High Dynamic Range Mini-LED and Dual-Cell LCDs

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Abstract
Two high dynamic range displays: dual-cell LCD and mini-LED backlit LCD, are investigated. In a dual-panel display, the parallax error at large viewing angles is analyzed and mitigated by a newly proposed splitting algorithm. Besides, the image qualities of mini-LED backlit LCD are compared with OLED under different display brightness, ambient reflectance, and ambient light illuminance. The halo effect of mini-LED based LCD becomes less noticeable as the ambient light brightness increases.

Keywords
High dynamic range; mini-LED; dual panel display; ambient light; parallax error.

1. Introduction
High dynamic range (HDR) [1] is a critical requirement for display devices. HDR technology should fulfill 1) true dark state and high peak brightness, i.e. high contrast ratio, 2) wide color gamut (BT 2020), and 3) over 10-bit depths. The contrast ratio of a LCD is limited by the depolarization effect originated from TFT array, LC layer, and color filters [2]. Normally, the contrast ratio of MVA LCD is CR~5000:1 and FFS LCD is ~2000:1. The bit depth of LCD is limited by the large voltage swing, which is about 20V for the 12-bit display, and slow gray-to-gray response time.

Recently, local dimming method has significantly enhanced the dynamic range of LCDs. The backlight unit is segmented into thousands of zones and the backlight illuminance can be modulated according to the image content in different zones independently. At the dark image area, the corresponding backlight can be dimmed. Therefore, the dynamic contrast ratio of LCD can be enhanced dramatically. Moreover, this extra backlight modulation layer can provide more bit depth. With different driving circuit, the maximum voltage swing can be controlled within 5 volts.

Two main approaches for achieving local dimming have been developed: mini-LED backlit LCD and dual-cell LCD. In the former, how to choose the brightness of each backlight zone and the transmittance of LC panel simultaneously to reconstruct the targeted HDR image is important [3]. In our previous report [4], a scheme to drive backlight intensity and LC panel transmittance to achieve 12-bit perceptual quantizer (PQ) curve has been proposed.

In a dual-panel LCD, because the electro-optic properties of TN, FFS, and MVA are different so that the contrast ratio, response time, and driving scheme will also vary. In [5], we proposed a dual-cell LCD using a black-and-white TN panel as sub-cell and a full color FFS as main cell. Such a dual-panel display exhibits CR≈1,000,000:1 and over 14-bit depth at only 5 volts.

The local dimming method can be fulfilled by both direct lit or edge lit LED [6, 7]. The zone number and intrinsic LC contrast ratio are two key factors to influence the image quality [8]. The number of mini-LED zones to achieve comparable image quality with OLED display is crucial. From human visual experiment [9], we established an important guideline on the required zone number, which depends on the LCD's static contrast ratio, in order to achieve indistinguishable image quality between mini-LED backlit LCD and OLED display.

In this paper, we address two critically important issues on HDR LCDs: 1) the parallax error in dual-panel display at large viewing angles, and 2) ambient light effect on the image quality of mini-LED backlit LCD.

2. Parallax error in a dual-cell LCD
The device structure of a dual-cell LCD consists of two LC panels: sub cell (B/W) and main cell (full color). The backlight intensity will firstly be modulated by the sub cell with lower resolution, e.g. 2K1K. According to the spatial intensity profile of the sub cell, the transmittance of high-resolution (e.g. 4K2K) main cell is designed to reconstruct the HDR image. However, parallax error is a critical issue for the dual-cell LCD [10]. The parallax error originates from the misalignment of sub cell and main cell in a large viewing angle. As Fig. 1 depicts, at normal view (θ=0), the light coming from each zone of sub cell passes through the corresponding zone in main cell. However, as θ increases, the brightness of the main cell in zone 2 will be affected by the light from zone 1 and zone 2 of the sub cell. As a result, crosstalk happens at large viewing angels.

