Color separation system with angularly positioned light source module for pixelized backlighting

Po-Chou Chen,[1] Hui-Hsiung Lin,[2,3,*] Cheng-Huan Chen,[1] Chi-Hung Lee,[3] and Mao-Hong Lu[2]

[1]*Department of Power Mechanical Engineering, National Tsing Hua University, 101, Section 2, Kuang-Fu Road, Hsinchu 30013, Taiwan, Republic of China*

[2]*Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, Republic of China*

[3]*Mechanical and Systems Research Laboratories, Industrial Technology Research Institute, Chutung, Hsinchu 310, Taiwan, Republic of China*

**phranklin@itri.org.tw;*

Abstract: A color-separation system that angularly positions color LEDs to produce color separation and a lens array to focus this light onto the pixels is proposed. The LED rays from different incident angles are mapped into corresponding sub-pixel positions to efficiently display color image, which can be used to replace the absorbing color filter in the conventional liquid crystal layer. In this paper, the prototype backlight has been designed, fabricated and characterized. The measurement results of this module showed that a gain factor of transmission efficiency three times more than that of conventional color filters efficiency improvement and a larger color gamut are expected.

©2010 Optical Society of America

OCIS codes: (220.0220) Optical design and fabrication; (80.3620) Lens system design; (110.2945) Illumination design; (120.2040) Displays.

References and links

1. T. V. Gunn, and W. Haistead, "Diffractive color separation fabrication," Proc. SPIE **3363**, 198–208 (1998).
2. H. Dammann, "Color separation gratings," Appl. Opt. **17**(15), 2273–2279 (1978).
3. M. W. Farn, M. B. Stern, W. B. Veldkamp, and S. S. Medeiros, "Color separation by use of binary optics," Opt. Lett. **18**(15), 1214–1216 (1993).
4. C. Joubert, B. Loiseaux, A. Delboulbé, and J. P. Huignad, "Phase volume holographic optical components for high-brightness single-LCD projectors," Appl. Opt. **36**(20), 4761–4771 (1997).
5. R. P. Gale, and G. J. Swanson, "Efficient illumination of color AMLCD projection displays using binary optical phase plates," J. Soc. Inf. Disp. **5**(4), 375–378 (1997).
6. Y. Taira, D. Nakano, H. Numata, A. Nishikai, S. Ono, F. Yamada, M. Suzuki, M. Noguchi, R. Singh, E. G. Colgan, "Low-power LCD using a novel optical system, " SID 02 Digest **33**, 1313–1315 (2002).
7. Y. Taira, H. Numata, D. Nakano, K. Sueoka, F. Yamada, M. Suzuki, M. Noguchi, R. Singh, and E. G. Colgan, "Color filterless liquid crystal illuminated with LEDS," SID 03 Digest **34**, 1250–1253 (2003).
8. D. K. G. de Boer, R. Caputo, H. J. Cornelissen, C. M. van Heesch, E. J. Hornix, and M. J. J. Jak, "Diffractive grating structures for colour-separating backlights," Proc. SPIE **6196**, 241 (2006).
9. M. Xu, H. P. Urbach, and D. K. de Boer, "Simulations of birefringent gratings as polarizing color separator in backlight for flat-panel displays," Opt. Express **15**(9), 5789–5800 (2007).
10. R. Caputo, L. D. Sio, M. J. J. Jak, E. J. Hornix, D. K. G. De Boer, and H. J. Cornelissen, "Short period holographic structures for backlight display applications," Opt. Express **15**(17), 10540–10552 (2007).
11. H. H. Lin, and M. H. Lu, "Design of Hybrid Grating for Color Filter Application in Liquid Crystal Display," Jpn. J. Appl. Phys. **46**(No. 8B), 5414–5418 (2007).
12. H.-H. Lin, C. H. Lee, and M.-H. Lu, "Dye-less color filter fabricated by roll-to-roll imprinting for liquid crystal display applications," Opt. Express **17**(15), 12397–12406 (2009).
13. A. Travis, T. Large, N. Emerton, and S. Bathiche, "Collimated light from a waveguide for a display backlight," Opt. Express **17**(22), 19714–19719 (2009).
14. Optics Software for Layout and Optimization (OSLO), Lambda Research Corporation, *http://www.lambdares.com/*.
15. Advanced System Analysis Program, (ASAP ™), Breault Research Organization, Inc., *http://www.breault.com/index.php*.
16. Topcon Technohouse Corporation, *http://www.topcon-techno.co.jp/eng/*

1. Introduction

In recent years, liquid crystal displays (LCDs) have been the most widely used apparatus in various applications as information display devices, such as computer, communication, and consumer electronics due to the thinner size and lighter weight.

