

Lateral field effect in twisted nematic cells

by A. Lien
R. A. John

The lateral field existing in the ON state of a liquid crystal display (LCD) can result in an undesired reverse tilt domain in each pixel, thereby leading to poor contrast ratio of the display. As pixel size becomes smaller to meet the requirements of a high-information-content display, the problem becomes worse. In this paper, we present experimental results and theoretical analysis of the lateral field effect in the twisted nematic (TN) cell, which is most commonly used in the thin-film-transistor liquid crystal displays (TFT/LCD). The effects of various cell parameters, such as pretilt angle, bus-line-to-pixel spacing, and cell gap thickness, on the pixel reverse tilt domain and on the corresponding optical performance have been studied in detail. The results are useful for TFT/LCD design and cell fabrication.

1. Introduction

The thin-film-transistor matrix-addressed liquid crystal display (TFT/LCD) [1] is one of the most promising flat-panel displays having the potential to replace the cathode ray tube display in the future. However, a reverse tilt domain which can occur in the pixel still remains an

important issue for this kind of display. To understand the reverse tilt phenomenon, let us look at a simple case of a pixel in a parallel-aligned electrically controlled birefringence (ECB) [2] liquid crystal display having tilt only in the region of the applied electric field, as shown in Figure 1. A surface alignment is made for this kind of display such that, in the OFF state, the long axes of liquid crystal molecules are almost parallel to the substrate surfaces but are tilted with an angle (typically 1–2°) away from the substrate surface and pointing to the right. When a voltage is applied, most of the LC molecules in the pixel will follow the pretilt direction and tilt up from the right, as shown on the left-hand side of the cell under the upper electrode. This area is called the normal tilt domain. Notice that the upper electrode is shorter than the lower electrode in the figure. The direction of the fringe electric field produced at the left edge of the cell is the same as the pretilt direction. However, at the region near the right edge of the upper electrode, the direction of the fringe field at the right edge is opposite to the pretilt direction; thus, the fringe field drives the LC molecules in this region to tilt to the left, against the pretilt direction. This area is called the reverse tilt domain. The boundary between these two domains is either a wall [3], if the voltage applied to the pixel is below a critical voltage, or a disclination line pair [3], if the voltage applied to the pixel is above the

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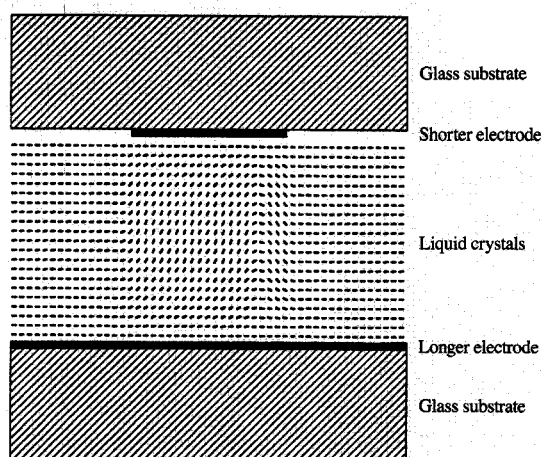


Figure 1

Cross section of a pixel in a liquid crystal display with tilt. When a voltage is applied, a reverse tilt domain appears on one edge (right edge) of a parallel ECB pixel in which the upper electrode is shorter than the lower electrode. The cell dimensions are not drawn to scale.

critical voltage. Thus, in the ON state, the LC molecules in the reverse tilt domain are tilted in the direction opposite to that of the normal domain.

Between a pair of polarizers, either in parallel or crossed configurations, the transmission vs. viewing angle characteristics are different between these two domains in certain viewing zones, especially for the upper (viewing the panel from the 12 o'clock direction) and lower (viewing the panel from the 6 o'clock direction) viewing zones. Also, the optical behavior of a pixel for the region inside the boundary wall or on the disclination line pair is different from that for other areas, as is discussed below. Therefore, the contrast ratio of the display is reduced for some viewing zones if a reverse tilt domain occurs in each pixel. Furthermore, our experimental results and theoretical analysis indicate that the width of the reverse tilt domain remains almost the same when the pixel size is reduced, if the pixel has a nonzero pretilt angle greater than 0.5° and the pixel size is more than 10 times the cell gap thickness. This implies that the reverse tilt problem becomes worse as the pixel size becomes smaller. Nevertheless, small pixel size is required for a high-information-content display. Thus, the reverse tilt domain is an important issue for the advanced liquid crystal display and is worthy of detailed study.

