Volumetric Scattering Layer for Flexible Transflective Display

2008 Jpn. J. Appl. Phys. 47 1016

(http://iopscience.iop.org/1347-4065/47/2R/1016)

Japanese Journal of Applied Physics
Vol. 47, No. 2, 2008, pp. 1016–1018

Communication

Volumetric Scattering Layer for Flexible Transflective Display

Bo-Ru YANG*, Kang-Hung LIU, Shih-Nan LEE[1], Jen-Chieh HSIEH,
Han-Ping D. SHIEH[2], and Chin H. CHEN[2,3]

*Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University,
Hsinchu, Taiwan 30010, R.O.C.*
[1]*Department of Applied Chemistry, National Chiao Tung University, Hsinchu, Taiwan 30010, R.O.C.*
[2]*Department of Photonics and Display Institute, National Chiao Tung University, Hsinchu, Taiwan 30010, R.O.C.*
[3]*Microelectronics and Information Systems Research Center, National Chiao Tung University, Hsinchu, Taiwan 30010, R.O.C.*

(Received September 25, 2007; accepted November 15, 2007; published online February 15, 2008)

A flexible transflective liquid crystal display (FTF-LCD) which combined a flexible LCD and a flexible organic light emitting diode was demonstrated. Under high light ambience (reflected luminance of 250 nits), a LCD incorporated with a volumetric scattering layer (VSL) showed a contrast ratio of 10 : 1 at the viewing cone of 60° in the reflection mode. By adding the VSL to the LCD, the haze component was increased by a factor of 3.3. With the advantages of small form factor, flexibility, power-saving, and legibility in bright ambience, the FTF-LCD is very applicable to mobile products.

[DOI: 10.1143/JJAP.47.1016]

KEYWORDS: liquid crystal display, organic light emitting diode, flexible display, transflective display

The key features of a mobile display are high contrast ratio, wide viewing angle, small form factor, light weight, low power consumption, sunlight legibility, and flexibility. To realize these requirements, an integrated device which combined an organic light emitting diode (OLED) and a reflective liquid crystal device (RLCD) was proposed.[1–8] The design concept was originated from utilizing RLCDs for preventing OLEDs from the wash-out and further for saving the power by using ambient light as the light source.[9]

In this letter, we demonstrate a flexible transflective liquid crystal display (FTF-LCD) which can realize all of the above-mentioned features for mobile display. FTF-LCD is composed of an RLCD and an OLED; especially the components of this device are capable of being fully flexible. Moreover, to eliminate the *wash-out* phenomenon induced by the planar cathode of OLED, we designed and fabricated a volumetric scattering layer (VSL) for enhancing the sunlight visibility of display. In addition, the VSL can also be used to enhance the output coupling efficiency.[10–14]

The wash-out phenomenon of display device can be described by Fresnel's law. When incident light impinges to a surface at a certain angle; according to Fresnel's law, there will be a portion of reflected light reflected at the same angle (termed as glare angle here). At this angle, image is impossible to be observed owing to the strong intensity of reflected light; this phenomenon is the so-called wash-out. Here, we define the light at glare angle as glare component, and the light from the display device apart from glare angle is defined as haze component.[15–17]

Integrating OLED with RLCD can provide many kinds of combination possibility. One of the configurations used for explaining the operational principle here is using OLED as a backlight in the darkness and using RLCD as a display device for showing the gray scale of each pixel. As shown in Fig. 1, when FTF-LCD is operated in the bright ambience, the OLED is turned off, so the ambient light is used as the light source. As the ambient light impinges the device, it will be reflected by the VSL and the cathode of the OLED, and then its intensity will be controlled by RLCD to perform the image. When FTF-LCD is operated in the darkness, the OLED is turned on to replace the ambient light as a light source. The light emitted from OLED will pass through the VSL, and its intensity will be controlled by RLCD for showing the image.

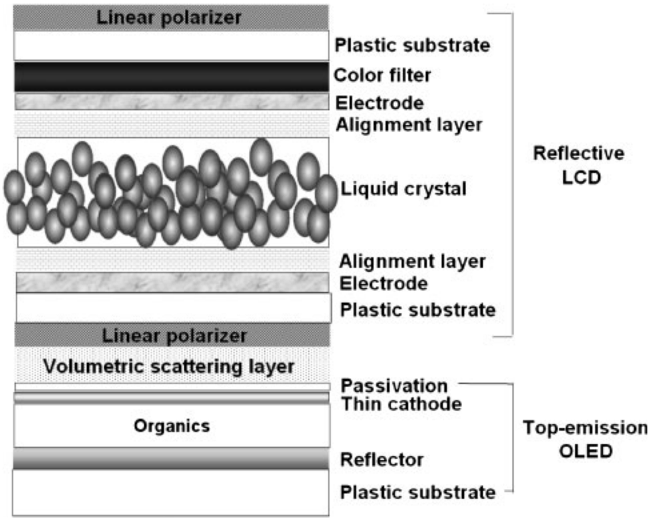

Fig. 1. Structures of flexible transflective display with VSL.