One problem facing current LCD is its low efficiency. The conventional color filter is made of dye material, which transmits the desired bandwidth of incoming white light and eliminates the remaining spectra to produce visible color such that over two-thirds of the energy is wasted [1]. In addition, the fabrication procedure of the dye color filter is complicated in constructing the RGB patterns onto the corresponding sub-pixel areas.

Several approaches have been proposed to improve the light efficiency by discarding the absorption-type color filter in LCD system. One method is by using diffractive components. H. Dammann introduced a sandwich grating structure, which deflects three primaries (RGB colors) into different diffractive orders to spatially separate colors [2]. Another well-known color-separation approach is combining a blazed grating with a micro lens array. The grating separates the incident light into angular distribution according to the wavelengths, and each micro lens focus these angular components into positional distribution at the focal plane. Based on this concept, the hybrid refractive-diffractive element [3], the holographic component [4], or the fractional Talbot plane of the grating [5] were designed for the color separation in the LCD projector or the color image detector. To apply this concept in a LCD backlight [6–12], the design must fulfill two conditions in order to obtain a working device. First, the incoming light has to be highly collimated to reduce cross-talk after diffraction by the grating. According to calculation, the pitch of the grating has to be sub-wavelength (<500nm) structured while the divergence angle of the incident beam is +/− 4°. For LCD applications, no commercially available light guide can create such high collimated beam. Secondly, e-beam or interferometry has to be used to pattern sub-wavelength grating on an optical film or on top of a light guide. It is not suitable for mass production. Besides, although sub-wavelength grating can produce a single diffracted transmitted order with the other orders being recycled in the light guide for all colors, the total out-coupled efficiency is still low because of the absorption of light guide material during recycling.

In order to overcome the above problems from using a grating to separate color, one method is utilizing light collimation from a point source and a blunt wedge light-guide to produce color separation [13]. In this study, which is an advanced design for previous research [11,12], we propose another novel structure that consists of angularly positioned color LEDs and a lens array to produce color separation.

2. Backlight system

Before describing our configuration, we review the role of the grating for display applications. The grating is usually used to separate the incoming light into primary colors with different angles. The obtained light rays then pass through a cylindrical lens array that properly redirects the colors to the pixels of the LCD [6–9,13], as shown in Fig. 1.

In optics, a suitable arrangement of light sources can also perform the angular color-separation as a grating does, if each LED is situated in a specific position to a collimated lens. A v-groove light guide plate and a cylindrical lens array are then used to convert the angular color-separation components to positional-separation on the LC layer. Hence, the proposed system can be divided into three modules: (1) the light source collimation module, (2) the light guide and (3) the cylindrical lens array, as depicted in Fig. 2.
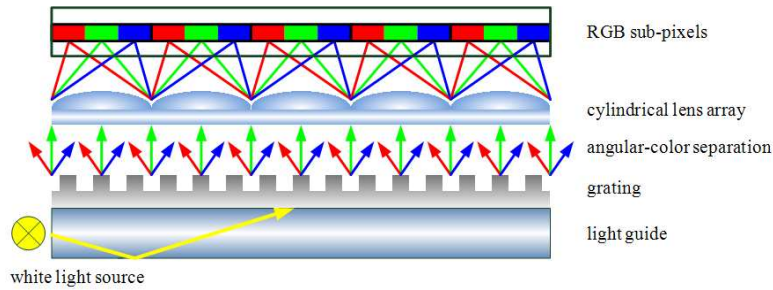
Fig. 1. For a backlight using grating to angularly separate color, a cylindrical lens array is usually adopted to form the color sub-pixels in the liquid crystal layer.
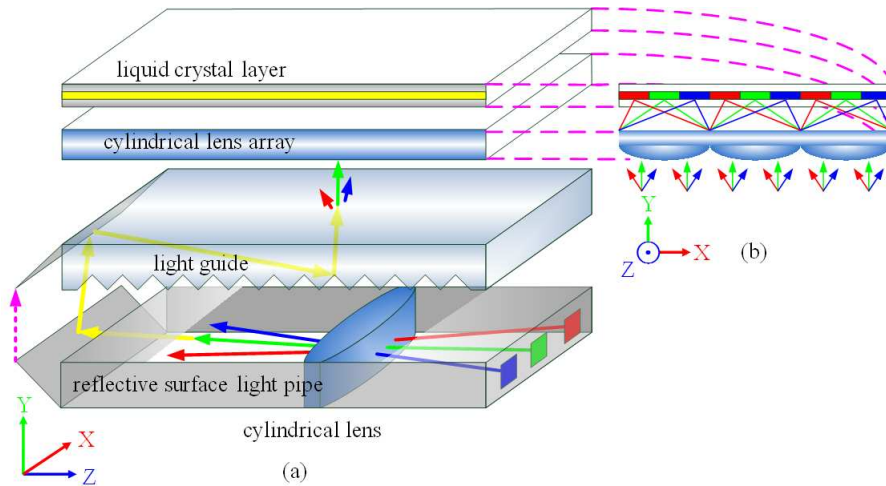

