Mini-LED Backlight with Reduced Halo and Narrowed PSF for Virtual Reality Application

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Abstract
This study optimizes the PSF curve and brightness of mini-LED backlight units (BLUs) for VR applications, addressing halo reduction, brightness enhancement, and contrast improvement. A customized light guide plate (LGP) effectively minimizes halo diffusion, enhances luminance, and maintains uniformity. The approach supports local dimming algorithms, contributing to better image contrast and overall display quality.

Author Keywords
mini LED; Halo Effect; PSF; Luminance; Contrast ration.

1. Introduction
As a carrier for entering the 'metaverse', VR immerses users completely in a virtual environment through interactive devices such as head mounted displays and controllers. Users can interact with the virtual environment through head tracking and joystick operation, experiencing a sense of immersion. In order to provide a more realistic user experience, VR backlight(BLU) display modules need to have higher luminance, color gamut, and contrast. Mini LED BLU module is an important component of LED display. Due to its advantages of small size, ultra-thin design, and low power consumption(1), Mini LED can achieve more precise local area dimming when applied to LCD BLU, which is of great significance for achieving high dynamic contrast LCD display. The research on high dynamic range (HDR) has become a hot topic(2)(3)(4). and high dynamic range displays are increasingly sought after due to their ability to present image effects that are very close to natural scenes. In the real world, the dynamic range of light that can be perceived by the human eye far exceeds the display range of current Normal displays. Most HDR displays tend to use OLED displays(5), but due to the short lifespan of OLED displays and other defects, researchers have proposed LCD screens with local dimming to better match HDR displays(6). Therefore, Mini LED BLU technology has emerged, specifically replacing the entire BLU area in the original LCD with locally dimmed Mini LED BLU. Mini LED BLU technology significantly improves the thickness and dynamic range of display panels, while also significantly reducing display power consumption due to finer area dimming(7).

In natural images, the aperture that propagates from the edge of the image is called a halo(8). When using local dimming units, due to the inevitable transition from bright to dark areas at the edges of the image, halo effects are more likely to occur at edges with contrast between light and dark(8). Excluding the influence of BLU partitioning, in Mini LED BLU LCD, due to the electronic component characteristics of the LCD, there will be light diffusion between Mini LED BLU blocks, especially in HDR image display with obvious contrast between light and dark(9). The light emitted by one Mini LED BLU block will diffuse to adjacent BLU blocks, resulting in uneven luminance of the LCD display and causing halo effect. For the human eye: when the halo effect is within a certain threshold, the human eye cannot clearly distinguish the halo effect at the image boundary, and at this time, the halo effect will not significantly affect the overall quality of the image; If the threshold is exceeded, the human eye can clearly perceive the halo effect, which will greatly damage the integrity and detail information of the overall image. Therefore, optimizing the single zone halo reduction and PSF curve narrowing of VR BLU modules has important research significance.

2. Proposed method for Reduce Halo Effect
Firstly, based on the Normal direct type mini LED BLU with a module size of 2.56 inches, the Normal stacking architecture of the film material is as follows from bottom to top: Mini LED light board, blue transparent anti red green film, QD film, lower diffusion, upper diffusion, lower prism, upper prism, and liquid crystal glass. The principle of white light generation is that the light-emitting chip on the Mini LED light board emits blue light, which is transmitted through a blue transparent anti red green film to the QD film. The blue light excites the red green quantum dots inside the QD film to produce red and green light, red light, green light, and blue light, which are superimposed and mixed into white light. Uniform white light is generated through the lower and upper diffusion films, and then the luminance is improved through the lower and upper prisms. As shown in Figure 1, due to the presence of an air layer between each layer of film material when light passes through, there will be reflection and refraction phenomena at the interface between the film material and air when light enters. Due to multiple refractions and reflections of light between film materials, the lateral path length of light increases, resulting in a larger halo and a larger PSF diffusion for a single zone.

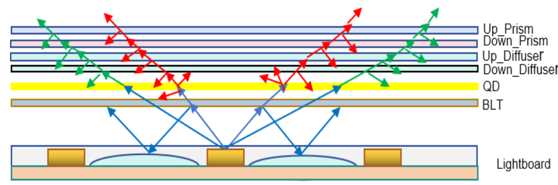

Figure 1. Reason for halo enlargement

In this study, we designed a customized light guide plate(LGP) for use in a Normal 2.56 inch VR mini LED BLU. The LGP has a significant effect on reducing halo and narrowing PSF in VR mini LED BLU, while also improving module luminance, which is helpful for later local dimming and enhancing image contrast.

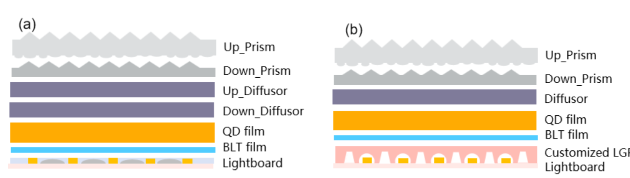

Figure 2. (a), Normal BLU scheme (b), The customized LGP scheme.

