Patterned Glass Diffuser (PGD) for Mini-LED Backlights

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Abstract

We report on a monitor-sized, thin, dimensionally and thermally stable mini-LED backlight enabled by a patterned glass diffuser (PGD). Our backlight has a luminance between 0.9× and 1.05× compared to a reference mini-LED backlight using a thick diffuser plate, while providing a better local dimming control, comparable zone, panel luminance uniformity and color uniformity. The PGD technology can reduce the number of LEDs.

1. Introduction

A few years ago, the trend towards thin liquid crystal displays was enabled by edge-lit backlight units (BLUs) using light guide plates (LGP) with LED sources coupled into one or more sides [1], [2], [3], [4]. The contrast can be enhanced using lenticular lenses on the front surface of the LGP to confine the light from the LEDs in one dimension and allow 1D local dimming. Several designs for 2D local dimming in edge-lit backlights were demonstrated, but so far, they cannot achieve the performance of direct-lit BLUs [5], [6], [7]. However, direct lit BLUs are typically much thicker due to the larger optical distance (OD) required to achieve the desired luminance uniformity.

A tiled LGP [8] has been proposed to implement an ultra-thin, edge-lit backlight capable of 2D local dimming. High thermal gradients near the LEDs and the wide ranges of operating temperature and humidity experienced in operation makes the use of plastic as the LGP material challenging due to its high thermal expansion and moisture swelling, especially in a configuration requiring accurate alignment of multiple tiles. We have previously reported on a backlight design as thin as an edge-lit backlight, yet capable of 2D local dimming as a direct-lit backlight, based on the use of a glass LGP with holes [9]. This design, although promising, is presently limited by the unavailability of in-plane, all-side emitting LEDs.

With the recent adoption of mini-LEDs [10]-[13], direct-lit BLUs become more attractive than edge-lit BLUs because they maintain the advantages in luminance and local dimming control while closing the gap in the total thickness. Typical mini-LED backlights, like direct-lit backlights using regular sized LEDs, mainly rely on three approaches to convert point-like light sources into a uniform surface light source: 1) using a thick enough plastic diffuser plate; 2) using a large enough air gap between the light sources and the diffuser plate; and 3) using a large enough number of the light sources (or light source pitch being small enough). Approaches 1 and 2 result in undesired large total thickness, while approach 3 leads to higher cost.

In this paper, we report on the use of a patterned glass diffuser (PGD) in a mini-LED backlight to reduce the total thickness while maintaining the luminance and uniformity. The PGD can also be used to reduce the number of LEDs, resulting in cost savings.

2. Patterned Glass Diffuser (PGD) in Mini-LED Backlights

2.1 Reference mini-LED backlight: Figure 1 shows a reference mini-LED backlight, to which the PGD based backlight is to be compared. The reference mini-LED backlight includes a light board that has an array of blue mini-LEDs protected by an encapsulation layer, a thick plastic diffuser plate of thickness, *T*, a quantum dot (QD) film or other types of color conversion film, and a set of typical optical film stack. The optical film stack can include one or more diffuser sheets or thin diffuser plates, one or two prismatic films such as brightness enhancement film (BEF), and a reflective polarizer such as a dual brightness enhancement film (DBEF).

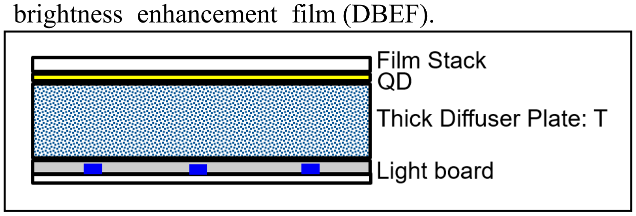

Figure 1. A reference mini-LED backlight including a light board, a thick plastic diffuser plate of thickness *T*, a QD film, and a film stack.

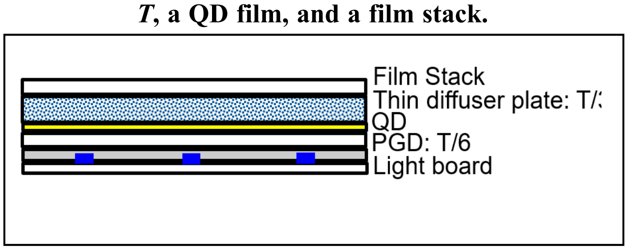

Figure 2. PGD based mini-LED backlight including a light board, a PGD of thickness T/6, a QD film, a thin diffuser plate of thickness T/3, and a film stack.

2.2 PGD: The PGD is made of glass from Corning Inc. and has a proprietary pattern on one or both surfaces. The pattern is referred to as a variable diffusive pattern (VDP) when it varies in space and as a uniform diffusive pattern (UDP) when it does not vary in space at the scale of about 0.2 mm or larger.

