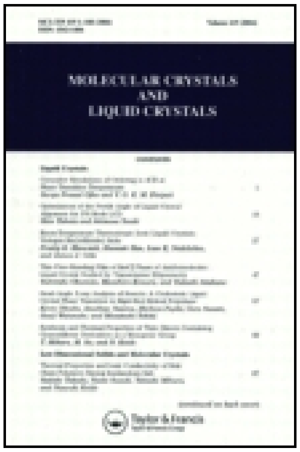

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Threshold Voltage Biased E-Mode TN LCD—Optimum Optical Design for Grayscale Application

Hideo Takano [a] , Mitsuru Ikezaki [a] & Shunji Suzuki [a]

[a] Display Technology & Design Center, IBM Japan, Ltd., 1623-14, Shimotsuruma, Yamato-shi, Kanagawa-ken, 242, Japan

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THRESHOLD VOLTAGE BIASED E-MODE TN LCD --OPTIMUM OPTICAL DESIGN FOR GRAYSCALE APPLICATION--

HIDEO TAKANO, MITSURU IKEZAKI, and SHUNJI SUZUKI
Display Technology & Design Center, IBM Japan, Ltd.
1623-14, Shimotsuruma, Yamato-shi, Kanagawa-ken 242, Japan

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Abstract In a normally white (NW) twisted nematic (TN) liquid crystal displays (LCDs), there are two optical eigenmodes, an extraordinary-ray mode (e-mode) and an ordinary-ray mode (o-mode). With zero or a low-bias voltage as the brightest state of the display, both eigenmodes have insufficient display performance for the analog grayscale application. The former has a large color change as a function of viewing angle and a narrow vertical viewing zone. The latter has quite a narrow horizontal viewing zone. By applying a threshold voltage as a bias to represent the brightest level of the e-mode NW, the optical performance in the vertical viewing zone was much improved. Further optimization of the d*delta-n for this mode of operation resulted in a small color change and a wide viewing zone by choosing d*delta-n = 0.47 micrometers. We conclude that the threshold-voltage biased e-mode NW of the first-minimum thin-film-transistor (TFT) driven TN can achieve a wide viewing angle for analog-grayscale applications.

INTRODUCTION

It is well known that there are two display modes in a 90 degree TN LCD, a normally white (NW) and a normally black (NB), in which the optical axes of the exit polarizers are placed perpendicular and parallel to those of the entrance polarizers, respectively. We have compared the optical performances of these two display modes and found that the first minimum NW is more suitable for TFT driven TN color LCD than the NB for its high color fidelity, high contrast ratio, and large cell gap tolerance.[1]

In both the NW and the NB modes, there are two optical eigenmodes, an e-mode and an o-mode, in which the transmission axes of the entrance polarizers are parallel and perpendicular to the entrance rubbing directions, respectively. The optical performances of these two optical eigenmodes are, in general, similar except some minor differences. We have investigated the optical performances of four combinations of two display modes and two optical eigenmodes, and reported that the e-mode and the o-mode are basically different for the NW case[2,3] We have to choose the proper optical eigenmode for each application.[4] The geometries of the e-mode NW and the o-mode NW are illustrated in Figure 1. In the same figure, four viewing zones are also defined in connection with rubbing directions.

