# P-107: Analyses of Whiteness of Reflective TFT-LCDs

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## Abstract

*Whiteness appearance is an important issue to improve the readability of reflective LCDs. Factors affecting the whiteness appearance, such as metal reflector, liquid crystal dispersion, color filter, oblique incidence, brightness,and uniformity were analyzed in order to achieve a paper-white image for reflective LCDs.*

## 1. Introduction

Reflective color-LCDs have been widely used as mobile information display devices. Low power consumption, thin format, light weight and sunlight-readability are the advantages of conventional reflective LCDs. Furthermore, instead of printed-paper, 'Electronic Paper' made by reflective LCDs shows high potential for convenience in daily life. However, compared with transmissive LCDs, conventional reflective LCDs have inadequate whiteness as the image photos shown in Figs. 1(a) and (b). The factors that may affect the whiteness are elaborated below.

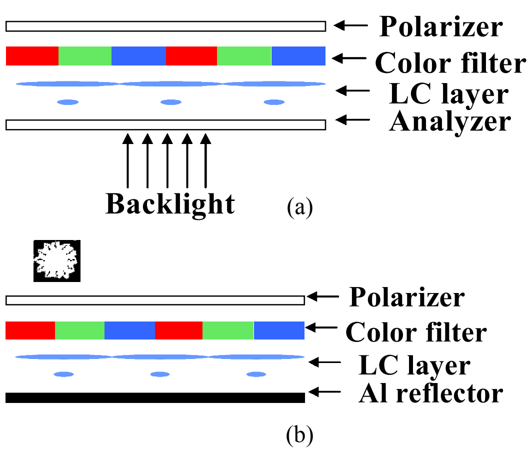


**Fig. 1** Schematic plot (a) transmissive and (b) reflective LCD

## 2. Factors of whiteness issue

Compared with transmissive LCDs, reflective LCDs have different components to the former. Hence, these distinct components may be the factors leading to the difference in whiteness elaborated below.

### 2.1 Reflective light Spectrum of Reflector

Reflective LCDs require a reflector to reflect the ambient light to display the image, which is not required for transmissive LCDs. Thus, the reflective light spectrum of the reflector may cause the color shift and lower the purity of the whiteness appearance.

### 2.2 Dispersion of LC Layer

The dispersion of liquid crystal layer plays an important part in the color shift of the reflective LCDs. Nowadays, reflective MTN[1,2] and STN mode[3] have been widely used to form a high quality display. However, reflectance of MTN and STN LC layer is different corresponding to the entire visible wavelength. Therefore, after the reflected light passing through the LC layer twice, the dispersion is induced, thus affecting the whiteness of the image.

### 2.3 Spectrum of Color Filter

In reflective color-LCDs, light passes through the color filter twice rather than once in transmissive LCDs. Therefore, the spectrum of color filter used on reflective LCDs shall be different to maintain the color saturation. Besides that, spectrum of color filter determines the color purity of RGB, hence color shift is induced from improper spectrum. Thus, an improper color filter may affect the whiteness appearance.

### 2.4 Oblique incidence

Additionally, ambient light obliquely illuminating the panel rather than backlight directly passing through the LCD panel causes optical path difference for ordinary and extraordinary rays, which may induce color shift and in turn lower the purity of whiteness.

### 2.5 Brightness of reflective LCDs

Low brightness affects the whiteness appearance of the human eye. The reflective light efficiency of reflective LCDs is around 8%, which can display


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around 0.4 x MgO standard white, and is only half of the reflectance of white paper. Therefore, inadequate whiteness of reflective LCDs is also caused by the low illumination.

## 2.6 Uniformity of reflective LCDs

Uniformity is also a key of whiteness appearance for the human perception. Compared with white paper as Lambertian surface, the reflective light distribution of reflective LCDs is not uniform enough that might reduce the whiteness appearance.

