Optimization of the optical structure of thin direct-lit LED backlights for LCD applications by using micro-LEDs

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ABSTRACT

The optimized optical structure of the micro-LED-based direct-lit backlight was investigated through optical simulation. The backlight consisted of only one diffuser plate and an array of micro-LEDs with a reflection film positioned on the bottom of the backlight. An additional reflector was put on top of each micro-LED to prevent the formation of bright spots. Under several number density conditions of the microbeads in the diffuser plate, stable regions were found on the gap-pitch plot, where a high Mura index of $\sim 1$ was secured. The bead density needed to be small (around $10^4 \text{ mm}^{-3}$) to maintain above 60% transmittance, because the transmittance of the backlight was significantly reduced at higher bead densities. Under the $10^4 \text{ mm}^{-3}$ bead density condition, the gap can be reduced to 1.5 mm at a 3 mm pitch. The gap can be further reduced if additional optical films, such as a diffuser sheet, a prism film, and a reflective polarizer, will be adopted in the backlight. This work demonstrated that micro-LEDs are ideal light sources for realizing a thin direct-lit backlight for LCD applications.

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1. Introduction

Form factor has become one of the most important aspects of modern displays. Thin, foldable, and flexible displays have attracted great attention of late and are beginning to appear in the market. The micro-light-emitting diode (micro-LED) is a small luminous element actively being developed for applications in various fields, such as wearable devices, automobiles, medical and bio-devices, and displays [1–3]. Micro-LEDs have been applied of late to large-size self-emitting displays. The micro-LED-based display has advantages, such as low power consumption, miniaturization, light weight, and flexibility. Micro-LED is a small LED with a 5–100 $\mu\text{m}$ chip size, which can be used to realize a high-resolution display at a high-efficiency level [4–7].

On the other hand, micro-LED can be used as a light source in backlights for liquid crystal display (LCD) applications. LEDs are usually adopted in LCD backlights in two forms: direct- and edge-lit backlights [8]. Edge-lit backlights adopt a light guide plate (LGP) for guiding and homogenizing the light emitted from the LEDs positioned at the edges of the LGP. On the other hand, LEDs are located directly below the LCD screen together with several optical films including a diffuser plate, a diffuser sheet, a prism film, and/or a reflective polarizer. For securing enough luminance uniformity, an appropriate distance between the LEDs and the diffuser plate should be maintained, which is the reason for the difficulty of designing a thin direct-lit LED backlight by using the typical LEDs. Due to the small size of micro-LEDs, an ultra-thin direct-lit backlight showing high luminance uniformity may be possible. In addition, micro-LED-based direct-lit backlights are more ideal for realizing smaller dimming blocks, which are favorable for achieving a high contrast ratio and a high dynamic range as well as for developing flexible backlights [9].

This study was conducted to design thin direct-lit backlights by using micro-LEDs. The important parameters affecting the luminance uniformity in the direct-lit backlight include the pitch between the LEDs, the gap distance between the LED and the diffuser plate, the number of bead particles in the diffuser plate, and the reflectance of the mirrors on top of the micro-LED. The uniformity was investigated as the functions of these parameters and an optimized optical structure could be obtained via ray-tracing optical simulation. This study may be the first study that revealed the correlation between the design parameters and the optical structure.
performances of direct-lit backlights based on the micro-LED technology.

2. Simulation
In this study, a commercial software (LightTools 8.6.0, Synopsys) was used to investigate the luminance uniformity of a direct-lit backlight where micro-LEDs were used as a light source. The structure of the direct-lit backlight based on micro-LEDs is shown in Figure 1. The area is a square 14 mm long and 14 mm wide. The micro-LEDs that were used in the simulation were 0.1 mm long, 0.1 mm wide, and 0.12 mm thick. The emitting spectrum was Gaussian-shaped, with a 450 nm center wavelength. The micro-LEDs were arranged in a two-dimensional hexagonal lattice, as shown in Figure 1. The reflecting property of the reflection film positioned on the bottom of the backlight was diffuse Gaussian with a 25° distribution angle. This angle is among the typical values for the distribution of the reflection scattering function [10]. The dimensions of the diffuser plate were $14 \times 14 \times 1$ mm$^3$. The material of the diffuser plate was polycarbonate with a 1.5896 refractive index. Microbeads with a 1.43 refractive index were dispersed in the diffuser plate. The beads’ diameter was 4 μm, which was small enough to induce the Mie scattering effect. The number density of the microbeads was changed to between $10^4$ and $10^6$ mm$^{-3}$. In direct-lit backlights, the LEDs tend to be recognized as bright spots. To cut the light directly emitted from the top surface of the micro-LEDs towards the normal direction, a reflector, such as a distributed Bragg reflector, may be formed on the emitting surface of each LED. Either of the mirrors or a side-lit lens, which induces total internal reflection, may be used for preventing hot spots [11]. In this study, a mirror was placed on each micro-LED and the reflectance was changed in a certain range. Therefore, only four vertical areas of micro-LEDs were emitting surfaces with a Lambertian distribution. A plane detector was put over the backlight, with a 0.1 mm distance.

