Cell design of gray-scale thin-film-transistor-driven liquid crystal displays

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The desirable liquid crystal (LC) panel design (here called "cell design") for a gray-scale thin-film-transistor (TFT) -driven twisted nematic (TN) liquid crystal display (LCD) is discussed in terms of display legibility and ease of fabrication. To optimize cell design for gray-scale application, some key display factors such as contrast ratio, color change, and viewing cone are evaluated for various cell geometries and cell thicknesses. The cell geometries discussed are combinations of two display modes (a normally white mode and a normally black mode, in which the optical axes of the exit polarizers are placed perpendicular and parallel to those of the entrance polarizers, respectively) and two optical eigenmodes (an extraordinary-ray mode and an ordinary-ray mode, in which the transmission axes of the entrance polarizers are parallel and perpendicular to the entrance rubbing directions, respectively). A new driving scheme of threshold-voltage bias application to the LC cell is proposed to overcome the TN LCD shortcoming of a narrow viewing cone. We have adopted a cell design for a 512-color TFT LCD: 1) a first minimum normally white (NW) mode as polarizer arrangement for ease of fabrication, 2) an extraordinary-ray mode (e-mode) as optical eigenmode with a novel driving scheme (threshold-voltage biased) for gray-scale improvement in eliminating brightness reversals, and 3) a retardation ($d\Delta n$) value of 0.47 μm for further optimization of proper gray-scale order and color change. We have called this mode "threshold-voltage-biased e-mode NW," or "biased e-mode NW."

Introduction

Recently, a large-area, high-information-content twisted nematic (TN) liquid crystal display (LCD) driven by an array of thin-film transistors (TFTs) has been developed [1–3]. There are several modes of operation in LCDs, such as twisted nematic (TN) [4], super-twisted nematic (STN) [5], super-homeotropic (SH) [6], electrically controlled

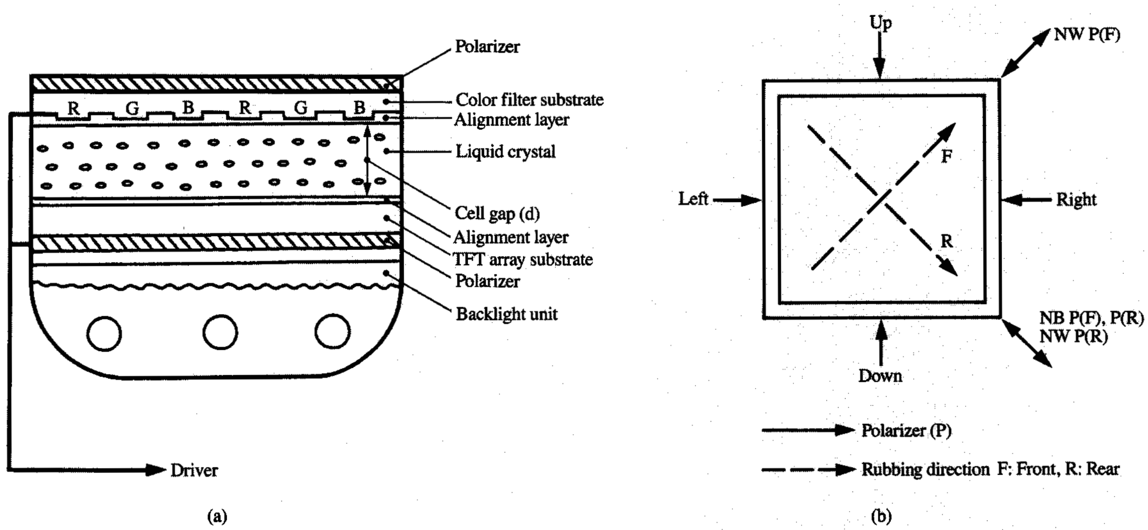

Figure 1

Typical sandwiched structure of a TFT-driven color LCD: (a) Cross section; (b) plan view.

birefringence (ECB) [7], guest–host (GH) [8], and ferroelectric liquid crystal (FLC) [9]. Among them, a 90° TN is widely used in commercial products, especially for a TFT-driven LCD, because of its low threshold voltage, quick response time, and analog-gray-scale capability. From its optimum viewing direction, a high-resolution TFT-driven TN LCD is as legible as the cathode-ray tube (CRT) display. However, it still has the shortcoming of a narrow viewing cone.

A color TFT LCD panel is a sandwiched structure, as shown in **Figure 1**, which is composed of backlight, driving circuits, entrance and exit polarizers, color-filter and TFT array substrates, entrance and exit alignment layers, and liquid crystal mixture. Figure 1 also shows the arrangement of polarizers and rubbing directions with the definition of viewing direction.

It is well known that there are two display modes in a 90° TN LCD [4], normally white (NW) and normally black (NB), in which the optical axes of the exit polarizers are placed, respectively, perpendicular and parallel to those of the entrance polarizers, as shown in Figure 1. In both the NW and NB modes, there are two optical eigenmodes, an extraordinary-ray mode (e-mode) and an ordinary-ray mode (o-mode), in which the transmission axes of the entrance polarizers are respectively parallel and perpendicular to the entrance rubbing directions. Figure 1 shows the e-mode configuration of polarizers and rubbing directions.

This paper reviews optimization processes for cell design. **Figure 2** shows a 90° TN cell design factor for a gray-scale TFT LCD. It is important to optimize the key design factors with respect to fabrication and display quality, which is directly related to front-of-screen (FOS) quality. We have taken the following steps for optimization:

1. Display mode (NW, NB) selection with optimization of the retardation $d\Delta n$ (d is the cell thickness, Δn is the optical anisotropy, $n_e - n_o$, where n_e and n_o are refractive indices for extraordinary-ray and ordinary-ray, respectively).
2. Optical eigenmode (e-mode, o-mode) selection.
3. Implementation of a threshold-voltage-biased driving scheme proposal.
4. Further tuning of $d\Delta n$.

Display mode selection with $d\Delta n$ optimization

The opto-electrical characteristics of a 90° TN cell with parallel and crossed polarizers have been precisely studied and evaluated in order to optimize the legibility (contrast ratio, background color, etc.) of TFT LCDs. Optical transmission expressions [10, 11] have generally been used for the optimization of conventional 90° TN LCDs. Optimization of the contrast ratio in the normal direction for the NB and NW modes has been carried out experimentally and compared to the theoretical calculation

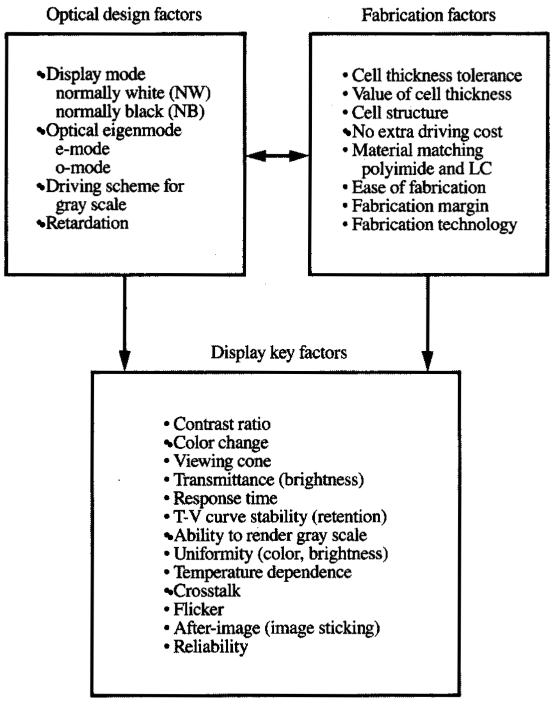

Figure 2

A 90° TN cell design concept for gray-scale TFT LCD.

as a function of retardation ($d\Delta n$) [12]. The contrast ratio (CR) as a function of $d\Delta n$ for the NB and NW cases is plotted in **Figures 3** and **4**. For the NB case, maximum contrast ratios occur at the values of $d\Delta n$ = 0.5–0.55 μm, 1.1–1.2 μm, and 1.6–1.7 μm, which are defined respectively as the first, second, and third minimum. A theoretical calculation also shows that the maximum contrast ratios occur at the values of $d\Delta n$ = 0.49 μm, 1.09 μm, and 1.67 μm [12]. The contrast ratio depends strongly on $d\Delta n$ for the NB case. For the NW case, the maximum contrast ratio appears at around $d\Delta n$ = 0.45 μm, as is indicated by the scattered data. A theoretical calculation shows that there is only one clear maximum contrast ratio at around $d\Delta n$ = 0.47 μm with relatively broad peak.

The background color of a TN LCD is one of the important issues of LCD design, especially as the panel size becomes larger and the information content increases [13]. The display background color changes drastically even for a small change in $d\Delta n$, e.g. 0.05 μm, for the NB mode case. In contrast, the background color does not change much for the NW case.

The viewing-angle dependences of the contrast ratio (CR) at the first, second, and third minimum are shown in **Figure 5** for the left–right and the up–down directions, respectively. **Figures 6** and **7** show the dependence of the contrast ratio on $d\Delta n$ around the first minimum ($d\Delta n$ = 0.43–0.72 μm) for the NB and NW modes. The NB mode at $d\Delta n$ = 0.5–0.55 μm has the widest viewing cone. However, it requires a severe cell thickness control ($\pm$0.1 μm) because the contrast ratio depends strongly on $d\Delta n$. On the contrary, NW mode has a large cell-thickness tolerance because the CR does not depend strongly on $d\Delta n$. The NW mode has a wide viewing cone at around $d\Delta n$ = 0.45 μm. However, the NW mode has a very poor contrast ratio in the up direction. **Figure 8** shows the color change of several $d\Delta n$ ranges in the NB mode. While the background color changes drastically in the NB mode at low values of $d\Delta n$, it becomes stable where $d\Delta n$ is larger than 1.5 μm. The NW mode has a stable background color and exhibits a slight coloration at oblique viewing angles. The experimental results on viewing-angle dependences are summarized in **Table 1**.

