Ultra-slim Direct-lit LCD Backlight Using Glass Light Guide Plate

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Abstract

We report on the design and performance of a direct-lit LCD backlight prototype which is only 5 mm thick and capable of full array 2D local dimming. Equipped with a 15.6" LC display panel, the prototype reaches peak brightness of 2000 nits. The measured contrast numbers meet VESA Display HDR 600 specification.

I. Introduction

To remain competitive with OLED and other emerging display technologies, liquid crystal displays (LCD) follow general trends of increasing resolution, higher peak brightness and dynamic range (HDR), higher contrast, thinner set design, and narrower bezels. The demands of increased peak brightness and contrast can currently only be met using so-called direct-lit backlights, with a 2D array of light sources directly behind the LCD panel. As was shown in the pioneering work by H. Seetzen and co-authors [1], so-called local dimming, or selective addressing of the individual light sources in the array, allows reaching ANSI (checkerboard pattern) contrast approaching 300000:1, even with 2004 technology. Since then, the performance of light sources, algorithms used for local dimming [2], and the native contrast of the LCD panels were steadily improving.

One challenge that remains difficult for the direct-lit backlights to address is reducing the thickness. The sources in modern designs are typically either blue or white light emitting diodes (LED), capable of generating significant light power from a relatively small package. To make the backlight brightness uniform, so-called optical diffuser plates (DP), sometimes in a combination with lenses modifying (widening) angular distribution of the LED output (so-called 2nd lenses), are placed over the LED array at a distance known as "optical distance" (OD). However, even when using 2nd lenses, it is very difficult to achieve OD < about 1/4 of the LED pitch P (distance between LED centers in the 2D array). In current high-end commercial TV sets, the pitch P is typically in the range 30-40 mm and OD is 9-10 mm, which is achieved by using a thick (1.5-3 mm) and dense optical diffuser.

We have previously reported on a thin backlight design where side-emitting LED sources are inserted into holes in the glass light guide plate (LGP) [3]. Essentially, the design preserves the thin form factor of the edge-lit backlight while enabling 2D dimming capability. Promising performance was demonstrated, but prospects of this design are limited by the lack of commercially available side-emitting LED devices.

In this work, we describe a backlight unit (BLU) design with the LED pitch P of 43 mm and the effective OD of 1.35 mm, less than 1/30 of the LED pitch. The design is using a glass LGP optically bonded to the LED sources. The total backlight thickness, including the printed circuit board (PCB), is ~ 5 mm. The prototype LCD display constructed to evaluate the performance of the backlight is less than 8 mm thick.

II. Ultra-slim Direct-lit Backlight Design

The working principle of the ultra-slim direct-lit backlight is schematically illustrated in Figure 1. The figure shows a segment of the backlight cross-section near one of the LED devices. For simplicity, the optical diffuser plate, quantum-dot (QD) color converter and brightness enhancement films (BEF) are not shown.

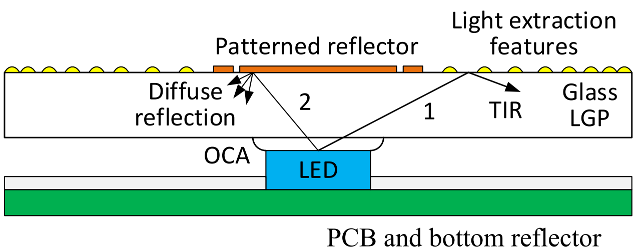


Figure 1. Schematic of an ultra-thin BLU cross-section segment near one of the LED sources.

At the heart of this design is the glass LGP. Light guide plates are commonly used in edge-lit backlights to distribute light coupled into their edge over the entire backlight area. The reason they are not normally used in direct-lit BLUs is the lack of surface couplers. An advantage of guiding light in the plane without loss by total internal reflection (TIR) cannot be used without first coupling the light into the guide.

