Numerical Analysis of High-Luminance, Spatial, Multiple-Layer, Light Emitting Diode, Backlighting System

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Abstract. Currently, light emitting diodes (LED) have replaced cold cathode fluorescent lamps (CCFL) as backlighting systems in liquid crystal displays (LCD). However, the original single layer alone can only satisfy the needs of the panel display and cannot satisfy the requirements for a 3D display system or outdoor displays. In this paper, a new method is proposed to demonstrate that a high output can be achieved using spatial stacking of integrated LED light sources. Moreover, we also simulate the system and measure the light output and the distribution of the light. The system is efficient to provide high luminance while keeping a balanced light distribution. With this proposed high luminance spatial multiple-layer LED back-lighting system, many requirements, especially for the high light source, are supposed to be satisfied.

Keywords: integrated light source, backlight, lens, LED, simulation

1. Introduction

Recent years have witnessed the advent and employment of new types of display systems, among which plasma display panels (PDP) had previously shared almost the same market with liquid crystal displays (LCD) but finally failed. Currently, we are looking forward to organic light emitting diodes (OLED). However, LCDs have occupied the biggest market and have been renewed.

Unlike PDPs and OLED, an LCD cannot emit by itself. The backlight plays a vital role in the LCD display system. The market of the display arena requires a lifetime, high-output light source. Taking environmental protection and energy saving into consideration, light emitting diodes (LED) constitute the best choice.

In certain fields, where small, compact light sources with high power of radiation are in demand, super high pressure mercury lamps cannot be replaced by LEDs, even when multiple LEDs are arrayed. Some projector manufacturers are dedicated to developing a novel integrated
light source with combined LEDs and lasers, which can replace super high pressure mercury lamps. However, this technique is expensive. In addition, its safety risks have aroused mounting concern, as exemplified by America and Europe’s verdict of not granting permission to its application. In addition, with the development of 3D imaging systems, traditional pixels have evolved into voxels, upgrading the resolution into three dimensions. Chances are that the technique has not been widely applied outside the laboratory in 3D holographic imaging or 3D TVs via stacked LCDs [1]. Moreover, the power is insufficient in a signal-layer LED panel. However, the LED substrate is opaque, depriving rays from the rear layers of the possibility of reaching the front, which is why the application of LEDs is limited not only in panel display systems but also optical projection systems.

This paper probes this problem using lenses and LEDs and implements a spatial multiple-layer, LED backlight system. The hole in the LED panels and lens makes the light radiate from the rear panel to the front panel by multiplying the power of radiation. As a result, a high light output can be achieved. The whole model is simulated and tested with the optical software Tracepro, which can use the Monte Carlo ray tracing technique to describe the route of the rays. Upon the completion of computing transparent and missing rays, the illuminance maps are simulated to evaluate the light distribution. We also compare the results with the normal LED backlight system and verify that the proposed system is efficient to provide a high output light source.

2. Related Works

Since LCDs grabbed the greatest share of the market, the backlighting system has been under intense research along with the development of the LCD. Several years ago, CCFL dominated the backlighting market. However, as the price of LEDs decreased, they have replaced CCFLs to become almost the only light source in backlighting systems.

There also some new light sources that are designed to challenge the leading position of LEDs in the backlighting arena, among which lasers are conspicuous [2]. Lasers are different from LEDs, even if they are endowed with the same lifetime durability. The most obvious characteristic of laser is its monochromaticity, which enables the semiconductor of the RGB laser to present a better color gamut than the LED. However, taking the cost, stability and many other factors into consideration, lasers are no match for LEDs.

The multitude of research work in the arena of backlighting systems revolves around two sub-fields: LED backlighting and backlighting modules.

Unlike a light source, a backlighting module functions to increase the operation rate of light. The backlight module is mainly positioned in the middle of the LED panel and LCD. The operating principle of liquid crystal molecules is to turn on/off the rays directed into the pixel
The research shows that when the rays under the condition of oblique incidence are directed into the liquid crystal molecule, the function of turning on/off is decreased [3]. Based on this characteristic, the backlighting module mainly includes brightness enhance film (BEF), diffuser plane (DP), and diffuser sheet (DS) [4].