The twisted nematic (TN) cell, in which the axes of the liquid crystal molecules take up a static spiral alignment from bottom to top substrate, was invented in 1971 [4]. The rubbing directions of top and bottom substrate are aligned perpendicular to each other, which introduces a twist of 90° in the long axis of the liquid crystal molecules from one substrate surface to the other. The rubbing direction is defined by the mechanical contact of a polyamide film deposited on the substrate with a cloth-covered rotating roller. The rubbing direction is established at right angles to the roller axis and in the direction of the relative velocity of the rotating cloth with respect to the substrate.

The origin of the reverse tilt domain of a passive-matrix TN display was first described by Sussman [5], but no detailed theoretical analysis was given. Recently, Kilian and Hess [6] have reformulated equations of continuum theory in terms of the alignment tensor. Haas et al. [7] then used the theory of Kilian and Hess (KH) to study the reverse tilt domain of a parallel ECB. Since the TN cell is

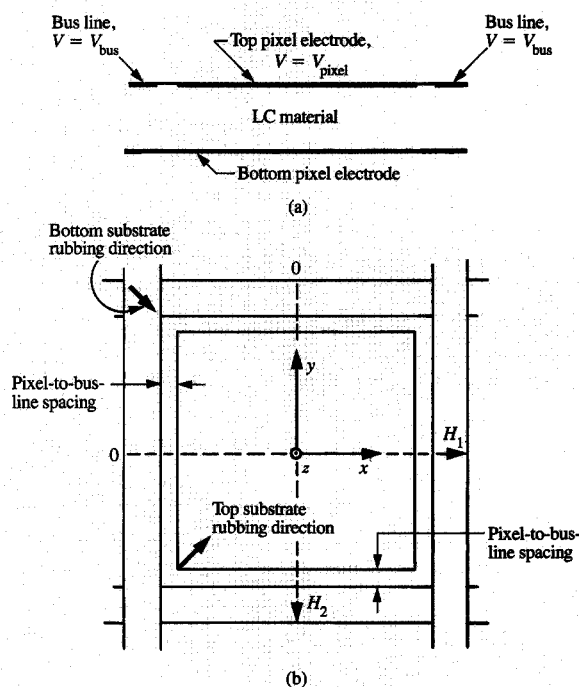


Figure 2

Structure of a TFT driving a 90° TN cell. (a) Pixel cross section. The bottom electrode is grounded; the top pixel electrode is supplied with a voltage of V_{pixel} . Four bus lines are located adjacent to each pixel, one for each side. The bus lines are supplied with a voltage of V_{bus} , which may be different from V_{pixel} . (b) Pixel top view. The rubbing direction, the xyz coordinate system, and the H_1 and H_2 axes are also shown.

now widely used in the active-matrix LCD, both Lien [8] and Haas et al. [9] also used the KH theory to study the reverse tilt phenomenon of the TN cell. Realizing that there was a difference between the cell structure of simple passive-matrix and active-matrix displays, Lien in his previous paper [8] focused on the type of TN cell structure used in the TFT/LCD. On the other hand, to our knowledge, there are no detailed and systematic experimental data in the literature on the pixel reverse tilt domain for comparison with theoretical results. Therefore, in this paper we report for the first time a systematic experimental study of the reverse tilt domain of 90° TN cells under the influence of the driving bus lines (gate lines and data lines). The experimental data have been compared with the theoretical results computed using the KH theory. We have also obtained the effects of various cell parameters (such as the pretilt angle, bus-line-to-pixel spacing, and cell gap thickness) on the pixel reverse tilt domain and on the corresponding optical performance. These results are useful in TFT/LCD design and cell fabrication.