A very simple surface coupler can be created by forming an optical bond between the LED package and the LGP through a layer of an optically clear adhesive (OCA). Note that if an LGP is placed over an array of LEDs without bonding, the light will simply pass through the plate without being coupled in. In the presence of bonds, the Fresnel refraction at the bottom surface of the LGP disappears. For a typical LED chip/ package with a so-called Lambertian (intensity proportional to the cosine of angle) angular distribution, about 55% of the output is emitted at angles higher than ~42 degrees critical angle of the TIR (ray labeled 1 in Figure 1) and will therefore be immediately coupled into and propagate in the glass plate. To deal with the remaining 45% (ray labeled 2 in Figure 1), a patterned reflector with as high as possible reflectivity and spatially (in plane) varying transmission is formed at the top surface of the LGP. It is very important to ensure that the reflection is diffuse (has a strong scattering component), in which case a significant portion of the light after first reflection will be also coupled into the LGP. Our numerical modeling results indicate that up to 80% of the LED output can be coupled into the LGP in this manner.

Once light is propagating in the LGP, it needs to be extracted before it can illuminate the LCD panel. For this purpose, just like in the edge-lit BLUs, light extraction features must be formed at the top or bottom (or both) surface(s) of the glass. Also, like in the edge-lit BLUs, the aerial density of the light extraction features needs to increase with the distance from the LCD. The density gradient should be stronger than in the edge-lit case because the light power propagating radially from a point source decreases as a square of the distance from the source even if no extraction happens. If a design is using one LED per local dimming zone of the backlight, it is desirable that the light extraction feature's density is the maximum possible at the edges of the zone, in order to improve light "confinement" within the dimming zone or, in other words, to make the point spread function (PSF) associated with each LED source narrower.

III. Prototype fabrication

To demonstrate the feasibility of the ultra-slim BLU design concept and evaluate the limits of its performance in experiment, we constructed a working prototype, including an LCD panel. The size of the backlight, and of the LCD panel working area, was 344 by 195 mm (15.6" diagonal).

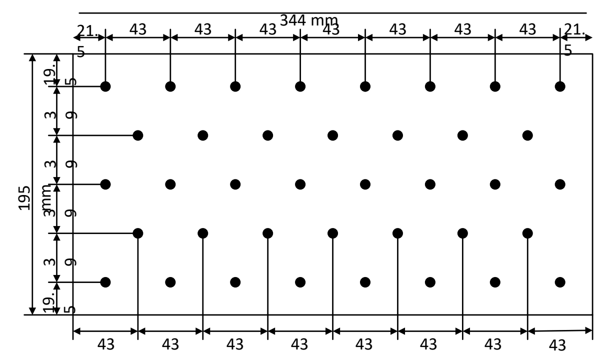


Figure 2. LED grid layout for the ultra-slim BLU prototype.

The light board (circuit board with LED sources) was made using standard single layer 0.5 mm thick PCB with a nearly hexagonal pack LED array, as illustrated in Figure 2. Since an external driver was used for the LED array, an additional 10 mm width was added on one of the long sides to house connectors. The LEDs are blue (450 nm) 8-die chip scale packages (CSP) with a total active die area of approximately 1.1 by 1.1 mm. They are capable of emitting > 1 W of power for short periods of time. The separate driver board is using 5-channel Analog Devices LTC 2662 current output DAC with each channel capable of sending up to 300 mA with 16-bit resolution to each individual LED package on the light board. T o achieve a consistent optical bond between each of the 38 LED packages and the glass LGP, the LGP is mounted on the backing board taking special care to ensure that the top surfaces of the packages lie in the same plane with +/- 0.1 mm accuracy. A white back reflector film with holes punched for the LEDs is laminated to the PCB. A drop of OCA is then dispensed on top of each package, the glass LGP is aligned with the light board and brought in contact with the LEDs, and the OCA is cured. To avoid undesirable light trapping, it is important to use an OCA with refractive index matched to, or higher than, that of the glass. For our prototype, we use Dow Chemical Dowsil VE-1303 H UV-curable silicone with n=1.54. To improve the mechanical robustness of the prototype and relieve excess stress on the OCA bonds that might be created by accidental shock and vibration, a bead of white silicone sealant (Loctite 594) was applied around the backlight perimeter between the glass edge and the metal frame. The white silicone serves a dual purpose as the edge reflector for the backlight.