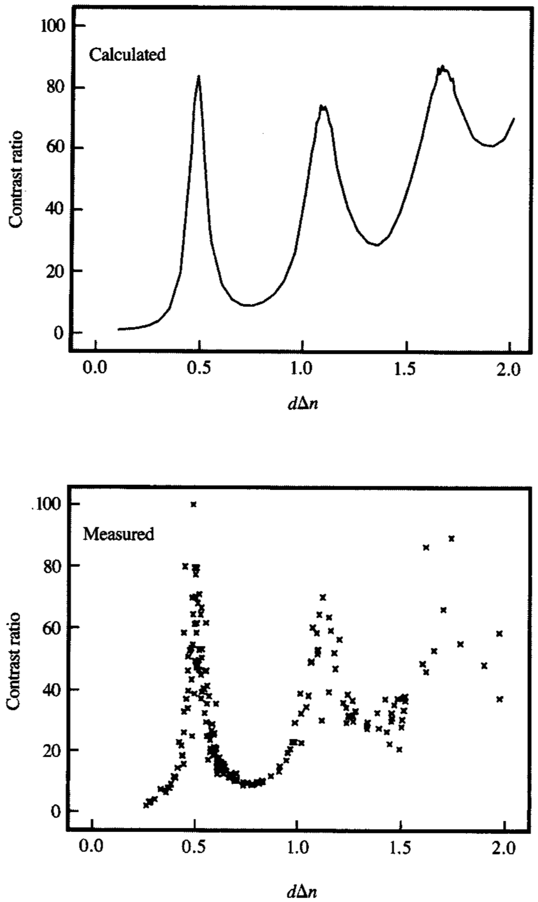

Figure 3

Experimental and theoretical contrast ratio vs. $d\Delta n$ (NB case).

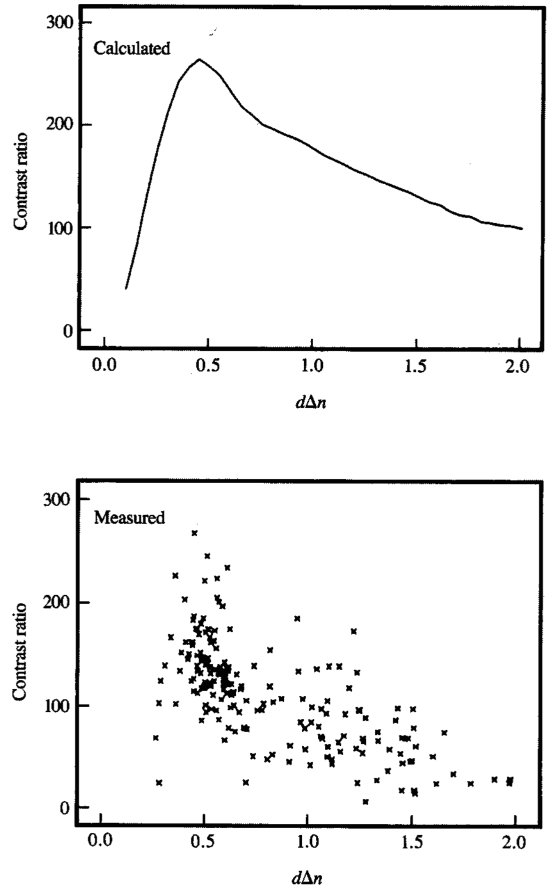

Figure 4

Experimental and theoretical contrast ratio vs. $d\Delta n$ (NW case).

Taking those experimental results into account, we decided to take a two-step approach to fabricate the large-sized TFT LCD. At first, we adopted the NB mode of $d\Delta n = 1.5$ μm because of ease of fabrication, small color change at oblique viewing angles, and large tolerance on cell thickness [1]. In the next step, we progressed to the first minimum NW cell to obtain fast response time (small cell thickness), high contrast ratio, small color change, and large cell-thickness tolerance compared with the first minimum NB case. For the first minimum NW mode, a response time of less than 20 ms (cell thickness d = 4.8÷5.7 μm) has been obtained and is fast enough for video displays. This section is a discussion of our results based on a bilevel (binary) driving scheme. The optimization of the first minimum NW mode for gray-scale application is the subject of the following sections.

First minimum e-mode NW vs. first minimum o-mode NW

The geometries of the e-mode NW and the o-mode NW are illustrated in **Figure 9**. We have investigated the optical performances of two optical eigenmodes of both the NW and the NB LCDs for an analog-gray-scale application. We have found symmetries in the optical properties between the e-mode NB and the o-mode NB by an argument based on the time-reversal transformation. The optical properties of the e-mode and the o-mode were basically different for the NW case [14, 15].

We have compared the optical performances of two eigenmodes for analog-gray-scale application [16]. Transmittances of white, red, green, and blue colors have been measured as a function of viewing angle for 10.4-in.-diagonal TFT-driven 90° TN LCDs, with $d\Delta n$ of 0.44 μm.

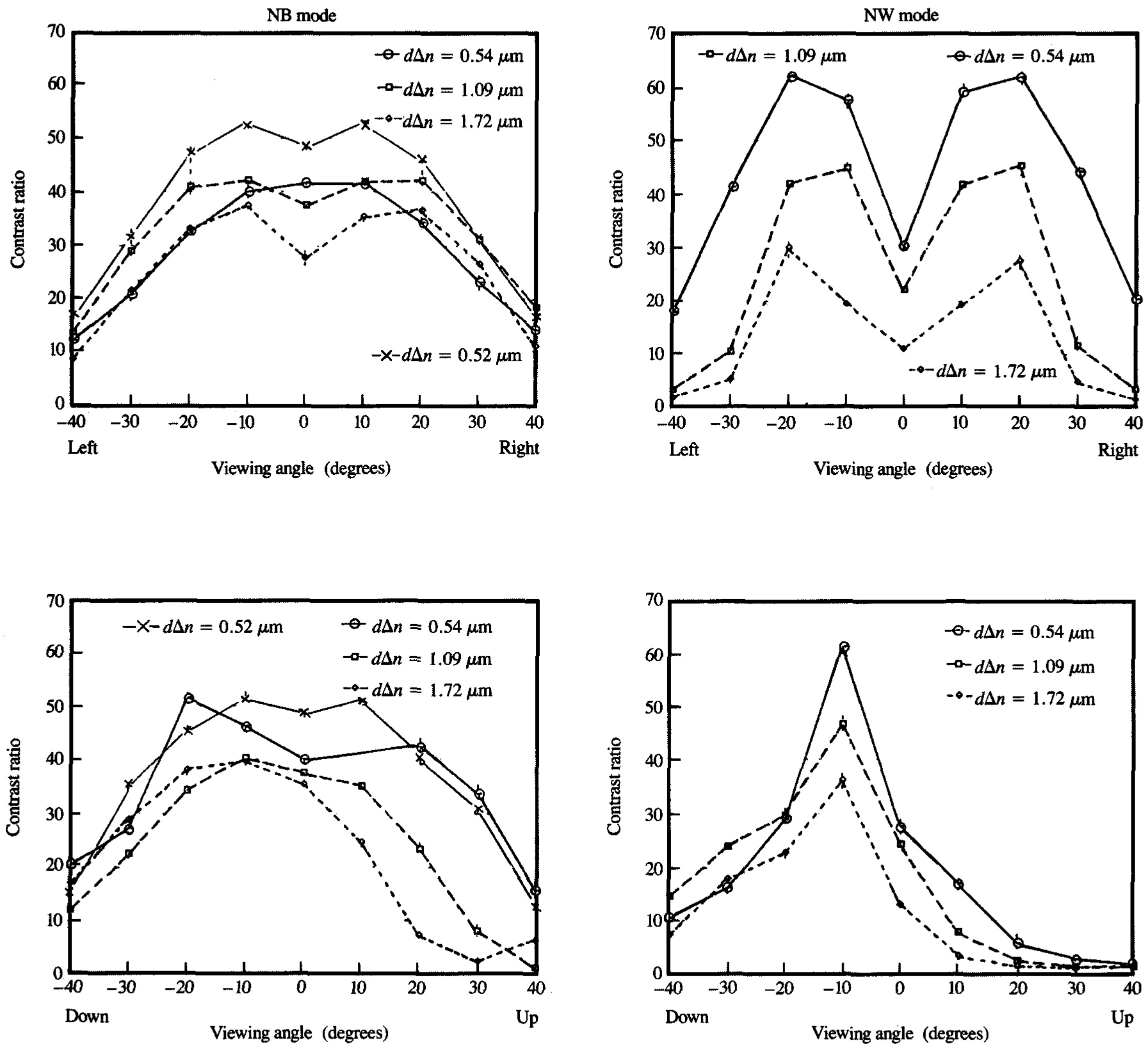

Figure 5

Viewing-angle dependences of contrast ratio in NB and NW mode.

Gray-scale transmissions, gray-scale contrast ratios, and gray-scale chromaticities are compared as a function of viewing angles between the e-mode NW and the o-mode NW.

Viewing-angle dependences of eight levels of brightness (gray scale) are shown in **Figure 10**, where applied voltages for a gray-level 7 [GL(7), the brightest level] and a gray-level 0 [GL(0), the darkest level] are 0 V_{RMS} and 5 V_{RMS}, respectively. Six intermediate gray levels between the GL(7) and the GL(0) are determined to provide appropriate gray scale for human eyes. The viewing-angle dependences of gray-scale contrast ratios [GL(n)/GL(0)], the chromaticity of GL(7) for white, and the chromaticity of GL(7) for the three primary colors are shown in **Figures 11, 12,** and **13,** respectively. Gray-level dependences of the three primary colors at horizontal +30 degrees and vertical +20 and −20 degrees are shown in **Figure 14.** On the upper sides of each chart in Figures 10 and 11, the symbol ● indicates the region in which the proper gray-scale order is preserved.