Fig. 2. Color-separation backlight using a suitable arrangement of LEDs (a) Schematic configuration (b) Cross-section view.

2.1 Light source collimation module and light guide

In ordinary case, three color (RGB) LEDs are used as light source. Our starting point of the light source arrangement is the geometry sketched in Fig. 3. In order to reduce efficiency loss we can coat a reflector on the side of the light-guide. One drawback, however, immediately emerges. For example, part blue rays reflected from the side-reflector of the light-guide propagate along the angles of red rays. This causes a color-mixing effect that generates a magenta-green-magenta pixel structure on the LC layer. Another drawback is part of the light guide are not illuminated by the red LED, while the symmetrical part not being illuminated by the blue LED.
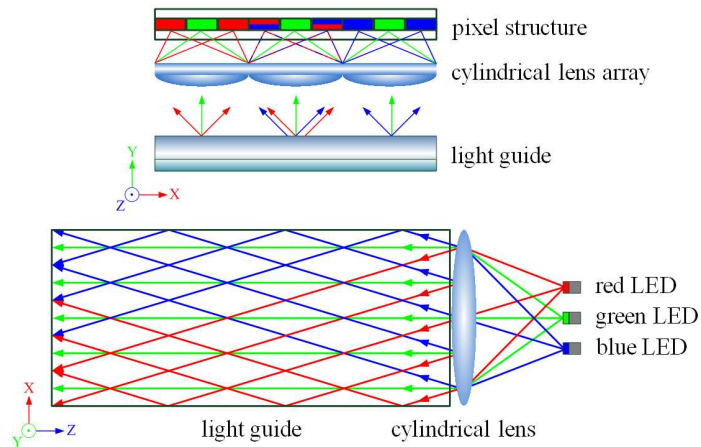
Fig. 3. An arrangement of R-G-B LEDs to a cylindrical lens performs the angular color-separation, but induces asymmetrical illumination in the light guide and color mixing after passing the cylindrical lens

An alternative configuration to solve the color mixing problem is illustrated in Fig. 4. In this new configuration, the positions of each LED can be designed in such a way to have the blue ray propagate along the normal direction while green and red will be reflected at respective larger angles. After being extracted from the light guide and passing through the cylindrical lens array, the light from opposite directions adds up generating a symmetric red-green-blue-green-red pattern without color mixing.
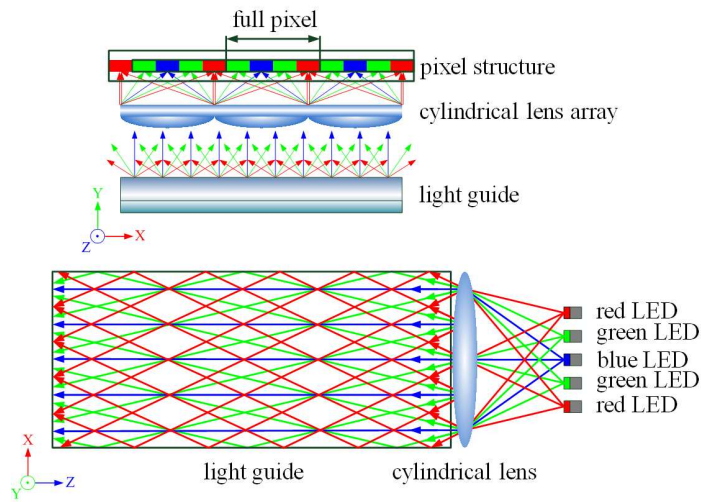

