

# A Color-Filterless LCD with RGB LED and Lenticular-Lens Arrays

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## Abstract

A direct-lit liquid crystal display that does not use color filters is proposed. A backlight unit that employs compartmentalized RGB LED and lenticular-lens arrays is used instead of color filters to direct the RGB LED lights into the RGB subpixels. The color-filterless LED backlight design, simulation, and experiment results are presented.

**Keywords:** Color filter, lenticular lens, LED

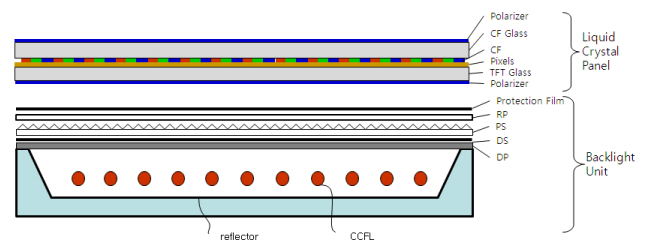
## 1. Introduction

Liquid crystal display (LCD) has become a major flat panel display due to its large size, good image quality, and affordable cost. The requirements of the future LCD will be a high contrast ratio through the use of a local dimming technology, low motion blur, more natural color, and an energy-saving technology. Among the key issues related to the LCD is that its light energy efficiency is poor (about 5-7%) because most of the lights from the backlight disappear while passing through the liquid crystal panel. Fig. 1 shows the typical structure of an LCD, including the backlight unit (BLU). When the lights from the BLU pass through the liquid crystal panel, the polarizer absorbs more than 50% of the incident light, and the color filter (CF), about 70% thereof. As such, the light efficiency can be improved by as much as 300% if the color filter will be removed. The field sequential color (FSC) technology has been studied widely because the subpixels and color filters are actually not needed. Moreover, the aperture ratio is greatly increased when the FSC technology is used. It has been shown to be very difficult to commercialize, however, because of its color breakup (CBU) and fast scan rate, which should be as high as six times that of the conventional LCD [1-3]. For example, a white moving image is divided into red, green, and blue images because red, green, and blue LEDs are turned on sequentially, or if the eyes move while watching

the LCD screen, the CBU phenomenon will occur for the same reason.

Y. Taira et al. proposed an edge-lit color-filterless LCD that uses grating and lenticular-lens arrays [4-6]. They were successful in removing the color filter and presented a prototype notebook with their color-filterless LCD. Their method, however, is hard to apply to the direct-lit LCD backlight because there are scattered rays with random directions in the backlight unit. K. Kitamura invented a color-filterless projection-type LCD by employing a dual microlens array [7].

In this paper, for the first time, to these authors' knowledge, a direct-lit color-filterless LCD is proposed by introducing a backlight that employs compartmentalized RGB LED and lenticular-lens arrays. The lenticular lenses are grouped and designed to image the RGB LEDs onto the RGB subpixels in a one-to-many manner so that the red subpixels will receive only red lights from the red LEDs, and the same for the G and B subpixels. Moreover, color uniformity can be obtained by placing a Lambertian diffusing layer in the position of the color filter or outside the color filter glass. The operation principle and simulation



**Fig. 1.** Typical structure of a direct-lit LCD. CF: color filter; RP: reflective polarizer; PS: prism sheet; DS: diffuser sheet; DP: diffuser plate; CCFL: cold-cathode fluorescent lamp.

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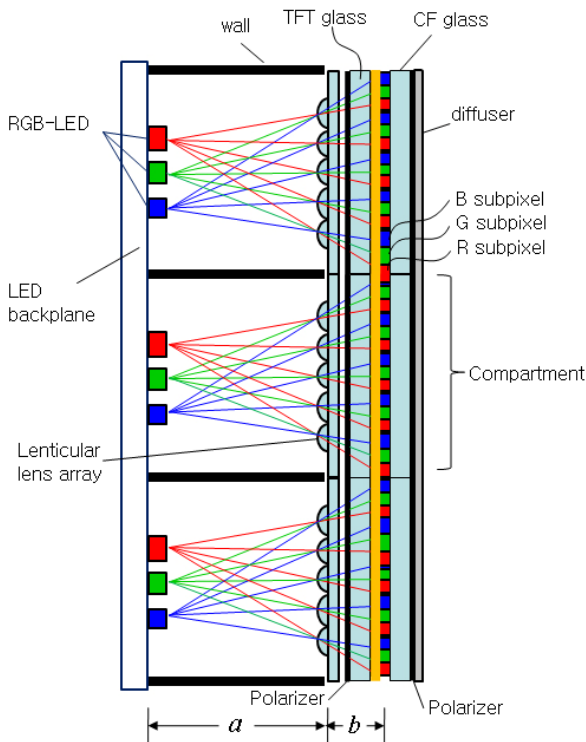
and experiment results are presented herein.