The results of the comparison between the e-mode and the o-mode optical performances are summarized in **Table 2.** The box, circle, triangle, and cross symbols indicate performance that is very preferable, preferable, fair, and

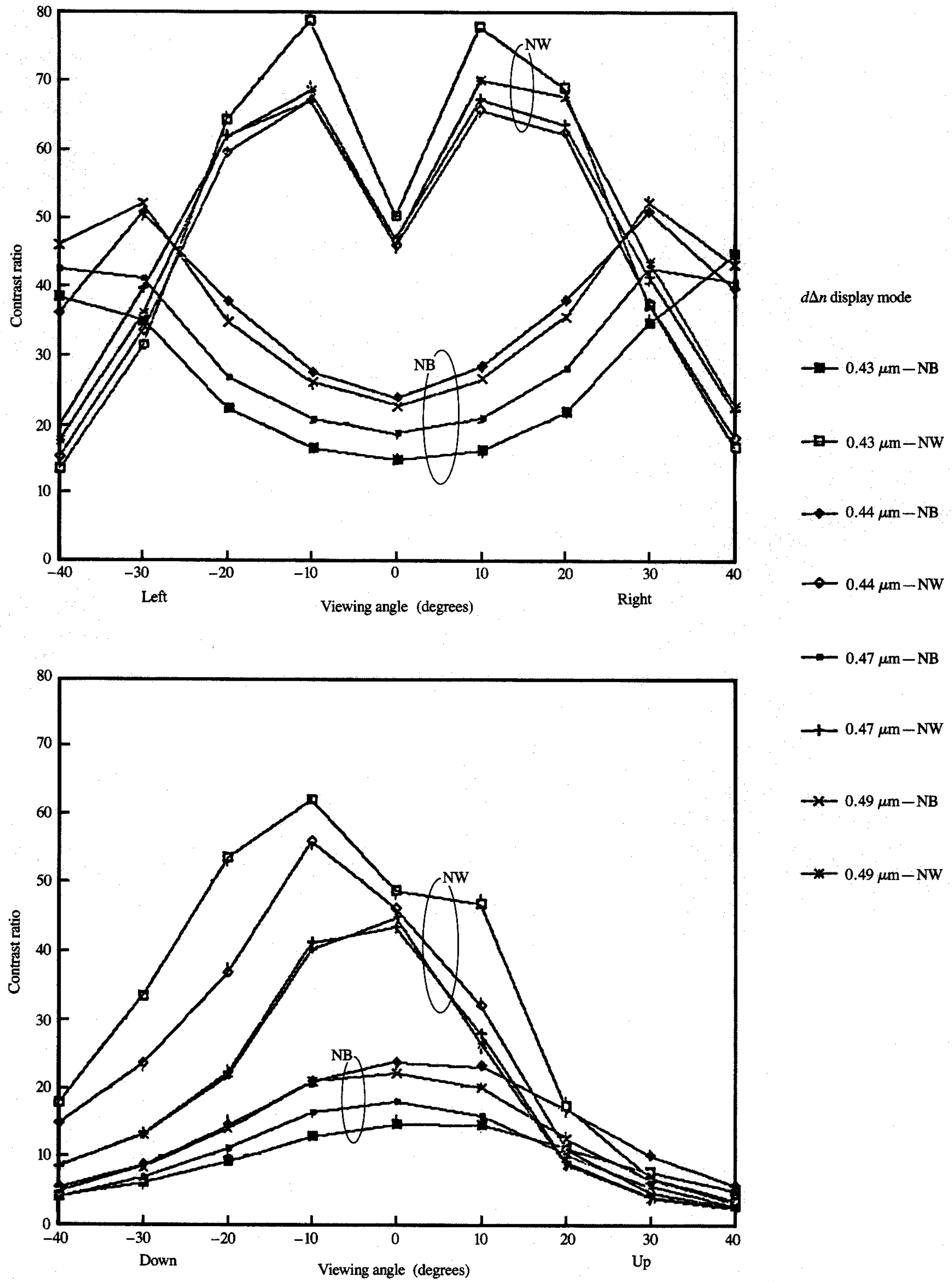

Figure 6

Viewing-angle dependences of contrast ratio ($d\Delta n = 0.43 - 0.49\ \mu m$).

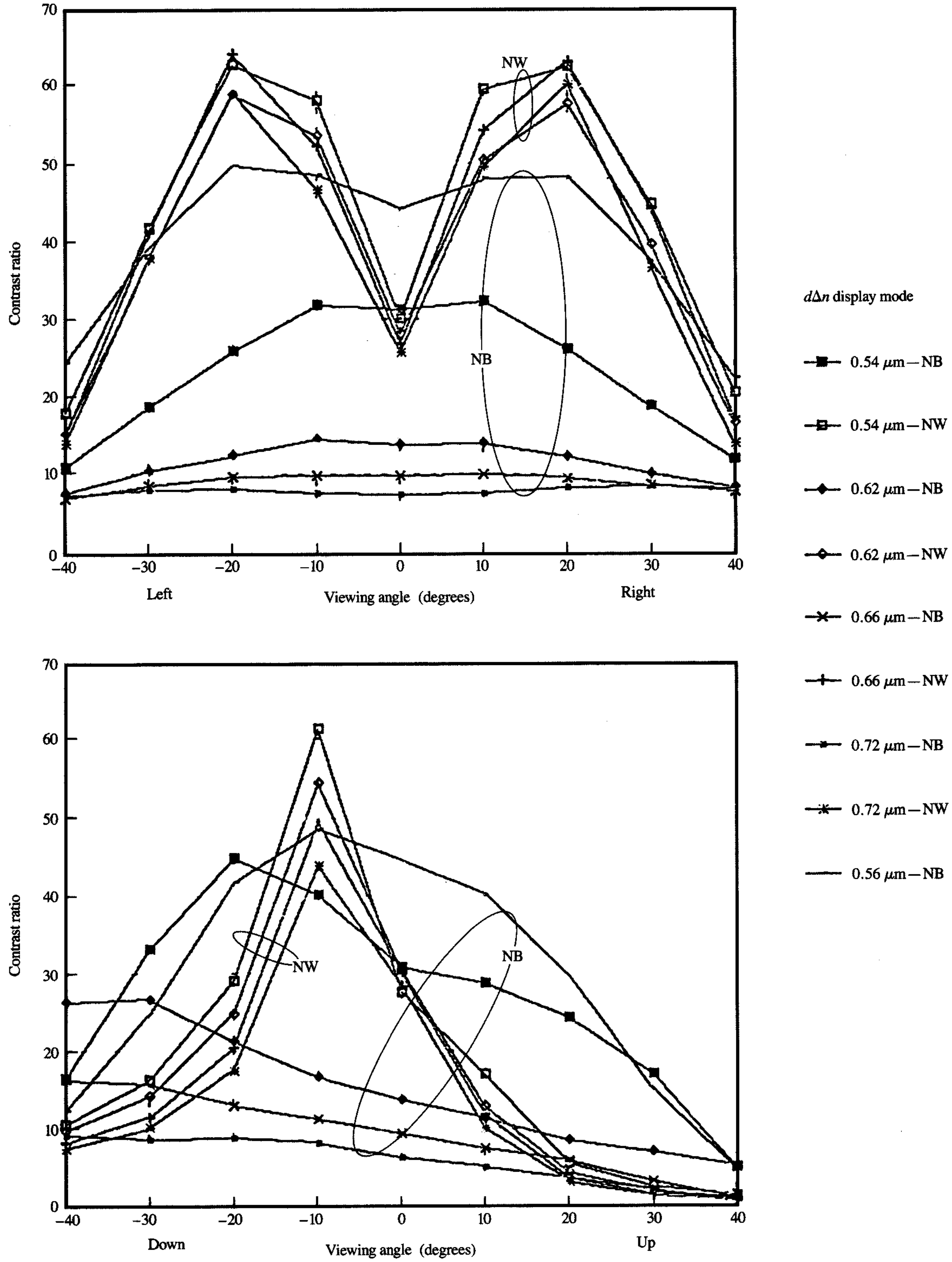

Figure 7

Viewing-angle dependences of contrast ratio ($d\Delta n = 0.54 - 0.72$ μm).