2. Experimental results

The pixel cell structure of a TFT/LCD is shown in Figure 2. The common electrode is larger than its counter electrode on the TFT substrate. There are four bus lines adjacent to each pixel; two are gate bus lines, and the other two are data bus lines. The rubbing directions are also shown in Figure 2 to define the panel orientation by which the four viewing zones are defined. This means that if the panel is oriented as shown in Figure 2, viewing from the 12 o'clock direction is defined as the upper viewing zone. Similarly, viewing from the 6 (3, 9) o'clock direction is defined as the lower (right, left) viewing zone. An xyz coordinate system depicted in Figure 2(b) is used in Section 3.

The lateral field originates from both the cell structure and the influence of the bus lines. This lateral field is the major factor which causes the pixel reverse tilt domain.* Experimentally, we study the pixel reverse tilt domain under the influence of the bus lines. To do this, we have built special test panels in which the indium tin oxide (ITO) electrode layer on one substrate is specially patterned, while the ITO electrode layer on the other substrate is unpatterned. Figure 3 shows a micrograph of a typical pixel with its bus line in such a test panel. The rubbing directions are also shown for orientation. The pixel area is $300\ \mu\text{m} \times 300\ \mu\text{m}$ and the cell gap is about $5\ \mu\text{m}$. For the pixel shown in Figure 3, the bus line was located adjacent to the lower edge of the pixel and the bus-line-to-pixel spacing was designed for $5\ \mu\text{m}$. However, due to over-etching it was observed to be $6.7\ \mu\text{m}$. In the same

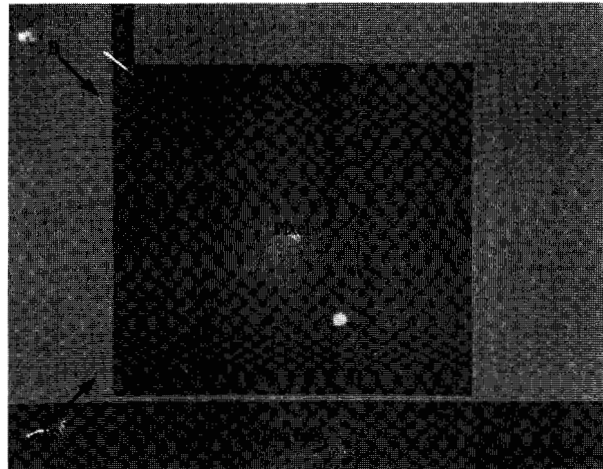


Figure 3

Micrograph of a typical pixel with its bus line in a test panel. The pixel area is $300\ \mu\text{m} \times 300\ \mu\text{m}$. For this pixel, the bus line was located adjacent to the lower edge of the pixel and the bus-line-to-pixel spacing was measured to be $6.7\ \mu\text{m}$. (The white round spots in the picture are spacer balls between upper and bottom substrates for maintaining cell gap spacing.)

test panel, we have designed various bus-line-to-pixel spacings ranging from $5\ \mu\text{m}$ to $25\ \mu\text{m}$ in steps of $5\ \mu\text{m}$, located in different areas of the panel. Also, the bus line can be located adjacent to any of the four edges of a pixel (top, bottom, left, or right edges) for studying the effect of the bus line on the pixel reverse tilt domain from different orientations. The pixel and bus line were driven with two separate square-wave voltages which had the same frequency, but the phases could be either in phase or 180° out of phase. The amplitudes of the two square waves could also be different.

We next discuss the experimental results for the reverse tilt domain of a pixel in the test panel under the influence of the bus lines located adjacent to the different edges of the pixel. The panel has a surface pretilt angle of 1° , which was measured by the retardation extrema method [10]. Figure 4 shows the same pixel as in Figure 3, observed between a pair of parallel polarizers when a square wave of amplitude $2.6\ \text{V}$ was applied to the pixel and another square wave of amplitude $8\ \text{V}$ was applied to the bus line. The frequencies of both square waves were $60\ \text{Hz}$, and they were 180° out of phase. Figure 4 clearly shows a reverse tilt domain appearing at the lower edge of the pixel. The width of the reverse tilt domain was measured to be $6.6\ \mu\text{m}$ (measured from the upper electrode edge to the center of the boundary wall or disclination line pair). If these two square waves were in phase, the reverse tilt domain would be reduced to zero width.

