Frontlight System for Semi-Specular Reflective Displays

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ABSTRACT

We present a frontlight system for semi-specular displays such as reflective LCDs. These displays require illumination with a high degree of angular control and uniformity from a transparent substrate. The frontlight enables proper matching of the illumination field to the display reflectivity profile for improved contrast, color and efficiency.

1 Introduction

Reflective displays are a commonly chosen solution for low-power grayscale devices such as e-readers. The addition of color filter arrays (CFA) to the displays greatly reduces their reflectivity, which is particularly problematic for Lambertian-type reflective displays. There are two primary options to give the CFA-based higher perceived reflectance. The first is to widen the pass band of the filters, which results in a lower color gamut. The second method is the use of a semi-specular reflectivity profile, which can range from simple gaussian to highly functionalized anisotropic. Unlike Lambertian displays, these semi-specular displays require finely-tuned directional frontlighting for the highest brightness, contrast and color gamut performance.

Reflective liquid crystal displays (RLCDs) are the most common form of semi-specular reflective displays. They utilize much of the same technology as transmissive LCDs but replace the backlight with a mirror and moderate optical diffusion within the display stack. Beyond the color filter array loss described above, there is also a typically >60% reflectivity loss due to the required polarization and the opaque border between pixels. Therefore, designing for optimal semi-specular gain is critically important to compensate for these losses. A number of innovative designs have been developed[1], which require corresponding frontlight designs for best use in low-lighting conditions. Azumo has worked with the industry to deliver frontlit RLCD display packages with *high resolution, good color and high refresh rate* at much lower power in virtually all ambient lighting conditions.

Figure 1 shows sideview schematics of various display systems to illustrate some of the requirements for RLCD lighting. A typical electrophoretic display (EPD) with frontlight is shown in 1a. Since the display is paper-like, light rays leaked at slight angles from the FLP hit the display and scatter in all directions[2]. In comparison, Figure 1b shows the more mirror-like RLCD reflecting the light with only slight scatter. Backlit LCDs can overcome the low-diffusion of the LCD by adding multiple optical films including diffusers. These additional films cannot be used in a frontlighting system because they substantially reduce the image quality and typically require an air gap. Previous attempts to frontlight with traditional edge-lighting[3] have not overcome these challenges due to the competing problems of tightly controlling light angles, viewing uniformity and maintaining high clarity of the frontlight.

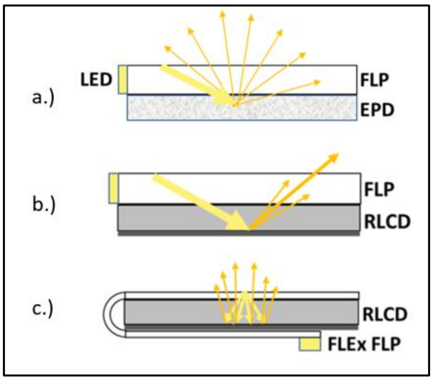

Figure 1: Sideview schematic of (a) Electrophoretic display with edge-lit frontlight, (b) RLCD with edge-lit frontlight. (c) The Azumo frontlight on RLCD.

To overcome these challenges, Azumo has commercialized a high-performance optical system for lighting displays using 25 to 50 micron thick lightguide films. Figure 2a shows a top view schematic of the system. The system includes a proprietary Lightbar for efficiently and uniformly coupling collimated light into film that is much thinner than the size of the LED. Critically, there is a flexible Light Mixing Region between the Lightbar and Display Region to further condition the light distribution for high uniformity. Since the film is ultra-flexible, the Light Mixing Region can be folded behind the display for a bezel-free system as shown in Figure 2a. The equivalent edge-lit system shown in Figure 2b results in a substantial bezel for adequate light mixing from the discrete collimated LEDs[4].

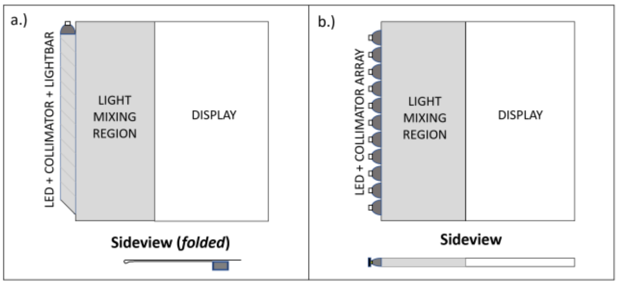

Figure 2: Schematics of collimated lightguide systems with (a) the Azumo System compared to (b) traditional edge-lit system. The Azumo System can be folded behind the display as shown in the Sideview.

The reduced lightguide thickness additionally reduces the image distortion from the frontlight. Since lightguide extraction feature density scales inversely with the lightguide thickness, the system achieves controlled lighting angles while maintaining high clarity. The ability to illuminate with virtually any angle distribution has driven a deeper understanding of the ideal lighting distributions for RLCDs. This paper demonstrates new models and experimental data using the Azumo optical system for high-gain, high-contrast illumination of RLCDs.

