

Brightness management in a direct LED backlight for LCD TVs

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Abstract — A method of calculating the luminance and luminance uniformity of a bottom LED backlight is proposed and demonstrated. Both the power consumption and brightness uniformity as a function of screen brightness, screen size, backlight thickness, transmittance of the LCD panel, reflective cavity efficiency, gain, cone angle of the enhancement films, LED array configuration, and the average luminous flux, radiation pattern, and input power of individual LEDs. Moreover, a 42-in. LCD TV using this backlight design approach was fabricated. The bottom backlight incorporates an array of RGGB 4-in-1 multi-chip LEDs within a highly reflective box behind a diffuser and a dual brightness-enhancement film. The brightness uniformity can be predicted within an accuracy of 94% and the luminance level within an accuracy of 96%.

Keywords — Light-emitting diodes, optical engineering.

1 Introduction

Large-area LCDs are widely used in monitors and commercial TVs. However, an LCD panel is not emissive and thus requires a backlight system. And it is LED backlighting that is pushing LCDs to remain the leader among several competing technologies. Red-green-blue (RGB) LED backlighting provides long life, wide color gamut, no mercury, blinking to reduce motion artifacts, dynamic dimming, etc.¹⁻⁴ LED backlights are beginning to appear in large commercial LCD TVs, and a rapid market penetration is expected in the next few years.⁵ A direct or bottom RGB LED backlight is a key concept in large-area LCDs because it does not use a light guide, is flat, and is easy to assemble. Simply, an array of LEDs is placed in a cavity directly behind the LCD panel (see Fig. 1).^{2,6} Moreover, a bottom backlight enables local dimming and scanning of LEDs in time with the video displayed on the screen. This feature can increase the color contrast and reduce both the movement blurring and power consumption.

There are two main approaches for direct backlighting: (a) Based on side-emitting LEDs, its main advantage is that the backlight cavity can be made very thin because the

side emitter has a highly divergent radiation pattern. (b) Based on Lambertian or on Batwing LEDs. Its main advantage is that a high optical efficiency can be achieved because these LEDs have a directional radiation pattern that is slightly obstructed by adjacent LEDs and is easy to couple to the LCD panel.

To design and efficiently make an LCD, there are several parameters to optimize such as the calibration of the LCD panel and the management of color and luminance.⁶⁻⁸ Luminance or brightness is defined as the luminous flux per area per solid angle ($\text{lm}\cdot\text{m}^{-2}\cdot\text{sr}^{-1} = \text{cd}/\text{m}^2 = \text{nit}$).⁹ It is the photometric standard used to rate the visual stimulus produced by displays. In this paper, we address two key points in the luminance management of a direct LED backlight: luminance level and luminance uniformity.

2 Luminance management

A successful backlighting management ensures that the lighting system consistently provides proper quantity and quality of brightness at the lowest manufacturing and operating cost. Reaching this goal involves providing uniform lighting to the display and installing only the necessary LEDs to reduce energy consumption.

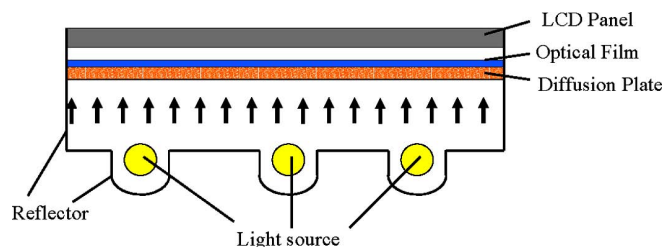


FIGURE 1 — Basic framework of a bottom LED backlight LCD.

2.1 Power management

To meet the backlight demands of a sufficient luminance level, multi-LED arrangements could be simply placed under a diffusing plate for direct lighting conditions. Also, in most cases, a set of brightness-enhancement plates are used. Luminance at the LCD-TV output is almost independent of the position across the screen because this is

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designed to be uniform, and the angular variation mostly depends on the backlight (mainly due to the brightness-enhancement plates). Then the luminance can be expressed as^{9,10}

$$L(\theta, \varphi)_{TV} \approx T_{LCD} L(\theta, \varphi)_{backlight}, \quad (1)$$

where T_{LCD} is the transmittance of the LCD panel, which in most cases is about 4%. The angular variation of the backlight luminance is mostly due to the brightness-enhancement plates located over the diffuser that cover the reflective cavity with the LEDs. The LCD panel also can introduce an angular dependence of luminance but as a function of pixel gray levels.¹¹ However, the luminance must be matched to the particular specifications, which consider the peak screen luminance $L_{peak} = L(0,0)_{TV}$ for a white color point. A regular desktop color display device has a peak luminance of approximately 100 nits, while a high-luminance TV can have a peak luminance up to 300–600 nits.