The glass choice for the prototype is 1.1 mm thick Corning Iris™ glass. Iris™ glass was developed specifically for backlight applications and is engineered to have both exceptionally low optical attenuation and low color shift (wavelength-dependent attenuation). While low attenuation is somewhat less critical for the direct-lit backlight application compared with edge-lit, since the light does not have to travel in glass nearly as far, other properties of glass are still very important. Excellent surface quality of glass made by Corning proprietary fusion process facilitates reliable optical bonding to LED packages. Thermal stability allows glass to work in direct contact with the LED devices rated for operating temperature of up to 85 C. Chemical stability means that it will not swell due to absorption of moisture. Low thermal expansion means that it will not warp due to local variations in temperature. Dimensional stability will ensure that the reflectors and light extraction patterns will not get distorted. And finally, in the ultra-thin display set design, the glass could serve as an additional mechanical strength element.

Both, the patterned reflectors and the light extraction features on the top surface of the LGP, were made by printing. While we determined that similar performance can be obtained using either inkjet or screen printing, inkjet was used for the development work due to a faster turnaround. Mounting patterned reflectors made by laminating a plastic diffuser film and a perforated metal foil on a PMMA LGP was previously described in [5]. This approach is not without challenges, since metallic mirrors add loss and additional steps of perforation, lamination and assembly are required to build the backlight. We determined that using only commercially available high opacity white ink and printing a sufficiently thick layer, the reflectivity of the patterned reflector could be raised to above 95% and its total transmission decreased below 2%. Most importantly for the application, the reflection of white ink is highly diffuse, very close to perfect Lambertian, at least at normal incidence. For the light extraction features, single isolated droplets of the same white ink, jetted to the glass surface, were used. As confirmed by the results of Zygo interferometer measurement presented in Figure 3, after curing, the ~50 pl ink droplet forms a slightly narrower than a perfect spherical cup dome-like shape about 90m in diameter and 14m tall. Such small individual feature size is helpful in producing a very wide range of aerial densities required for this design.

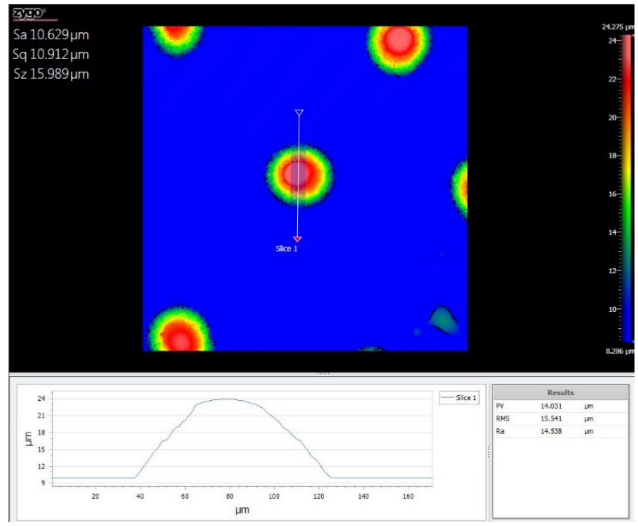
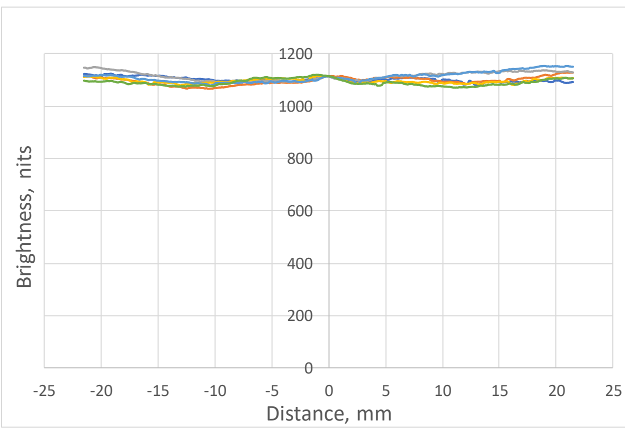


Figure 3. Zygo interferometer measurement results for a single droplet of white ink on glass.