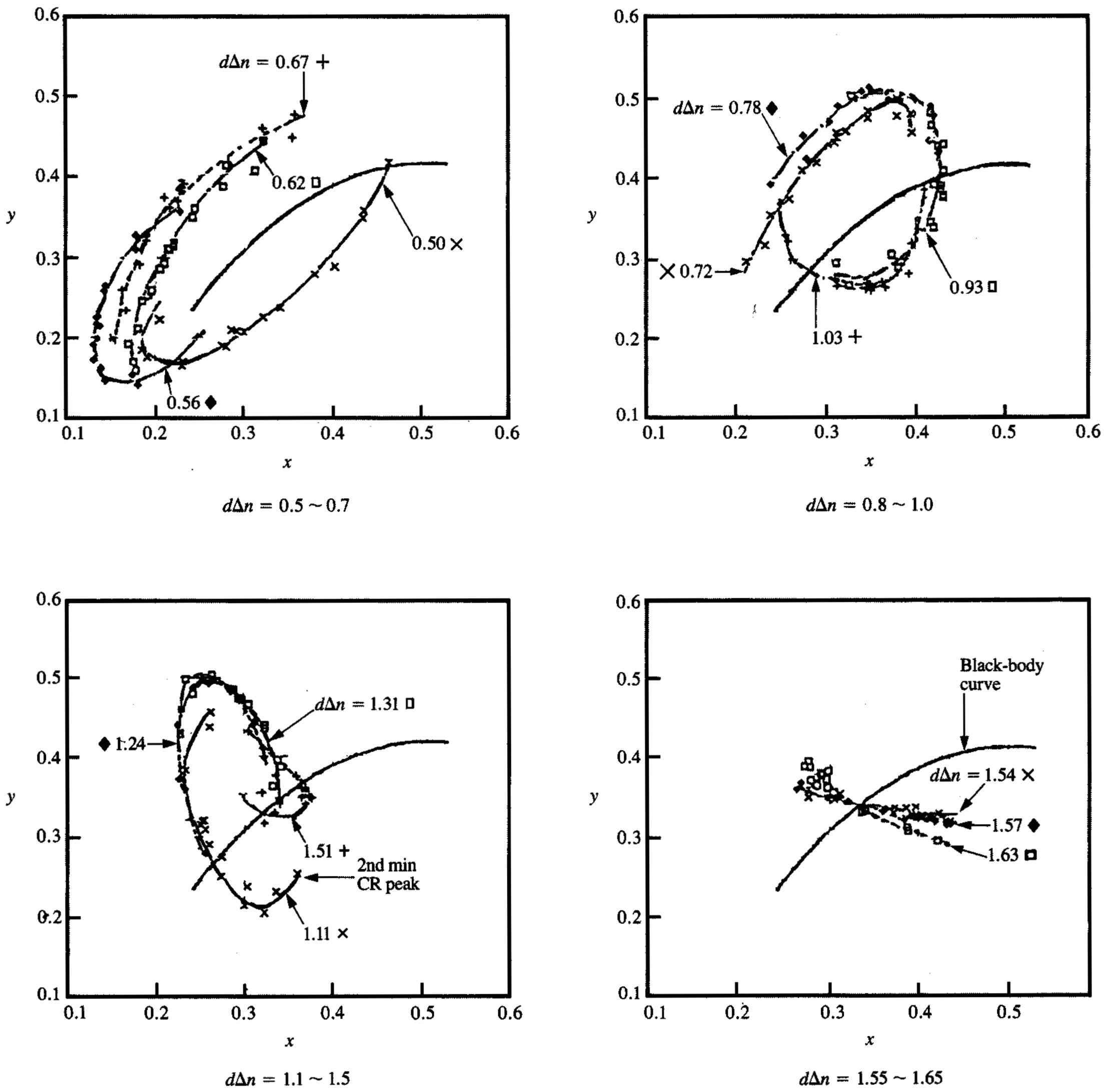

Figure 8

Viewing-angle dependences of chromaticity for different $d\Delta n$ (NB case).

not preferable, respectively. Horizontally, the e-mode optical performance is much superior to the o-mode one. In the down viewing zone, the optical performance of the o-mode is equal to or better than that of the e-mode. On the other hand, in the up viewing zone, the e-mode optical performance is generally better, except for the angular dependence of GL(7), where brightness inversion occurs.

For the vertical direction, the region of proper gray-scale order is wider in the up viewing zone than in the down viewing zone for both the e-mode and the o-mode NW. The up viewing direction is preferred for gray-scale applications [17]. It is worth mentioning that in this commonly used direction, the optical performance of the e-mode NW is preferred, especially for color (R, G, B) legibility and proper gray-scale order, except for GL(7). This is quite opposite to the binary application. In the binary application there are only two brightness levels, a bright level [GL(7)] and a dark level (GL(0)]. From Figure 11, the binary (bilevel) contrast ratio GL(7)/GL(0) is much better in the down viewing zone than in the up viewing zone for

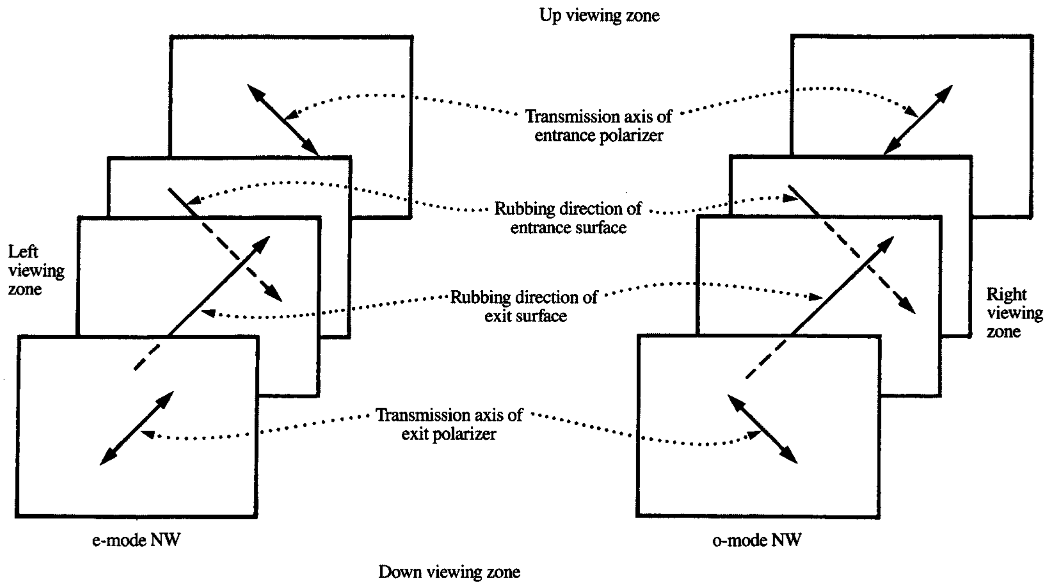

Figure 9

Geometries of the e-mode and the o-mode NW and four viewing zones.

Table 1 Summary of viewing-angle dependences for the NB and NW modes.

Mode	*Item*	*First minimum*	*Second minimum*	*Third minimum*
NB mode	Viewing cone CR > 20:1	Wide ($d\Delta n$ = 0.55) L=40°, R = 40°, U = 25°, D = 35° ($d\Delta n$ = 0.55) max CR = 50	Fair L = 35°, R = 35°, U = 20°, D = 25° ($d\Delta n$ = 1.1) max CR = 40	Narrow (poor Up) L = 30°, R = 30°, U = 10°, D = 20° ($d\Delta n$ = 1.7) max CR = 35
	$d\Delta n$ tolerance	Small	Fair	Large
	Color change	Large (blue-violet)	Fair (green, red-violet)	Relatively small (red-violet, dark green)
NW mode	Viewing cone CR > 20:1	Narrow (poor Up) L = 35°, R = 35°, U = 15°, D = 35° ($d\Delta n$ = 0.43) max CR = 80	Narrow (poor Up) L = 25°, R = 25°, U = 3°, D = 30° ($d\Delta n$ = 1.1) max CR = 40	Narrow (very poor Up) L = 25°, R = 25°, U = 3°, D = 35° ($d\Delta n$ = 1.7) CR > 10
	$d\Delta n$ tolerance	Large	Large	Large
	Color change	Small	Small	Small

both the e-mode and the o-mode NW. Thus, for the binary application, we must use the down direction as the preferred one. In this direction, the o-mode NW is preferable, especially for contrast ratio and GL(7) color stability.

Overall, in practical viewing zones, the optical performance of the e-mode NW is superior to that of the o-mode NW. The remaining problems of the e-mode NW are brightness reversals in the up viewing zone and white