The main function of the VDP is to provide lower transmittance and higher reflectance near each LED, compared to away from the LED, through spatial modulation of reflection, transmission and scattering. So, the VDP can help offset the spatial non-uniformity caused by the mini-LEDs, provided that the VDP is registered with each LED within certain horizontal and vertical alignment tolerances. The VDP can vary in opening aperture, and/or vary in height profile, and it can be located on the top or bottom surface of the PGD.

The main function of the UDP is to widen the angular distribution of the LED light when the UDP is placed on the bottom surface of the PGD, while it is to increase the alignment tolerance when the UDP is placed on the top surface of the PGD. The PGD can take a variety of forms depending on the location of the UDP and VDP.

2.3 PGD based mini-LED backlights: Figure 2 shows a configuration of PGD based mini-LED backlight. It has the same light board, QD film, and optical film stack as the reference mini-LED backlight. It uses a PGD of thickness *T*/6 and a thin diffuser plate of thickness *T*/3 in place of the thick plastic diffuser plate of thickness *T*. The QD film is placed between the PGD and the thin diffuser plate. The total thickness of the backlight is reduced by a half the thickness of the thick diffuser plate used in the reference mini-LED backlight.
In an alternative configuration, the QD film can be placed above the thin diffuser plate. In another alternative configuration, the thin diffuser plate is removed, while the PGD thickness remains the same at *T*/6 or increases to about *T*/3. All these configurations have been demonstrated.
In the following, the PGD based mini-LED backlight as shown in Figure 2 will be described.

2.4 Prototype: A monitor-sized PGD has been designed, fabricated, and assembled in a backlight with 10,000+ mini-LEDs. The mini-LED pitch is about 5 mm.

2.5 Measurement results: For a mini-LED backlight, the visual assessment of the LED, or pattern visibility, is very important and often subjective. Recognizing no measurement data can completely replace the visual assessment, we believe the measurement data, when properly measured and used, can guide the improvement of the backlights. In the following, we discuss the luminance uniformity and color uniformity within a single LED zone, referred to as zone uniformity. We have found the plots of optical metrics such as Luminance *L*, 1931 CIE x (shortened as *Cx*), CIE y (shortened as *Cy*), tristimulus values *X*, *Y* (*L*), and *Z*, as a function of radiant position r, can provide clear insight into the zone uniformity. Figure 3(a) shows an example of a 2-dimensional (2D) spatial luminance distribution measured by imaging colorimeter and rendered in false color, each data point spanning about 0.03 mm × 0.03 mm.

To reduce data noise while still maintaining sufficient spatial resolution, we average the 2D spatial luminance data over an area of about 0.3 mm × 0.3 mm and plot it in Figure 3(b) as a function of radial position r, which is measured from the center of the zone. After applying the same technique to Cx, Cy, X, and Z, and normalization by values at radial position r = 0, we further plot the ratios of Cx/Cx(0), Cy/Cy(0), and L/L(0) in Figure 3(c), and the ratios of L/L(0), X/X(0), and Z/Z(0) in Figure 3(d), respectively. Ideally, all the ratios should be flat and equal to 1.0. Any deviation from the ideal value of 1.0, defined as | ratio – 1.0|, where the ratio is one of Cx/Cx(0), Cy/Cy(0), L/L(0), X/X(0), and Z/Z(0), quantifies the non-uniformity around the LED.

We have found that Cx/Cx(0) always has a smaller deviation than Cy/Cy(0), and X/X(0) and L/L(0) always have a smaller deviation than Z/Z(0). We further find that the ratio Z/Z(0) tends to show a larger deviation than Cy/Cy(0). All these conclusions can be understood from the fact that the dominant factor for the non-uniformity is the spatially varying blue LEDs. The tristimulus value Z is the closest measure of the blue light, while the tristimulus values X and Y (or Luminance L) are mainly affected by red and green light, respectively. The Cx and Cy are linear functions of X, Y, and Z, therefore they show smaller deviations than Z. These learnings help us focus on solving the dominant problem of the non-uniformity measured by Z/Z(0).