The studies on LED backlighting are the other major concern of backlighting system research. Unlike the backlighting module, the LED is a light source that plays a crucial role in the display. To support the LCD, there are two ways of installing LEDs for liquid crystal panels that are dominating the backlighting market: direct backlight (light box) and edge-light or light-guide-based backlight [5]. As the names suggest, direct backlight is the method of installing the LED directly behind the liquid crystal panel, allowing the rays from LED to go directly into the panel. Whereas edge-light refers to the method of installing the LEDs at both sides of liquid crystal panel and then illuminating the liquid crystal panel though the light guide panel (LGP) [6]. These two methods have their respective advantages and disadvantages. Direct backlight, to decrease the thickness, uses LEDs with small chip size, making the cost surpass that of the edge-light for the same size of LCD. In addition, the efficiency of the small chip size LED is also inferior to high efficiency LEDs, which have a bigger chip size [7]. However, the uniformity and the dynamic color performance are better than the edge-light backlight because the LEDs can be individually controlled by the panel.

3. Proposed Method

3.1. Stacking Multiple LED Panel

LED panels are opaque. If we stack several layers of LED panels spatially, the rays from the rear are bound to fail to reach the front. A solution has been proposed and is shown in Fig. 1.

![Figure 1: Stacked LED panel and LCD panel](image)

Because the transmittance ratio of LCDs is very low (10–15%), stacked LCDs, which can be used as 3D display, requires much more luminance than usual. This stacked LED applying
concave lens panel has been proposed to solve the problem. The convex lens is used to gather the rays from the LED, followed by the concave lens to turn these rays into collimated light and though the hole to the next LED panel.

3.2. Choosing Types of LEDs

LEDs can be classified into many types based on shapes and numbers of cores. Surface mounted devices (SMD) and dual inline-pin package (DIP) are the different shapes. If we use white LED for the illuminance, the LEDs can be divided into one-core LEDs and three-core LEDs. However, there is some research on more than three cores for LEDs for some special purposes [8].

Because of the advantages in terms of thickness and wide emitting angle, most LCD backlighting has adopted SMD LEDs.

To test the performance of SMD in this method, a single-layer SMD has been combined with a convex lens. Fig. 2 shows the simulation result of the SMD and convex lens array.

![Figure 2: Preliminary test result of a single SMD LED panel and lens array](image)

The simulation result illustrates that even a strong lens array is unsuccessful to convert divergent light into collimated light.

Compared to the SMD LED, the emitting angle of approximately 15–60 degrees of the DIP LED is far behind that of the 120 degree of the SMD LED. Single DIP LEDs combined with lenses have been verified. Fig. 3 shows the simulation result of a single DIP LED panel and a single lens on a lens array.
3.3. DIP LED Backlighting Model

Under consideration of final uniform illumination, the entire panel has been divided into many small units, with each unit encompassing 4 LEDs and independent lenses and holes. The size of one LED is φ5 mm, and one panel needs 560 LEDs. In the setting of the simulation, tracing rays of one LED have been set at 1000 pieces. The definitive model stacks 3 layers of units spatially. One panel adopts 14×10 units, which make it close to 14 in, as is shown in Fig. 4.

4. Result

To verify the efficiency of the proposed system, we conduct an experiment using Tracepro software. We have conducted this experiment on a notebook PC with an Intel Core i7-4700MQ CPU (2.4 GHz), GTX 870M GPU (3 GB), and 16 GB of system memory. The operating system
4.1. Model

Fig. 5 demonstrates the smallest unit and 3-layer units of the DIP LED model highlighted in the current research. The proposed model is composed of four DIP LEDs, four front-positioned parallel Fresnel lenses, which transfer divergent emitted light from the DIP LED into parallel light, as well as an achromatic convergent lens (right behind the Fresnel lens), which converges light, and a concave lens, which transfers the converged light into parallel light through a much smaller hole.

![Figure 5: One unit of the DIP LED model and 3-layer units](image)

4.2. Illuminance of the DIP Simulation Model

Considering that a one-unit DIP LED emits overly concentrated light, four layers of the smallest unit are utilized in this paper as the basic simulation model to facilitate the analysis of the light spectrum and color distribution of space between units posterior to the formation of the backlight module.