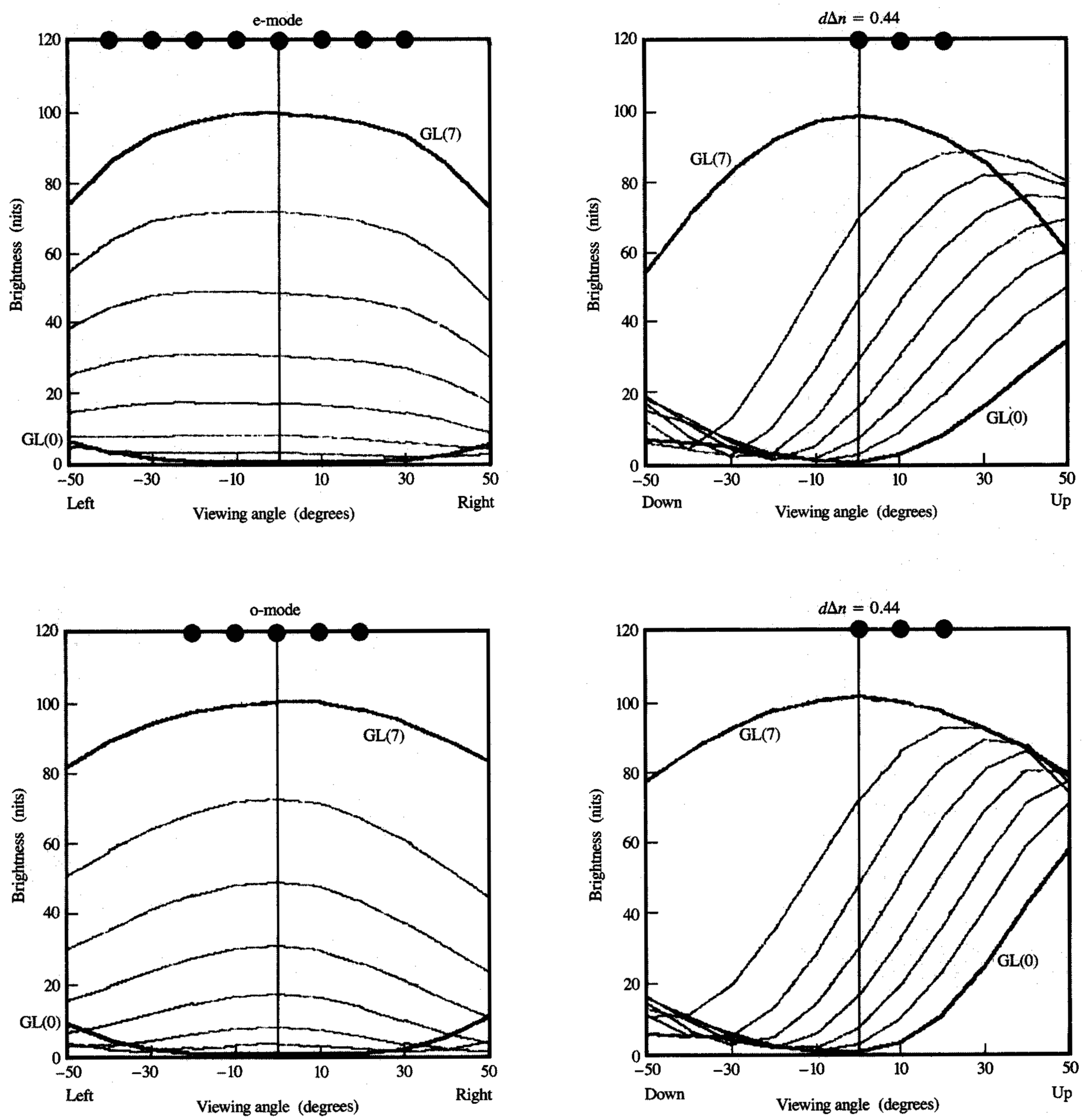

Figure 10

Viewing-angle dependences of the brightness of eight levels of gray scale (1 nit = 1 cd/m^2).

color change as a function of viewing angle. The resolution of these problems will be discussed in the following sections.

Threshold-voltage-biased E-mode NW

Figure 15 shows transmission-voltage (T-V) curves of the e-mode and the o-mode in the up viewing zones. In comparison to the o-mode T-V curves, the e-mode T-V curves offer the following features:

1. Below the threshold voltage (about 2 V), transmittance in the normal direction does not change with applied voltage; above the threshold voltage, it shows a monotonic decrease with increasing applied voltage.

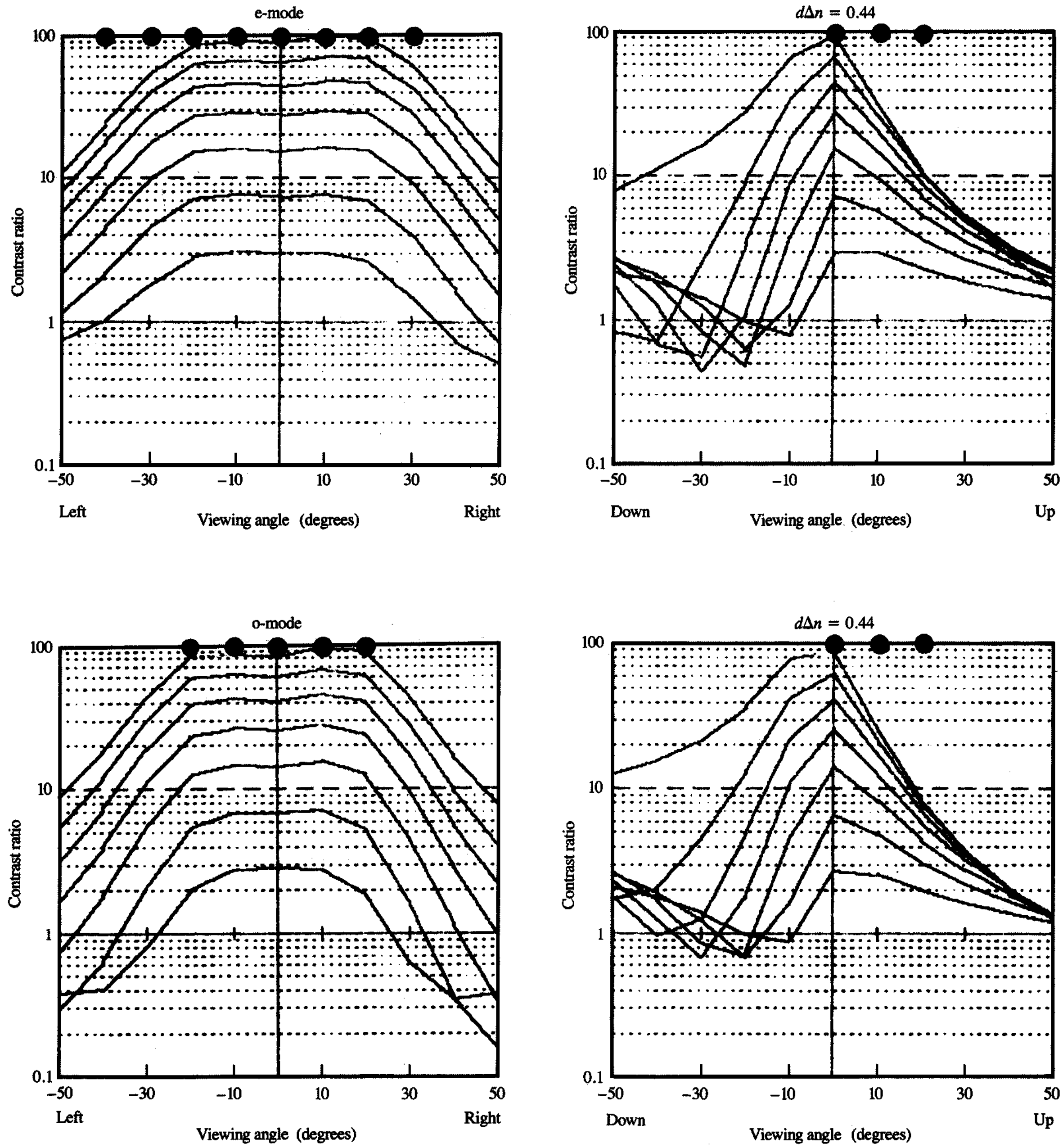

Figure 11

Viewing-angle dependences of gray-scale contrast ratios [GL(n)/GL(0)].

2. Each T-V curve shows maximum brightness at around 2 V, which is the threshold voltage of the T-V curve from the normal direction.
3. Each T-V curve shows a monotonic decrease in transmission with increasing applied voltage greater than the threshold voltage of the normal direction.

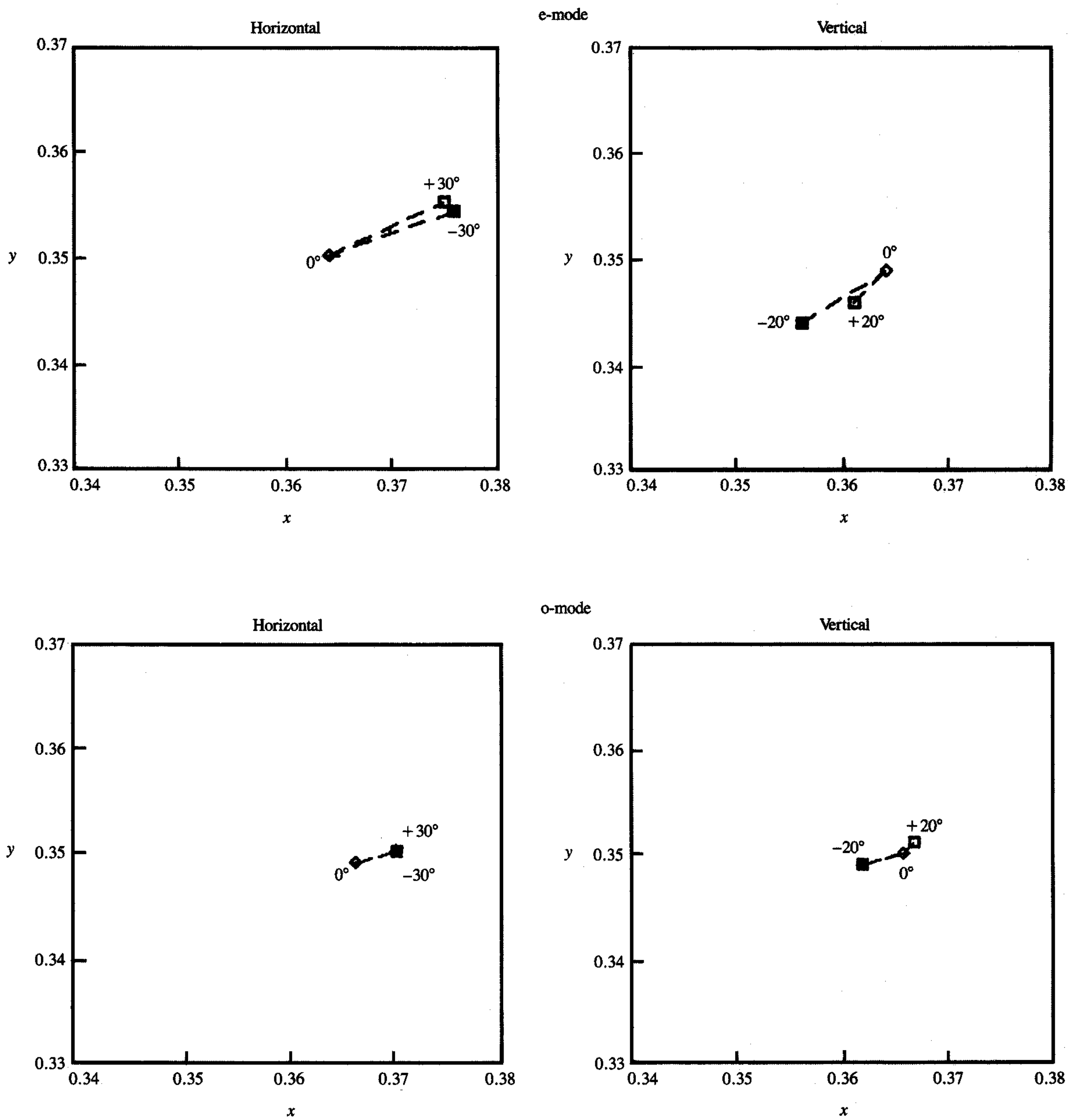

Figure 12

Viewing-angle dependences of the chromaticity of GL(7) for white.