The backlight luminance can be written in terms of a normalized angular distribution f :

$$L(\theta, \varphi)_{backlight} = L_0 f(\theta, \varphi)_{backlight}, \quad (2)$$

where $L_0 = L(0,0)_{backlight}$ can be approximated by

$$L_0 \approx \frac{\eta_{cavity} G_0 \sum_{i=1}^N \Phi_{LED}^i}{\Lambda_{backlight} \int f(\theta, \varphi)_{backlight} \cos \theta d\Omega}, \quad (3)$$

where Φ_{LED}^i is the luminous flux (lm) of the i th LED from N LEDs in the backlight, $\Lambda_{backlight}$ is the backlight area

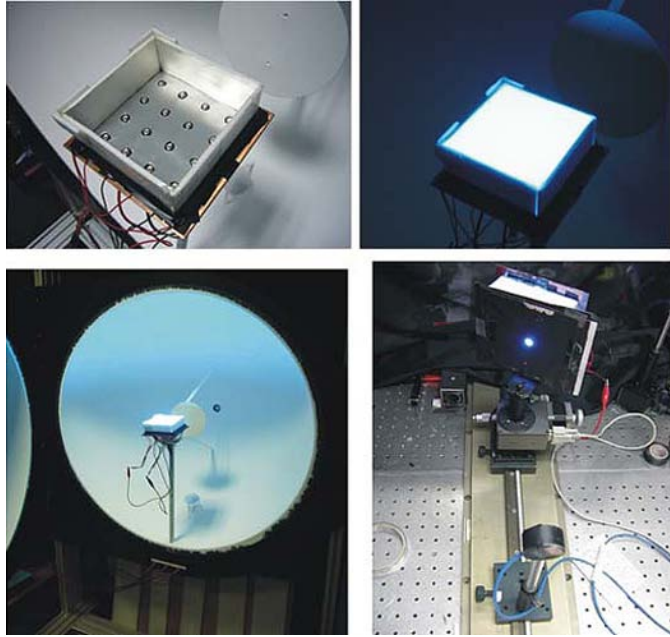


FIGURE 2 — Small backlight module used to measure some optical properties for the management of luminance. (Top left) 4×4 LED box, (Bottom right) LED box with diffuser, (Down left) integrating sphere set up for the measurement of cavity efficiency, and (Bottom right) set up for the measurement of G_0 and the angular distribution f .

(m^2), and Ω is the solid angle (sr) of the emission cone of the backlight. $G_0 = G(\theta = 0, \varphi = 0)$ is the overall axial gain of the stack of brightness-enhancement plates, and η_{cavity} is the transmission efficiency of the cavity with the diffuser plate (output luminous flux/LED-array luminous flux). We found that it is difficult to perform an accurate calculation of η_{cavity} by using optical software. However, a theoretical analysis and simulation algorithms to calculate it will be pursued in future work. But η_{cavity} can be easily measured by using a small reflective box with a few LEDs, covering it with the diffuser, and then putting it inside an integrating sphere. We experimentally found that η_{cavity} practically does not depend on the number of LEDs. For example (see Fig. 2), a small $10 \times 10 \times 4\text{-cm}^3$ reflective cavity (with a diffuser transmittance $T_d = 0.7$ and a wall reflectivity $R_C = 0.9$) has an $\eta_{cavity} = 0.73$ for four LEDs and $\eta_{cavity} = 0.725\%$ for 16 LEDs. The luminous flux to calculate η_{cavity} was measured using a LabSphere 40-in.-diameter PLMS integrating sphere photometer. G_0 can be simply obtained by adding the brightness-enhancement plates over the small lighting box and measuring the on-axis luminance gain.

Approximating $\sum \Phi_{LED}^i \approx N \Phi_{LED}$, where Φ_{LED} is the average luminous flux from one LED of the array, the necessary number of LEDs for a given set of design parameters is

$$N \approx \frac{A_{backlight} L_{peak}}{T_{LCD} \eta_{cavity} G_0 \Phi_{LED}} \int_0^{2\pi} \int_0^{\pi/2} f(\theta, \varphi) \sin \theta \cos \theta d\theta d\varphi, \quad (4)$$

where, in most cases, $A_{backlight} \approx A_{LCD}$. The normalized angular variation mainly depends on the plates that cover the reflective cavity, *i.e.*, $f(\theta, \varphi) = f[\text{diffuser}, G(\theta, \varphi)]$. This function can behave in a variety of ways;⁴ however, in most of the cases f has elliptical symmetry.¹² In such a case, the integral in Eq. (4) can be simplified by means of a simple formula proposed by Chang *et al.*^{12,13} Then f can be written as

$$f(\theta, \varphi) = \exp \left[-\ln 2 \left(\frac{\cos^2 \varphi}{\theta_x^2} + \frac{\sin^2 \varphi}{\theta_y^2} \right) \theta^2 \right], \quad (5)$$

where θ_x and θ_y are the half-angle $\theta_{1/2}$ (the viewing angle when the luminous intensity is half of the value at 0°) along the horizontal and vertical directions, respectively. When numerical values of θ_x and θ_y are provided, Eq. (4) can be easily evaluated using any mathematical software. Also, the implicit solution given by Chang *et al.* can be used.¹²

