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IBM Research Report

Status of TFTLCD Color and Metrology

S. L. Wright, K. Ho, A. Lien

IBM T. J. Watson Research Center
P. O. Box 218
Yorktown Heights, NY 10598

Research Division
Almaden - Austin - Beijing - Haifa - T. J. Watson - Tokyo - Zurich

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Steven L. Wright, Kenneth Ho, Alan Lien
IBM T.J. Watson Research Center
Yorktown Heights, New York

Abstract

The changes in TFTLCD color with pixel level and with viewing angle are critical issues, which need to be understood for TFTLCDs to gain acceptance for color-intensive applications in the marketplace. The latest wide-viewing angle technologies have adequate color performance for most applications, yet far from ideal. These developments, when combined with the high pixel density, high local contrast ratio, and lack of distortion achievable with TFTLCD technology, will lead to displays with image quality superior in many ways to both CRTs and print. As TFTLCD image quality improves, many challenges remain for meaningful characterization, especially to compare image quality to other media.

Introduction

The characteristics of Thin Film Transistor Liquid Crystal Displays (TFTLCDs) are rapidly improving, particularly for desktop monitors, which are beginning to penetrate the marketplace. Due to their pixel structure and drive method, TFTLCDs can have very sharp image quality and freedom from distortion. TFTLCDs have been made with pixel densities of 200 ppi and larger, with high brightness and contrast ratio, as viewed at normal incidence. Low resolution, wide-viewing angle TFTLCD monitors are commercially available, but the contrast ratio and color still have a dependence on viewing angle. Examples of contrast ratio data are shown in Table 1, showing that the average contrast ratios are much smaller than the maximum contrast ratio. To faithfully render high quality images, the color must be accurate and reproducible, over the entire viewing range, and over all graylevels. For some TFTLCDs, non-negligible black state luminance and chromaticity shift with graylevel create problems for color additivity and calibration.[1,2] Over a restricted range of viewing angles and colors, however, satisfactory results can be obtained. We seek an understanding of the color characteristics as a function of viewing angle in terms of the LC mode and technology, and represent the characteristics with as few parameters as possible. Previously, TFTLCD subjective color quality was found to have the strongest correlation with hue shifts and to some extent with chroma shifts.[3] In this paper, we review the current status of TFTLCD color and discuss various metrology issues which are unique to flat panel displays. We present examples of viewing angle characteristics of the fully bright and fully dark states, and some results at normal incidence for intermediate graylevels.

LC mode	CR (max)	CR (ave)
TN+CF	268	116
SD-IPS (1)	283	206
SD-IPS (2)	230	170
DD-IPS	280	201
MVA	330	166

Table 1. Contrast Ratio Characteristics (over a 40° viewing cone).

Experiment

The color characteristics were measured for a number of commercially-available TFTLCDs with different liquid crystal modes, developed to improve the viewing angle characteristics. Some results of this study were previously published,[4] adding to other reports on TFTLCD color quality.[3,5-7] The liquid crystal modes examined included twisted-nematic plus compensation film (TN+CF), single and dual-domain in-plane-switching (SD-IPS and DD-IPS), and multi-domain vertical alignment (MVA). Color measurements were done with a conoscopic instrument (ELDIM EZcontrast 160) equipped with color filters for chromaticity measurement. A Minolta CS-100 colorimeter and Photo Research PR704 spectraphotometer were used for other on-axis measurements. L*, a*, b*, ΔE*, ΔH*, and ΔC* values were extracted as a function of viewing angle, and simple metrics were explored for describing both average color shift and variations in color with viewing angle. Changes in color which occur within a viewing cone of 40° are of the most interest, corresponding to viewing panels with screen diagonals of 18 inches or less, at a reading distance of 40 cm. Although shorter viewing distances or larger panels create a larger viewing cone, incident viewing angles larger than 40° increase task difficulty in the workplace environment.[8]

Viewing Angle Characteristics

The measured TFTLCD white state characteristics are shown in Table 2. Using the measured on-axis light as the reference illuminant, the average values of L*, a*, and b* over a 40° viewing cone are given. The values are close to

LC mode	ΔE*	L*	a*	b*
TN+CF	11	89	0.9	1
SD-IPS (1)	22	95	-20	8.5
SD-IPS (2)	5	95	1.8	1.8
DD-IPS	5	95	-1.4	2
MVA	6	94	-0.5	2.5

Table 2. White State Characteristics (40^o viewing cone), using the on-axis white state as reference illuminant

the on-axis values, L*=100, a*=b*=0 by definition. Typical variations over the viewing cone were about 2 or less for a* and b* and about 6 for L*. The average color shift from the on-axis value, ΔE*, is much lower for the DD-IPS and MVA modes than the other modes. There was a large difference in the color characteristics of the two SD-IPS panels tested, which were from different manufactuers. Examples of polar plots of ΔE* are shown for SD-IPS and MVA modes in Figures 1 and 2.