*H. Takano, IBM Japan Ltd., private communication.

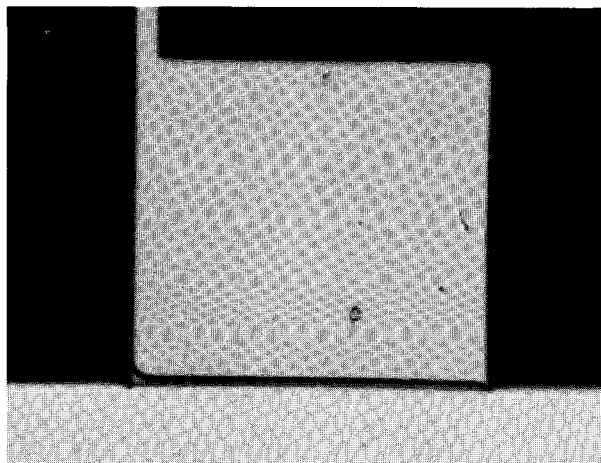


Figure 4

Micrograph of the pixel of Figure 3. A reverse tilt domain appeared at the lower edge of the pixel when a square wave of amplitude 2.6 V was applied to the pixel and another square wave of amplitude 8 V was applied to the bus line. The frequencies of both square waves were 60 Hz; they were 180° out of phase.

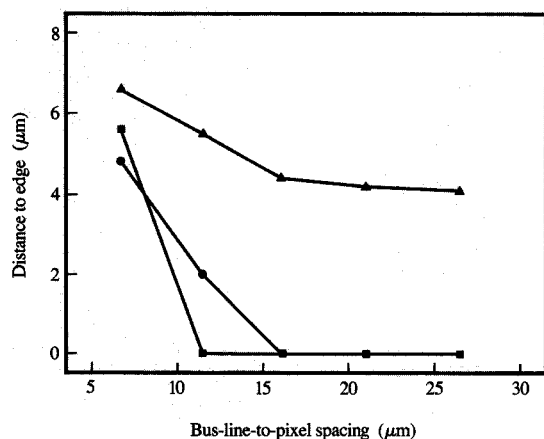


Figure 5

Experimental results of the effect of the bus-line-to-pixel spacing on the pixel reverse tilt domain for the bus line located in different orientations relative to a pixel, whose surface pretilt angle is about 1° and $V_{\text{pixel}} = \pm 2.6$ V, $V_{\text{bus}} = \pm 8$ V. Circles show the maximum appearance of the reverse tilt domain occurring at the left edge, triangles show the maximum appearance of the reverse tilt domain occurring at the lower edge, and squares show the maximum appearance of the reverse tilt domain occurring at the upper edge.

Measurements were carried out for various bus-line-to-pixel spacings and for bus lines in all the relative positions.

The data are summarized in **Figure 5**, which shows the experimental results of the effect of the bus-line-to-pixel spacing on the pixel reverse tilt domain for the bus line located in different orientations relative to a pixel, whose surface pretilt angle is about 1°. The circle curve shows the maximum appearance of the reverse tilt domain occurring at the left edge of the pixel, the triangle curve shows the maximum appearance of the reverse tilt domain occurring at the lower edge of the pixel, and the square curve shows the maximum appearance of the reverse tilt domain occurring at the upper edge of the pixel. The results given in Figure 5 indicate that if the bus-line-to-pixel spacing is less than 15 μm, the bus line begins to affect the pixel reverse tilt domain. If the spacing is less than 10 μm, the effect becomes stronger, and the reverse tilt domain appears on three edges instead of two. Figure 5 also shows that the reverse tilt domain always appears at the lower edge of a pixel, even though there is no bus line located adjacent to its lower edge.

