A Direct-View Backlight With UV Excited Trichromatic Phosphor Conversion Film

Hsin-Tao Huang, Chuang-Chuang Tsai, and Yi-Pai Huang

***Abstract*—This work presents a novel ultraviolet (UV) excited flat lighting (UFL) system consisting of remote phosphor converter (RPC) for liquid-crystal display (LCD) backlight applications. A trichromatic RPC is excited using 254 nm UV lamps to achieve a slim, high color saturation and high luminance backlight. Experimental results indicate that the module thickness reduces to 14.5 mm, along with a high color saturation (92% of the NTSC standard) as well as a high luminance (573 cd/m^2) when applied to large sized display (42-inch). Additionally, the proposed UFL backlight configuration has already been certified by a lifetime test to ensure the feasibility of proposed system in mass production.**

***Index Terms*—Color deviation, color saturation, FWHM, lamp mura, NTSC, remote phosphor converter (RPC), slim backlight, ultraviolet (UV) excited, UV excited flat lighting (UFL).**

I. INTRODUCTION

DIRECT-VIEW backlight (BL) is especially useful for large TFT-LCD applications in terms of high power efficiency and high luminance in contrast with edge-view BL. The conventional configuration of a direct-view BL set generally consists of a metal holder with plural light sources, e.g., CCFL and LED, inside and a diffuser plate above the light source to effectively suppress the non-uniform luminance distribution. The BL design (Fig. 1(a)) with either a CCFL or LED light source lacks a slim configuration. According to Fig. 1(b), despite the edge-view BL sets to thin the BL outline, LED light source with inadequate color saturation, LED color binning and thermal effect are still the issues for commercialization purposes [1]–[9].

The remote phosphor converter (RPC) method has been utilized in white LED packages for many years, with related studies focusing on increasing luminous efficiency [10]–[15]. By using an array of blue LED light sources, Ito *et al.* generated a planar white light for BL applications by exciting a yellow remote phosphor film [Fig. 1(c)]. Owing to difference in luminance-angular distribution between a blue light and an excited yellow light, color deviations can be easily observed as the viewing angle changes from a normal to large viewing angle [16].

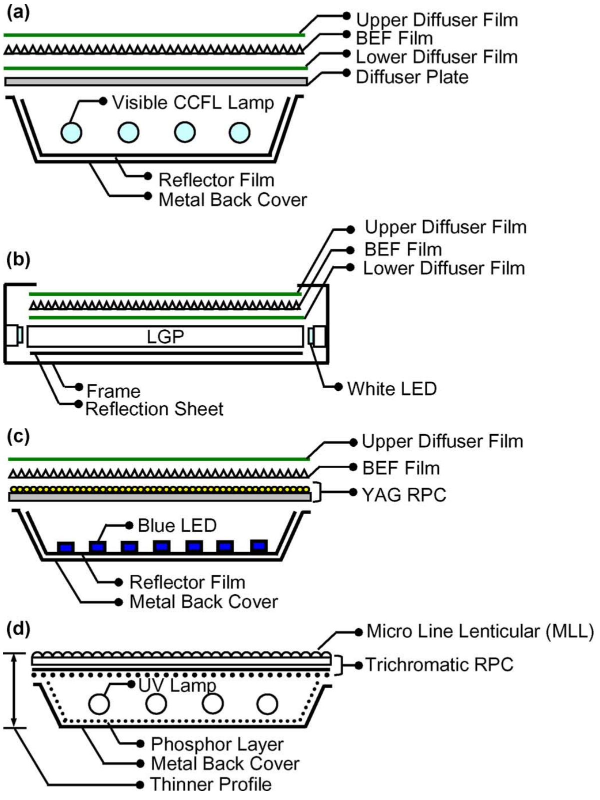

Fig. 1. BL configuration. (a) Typical direct-view. (b) Typical edge-view. (c) Other RPC BL. (d) Proposed UFL BL.

This work presents a novel BL system that depends on a UV light to excite a trichromatic RPC, instead of a blue light to excite a YAG RPC [17]. The proposed system can combine the advantages of a direct-view BL system, i.e. capable of satisfying a high power efficiency and high color saturation requirement by mixing the emitted R, G and B lights, and an edge-view BL system, capable of generating a uniform, planar and slim BL configuration. Table I compares the optomechanical features of the above-mentioned BL systems, indicating that UFL BL is the optimal scheme in large sized backlight applications.