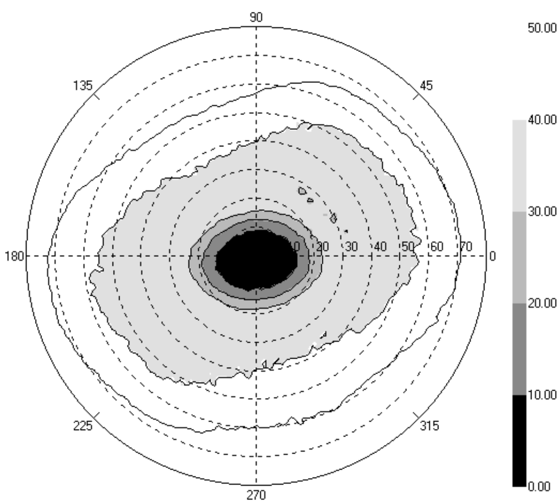

Figure 1. Isocontour polar plot of Δ E for the white state of a typical IPS mode panel.*

As the graylevel is reduced, L*, a* and b* generally exhibit increasingly larger variation with viewing angle. For conventional TN or TN+CF modes, typically used in notebook computers and some monitors, midtone or dark grayshades viewed at certain angles exhibit luminance level reversal phenomena.[9,10] Level reversal refers to a situation in which a portion of the tone reproduction curve slope reverses sign, that is, a change in luminance versus change in graylevel changes sign, corresponding to reverse contrast. Reverse contrast dramatically reduces image quality in TN-mode panels, but is absent for IPS and MVA modes.

One might expect that since the luminance characteristics are improved for IPS and MVA modes, these modes would also have inherently better color characteristics than TN or TN+CF modes. However, for the

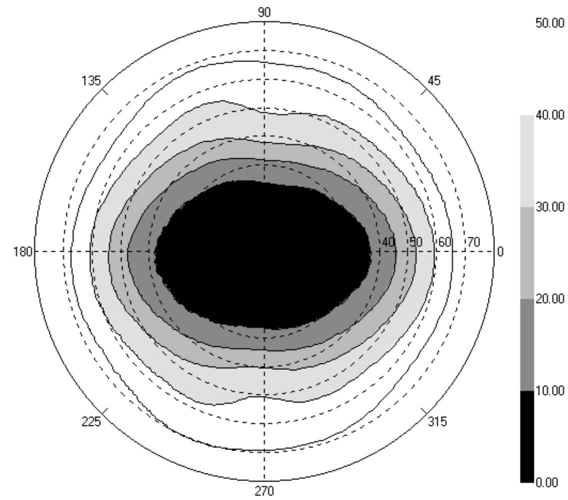

Figure 2. Isocontour polar plot of Δ E for the white state of a typical MVA mode panel.*

dark state, typical measured color variations with viewing angle for IPS and MVA modes were about the same as for TN modes, and some aspects were worse. Although the level reversal problems with TN and TN+CF modes clearly result in image quality which is poorer than the IPS and MVA modes, from a strictly color balance viewpoint, the TN modes perform surprisingly well for dark colors. The color quality of the dark states is one of the factors limiting the color performance of wide-view TFTLCD technology. A sensitive measure of the dark state color can be achieved using the on-axis black-state light as the reference illuminant, corresponding to viewing dark images on a panel in a dark room. For this illuminant, the average ΔE* values over a 40^o viewing cone were in the range 14 to 39, (Table 3), with relative variations of ΔE* as large as 100%. Note that the average L* values for this normalization exceed 100, due to the fact that the off-axis luminance for these LC modes in the dark state is generally larger than the on-axis value. Viewed off-axis in a dark room, at certain viewing angles, the black state of many LC modes appears either yellowish or purplish, not black.

LC mode	ΔE*	L*	a*	b*
TN+CF	29	116	-2.9	13.4
SD-IPS(1)	17	106	7.5	-6.2
SD-IPS(2)	14	105	2	12.9
DD-IPS	17	111	-0.7	13.7
MVA	39	138	0.3	9.1

Table 3. Black State Characteristics (40^o viewing cone), using the on-axis black state as reference illuminant.