Equation (4) shows that the number of LEDs per unit area varies approximately linearly with the LCD-TV peak brightness. And using Eq. (4), the power consumption of the backlight is simply

$$\text{Power} \approx P_{LED} N \text{ [W]}, \quad (6)$$

where P_{LED} is the average power of a single LED with a luminous flux Φ_{LED} . As shown in Eq. (4), N also depends on Φ_{LED} and then on P_{LED} .

Typically, Φ_{LED} is proportional to $(P_{LED})^a$, in such a case the backlight power consumption should be proportional to $(P_{LED})^{a-1}$, where a usually is between $1/2$ and $2/3$.

Equations (4) and (6) provide information to reduce energy consumption by using only the required amount of LEDs in the backlight. To calculate the total backlight power, the driver efficiency must be taken into account, we do not consider this loss in our approach, but the LED driver efficiency is usually 90%. An additional key point in the backlighting management is the analysis of brightness uniformity.

2.2 Uniformity management

The improvement in luminance uniformity across the display area of an LCD is a common task. For an LED-based backlight, a hot-spot distribution across the screen can result because LEDs are intrinsically point-like sources. An efficient management of the backlight parameters allows for spreading the light from LEDs more uniformly over the entire display area. In what follows, we study the dependence of the brightness uniformity as a function of several parameters such as LED-to-LED pitch, backlight thickness, and display size.

Commonly, the luminance uniformity of an LCD is defined as $U = L_{\min}/L_{\max}$. For practical purposes, the luminance uniformity only depends on the illuminance distribution (lm/m^2) across the display. Then, in the following analysis, we will speak interchangeably of luminance uniformity and illuminance uniformity. Moreover, we compute illuminance with arbitrary units because the absolute value of illuminance is not necessary to compute uniformity.

The illuminance distribution over an LCD screen mainly depends on the backlight distribution. And the illuminance variation across the backlight unit is mainly determined by the illuminance distribution over the diffuser. The illumination pattern over the diffuser can be approximated by the addition of two components. One is the light pattern directly produced by all LEDs, *i.e.*, the distribution of light transmitted at the first time through the diffuser. And the second component is an illuminance background produced by the multiple reflections inside the cavity. We consider it constant because of the diffuse nature of the light reflected inside the cavity (all internal surfaces diffusely reflect light). The ratio of the second component versus the first component depends on the size and thickness of the backlight cavity. It is smaller for large-sized displays and is larger for thick backlights.

Most LEDs emit light into one hemisphere with some degree of directionality. As a consequence, the illuminance uniformity will be mainly determined by the light distribution directly produced by the LED array. We approximate the luminance uniformity in terms of the effective illuminance distribution over the backlight as

$$U = \frac{L_{\min}}{L_{\max}} \approx \frac{\min(E_{\text{eff}})}{\max(E_{\text{eff}})}. \quad (7)$$

We define the effective illuminance over every point (x, y) on the backlight with thickness z as

$$E(x, y, z)_{\text{eff}} = E(x, y, z) + R_C(1 - T_d)E_B, \quad (8)$$

where T_d is the diffuser transmittance and R_C is the wall reflectivity. The background illuminance is approximated by $E_B = (N \int I d\Omega)/A_{\text{backlight}}$, where N is the number of LEDs, I is the normalized luminous intensity pattern of an LED, and Ω is the solid angle. The relative illuminance pattern of the LED array is

$$E(x, y, z) = \sum_{i=1}^N E(x, y, z; x_i, y_i)_{LED}, \quad (9)$$

where $E(x, y, z; x_i, y_i)_{LED}$ is the normalized illuminance pattern of the i th LED in the backlight. To evaluate Eq. (9), a simple analytical function $E(x, y, z)_{LED}$ for Lambertian, batwing, and side emitting can be used.^{14–16} For side emitters, an extra term must be added to the background component of Eq. (8) because a significant fraction of the radiation is not emitted directly through the diffuser plate.