3. Theoretical analysis

In order to analyze theoretically the pixel reverse tilt domain described in Section 2, we must first calculate the liquid crystal director orientation profile and voltage distribution inside the cell shown in Figure 2. The liquid crystal director is defined as the average long-axis direction of the liquid crystal molecules in a localized area. In principle, we must calculate the liquid crystal director orientation profile inside the cell in three dimensions. However, if we neglect the corner effect, the three-dimensional problem becomes a two-dimensional one. Thus, we calculate the liquid crystal director distribution profile along two axes. One calculation is along the H_1 axis, which is parallel to the x axis, starting from the middle of the left bus line to the middle of the right bus line, as shown in Figure 2(b). The other is along the H_2 axis, which is parallel to the y axis, starting from the middle of the top bus line to the middle of the bottom bus line, also shown in Figure 2(b). Along the H_1 axis, we can study the pixel reverse tilt domain influenced by a bus line located adjacent to the left or right edge of the pixel. Along the H_2 axis, we can study the pixel reverse tilt domain influenced by a bus line located adjacent to the top or bottom edge of the pixel. The voltage distribution and the liquid crystal director orientation profile inside the cell, along either the H_1 or the H_2 axis for a set of given cell and voltage parameters, are calculated in two steps:

1. Given a director configuration $\vec{n}(h, z)$, one calculates the corresponding voltage distribution $V(h, z)$ and electric field $\vec{E}(h, z)$ by using

$$\nabla[\epsilon(h, z)\nabla V(h, z)] = 0, \quad (1)$$

$$\vec{E}(h, z) = -\nabla V(h, z). \quad (2)$$

Here, $\epsilon(h, z)$ is the dielectric constant tensor of the liquid crystal and $h = x$ or y . The numerical method of successive over-relaxation (SOR) line by line vertically together with the Thomas algorithm [11] were used to compute the voltage distribution.

- Given $\tilde{n}(h, z)$ and $\tilde{E}(h, z)$, one calculates the new director configuration $\tilde{n}(h, z)$ by the tensor version of continuum theory [6],

$$\eta \frac{\partial n_\mu}{\partial t} - K n_\nu \nabla_\lambda \nabla_\lambda (n_\nu n_\mu) - \epsilon_0 (\epsilon_p - \epsilon_v) n_\nu E_\mu E_\nu = 0, \quad (3)$$

where η is the Leslie coefficient [12], K is the average of three Frank elasticity coefficients [3, 13], and ϵ_p and ϵ_v are the dielectric constants parallel and perpendicular to the nematic director. Equation (3) preserves the nematic symmetry, i.e., the equivalence of $\tilde{n}$ and $-\tilde{n}$. The so-called simple explicit method [11] is used for this computation.

We iterate between step 1 and step 2 until a consistent set of electric field distributions and the director deformation profile are reached.

Once the liquid crystal deformation profile along the H_1 or H_2 axis is obtained, we can easily calculate the optical transmission at various viewing angles along the H_1 or H_2 axis by the faster 4×4 matrix [14] or by the newly developed extended Jones matrix method [15].

To illustrate the above procedure and the corresponding results, a typical case with the following parameters is used: unit cell area = $100 \mu\text{m} \times 100 \mu\text{m}$ (including half of the bus line area from each side), $V_{\text{pixel}} = 2.6 \text{ V}$, $V_{\text{bus}} = -8 \text{ V}$, bus-line-to-pixel spacing = $10 \mu\text{m}$, cell gap = $5 \mu\text{m}$, and surface pretilt = 0.5° . Figure 6 shows the calculated voltage distribution along the H_2 axis. Notice that a bump appears about $10 \mu\text{m}$ in from the lower edge of the top pixel electrode. Figure 7 shows the projection of the liquid crystal director on the yz plane. The figure shows a boundary wall whose center also occurs about $10 \mu\text{m}$ in from the edge of the top pixel electrode. The optical transmission for the down viewing zone between parallel polarizers along the H_2 axis is shown in Figure 8. A transmission minimum occurs at the location of the center of the boundary wall in Figure 7. This calculated transmission minimum corresponds to the black lines illustrated in Figure 4. Results were obtained along the H_1 axis, and a reverse tilt domain was found to occur at the left edge of the pixel with a width of about $7 \mu\text{m}$.

