Reflector Plate Design for Reflective Liquid-Crystal Displays

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Abstract

This paper introduces new reflector plate designs to improve the brightness and uniformity of Reflective Liquid Crystal Displays (RLCD) in broad ambient light conditions. We present both modeling and experimental results from samples made using Nano-Imprint Lithography (NIL).

Author Keywords

Reflective displays, micro-optics, nano imprint lithography, liquid crystal, RLCD, brightness enhancement,

1. Introduction

Reflective displays leverage ambient light to show information on the screen [1-5]. Thus, they are reliant on external light source's location and angular profile to deliver a pleasant user experience. Electrophoretic displays are today's gold standard for such displays [2-4]. In their traditional configuration, black and white inks are driven to the display surface to generate content [2-3]. The reflection of the inks behaves almost like Lambertian reflectors, which helps the flexibilities of ambient light source location and the viewing angle of the device. In addition, colored inks [4] can be used. However, existing devices have the limitations of color gamut and frame rate.

Compared to electrophoretic displays, RLCDs [1, 5] are better suited to enable dynamic content and vivid colors. However, they lack the brightness achieved by e-papers, limiting their current share on reflective displays market.

Figure 1 show the typical stack for a RLCD with a reflector plate. The reflector plate is located on the TFT glass, underneath the LC cells. Ambient light comes from an incident angle with an angular distribution, crosses the polarizer and the LC cells before getting reflected by the reflector plate. If its surface is flat and minimal light diffusion happens through the multiple display layers, then mirror reflection occur, potentially generating unwanted optical effects that degrade the image quality. Therefore, it is necessary to optimize the ambient light collection and the light reflection across a given viewing angular range with high brightness uniformity.

This can be achieved by structing the reflector plate with refractive microstructures [5]. In the past, roughnessed metallic surface has been used to mimic the behavior of electrophoretic inks. However, due to the higher loss of light through the LC device, this strategy cannot be implemented efficiently, generating dull display devices.

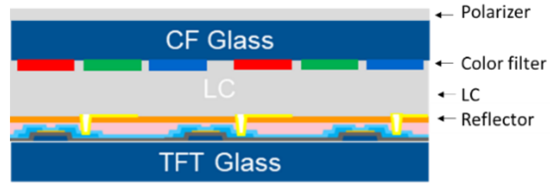

Figure 1. RLCD stack

2. New reflector plate design

New reflector plate design cannot be Lambertian. To enhance brightness and uniformity of a RLCD, one needs to design refractive elements taking in account a pre-determined range of ambient light incident angles and a viewing angle cone. In this paper, we introduce refractive microstructures optimized for incident light centered at 30° ±15°. Viewing angle is centered at normal angle with a range of ±20°.

Figure 2 shows the new geometry of one of our designs. It consists of multiple reflector unit tiles. Each reflector unit includes four-unit cells respectively oriented in the four typical directions of displays (two landscape and two portrait). Each unit cell is formed by a concave mirror. The concave mirror shows two radii of curvature: on horizontal R_h and one vertical R_v. The size of the unit cell typically is about 25 µm by 10 µm. Such a structure is coated with a metallic layer (silver or aluminum) to enhance its reflectivity.

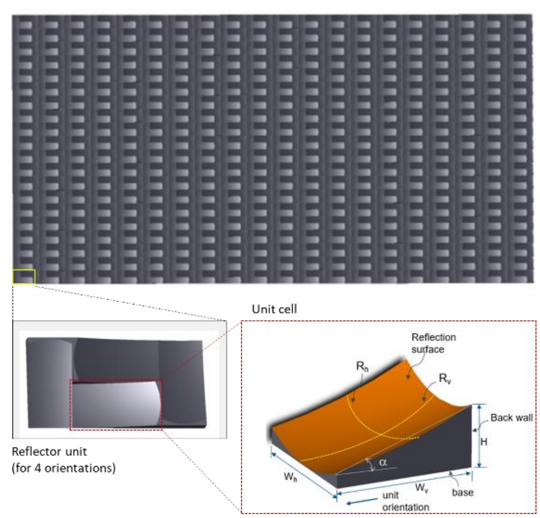

Figure 2. Structure of reflector plate design. Top: top view of reflector plate. Bottom left: reflector unit for 4 orientations. Bottom right: unit cell.