Fig. 4. A suitable arrangement of R-G-B-G-R LEDs to a cylindrical lens performs a feasible angular-color separation

The collimation module determines the direction of the light extraction from LEDs. These angular-separated color rays are created by putting different color LEDs on the focal plane of a cylindrical lens. To achieve the proposed configuration above, the blue LED is positioned at the focal point, while the red and green LEDs are situated at off-axis distances of $\pm L_R$ and $\pm L_G$, respectively, as shown in Fig. 5(a). To have a higher light transmission rate, both the cylindrical lens and the LEDs are sandwiched between two reflectors, which provide a function of reflecting light that has escaped from the x-z plane. The relation between the focal length (f) of the cylindrical lens, the off-axis distance (L) of a LED position and the propagation direction of generated collimated rays (θ) is described by:

$$L = f \times \tan \theta \qquad (1)$$

Since a LED has a lambertian radiation, one reflective cup for converging outer light from each LED is necessary. The reflective cup comprises an internal alumina-coated reflection surface for reflecting the outer light to the collimation lens. The reflective cup has a polygon shape. As shown in Fig. 5(b), the incident angles θ_0 in the x-z plane measured from the normal of the collimation lens are estimated as follows,

For rays without hitting the reflective cup:

$$\theta_o = \theta_i \qquad (2)$$

For rays hitting the reflective cup:

$$\theta_o = 2\Omega_j - \theta_i \qquad (3)$$

in which θ_i is the emitting angle from the LED chip and Ω_j is the inclination angle of jth part of the reflective cup. Considering each LED chip has a limited size, which would induce aberration, two ray-tracing simulation tools OSLO [14] and ASAP^{TM} [15] are used to optimize the geometrical parameters and mitigate the divergence of the incident light that illuminates the side facet of the light guide.
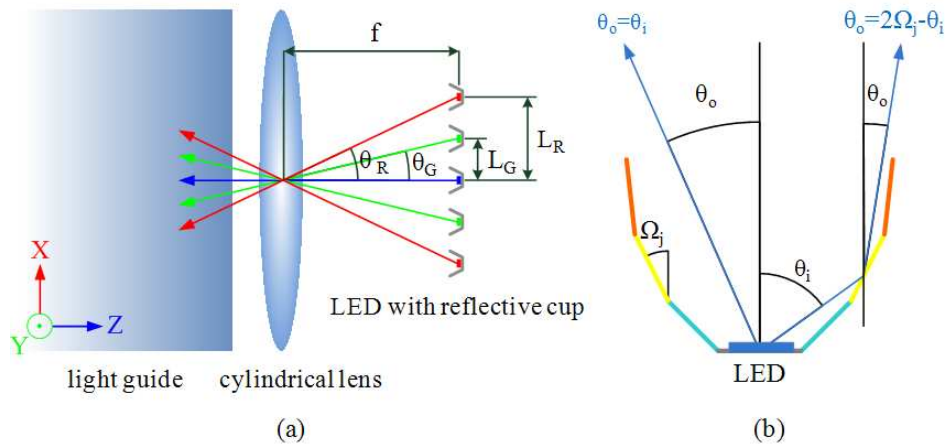

Fig. 5. (a) A cylindrical lens is applied to generate collimated beams with color LEDs being put at different positions on the focal plane. (b) The propagation directions of rays are redirected by the reflective cup.