Eventually, UFL BL system, [Fig. 1(d)], is optimized to exhibit a planar and uniform luminous distribution, slim configuration, high luminance, high color saturation, long lifetime and fast manufacturing process, making it feasible for commercial applications.

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TABLE I
COMPARISON OF DIFFERENT BL SYSTEM

BL Type	Direct-view BL	Edge-view BL	Other RPC BL	UFL BL
Light Source	**CCFL**	**White LED**	**Blue LED**	**UV Lamp**
Large Configuration	◇	▽	○	○
Slim Configuration	▽	○	--	○
Color Saturation	○	▽	◇	○
Luminous Efficiency	○	▽	--	○
Thermal Releasing	○	▽	○	○

○ Superior ◇ Middle ▽ Inferior (--) Unknown

II. UV-EXCITED FLAT LIGHTING (UFL)

UFL scheme is based on a direct-view BL configuration with a UV light source to excite phosphor film placed remotely. Characteristics of the UFL scheme, e.g., luminous uniformity, luminance, slim configuration, color uniformity and color saturation are discussed. Such features are especially attractive for large scale TFT-LCD applications. With respect to UFL BL, the 254 nm wavelength is irradiated by UV lamps. The UV rays are then converted by RPC to achieve a visible, uniform and planar light distribution. Therefore, the UFL could yield a thinner backlight system than that of the conventional direct-view BL with CCFL or a white-LED light source.

The proposed UFL BL design can also ensure an adequate uniformity and lifetime of phosphor coating. For conventional CCFL lamps, uniformity of phosphor coating inside the lamp tube by siphon theorem worsens with an increasing lamp tube size. Meanwhile, the ion bombardment and 185-nm UV deteriorate the phosphor coating, subsequently decreasing the lifetime of CCFL lamps [18], [19]. However, in this work, phosphor is coated using slot die coating and has a longer lifetime than in conventional CCFL lamps owing to its ability to prevent phosphor from contacting with a vapored mercury atom and 185- UV wavelength radiations directly. Therefore, UFL scheme allows for phosphor to achieve uniform coating and a long lifetime simultaneously when applied to large scale display applications.

III. EXPERIMENT COMPONENTS AND STRUCTURE OPTIMIZATION

This section describes the experimental key components of high color rendering (HCR) phosphor and RPC. Optimization of UV excitation is then discussed, and the experimental indices are defined for evaluation.

A. *UV Excited Trichromatic Phosphor*

Color saturation of a LCD is determined by integrating the spectral properties of the BL light source and the spectral transmission factor of color filter (CF). The HCR phosphor adopted here is blended mainly by trichromatic phosphor with red phosphor of $Y(P,V)O_4 : Eu^{2+}$ phase (620 nm emission), green phosphor of $BaMg_2Al_{10}O_{17} : Eu^{2+}, Mn^{2+}$ phase (515, 545 nm) and blue phosphor of $Sr_5(PO_4)_3Cl : Eu^{2+}$ phase (450 nm). The derived HCR phosphor prescription shows less phosphor irradiation at wavelengths of 590 and 490 nm than the conventionally adopted phosphor does (Fig. 2), where the two wavelength peak decreases the color rendering [20], [21].

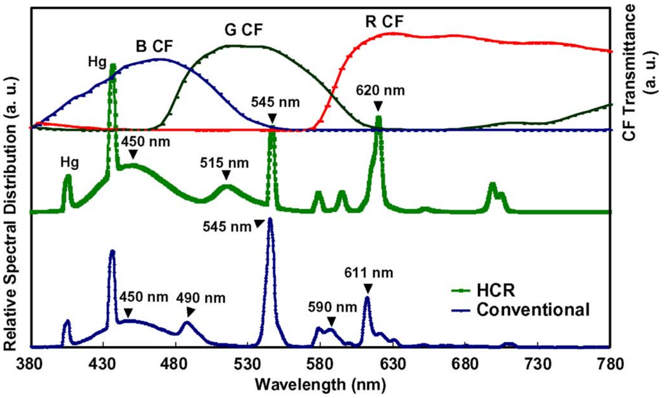

Fig. 2. Spectral properties of the phosphor versus the spectral transmittance factor of CF.