![Figure 6: Four units of the DIP LED model and a 3-layers unit](image)

Tracepro has been employed to simulate the model shown in Fig. 6 via the Monte Carlo
method of ray tracing. The adopted LED model uses a NSDW510GS-K1 DIP White LED produced by Nichia for reference. The surface source property generator of Tracepro gathers data from the light distribution curve and light spectrum distribution curve of the NSDW510GS-K1 DIP White LED and imports the data into Tracepro to determine the characteristics of the light source. The number of lights emitted from each LED is set as 1000, which then completes the core-parameter setup of LED lighting in this model. Furthermore, an LED panel is added to the front of the model, and the light absorption characteristics of the LED panel are defined. Then, energy analysis of the energy emitted to the LED panel is conducted using Tracepro. Fig. 7 shows the simulation product of utilizing a single-layer backlight module. In the figure, the left energy distribution curve displays the distribution areas and evenness of high and low energy. The color bars, varying from blue, indicating low energy, to red, indicating high energy, are labeled by the Lux value - the illumination produced by luminous flux of one lumen falling perpendicularly on a one meter square surface. The numerical energy distribution curve on the right depicts the energy distribution within the LED panel. Judging from the left distribution curve, we can observe that the optical lenses are separated by gaps due to cutting round lenses into rectangular lenses, considering the overall structure of the model. Therefore, the center of the four lenses has reduced energy. A closer analysis of the right distribution curve shows that in each of the smallest original units, the center is home to the highest energy, and the energy is progressively decreases toward the margin because the energy emitted from the four LEDs overlaps in the center.

![Image](image_url)

Figure 7: Illuminance distribution of one unit under logarithmic treatment

The simulation of a three-layer backlight module is conducted in accordance with the right model in Fig. 6 and the results in Fig. 8. From Fig. 8, we can readily see that under the same color value, the red color is darkened in the left, indicating the increasingly intensified light
energy as a result of the three-layer overlapping of the LED backlight module. The right distribution curve in Fig. 8 demonstrates that the energy distribution is more even when stacking multiple layers of LED panels.

One unit is then expanded into three units. The purple small screen on the right side of Fig. 6 is used to absorb the rays from 3 units of the LED panel.

The right distribution curve in Fig. 8 demonstrates that the energy distribution is more even when stacking multiple layers of LED panels.

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Figure 8: Illuminance distribution of the 3-unit model under logarithmic treatment

The red color and color bar of Fig. 7 and Fig. 8 shown in the illuminance map illustrate the level of power. The curve on the right side of these two figures clarifies the accurate power distribution.

4.3. CIE Color Map Simulation

Color analysis constitutes a vital factor in the analysis of the backlight module, exerting direct influence on crucial parameters, including the color saturation level and the color temperature in the ultimate LED display. The NSDW510GS-K1 DIP White LED from Nichia is adopted as our structure model, and the parameters are imported to analyze the colors of the DIP LED using the u’v’ color axes.

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Fig. 9 shows the color distribution of one DIP LED. Although this DIP LED is a white LED, the color presented on the screen though the software is not pure white. Similar results have been obtained by other researchers [9].

Moreover, color simulation is conducted using four units of a single-layer module presented in the left of Fig. 6. Judging from the simulation results, although the overall color is not pure white, its distribution evenness surpasses that of a single white LED. Similarly to the energy distribution, unevenness of the overall distribution caused by the space and margins of the model persists.

Because the white LED has a unique spectral distribution, the color distribution is not entirely white in the simulation of the software. However, Fig. 10 shows a better effect than Fig. 9 with respect to color distribution.

4.4. Energy Efficiency of the Three-Layer DIP LED Backlighting System and
For original LCD displays, the illuminance of a one-layer SMD LED backlight suffices. The distribution of SMD LEDs is loose. Amplifying the illuminance by 2 or 3 times increases the density of the distribution. Considering the size of a circuit board and the thermal effect, the approach of increasing the density of SMD LEDs has limited effect and is unreliable. However, by means of the evaluation software of the performance of stacked DIP LED backlighting systems, the increased density of an SMD LED backlighting system is simulated.

Fig. 11 and Fig. 12 show a 12 W difference of the color distribution and different illuminance under the same power. Fig. 11 demonstrates the illuminance of an SMD LED reaching 1197.5 lm, whereas Fig. 12 illustrates the illuminance of the three-layer DIP LED reaching 536.1 lm.