By using a cylindrical lens with a focal length 56 mm and a 3.2" light guide with a v-grooved patterned bottom reflector, the simulation shows that the angular distributions (FWHM, full width at half maximum) of the extracted beams from the surface of the light guide are: $-16° \pm 3°$ and $16° \pm 3°$ for red rays, $-8° \pm 2.5°$ and $8° \pm 2.5°$ for green rays, and $0° \pm 2.2°$ for blue rays (see Fig. 6).
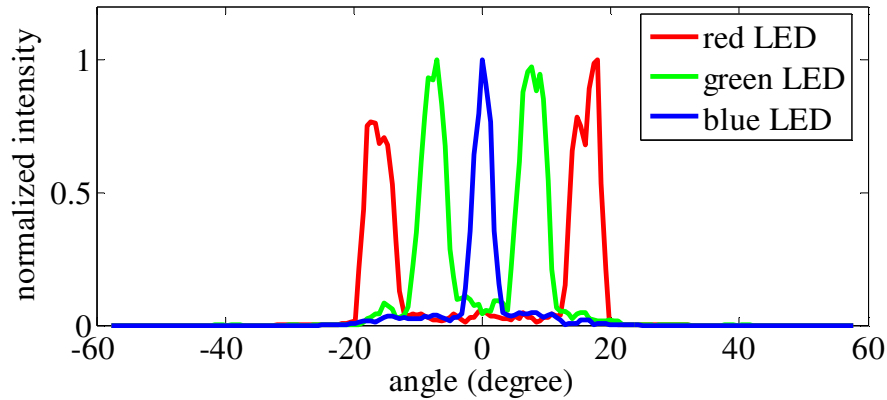
Fig. 6. Simulated distributions of the line pattern generated by our side emitting backlight, which is illuminated by a series of color LEDs on the focal plane of a cylindrical lens.

2.2 Cylindrical lens array

The array of cylindrical lenses to image the colors on the appropriate pixels has to match exactly the pixel structure of the LCD panel after extracting the light angularly from the light guide. The geometry is illustrated in Fig. 7. It generates a sequence of red-green-blue-green-red pattern on the focal plane, which is designed as the liquid crystal layer of a display.
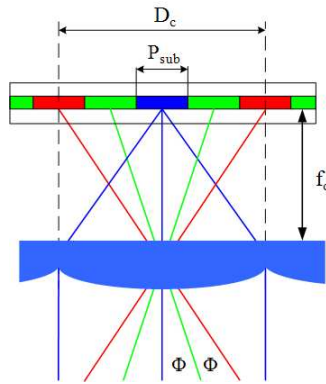

Fig. 7. Geometry of the cylindrical lens array with respect to the pixels.

The parameters of the cylindrical lens array related to the pixel structure and angular components from light guide are denoted in Fig. 7. In the case, the period of the proposed pixel was set to be 440um, which was composed of four sub-pixels, according to a commercial 26-inch display. To have a better pixel resolution or a smaller pixel size, usually the period of the cylindrical lens array can be directly reduced. The limit of the available highest resolution or the available smallest pixel size depends on many factors, including the cylindrical lens quality for collimation, the size of light source and the aberration from the cylindrical lens array. The width D_c of the cylindrical lenses thus determined the sub-pixel spacing $P_{sub} = 110\mu m$ of the display under the design that the angle between the green and blue rays is equal to the angle between the red and green rays (denoted by $\Phi = 8°$). The focal length f_c is therefore determined by the pixel spacing of the display and by the angular range of the colors extracted from the light guide according to the formula:

$$f_c = \frac{P_{sub}}{\tan(\Phi)} \qquad (4)$$

To reduce the aberration, the ray-tracing tool OSLO was first applied to calculate the optimal profile of the cylindrical lens. A radius of curvature 510μm and a refractive index of 1.595 were therefore chosen to fabricate the cylindrical lens array (see Fig. 8). The best image plane is 610μm above the cylindrical lens array and has a range of ± 110μm without color crosstalk. The liquid crystal layer is corresponding to this best image plane. All parameters from OSLO are then substituted into ASAP^{TM} to analyze the system's overall performance. The system's color distribution shows a RGBGR sequence of stripes (see Fig. 9(a)). Its normalized intensity in between the lines almost approaches zero, which means a large color gamut could be expected (see Fig. 9(b)).
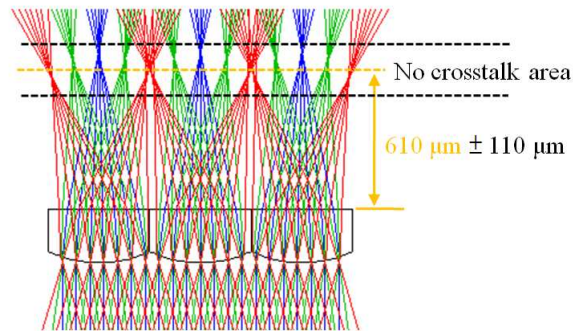