The phosphor was excited mainly by a 254-nm UV light to emit a visible light. Currently, the UV LED light source can not be produced efficiently. Therefore, UV radiation in this experiment was generated using mercury vapour lamps. The quartz made lamp body consists of mercury, noble gas (He: Ne) and electrodes. By selecting the doping materials in a quartz lamp, the UV rays of 254-nm wavelength could be generated efficiently.

B. *Remote Phosphor Converter (RPC)*

HCR phosphors were mixed together with binders, i.e. fluoride content, in a tank and applied on the polyethylene terephthalate (PET) film by slot die coating. Fig. 3 schematically depicts the simplified process. Notably, controlling the applied phosphor layer thickness to within 15–20 μm could yield the optimum luminance conversion efficiency. The phosphor film was then adhered to a plastic substrate to achieve a RPC (Fig. 4). This composite plate was used in UFL BL and placed remotely from the UV light source. The optimum optomechanical and power parameters are discussed later.

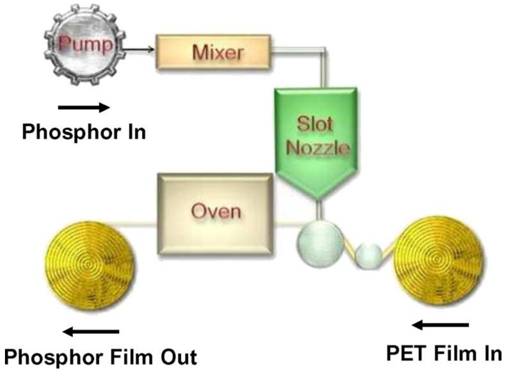

Fig. 3. Schematically depicts the simplified process of slot die coating.

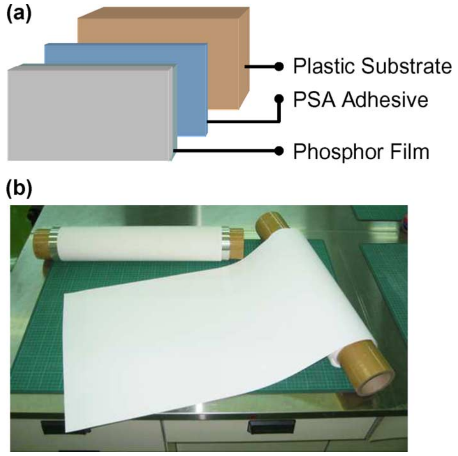

Fig. 4. (a) Remote phosphor converter (RPC). (b) Coated PET films with trichromatic phosphor.

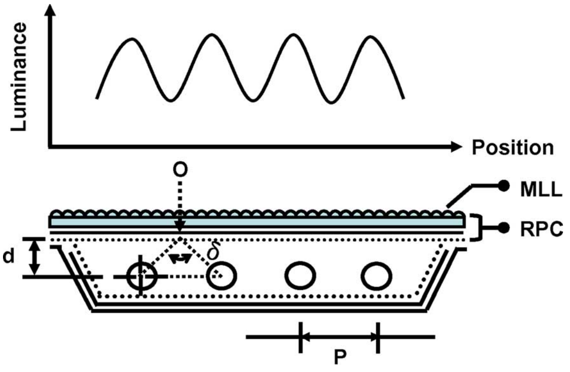

Fig. 5. Schematic relations between the included angle (δ) and luminous distribution in the entire illumination area.

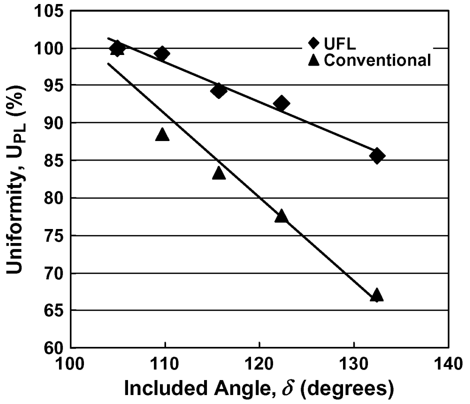

Fig. 6. Relationship between (δ) and (U_{PL}) according to UFL and conventional direct-view BL system.