In practice, the most popular standard for choosing the location of the sampling points is from VESA (Video Electronics Standards Association).¹⁷ To evaluate Eq. (7), the VESA standard considers nine sampling points on the screen at positions $[(0, 0), (0, 0.4b), (0.4a, 0), (0.4a, 0.4b), (0, -0.4b), (-0.4a, 0), (-0.4a, -0.4b), (-0.4a, 0.4b), (0.4a, -0.4b)]$, where $(x = 0, y = 0)$ is the center of the screen and the display area is $A_{\text{LCD}} = a \times b$. Due to the symmetry of our analytical approach, $\min(E_{\text{eff}})$ and $\max(E_{\text{eff}})$ in Eq. (7) are the minimum and maximum values from $[E(0, 0, z)_{\text{eff}}, E(0, 0.4b, z)_{\text{eff}}, E(0.4a, 0, z)_{\text{eff}}, E(0.4a, 0.4b, z)_{\text{eff}}]$. The uniformity can be evaluated in any other standard by simply modifying the number and location of sampling points.

A hot-spot distribution across the screen can result because the LEDs are intrinsically point-like sources. Then we propose an additional set of sampling points to measure the uniformity. To calculate the hot-spot uniformity, the values in Eq. (7) must be chosen from four locations in the central region of screen. Sampling points should be located on one central LED and the other three places should be located between adjacent LEDs. Then these points will be sensitive to the appearance of local minima and maxima due to the discrete nature of the LED assembly. In a rectangular LED array, the hot-spot sampling points for Eq. (7) can be selected from $[E(0, 0, z)_{\text{eff}}, E(0, 0.5d, z)_{\text{eff}}, E(0.5d, 0, z)_{\text{eff}}, E(0.5d, 0.5d, z)_{\text{eff}}]$, where d is the distance between two adjacent LEDs.

As an example, consider a backlight with an array of $N = X \times Y$ Lambertian LEDs with $\theta_{1/2} = 60^\circ$. In such a case, Eq. (9) is

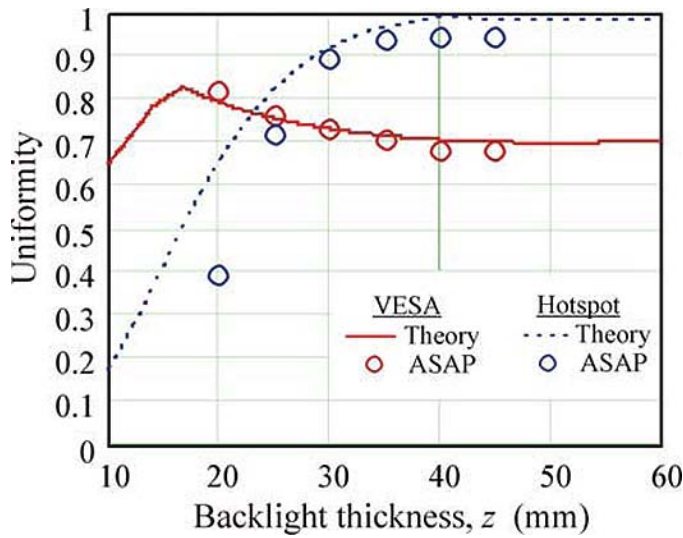


FIGURE 3 — Luminance uniformity of an LED backlight unit as a function of the backlight thickness for an array of $N = 4 \times 7$ LEDs with a packaging density of $d = 36$ mm. This figure additionally shows the uniformity from the realistic simulation performed with ASAP optical software.

$$E(x, y, z) = \sum_{i=1}^X \sum_{j=1}^Y \frac{z^2}{\left\{ \left[x - (X+1-2i)d/2 \right]^2 + \left[y - (Y+1-2j)d/2 \right]^2 + z^2 \right\}^2}, \quad (10)$$

where d is the LED-to-LED spacing. And the background can be approximated by all the hemisphere contribution, *i.e.*, $E_B = \pi N / A_{\text{backlight}}$. Using this value and Eq. (10) in Eq. (8), we can approximate the illuminance uniformity as a function of the LED-to-LED pitch, backlight thickness, and display size.

Figure 3 shows the uniformity as a function of the thickness for $T_d = 0.6$, $R_C = 0.9$, and $d = 36$ mm. This graph is for an array of $N = 4 \times 7$ LEDs, $A_{\text{backlight}} = 261 \times 175$ mm², and a display size of $a = 246$ mm and $b = 163$ mm. Figure 3 shows a trade-off between hot-spot and VESA uniformity, which is evident in the realistic simulations performed with optical software ASAP.¹⁸ From a fundamental point of view, to bridge the gap between VESA uniformity and hot-spot uniformity, it is necessary to increase the number of LEDs with respect to the backlight thickness.