With this technique we can now study the general trend of the effect of various cell parameters on the pixel reverse tilt domain. The results are summarized as follows:

1. *The effect of the pretilt angle on the pixel reverse tilt domain:* The result for the case of $V_{\text{pixel}} = \pm 2.6 \text{ V}$,

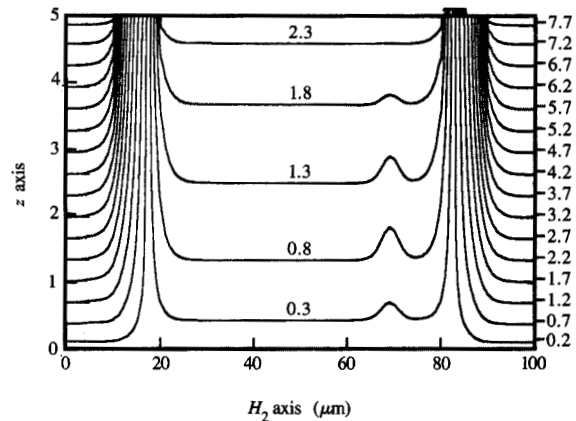


Figure 6

Calculated voltage distribution along the H_2 axis of a pixel, with $V_{\text{pixel}} = 2.6 \text{ V}$, $V_{\text{bus}} = -8 \text{ V}$, cell gap = $5 \mu\text{m}$, bus-line-to-pixel spacing = $10 \mu\text{m}$, and surface pretilt angle = 0.5° .

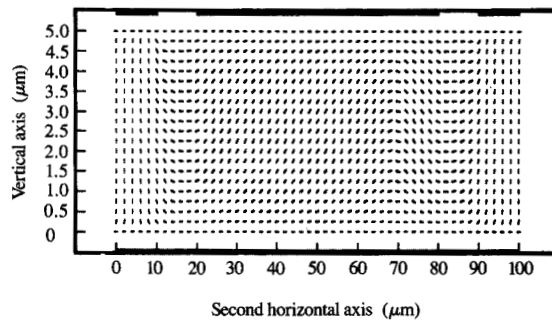


Figure 7

Calculated projection of the liquid crystal director on the yz plane along the H_2 axis of a pixel, with $V_{\text{pixel}} = 2.6 \text{ V}$, $V_{\text{bus}} = -8 \text{ V}$, cell gap = $5 \mu\text{m}$, bus-line-to-pixel spacing = $10 \mu\text{m}$, and surface pretilt angle = 0.5° .

$V_{\text{bus}} = \pm 8 \text{ V}$, cell gap of $5 \mu\text{m}$, and bus-line-to-pixel spacing of $10 \mu\text{m}$ is shown in Figure 9. The symbols are defined as in Figure 5. Notice that the example we have just discussed corresponds to the two leftmost points in Figure 9. From this figure, we see that a pretilt angle as high as 3° is required to reduce the reverse tilt domain to an acceptable level. The 3° pretilt angle is achievable

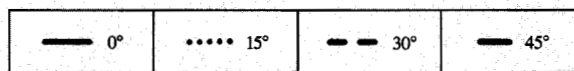
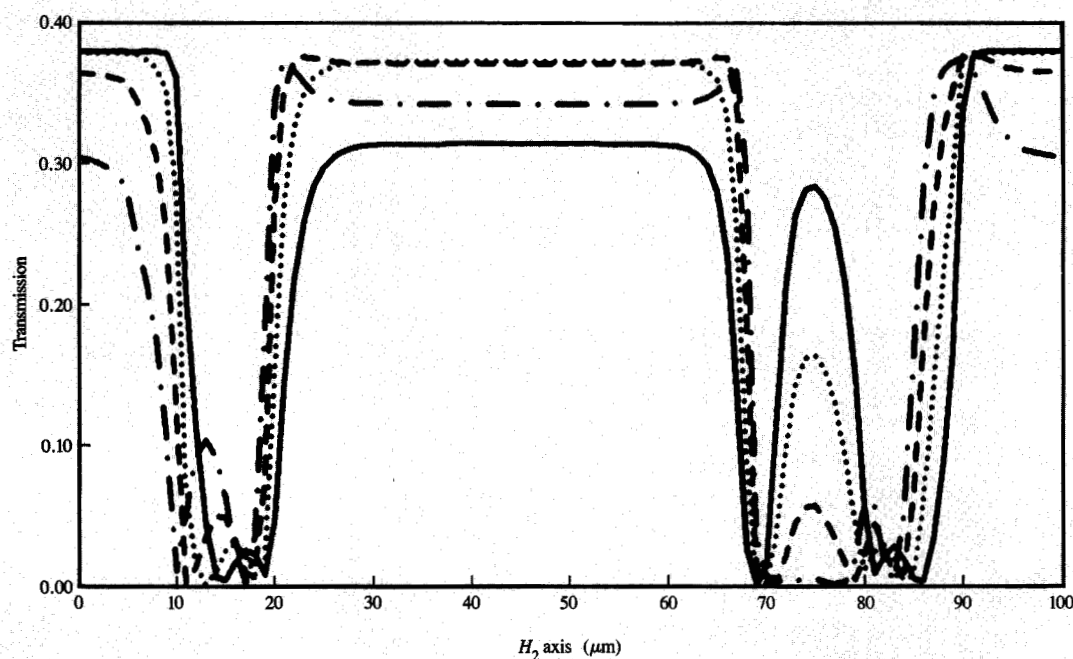