To check the luminance uniformity, a Mura index was defined as shown in Figure 2. P1 is the center position of one micro-LED. The P2-P9 points were positioned on a circle with equal distances along the arc, where the radius was the length from P1 to the bisector of the length between the nearest neighboring lattice points. The Mura index was defined as the average luminance of P2-P9 divided by the luminance of P1. If the index is 1, there is high luminance uniformity. If a bright spot appears on each micro-LED, the Mura index will be lower than 1. Thus, it may serve as a good indicator of luminance uniformity. In this paper, the Mura index was investigated by changing the design parameters of the direct-lit backlight based on micro-LEDs.

The pitch and the gap were modified, the density of the beads in the diffuser plate was controlled, the reflectance of the mirror was adjusted, and optical simulation was carried out under various conditions to find the optimal structure of the backlight with high luminance uniformity. First, the Mura index was examined by changing both the pitch and the gap. The definition of the pitch and the gap is shown in Figure 3. Simulations were conducted over the gap change from 1.25 to 2.25 mm and over the pitch change from 3 to 18.75 mm. In these cases, the number density of beads in the diffuser plate was changed from $10^4$ to $10^6$ mm$^{-3}$. The beads were randomly arranged in the diffuser plate. Random arrangement is important for preventing the Moire pattern caused by the interference between regularly spaced structures. Second, the mirror reflectance on the top of the LED was changed from 100 to 0% in 5% increments.

3. Results and discussion
Figure 4(a) shows the Mura index as a function of the gap and the pitch at a fixed bead density of $10^4$ mm$^{-3}$ in the diffuser plate. The mirror reflectance on top of the micro-LEDs was fixed at 100%. The standard deviation was usually less than 5% of the average luminance. The Mura index was constant when the measurement points were rotated along the arc of the circle. Figure 4(b) shows the same data in a different format. The Mura index decreased with increasing pitch and decreasing gap. The area below the line of 1.000 in Figure 4(a) reflects the stable high luminance uniformity condition, where the Mura index was close to 1. The result in Figure 4 shows

![Figure 1](https://example.com/figure1.png)  
**Figure 1.** (Color online) Structure of the direct-lit backlight based on micro-LEDs investigated in this study. The micro-LEDs are arranged on a two-dimensional hexagonal lattice.
that the Mura index became 1 when the gap was equal to or larger than 1.5 mm at the 3 mm pitch. Figures 5 and 6 show the same data at the bead densities of $10^5$ and $10^6$ mm$^{-3}$, respectively. When the number density of beads was $10^5$ mm$^{-3}$, the uniform area was slightly larger compared to the previous case shown in Figure 4. Under the $10^6$ mm$^{-3}$ number density, the stable area on the gap-pitch domain became much larger compared to the previous two cases. The pitch can be increased to $\sim$ 5 mm for nearly all the gap values larger than 1.5 mm, for securing an above 0.9 Mura index. This is mainly due to the large number density of beads and thus the strong diffusing function of the diffuser plate.

A higher number density of beads, however, indicates lower transmittance, which is unfavorable for achieving high light utilization efficiency in the backlight. When the transmittance was examined by shining a 450 nm plane wave onto the diffuser plate, the transmittance was more than 85% until the density increased to $10^4$ mm$^{-3}$, but it substantially decreased beyond such density, particularly to below 20% at the $10^6$ mm$^{-3}$ density. Increasing the bead density enhances the amount of light trapped in the diffuser plate, substantially resulting in lower transmittance. Considering the conventional diffuser plate’s typical transmittance of $\sim$ 60% [12], the $10^6$ mm$^{-3}$ density is too high to ensure satisfactory light efficiency. Therefore, it is necessary to find out the appropriate conditions under which the transmittance will be at least larger than 60%.

