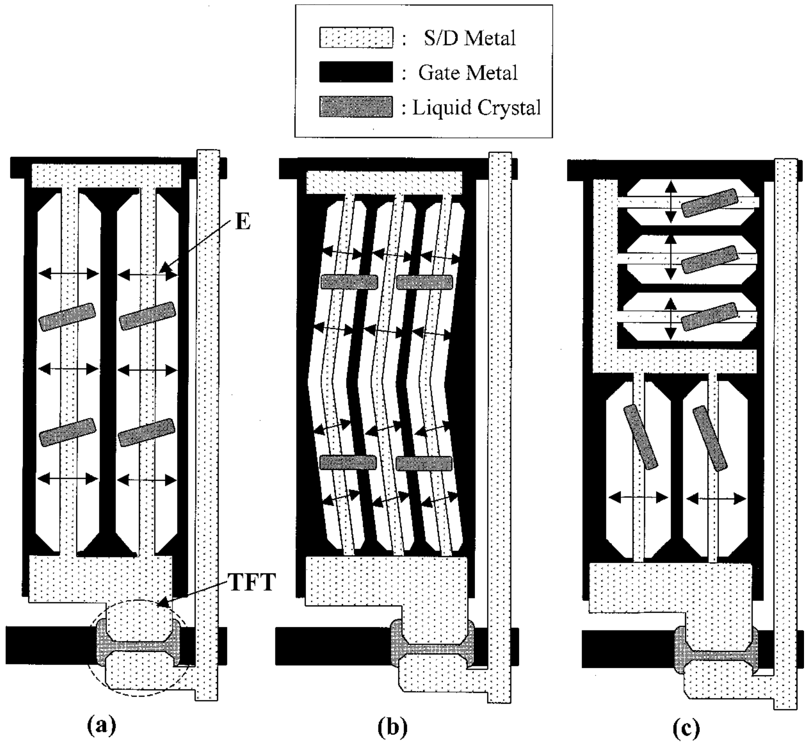

Figure 2. One pixel structure of the IPS device with TFT and configurations of the LC director for (*a*) 1-D, (*b*) V2-D and (*c*) R2-D structures.

device with 1-D structure the LC director rotates only in one direction so that the difference in retardation values parallel (δ_1) and perpendicular (δ_2) to the LC director in the twisted state is a maximum in all grey levels, causing bluish and yellowish colour shifts in the white state parallel and perpendicular to the LC directors [9]. In the IPS device with V2-D structure, the difference (δ) in phase retardation along and perpendicular to the LC director becomes reduced compared with that of the 1-D structure in the grey levels, although it is still