The variation in a* and b* is about the same for the various modes, averaged over incident angles ($\theta<40^o$) and all possible azimuthal angles ($0<\phi<360^o$), with variations in b* (yellow-blue response) generally larger than a* (red-

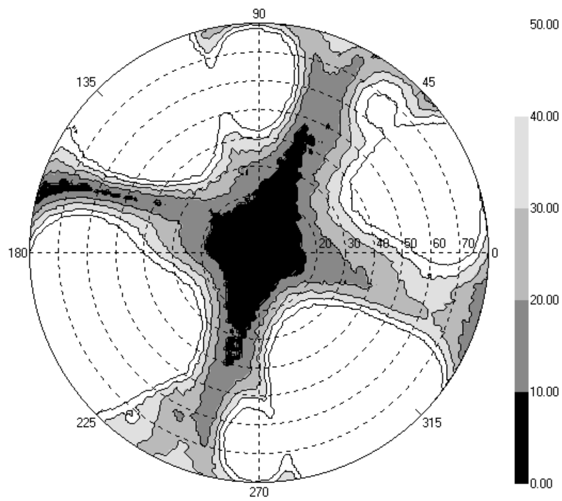

Figure 3. Isocontour polar plot of Δ E for IPS black state.*

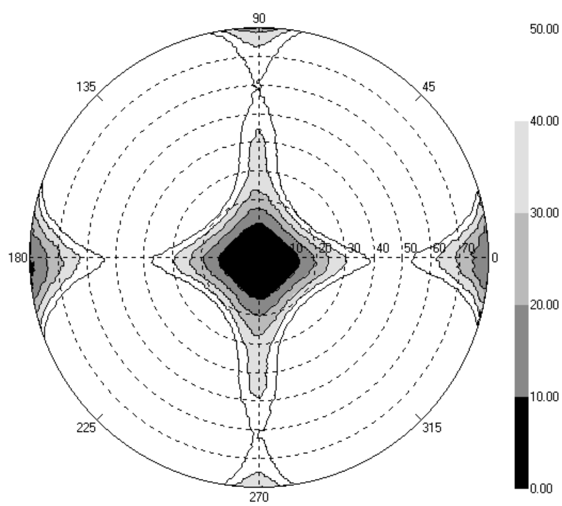

Figure 4. Isocontour polar plot of Δ E for MVA black state*

green). Another way to examine color variations is to consider the characteristics along particular cuts through the viewing cone. Plots of the locus of of a* and b* for isoincident values of $\theta = 40^{o}$ have a larger variation for IPS modes than the other modes with viewing azimuth.[3] Typical variations over the viewing cone were about 6 for a*, 15 for b*, and about 10-20 for L*. The L* variation for MVA mode was larger than the other LC modes. Examples of polar plots of ΔE* for the black state of SD-IPS and MVA modes are shown in Figures 3 and 4. The symmetry of the patterns follow the polarizer orientation. For this particular MVA mode, the polarizers are aligned vertically and horizontally, and for IPS mode, the polarizer axes are rotated by 15^{o}. Note that these dark state color variations would not be noticeable for bright images viewed under normal room illumination. Since these panels had contrast ratios in the range 230-330, using the on-axis white state light as the reference illuminant reduces ΔE* for the black state by a factor of 30 to 100.

Changes with Pixel Level

Color changes of grays (R=G=B) with level also occur for LCDs, typically becoming more bluish as the level is decreased. Examples of chromaticities measured for different LC modes are shown in Figure 5. Depending upon

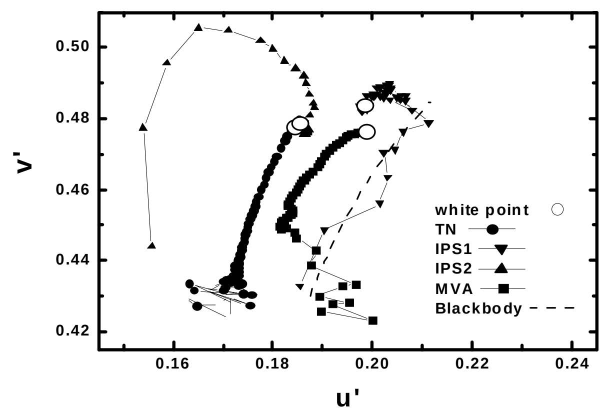

Figure 5. Typical chromaticity shift of grays.

