An LCD with OLED-like Luminance Distribution

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Abstract

We report a single-domain LCD with quasi-collimated backlight and freeform optics engineered diffuser. Such a novel LCD exhibits similar luminance distribution to OLED for the first time, while keeping high transmittance, high contrast ratio over the entire 80° viewing cone, indistinguishable color shift, low ambient reflection, and minimum off-axis gray level distortion.

Author Keywords

Liquid crystal display, single domain, OLED-like luminance distribution, fringe field switching, in plane switching.

1. Introduction

"LCD or OLED: who wins?" is recently a hot topic [1, 2]. LCD has advantages in lifetime, power consumption, and cost, comparable performances in resolution, ambient contrast ratio, color gamut (with quantum-dot backlight), and thin profile, but disadvantages in flexibility, true black state, and response time. However, one important feature of OLED which is often neglected by the LCD camp is much broader luminance distribution due to its emissive nature [3]. While this might not be a great advantage in cell phones or other display devices intended for single user, wide luminance distribution can be very favorable for large screen displays, where multiple viewers expect to enjoy the display from different angles. Therefore, introducing a high performance LCD with wide luminance distribution (OLED-like or even Lambertian) is necessary and should be a future trend.

In this paper, we propose a new LCD consisting of single-domain structure, quasi-collimated backlight (quasi-CBL) and engineered diffuser film (EDF). Four widely used LC modes are considered: twisted nematic (TN), vertical alignment (VA), in-plane switching (IPS) and fringing field switching (FFS). Single-domain LCD with collimated backlight and diffuser was first demonstrated by Allied Signals about two decades ago [4]. In their design, the light beams exiting the quasi-CBL are confined within ±10° (half-maximum), so that within LC layer these beams experience about the same phase retardation. A diffusing screen is laminated above the LC layer, within which there is an array of 3-D tapered microstructures that transmits and redirects the light via total internal reflection (TIR), and the output light obtains a broader angular distribution due to the tapered microstructures. The major limits of the original design are: 1) the FHWM of the final angular distribution is about ±30°, a typical value for current LCDs, which is still quite narrow compared to that of OLED displays, and 2) the efficiency and spatial uniformity of the collimated backlight are inferior to conventional backlight units. Other approaches adopted diffusers with scattering beads to achieve a more uniform brightness distribution throughout a wider viewing angle [5]. However, for most designs, the ambient contrast ratio is rather poor because of severe reflection by the adopted heavy diffuser. In this paper, we overcame this problem by using free-form optics to optimize the EDF, and obtain a LCD with OLED-like luminance distribution for the first time, while keeping outstanding performance in high transmittance, high contrast ratio throughout the entire 80° viewing cone, indistinguishable color shift, minimal gray level distortion at off-axis viewing angle, and low ambient reflection (good sunlight readability).

2. Structures of Collimated Backlight and Engineered Diffuser

Fig. 1 illustrates the schematic design of our LCD system. In brief, the backlight emitted from quasi-CBL is reasonably collimated (FWHM~15°). It enters LCD panel, rendering high transmittance and high contrast ratio. The EDF further spreads the outgoing light to generate OLED-like brightness distribution.

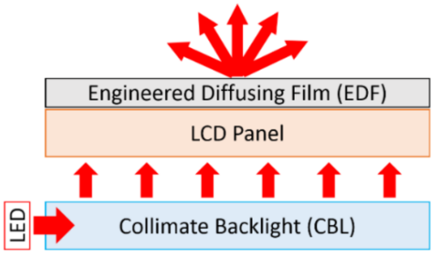

Figure 1. Schematic diagram of the LCD system with CBL and EDF.

Quasi-Collimated Backlight: The structure of the quasi-CBL is shown in Fig. 2.

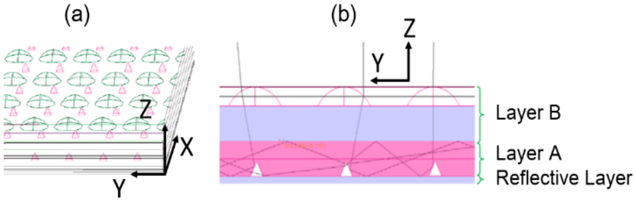

Figure 2. Schematic diagram of the backlight plate: (a) top view and (b) cross section.