The FTF-LCD was carried out by covering a prepared flexible liquid crystal device (FLCD)[18] on the double-sided transparent flexible organic light emitting diode (FOLED) which was encapsulated by multi-layer thin films of SiN_x/MADN/SiON,[19] where MADN is the abbreviation of 2-methyl-9,10-di(2-naphthyl) anthracene. The integrated device is shown in Fig. 2 where the thin-film-encapsulation protected FOLED from the physical damage during integrating process.

The FLCD (twisted nematic mode) was made by sandwiching the positive type LC material (MJ01744, Merck) with two plastic substrates [poly(ether sulfone)] on which the homogeneously aligned polyimide (SE7492, Nissan Chemical) has been coated. In this cell, a prepared micro-cell structure (5 µm in height, 10 µm in width) was used to sustain the space between the two substrates.[18]

The VSL was made by spin-coating the solution with ZnO particles dissolving in the poly(methyl methacrylate)

---

*E-mail address: ybr.eo93g@nctu.edu.tw

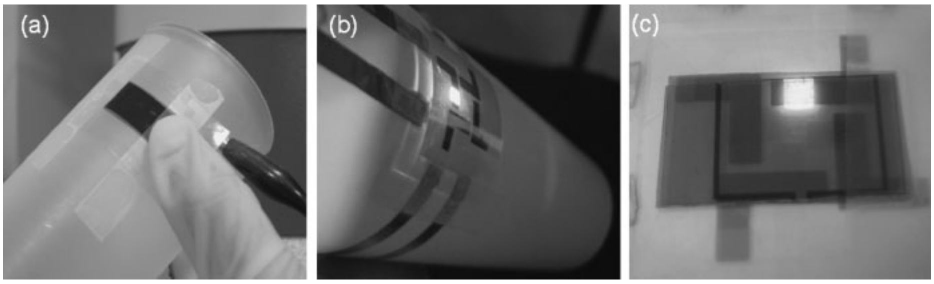

Fig. 2. Photographs of (a) FLCD, (b) FOLED, and (c) integrated FTF-LCD.

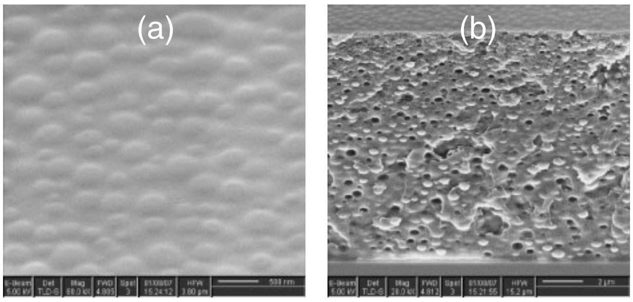

Fig. 3. Scanning electron microscopy images of (a) surface and (b) cross-section of VSL.

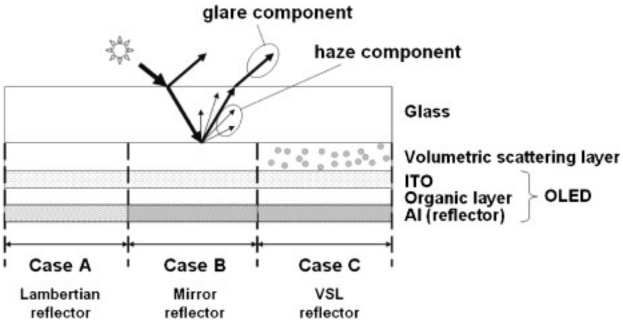

Fig. 4. Configuration used for simulation.

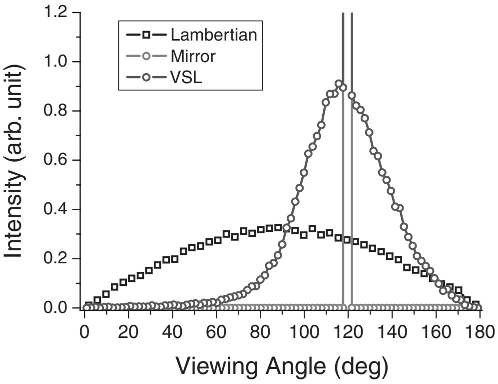

Fig. 5. Simulated haze component comparison between mirror, Lambertian, and VSL reflectors. Where the incident light impinges at 30° apart from the normal direction (i.e., 60° in this figure) and then be reflected at the glare angle (i.e., 120° in this figure). Besides, the benchmark of haze component is set as the intensity of the light reflected by Lambertian reflector (the ideal diffusive reflector) at normal direction (90°).