This simulation result is obtained under the same conditions, the same size of absorption screen and without cover of the backlighting system. However, the construction of these two
types of backlighting systems is different, giving rise to different test results. Another test shows if the size of the absorption screen is increased and the reflective cover of the backlighting system is given, the SMD backlighting system stays the same but the DIP backlighting system is increased to 700 lm.

5. Discussion

5.1. Analysis of Energy Degradation

![Figure 13: Trace performance of real rays](image1)

![Figure 14: Trace performance of perfectly collimated light rays](image2)

Fig. 13 shows the test result of the one-unit irradiance model. The rays from the four DIP LEDs on the panel with a 35 degree emitting angle pass through 4 Fresnel lenses and a lens group. This result directly shows why the energy degradation is so large. In addition, it also shows that the lost energy is coming from the large amount of missing rays.

To analyze the cause of the large amount of missing rays, we attempted to shut down the emitting part of LED and use a standardized grid light source to emit a group of perfectly collimated light to test the performance of the lens group. The result proves that the design of the lens group is correct.

By comparing these two figures, it is obvious that the 35 degree emitting angle from LED produces a large amount of missing rays from the concave lens and can maintain collimated light for only a short distance. How to design the lens or redesign the lens array remains a
challenging issue.

5.2. Analysis of the Illumination Uniformity

Figure 15: Comparison between the model of the three-layer DIP LED backlighting system and the single-layer SMD backlighting system

We use the software to simulate a simplified model of a small array of a three-layer DIP LED backlighting system, as shown in Fig. 15 (left). The structure of the current most widely used conventional SMD backlighting system model is presented in Fig. 15 (right). Then, we compare the distribution of the illumination uniformity.

Figure 16: Illumination distribution of the three-layer DIP LED backlighting system
The green and blue curves showed vertical and horizontal illumination distribution of the left map both in the Fig. 16 and Fig. 17. Considering the structure of the emitting model, the traditional single-layer backlighting system contains a white light SMD LED lamp with a light emitting angle of 120 degrees, which the most commonly used in recent displays can not be used in the new system. However, the three-layer DIP LED backlighting system using the white light DIP LED with a light emitting angle of approximately 35 degrees can be used in this spatical stacked blacklighting system.

The illumination uniformity is calculated by the minimum value of the light field illumination divided by the average value. In the process of simulation, the software automatically calculates the minimum, the maximum, and the average value of the entire light field illumination. As a result, the illumination uniformity of the three-layer DIP LED backlighting system is 9.5%, as shown in Fig. 16. The illumination uniformity of the traditional single layer SMD backlighting system is 10.7%, as shown in Fig. 17. Although we can see the illumination distribution in Fig. 16 is not as good as the one in Fig. 17 with respect to the illumination uniformity, the calculated results are similar, which proves the reliability of the illumination uniformity of the spatial-enhanced backlighting systems.

5.3. Color evaluation of the three-layer DIP LED backlighting system and the conventional single-layer SMD backlighting system

According to the model in Fig. 15, through the simulation, the analysis result on the color distribution after the simulation is shown in Fig. 18 and Fig. 19.
Figure 18: Color distribution of the three-layer DIP LED backlighting system

Figure 19: Color distribution of the traditional single-layer SMD backlighting systems

From Fig. 18 and Fig. 19, we can see the color distribution on the simulated LCD surface is quite different, even when using a similar white light spectral distribution of the LED. We use software to export the color coordinates \((u, v)\) of the color distribution, and the CIE-related color difference formula is used to calculate the color difference of the two models.

The color difference between the color coordinates \(u_k,v_k\) of the testing light sources and the color coordinates \(u_r,v_r\) of the reference lighting body is presented as (1).

\[
\Delta C = \left[ (u_k - u_r)^2 + (v_k - v_r)^2 \right]^{\frac{1}{2}}
\]  

(1)

The color temperature of the LED lighting is usually the closest to the standard D65 light source, and the D65 color spectrum also represents the average solar spectrum color. Therefore,
we choose the D65 light source for the color coordinates \((u = 0.1978, v = 0.3122)\) in the CIE1960USC (CIE 1960 UCS, variously expanded Uniform Color Space, Uniform Color Scale, Uniform Chromaticity Scale, Uniform Chromaticity Space) is another name for the \((u, v)\) chromaticity space devised by David MacAdam) chromaticity diagram.