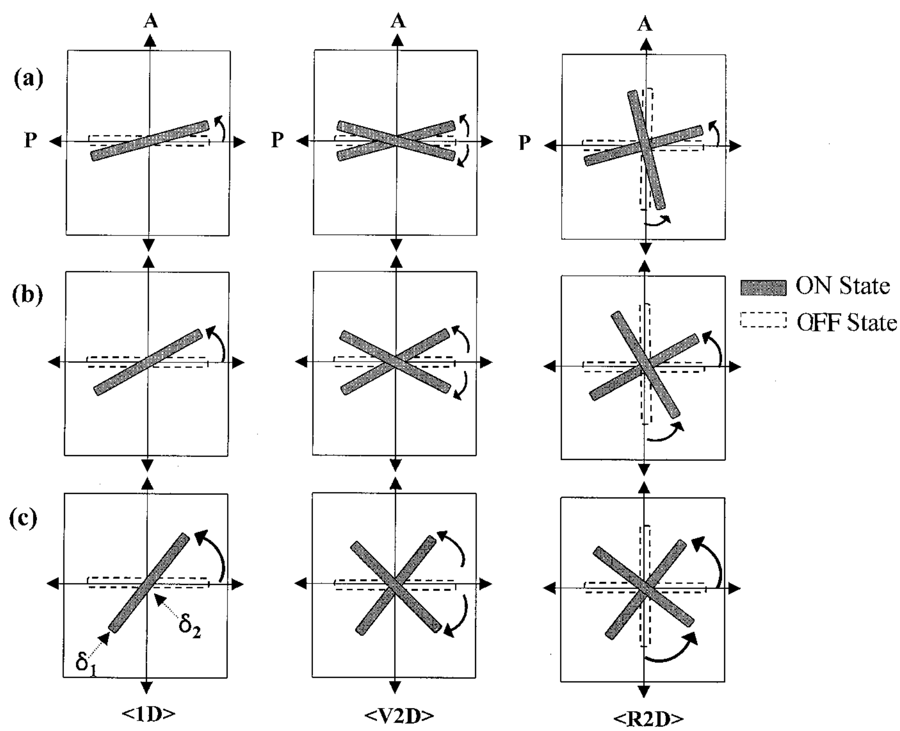

Figure 3. Configuration of the LC director in the IPS devices with 1-D, V2-D and R2-D structures at (*a*) V_{10}, (*b*) V_{50} and (*c*) V_{100}.

not enough to minimize it. Nevertheless, in the white level it becomes a minimum, reducing the colour shift to the viewing directions, since the two LC directors in one pixel are twisted perpendicular to each other. However, for the IPS device with R2-D structure, the two LC directors in one pixel are aligned perpendicular to each other in all grey levels so that δ becomes smaller than that of the V2-D device except for the white level in which the effect of compensation is the same for both V2-D and R2-D structures.

3. Simulation results and discussion

In order to confirm the effect of the R2-D structure in the IPS device, we have performed simulations using commercially available 2-dimensional software (Shintech, Inc., Japan) and analysed the results in terms of iso-luminance and colour shift with varying viewing angles in three grey levels for the 1-D, V2-D and R2-D cases. For these simulations, the LC has a birefringence $\Delta n = 0.077$ and dielectric anisotropy $\Delta\varepsilon = -4.0$ the cell gap is 3.9 µm and the pretilt angle 2°. The width (8 µm) of the electrodes and the distance (10 µm) between them has been chosen to generate the in-plane field. The transmission is calculated only between the electrodes. Initial alignment of the LC molecules is defined to have an angle of 12° from the direction of the horizontal field.

For comparison of the three cases, we selected the voltages that have light transmission, 10% (V_{10}) and 50% (V_{50}) of the maximum transmission at normal direction. We then calculated the variation of the transmission in terms of the viewing directions up to a polar angle of 80° in all azimuthal directions with increasing steps of 10°. Figure 4 shows iso-luminance contours of the light transmission of the IPS devices for the 1-D, V2-D, and R2-D cases to the viewing angle at V_{10} and V_{50}. Here, the iso-luminance lines have been selected to represent 90, 75, 50, 25, and 10% of maximum transmission at given voltages. From the iso-luminance contour, the degree of viewing angle dependence can be defined by inducing eccentricity (e) that represents the ratio of long and short axes of the ellipse. As indicated in figure 4, in 1-D at V_{10}, the maximum transmission does not exist even at normal direction and also e at a relative intensity of 50% is much larger than those in the V2-D and R2-D cases. Furthermore, e becomes slightly smaller for the R2-D case than for V1-D. Even at V_{50}, e is much larger than one for 1-D but becomes small with V2-D and close to one for the R2-D case, meaning that the change of luminance with viewing direction is the least for R2-D owing to the configuration of the LC director in two directions perpendicular to each other. In other words, in the grey level the light propagates along the long axis of the twisted LC molecules in half of one pixel but propagates along the short axis of the twisted molecules in its other half, so that the viewing angle dependence of luminance is minimized in all directions given a polar angle.