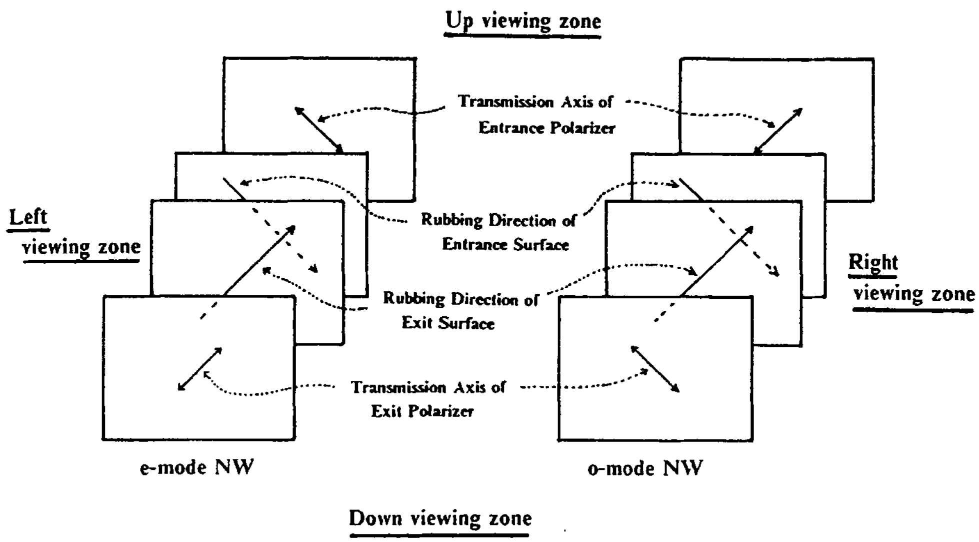

FIGURE 1 Geometries of the e-mode and o-mode NW and four viewing zones.

Recently, the TFT driven NW TN LCD has become commercial products because of its good legibility. Actually, from its optimum direction, the high resolution TFT driven first minimum NW TN LCD is as legible as the cathode-ray tube (CRT) display. However it still has a short-coming of narrow viewing cones. This problem becomes more serious in a grayscale (full-color) display than in a binary (multi-color) display.

To improve it, some ideas which used either retardation films[4,5] or a combination of a compensation LC cell and retardation films[6] were proposed. The adoption of the compensation cell or retardation films increases the manufacturing cost. Moreover, the published ideas using compensators do not improve the brightness reversals of the grayscales.[7] In a grayscale display, a viewing angle region which provides proper grayscale order is a key characteristics.

This paper is devoted to clarify which optical eigenmode is advantageous to the grayscale application and proposes a novel mode of operation and an optimum d*delta-n for further improvement on the grayscale quality of TFT driven TN LCDs. It is worth mentioning that our approach to the wide viewing cone grayscale LCD requires no extra compensations and no extra manufacturing cost. After introduction, this paper is organized under the sections of optical performances of the e-mode NW and the o-mode NW, threshold-voltage biased e-mode NW, optimization of d*delta-n, results, discussions, and conclusion.

OPTICAL PERFORMANCES FOR THE E-MODE NW AND THE O-MODE NW

Transmittance of white, red, green, and blue colors are measured as a function of a viewing angle for 10.4″ diagonal TFT driven 90 degree TN LCD; its d*delta-n is 0.44 micrometers. Grayscale transmissions, grayscale contrast ratios, and grayscale chromaticities are compared as a function of viewing angles between the e-mode NW and the o-mode NW.

Viewing angle dependences of the brightness of 8 levels of grayscale are shown in Figure 2[3] 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 Vrms and 5 Vrms, respectively.

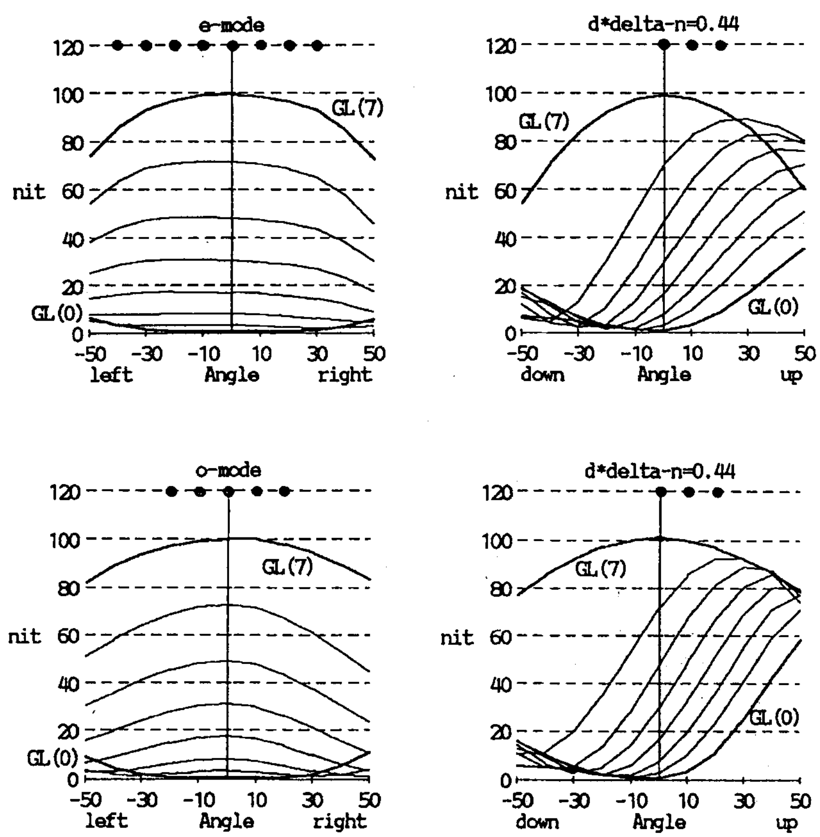

FIGURE 2 Viewing angle dependences of the brightness of 8 levels of grayscale.