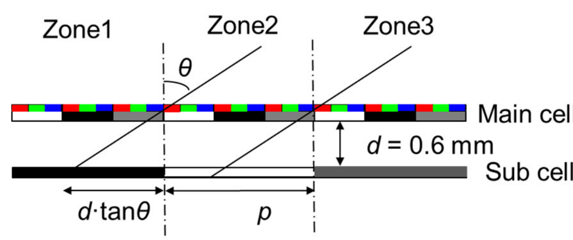

Fig. 1. The shift of backlight zone at a large viewing angle

To evaluate the parallax error effect of a dual-cell LCD, we perform simulations by MATLAB. In our simulation, the gap distance between sub cell and main cell is 0.6 mm, including TFT substrate (300µm), polarizer (100 µm), analyzer (100 µm), and glass substrate (100 µm). As Fig. 1 depicts, the shift distance is $d \times \tan\theta$. Figure 2 shows the simulation results. The control image, dual-cell image, and the dual-cell image with our newly proposed splitting algorithm at normal angle is shown in Fig. 2(a-c) and the result at 60º viewing angle is shown in Fig. 2(d-f), respectively. From Figs. 2(d) and 2(e), the parallax error is noticeable near the fire area. However, the dual panel with our new splitting algorithm shows a much improved image quality at large viewing angle (Fig. 2(f)), while maintaining high image quality at normal angel (Fig. 2(c)). Details of our new method will be discussed later.

In addition to visual comparison, we also use the color difference to quantitatively analyze the parallax error between two images. In Fig. 3, a relatively large color difference appears in the boundary of the candle, which represents the high frequency area in the picture. The misalignment in the high frequency area will cause backlight illuminance to vary dramatically. The ΔL values (the intensity of control image minus the intensity of dual panel image) are plotted in Fig. 3(b). At θ >0, the backlight shifts toward the right so that the intensity at the left side of candle decreases, and that at the right hand of candle increases.

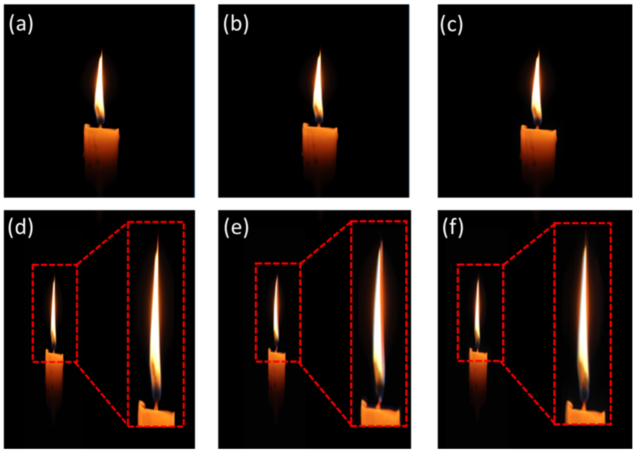

Fig. 2. (a-c) The target image, dual panel image, and the dual panel image with our new proposed splitting algorithm at θ=0°, and (d-f) Simulated results at θ=60° viewing angle.

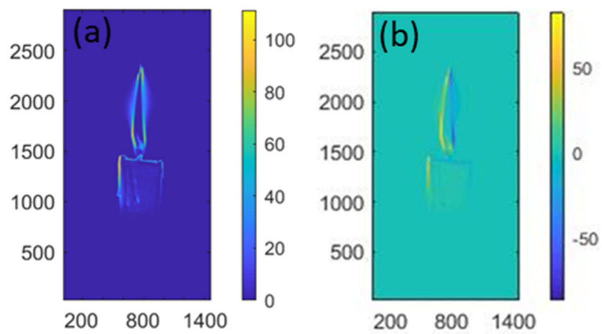

Fig. 3. (a) The color difference, and (b) the delta L at θ=60° viewing angle.

To reduce parallax error, we add a low pass filter in the sub cell to smoothen the backlight intensity variation at high frequency area. In our simulation, we applied 2D Gaussian filtering:

$$I = \exp[-\frac{(x-x_0)^2+(y-y_0)^2}{2\rho^2}] \quad (1)$$

to smoothen the backlight intensity distribution. In Eq. (1), ρ is a Gaussian fitting parameter. As ρ gets larger, the frequency of the image decreases. Therefore, the parallax error can be reduced. However, due to the blurred backlight illuminance, the reconstructed image quality at normal angle is decreased. To restore the image quality, we propose a new method in which the sub cell intensity in each zones is defined by:

$$L_{nm} = \text{Max}\,(L_{nm}(\text{w/o filter}), L_{nm}(\text{Gaussian filter})) \quad (2)$$

where [n, m] stands for the sub-cell's resolution. We take the maximum value of original image and Gaussian filtering image as the intensity of sub cell. Figure 4(a) depicts the intensity in sub cell without Gaussian filter and Fig. 4(b) shows the Gaussian filtering with ρ = 3mm, which is the optimized value in our simulation. Finally, Fig. 4(c) shows the intensity distribution of our proposed method.