Figure 3 shows the ray-tracing simulation results on the angular distributions of the light reflected by the reflector with one single-

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orientation unit cells for three different angle of incidence θ_c in the vertical direction. This geometry shows a consistent reflectivity pattern in the range of incidence vertical angles between 20° and 40°.

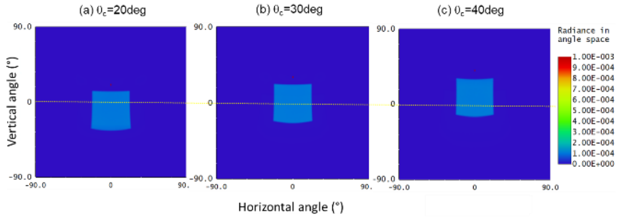
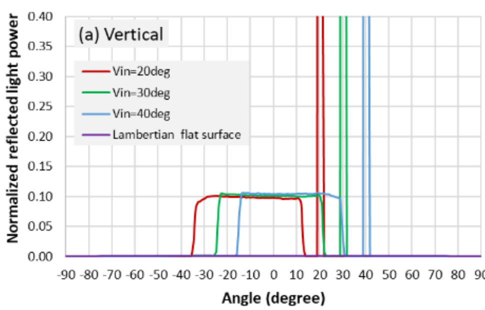


Figure 3. Angular distribution of the light reflected by the proposed reflector with single-orientation cells for three angles of incidence in vertical direction: 20°, 30° and 40°

Figure 4 shows the cross sections along the vertical and horizontal angular directions at 0°. The results confirm the excellent uniformity performance of this design. For comparison, the Lambertian reflector performance is also plotted by the purple curve in Figure 4, well below the reflectivity of our microstructure reflector. Uniformity is evaluated at 95% across a cone viewing angle of ±20° around the normal viewing angle and along the two angular directions. Along the vertical direction, the cone viewing angle slightly tilt with the incidence angle delivering a constantly uniform reflectivity at viewing angles between -14° and 11° for incidence angles ranged between 20° and 40°. This result ensures a good user experience without brightness drops when the device is titled with a reasonable angle range.



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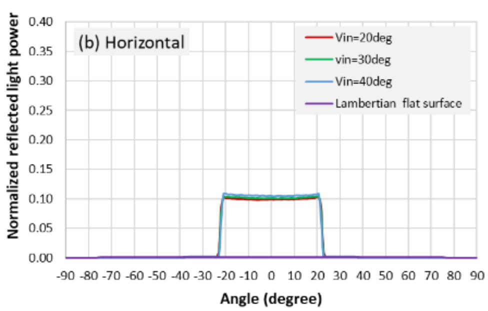


(b)

Figure 4: Cross sections of data shown in Figure 3 for (a) vertical and (b) horizontal angular directions crossing at 0°.

Compared to the Lambertian reflector, this single-orientation cell reflector (for one-orientation reading display) delivers over 70x improvements. Figure 5 shows the reflection efficiency of the reflector as a function of the cone viewing angle. Most of the light is including in a 30° cone angle along the normal direction with a reflection efficiency toping at ~90%.

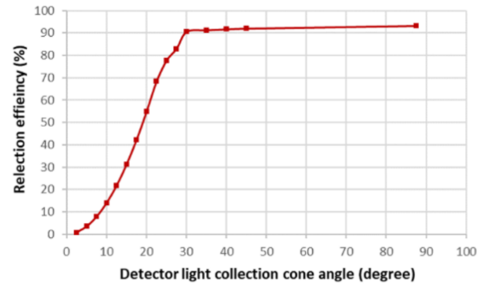


Figure 5. Reflection efficiency of the reflector vs. detector collection cone angle

The results presented so far were obtained for the reflective structure with single-orientation cells. In typical displays, four main directions need to be considered. Therefore, as shown in Figure 2, one needs to organize four-unit cells with respectively oriented in the four typical directions of displays (two landscape and two portrait) to form one reflector unit, and then tile multiple reflector units to form a reflector plate. In this configuration, the overall performance of the reflector is expected to drop since only one out of four cells will be oriented to the right direction for a specific use case.

Figure 6 presents the theoretical results of the reflected light angular distribution of the reflector with four-cell-orientation configuration showed in figure 1. One square and three partial squares in Figure 6 are visible. One is centered around 0° and is the reflected light from the reading orientation cells for the display. The two partial squares centered along a vertical angle of 30° and horizontal angles at -30° and 30° correspond to the light reflected by the reflector cells arranged at ±90° from the display reading orientation. The fourth square shows on the top of the plot corresponding to the reflector cells oriented at 180° from the display reading orientation.