Fig. 8. The analysis of the cylindrical lens array was by using OSLO with angular distribution of ± 16° for red rays, ± 8° for green rays and 0° for blue rays. The image plane without color crosstalk is between 610 ± 110μm from the cylindrical lens array.
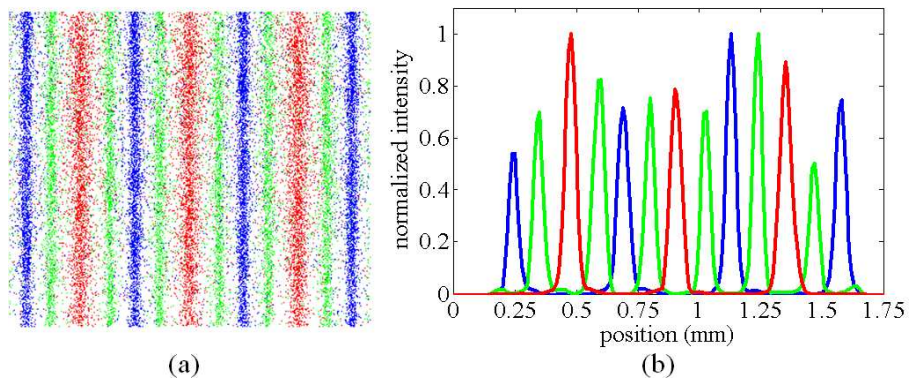

Fig. 9. Simulated results of system's color distribution: (a) the footprint diagram, (b) the cross section of normalized intensity.

3. Experimental results

An experimental testing module of 3.2" backlight has been manufactured. The cylindrical lens array was formed on an 188μm thick PET film (T-A4300 by Toray Corp.) by using roll-to-roll UV–cured imprinting process. A roller cutter with the designed profile was first utilized to form a mechanically grooved structure on an imprinting Cu roller, as shown in Fig. 10(a). Then the UV resin was then distributed on the PET film, imprinted by the roller, hardened by UV source, and separated from the roller as shown in Fig. 10(b). A micro-scope photo of the cylindrical lens array is shown in Fig. 10(c). The reflective cups, the planar cylindrical lens and the V-grooved light guide have been fabricated by using ultra-precision machining technology. The working prototype is shown in Fig. 11.
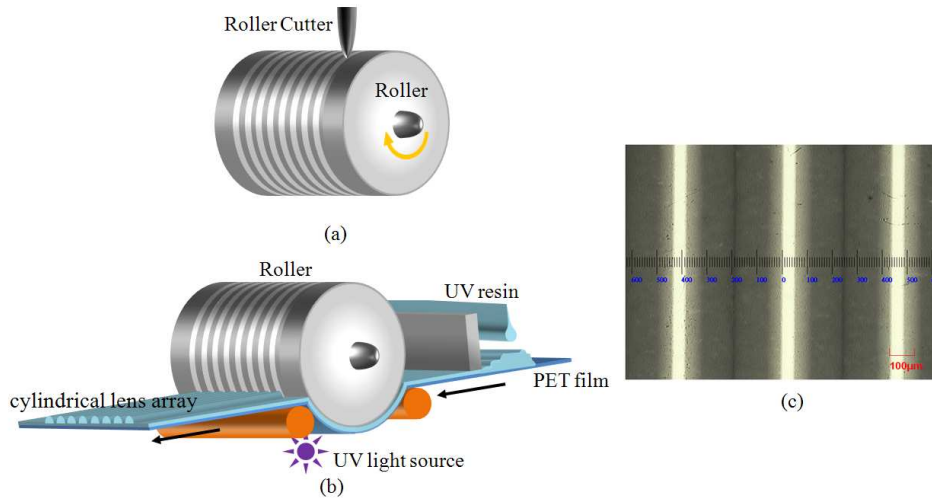
Fig. 10. (a) The roller is processed by a roller cutter with the designed profile. (b) The roll-to-roll UV–cured imprinting process is applied to form a cylindrical lens array on a PET film. (c) A micro-scope photo of the cylindrical lens array, the pitch of each lens is 440μm.
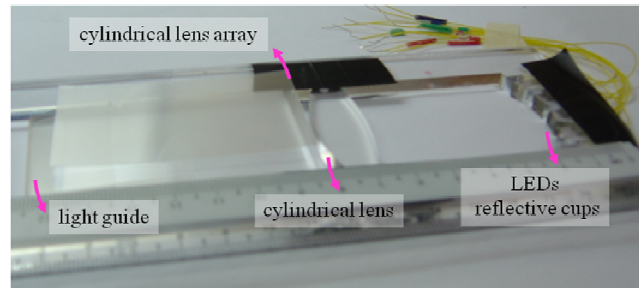