We include some uniformity values obtained from the ASAP simulations shown in Fig. 4. We realistically simulated the reflective box with a diffuser using the same parameters as the analytical approach in Fig. 3. In particular, we used a precise optical source model,¹⁹ considering the conventional LED package (Lambertian chip with a hemispherical dome), and the reflective-box area (261×175 mm²) was slightly larger than the display. We omitted the simulation of larger backlights because the computation time required to realistically model larger LED arrays is overwhelming. However, we are working on optimization algorithms based on optical symmetries and other key points to speed the simulation process.²⁰

Figure 5 illustrates the uniformity as a function of the display size for a screen with an aspect ratio of 16:9, A_{back}

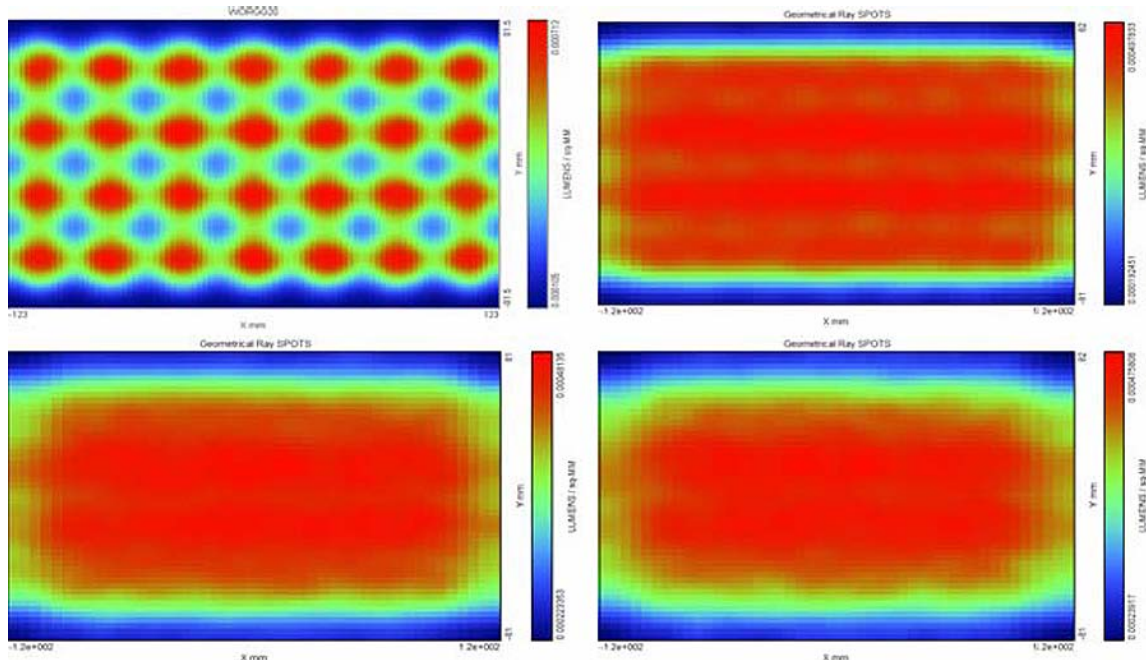


FIGURE 4 — Luminance pattern of an LED backlight unit with $N = 4 \times 7$ LEDs. The simulations are carried out using ASAP optical software for various backlight thicknesses: 20 mm (top left), 30 mm (top right), 40 mm (bottom left), and 45 mm (bottom right).

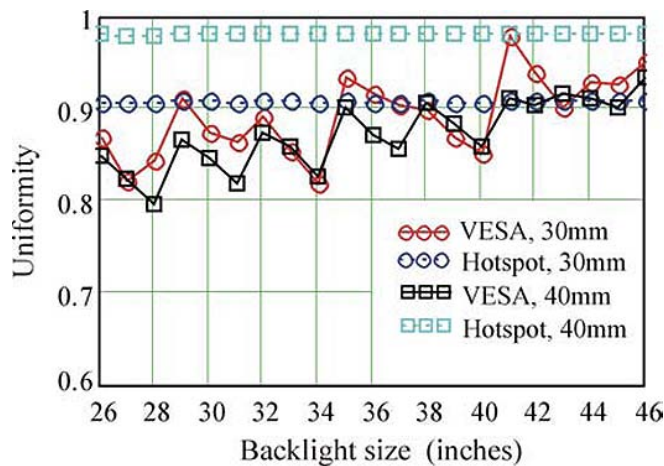


FIGURE 5 — Luminance uniformity as a function of the display size for backlight thicknesses of 30 and 40 mm.

light = A_{LCD} , and with a packaging density of $d = 36$ mm. The plot shows a zigzag effect in VESA uniformity due to the boundary conditions. This happens because the array size must be coupled to every display size, and then the distance between a border LED and the wall varies periodically with the display size. However, the hot-spot uniformity does not depend on the display size; it is a function of the LED-array packaging density and the backlight thickness.