The LabPSNR of dual panel image against the control image is shown in Fig. 5. We find that the new splitting algorithm can substantially enhance the image quality at large viewing angles. At θ=0°, the LabPSNR in both conditions are all over 47.4dB, which indicates that most of people cannot notice the image difference between the dual-cell image and the target image [9].

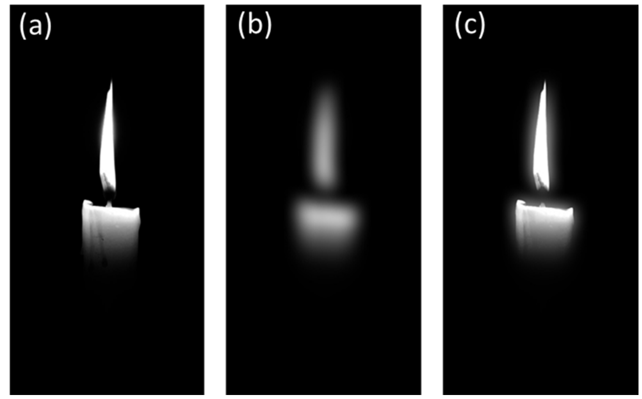

Fig. 4. Simulated intensity distribution of (a) without Gaussian filter, (b) with Gaussian filter at ρ = 3mm, and (c) our newly proposed method.

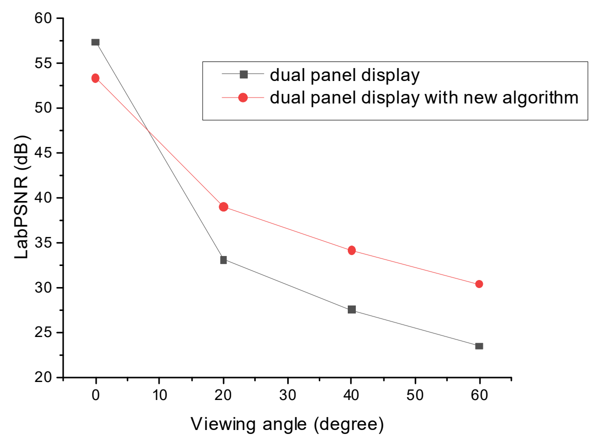

Fig. 5 The PSNR of dual panel display with and without improvement at various viewing angle.

3. Ambient light effect on Mini-LED LCD

The goal of local dimming is to minimize the light leakage in the dark state so the contrast ratio can be improved. In our previous work, we have investigated how local dimming zones and LC contrast ratio influence the image quality at dark environment [8]. However, in practical applications the ambient light effect should be considered as well because it could wash out the local detail of image content and shrink the color saturation of the image. On the positive side, the halo effect, which degrades the image quality of mini-LED backlit LCD, is also lessened because of the reduced ambient contrast ratio.

We simulate a 6.4-inch 2880 × 1440 LCD system with mini-LED backlight, which is same as our previous study. The LCD's static contrast ratio is 2000. The spacing of mini-LED is 1 mm and the number of local dimming zones is 288. Two types of ambient reflectance at normal angle: 4% (without anti-reflection film), and 1.2% (with anti-reflection film) of OLED display and mini-LED LCD are investigated. Here, just noticeable difference (JND) is used to evaluate the image quality under the ambient light environment [11]. Because human visual system is most sensitive to the luminance variation at white color, we convert our image to grayscale image in the following simulations.

The threshold versus intensity curve [12] defines the threshold luminance variation that human can distinguish the difference in each luminance. Figure 6 shows how many JNDs in each luminance in the linear scale.

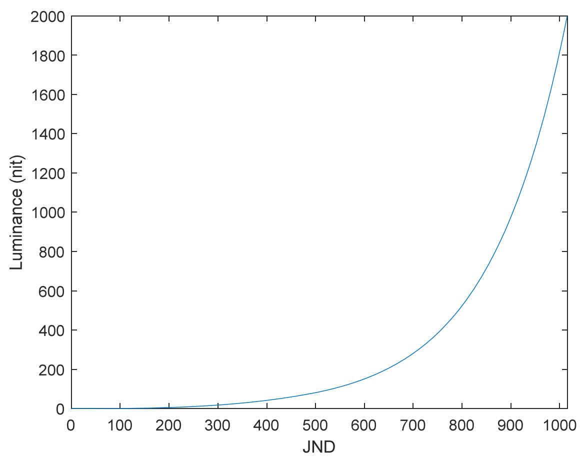

Fig. 6. The luminance as a function of just noticeable difference

The JND of each pixel between two different images can be calculated by following equation:

$$E_{12}(m,n) = JND@L_1(\mathrm{m,n}) - JND@L_2(\mathrm{m,n}) \quad (3)$$

where E_{12} represents how many JND between two images in each pixel, [m, n] stands for the LC panel's resolution., and L_1 and L_2 stand for the luminance on each pixel in image 1 and image 2. For example, if $L_1 = 400$ nits, then from Fig. 6 its corresponding JND level is 756, and for $L_2 = 200$ nits, its corresponding JND level is 645. Thus, E_{12} is equal to 756–645, which is 111.