An important step in the design of the ultra-slim BLU is the optimization of the printed patterns. The main objective of the optimization is to produce both the uniform brightness and the uniform color across the entire backlight area. As discussed above, there are two distinctly different types of features printed on the LGP top surface: patterned reflectors and variable aerial density light extraction features. The approaches for optimization of these two different types of features are also different.

The light extraction pattern (EP) is optimized using a comprehensive numerical modeling in the Synopsys LightTools software. A full system model is implemented, including back reflectors, LED packages and bonding geometry, glass LGP and additional films in the stack: DP, QD color converter and BEFs. The measured geometry and optical properties of the ink are converted into parameters of the bi-directional scattering distribution function (BSDF) that can be used in the model. The EP density versus coordinate is adjusted until the model predicts perfectly uniform brightness, then converted into a 1-bit bitmap for printing on glass. The printed LGPs are evaluated in experiment (the OCA used to bond LED packages to the glass LGP is not cured, so that it could be washed off and the light board re-used for a new measurement). The ink parameters in the model are adjusted to match the brightness distribution observed in experiment, and the optimization/printing/ measurement cycle is repeated. Two to three iterations are normally sufficient to arrive at the final fully optimized EP design.

As it turns out, both the color point and brightness at the very center of each dimming zone (directly above the LED package) are only weakly dependent on the EP design and primarily determined by the properties of the patterned reflector. Unfortunately, it is difficult to adequately represent this area in the numerical model, primarily due to a practical challenge of accurately measuring the reflection properties of the LED package. In this case, empirical optimization has proven to be a more efficient approach, mainly because in principle up to 38 different variations (as many as LEDs in the prototype) can be created and evaluated in a single printing round. The thickness and shape of the reflector versus radial coordinate are tuned until the brightness and the color above the LED match those at the edges and corners of the dimming zone between the LEDs. A final tweak to the EP might still be required in the "transition" area immediately adjacent to the patterned reflector.



Once EP and patterned reflector optimization is completed, the pattern is printed on glass and the LGP is bonded to the LED packages on the light board. Additional stack elements (optical diffuser plate, QD color conversion film with a blue bandpass coating, a combination crossed BEF and diffuser film) are placed on top of the LGP as shown in Figure 4. The full thickness of the BLU is 5.05 mm without and 6.65 mm with the decorated backing board. As a final step, the completed BLU prototype is used to replace a stock backlight in a commercially available 15.6" laptop with a 1920x1080 pixels in-plane-switching (IPS) LCD panel. Although the retrofit backlight is driven using a separate driver board (the connection between the laptop CPU and the LCD panel is kept intact) for the convenience of displaying test images.

IV. Characterization

The BLU performance is first measured before adding the LCD panel. The luminance and color uniformity are evaluated using Radiant Vision Systems ProMetric I16 imaging colorimeter to collect luminance maps at several locations. The measurement results are presented in Figures 5 and 6.

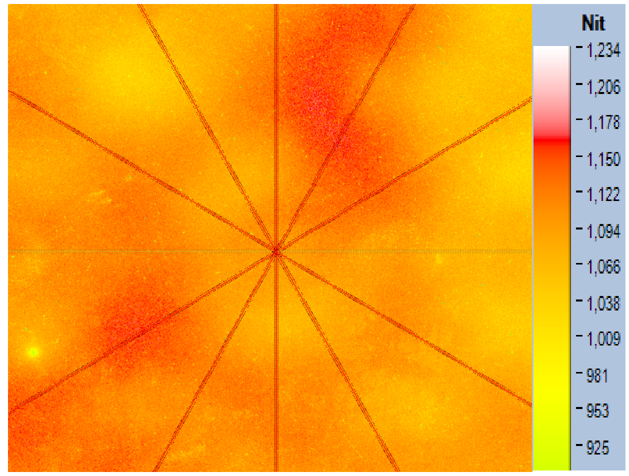


Figure 5. False color luminance map of approximately 86 x 76 mm area in the center of backlight.