We export the color coordinate data of the enhanced backlighting systems and use the color difference formula to calculate the color difference \(\Delta C_{av1} \approx 0.2320\). Then, the color coordinates of the traditional backlight systems are imported, and the average value of the color difference \(\Delta C_{av2} \approx 0.1254\) is calculated. Because the spectrum and the color temperature of the white LED light source are different from the standard reference illuminant D65, there is a deviation, so a color difference exists within a reasonable range. Due to some factors adopted in the enhanced light source structure that influence the spectra, such as the lens, the color deviation is greater than the one of the traditional backlight system.

6. Limitation

One major problem is the thermal analysis. As seen from Fig. 4, the final model uses a large device that is 14 in in width and 3 layers in depth. This structure would accumulate heat, resulting in breaking of the lens and an effect on the LED [10]. Heat can reduce the durability of LEDs. In following work, we will not only analyze the power efficiency but also discuss the thermal solution; otherwise, the lens will break or reduce the durability of the LED [11].

7. Future Work

In our future work, we will apply this model to practice and test the efficiency in the real world. It is our sincere hope that there will be more exploratory research into the recently emergent backlight sources, such as the laser backlight source, which has already been utilized as the main light source in projectors and a small number of newly designed LED television sets. The laser backlight source has the virtue of durability and stability similar to LEDs because they both belong to solid light sources. However, compared with LEDs, the laser backlight source is much more advantageous in that its smaller size and greater luminance contribute to its relatively mature application in marketized projectors. Furthermore, because a laser is a collimated light source with a small angle of divergence, the ideal effect demonstrated in Fig. 14 can be readily achieved to greatly lessen the energy loss if a laser is utilized in the model proposed in the current research. Moreover, taking into consideration the high luminance of the laser itself, we can safely predict that the backlight luminance provided by the ultimate structure will be increased significantly.

On the other hand, the increasing popularity of the LED backlight in everyday devices, such as computer screens, LED television sets and smart phones, has brought into the spotlight the resultant health issues, especially blue light-reducing. In view of multiple factors, including
cost and efficiency, an overwhelming majority of LED screen devices adopt single-core, white-light LEDs instead of RGB three-core LEDs whose application is limited to a small number of professional fields with high demands on color effects. Therefore, the influence of white-light LEDs on users’ health is a primary concern. Recent research showed that energy from blue-light surpasses that from any other light because single-core white-light LEDs originate from yellow fluorescent powder generated by blue light. Moreover, due to its shorter wavelength and higher frequency, blue light exerts higher energy compared with longer wavelength red and green lights. If the wavelength is further reduced, the blue light wave band will then become ultraviolet wave band, which is widely known as extremely detrimental to living organisms, especially cells, and is thus extensively applied in sterilization. Therefore, single-core LEDs with high-energy blue light wave bands are exerting multi-faceted influence on users’ health, resulting in direct disastrous consequences, including compromising users’ eyesight because long exposure to high-energy blue light damages visual cells. Additionally, the latest research reveals that blue light also has a negative impact on hormone secretion of the human body, human energy and sleep. Some primitive methods have been devised to eliminate blue light, such as adding optical filters or simple filter glasses to LED screen devices to filter some blue light energy. Nevertheless, these approaches, while aiming to filter blue light, lead to distortion of the overall white light. Thus, the current model is proposed to explore how to reduce blue light without distorting the overall color performance. The simulation results of Fig. 11 and Fig. 12 indicate that the added lens in the backlight modules in Figure 11 enables the partial filtering of blue light. Therefore, although both use single-core white-light LEDs, Fig. 11 and Fig. 12 differ in color performance in their ultimate simulation. What remains as our future concern is the quantifiable analysis of the degree of blue light reduction and revolutionized structure and design of blue light reduction models.

8. Conclusion

In this paper, we proposed a high-luminance, spatial multiple-layer, LED backlighting system. We created the model using a hole in the LED panels and lens to make the light radiate from the rear panel to the front panel by multiplying the power of radiation. A high light output was achieved. The whole model was simulated and tested by the optical software Tracepro, which can use the Monte Carlo ray tracing technique to describe the route of the rays. Upon the completion of computing transparent and missing rays, the illuminance maps were also simulated to evaluate the light distribution. From the experimental results, we can see that the proposed system is efficient to provide a high output light source to meet many requirements.

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