Figure 7 shows the Mura index and the transmittance as a function of the reflectance of the mirror positioned on top of each micro-LED at the $10^4$ mm$^{-3}$ bead density, 3 mm pitch, and 1.75 mm gap. The transmittance is proportional to the luminance of the backlight. As the reflectance of the mirror on the micro-LED decreases, the Mura index is also reduced. This indicates that an appropriate reflectance level should be maintained by using mirrors to prevent the formation of bright spots over the micro-LEDs. On the other hand, the transmittance is not sensitive to the reflectance of the mirror. It slightly decreases as the reflectance increases, but it is larger than 62% even at 100% reflectance. This clearly indicates that the number density of beads should be

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**Figure 2.** (Color online) Example of the luminance distribution showing the nine points used to define and calculate the Mura index. The bright circular areas are the places where the micro-LEDs were positioned.

**Figure 3.** (Color online) Cross-sectional view of the backlight to show the definition of the pitch and the gap.
Figure 4. (Color online) (a) Intensity map of the Mura index as a function of the pitch and the gap at the $10^4$ mm$^{-3}$ bead density. (b) Mura index as a function of the pitch at several gaps.

Figure 5. (Color online) (a) Intensity map of the Mura index as a function of the pitch and the gap at the $10^5$ mm$^{-3}$ bead density. (b) Mura index as a function of the pitch at several gaps.

Figure 6. (Color online) (a) Intensity map of the Mura index as a function of the pitch and the gap at the $10^6$ mm$^{-3}$ bead density. (b) Mura index as a function of the pitch at several gaps.
small enough to ensure high transmittance of the backlight system while optimizing the other parameters, such as the gap, the pitch, and the reflectance of the mirrors on the micro-LEDs, to maintain high uniformity.

At the $10^4 \text{ mm}^{-3}$ bead density condition, the gap should be larger than $\sim 1.5 \text{ mm}$ under a $3 \text{ mm}$ pitch to secure a $\sim 1$ Mura index. This gap distance is not too small for realizing thin direct-lit backlights, but there are two methods by which the gap can further be reduced. First, the gap is expected to be significantly reduced when a diffuser sheet and/or one or two prism films are put over the diffuser plate. Figure 8 shows the Mura index at the $10,000 (1/\text{mm}^3)$ number density of beads with both a diffuser film and a prism film placed on the diffuser plate. It was clearly observed that the luminance uniformity was substantially improved compared to the backlight without these two films.

Another modification may be to use a quantum dot film on the diffuser plate below which only blue micro-LEDs are arranged [13]. Second, the difference in refractive index between the beads and the matrix of the diffuser plate can be increased, such as by using an air pore or a high-index particle such as TiO$_2$, to enhance the scattering efficiency caused by the beads. It can be used to reduce the bead density and thus to increase the light-utilizing efficiency. Finally, reflective polarizers sandwiched between diffusing layers will cause an additional change to further reduce the gap of the backlight and thus to develop super-slim backlights based on micro-LEDs.

4. Summary

In this study, the optimized parameters for obtaining uniform luminance of the direct-lit backlight structure using micro-light-emitting diodes (micro-LEDs) were obtained through optical simulation. The backlight consisted of one diffuser plate, micro-LEDs arranged on a hexagonal lattice, and a reflector on the bottom of the backlight. Under several number densities of beads in the diffuser plate, stable regions were found on the gap-pitch plot, where a high Mura index of $\sim 1$ could be secured. The number density of beads needed to be about $10^4 \text{ mm}^{-3}$ to maintain above 60% transmittance. The transmittance of the backlight was significantly reduced at bead densities higher than $10^4 \text{ mm}^{-3}$. Under the $10^4 \text{ mm}^{-3}$ bead density condition, the gap can be reduced to $1.5 \text{ mm}$ at the $3 \text{ mm}$ pitch. The gap can further be reduced through the use of additional optical films such as a diffuser sheet, a prism film, and a reflective polarizer, in addition to increasing the difference in the refractive index between the beads and the matrix of the
diffuser plate. This work demonstrated that micro-LEDs could be used to realize a thin direct-lit backlight for liquid crystal display (LCD) applications.

Disclosure statement
No potential conflict of interest was reported by the authors.

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Jung-Gyun Lee is presently an M.S. student at the Department of Physics of Hallym University. He has been researching on the optimization of the optical characteristics of OLED light sources through experiments and optical simulation. He is currently studying micro-LED- and quantum-dot-based backlight technologies through simulation and experiments.

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