# Novel Reflective LCD Technology

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## Abstract

RGB directive color reflectors with different directive angles were prepared and assembled into reflective color LCD panels with a single polarizer. A moving image with directive color reflection was successfully demonstrated using a TFT drive. It was revealed that brightness was enhanced by gain reflection, contrast was improved by off-axis reflection, and color gamut was expanded by holographic color reflection within a directive angle corresponding to half of a viewing angle.

## Introduction

An MIM-driven reflective color LCD was developed by replacing a backlight in transmissive LCDs with a diffusive reflector[1]. The display showed a brightness of 14% at the expense of color gamut to get a brighter image and showed a contrast of 8. A reflective LCD using an electronically controlled birefringence mode was also developed and showed a brightness of 20% and a contrast of 3[2]. The display was commercialized as a multi-color electronic organizer without a color filter. A Guest Host LC mode was employed to get 4096 colors in a reflective LCD without a polarizer[3]. The device was driven by TFTs and gave a brightness of 30% and a contrast of 5. A single polarizer mode was expected to give a higher contrast and a faster response than those of a GH mode. This mode was incorporated into the reflective display with a brightness of 30% and a contrast of 10 with a grayscale of 64[4].

Printed matter such as newspapers give a brightness of 50% and a contrast of 5. Therefore, it is very important to increase the brightness of reflective LCDs to give a display quality better than that of newspapers. The present technology was developed to give a reflective display of high brightness, high contrast, and wide color gamut under the new concept of directive color reflection.

## 1. Directive color reflection

A rough surface metallic reflector was placed in commercial products such as HR-TFT displays[5]. Due to its roughness, this reflector reflects incident light in a specular direction with diffuse components. Therefore, the display gives the brightest image in the specular direction. However, the contrast will be the lowest due to specular reflection based on many interfaces inherent in the device structure. Users usually look at the display from directly in front. Thus, if there is an off-axis reflection reflecting incident light with an incidence angle of 30 degrees into the surface normal direction, then it will give the brightest image with high contrast. The present technology of directive reflection utilizes off-axis reflection with a directive angle, within which reflected light is confined. **Fig. 1** summarizes reflection gain under various incident light as a function of the root mean square of the inclination angle with a Gaussian distribution. The maximum gain of 1.6 was estimated at the incident angle of 30 degrees. This maximum value was confirmed through experiments[5]. A reflection gain of 4 was derived using the equation of gain = $1/(\mathrm{Sin}\,\theta\ \mathrm{d})^2$, where directive

angle $\theta$d means a polar angle of 30 degrees. In the derivation of the equation, reflection luminance is assumed to be constant within the directive angle and zero outside the angle. In connection with this gain, the experimental reflection gain of 3.5 was revealed in the previous paper[6]. These results show that directive reflection holds promise for enhancing brightness.

Color gamut was made narrow to increase brightness in the device using an absorption-type[1] color filter. Reflective holographic color filters are expected to give highly saturated colors since a single mode frequency laser light source is employed to fabricate color reflectors. However, a low efficiency of ambient visible light with a wavelength



Fig. 1 Reflection gain of rough surfaces.

region of 380 to 780 nm occurs as long as the reflection bandwidth of the reflectors remains in the typical values around 20 nm, even if the spectral reflectivity reaches 100%. To avoid poor efficiency, the bandwidth of RGB reflectors has to be made up to about 100 nm wide to provide the same color gamut as transmissive LCDs.

This novel technology was developed to simultaneously give high brightness, high contrast, and wide gamut in reflective color LCDs, even though these three factors normally conflict with each other.

## 2. Fabrication of directive reflection film

A double beam exposure method in the holographic procedure was used to implement directive color reflection. To this end, a micro-lens array was employed to determine the directive angle. An object beam was prepared by passing one of the two laser beams through the array perpendicularly. The reference beam was exposed to a holographic recording medium (purchased from Dupont) from the opposite side of the object beam, with a polar angle (an off-axis angle) shifted from the surface normal direction of the medium.

