Display Technology Letters

Sunlight Readable Transmissive LCDs

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***Abstract*—We propose a novel sunlight readable transmissive LCD embedded with a transflective film. Such a transflective film has high transmission to the backlight and high reflection to the ambient light. This new display is particularly suitable for outdoor applications under strong ambient light condition.**

***Index Terms*—Microlens, sunlight readability, transflective liquid crystal display (LCD).**

I. INTRODUCTION

SUNLIGHT readability is a desirable feature for displays to be used under strong ambient light. In a typical transflective LCD [1], [2], each pixel is divided into transmissive (T) and reflective (R) sub-pixels. Under weak ambient lighting condition, the T-mode plays the primary role and R-mode makes little contribution. As the ambient light gets brighter, the T-mode is gradually washed out and the R-mode is gradually dominating. The existence of R sub-pixels blocks the beam path of some backlight and reduces the effective aperture of T sub-pixels. To overcome this problem, microlens array [3] is an attractive option because it channels the backlight through the T sub-pixels more effectively. A 2D focusing cones device [4], [5] is also proposed to increase the backlight utilization efficiency.

In this paper, we report a new transflective film which provides a high transmittance (>80%) to the backlight and high reflectance (~95%) to the ambient light. Embedding this transflective film in a transmissive LCD will greatly improve the display's sunlight readability.

II. DEVICE STRUCTURE

We design a transflective film which can replace the reflective region of a transflective LCD. Fig. 1(a) shows the structure of the transflective film. The film consists of three layers. The top and bottom layers are with microlens array structure on the surface. The microlens is arranged in hexagonal shape [see Fig. 1(b)] in order to obtain the densest packing. The middle layer is made of reflective material with periodic aperture. These three layers are laminated together and there is no air gap in between. When the transflective film is placed between liquid crystal cell and backlight module [see Fig. 1(c)], the microlens structure on the bottom surface can focus the backlight into the aperture of the middle reflective layer, as shown in Fig. 2(a) and 2(b). Therefore, most of the backlight can pass through this transflective layer. Meanwhile, the microlens structure on the top surface would focus the ambient light onto the reflective area of the middle layer. The diffusive reflective area on the middle layer, similar to the bumpy reflector in a transflective LCD, would reflect the ambient light to increase the overall display brightness. As a result, our new display preserves the major advantages of transmissive display while greatly improves the performance of reflective mode.

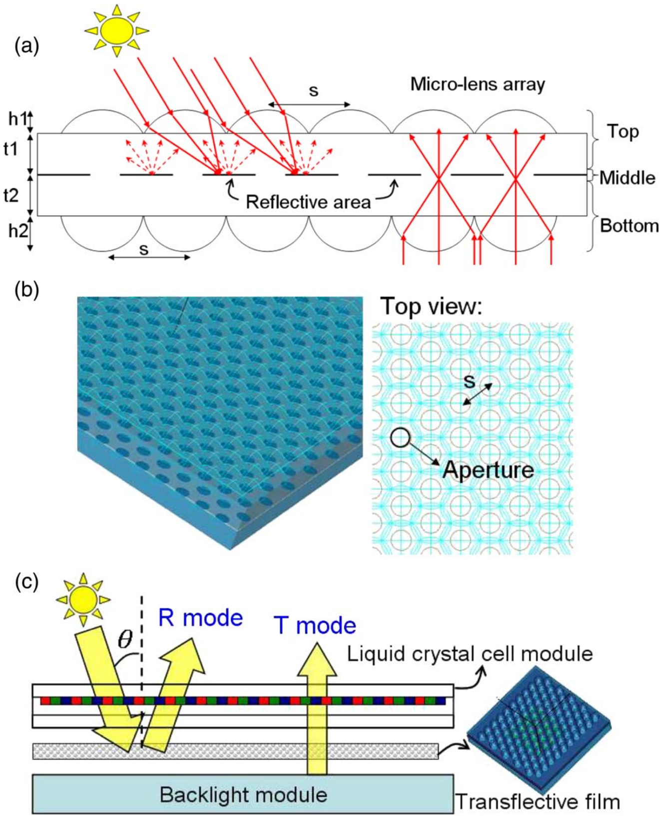

Fig. 1. Structure of the proposed transflective film.