C. Optimization of Included Angle

According to Fig. 5, the included angle (δ) denotes that the angle of neighboring adjacent lamps is linked to point "O" located on the bottom surface of the diffuser plate and in the central position of two lamps. Notably, a large (δ) implies a distant pitch (P) or a close gap (d).

The mechanical configuration and luminous uniformity of lighting system were evaluated by first defining the included angle (δ) and the 9-points planar luminous uniformity (U_{PL}) as (1) and (2), respectively

$$\text{Included Angle, } \delta = 2\tan^{-1}\left(\frac{P}{2d}\right) \tag{1}$$

$$U_{\mathrm{PL}} = \frac{\text{Minimum}(L_1, L_2, \cdots, L_9)}{\text{Maximum}(L_1, L_2, \cdots, L_9)} \times 100\% \tag{2}$$

where L_x takes values of nine measured luminance data in the entire illumination area $L_1, L_2, \ldots, L_9$. By using triangular relations, (δ) is then determined by the function of lamp gap (d) and lamp pitch (P), as shown in (1). In our experiment involving 42-inch BL, (δ) represents 135° ($P = 24.6$ mm, $d = 5.1$ mm). Equation (2) is defined to represent the luminous uniformity of the BL. $L_{\min}$ and $L_{\max}$ represent the minimum and maximum value of luminance in the entire illumination area, respectively.

These equations are also appropriate for a lighting system with a CCFL or LED type light source. In this study, however, the light source focuses mainly on the UV lamp since 254-nm UV-LED is insufficient for practical applications.

According to Fig. 6, (δ) 105° represents a point in which UFL BL must have luminous uniformity superior to that of conventional direct-view BL system. Varying (δ) from 105° to 135° ensures that UFL BL always displays a better uniformity (U_{PL}: 86%) than conventional direct-view BL (U_{PL}: 67%). When (δ) exceeds 120°, the (U_{PL}) of conventional direct-view BL is 79% and may not satisfy BL application requirement. The variation of illumination is maintained under an average value of ±15% to ensure uniformity (U_{PL}) of at least 85% for large scale TFT-LCD applications [7].

D. UV Intensity Versus Luminance

The generated luminance by UFL is related to the lamp driving current (I) and the UV propagation distance (d) in air as shown in Fig. 7(a) and (b), respectively. A high lamp driving current (I) yields a strong UV intensity to excite the phosphor. However, raising (I) inadvertently increases the lamp temperature to degrade the UV radiation efficiency. Additionally, when the UV lamp is close to RPC, the UV intensity loss in air is low and the converted output luminance is high. The drop in the lamp gap (d) is linearly proportional to the UV intensity. Therefore, the parameter of lamp gap (d) was adopted