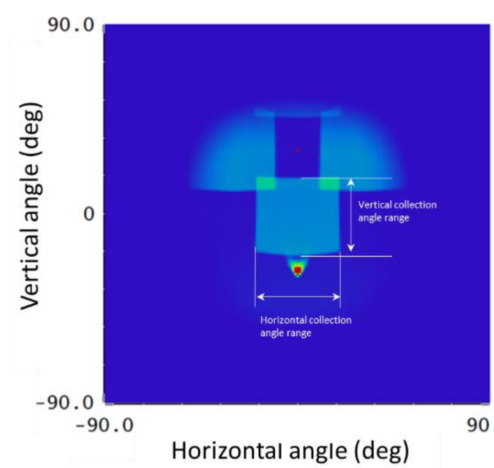
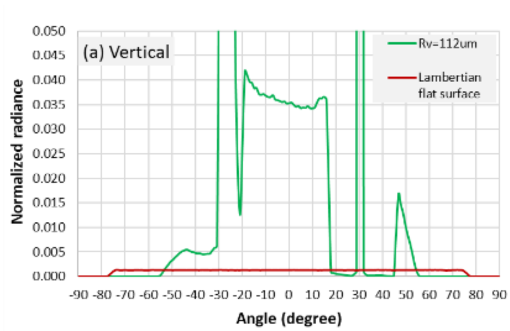


Figure 6. Modeling results of the reflected light angular distribution of a four-orientation arrangement reflector as shown in Figure 1.

Figure 7 shows the cross section along the vertical and horizontal angular directions at 0°. Uniformity decreased in the vertical direction Because only one out of four reflector cells are well-oriented respective to the incident light, the brightness enhancement for this structure drops to 27x compared to the Lambertian reflector but by a very high factor for a RLCD. Although, the uniformity in the horizontal direction is like the single-orientation-cell reflector, the uniformity in the vertical direction decreased too because of the crosstalk of the light reflected by other oriented cells.

Finally, based on these theoretical results, we fabricated samples and measured their performance.



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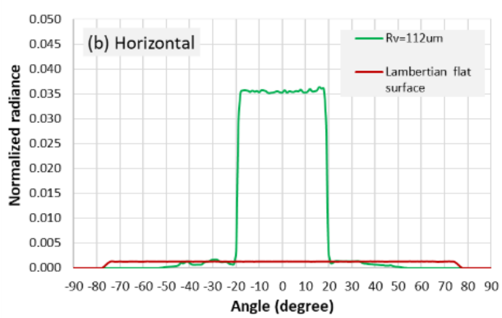


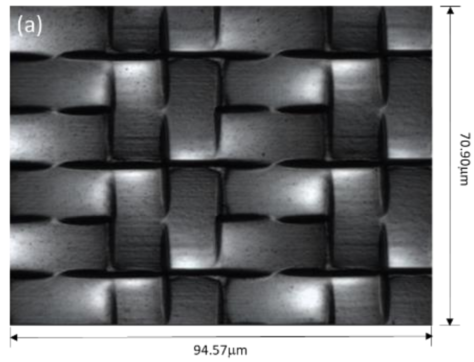
(b)

Figure 7: Cross sections of data shown in Figure 6 for (a) vertical and (b) horizontal angular directions crossing at 0°

3. Experimental results

In a previous paper [6], we have demonstrated that Corning® EAGLE XG® (EXG) glass is an ideal substrate to ensure dimensional stability of microstructures made using Nano Imprint Lithography (NIL). Therefore, we have used the above technology to make our protype samples to ensure the accuracy and stability of the microstructures of the reflectors for enabling a good optical performance.

Figure 8 shows the confocal microscope images of one prototype sample. The microstructure reflectors were made using a polymeric resin on EXG glass substrate. Then, a thin metallic layer was coated on the microstructure surface.