Six intermediate gray-levels between the GL(7) and the GL(0) are determined to provide appropriate grayscale for human eyes. The viewing angle dependences of grayscale contrast ratios (BGL(n)/BGL(0)), the chromaticity of GL(7) white, the chromaticity of GL(7) three primary colors are shown in Figures 3, 4, and 5, respectively.

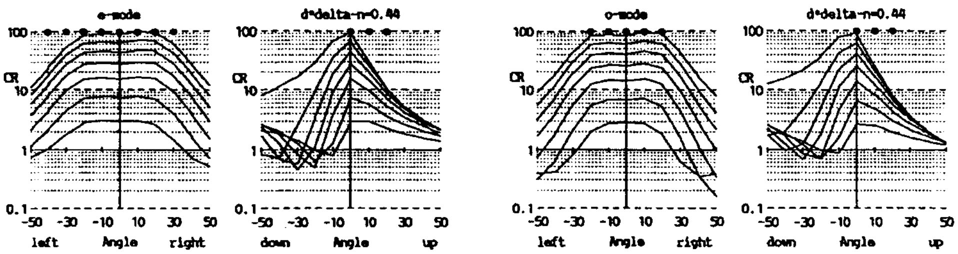

FIGURE 3 Viewing angle dependences of grayscale contrast ratios (BGL(n)/BGL(0)).

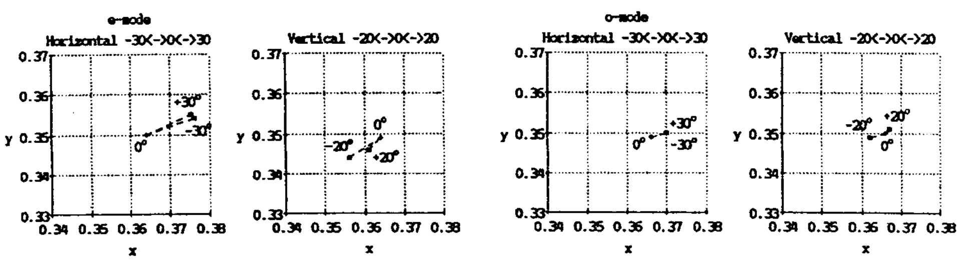

FIGURE 4 Viewing angle dependences of the chromaticity of GL(7) white.

Gray level dependences of the three primary colors at horizontal +30 degrees and vertical +20 and -20 degrees are shown in Figure 6.

TABLE I Comparison of the e-mode and the o-mode optical performances.

	e-mode			o-mode		
	horizontal	down	up	horizontal	down	up
angular dependence of BGL(7)	○	○	×	◎	○	○
angular dependence of BGL(0)	◎	○	△	×	○	×
proper-grayscale-order region	◎	×	×	○	×	○
angular dependence of BGL(n)/BGL(0)	◎	×	△	○	×	×
angular dependence of GL(7) white	△	○	○	◎	◎	◎
angular dependence of GL(7) RGB	◎	○	△	○	◎	×
gray level dependence of GL(n) RGB	◎	×	○	○	×	△

The comparison results are summarized in Table I. Double-circle, circle, triangle,