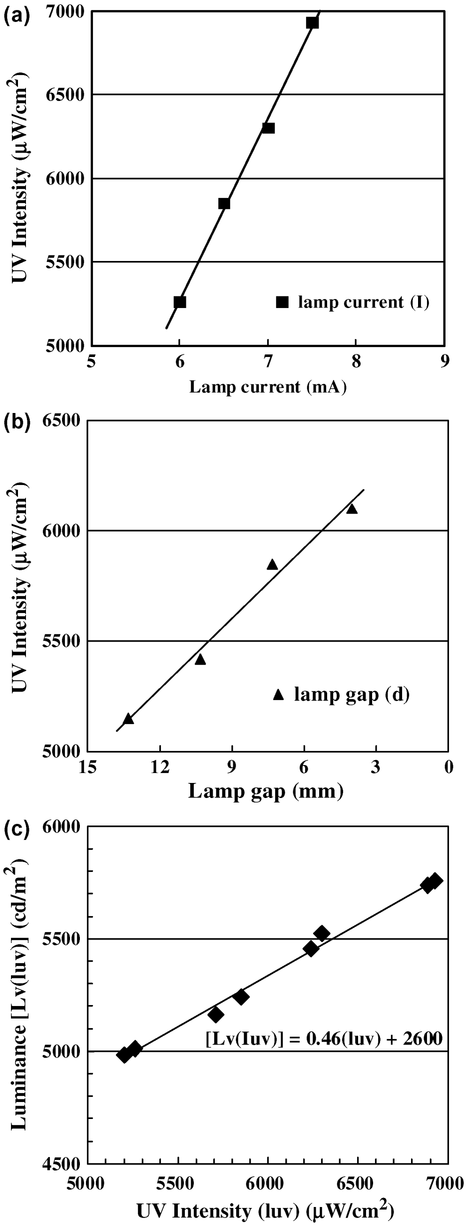

Fig. 7. The parameters influence the UV intensity (μW/cm^2): (a) lamp current (mA), (b) lamp gap (mm). (c) The relationship between the UV intensity and the conversion luminance.

to increase the luminance. According to Fig. 7(c), the converted luminance is proportional to the UV irradiation intensity and satisfies the linear function $[\mathrm{Lv}(\mathrm{Iuv})] = 0.46\ (\mathrm{Iuv}) + 2600$, where (Iuv) is the UV intensity and $[\mathrm{Lv}\ (\mathrm{Iuv})]$] is the converted luminance. Experimental optimization yields a UV intensity of 5850 μW/cm^2 when the experimental parameter (δ) is 135° and (I) is 6.5 mA. Therefore, the mean converted luminance of this UFL BL can reach 5240 cd/m^2.

IV. RESULTS

The LCD characteristics of conventional direct-view BL and UFL BL system are evaluated as well. UFL BL is constructed with RPC on a substrate with micro line lenticular (MLL) arrays (Figs. 1(d) and 8). MLL arrays are functioned for the improvement of on-axis luminance.

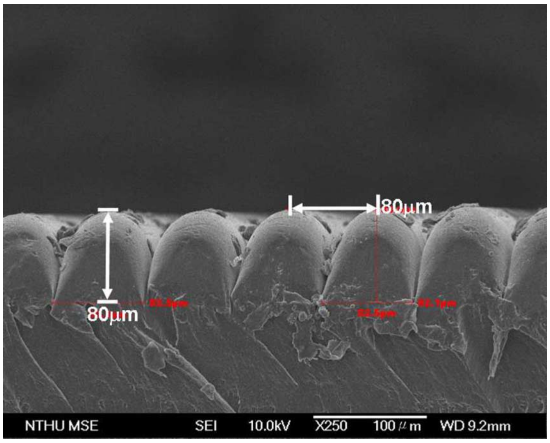

Fig. 8. The SEM picture of the plastic substrate with micro line lenticular (MLL) arrays for UFL BL. (pitch: 80 μm, height: 80 μm).

Fig. 9 and Table II show the luminance in angular distribution and mechanical configuration of the experimental samples. The z-axis is assumed to be the surface normal. Where $\varphi = 0°$ to 360° and $\theta = -80°$ to 80° denote the azimuthal and zenith angles in polar coordinates, respectively [Fig. 9(a) and (d)]. The curve of luminance versus angular distribution represents the inspection angle of (φ) along φ_y direction [Figs. 9(b) and (e)]. Based on the experimental results, conventional direct-view LCD has $\theta_{\mathrm{FWHM}} = 34°$ [Fig. 9(b)]. However, UFL LCD has broader angle of $\theta_{\mathrm{FWHM}} = 46°$, [Fig. 9(e)]. A high luminance associated with a broader angle of full-width at half-maximum (θ_{FWHM}), yields benefits for large scale display applications.

When UFL BL was combined with TFT-LCD panel (with 4.5% transmittance), the optical feature of luminance could reach 573 cd/m^2. The resulting color saturation satisfies 92% of the NTSC standard; in addition, the correlated color temperature of the white point, $(x = 0.281, y = 0.321)$ or $(u' = 0.178, v' = 0.459)$ is 8693 K. Furthermore, the LCD luminance can be enhanced 10.15%, i.e. from 527 to 573 cd/m^2 at the same power consumption (156 Watt). Additionally, for a situation in which (δ) is 135°, the lamp gap (d) can be reduced to 5.1 mm (with entire LCD thickness is 14.5 mm, as shown in Fig. 9(f)) and uniformity of UFL BL is 92%. Therefore, the volume of the proposed 42-inch UFL LCD can be reduced without deteriorating the optical performance. Fig. 9(f) demonstrates the UFL LCD configuration with thickness of 14.5 mm. The thickness of UFL LCD can be dramatically reduced 51.67%, i.e. from 30 mm (conventional direct-view, Fig. 9(c)) to 14.5 mm (UFL).