It consists of two micro-structured glass light guide layers, labeled A and B, and a bottom reflector. Layer A and B are made of glasses that can be laminated together with an optical glue with relatively low refractive index (e.g. NOA 1315). The index mismatch is to allow for total internal reflection (TIR) on the interface so as to guide light along layer A. One can also choose to simply leave a thin air gap between them to create an interface. Light from a group of edge-lit LEDs is coupled into layer A, and remains inside until hitting one of the small pyramid shaped hollows at the bottom of layer A, where light beams are deflected dramatically and leak into layer B. The focal points of the micro-lens array on layer B overlap with the hollows in layer A, so that the emitted light gets collimated. In our simulation, we set the thickness of layer A and layer B to be both 0.5mm. The side

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length of hollows is 250μm, and the radius of the micro-lens is 600μm. Shrinking or enlarging the CBL in proportion does not change the angular distribution of the output, giving that the sizes of the micro-structures are considerably larger than RGB wavelength. In order to achieve a reasonably uniform brightness over the backlight plate, lens and hollow array on layer B and A are more condensed at the far end of the LGP with respect to the position of the LED light source, over 85% uniformity is achieved, as shown in Fig. 3, and the optical efficiency of the backlight plate is about 70%, with the FWHM of the emission 15°.

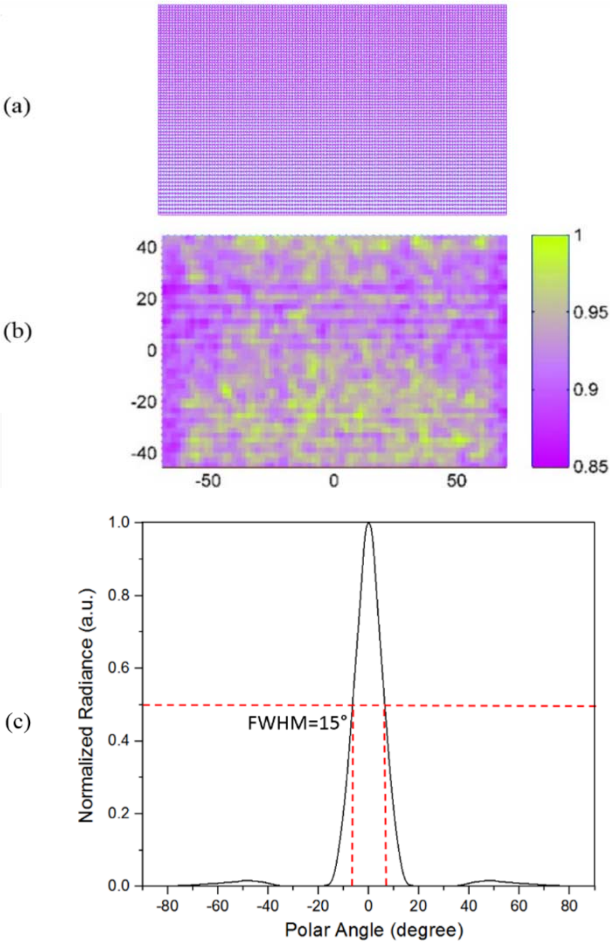


Figure 3. (a) Microstructure array on backlight plate; (b) brightness spatial uniformity; (c) normalized luminance angular distribution.

Engineered Diffuser: The engineered diffusing film (EDF) serves to broaden the viewing angle and reduce the color shift at oblique viewing direction.

Fig. 4 shows the structure of the engineered diffuser. It's a thin film whose bottom is covered by a hexagonal array of transparent ellipsoid-like microstructures. Fig. 4 (a) is the cross section of the EDF with ray tracing, and Fig. 4(b) is the top view. The yellow area represents black matrix which absorbs light, while the purple circles correspond to transparent pupils that are aligned with the center of each microstructure, who serve to focus beams to the positions of transparent pupils, and also to diffuse light. The EDF can be designed using free-form optics methods to specifically convert the quasi-collimated light from the above mentioned CBL to OLED-like luminance distribution. The principle of the free-form design is based on conservation of energy and ray tracing [6]. We first predesigned the shape of the microstructures by assuming the backlight is perfectly collimated at normal direction. The predesigned free-form surface was then used as the initial condition of a series of iterations to find the final free-form surface converting the backlight distribution shown in Fig. 3(c) to our target, i.e. OLED-like luminance distribution. After optimization, the shape of the freeform surface of the microstructure can be described with a polynomial:

$$z = 1.1765r^2 + 0.3578r^4 + 0.5361r^6 + 0.2807r^8, \tag{1}$$

where coordinates (z, r) stands for a point on the freeform surface, and z and r is its distance from the bottom plane of the freeform surface, and from the axis of the freeform surface, respectively, as illustrated in Fig. 4(c). The freeform parameters are normalized by r to represent a dimensionless shape, so that the range of r is from 0 to unity.