3 Application: 42-in. LCD TV

We made a bottom LED backlight for a 42-in. LCD TV (see Fig. 6), having an aspect ratio of 16:9. The backlight incorporates RGB 4-in-1 multi-chip LEDs within a highly reflective cavity behind a diffuser and a dual brightness-enhancement film (DBEF 3M®).

The backlight was designed in two parts. First, we calculated the LED number required to meet the standard luminance level of 550 nits. Then the optimal backlight thickness to meet the brightness uniformity standard of VESA was obtained. After assembling the 42-in. LCD TV, we compare its performance with predictions.

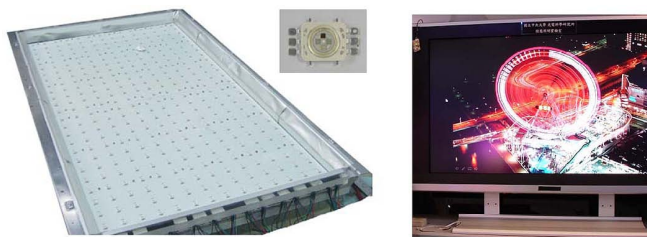


FIGURE 6 — (Left) Constructed LED backlight, (Inset) a RGB 4-in-1 multi-chip LED. (Right) The LED-based 42-in. LCD TV displaying images.

3.1 Number of LEDs in the 42-in. backlight

To calculate the required number of LEDs to achieve a peak luminance $L_{peak} = 550$ nits, we use the following parameters:

- The backlight area $A_{backlight}$ is 0.506 m^2 ($945 \times 535 \text{ mm}^2$).
- Transmittance of the LCD panel is $T_{LCD} = 0.04$.
- Measurements of a small reflective cavity (see Sec. 2.1, with a diffuser transmittance $T_d = 0.6$, and a wall reflectivity $R_C = 0.9$) give the values of $\eta_{cavity} = 0.73$ and $G_0 = 1.3$.
- Figure 7 shows the angular distribution of the small reflective cavity with one diffuser and one DBEF. We placed a mask of $10 \times 10 \text{ mm}^2$ over the box [see Fig. 2 (bottom right)] to measure the intensity pattern with a power meter (with a 2-mm aperture) located at 300 mm. The measured half-angle in the horizontal and vertical orientations of the small backlight are $\theta_x = 43^\circ$ and $\theta_y = 38^\circ$, respectively. The angular distribution of the 42-in. LCD TV is included for comparison.

Because LEDs become more efficient with lower drive current, we choose a luminous flux $\Phi_{LED} = 40.8 \text{ lm}$ for each LED. A tradeoff has to be made between the luminous flux per LED and the backlight efficiency because, in some cases, it could be cost-effective for practical use. However, as indirectly implied by Figs. 3 and 5, the use of many low-power LEDs increases the luminance uniformity.

- Table 1 shows other average characteristics of five sample LEDs (at same electric current) randomly selected. We set a high (19,377K) correlated color temperature (CCT) to compensate the red shift produced by the chromatic filters of the LCD panel. Then we obtain LCD performance with a CCT near 10,000K (standard).

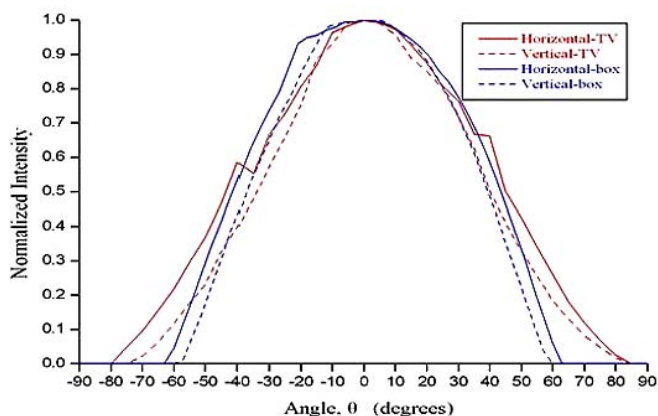


FIGURE 7 — Angular distribution measurement of a small reflective box with diffuser and DBEF. The distribution of the constructed 42-in. LCD TV is included for comparison.

TABLE 1 — Other average characteristics of five sample LEDs.

Parameter	Φ_v (lm)	I_R (A)	I_G (A)	I_B (A)	V_R (V)	V_G (V)	V_B (V)	Power (W)	Efficiency (lm/W)
Average ($\bar{A}$)	40.8	0.15	0.143	0.121	2	2.9	3.2	1.10	37.0
(Max-Min)/ $\bar{A}$	4.8%	0	0	0	0.4%	1.8%	1.6%	1.0%	5.9%

Using all these values, we can predict by using Eq. (4) that the required number of LEDs is 361. But this number must be adapted to a display with an aspect ratio of 16:9. Then we set $N = 364$ LEDs (rectangular array of 26×14 LEDs); and the expected luminance is slightly more, $L_{\text{peak}} = 554$ nits, operating at a power of 400 W.