The interference fringe is a plain structure with an inclination angle depending on the off-axis angle when the directive angle is zero. RGB reflectors with this structure give metallic RGB colors, which generate a mirror reflection as a result of color mixing. Thus, display image will deteriorate when an ambient light source is superimposed. It is very important to employ non-zero directive angles to display a white state instead of a mirror state. A small directive angle of $\theta$d gives high brightness at the narrow viewing angle of 2$\theta$d.



Fig. 2 Broad reflection bandwidth of chirp hologram.



Fig. 3 Pixilated directive color reflector.

The patterning of the RGB striped reflector as a reflective color filter was made by placing two sheets of photomasks to sandwich the medium, exposing RGB light three times after shifting the medium with the desired stripe width through the dry process of room temperatures and atmospheric pressures. A film containing a photomonomer was placed on the pixilated film under the optimized diffusion conditions of
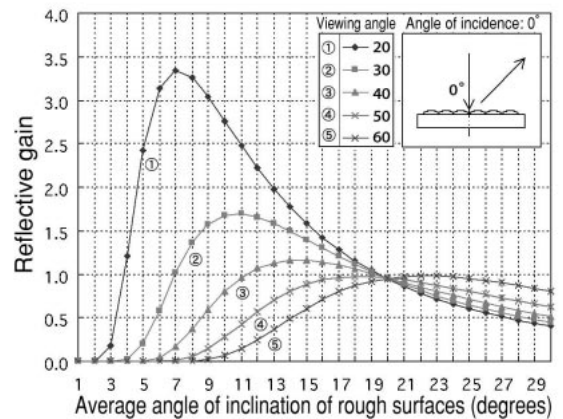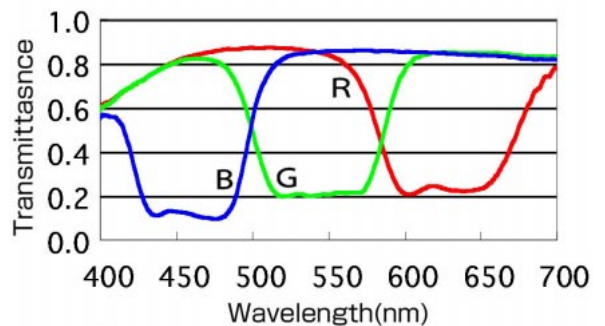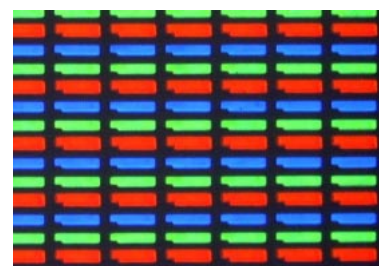
temperature and time to make a wide reflection bandwidth. After this treatment, interference fringe with a bent structure determined by the array was dilated with respect to the fringe periodicity[7]. A chirp hologram thus obtained was fixed by UV exposure (1 J/cm$^2$) and thermal curing at a temperature of 120 degrees Celsius for 2 hours.

Holographic fringe in the directive color reflector varies with respect to the periodicity among RGB regions and shows the same bent structure in the RGB regions to give the same reflection profile. This profile is necessary to display full colors based on a principle of color mixing. One of the optimized reflective color filters using the transmission spectra is shown in **Fig. 2**. **Fig. 3** shows a photo of the RGB pixilated reflector with a dot pitch of 96 mm compatible with a TFT array on an upper substrate.

## 3. Evaluation of TFT-driven panels

Reflective LCDs driven by TFTs were fabricated using a single polarizer and directive color reflectors with three different directive angles. The relation between directive angle and brightness is summarized in **Fig. 4**. A single polarizer reduces the utilization efficiency of incident light to 43%. If reflective color gamut were the same as that of transmissive LCDs, the efficiency would be further lowered to 30.7%. Therefore, the overall efficiency will be estimated to be 6.25% if the aperture ratio of the TFT panel is 50%. **Fig. 4** predicts that a brightness of 60% is available at the directive angle of 20 degrees under the conservation law of energy amounting to 6.25% of incident light. A viewing angle of 40 degrees is believed large enough to give satisfactory viewing to a single user using a mobile display with directive reflection.