From Fig. 2(a), the bottom microlens array focuses the normally incident backlight to the aperture. However, the light could be blocked as the incident angle increases. Therefore, for a backlight with Lambertian distribution, lots of off-axis beams cannot pass through the middle reflective layer the first time, resulting in an optical loss. To increase light transmittance, we could select a highly collimated backlight (a regular backlight

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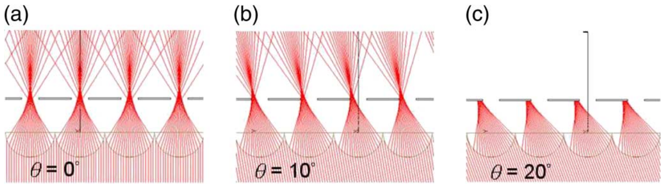

Fig. 2. Ray tracing of backlight with different incident angles.

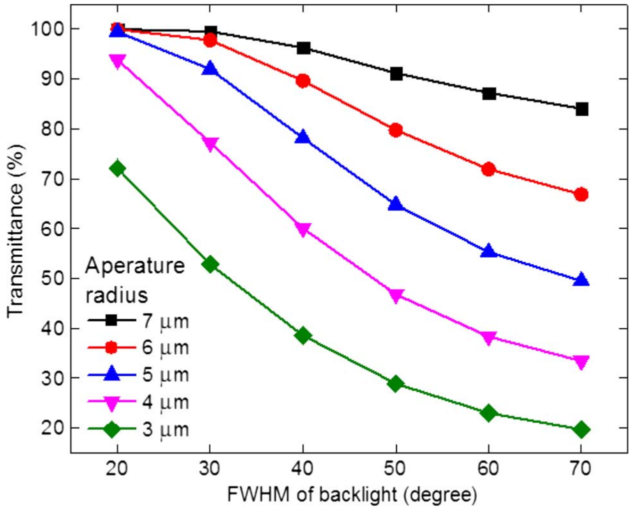

Fig. 3. Backlight divergence versus transmittance at different aperture radius.

laminated with a light turning film) [6], [7] or choose larger aperture size. However, there will be tradeoff between the aperture size and reflective area of the middle layer. A larger aperture could let more backlight pass through, but it also decreases the reflectance of the ambient light. Therefore, we design the microlens on the top surface to always focus the ambient light onto the reflective area of the middle layer. In this way, we can enlarge the aperture size of the middle layer to get a higher transmittance without sacrificing the reflectance of the ambient light.

Fig. 3 shows the relation between the diverging angle of the backlight and the transmittance of the middle reflective layer. We used the ray tracing software (i.e., LightTools) in our simulation. The space (s) for each top and bottom lens is 15 μm, the height for top lens (h1) and bottom lens (h2) is 10 μm, the top layer thickness (t1) is 10 μm and bottom layer thickness (t2) is 7 μm, and the radius of top lens is 12 μm and bottom lens is 10 μm.

For a practical situation, the backlight (or its brightness) has a certain angular distribution. Here, we assume the brightness has Gaussian distribution at different angles. Fig. 4 is an example of backlight with diverging angle of 60° full width at half maximum (FWHM). In this figure, 0° means normal direction. From Fig. 3, the transmittance decreases as the diverging angle of backlight increases. We could use a highly collimated backlight (e.g., $\mathrm{FWHM} = 20^\circ$) to improve transmittance, but this kind of backlight has some problems in light efficiency and narrow viewing angle. Another way to increase transmittance is to enlarge the aperture radius of the transflective film. For $\mathrm{FWHM} = 50^\circ$, the transmittance is $>80\%$ when the aperture radius is larger than 6 μm.

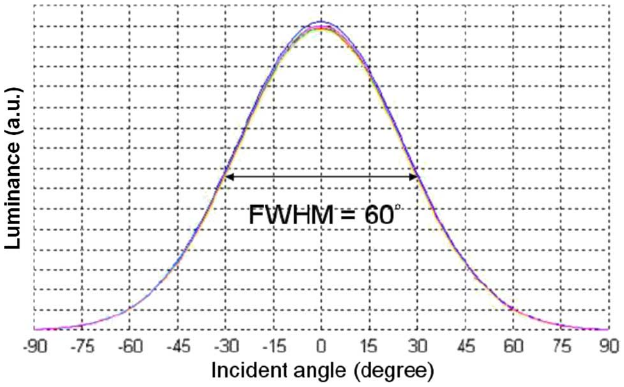

Fig. 4. Backlight's angular distribution.