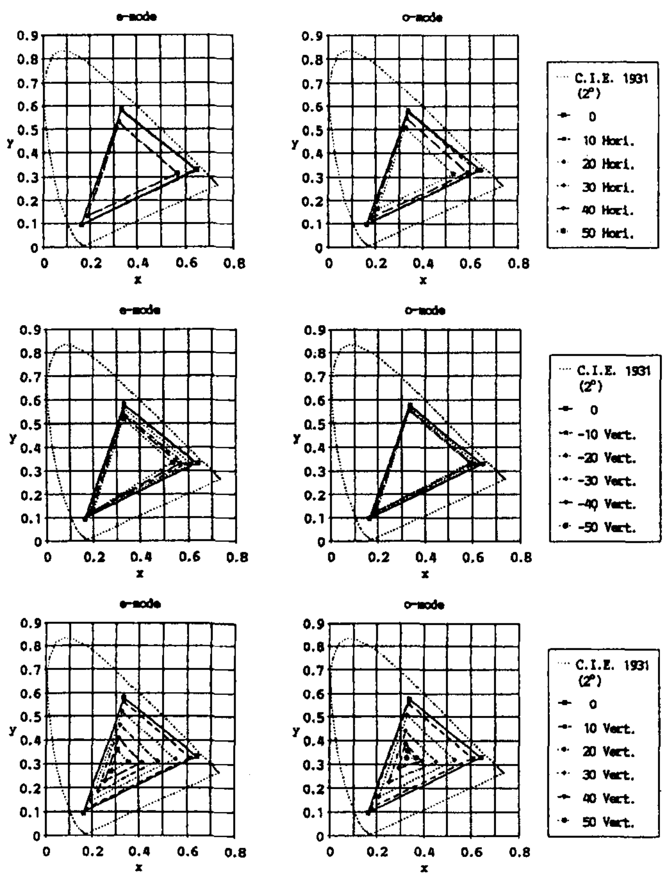

FIGURE 5 Viewing angle dependences of the chromaticity of *GL(7)* three primary colors

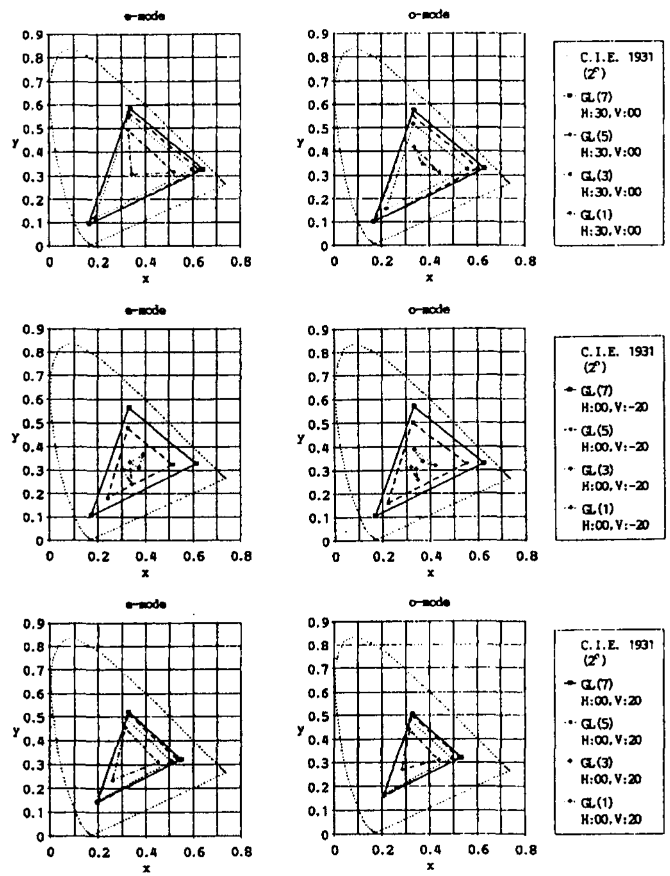

FIGURE 6 Gray level dependences of the three primary colors at horizontal +30 and vertical +20 and -20 degrees.

and cross indicate much preferable, preferable, so so, and 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 or better than that of the e-mode. On the other hand, in the up viewing zone, the e-mode optical performance is generally more advantageous than the o-mode one.

On upper sides of each chart in Figures 2 and 3, the symbol "o" indicates the region in which the proper grayscale order is provided. For the vertical direction, the proper-grayscale-order region is wider in the up viewing zone than in the down viewing zone for both the e-mode and the o-mode NW. We have to use the up direction as a direction in common use for the grayscale application.[8] It is worth mentioning that in this commonly used direction, the optical performance of the e-mode NW is advantageous. This is quite opposite to the binary application. From Figure 3, the binary contrast ratio BGL(7)/BGL(0) is much better in the down viewing zone than in the up viewing zone for both the e-mode and the o-mode NW. Thus, for the binary application, we have to use the down direction as a commonly used direction. In this direction, the o-mode NW is advantageous.

Overall, in the practically used 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 color change of the white. The improvement of these problems is discussed in the following sections.