## 3. Results

A 4-inch reflective color LTPS TFT-LCD with reflective MTN mode, wide band retardation film and diffusive micro slant reflector (DMSR)[4], was used to simulate and analyze whiteness appearance. In the simulation, illuminant $D_{65}$ was chosen to be the light source, which has chromaticity value x= 0.312 and y=0.329("●", Fig. 2). The simulated color coordinate of Al reflector illuminated by $D_{65}$ ( "**x**", Fig. 2) is nearly the same as $D_{65}$. Therefore, the reflective spectrum of Al reflector barely affects the whiteness appearance. Additionally, $D_{65}$ reflected by an Al reflector, passing through the MTN cell using wide band retardation film, with and without color filter ("■" and "♦", respectively, Fig. 2), has a more serious color shift than a simple Al reflector. Nevertheless, comparing their color coordinates to $D_{65}$, the above three cases have color difference (ΔE) of less than 6, which is almost indistinguishable by the human eye. Hence, Al reflector, MTN mode with wide band retardation film and color filter are not the major factors causing the inadequate whiteness.

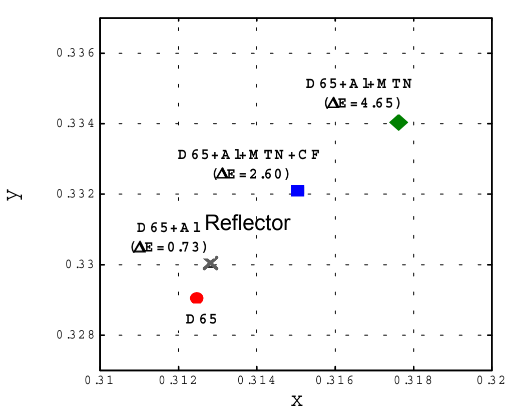



**Fig. 2** Simulated chromaticity coordinate and ΔE of a 4-inch reflective color LTPS TFT-LCD

To study the influence of oblique incident light, a diffusive white light source was used to illuminate an MgO standard white sample and the LCD panel. The color coordinates of different viewing angles were measured by using ELDIM EZContrast 160R. Neglecting the factor of brightness, the color difference between LCD panel and MgO standard white was calculated (thin line, Fig. 3). The color differences at viewing angles between -60° and 60° are at most 30, which is just distinguishable. On the other hand, by taking brightness into consideration, the color difference for most of the viewing angles dramatically increases to be larger than 60 (thick line, Fig. 3), which is easily distinguishable. Additionally, reflected light intensity distribution (Fig. 4) is not uniform enough in the viewing region from 0° to 30°; consequently affecting the human feeling of whiteness appearance of a reflective LCD. As a result, obliquity of incident light is the major cause of inadequate whiteness due to the inadequate reflective brightness and the non-uniform reflective light distribution.

In order to determine the minimum reflectance and uniformity to exhibit a paper-white image, the color difference with different reflectance was calculated within the viewing region from 0° to 30°. As shown in Fig. 5, the ripples in the curves are due to the bump structure of DMSR, so that the color difference varies with viewing angles. Obviously, the reflectance has to be larger than 0.6 times that of MgO standard white for the color difference to be less than 30 which is not easily distinguishable. Uniformity, however, is dependent on the reflectance of the panel. If the highest reflectance of a panel were only 0.6 x MgO, then the uniformity should be almost 100%; if the highest reflectance were 1.0 x MgO, the uniformity would be reduced to 60%. A reflective panel with both 100% uniformity and reflectance of 1.0 x MgO is difficult to achieve. Therefore, in the viewing region, the reflective panel should be improved to achieve reflectance and uniformity larger than 0.8 x MgO and 80%, respectively, in order to display paper-white image. In other words, the product of maximum reflectance and uniformity should be larger than 0.6 x MgO in the viewing region to achieve the paper-like image.