Therefore, if we adopt the threshold voltage of the normal direction as a bias voltage for the GL(7), we can expect the following advantages:

1. Improvement in the range of viewing angles of the GL(7) in the up viewing zone.
2. A monotonic decrease of the transmission, not only in the normal direction but also from any viewing angle. As long as the brightness shows a monotonic change, the brightness reversal does not occur.

Figure 16 shows an angular dependence of the eight-gray-

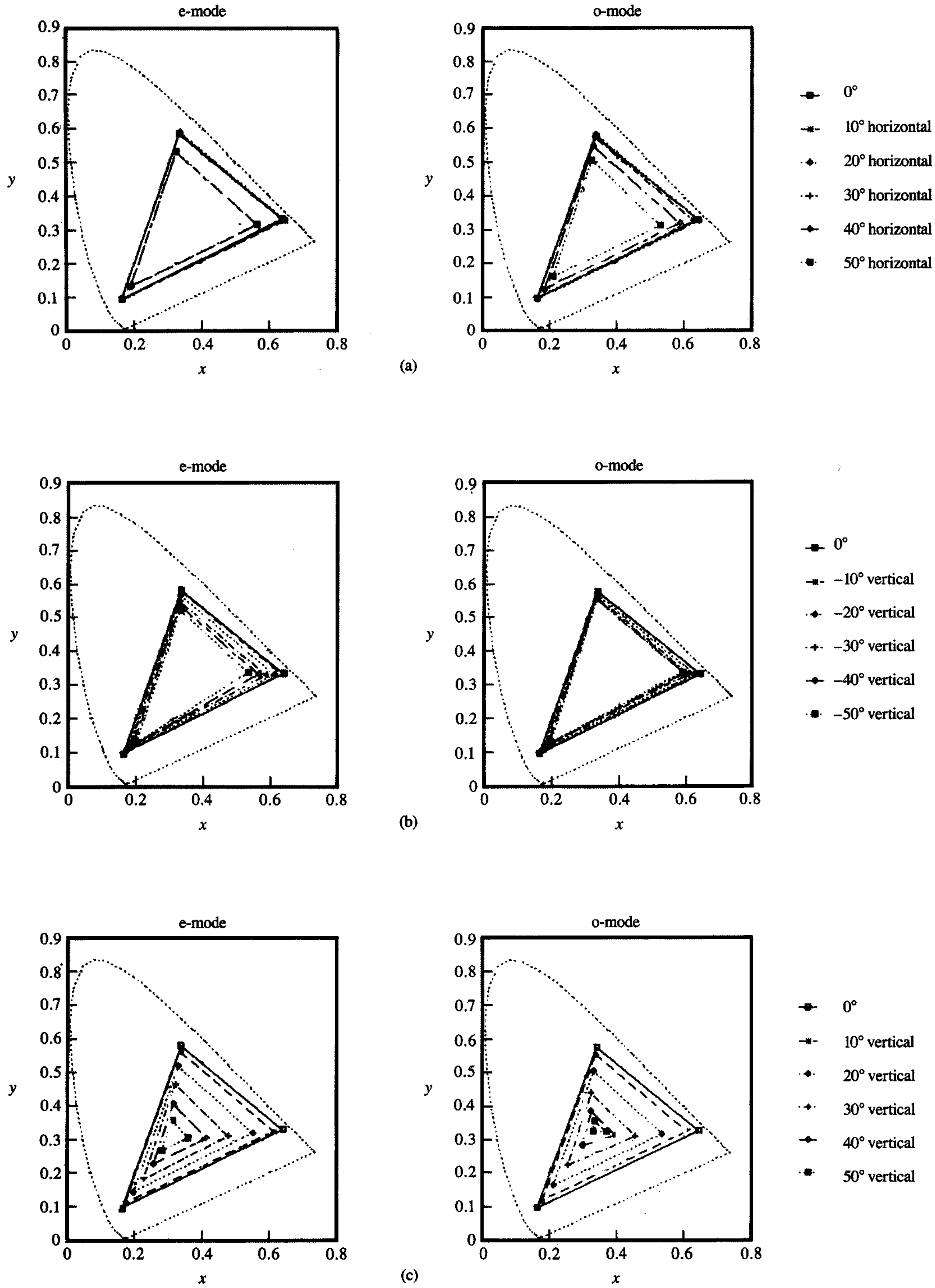

Figure 13

Viewing-angle dependences of the chromaticity of GL(7) for the three primary colors for the e-mode and the o-mode, viewed (a) in the horizontal direction; (b) in the down direction; and (c) in the up direction.

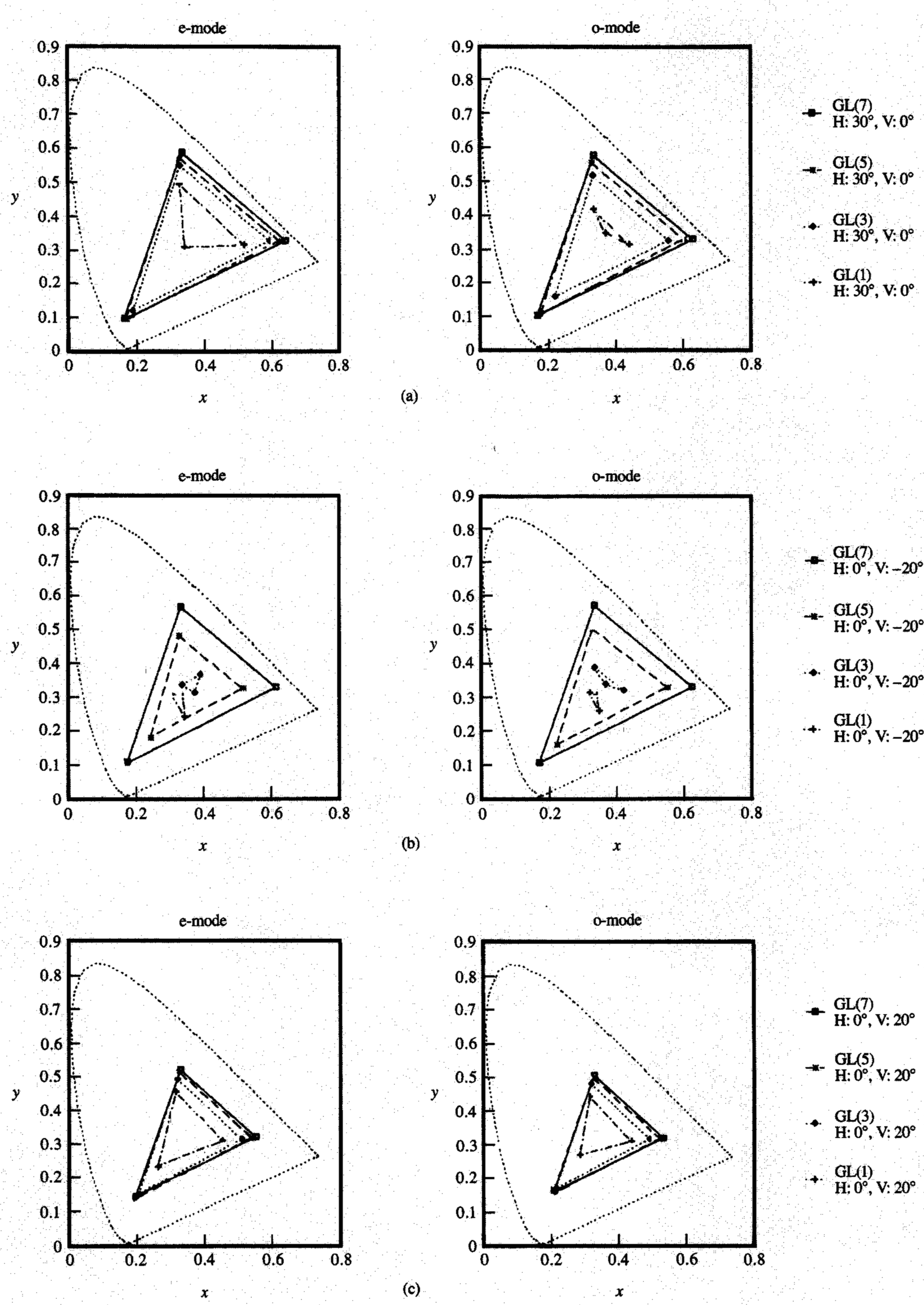

Figure 14

Gray-level dependences of the chromaticities of the three primary colors for the e-mode and the o-mode, viewed (a) at a vertical angle of 0° and a horizontal angle of 30°; (b) at a horizontal angle of 0° and a vertical angle of 20° downward; and (c) at a horizontal angle of 0° and a vertical angle of 20° upward.