Fig. 11. The setup of the optical elements in the working prototype

The drawing and the photograph of our optical experimental setup is shown in Fig. 12(a) and (b), respectively. To directly show the ray propagation, the light guide was illuminated by a side-lit collimation. Color LED rays from the focal plane of the collimated lens was collimated before coupling into the light guide. The cylindrical lens array on top of the light guide was then used to convert the angular-colored components into R-G-B-G periodical line pattern as the full-pixel array. To measure its optical characteristics, the CCD camera and spectroradiometer SR-UL1R for ultra-low luminance from Topcon Technohouse Corporation [16] were used to capture the line pattern and its color gamut. To determine color gamut, SR-UL1R used a diffraction grating, relay optics, and a linear CCD sensor to measure the dispersed colorful light on the image plane of the cylindrical lens array. The light intensity of each color was converted to electrical signals and reported as derived colorimetric results. The CIE xy values were computed from the full array of spectral data using precision functions (standard tri-stimulus integrals) prescribed by the CIE. The accuracy of luminance measurements was down to 0.001 cd/m^2.
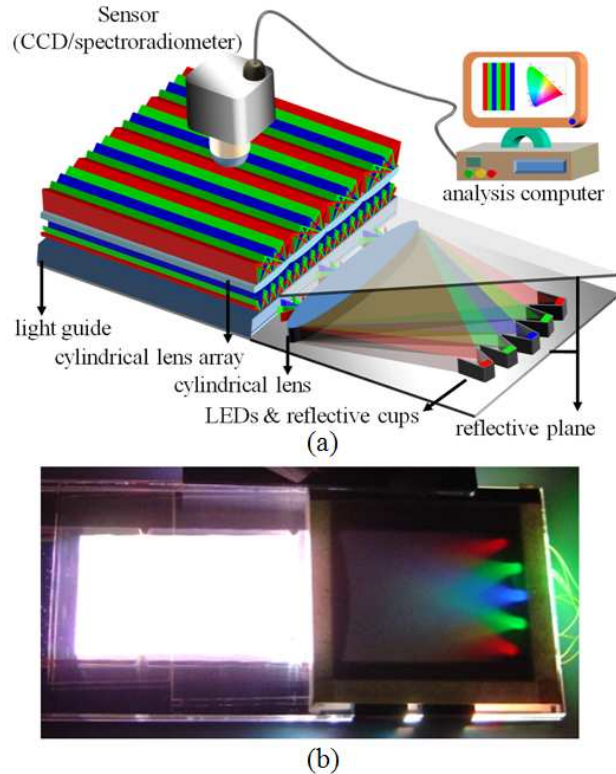
Fig. 12. (a) The optical measurement setup for color-separation by the proto-type. (b)The prototype backlight illuminated by the color LEDs.

The color gamut is commonly expressed as a percentage of NTSC to define the range of color that a system can reconstruct. NTSC is a color TV standard developed by the National Television System Committee and 100% of NTSC means the full range of color that can theoretically be displayed.

The distribution of measured color pattern matched our design well (see Fig. 13.). The un-illuminated spacing between each line is clearly visible, which reveals two merits of our system over the diffraction-based color separation methods [3–12]. First, most energy of the separated colors can pass through the liquid crystal layer without hitting the black matrix area in the TFT-LCD. Secondly, the primary colors can be clearly distinguished and overlap is significantly reduced. Several full pixels were measured to obtain the average color gamut, which was NTSC 85%, as shown in Fig. 14(a). The white dots represent the primary color points of the individual red, green, and blue LEDs (NTSC 128%). The spectrum distribution of the red, green and blue LEDs is shown for reference in Fig. 14 (b), with the peak values are 638nm, 521nm and 446nm, respectively. The normalized cross section of the corresponding line pattern of Fig. 13 is also shown in Fig. 14(c). The intensity in between the line does not completely drop to zero, which is the main reason of color desaturation (NTSC 85%) from theoretical maximum (NTSC 128%). The theoretical maximum was achieved by directly using SR-UL1R to measure LED light sources. At the position of the green line, approximately 5% of the red and 1% of blue light is visible; at the position of the blue line, approximately 2% of the green and 1% of red light is visible. The effect of this can be obviously observed from the color point variation of the green in Fig. 14(a): the color point for green is shifted to $(x, y) = (0.25, 0.68)$ from $(x, y) = (0.15, 0.75)$ of the green LED. The color desaturation was mainly attributed to the Fresnel reflection between two media having different refractive indexes. To achieve a much better NTSC performance, an anti-reflection layer can be added on the surface of the optical component to reduce the reflection. The