THRESHOLD VOLTAGE BIASED E-MODE NW

Figure 7 shows T-V curves of the e-mode and the o-mode up viewing zones.

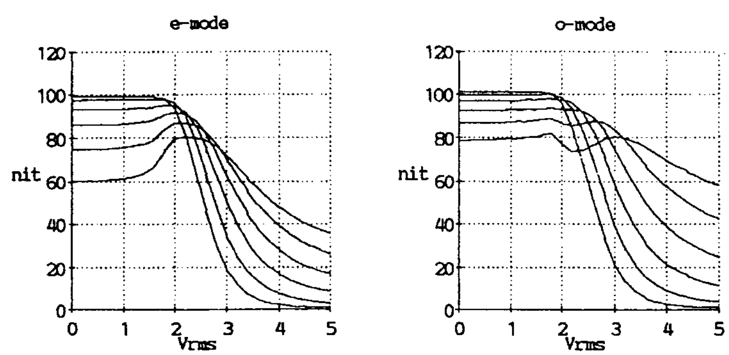

FIGURE 7 T-V curves of the e-mode and the o-mode up viewing zones.

Comparing to the o-mode T-V curves, the e-mode T-V curves have following features:

(1) under the threshold voltage (about 2V), the transmittance from the normal direction does not change with applied voltage, and over the threshold voltage, it shows monotonic decrease with increasing applied voltage,

(2) each T-V curve shows maximum brightness at around 2V 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 over the threshold voltage of the normal direction.

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

(1) improve the viewing angle dependence of the BGL(7) in the up viewing zone,

(2) monotonic decrease of the transmission is realized not only from the normal direction but also from any viewing angle. As far as the brightness shows a monotonous change, the brightness reversal does not occur.

Figure 8 shows an angular dependence of the 8 gray level brightness of the threshold voltage (1.8V) biased e-mode (we will abbreviate this to "biased e-mode" here). The dotted lines indicate the BGL(7) of non-biased e-mode for reference.

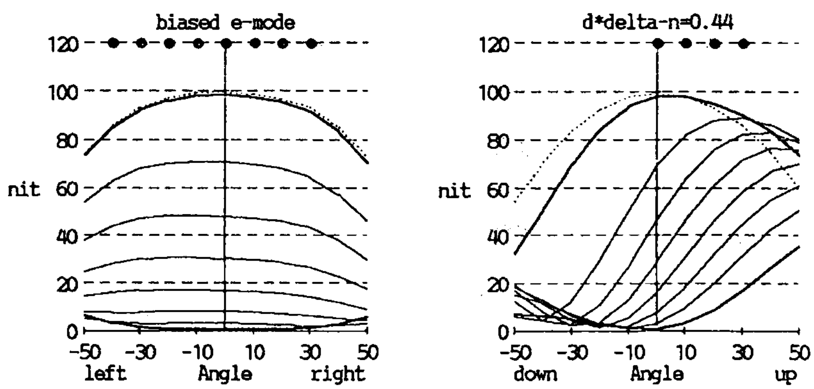

FIGURE 8 Angular dependence of the 8 gray level brightness of the threshold voltage (1.8V) biased e-mode.

Much improvement is realized in the biased e-mode up viewing zone. For the horizontal viewing zone, the biased e-mode shows same superiority as the non-biased e-mode. The proper-grayscale-order region in the up viewing zone of the biased e-mode is about 50% wider than both the non-biased e-mode and the non-biased o-mode. In return for the improvement in the up viewing zone, optical performance for the down viewing zone becomes worse in the biased e-mode. However, this disadvantage is not so serious, because the down viewing zone is the opposite to the direction in common use for the grayscale application. For the up viewing zone, the commonly used direction, the biased e-mode is superior to both the non-biased e-mode and the non-biased o-mode in the grayscale order. The comparison between the biased e-mode and the non-biased e-mode is summarized in Table II. The decrease in transmittance at normal incidence due to the biased voltage is negligibly small (1%).

TABLE II Comparison of the biased and the non-biased e-mode optical performances.

	biased e-mode			non-biased e-mode		
	horizontal	down	up	horizontal	down	up
angular dependence of BGL(7)	○	×	△	○	○	×
angular dependence of BGL(0)	◎	○	△	◎	○	△
proper-grayscale-order region	◎	×	○	◎	×	×

OPTIMIZATION OF D*DELTA-N

D*delta-n is one of the key factors influencing the optical performance of the TN cell such as grayscale capability, chromaticity, transmittance, contrast ratio, and so on. We examined both the proper-grayscale-order region and the white-color change for different d*delta-n TFT driven LCD.