(PMMA) medium; the scanning electron microscopic (SEM) images of the VSL are shown in Fig. 3. The pores and the particles made the transmitted light scattered and thus enhanced the output coupling efficiency; besides, the rough surface scattered the glare light to the non-glare angle, which depressed the glare effect (wash-out) and further enhanced the visibility under the sunlight ambience.

The optical characterization was performed by using a commercial Conoscope™ which can adopt both the diffuse and the collimated illumination as light sources. The light beam emitted from the sample at a certain incident angle would be focused on the focal plane at the same azimuth. In addition, by inserting a segment recording bar into the measurement setup, the unwanted light reflected from the first interface of the device could be eliminated.[15–17]

We simulated the parameters of the VSL on the sunlight visibility with a commercial simulator, LightTool™, whose algorithm was based on the ray optics along with the Fresnel equation.[20] The VSL structure used for the simulation is shown in Fig. 4, which was comprised of a reflective illuminator, a VSL with varied conditions, and the outer ambience. In order to compare the optical performance of VSL with a freestanding mirror and a Lambertian reflector, the simulation structure was further categorized into three cases as shown in Fig. 4. Moreover, to acquire the reflection profile, the light beam was projected at an incident angle of 30° and reflected to a semi-sphere detector.

To evaluate the RLCD image quality, a haze component enhancement is defined as eq. (1), where the benchmark is set as the intensity of the light reflected by Lambertian reflector (the ideal diffusive reflector) at normal direction (90°).

$$\text{Haze component enhancement} = \frac{I_\theta}{I_{\text{Lambt},90^\circ}} \qquad (1)$$

The haze component enhancement resulted from the shifting of the glare light to the other angles.[21] This phenomenon could be explained by the simulation results shown in Fig. 5. The original glare light was too strong and concentrated to be observed by human eyes. While the glare light scattered by the VSL, the image could be observed at an angle of 10° away from the glare angle. Thus the haze component at this angle got a significant enhancement which was even larger than the light reflected by Lambertian reflector at the normal direction by a factor of 2.5.

The contrast ratio of FTF-LCD in both the transmission mode (T-mode) and the reflection mode (R-mode) were measured with Conoscope. In dark ambience, the OLED mode showed a contrast ratio of 2000 : 1 at a viewing cone of 60°; however, while in bright ambience of 250 nits reflected light, the OLED got wash-out with a contrast ratio of only 3. By operating the device in RLCD mode instead of

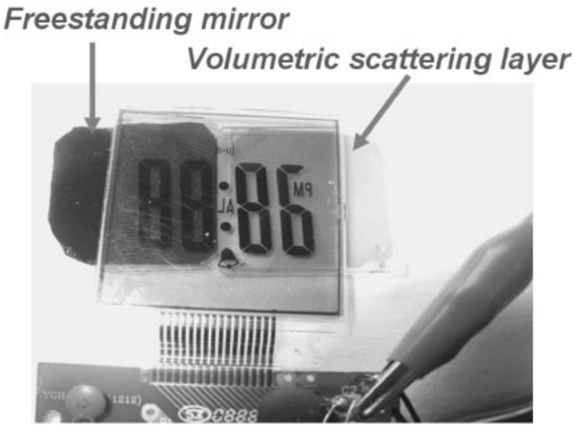

Fig. 6. Demonstration of the haze component enhancement by VSL.

OLED mode, though power was saved by using an ambient light source, the contrast ratio was not significantly increased due to glare effect.

To further increase the contrast ratio, the RLCD was integrated with the VSL which showed a contrast ratio enhancement by a factor of 3.3 to 10 : 1 at a viewing cone of 60° compared with the OLED mode. Moreover, to visualize the haze component enhancement, we photographed a RLCD incorporating with a freestanding mirror and a VSL at a non-glare angle as shown in Fig. 6. The image reflected by the VSL was much brighter than that reflected by a freestanding mirror.

Using nano-particle film as the VSL for enhancing the output coupling efficiency of OLED was reported.[10–14] Furthermore, we proposed using the VSL as a transflector in the display device, which can enhance not only the output coupling efficiency but also the visibility under the sunlight ambience. To achieve a higher visibility under the sunlight ambience, the optical compatibility between the particle size, particle concentration, and the medium refractive index shall be further optimized.

Combining OLED and RLCD provides more possibility for display applications, which is owing to the OLED can be used as a backlight or a display. If the OLED is used as a display (or a regional backlight), each lighting area can be turned off to show the complete dark state, which greatly increases the contrast ratio and decreases the power consumption. This advantage will result in higher dynamic range in the display applications. However, the fabrication yield of using OLED as a backlight is much higher than that of using OLED as a display.