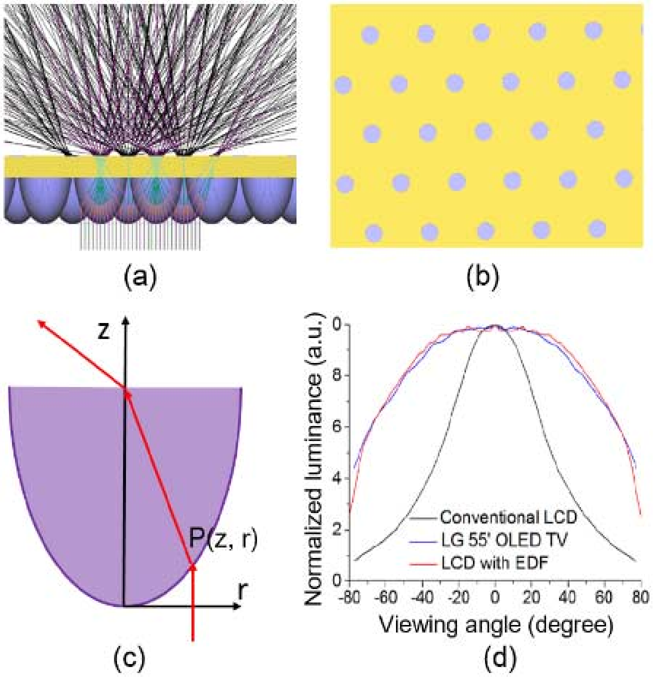


Figure 4. (a) Side view and (b) top view of the EDF, (c) schematic of a single freeform microstructure, and (d) normalized luminance distribution of conventional LCD, LG's 55-inch OLED, and LCD system with quasi-CBL and EDF.

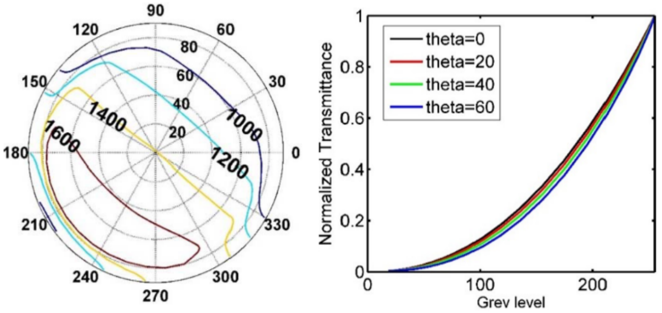
Fig. 4(d) demonstrates the normalized luminance vs. viewing angle after light passing through the EDF. To compare with state-of-the-art display technologies, we also plotted the luminance of a 55' OLED TV produced by LG [3] and a conventional LCD in the same graph. The luminance and viewing angle relation of our single-domain LCD resembles that of the OLED TV very well. The transmittance of the EDF is about 65%, and the ambient reflection is only 3%, which ensures superior image quality under direct sunlight or other strong ambient lights.

3. LCD system performance

Next, we evaluated how the quasi-CBL and EDF configuration enhances the performance of single-domain TN, VA, IPS, and FFS LCDs for various display applications. We find that our designs exhibit outstanding performances in all modes.

3.1 TN LCD

TN mode was first proposed and analyzed by Dr. Schadt [7], and is still being widely used in computer monitors today. We use Merck MLC-6686 (Δn=0.097 and $\Delta\varepsilon$=10) as the LC material for a normally-white 90^o TN LCD simulation. The cell gap is chosen to be 5μm. Fig. 5 shows the simulated (a) isocontrast contour and (b) gamma curve at 0° alpha angle. Apart from quasi-CBL and EDF, a wide-view Fuji film [8] is also employed. To quantitatively characterize the off-axis image quality, an off-axis image distortion index D defined in [9] is used. From Fig. 5(b), we find D=0.1644. Such a small D implies that the color shift is almost negligible, even for a single-domain TN LCD.