In Figure 7(a-d), the JND between OLED display and mini-LED backlit LCD is illustrated. The ambient reflectance is 4%, the ambient light is [0, 100, 300, 10000] lux, and the peak brightness of both displays are 500 nits. We can clearly observe that the JND value at the edge of the candle is large in the low ambient light condition. This is attributed to the inadequate zone number (288). Therefore, the halo effect can be easily detected by human eye. However, as the ambient light illuminance increases, the JND value decreases, as noticed by the vertical scale bars. As a result, the halo effect gradually becomes unnoticeable.

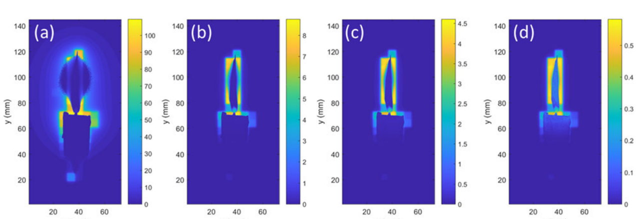

Fig. 7. (a-d) JND between OLED display and mini-LED backlit LCD. Ambient reflectance is 4% and ambient light illuminances is [0, 100, 300, 10000] lux, respectively.

The anti-reflection film is applied in many applications such as TVs and monitors. To evaluate the influence of different ambient reflectance, we set the ambient reflectance at 1.2%. Figures 8(a) and 8(b) show the simulated JND at different ambient reflectance 4% and 1.2%, respectively, at 100-lux ambient light. As the ambient reflectance gets smaller (Fig. 8(b)), the halo effect is more noticeable. On the other hand, if the ambient reflectance gets larger (Fig. 8(a)) or the ambient illuminance increases, the reflected light from the display panel will increase, which in turn will smear the halo effect of mini-LED backlit LCD.

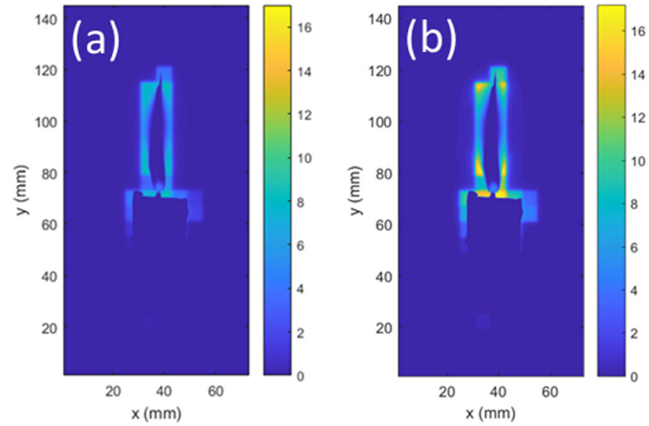

Fig. 8. JND between OLED display and mini-LED LCD at (a) 4% and (b) 1.2% ambient reflectance. The ambient light illuminance is 100 lux.

For an OLED display, there is always tradeoff between brightness and lifetime. However, the brightness of mini-LED backlit LCD can be much higher. The high brightness of display helps maintain image detail at strong ambient light condition. In the following, we set the peak brightness of mini-LED LCD at 2000 nits and OLED display at 1000 nits, while the ambient light is 500 lux. The JND between mini-LED backlit LCD and target image is shown in Figure 9(a), and the JND between OLED display and target image is shown in Figure 9(b). Here, the reference is target image without ambient light, i.e. the dark state is almost zero luminance. Therefore, the JND is large at dark area. To present the JND in the candle area, we set the maximum scale bar at 20 JND, as Figures 9 (c) and 9(d) depict. In comparison with OLED display image, mini-LED LCD exhibits less JND in the candle area. As a result, more image detail can be resolved by the high brightness mini-LED LCD when a 500-lux ambient light is present.