It is very important for a reflector to show no retardation of reflection at the reflector in the LCDs using a single polarizer mode, since the optical phase is modulated by an electric field. In other words, the ellipsometric parameter $\Delta$ should be 180 degrees at the air-reflector



Fig. 4 Luminance enhancement as a function of directive angle.
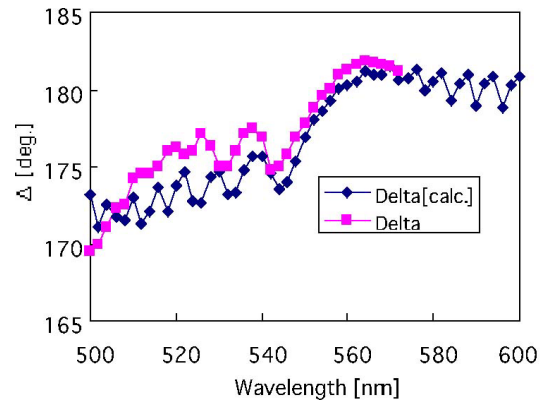


Fig. 5 Retardation generation at directive reflector (Green).

interface, where the parameter $\Delta$ is the phase difference between the p- and s- reflection coefficients. The parameter was measured ellipsometrically on a sample of the green reflector with chirp structure and an off-axis angle of 30 degrees. This parameter was calculated assuming a dilation of 0.01% per interference fringe for the sample mentioned above. The calculated and measured parameters were found to be similar and the magnitude to be close to 180 degrees, as shown in **Fig. 5**.

After a sheet of thin glass with a thickness of 50 $\mu$ m was placed on the directive film to prevent deterioration of the film, a TFT panel was fabricated. This thickness is small enough to suppress parallax. Three TFT panels (DDA10, DDA20, DDA30) were prepared using three different directive angles of 10, 20, and 30 degrees, operating on a single polarizer mode.
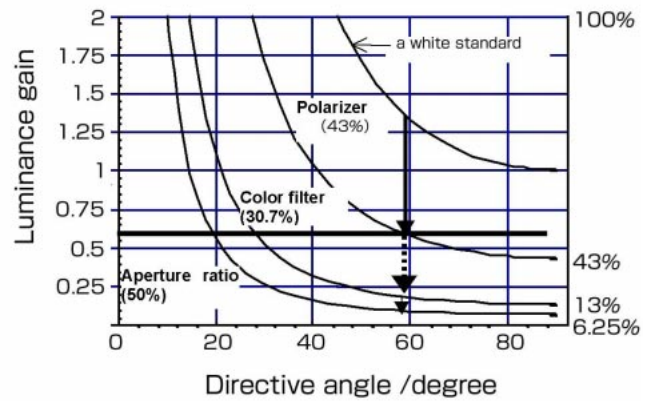
Fig. 6  Reflection profiles of three samples. (DDA10, DDA20, DDA30)
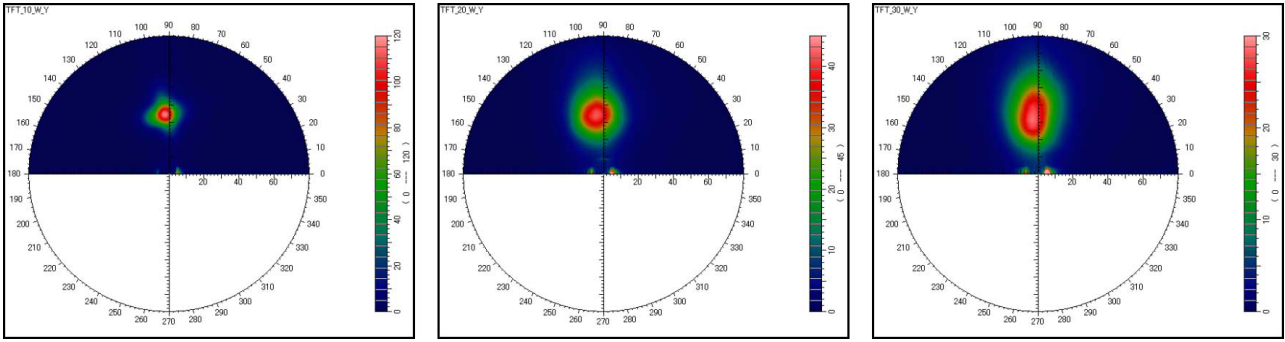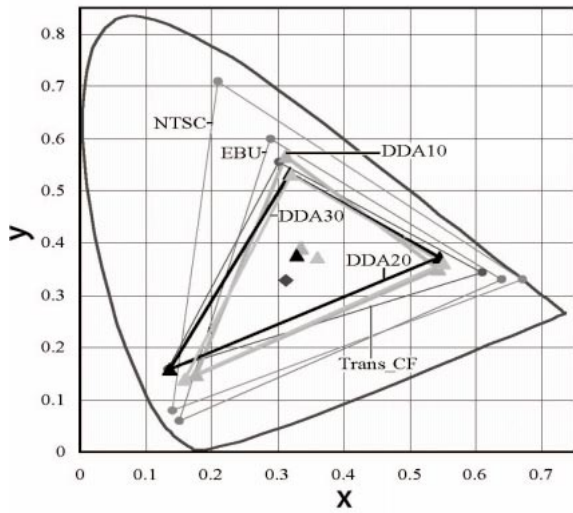