### 2. Design

Fig. 2 shows a schematic diagram of the color-filterless LCD. The red lights from a red LED are imaged onto the multiple red pixels by the multiple lenticular lenses according to the imaging formula.

$$\frac{1}{a} + \frac{1}{b} = \frac{1}{f}, \tag{1}$$

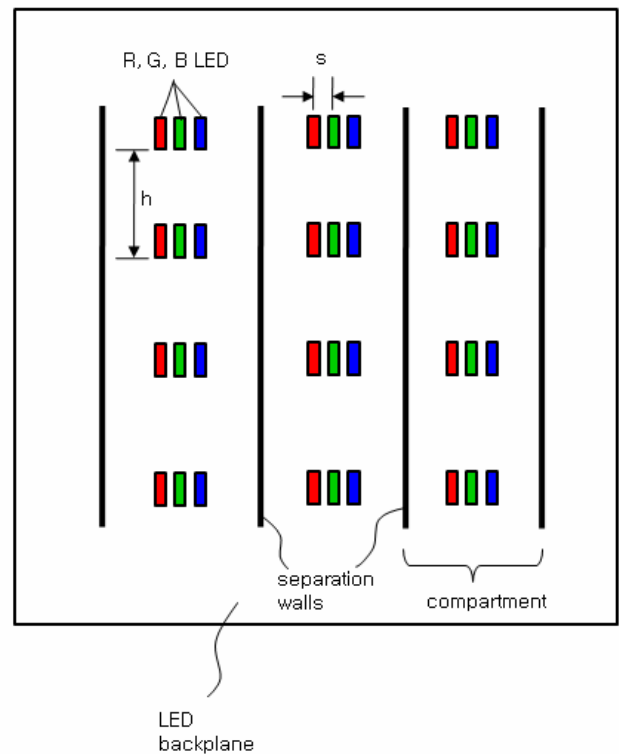
where  $a$  and  $b$  are the distances between the RGB LED and lenticular-lens arrays and between the lenticular-lens array and the color filter, respectively, and  $f$  is the focal length of the lenticular lenses. Similarly, the green and blue lights from the green and blue LEDs are incident on the multiple green and blue subpixels, respectively. There exist multiple compartments of the above structure that are parallel with one another, and each compartment is separated from the others by separation walls to prevent light mixing



**Fig. 2.** A schematic diagram of the color-filterless LCD with RGB LEDs and lenticular lenses.

on the same subpixel from the adjacent compartments. The LCD may further include a Lambertian diffusing layer interposed between the CF glass substrate and the R, G, and B liquid crystal subpixels or outside the CF glass, to make the lights diffuse and propagate in the normal direction of the CF glass. The Lambertian diffusing layer may be formed of transparent resin in which beads or particles are dispersed. The lenticular-lens array sheet can be attached to the thin-film transistor (TFT) glass of the liquid crystal panel so that the positions of the lenticular-lens elements and the pixels will coincide with each other. The width of each lenticular-lens element is almost the same as that of the pixel. As the RGB LEDs are separated by separation walls placed between the LEDs and the lenticular lenses, the lenticular lenses are also grouped in the compartments.

Fig. 3 shows a layout of the RGB LEDs, compartments, and separation walls. The RGB LEDs are grouped and placed periodically along the horizontal and vertical directions, and the separation walls along the vertical directions between the RGB LED groups. The spacing  $s$  between the LEDs is determined by the magnification ratio of the

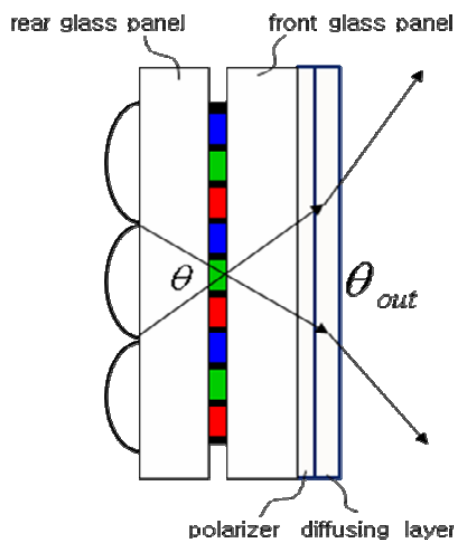


**Fig. 3.** Layout of the RGB LEDs, separation walls, and compartments in the LED backplane.

lenticular lens and is given by  $s=Mp$ , where  $M$  is the magnification of the lenticular-lens elements and  $p$  the spacing between the RGB subpixels.

The directions of the RGB lights from the RGB LEDs differ with one another after passing through the RGB subpixels, which may cause angular color breakup and luminance non-uniformity. This angular color breakup can be eliminated by placing a Lambertian diffusing layer between the RGB subpixels and the CF glass panel, or outside the CF glass panel. If the diffusing layer is placed outside the polarizing sheet of the CF glass panel, the image sharpness may deteriorate. If it is placed between the subpixels and the front glass panel, there should be no polarization change due to the diffusing layer.