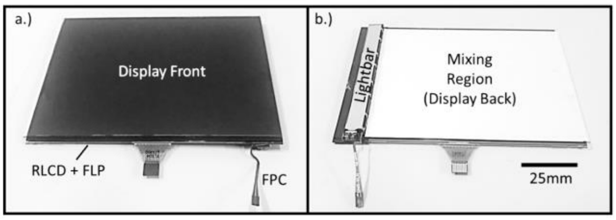

Figure 3: The Azumo FLP integrated on a 4.4” RLCD (a) Front View and (b) Back View

2 Experiment

A JDI 4.4” reflective color LCD (LPM044M141A) was tested to obtain the reflectivity and contrast profile of a commercial RLCD. The JDI 4.4” datasheet specifies an 18% reflectivity and 40:1 contrast ratio (CR) at normal, when illuminated from a preferential 30º degrees from display normal. The display was placed within a goniometer illumination system (Figure 4a) with 2.5º full width illumination divergence and viewed at the display normal. The illumination angle, θ , was rotated and the reflectivity and contrast angle viewed at normal were measured at different display rotations, φ . Figure 4b shows the measured reflectivity in white state as compared to a perfect Lambertian reflector. Figure 4c shows the black state reflectivity with the resultant contrast (white/black) shown in 4d. When considering brightness, the displays are preferentially lit as close to the normal as possible but contrast peaks when illumination is near $(\varphi, \theta) = (90°, 30°)$ and $(270°, 30°)$.

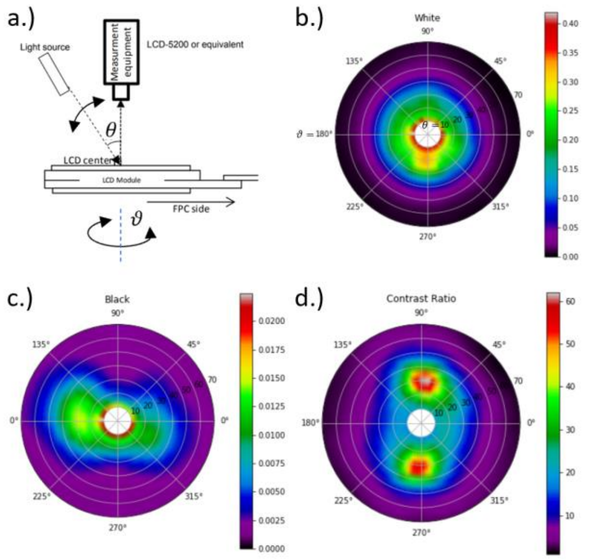

Figure 4: (a) Display measurement schematic (a) to measure the JDI MIP 4.4” for (b) white reflectivity, (b) black reflectivity and (c) resultant contrast.

Three parabolic collimating coupling optics were custom designed for 10º, 20º and 40º FWHM gaussian light distribution from an LED. These were designed to fit the Azumo 4.4” diagonal frontlight system. The angular distributions of the LED/optic assemblies were measured with a far-field target (Figure 5a). This was followed by measuring the same assemblies in an integrating sphere (5b) to measure the luminous flux in lumens exiting the optic face. These LED/optic assemblies were then used as described in the following section.

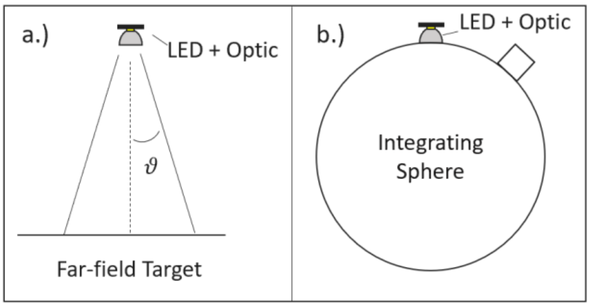

Figure 5: Experimental steps of measuring the (a) LED/optic light distribution and (b) overall lumen output.

3 Results and Discussion

A standard 4.4” Azumo frontlight system with peak illumination near θ=6° in one axis was laminated to the 4.4” JDI MIP RLCD. For this experiment the frontlight was oriented in the non-preferential direction (φ=180°). When inserted into the frontlight system, the brightness performance at the display normal was measured as a ratio with the input lumens. Figure 6 shows the measured data compared to a model simulation. The 90° collimation datapoint is the emission from the LED without any optic. This experimentally demonstrated a more than 3X brightness gain at normal when collimating with a narrow illumination cone of ±10°.