After building the 42-in. LCD TV with 364 LEDs, the white point of the display showed a CCT = 9256K with a color gamut of about 96% NTSC (about 35% more than a common LCD TV using CCFL backlights). CCT and luminance were measured with a color analyzer and luminance meter (Laico Co., Ltd., model DT-100/LM-100).

The measured peak brightness was 575 nits for the LCD TV operating at an electric power of 400 W (with LEDs operating at voltage and current levels indicated in Table 1). Therefore, the agreement between expected and real performance is within an accuracy of 96% for brightness. This accuracy is high considering that there are too many parameters involved. For example, from Table 1, the luminous flux variation could by itself reduce the accuracy up to 95.2% for brightness.

3.2 Lighting uniformity for the 42-in. backlight

The backlight incorporates RGB 4-in-1 multi-chip LEDs (that produce a nearly Lambertian pattern) in a rectangular array. Then, we can calculate the luminance uniformity in Eqs. (7) and (8) by using Eq. (10) for $X = 26$ and $Y = 14$. The other parameters are $T_d = 0.6$, $R_C = 0.9$, $a \times b = 930 \times 523 \text{ mm}^2$, $d = 36 \text{ mm}$, $A_{\text{backlight}} = 945 \times 535 \text{ mm}^2$, and $E_B = \pi N/A_{\text{backlight}}$.

Figure 8 shows the luminance uniformity as a function of backlight thickness, from which one can expect that the optimal thickness would be between 30 and 40 mm. We set $z = 40 \text{ mm}$ to make room for other non-uniform sources such as LCD non-homogeneity, thermal effects, and the flux or radiation pattern variation among LEDs. Then, under ideal conditions the expected luminance uniformity is 0.94 for VESA and 0.98 for hot-spot uniformity. Additionally, we performed a realistic simulation with ASAP for this thickness, giving 0.96 for both VESA and hot-spot uniformity.

The backlight was built with a 40-mm thickness. After assembling the 42-in. LCD TV, the measured luminance uniformity was 0.85 (VESA) and 0.99 (hot-spot) uniformity. The color uniformity was also high, with a small color vari-

ation across the display in CIE $u'v'$ chromaticity coordinates, $\Delta uv < 0.009$ with respect to the average value of 100 sampling points.²¹

The agreement between expected and real performance was within an accuracy of 90% (VESA) and 99% (hot-spot). The measured uniformity is higher than the 0.8 standard limit of VESA. Additionally, the high hot-spot uniformity and the uniformity peak at around 32 mm (see Fig. 8) suggest that there is room for reducing the backlight thickness to 30 mm.

Figure 9 (top) shows the measured luminance distribution across the LCD screen, which is measured with a color analyzer and luminance meter (Laico Co., Ltd., model DT-100/LM-100). Measurement takes 100 sampling points

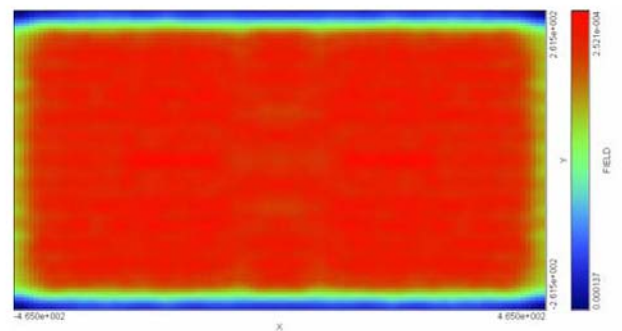
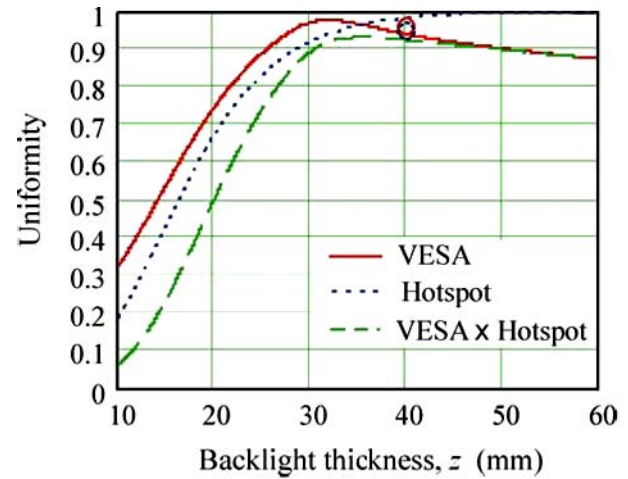


FIGURE 8 — (Top) Luminance uniformity of the LED-based 42-in. LCD TV simulated as a function of the backlight thickness. The ASAP simulation for a selected thickness of 40 mm is included for comparison. (Bottom) ASAP simulation of the luminance pattern across the screen for a 40-mm thickness.