V. DISCUSSION

A. *Lamp Mura*

The undesirable lamp mura is difficult to eliminate by using conventional direct-view structure for slim backlight. Fig. 10(f) displays the quality of UFL BL without undesirable lamp mura-related phenomena issue when compared with conventional direct-view BL (Fig. 10(c)) at the same parameters of $(\delta) = 135°$ and $(d) = 5.1\ \mathrm{mm}$. Obviously, UFL BL can alleviate undesirable lamp mura-related issue, and thus, slim thickness with

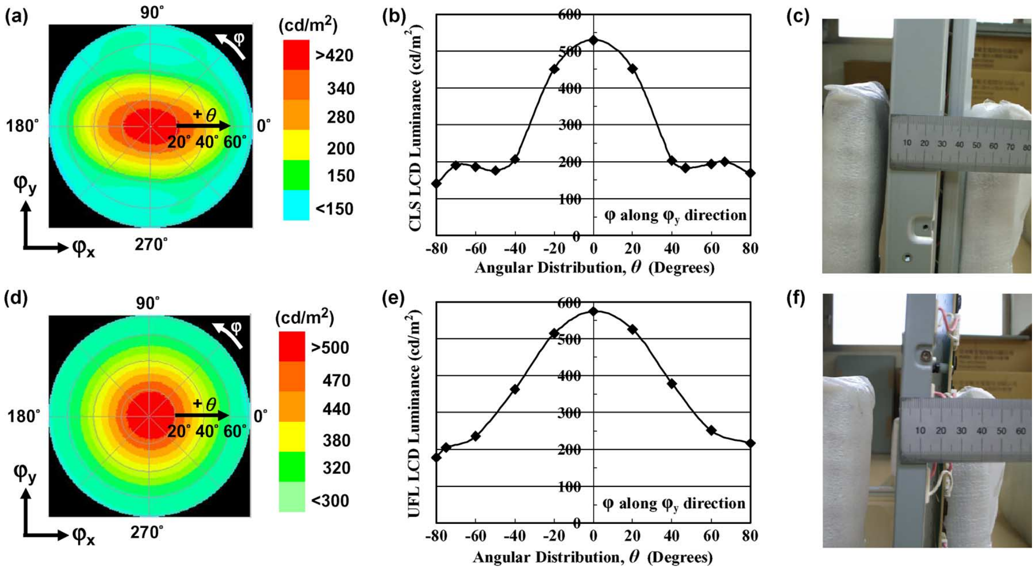

Fig. 9. LCD luminance in angular distribution with conventional direct-view BL system at $\mathrm{I} = 6.5\ \mathrm{mA}$, $\mathrm{power\ consumption} = 156$ W. (a) when $\theta = -80^\circ$ to 80°, $\varphi = 0^\circ$ to 360°; (b) when $\theta = -80^\circ$ to 80°, φ along φ_y direction; (c) entire LCD thickness; (d), (e) and (f) represent LCD with UFL BL system.