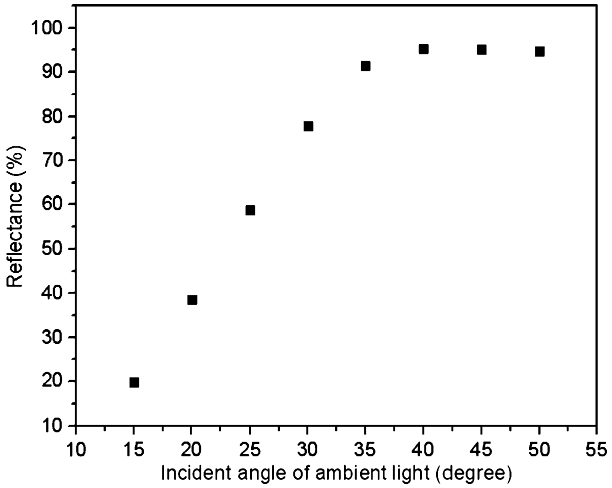

Fig. 5. Reflectance of the transflective film at different incident angle of ambient light.

Fig. 5 shows the incident angle (θ) of ambient light versus reflectance when the aperture radius equals to 6 μm. The reflectance is more than 90% as $\theta > 35^\circ$. Although the large hole- aperture (e.g., 6 μm in radius) reduces the reflective area of the transflective film, the top microlens still focuses the ambient light to the reflective region. Therefore, we can keep a very high reflectance when using a large transparent aperture size to achieve high transmittance.

Similar to a typical transflective LCD, the combination of transmissive LCD with a transparent film can also have some reflective feature. For a transflective LCD, we assume that the maximum transmittance of a pair of linear polarizers is 35%, the TFT aperture ratio of the LC cell is 60%, the transmittance for liquid crystal is 95%, the transmittance of color filters (i.e., red, green, and blue) is 28%, and the bumpy reflector has 20% area ratio and the aluminum reflectivity is 92%. Therefore, the reflectance of a transflective LCD to the ambient light is $\sim$0.99%. Here we assume the bumpy reflector does not depolarize the light. In reality, the depolarization by the bumpy reflector would reduce the reflectance. For our new design with the same aperture ratio (60%) of a transmissive LCD, the transflective film has

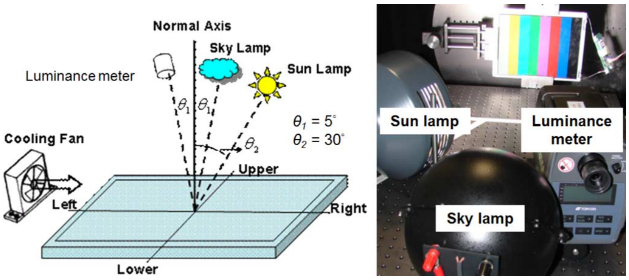

Fig. 6. Setup for evaluating contrast ratio under strong ambient light.

~1.07% reflectance, which is comparable to the typical transflective LCD. Again, we also assume the transflective film does not depolarize the light for a fair comparison to the transflective LCD. In fact, the aperture ratio of our design could be larger than 60% because no reflective area is needed in the cell. Therefore, the reflectance of our design has potential to be larger.

Referring to the military specification (MIL-L-85762A), we measured the contrast ratio (CR) under simulated strong ambient light, as shown in Fig. 6. The sky lamp which has 6852 Nits in brightness is used to simulate the specular reflection. The sun lamp illuminates on the panel with 100 000 lux to simulate the diffusive reflection. Our panel is 500 Nits in brightness and has anti-reflection treatment (ReaLookX4001, NOF) on its surface. From our measurement, the refection from backlight module can boost the brightness by ~170 Nits under strong ambient light. However, the surface reflection which is ~30 Nits decreases the CR to only ~7.6. In our result, the backlight module behind the cell module has 0.13% reflectance. The reflectance of the backlight module might vary by different films used inside. In general, the backlight module is not a very good Lambertian-type reflector and cannot reflect sunlight to the normal direction to boost the brightness. For our design with 1.07% reflectance, we can gain the brightness by ~1400 Nits for a transmissive LCD under strong ambient light and CR could reach ~20:1.