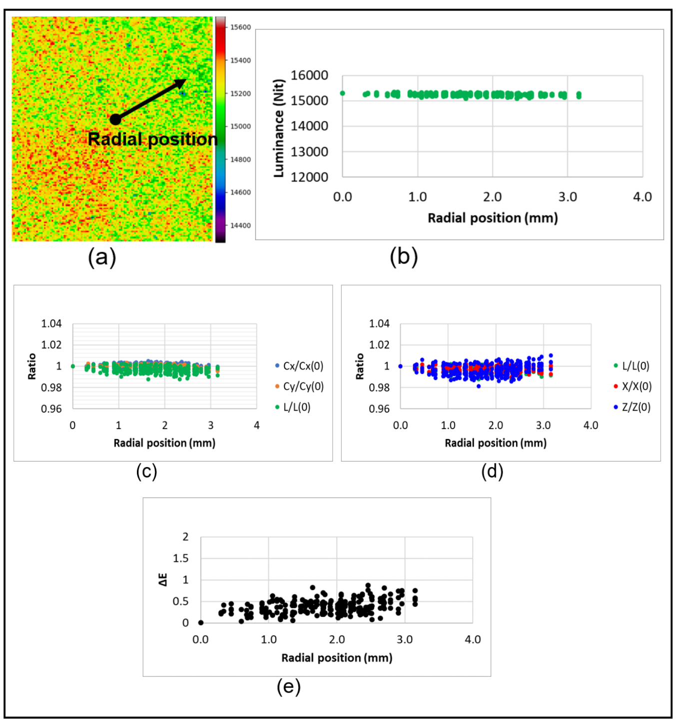

Figure 3. (a) Measured 2D spatial luminance distribution; (b) Luminance vs. radial position; (c) Ratios of Cx/Cx(0), Cy/Cy(0), and L/L(0) vs. radial position; (d) Ratios of L/L(0), X/X(0), and Z/Z(0) vs. radial position; and (e) ΔE vs. radial position.

We further calculate the color difference ΔE [14] between the center of the LED zone and all other points using:

$$= \sqrt{(L^* - 100)^2 + a^{*2} + b^{*2}}$$

where (L^*, a^*, b^*) are the CIEL*a*b* coordinates at other spatial point. The CIEL*a*b* coordinates are derived from the tristimulus values (X, Y, Z) at any spatial point and (Xn, Yn, Zn) at the center point as the white reference point, according to the following equations:

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right);\ b^* = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right)$$

$$f(t) = \begin{cases} \sqrt[3]{t}, & \text{if } t > \delta^3 \\ \frac{t}{3\delta^2} + \frac{4}{29}, & \text{otherwise} \end{cases};\ \delta = \frac{6}{29}$$

Figure 3(e) shows the color difference ΔE vs. radial position using the measured spatial X, Y, and Z distributions. A just noticeable difference (JND) threshold is often considered as ΔE = 2.3 for significantly different colors and ΔE = 1.0 for neutral colors, such as shades of white. Color difference of ΔE < 1.0 is considered not perceivable by a human eye. We find that the maximum color difference max(ΔE) within a zone can be made smaller than 2.0, 1.5, and sometimes 1.0. With max(ΔE) < 2.0, the color difference based illumination uniformity metrics may be sensitive to data outliers caused by minor local damage or contamination of the sample and may be approaching the noise floor of measurement instrument. Therefore, care or additional statistical data post processing must be taken to exclude factors not relevant to the subject.

2.6 Comparisons to the reference mini-LED backlight: **Zone uniformity:** To better assess the zone uniformity of the PGD based backlight, it is beneficial to assess the zone uniformity of the reference mini-LED backlight. Figure 4(a) shows the ratios of $L/L(0)$, $X/X(0)$, and $Z/Z(0)$ in the reference mini-LED backlight shown in Figure 1 when the film stack includes a diffuser sheet and a composite film of a BEF and a DBEF (referred to as film stack 1). Figure 4(b) shows the corresponding color difference ΔE vs. radial position. Similarly, Figure 4(c) shows the ratios of $L/L(0)$, $X/X(0)$, and $Z/Z(0)$ in the reference mini-LED backlight when the film stack includes a diffuser sheet and a composite film of two crossed BEFs and a DBEF (referred to as film stack 2). Figure 4(d) shows its corresponding color difference ΔE vs. radial position.

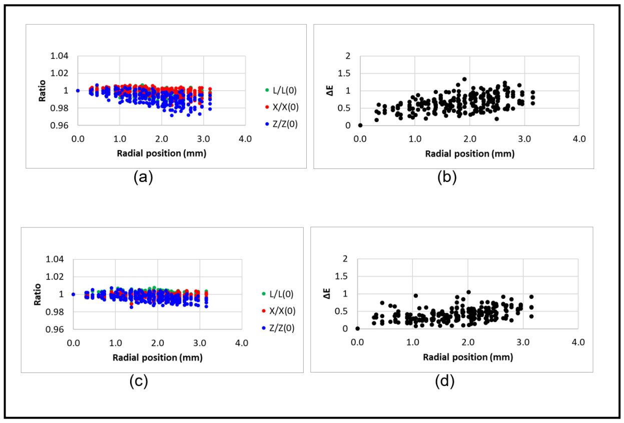

Figure 4. Measured zone uniformity over the reference mini-LED backlight including a thick diffuser plate of thickness *T*. (a) Ratios of *L*/*L*(0), *X*/*X*(0), and *Z*/*Z*(0) vs. radial position for film stack 1; (b) ΔE vs. radial position for film stack 1; (c) Ratios of *L*/*L*(0), *X*/*X*(0), and *Z*/*Z*(0) vs. radial position for film stack 2; and (d) ΔE vs. radial position for film stack 2.