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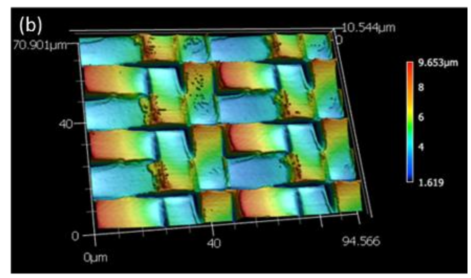


(b)

Figure 8. Confocal microscope images of one protype sample. (a) two-dimensional image. (b) three-dimensional image.

Figure 9 shows the BRDF measurement data from the protype sample after a 100nm thick aluminum layer was coated on the resign microstructure surface. Experimental results show a good uniformity between the four directions. We also recognize the pattern with the four quadrants centered around the specular direction. One quadrant is centered close to 0°, the viewing direction of the device. Contrary to calculated data, light is also reflected at larger angles due to several defects inherent to the fabrication process such as rounded edges, un-wanted deep valleys. But overall, the results are in line with theoretical expectations.

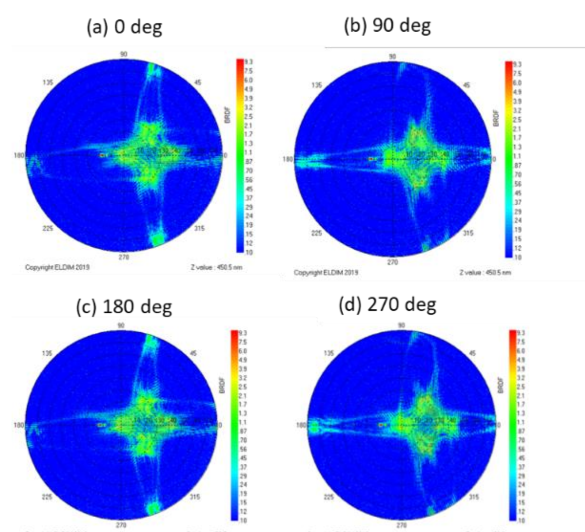
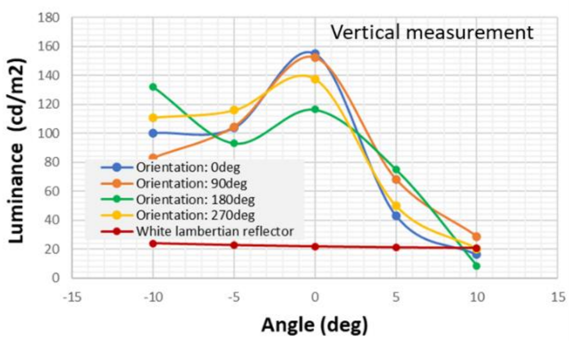


Figure 9. BRDF measurement results of the protype sample made using NIL on EXG glass substrate for the four orientations of the reflector.

Figure 10 presents the luminance measurement results of the protype sample in both vertical and horizontal directions for various viewing angles around the normal angle. Compared to standard white Lambertian reflector, our reflector shows a 7x improvement factor. Uniformity and enhancement factor could be improved by optimizing the NIL and metallization processes. The angular spread will be enlarged by adding the planarization layer by a factor 1.5 like its refractive index.



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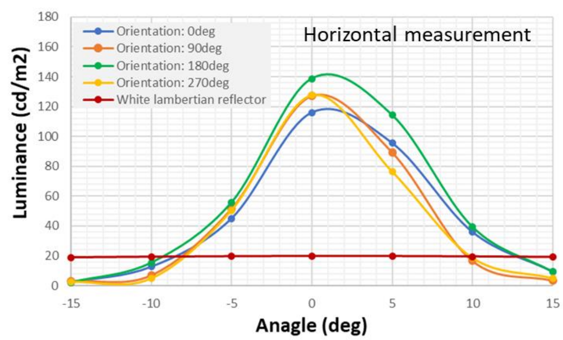

(b)

Figure 10. Luminance measurement results of a sample for an incidence angle set at 18.8° and viewing angles between -15° and 15° in (a) vertical and (b) horizontal directions for the four-orientations of the protype reflector.

4. Conclusions

We have presented a new reflector design using microstructures on Corning EXG substrate to enhance the brightness and uniformity of RLCDs. Our modeling results predicted that we could achieve a 27x enhancement compared to the typical Lambertian reflector in a 4-orientation display configuration. First protype samples made by NIL have demonstrated that at least a 7x brightness enhancement factor is possible. Further improvements should be possible by optimizing the process and, thus, reducing the impact of defects on the optical performance.

Acknowledgements

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