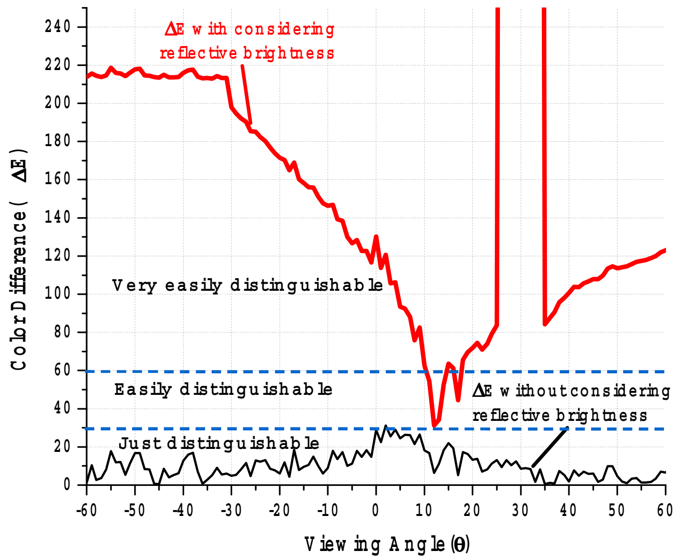



**Fig. 3** Measured color difference (ΔE) of an LCD panel with DMSR structure.

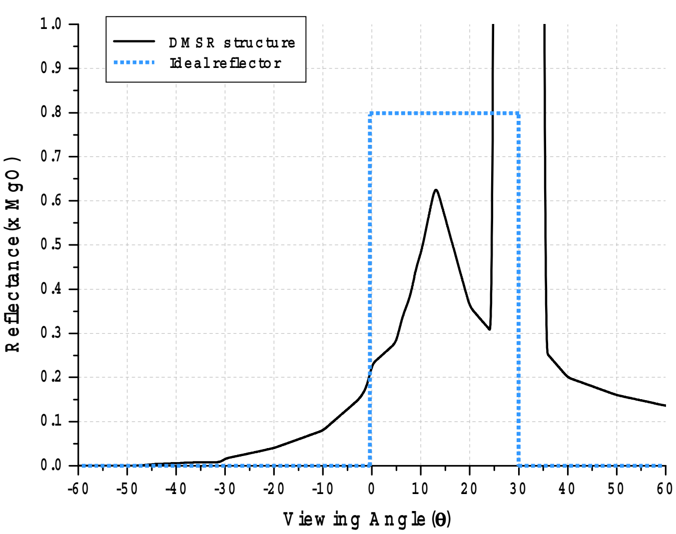



**Fig. 4** Reflective light intensity distribution of an LCD panel with DMSR structure.

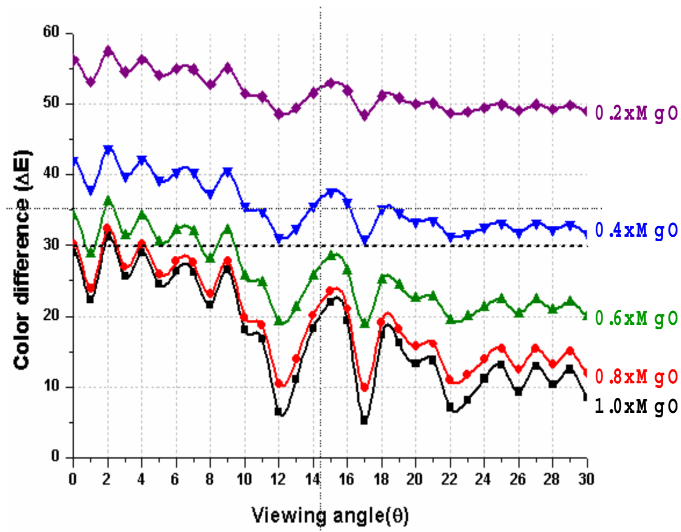
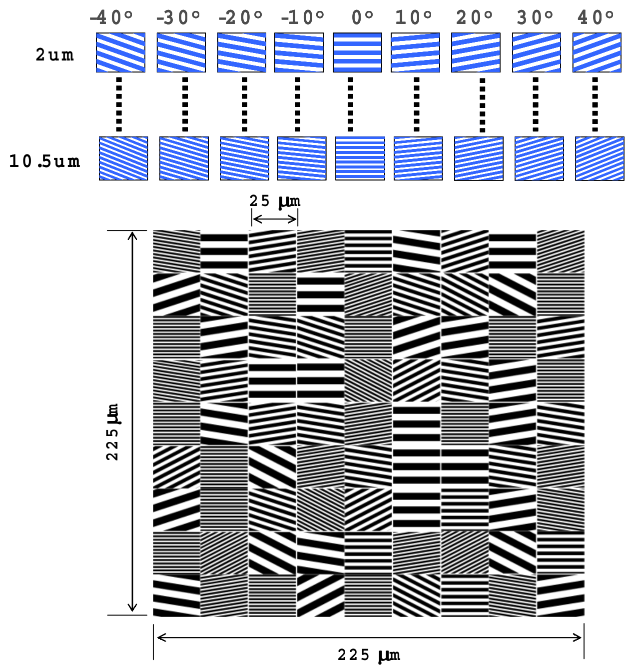