the contrast ratio and other factors, the path and rate at which the chromaticity of the grays changes with level are different for different kinds of panels. In some cases, the chromaticity shift from the whitepoint can become significant at pixel luminances of about 20% of maximum[1], in others, as low as about 1%. As with print, it is important to maintain achromatic grays. Partial correction can be achieved by taking into account the contribution of the dark state pixels, and modifying the image data, through lookup tables or via a model, particularly as part of a calibration process for images intended for print. Care must be taken to properly account for the fact that the light from a nearly dark state R, G, or B primary contains contributions from two additional dark subpixels from the two other primaries. To achieve good results, it is necessary to reduce the allowed luminance dynamic range. Alternatively, automatic color correction can be done by changing the pixel data within the display drive electronics. For simple algorithms applied to digital data, the correction can be performed at frame rates. If the contrast ratio is large, good color calibration and additivity can be achieved over a range of viewing angles. Over a broad range of viewing angles, color changes with graylevel and viewing angle are interdependent.

A partial list of factors influencing TFTLCD color performance includes backlight and color filter characteristics, quality of panel drive electronics and analog or digital graphics adapter electronics, TFTLCD array design, pixel/cell design, and liquid crystal mode. In principle, color variations with viewing angle and graylevel can be modeled and understood on the basis of phase retardation of different light rays as they pass through the liquid crystal layer. Improved design methodology for LC cell parameters, combined with new approaches to tailor the optical path and improve the color filter and backlight characteristics will further improve the color quality. Film optical compensation techniques significantly improve the viewing angle characterisitcs, but can only be optimized for a small range of liquid crystal cell drive voltages, with a corresponding small range of pixel luminance. A major challenge is to improve viewing angle characteristics with acceptable cost.

Metrology Issues

Because displays emit light, the appearance of colors can either be related or unrelated, depending upon viewing ambient and the detailed rendered colors on the display.[11,12] For most viewing environments, the observer will be partially adapted to the display and partially adapted to the ambient illumination. For CRTs and prints viewed under various illumination conditions, this partial adaptation effect has been studied.[13-15] For monitor TFTLCDs, which are typically brighter than CRTs, the adaptation should be stronger to the display, but the changes in color and brightness with viewing angle introduce additional complications.

Simple methods are needed to calculate and describe the variations of LCD color with viewing angle in a way that is useful to color scientists, and also engineers and customers. Over the viewing cone, both the average shift in color and also the variation in color are important. These characteristics are different for different LC modes. While some trends are common to all LCDs, presently there are no standard characteristics such as those exhibited by CRTs. As LCD technology matures, this situation will change.

The characterization of color with viewing angle dependencies has little common ground with print color characterization, where changes of print reflectance with viewing angle are small, and characterization is done at a fixed viewing angle. For LCDs, we must consider a range of viewing angles, such as that presented to a single viewer which encompasses the entire rendered image. No single viewing angle is appropriate for analysis. Taking a reference illuminant as the average over the viewing cone guarantees that for some portions of the viewing cone, lightness values will exceed 100. Taking the reference illuminant as the maximum value over the viewing cone may not be appropriate, because for any particular viewing condition, this portion of the emitted light may not be observed. Using the on-axis light as the reference illuminant may not be the best choice, and altering the reference illuminant for each viewing condition is complicated and impractical.

Much of color science and color appearance has been oriented toward print. A strong source of light, which has strong viewing angle dependencies, is not normally encountered when observing a print under diffuse illumination. Some aspects of display appearance are similar to real world objects that exhibit light relections or interference, viewed under direct illumination in an otherwise dark room. Conventional lightness scale and color difference formulas are appropriate under conditions where maximum image contrast ratio is about 100 with perhaps 200 discernable luminance steps, well suited for prints viewed under diffuse illumination. Displays have much higher contrast ratios with a larger number of luminance levels, which under some viewing conditions, can be clearly discernable.[16] However, large measured display contrast may not correlate with image quality preference, or with perceived contrast ratio.[17]

Conclusions

The color quality of present wide-viewing angle TFTLCDs is sufficient for most applications. TFTLCD color gamut, brightness, and contrast ratio exceed CRTs, but the dependencies of color on viewing angle for TFTLCDs are large. Further improvements in the viewing angle characteristics are forthcoming, but achievement of full viewing angle independence is unlikely. For color-critical applications on TFTLCDs, corrections are needed to achieve color additivity and the field of view must be controlled. As electronic commerce increases, with decreased use of paper prints, increased demands will be placed on display color quality. To gain full benefit of the high image quality achievable with TFTLCDs, improved color characterization and specification are needed.

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