Brightness scans across single dimming zone

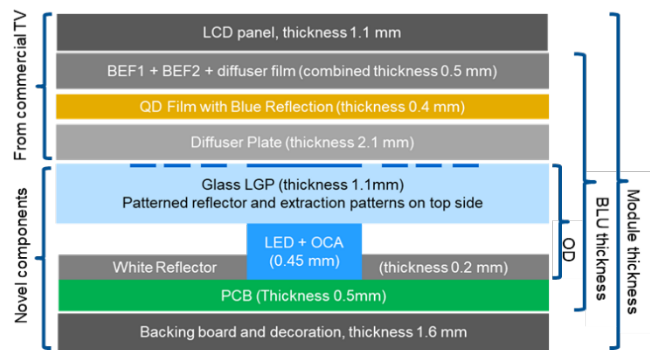


Figure 6. Brightness scans across 6 symmetry axes of a single dimming zone in the center of backlight.

Figure 5 shows the luminance map for an area approximately four diming zones big, in the middle of the backlight, in so-called false color (red is brighter). Figure 6 presents brightness scans across six symmetry axes (0, 30, 60, 90, -30 and -60 degrees to the short side of the backlight, respectively) of a single dimming zone in the middle of the backlight. The brightness uniformity of the BLU prototype is ~ 93%, approaching the limit where it would appear perfectly uniform to the observer. The residual non-uniformity is due to imperfections unavoidable in a laboratory prototype, primarily due to inconsistencies in the shape and thickness of the OCA used to bond the LED packages to the glass LGP, which was dispensed by hand.

After the BLU was assembled with the display panel, additional measurements were carried out. The maximum brightness from the BLU achievable at the specified maximum operating current of the LED packages was 32000 nits, and after the panel the maximum brightness was 2000 nits, consistent with the panel transmission of 6.25%.

It is interesting to note that even with all LEDs driven at the maximum current, the LED package temperature did not exceed the 85 degrees C specification. In fact, it was lower than when the light board with the LED array was operated by itself, without any additional components on top. We attribute this reduction in the operating temperature to the heat-spreading effect of the glass LGP bonded to the LEDs. While the thermal conductivity of glass is not high, it is still a lot better than air, especially with a very limited space for convection.

The contrast of the prototype was tested with several test images shown in Figure 7. In each case, the local dimming pattern (drive currents supplied to the individual LED packages) was adjusted to suit that specific image. The peak brightness in each case was set at 19,500 nits (1220 nits after the panel).

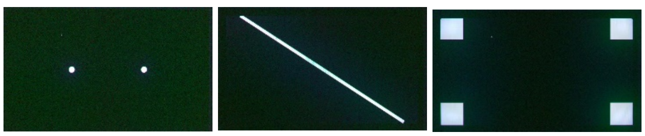


Figure 7. The test images used to evaluate the ultra-thin display module contrast with local dimming.

The results, for the images shown in Figure 7, were as follows:

- Two dots: 1210 nits at the dots, 0.16 nits in the center (7500:1 contrast)
- Diagonal line: 1220 nits on the line, 0.12 nits in the corners (10000:1 contrast)
- Four corners: 1220 nits in corners, 0.23 nits in the center (5300:1 contrast).

Based on the numbers for the four corners image, which is similar to one of the standard tests for HDR monitors, the ultra-slim display module prototype meets the VESA DisplayHDR 600 specification but not the HDR 1000. This is related primarily to a relatively small size of the BLU given the ~ 40 mm LED pitch, rather than any fundamental shortcoming of the ultra-slim design.

V. Conclusions

In summary, design, fabrication and performance of an ultra-slim direct-lit LCD backlight prototype were presented. The design is based on an Iris™ glass light guide plate optically bonded to an array of LED packages arranged in a hexagonal grid. The backlight is only 5 mm thick and capable of full array 2D local dimming. Equipped with a 15.6" LC display panel, the prototype reaches peak brightness of 2000 nits. The measured contrast numbers meet VESA DisplayHDR 600 specification.

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