We have also compared the degree of the colour shift at V_{50} with the viewing directions for these cases, as shown in figure 5. In the 1-D device, the colour coordinates (x, y) [11] change a maximum of about (0.1, 0.1) as the viewing direction changes. However, the degree of colour shift is reduced in V2-D, and furthermore the maximum is less than (0.05, 0.05) in the R2-D case. Although in figure 5 it is difficult to identify data associated with each viewing angle due to the small amount

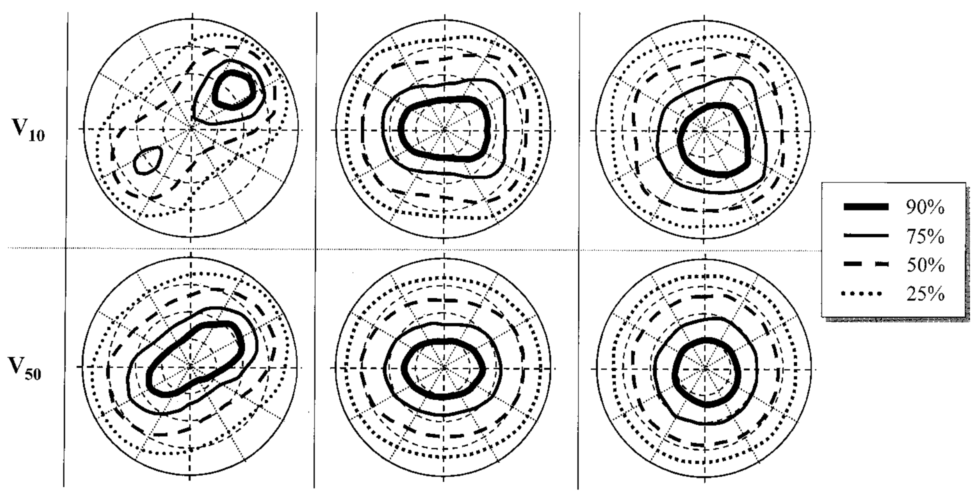

Figure 4. Iso-contour of the light transmission of the IPS device in relation to the viewing angle for (*a*) 1-D, (*b*) V2-D, and (*b*) R2-D modes at V_{10} and V_{50}.

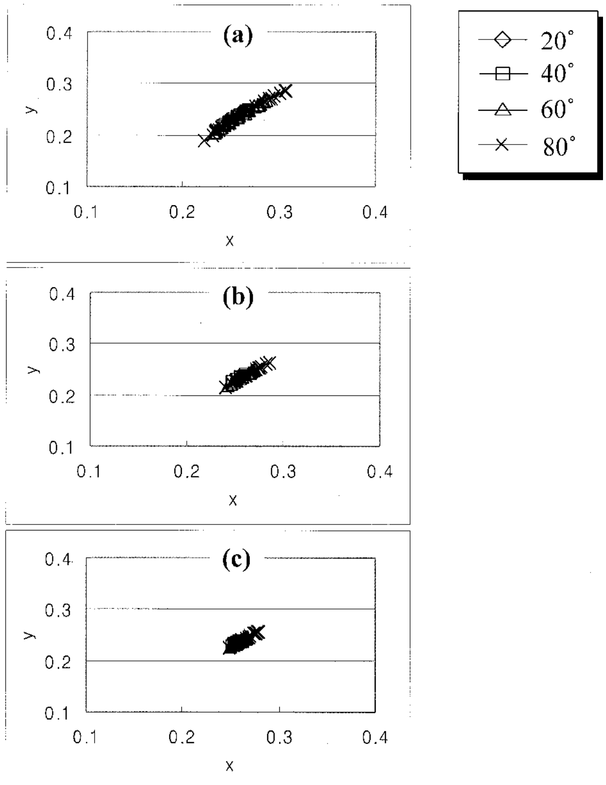

Figure 5. Colour shift in relation to the viewing angle in IPS devices with (*a*) 1-D, (*b*) V2-D, and (*b*) R2-D structures at V_{50}.

of the colour shift, we are able to know from the degree of dispersion of the data that the R2-D device is the most effective in reducing the viewing angle dependence of luminance and colour coordinates.

4. Summary

We propose a new cell structure from IPS device that generates fields in vertical and horizontal directions with two different alignments of the LC molecules perpendicular to each other. We have performed simulations to evaluate the viewing angle characteristics by calculating luminance and colour coordinates in relation to the viewing directions and found that the new device is the most effective in reducing the viewing angle dependence of luminance and colour characteristic, compared with single and virtual 2-domain structures.

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