In this scheme, the film stacking scheme for Mini LED BLU we use includes Mini LED light board, customized LGP, blue transparent and anti red green film, QD film, diffusion film, lower prism, upper prism, and liquid crystal glass. The comparison of the film structure between the customized LGP scheme and the Normal mini LED BLU scheme is shown in Figure 2 (a) and Figure 2 (b).

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In this customized LGP solution, one side of the customized LGP is an array microstructure unit, and its microstructure corresponds one-to-one with the blue light chip below, Each microstructural unit is a quadrangular frustum platform structure, with the bottom of the quadrangular frustum platform being an inwardly concave hemispherical structure. The diameter of the hemispherical structure is greater than the diagonal length of the light-emitting chip, and the light-emitting chip is placed inside the hemispherical structure. The divergence angle of the light-emitting chip is 2θ, and the large angle light emitted by the light-emitting chip is emitted from the hemispherical surface to the side of the quadrangular frustum platform structure, where total reflection occurs, narrowing the large angle emitted light. The refractive index of the customized LGP material is n, and the inclination angle of the quadrangular frustum platform can be derived from geometric relationships as $\alpha = 180^\circ - \theta - \arcsin(1/n)$ as shown in Figure 3. For our VR BLU module, it is 2.56 inches, the light-emitting chip is 0912 LED, the divergence angle 2θ is 140°, and the pitch of the light-emitting chip is 1.3mm; The customized LGP material used is PMMA with a refractive index of 1.49. Therefore, the inclination angle of the four inclined surfaces of the four sided pyramid microstructure of the customized LGP is 68°, and the microstructure pitch is also 1.3mm. The hemispherical diameter and height of the bottom surface of the pyramid are both 0.5mm, and the thickness of the customized LGP is 0.7mm.

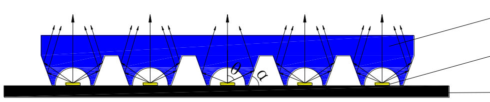

Figure 3. The customized LGP design principle

The customized LGP can be produced using injection molding, CNC machining, hot pressing and other process methods. As shown in Figure 4 (a) and Figure 4 (b), they are respectively the 3D design and CNC machined physical images of our customized LGP. To ensure the smoothness of the processed sample and reduce the diffuse reflection phenomenon caused by light shining on the surface, a specific polishing solution is used to polish the sample surface.

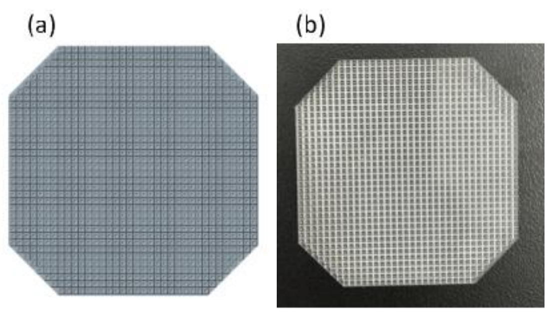

Figure 4. (a), 3D design drawing (b), Physical image of processing.

In order to analyze the size of halo diffusion in the BLU when a single zone LED is light up, we used the CA2000 color analyzer for testing and analysis. This device can collect and test the luminance distribution of the surface light source. When a single zone LED lights up, it will spread to adjacent areas around it. By extracting data in the x and y directions from the data collected by the software, it can be traced and fitted into a PSF curve.

3. Experiment and Result

Single zone lighting tests were conducted on Mini LED BLU based on Normal membrane architecture and Mini LED BLU using customized LGP scheme. The collected luminance distribution data was fitted with PSF diffusion curve, and the diffusion distance d corresponding to 1% and 50% peak luminance was evaluated.

The schematic diagram of diffusion distance is shown in the following figure 5, Figure 5 (a) shows the lighting effect of VR mini LED BLU in a single zone, and Figure 5 (b) shows the data extraction method after the BLU is lit in a single zone.

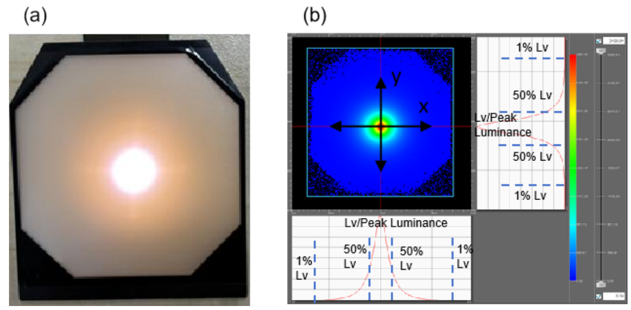

Figure 5. (a), Single zone BLU illumination effect. (b), Data extraction method after the BLU is lit in a single zone.