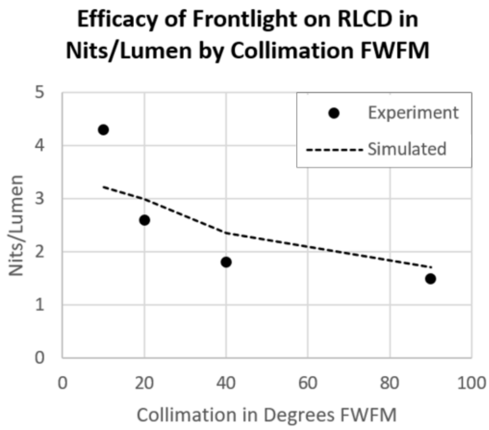

Figure 6: Experimental results compared to simulation for collimating the input illumination.

The experiment showed that illuminating a semi-specular display with selected controlled lighting angles can enhance brightness performance. Similar optimizations can be applied for contrast and viewing angles. There is a great variety in the reflectivity and contrast distributions of RLCDs. Figure 7 shows a range of reflectivity and contrast measurements of commercially available RLCDs. Azumo has developed custom modelling software to import the display goniometer data (Figure 8a) and overlay frontlight lighting fields (Figure 8b). This is used to estimate the brightness and contrast at the display normal. Further model upgrades and metrology devices are being developed for optimization based on viewing angles and overall brightness distribution.

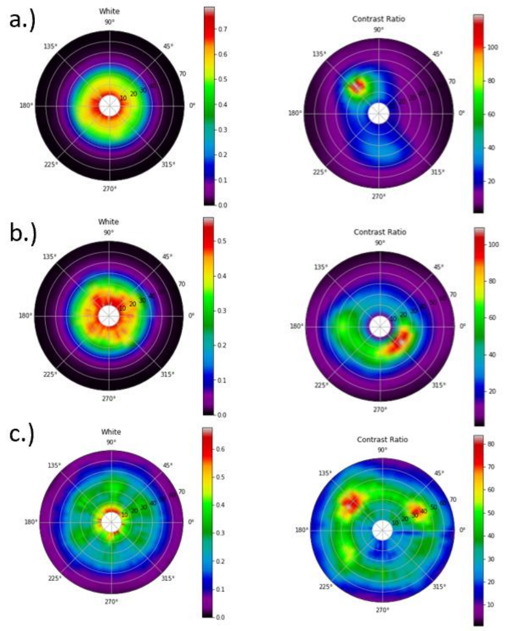

Figure 7: Examples of RLCD reflectivity and contrast profiles for commercially available displays (a-c).

Simulation studies have informed a number of key findings. First, semi-specular displays that have matching angular locations of maximum reflectivity and maximum contrast are ideal for frontlighting. This allows for high efficacy and high contrast when in front-lighting mode. Secondly, moving the peak reflectivity away from the display normal minimizes internal Fresnel reflections that cause a decrease in contrast to the viewer. These Fresnel reflections occur at optical interfaces within the display stack due to a change in refractive index by layer. With ambient illumination, this is normally a minimal effect compared to the reflection at the top air interface. However, with a direct-bonded frontlight, the internal interfaces become more pronounced. Designing an RLCD to have an isotropic reflectivity profile is beneficial for decoupling the viewing angles from the illumination angles.

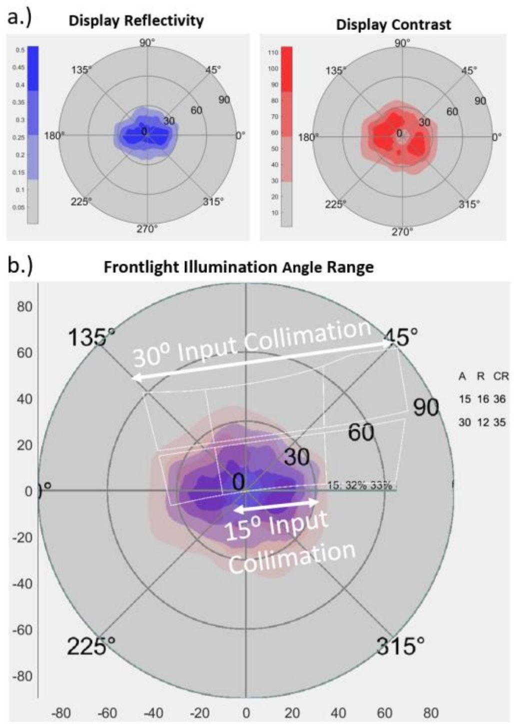

Figure 8: Design software which imports the display (a) Reflectivity and contrast maps and analyzes the (b) frontlight illumination field at different collimation levels shown overlaid on the display maps.

4 Conclusions

The many benefits of the Azumo system– thin, directional, invisible, uniform and efficient– combine to overcome the previous limitations in semi-specular display frontlighting. The net result is a breakthrough in low power displays with high uniformity, good contrast, good color gamut and full viewing angles. The ability for high gain frontlighting makes LCDs directly competitive with EPDs on a brightness per Watt comparison. The benefits of a well-established LCD manufacturing industry as well as available video and color options enable new applications in informational displays, such as educational tablets. New frontlighting systems are being developed based on these experimental results that will further the display performance and user experience.

5 References

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