Figure 8

Calculated optical transmission for several directions in the down viewing zone between the parallel polarizers along the H_2 axis of a pixel, with $V_{\text{pixel}} = 2.6$ V, $V_{\text{bus}} = -8$ V, cell gap = $5 \mu\text{m}$, bus-line-to-pixel spacing = $10 \mu\text{m}$, and surface pretilt angle = 0.5° .

by selecting appropriate commercially available polyamide for alignment material.

2. *The effect of the bus-line-to-pixel spacing on the pixel reverse tilt domain:* Figure 10 shows the result for the case of $V_{\text{pixel}} = \pm 2.6$ V, $V_{\text{bus}} = \pm 8$ V, cell gap of $5 \mu\text{m}$, pretilt angle of 1° , and bus-line-to-pixel spacing ranging from 5 – $25 \mu\text{m}$. The symbols are defined as in Figure 5. It clearly shows that if the bus-line-to-pixel spacing is smaller than $15 \mu\text{m}$, the bus line begins to affect the pixel reverse tilt domain. If the spacing is smaller than $10 \mu\text{m}$, the reverse tilt domain occurs at three edges (left, down, and up), instead of two edges (left and down). This result agrees reasonably well with the experimental result given in Figure 5. Most of the theoretical predictions for the width of the reverse domain are larger than the measured ones. The major discrepancy may be caused by the uncertainty of the

pretilt angle measurement ($\pm 0.5^\circ$). Furthermore, our test cell may have a pretilt angle slightly less than 1° .

3. *The effect of the cell gap thickness on the pixel reverse tilt domain:* The result for the case of $V_{\text{pixel}} = \pm 2.6$ V, $V_{\text{bus}} = \pm 8$ V, pretilt angle of 1° , and bus-line-to-pixel spacing of $5 \mu\text{m}$ is shown in Figure 11. The symbols are defined as in Figure 5. The results show that the reverse tilt domain becomes smaller as the cell gap thickness gets smaller. This is another advantage of the small cell gap (typically 4 to $6 \mu\text{m}$) over the large cell gap (typically 8 to $10 \mu\text{m}$) in addition to its wider viewing angle.

4. Conclusions

We have studied the pixel reverse tilt domain both experimentally and theoretically. The theoretical results agreed reasonably well with the experimental data. We

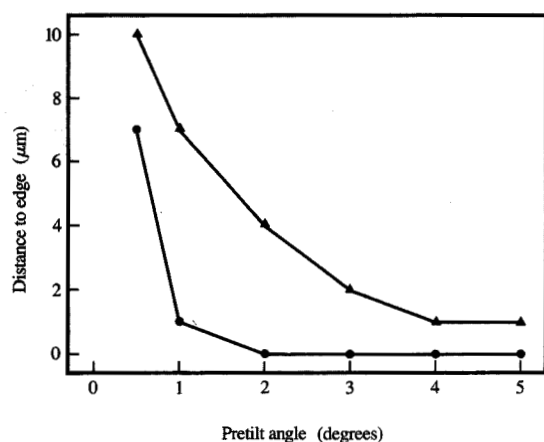


Figure 9

Calculated locations of the maximum appearance of the reverse tilt domain as a function of the pretilt angle for the cell, with $V_{\text{pixel}} = \pm 2.6$ V, $V_{\text{bus}} = \pm 8$ V, cell gap = $5 \mu\text{m}$, and bus-line-to-pixel spacing = $10 \mu\text{m}$. The symbols are defined as in Figure 5.