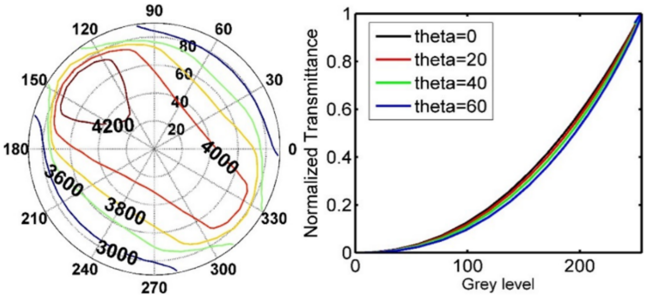


(a) (b)

Figure 5. TN-LCD with quasi-CBL, EDF and WV film system: (a) isocontrast contour and (b) gamma curve.

3.2 VA LCD

Similarly we calculated the system performance of a VA LCD. The advent of VA mode was made by Dr. Schiekel in 1971 [10]. The principle is to align liquid crystals with negative electrical anisotropy ($\varepsilon_{\parallel} < \varepsilon_{\perp}$) vertically to the substrates, and phase retardation is induced when voltage is applied between planar electrodes on both substrates. The LC material is Merck MLC-6882 (Δn=0.097 and $\Delta\varepsilon$=–3.1), and the cell gap is 4μm. Fig. 6 depicts the simulated (a) isocontrast contour and (b) gamma curve of a single-domain VA LCD. Since in VA mode the transmittance is extremely sensitive to viewing angle, to achieve wide view, a C-plate and an A-plate compensation films are employed. The off-axis image distortion index D is 0.1510.

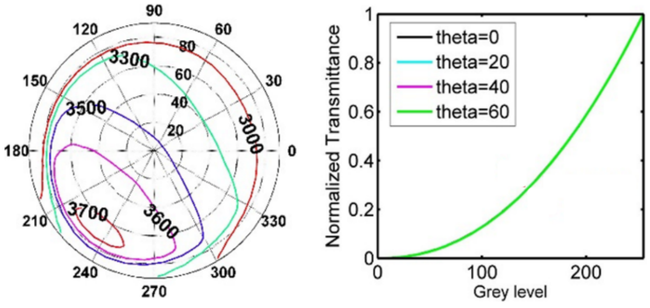


(a) (b)

Figure 6. VA-LCD with quasi-CBL, EDF and C&A compensation films: (a) contrast ratio and (b) gamma curve.

3.3 IPS LCD

IPS mode, invented by Dr. R. A. Soref in 1974 [11], is prevalent in touch screen displays since the transmittance is insensitive to cell gap. Similar analysis can be applied to IPS LCD as well, which is a key technology for wide-view desktop monitors and TVs. Fig. 7 shows the simulated isocontrast contours and gamma curves. We used MLC-6686 (Δn=0.097 and $\Delta\varepsilon$=10) in the simulation, and the cell gap is 3.86 μm, rubbing angle is 80°, pretilt angle is 2°, and electrode width and gap are 5 μm both. Note that in this LC mode, *no compensation film is employed*, so the maximum CR is not as high as that of above mentioned VA mode. However, the 3000:1 contour covers the entire 70^o viewing cone. More amazingly, the off-axis image distortion index D is as small as 0.0410.



(a) (b)

Figure 7. IPS-LCD system performance with quasi-CBL and EDF. (a) Contrast ratio and (b) gamma curve.