Fig. 7  Color gamut of panels.

Table 1  Specifications of panels.

| Panels | DDA10 | DDA20 | DDA30 |
|---|---|---|---|
| Brightness | 117.5 | 42.3 | 28.9 |
| Contrast | 14.4 | 28.4 | 19.1 |
| Color gamut | 79.9 | 71.9 | 74.6 |
| Viewing angle | 12.5 | 24.5 | 35 |

Brightness is normalized as 100% for a white standard.
Color gamut is normalized as 100% for a color filter of transmissive LCDs (Illuminant D65)

A commercially available personal digital assistant (Sharp Zaurus) was employed to drive the panels to display 8 colors (Red, Green, Blue, Cyan, Magenta, Yellow, Black, White). The brightness and reflection profile was evaluated at the white image region in the panel. After measuring the black display image, contrast was evaluated. Color gamut was evaluated by measuring the color coordinates of red, green, and blue images. **Fig. 6** describes luminous reflectance profiles at the normal incidence, showing the off-axis angle of 30 degrees. The profile was used to determine the peak reflectance and the directive angle at half the width and half the height. Color gamut is summarized in **Fig. 7**, showing that the present gamut of three panels is as wide as that of transmissive LCDs. **Table 1** summarizes the characteristics of the panels, showing a brightness of 42%, a contrast of 28, and a color gamut of 72% for the DDA20 sample. It is possible to get a brightness of 60% by employing an aperture ratio of 70% instead of 50%. It is worth noting here that the 8-color bar display fabricated last year showed a brightness of 127%, a contrast of 29, and a gamut of 100%, with a viewing angle of 17 degrees[8].

The directive color reflectors themselves showed an energy efficiency of 11 to 12% at an aperture ratio of 50%. Therefore, the overall efficiency will be 5-6% for the single polarizer display mode. However, the experimental value was 2.5%. On the other hand, the panels driven by MIMs showed an efficiency of 5% with the reflectors placed inside of them. The small efficiency is due to the light-guiding effect of a sheet of thin glass placed externally in the present fabrication.

## 4. Conclusions

It was demonstrated that reflective LCDs with high brightness, high contrast, and wide gamut are possible using directive color reflection. Directive color displays will be a very promising application as mobile displays on networks are used by large numbers of people. Although viewing angle was sacrificed, these displays provide electronic added value as secure displays in an era of e-commerce and on-line transactions.

## Acknowledgement

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