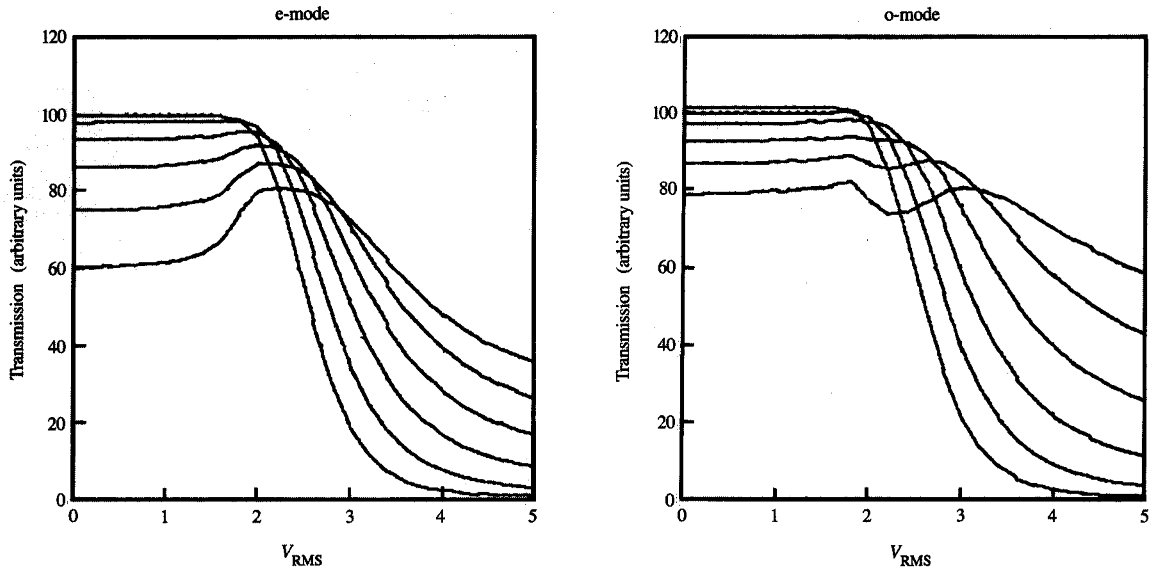

Figure 15

T-V curves of the e-mode and the o-mode up viewing zones.

Table 2 Comparison of the e-mode and the o-mode optical performances.

	e-mode			*o-mode*		
	horizontal	*down*	*up*	*horizontal*	*down*	*up*
Angular dependence of GL(7)	○	○	×	□	○	○
Angular dependence of GL(0)	□	○	△	×	○	×
Region of proper gray-scale order	□	×	×	○	×	○
Angular dependence of GL(n)/GL(0)	□	×	△	○	×	×
Angular dependence of GL(7) for white	△	○	○	□	□	□
Angular dependence of GL(7) for RGB	□	○	△	○	□	×
Gray-level dependence of GL(n) for RGB	□	×	○	○	×	△

Box, circle, triangle, and cross indicate performance that is very preferable, preferable, fair, and not preferable, respectively.

level brightness of the threshold-voltage (1.8 V)-biased e-mode (we abbreviate this to "biased e-mode" here). The dotted lines indicate the GL(7) of the nonbiased e-mode for reference. Much improvement is realized in the up viewing zone of the biased e-mode. For the horizontal viewing zone, the biased e-mode shows the same superiority as the nonbiased e-mode. The region of proper gray-scale order in the up viewing zone of the biased e-mode is about 50% wider than for both the nonbiased e-mode and the nonbiased o-mode. Despite the improvement in the up viewing zone, optical performance for the down viewing zones becomes worse in the biased e-mode. However, this disadvantage is not serious, because the down viewing zone is opposite to the direction normally used for gray-scale applications. For the up viewing zone, the biased e-mode is superior to both the nonbiased e-mode and the nonbiased o-mode in the gray-scale order. The comparison between the biased e-mode and the nonbiased e-mode is summarized in **Table 3**. The decrease in transmittance at normal incidence due to the application of the bias voltage is negligibly small (1%).

The purities of the three primary colors are determined by the ON transmittance of the pixel under consideration and the OFF [GL(0)] transmittances of the other pixels. The poor color fidelity of the o-mode NW is well explained by the large angular dependence of its GL(0) level, as

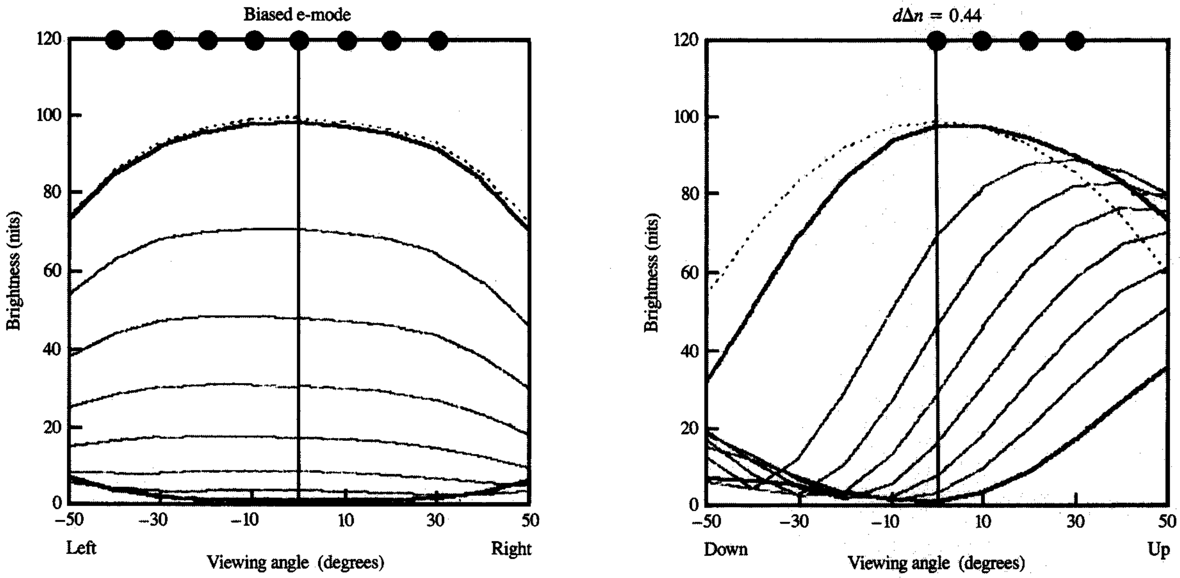

Figure 16

Angular dependence of the eight-gray-level brightness of the threshold-voltage (1.8 V) -biased e-mode.

Table 3 Comparison of the biased and nonbiased e-mode optical performances.

	Biased e-mode			*Nonbiased o-mode*		
	horizontal	*down*	*up*	*horizontal*	*down*	*up*
Angular dependence of GL(7)	○	×	△	○	○	×
Angular dependence of GL(0)	□	○	△	□	○	△
Region of proper gray-scale order	□	×	○	□	×	×
Angular dependence of GL(n)/GL(0)	□	×	○	□	×	△

Box, circle, triangle, and cross indicate performance that is very preferable, preferable, fair, and not preferable, respectively.

shown in Figure 10. It is obvious that the bias voltage on the e-mode NW affects its GL(7) level but not its GL(0) level; the GL(0) level affects the angular appearance of the three primary colors. Therefore, the good color fidelity of the e-mode NW is preserved regardless of the bias.

Optimization of the retardation

The value of the retardation $d\Delta n$ is one of the key factors influencing the optical performance of the TN cell with respect to gray-scale capability, chromaticity, transmittance, and contrast ratio. We have examined both the region of proper gray-scale order and the white-color change for different $d\Delta n$ in TFT-driven LCDs [16].

Figure 17 shows viewing-angle dependences of GL(n) for the different $d\Delta n$. The GL(7) of the nonbiased e-mode is also shown by the dotted line in both the horizontal and the vertical charts. On the upper side of each chart, the symbols ● and + indicate the region of proper gray-scale order for the biased and the nonbiased e-modes, respectively. The color changes of the GL(7) white for different $d\Delta n$ are shown in **Figure 18.** Since these samples are composed of different color filters and polarizers from the samples discussed before, a comparison of absolute values of the chromaticity between Figures 12 and 18 is not meaningful.

The observed results of the region of proper gray-scale order and the angular dependence of GL(7) white color are summarized in **Table 4.** The angular dependences of the GL(7) and GL(0) are also summarized in Table 4 for reference. The wide horizontal region of proper gray-scale