These results indicate that the deviation of *Z*/*Z*(0) is between 1% and 2% and the maximum ΔE is between 1.0 and 1.5. These results also show that the use of more recycling film stack 2 reduces both the deviation of *Z*/Z(0) and the maximum color differenceΔE, compared to using a less recycling film stack 1. PGD based mini-LED backlight shows a similar level of deviation of normalized tristimulus values in Figure 3(d) vs. Figure 4(c), and a similar level of the maximum color difference ΔE in Figure 3(e) vs. Figure 4(d) when the same film stack 2 is used.

Panel uniformity: We also measure the typical backlight uniformity across the entire backlight, referred to as panel uniformity, in a 13-point map. Both, the PGD based backlight and the reference backlight, show 90%+ luminance uniformity, defined as Lmin/Lmax, where Lmin and Lmax are the minimum and maximum luminance values.

Luminance and color coordinates: The PGD based mini-LED backlight generally behaves similarly as the reference mini-LED backlight. Its relative luminance varies between about 90% and 105% depending on the film stack and the QD film. Its CIE 1931 color chromaticity coordinates x and y are typically within 0.02 relative to the reference backlight.

Local dimming control: The PGD based mini-LED backlight shows better local dimming control than the reference mini-LED backlight when LEDs are set to alternating ON and OFF states.

2.7 Optics simulation: We have built an optics model including all the components shown in Figure 2. A mirror boundary condition is used around a single LED zone. The 2D distributions of the tristimulus X, Y, and Z are simulated and plotted in Figure 5 in the same way as discussed above referring to the measurement data shown in Figure 3. When the VDP is optimized, a good luminance uniformity and color uniformity can be achieved, with | ratio – 1| < 0.02. These simulation results are very close to the measurement results shown in Figure 3(d). With this model we can study how the PGD interacts with other components and how the PGD can reduce the number of LEDs.

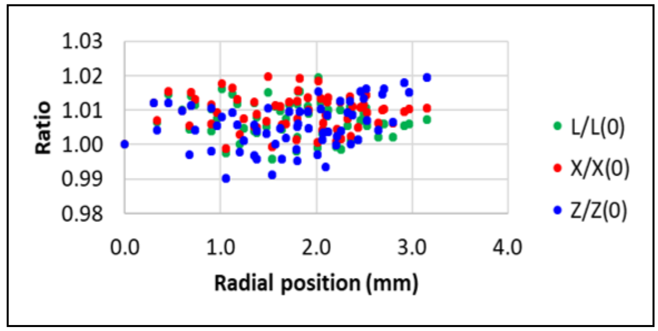

Figure 5. Simulated ratios of *L*/*L*(0), *X*/*X*(0), and *Z*/*Z*(0) vs. radial position.

2.8 Value of PGD: As described above, the PGD has been demonstrated to reduce the total thickness of the mini-LED backlight using the same light board on which the pitches of the LEDs are fixed. The reduced space enables a slim design or can be used for other functions. Alternatively, the PGD can reduce the number of the LEDs if the total thickness is fixed or reduced to a less degree, resulting in cost savings associated with the LED cost, LED driving circuit, and the yield of the light board.

Compared to conventional plastic-based solutions, a glass-based PGD solution further provides desired dimensional and thermal stability. As discussed previously [3], glass from Corning Inc. can have much smaller humidity swell (nearly 0), smaller coefficient of thermal expansion (CTE) (about one tenth), and higher Young's modulus (more than 20×) compared to typical plastics. These attributes make the glass more suitable when high luminance, small total thickness, and a large size are required.

3. Summary and Impact

In summary,we have demonstrated a monitor-sized, thin, dimensionally and thermally stable mini-LED backlight enabled by a patterned glass diffuser. Our backlight has a luminance of between 0.9× and 1.05×, compared to a reference mini-LED backlight using on a thick diffuser plate, while providing better local dimming control, comparable zone, panel luminance uniformity, and color uniformity.

We have also identified the normalized tristimulus value Z/Z(0) as the most sensitive metric to quantify LED zone uniformity and guide the PGD optimization.

We have also identified the normalized tristimulus value $Z/Z(0)$ as the most sensitive metric to quantify LED zone uniformity and guide the PGD optimization. We have built an optics model that produces simulation results in good agreement with measured results and can be used to shorten the design cycle for new backlight configurations.

The PGD technology can be used to reduce the total thickness of a backlight using mini-LEDs or regular sized LEDs, enabling a slim design. Also, it can reduce the number of LEDs, resulting in cost savings.

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