**Fig. 5** Calculated color difference (ΔE) with different reflectance in the viewing region from 0° to 30°.

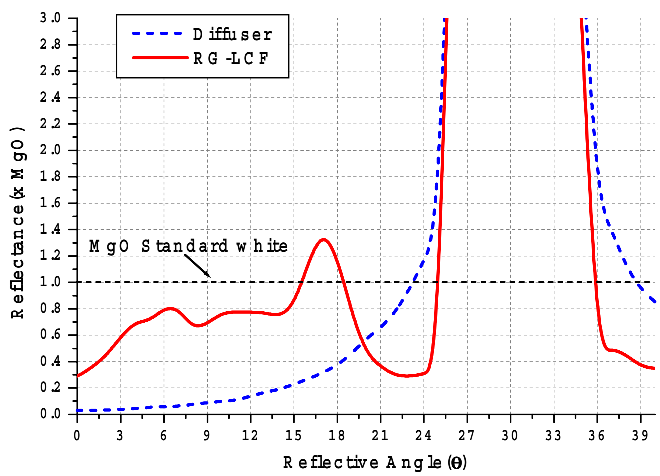
## 4. Random grating LCF (RG-LCF)

There are several reflected light enhanced components had been proposed to improve the brightness effectively, such as rough surface reflector[5], holographic reflector[6], front scattering film[7], and light control film[8], that can much improve the brightness to realize a paper-like reflective display. However, according to the calculation of Fig. 5, these components are still can not achieve both high reflectance and high uniformity as white paper.

We proposed random grating light control film[9], as shown in Fig. 6(a), to enhance the reflectance and uniformity for reflective LCDs. The new grating structure can control the uniformity of the reflected light if the grating pitches and orientations are properly designed. Optical simulation software, ASAP, was used to design and analyze the reflected light distribution of a reflective TFT-LCD. In our design, the gratings of the light control film has 18 different pitches, 2 to 10.5µm, and 9 different orientations ranging from -40° to +40°, as shown in Fig. 6(a). Additionally, the size of each grating is 25×25µm$^2$ and the arrangement in a single pixel is totally randomized, as shown in Fig. 6(b), in order to avoid the moiré patterns and dispersion.




(a)




(b)

**Fig. 6** (a) Top view pattern and (b) reflective light intensity distribution of random grating LCF.

Yet, the random grating LCF is still not qualified to achieve the ideal reflective light intensity distribution, as shown in Fig. 5(b), due to the diffraction efficiency is not high enough. However, it appears that the grating structure really can control the distribution of reflective light to have better uniformity and brightness. In order to increase the diffraction efficiency, we are working on designing and fabricating the random grating structure onto the bottom reflector. In addition, the grating pitches can be modified for R, G, and B, three sub-pixels, respectively, to avoid the color dispersion. Thus, the reflective light can be easily controlled by the gratings to have much more uniform distribution and high reflectance in the viewing region to display a pure white image.

## 5. Conclusions

Whiteness appearance of reflective LCDs is required for paper-like readability. Among the factors affecting whiteness appearance, conventional reflective TFT-LCDs using Al reflector, MTN mode with wide band retardation film and color filter have minor effect on color shift. In addition, oblique incidence only causes "just distinguishable" color shift. However, the most serious factors affecting whiteness appearance are the inadequate reflective brightness and the non-uniformity of reflective light distribution. Accordingly, a reflective TFT-LCD which has the reflector constructed by specially designed gratings is still on working to yield reflectance of 0.8 x MgO and 80% uniformity in the viewing region to achieve the paper-white image.

## 6. Acknowledgements

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