Compare and analyze the single zone diffusion in both the x-axis and y-axis directions of the Mini LED BLU with Normal film architecture and the Mini LED BLU with customized LGP scheme. Figures 6 (a) and 6 (b) show the PSF diffusion curves fitted in the x and y directions for the two schemes, respectively. The Normal Mini LED BLU scheme has a single zone halo diffusion distance d_1 of 4.8mm and 4.9mm in the x-axis and y-axis directions, respectively, while the customized LGP scheme has a diffusion distance d_1 of 3.0mm and 3.1mm in the x-axis and y-axis directions, respectively,a reduction of 37%; The Normal mini LED BLU scheme has a single zone halo diffusion distance d_2 of 26.0mm and 26.6mm in the x-axis and y-axis directions, respectively, while the customized LGP scheme has a diffusion distance d_2 of 22.2mm and 22.4mm in the x-axis and y-axis directions, with an average diffusion distance reduction of 16%; The center brightness of the single zone spot in the Normal Mini LED BLU scheme is 2152nit; The center brightness of the BLU single zone spot in the customized LGP scheme is 2826nit, which has increased the center brightness by 24%.

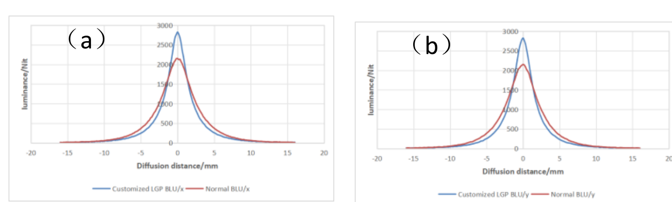

Figure 6. (a), Diffusion curves of the customized LGP BLU scheme and Normal BLU scheme in the x-axis direction. (b), Diffusion curves of customized LGP BLU scheme and Normal BLU scheme in the y-axis direction.

At the same time, we also compared and analyzed the shading of the light shadow between the Normal Mini LED BLU module and the customized LGP BLU module scheme in both full white and full blue images. As shown in the following figure, Figure 7 (a) and

Figure 7 (b) are the images of the customized LGP scheme module in full blue and full white images, respectively. Figure 7 (c) and Figure 7 (d) are the images of the Normal Mini LED BLU module in full blue and full white images, respectively. There is no difference in shielding performance between the two, and both have good shielding effects.

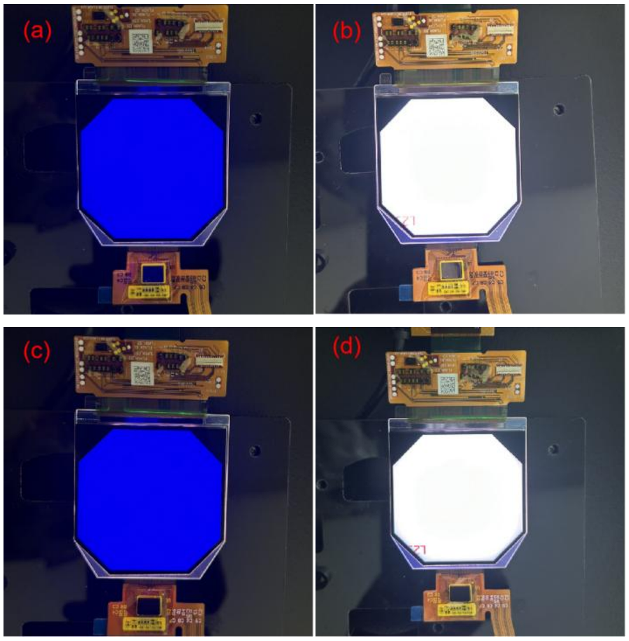

Figure 7. (a), The customized LGP scheme module in full blue images. (b), The customized LGP scheme module in full white images. (c), The Normal scheme BLU module in full blue images. (b), The Normal scheme BLU module in full white images.

In addition, we also compared and analyzed the luminance and uniformity of the Normal Mini LED BLU module and the customized LGP scheme BLU module. As show in table 1, The comparison between the two is shown in Table 1. The nine point uniformity test results of the module show that their levels are basically equivalent; For module luminance, the customized LGP solution has increased the luminance by about 8% compared to the Normal mini BLU solution.

Table 1. Sample Compare the brightness and uniformity of two module schemes

ITEM	MDL Uniformity/ Nine Point	MDL Luminance/nit
Customized LGP Mini_LED BLU	91%	592
Normal Mini_LED BLU	92%	550

4. Conclusion

In summary, based on the above comparative verification, the customized LGP scheme has a good reduction effect on the halo diffusion of a single zone. The diffusion distance corresponding to 50% peak luminance(FWHM) has narrowed by 37%, The diffusion distance corresponding to a peak luminance of 1% is narrowed by 16%, and the center luminance of a single zone is increased by 24%. At the same time, it also has a good shading effect on the lamp shadow. The uniformity of the module is basically the same as that of the Normal solution, and the luminance of the module has increased by nearly 8% compared to the Normal solution. This scheme is beneficial for algorithm calculation in local dimming, and is of great significance for improving image contrast and image quality.

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