Figure 9 shows viewing angle dependences of the BGL(n) for different d*delta-n. The BGL(7) of the non-biased e-mode is also drawn by dotted line in both the horizontal and the vertical charts. On upper sides of each chart, the symbols "o" and "+" indicate the proper-grayscale-order region for the biased and the non biased e-modes, respectively. The color changes of the GL(7) white for different d*delta-n are shown in Figure 10. Since these samples are composed of different color filters and polarizers from the sample discussed before, only a relative comparison between Figures 4 and 10 is meaningful.

The measured results of the proper-grayscale-order region and the angular GL(7) white-color are summarized in Table III. The angular dependences of the BGL(7) and BGL(0) are also summarized in Table III for reference. The wide horizontal proper-grayscale-order region is obtained in cells of d*delta-n from 0.45 to 0.47 micrometers. The proper-grayscale-order region in the up viewing zone has its maximum value when d*delta-n is from 0.47 from 0.49 micrometers. Thus, the biased e-mode NW with d*delta-n = 0.47 micrometers realizes a wide viewing cone in both the horizontal and vertical viewing zones.

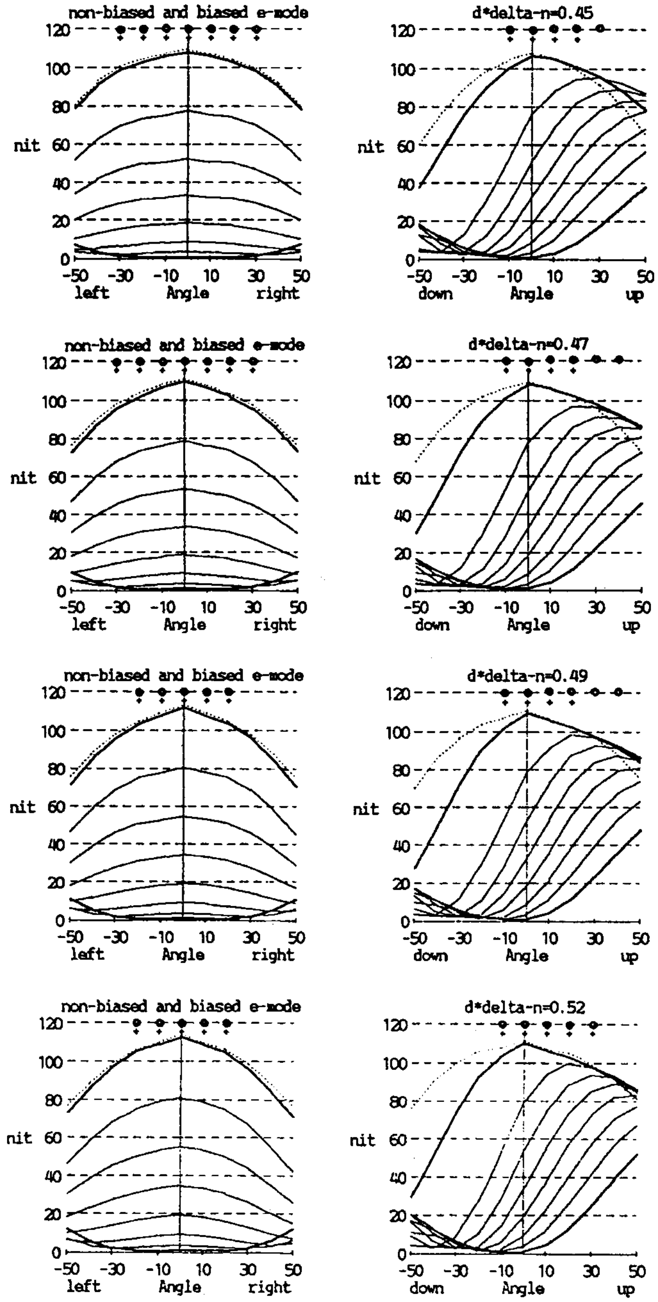

FIGURE 9 Viewing angle dependences of the BGL(n) for different d*delta-n.