We also put the panel under sunlight (~40,000 lux) with backlight off. On the left-hand side of Fig. 7, we placed a Lambertian-type reflector under the cell to simulate the reflectance of the transflective film [Fig. 1(c)]. On the right-hand side is the original backlight structure. We can observe that the left side has better legibility than the right side. In our design, the transflective film can contribute more brightness which will certainly improve the ambient contrast ratio and sunlight readability under strong ambient light condition. In the dark ambient, our new design preserves the major advantages of a transmissive LCD.

Although our approach is simple, we need to consider the undesirable parallax. We could decrease the parallax by reducing the thickness of transflective film and laminating it to the bottom of the cell. However, parallax is a problem in small size or high-resolution LCDs. Therefore, our design is more suitable for the middle or large size display applications.

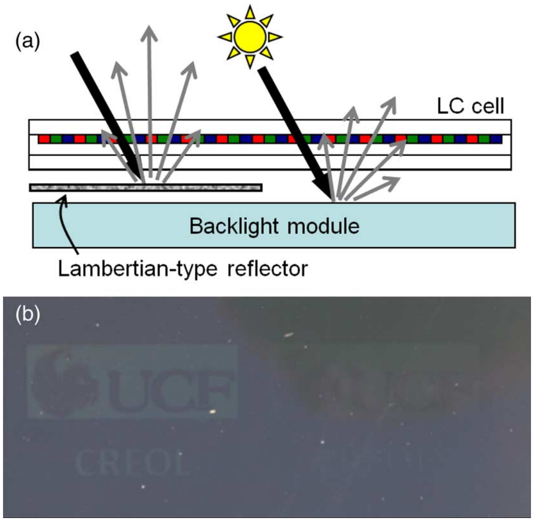

Fig. 7. Comparison of the CR of traditional backlight module (right) and with a simulated transflective film (left) under ambient light. The backlight is off.

III. CONCLUSION

We propose a novel design of transmissive LCD incorporating a transflective film which has high transmittance to backlight and high reflectance to ambient light. When used under sunlight, the new display offers a comparable or higher reflectance as compared to a transflective LCD. The fabrication of our transflective film should be simpler than that of transflective LCDs, in which the bumpy reflectors are located inside the LC cell. This new device is particularly attractive for outdoor applications with strong sunlight ambient.

REFERENCES

[1] X. Zhu, Z. Ge, T. X. Wu, and S. T. Wu, "Transflective liquid crystal displays," *J. Display Technol.*, vol. 1, no. 1, pp. 15–29, Sep. 2005.
[2] Z. Ge and S. T. Wu, *Transflective Liquid Crystal Displays*. Hoboken, NJ: Wiley, 2010.
[3] T. Sato, H. Watanabe, S. Shibata, T. Tomotoshi, Y. Narutaki, Y. Itoh, and K. Okamoto, "Novel transflective LCD with micro-lens array to double the brightness," *SID Symp. Dig. Tech. Papers*, vol. 38, pp. 1274–1277, 2007.
[4] P. N. Andrew, "2-D FOCON arrays and their application in displays and planar illuminators," *J. Soc. Inf. Display*, vol. 16, pp. 819–823, 2008.
[5] H. P. Shieh, Y. P. Huang, and K. W. Chien, "Micro-optics for liquid crystal displays applications," *J. Display Technol.*, vol. 1, no. 1, pp. 62–76, Sep. 2005.
[6] K. Käläntär, "A monolithic segmented functional light guide for 2-D dimming LCD backlight," *J. Soc. Inf. Display*, vol. 19, pp. 37–47, 2011.
[7] M. Oe and I. Chiba, "Plane light source unit," U.S. Patent 5 126 882, Jun. 30, 1992.