Figure 10 shows the average JND difference between OLED and mini-LED backlit LCD. A negative value means the average JND of OLED is smaller than that of mini-LED LCD, that is to say, OLED has a better image quality than mini-LED LCD. On the other hand, a positive value means mini-LED LCD has better image quality than OLED. From Fig. 10, the crossover point happens at ~500 lux, which is about the office ambient lighting condition. This crossover point will shift toward left (i.e. a lower value) as the local dimming zone number of a mini-LED backlit LCD increases or the LCD's static CR increases.

Here, we show the trend of image quality variation at the presence of ambient light. Further human visual experiment to validate our analysis is still required. However, from above discussion, because the halo effect is less noticeable under ambient light, the required zone number for mini-LED backlit LCD to achieve the same image quality as OLED display at ambient light condition should be much smaller than that at dark environment.

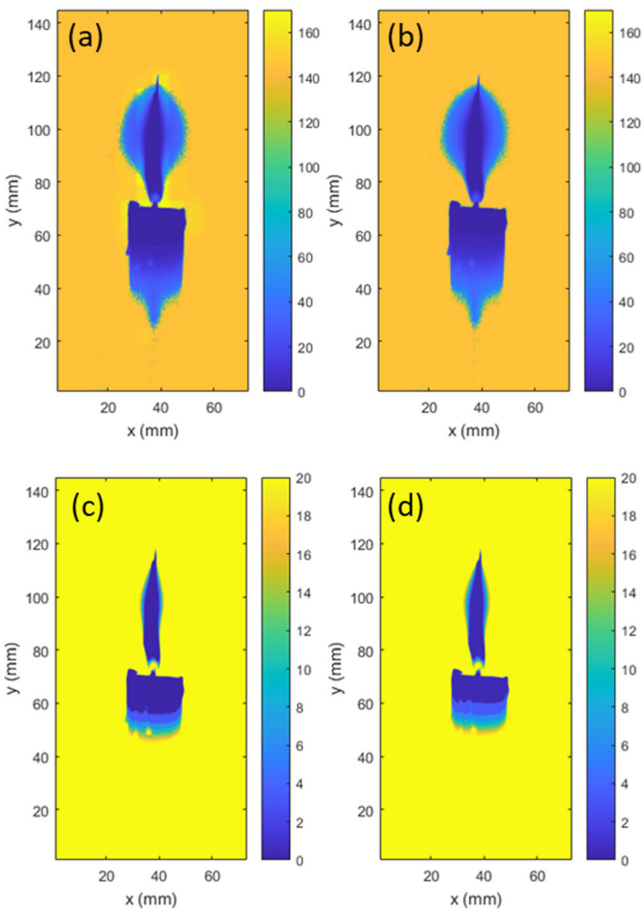

Fig. 9. (a) JND between mini-LED backlit LCD image and target image, (b) JND between OLED display image and target image. (c, d) represent Figure 9(a, b) with maximum scale bar = 20 JND.

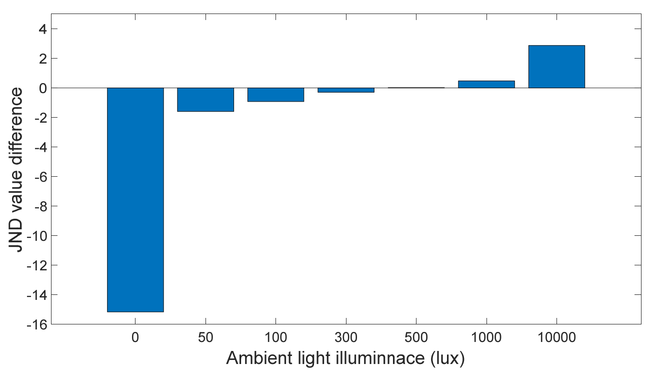

Fig. 10. Simulated average JND value difference between OLED and mini-LED backlit LCD at different ambient light illuminance.

4. Conclusion

We have analyzed the parallax error in a dual panel display and proposed a new LC splitting algorithm to relieve the parallax error, while retaining the image quality at normal angle. In addition, we discuss the ambient light effect on mini-LED LCD display. The undesirable halo effect is more forgiven as the ambient light increases. What's more, due to the tradeoff between brightness and lifetime in OLED displays, the higher brightness mini-LED LCD can provide better image quality than OLED display at ambient lighting environment. In our simulations as mini-LED LCD is 2000 nits and OLED display is 1000 nits, the image quality of mini-LED LCD is better than OLED display as the ambient illuminance in larger than 500 lux.

5. Funding

a.u.Vista, Inc.

6. References

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