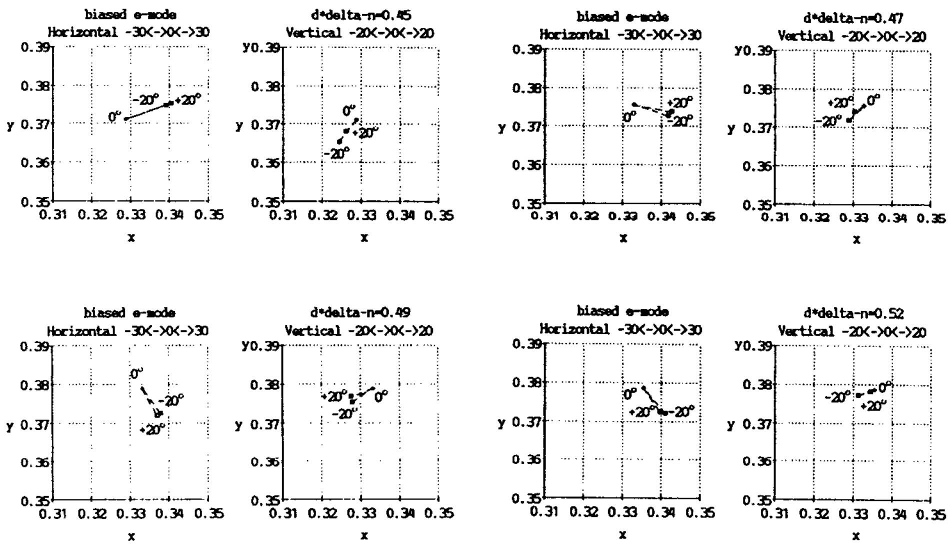

FIGURE 10 Color changes of the GL(7) white for different d*delta-n.

TABLE III 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 BGL(7)	○	△	○	○	○	○	△	○
angular dependence of BGL(0)	◎	△	○	△	△	△	△	×
proper-grayscale-order region	◎	○	◎	◎	○	◎	○	○
angular dependence of GL(7) white	△	○	○	◎	○	◎	○	◎

RESULTS

We compared the viewing angle dependences of the BGL(n) of the e-mode NW and the o-mode NW, and obtained following results:

(1) the e-mode NW shows a smaller angular dependence of BGL(0) in both the horizontal and vertical viewing zones,

(2) the o-mode NW shows a smaller angular dependence of BGL(7) in both the horizontal and vertical viewing zones,

(3) in the horizontal viewing zone, the e-mode NW shows a wider proper-grayscale-order region,

(4) in the up viewing zone, the o-mode NW shows a wider proper-grayscale-order region.

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

(5) the o-mode NW shows a smaller color change of GL(7) white,

(6) the e-mode NW shows good color fidelity of 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:

(7) the brightness reversal problem in the up viewing zone is much improved,

(8) all of the superiorities of the non-biased e-mode NW are preserved.

Finally, we optimize d*delta-n and obtain a value of 0.47 micrometers to maximize the region preserving a proper grayscale order and to reduce the white-color change.

DISCUSSIONS

The purities of three primary colors are determined by the ON transmittance of the pixel concerned and the OFF (GL(0)) transmittances of the other pixels. Poor color fidelity of the o-mode NW is well explained by the large angular dependence of its BGL(0). It is obvious that the biased voltage on the e-mode NW only affects its GL(7) but not GL(0) which affects the angular appearance of three primary colors. Therefore, the good color fidelity of the e-mode NW is preserved irregardless the bias.

CONCLUSION

We have developed a novel mode of operation for a grayscale TFT driven LCD. It was named threshold voltage-biased e-mode NW or simply called biased e-mode NW.

By this scheme, we can achieve a high grayscale (or color) fidelity LCD without any extra compensations. The horizontal viewing cone of the optimized biased e-mode is same as that of the non-biased e-mode NW, and 75% wider than that of the o-mode NW. The vertical viewing cone is also 50% wider than either the non-biased e-mode NW or the non-biased o-mode NW. The brightness reversals in the up viewing zone and the large color change of GL(7) white in the up viewing zone of the non-biased e-mode was improved by the threshold-voltage bias and its optimization in d*delta-n. In conclusion, the biased e-mode of the first minimum NW TN with d*delta-n = 0.47

micrometers can achieve 100% wider up viewing cone than non-biased e-mode with a small white-color change.

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