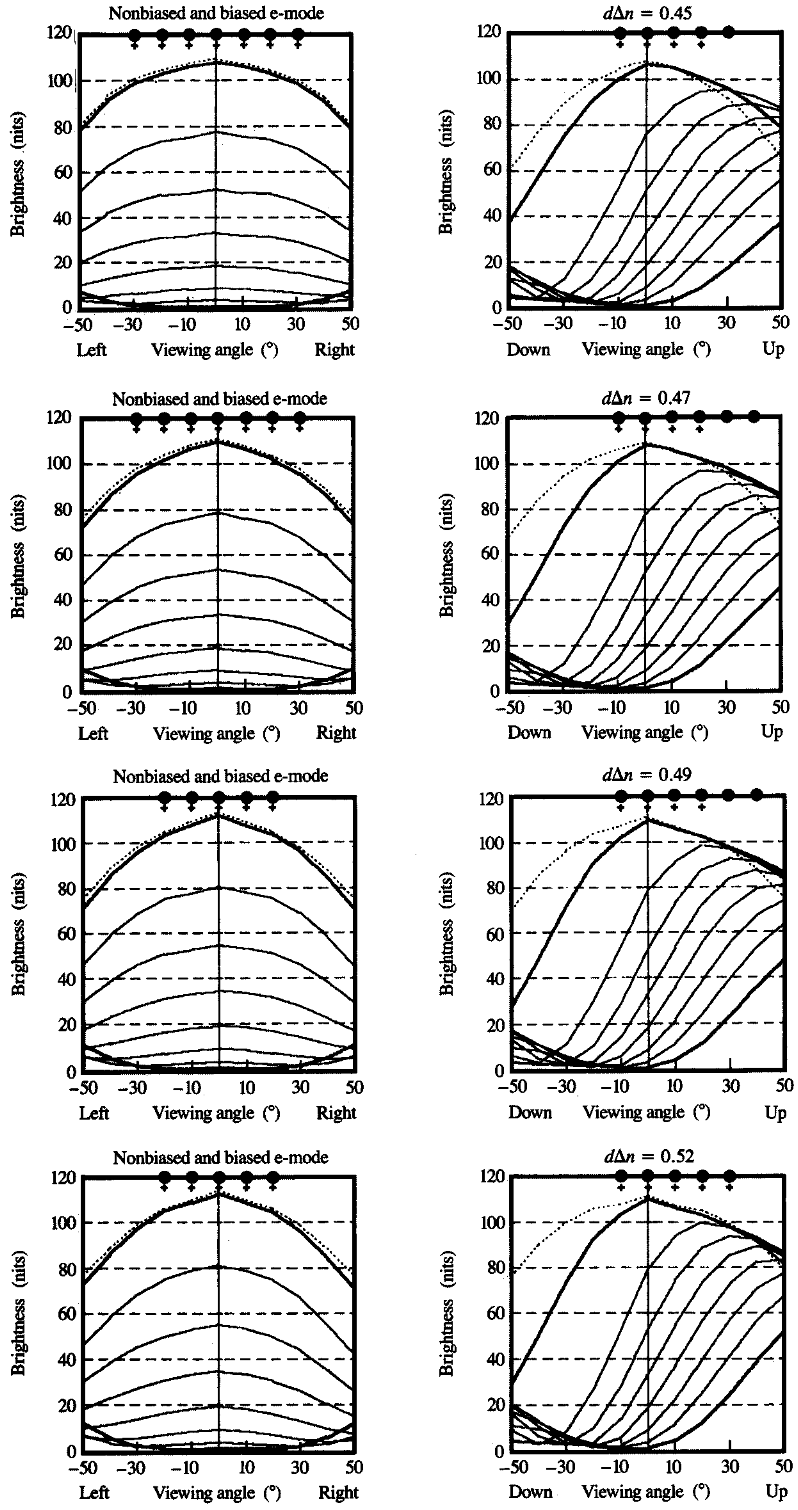

Figure 17

Viewing-angle dependences of the GL(n) for different $d\Delta n$.

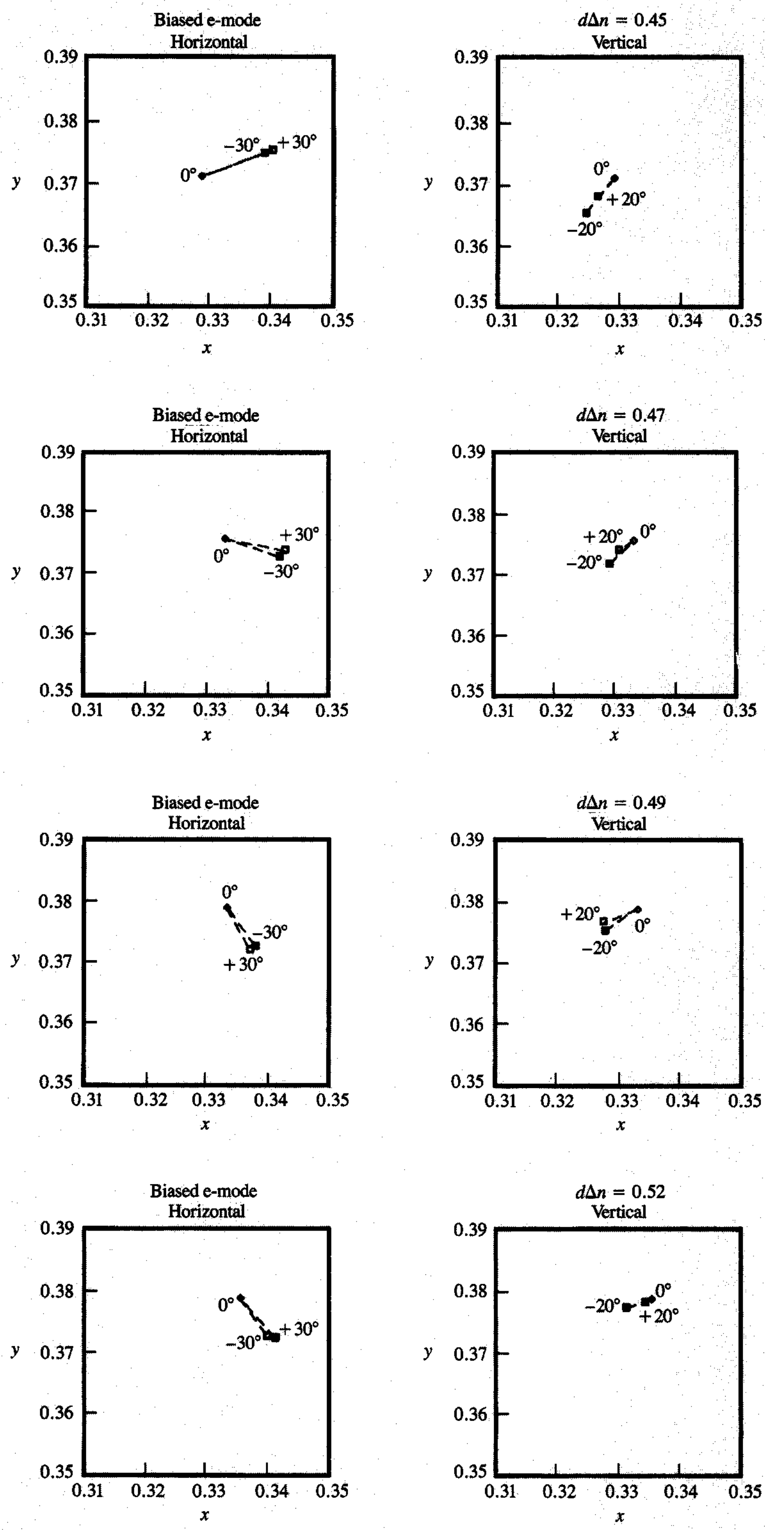

Figure 18

Color changes of the GL(7) for white for different $d\Delta n$.

Table 4 Optical performances of the biased e-mode for different $d\Delta n$.

	$d\Delta n = 0.45$		$d\Delta n = 0.47$		$d\Delta n = 0.49$		$d\Delta n = 0.52$	
	horizontal	*up*	*horizontal*	*up*	*horizontal*	*up*	*horizontal*	*up*
Angular dependence of GL(7)	○	△	○	○	○	○	△	○
Angular dependence of GL(0)	□	△	○	△	△	△	△	×
Region of proper gray-scale order	□	○	□	□	○	□	○	○
Angular dependence of GL(7) for white	△	○	○	□	○	□	○	□

Box, circle, triangle, and cross indicate performance that is very preferable, preferable, fair, and not preferable, respectively.

order is obtained in cells of $d\Delta n$ from 0.45 to 0.47 μm. The region of proper gray-scale order in the up viewing zone has its maximum value when $d\Delta n$ is from 0.47 to 0.49 μm. Thus, the biased e-mode NW with $d\Delta n = 0.47$ μm realizes a wide viewing cone in both the horizontal and vertical viewing zones. The value of $d\Delta n = 0.47$ μm agrees with the theoretical contrast peak of NW mode for bilevel driving [12]. For $d\Delta n = 0.47$ μm, maximum transmittance of the panel is also obtained.

Summary

For binary application, we prefer the first minimum NW mode because of fast response time, small color change, and large cell-thickness tolerance which eases fabrication tolerance.

For gray-scale application, we have compared the viewing-angle dependences of the gray level GL(n) of the e-mode NW and the o-mode NW, and have obtained the following results:

- The e-mode NW shows a smaller angular dependence of GL(0) in both the horizontal and vertical viewing zones.
- The o-mode NW shows a smaller angular dependence of GL(7) in both the horizontal and vertical viewing zones.
- In the horizontal viewing zone, the e-mode NW shows a wider region of proper gray-scale order.
- In the up viewing zone, the o-mode NW shows a wider region of proper gray-scale order.

From the comparison of the viewing-angle dependence of the chromaticity, we obtained the following results:

- The o-mode NW shows a smaller color change of GL(7) for white.
- The e-mode NW shows good color fidelity of the three primary colors in all viewing zones except the down viewing zone.

The evaluated results on the optical performance of the biased e-mode are as follows:

- The brightness reversal problem in the up viewing zone is much improved.
- All of the superiorities of the nonbiased e-mode NW are preserved.

Finally, we optimized $d\Delta n$ and obtained a value of 0.47 μm to reduce the white-color change and to maximize the viewing region while preserving a proper gray-scale order.

Conclusion

We have developed a novel mode of operation for a gray-scale TFT-driven LCD, called "threshold-voltage-biased e-mode NW" or, more simply, "biased e-mode NW."

With this scheme, we can achieve a high gray-scale (or color)-fidelity LCD with no extra compensation, such as retardation films or compensation LC cells. The horizontal viewing cone of the optimized biased e-mode is the same as that of the nonbiased e-mode NW, and 75% wider than that of the o-mode NW. The vertical viewing cone is also 50% wider than that of either the nonbiased e-mode NW or the nonbiased o-mode NW. The brightness reversals in the up viewing zone and the large color change of GL(7) for white in the up viewing zone of the nonbiased e-mode were improved by the threshold-voltage bias and the optimization of the retardation $d\Delta n$. In conclusion, the biased e-mode of the first minimum NW TN LCD with $d\Delta n = 0.47$ μm can achieve an up viewing cone 100% wider than that of the nonbiased e-mode operation, and shows only a small white-color change.

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