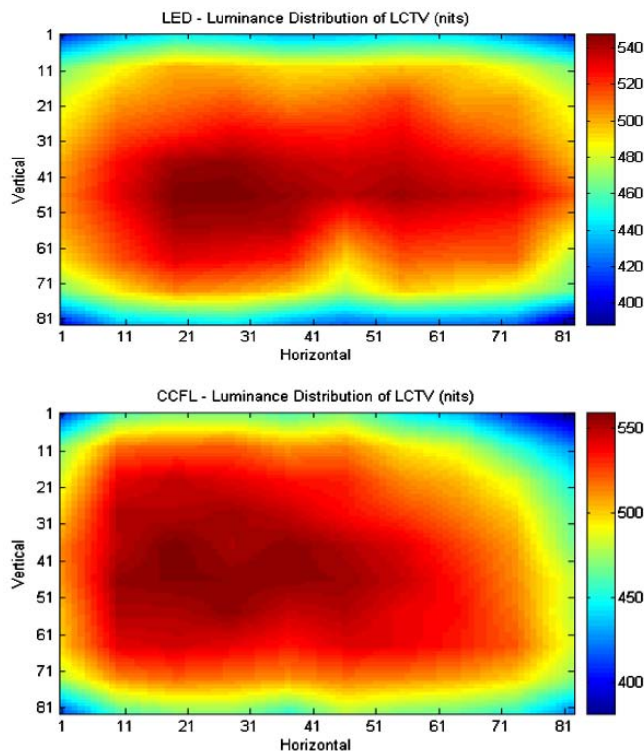


FIGURE 9 — (Top) Luminance distribution of the constructed 42-in. LCD TV, and for comparison, (down) a commercial available CCFL-based 42-in. LCD TV.

in an array of 10×10 over the screen. With the purpose of illustration, a smoothing algorithm is applied to the measured data for displaying a matrix of 82×82 . For comparison purposes, we include [see Fig. 9 (bottom)] the illuminance distribution of a commercial 42-in. LCD TV using CCFL backlights, which has a uniformity of 0.79 in VESA. From Fig. 9, it is evident that there are additional reasons for non-uniformity than those analyzed here. For example, the uniformity can be improved by choosing LEDs that have equal luminous flux among them. From Table 1, we can observe that the luminous flux shows a variation of 4.8%, which in

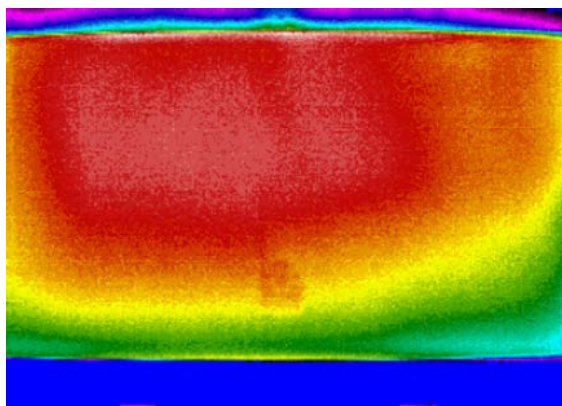


FIGURE 10 — Thermal distribution of the constructed LED backlight; with a driving time of 30 min and a peak temperature of 36.0°C .

the worst case could reduce the predicted VESA uniformity (94%) to 89.5%. Another factor is the thermal distribution across the backlight. Figure 10 shows the thermal distribution of the backlight module with a high-definition infrared camera. It can be noted how this thermal distribution resembles the luminance pattern in Fig. 9 (top), in particular at the edges.

4 Conclusion

A photometric method of LED-based direct-backlight LCD-TV luminance analysis has been proposed and verified by measurements on a prototype TV. We analytically calculated both the power consumption and brightness uniformity as a function of various parameters of influence. A prototype 42-in. LCD TV using this backlight technology demonstrated that luminance can be predicted with a high degree of accuracy (96%) and the brightness uniformity with 94% accuracy. In the case of uniformity, the high agreement between the method and realistic simulations with ASAP software suggests that the uniformity can be improved to higher levels. This can be done by reducing the LCD non-homogeneity, the thermal distribution across the backlight, and the variation of both the flux and radiation pattern among LEDs.

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