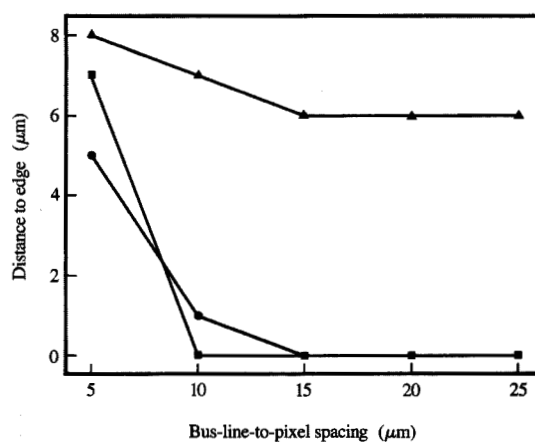


Figure 10

Calculated locations of the maximum appearance of the reverse tilt domain as a function of the bus-line-to-pixel spacing for the cell, with $V_{\text{pixel}} = \pm 2.6$ V, $V_{\text{bus}} = \pm 8$ V, cell gap = $5 \mu\text{m}$, and surface pretilt angle = 1° . The symbols are defined as in Figure 5.

also obtained general trends for the effects of various cell parameters on this domain. The results help us to understand the pixel reverse tilt domain occurring in the TFT/LCDs, and to reduce or eliminate it.

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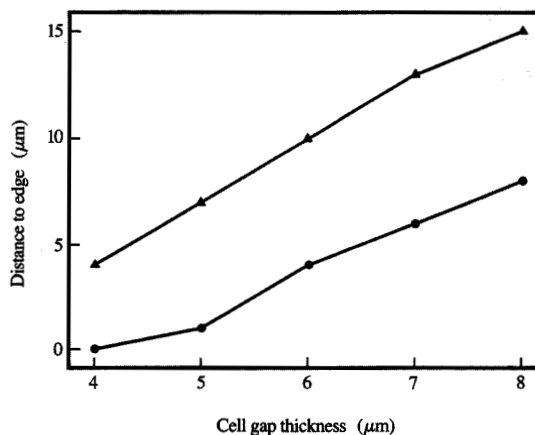


Figure 11

Calculated locations of the maximum appearance of the reverse tilt domain as a function of the cell gap thickness for the cell, with $V_{\text{pixel}} = \pm 2.6$ V, $V_{\text{bus}} = \pm 8$ V, surface pretilt angle = 1° , and bus-line-to-pixel spacing = $10 \mu\text{m}$. The symbols are defined as in Figure 5.

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Shui-Chih Alan Lien IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598 (SALIEN at YKTVMZ). Dr. Lien received the B.S. degree in physics from National Taiwan Normal University, Taipei, Taiwan, in 1977, and the M.S. degree in electrical engineering and the Ph.D. degree in physics from the University of Minnesota, Minneapolis, in 1984. From 1984 to 1987, he worked at Optical Imaging Systems, Inc., Troy, Michigan. He was involved in the development of large-area active-matrix liquid crystal displays. In 1987, Dr. Lien joined the IBM Thomas J. Watson Research Center, where he is currently an advisory engineer in the display group. His research interest is in liquid crystal display physics and technology.

Richard A. John IBM Research Division, Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598 (JOHNR at YKTVMV). Mr. John received an Associate degree in electronics technology from the RCA Institute, New York, in 1967. He joined the Research Division that same year, and is currently a senior laboratory specialist in the I/O Technology Department. Mr. John has worked in a variety of areas, including gas-panel displays, LED printing, high-resolution thermal printing, and color electrophotographic printing. He is currently involved with the design and processing of liquid crystal displays.

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