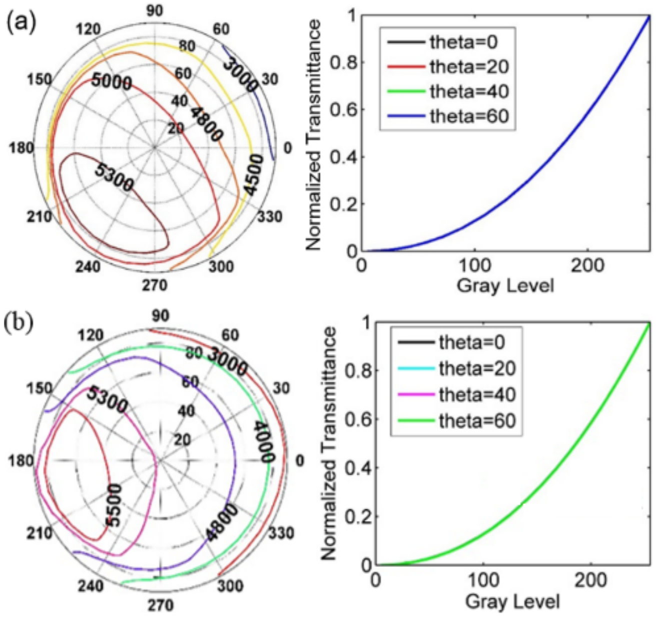


Figure 8. Simulated isocontrast contours and gamma curves of (a) n-FFS and (b) p-FFS with QCBL and EDF.

3.4 FFS LCD

In order to alleviate the transmittance reduction near electrode edges in IPS mode, Dr. Lee proposed FFS mode in 1998 [12], and it has been used in cutting edge touch screen displays. We analyzed the FFS-LCD with both positive $\Delta\varepsilon$ LC (p-FFS) and negative $\Delta\varepsilon$ LC (n-FFS). According to [13], n-FFS has advantages over p-FFS in higher transmittance, less cell gap sensitivity, and single gamma curve.The positive LC we used is Merck MLC-6686 (cell gap d=3.87µm, rubbing angle 80°, pretilt angle 2°, electrode width 2µm and electrode gap 3µm), and the negative one is Merck MLC-6882 (cell gap 3.02 µm, rubbing angle 10°, pretilt angle 2°, electrode width 2 µm, and electrode gap 3 µm). The results are shown in Fig. 8. The distortion in gamma curves at off-axis angles is indistinguishable. The off-axis image distortion index D is 0.0295 for p-FFS, and 0.0232 for n-FFS, which is the lowest so far to our knowledge. Note that in this FFS-LCD system, *no compensation film is utilized*, and the contrast ratio is over 3000:1 from almost all viewing directions.

Another impressive result is that the color shift of this single-domain FFS-LCD is also negligible. At 60° viewing angle, the white point color shift value Δu'v' is as small as 0.003, which is much smaller than 1 JNCD (Just Noticeable Color Difference, Δu'v'=0.02). Fig. 9 shows the calculated color shift of the p-FFS LCD in CIE 1976 diagram.

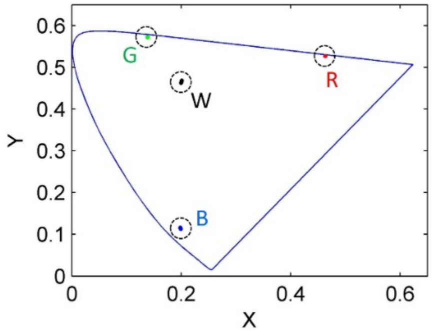


Figure 9. Color shift of the single-domain p-FFS LCD.

4. Summary and Impact

We proposed a quasi-collimated backlight whose FWHM is only 15°, with good transmittance and good spatial uniformity, and also demonstrated an engineered diffuser with free-form optical design. For the first time, LCDs with OLED-like luminance distribution are demonstrated. We have applied this design to four single-domain LCD systems: TN, VA, IPS and FFS (with both positive and negative materials). The outstanding features include high optical efficiency, indistinguishable color shift, high contrast ratio throughout the entire 80° viewing cone, and weak ambient reflectance for achieving good sunlight readability.

The designs of directional backlight and freeform diffuser are still evolving, and emphases can be put on the following aspects: 1) Further increasing the spatial uniformity and efficiency of the backlight. 2) Optimizing the design of the engineered diffuser to achieve higher transmittance and more versatile diffusing capability (such as Lambertian, isotropic, Gaussian, etc.). 3) Preferably making diffuser somewhat tunable, so that LCDs can be switched between privacy mode and multi-viewer mode. Despite these technical challenges, the combination of quasi-collimated backlight with engineered diffuser proves to enhance the display quality very effectively, and widespread application is foreseeable. The developments of directional backlights and diffusers are elevating LCD industry to the next level, and color-shift-free and ultra-wide-view LCDs are just around the corner.

5. Acknowledgments

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