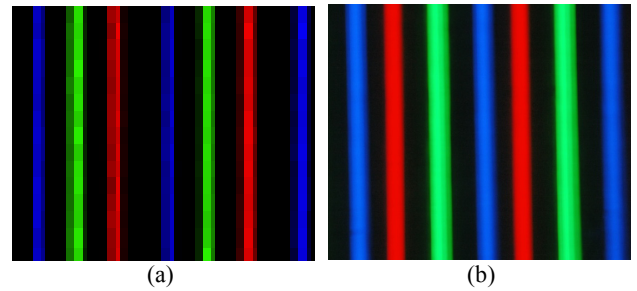
Fig. 4 shows the expansion of the view angle by the Lambertian diffusing layer placed outside the polarizer sheet. If there is no Lambertian diffusing layer, the view angle  $\theta_{out}$  will be less than  $60^\circ$ . As this is too small, the Lambertian diffusing layer placed outside the polarizer sheet or between the subpixels and the front glass panel can increase the view angle up to  $180^\circ$ .



**Fig. 4.** Expansion of the view angle by the Lambertian diffusing layer placed outside the polarizer sheet.

### 3. Simulation and Experiment

Fig. 5 shows a comparison of the simulation and experiment results of the system shown in Fig. 2. The simulation was performed using the Light Tools Simulation Pro-

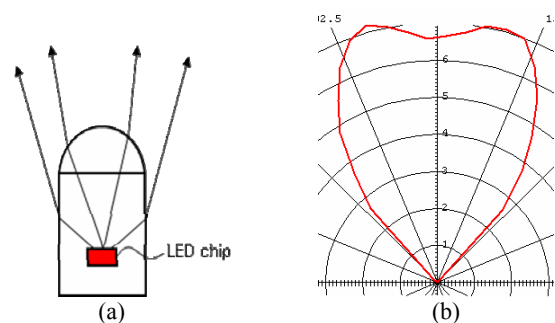


**Fig. 5.** Straight RGB lines formed by the lenticular-lens arrays obtained via simulation (a) and experiment (b).

gram. The simulation model corresponds to a single compartment of Fig. 2, with nine RGB LEDs in the compartment, because the system consists of units of the same structures. All the LEDs are aligned to aim at the center of the compartment, to reduce the color non-uniformity. About 70% of the LED lights are incident on the lenticular-lens array and on the RGB subpixels. Fig. 5(a) shows the straight RGB lines formed at the RGB subpixels obtained from the simulation. It can be clearly seen that the three color lines are very well separated, and little color crosstalks between the neighboring pixels are observed.

Fig. 5(b) shows the straight RGB lines that were obtained from the experiment setup consisting of 45 LEDs in the three compartments that were constructed according to Fig. 2. The lenticular-lens array had a width of 397 microns, with a focal length of 2.1 mm. A screen was placed at the image point of the lenticular-lens array, and magnified images were obtained using a microscope with 10X magnification. Like the simulation results, the experiment results also showed a clear separation between the three color lines.

Fig. 6 shows the simulation result for the intensity angular profile emitted from an oval-type LED. It shows a narrow angular width compared with the Lambertian angu-



**Fig. 6.** (a) An oval-type LED and (b) the angular profile of the intensity emitted from the oval-type LED.

lar profile from a LED without a coupling lens. Compared to the Lambertian profile from the LED with no coupling lens, this enhances the light energy's utility efficiency more by coming up with the angular width that best fits the compartment in which the light is confined.

#### 4. Conclusion and Discussion

A direct-lit LCD without a color filter was proposed for the first time by developing a backlight system that employs RGB LEDs and lenticular lenses disposed in the compartments. Both the simulation and experiment results show that there was little color crosstalk between the adjacent pixels in the proposed system. In addition, oval-type LEDs that emit a batwing-type intensity angular profile were designed and simulated to maximize the light utilization efficiency.

The optical-power consumption of an LCD with no color filter is as low as 30% of that of the normal LCD. As such, the number of LEDs can be reduced to a third of those in the normal LCD. Moreover, the manufacturing cost can be greatly reduced because the color filter process will be omitted in the production line and because the diffuser plate and prism sheets in the backlight unit will not be used. Uniformity can be achieved with the use of the Lambertian diffuser to be attached inside or outside the CF glass, and also by employing RGB LEDs with batwing-type intensity angular profiles. The use of RGB LEDs as a light source can extend the color gamut over that of the conventional

LCD, which uses CCFLs or white LEDs. As such, a very high image quality can be achieved. As for the thickness of the color-filterless LCD, it will be determined to be between 10 and 20 mm depending on the magnification of the lenticular-lens array. For example, assuming that the magnification and thickness of the TFT glass are 20 and 0.7 mm, respectively, the distance between the LEDs and the lenticular lenses will be about 9.3 mm. This value is smaller than that in any direct-lit LCD module. A full system, as shown in Fig. 2, is currently being developed, and further study is needed to resolve a number of important issues concerning luminance uniformity, color crosstalk, and the alignment of the lenticular-lens array and compartments with respect to the LCD pixels.

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