Moreover, to increase the light efficiency of the OLED section, the OLED should be monochromatic instead of white-lighted, which would prevent the elimination of light by color filter. In addition, replacing the two crossed polarizers with a circular polarizer can further increase the light efficiency of OLED (but the OLED cannot be modulated by the LCD section, i.e., the light intensity of the OLED shall be modulated by the current signal through it); however, considering the RLCD, to get a complete dark state with this one circular polarizer configuration, the particle size of VSL shall be larger to prevent the occurrence of Mie scattering which will transform the polarized light into unpolarized light.[23,24)]

To further prevent the parallax effect induced by the thick substrate between the LC layer and the reflector, replacing the intermediate substrate with a thin-film encapsulation is imperative. This integration process was reported in ref. 25 which would induce some device degradation owing to the physical damage from LCD process to OLED. This issue can be avoided if the thermal LC alignment process can be replaced by photo-alignment process or ion beam alignment.

The FTF-LCD has been demonstrated by integrating the FOLED and FLCD which exhibited a high contrast ratio of 2000 : 1 at a viewing cone of 60° in dark ambience. Moreover, in the bright ambience, FTF-LCD could save power (like conventional transflective LCDs) by utilizing ambient light as a light source. By implementing a VSL, the contrast ratio was enhanced by a factor of 3.3 to 10 : 1 at a viewing cone of 60°. These results demonstrated that FTF-LCD with VSL is a promising device for mobile applications.

Acknowledgements

The authors would like to express their appreciation to Electronics and Optoelectronics Research Laboratories, Industrial Technology Research Institute for their assistance of providing flexible LCDs. This work is partially supported by MOE ATU Program “Aim for the Top University” No. 95W803.

1) E. Lueder, M. Randler, H. Schenk, and E. Kluge: SID Int. Symp. Dig. Tech. Pap. **31** (2000) 1025.
2) A. Mosley, J. Burrage, N. Conway, M. Halim, S. Latham, J. Pommerehne, and P. Rundle: SID Int. Symp. Dig. Tech. Pap. **32** (2001) 298.
3) H. P. D. Shieh: Proc. IEEE Conf. Laser and Electro-Optics Society (LEOS), 2005, p. 650.
4) J. H. Lee, X. Zhu, Y. H. Lin, W. K. Choi, T. C. Lin, S. C. Hsu, H. Y. Lin, and S. T. Wu: Opt. Express **13** (2005) 9431.
5) M. Kimura: U.S. Patent Application 20020196387 (2002).
6) I. Fujieda: U.S. Patent Application 20030201960 (2003).
7) Y. J. Tung: U.S. Patent 6900458 (2005).
8) B. R. Yang, K. H. Liu, and H. P. D. Shieh: Jpn. J. Appl. Phys. **46** (2007) 182.
9) S. T. Wu and C. S. Wu: Appl. Phys. Lett. **68** (1996) 1455.
10) J. J. Shiang and A. R. Duggal: J. Appl. Phys. **95** (2004) 2880.
11) J. J. Shiang, T. J. Faircloth, and A. R. Duggal: J. Appl. Phys. **95** (2004) 2889.
12) T. Nakamura, H. Fujii, N. Juni, and N. Tsutsumi: Opt. Rev. **13** (2006) 104.
13) T. Nakamura, N. Tsutsumi, N. Juni, and H. Fujii: J. Appl. Phys. **96** (2004) 6016.
14) K. Neyts and A. U. Nieto: J. Opt. Soc. Am. A **23** (2006) 1201.
15) M. E. Becker, J. Laur, and J. Neumeier: SID Int. Symp. Dig. Tech. Pap. **32** (2001) 322.
16) M. E. Becker: J. Soc. Inf. Disp. **13** (2005) 81.
17) M. E. Becker: J. Soc. Inf. Disp. **14** (2006) 1003.
18) K. H. Liu, W. Y. Chou, C. C. Liao, C. T. Ho, and H. P. D. Shieh: Jpn. J. Appl. Phys. **45** (2006) 7761.
19) S. N. Lee, S. F. Hsu, S. W. Hwang, and C. H. Chen: Curr. Appl. Phys. **4** (2004) 651.
20) X. Z. Jin, P. Berger, and T. Graf: J. Phys. D **39** (2006) 4703.
21) H.-P. D. Shieh, Y.-P. Huang, and K.-W. Chien: J. Disp. Technol. **1** (2005) 62.
22) S. Hendy: Appl. Phys. Lett. **81** (2002) 1171.
23) G. Mie: Ann. Phys. (Leipzig) **25** (1908) 377 [in German].
24) T. Okumura, A. Tagaya, and Y. Koike: Appl. Phys. Lett. **83** (2003) 2515.
25) B. R. Yang, K. Y. Lin, H. P. D. Shieh, S. N. Lee, and C. H. Chen: SID Int. Symp. Dig. Tech. Pap. **38** (2007) 1813.