scattered light from the rough surface of each optical component also induced non-zero intensity in between the color lines. The cylindrical lens used to collimate the incident LED lights and the V-cut pattern at the bottom of the light guide used to redirect the collimated light were both made on the lathe by a knife cutting process, and their roughness was around R_a 50~80 nm according to our pretests. Besides the cylindrical lens, which was achieved by the roll-to-roll process, also had a surface roughness R_a 20~30 nm. The surface roughness can be further improved by tuning process parameters if necessary. Another issue is that the line spacing between the red and the green lines is smaller than that between the green and the blue lines in Fig. 14(c), which deviates from the simulation shown in Fig. 9(a). The quantity of deviation depends on the position, where the experimental image was captured.
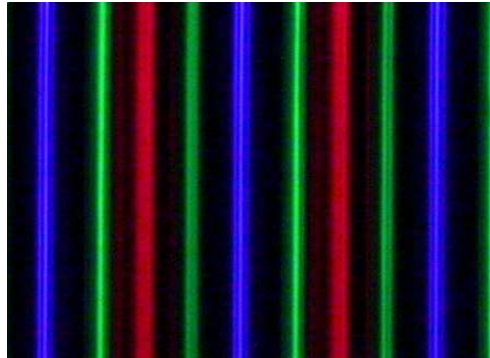

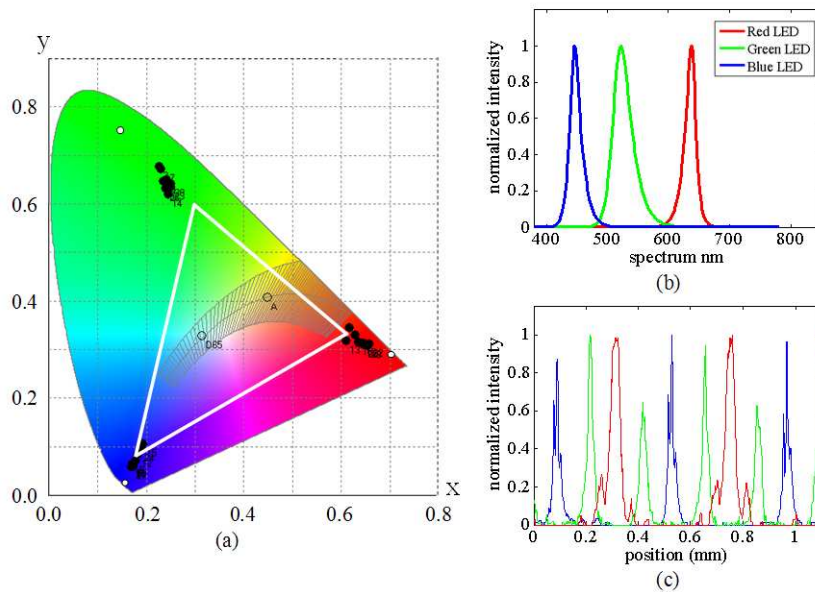Fig. 13. Photograph of periodic line pattern of the module captured by a CCD camera

Fig. 14. (a) Color points in CIE x y space, created by sampling the line pattern in Fig. 13. The white points indicate the color points of the individual LEDs and the white-line triangle shows the gamut of a common liquid crystal display. (b) Spectra of used red, green and blue LED. (c) Cross-sections of normalized intensity generated by the prototype.

4. Conclusion

A prototype of the color separation backlight module was fabricated and demonstrated. The color LEDs' light was collimated to generate angular-colored components in the light guide

before a cylindrical lens array transferring these components into RGBGR line pattern as the full pixel array. Our backlight has the potential to replace the absorbing-type color filter (dye-gelatin and dielectric film, etc) for LCD applications, since the power efficiency is fully utilized instead of being absorbed in producing colors. The NTSC color gamut is also as high as 85%, which is comparable to a LED-based display. Besides, all optical elements, including the cylindrical lens, the V-grooved light guide and the cylindrical lens array, were fabricated by using the conventional ultra-precision processes, which were low-cost mass production technologies.