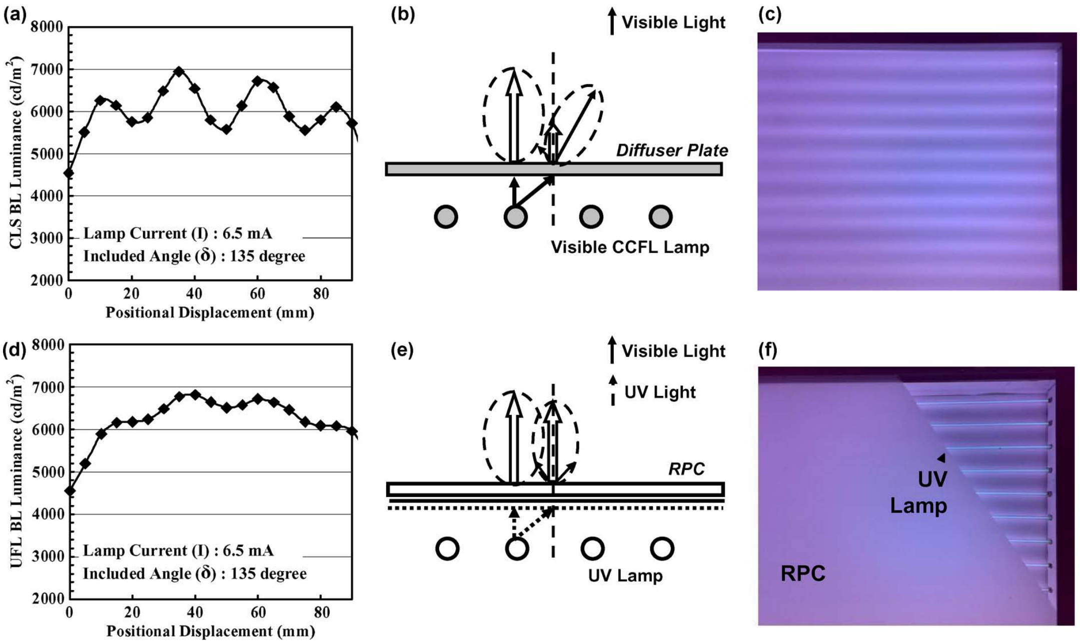

Fig. 10. BL luminance in spatial distribution, ray tracing and luminous uniformity of the experimental samples at $\delta = 135^\circ$, $\mathrm{I} = 6.5$ mA. (a)–(c) represent conventional direct-view BL; (d)–(f) represent UFL BL.

uniform luminance distribution can be achieved. According to Fig. 10(d), the luminance difference of UFL BL is smaller than that of conventional direct-view BL at the same (δ), as shown in Fig. 10(a). By ray tracing analysis, conventional direct-view BL shows the Lambertian distribution center of visible light located on the lamps [Fig. 10(b)]. UFL BL exhibits a trend in which the visible light Lambertian distribution center moves from lamps to the remote phosphor layer [Fig. 10(e)]. Therefore, for UFL BL system, the entire surface of RPC (includes the area between the lamps) has visible light irradiation with Lambertian distribution and the luminance difference between lamps can be eliminated effectively.

B. Color Uniformity

The color deviation of UFL system is evaluated and described as $\Delta\mathrm{u}'\mathrm{v}'$ [22]:

$$\mathrm{u}'_\mathrm{i} = 4\mathrm{X}_\mathrm{i}/(\mathrm{X}_\mathrm{i}+15\mathrm{Y}_\mathrm{i}+3\mathrm{Z}_\mathrm{i}),\ \Delta\mathrm{u}' = \mathrm{u}'_{\mathrm{i}=1} - \mathrm{u}'_{\mathrm{i}=2,3\ldots} \quad (3)$$

$$\mathrm{v}'_\mathrm{i} = 9\mathrm{Y}_\mathrm{i}/(\mathrm{X}_\mathrm{i}+15\mathrm{Y}_\mathrm{i}+3\mathrm{Z}_\mathrm{i}),\ \Delta\mathrm{v}' = \mathrm{v}'_{\mathrm{i}=1} - \mathrm{v}'_{\mathrm{i}=2,3\ldots} \quad (4)$$

$$\Delta\mathrm{u}'\mathrm{v}' = \left((\Delta\mathrm{u}')^2 + (\Delta\mathrm{v}')^2\right)^{1/2} \quad (5)$$

where $\mathrm{X}_\mathrm{i}\mathrm{Y}_\mathrm{i}\mathrm{Z}_\mathrm{i}$ are the tristimulus values in the XYZ color system and u'_i, v'_i represent the chromaticity index in the CIE 1976 chromaticity diagram [see (3) and (4)]. In this work, the

TABLE II
OPTICAL CHARACTERISTICS OF DIFFERENT BL SYSTEM. (A) CONVENTIONAL LCD; (B) UFL LCD

	(A)	(B)
BL System	**Direct-view BL**	**UFL BL**
LCD Thickness (mm)	**30**	**14.5**
Uniformity (%)	**88**	**92**
NTSC (%)	**87**	**92**
FWHM Angle (degree)	**±34°**	**±46°**
Central Luminance (cd/m^2)	**527**	**573**

°Experiment was tested under the same power consumption (156 W).

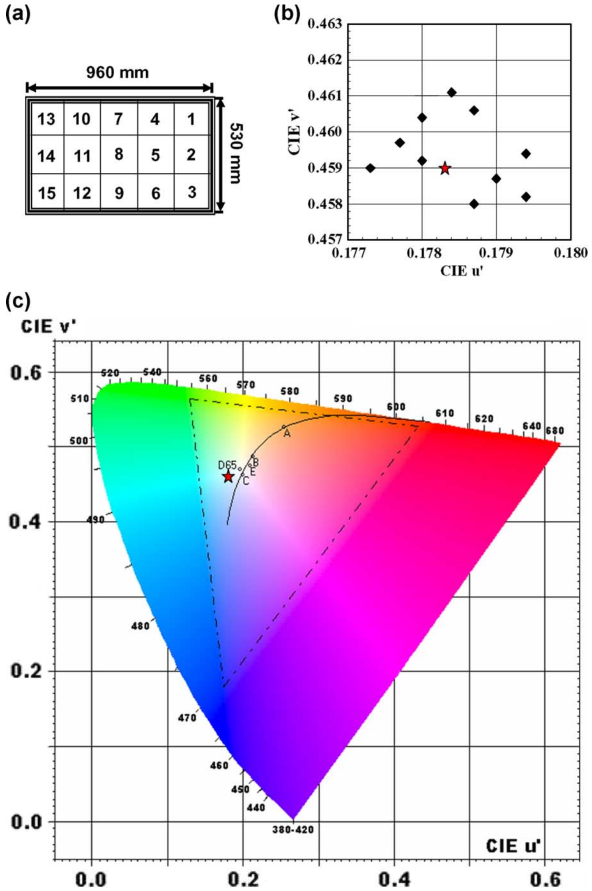

Fig. 11. Color uniformity of phosphor film coated by slot die coating technology. (a) Experimental film size; (b) Distribution of chromaticity index u′, v′; (c) The CIE 1976 chromaticity diagram. Red star denotes the white point of proposed UFL LCD.

phosphor film was coated by slot die coating and then divided into 15 partitions for u_i' and v_i' measurement [Fig. 11(a)]. The color deviation, $\Delta u'v'$ [see (5)] is limited to 0.015 for commercial display applications, which must have no perceptible color deviation. Fig. 11(c) presents the coordinate of the white point ($u' = 0.178$, $v' = 0.459$) of the proposed UFL LCD. Comparing the measured data with the white point reveals that the $\Delta u'v'$ varies from 0.001 to 0.002 in the overall 42-in display area [Fig. 11(b)]. Therefore, the experimental $\Delta u'v'$ performance indicates that the slot die coating can be scaled up steadily and applied in large LCD backlights. Meanwhile, slot die coating is a low-cost approach that supports fast manufacture and, therefore, economic mass production.

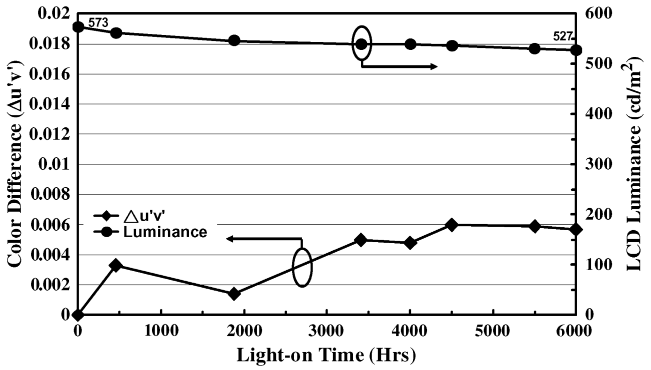

Fig. 12. Lifetime test result of UFL LCD.

C. *Lifetime Test*

One set of UFL LCD is arranged to conduct the lifetime test under a normal atmospheric temperature for 6000 hours (250 days) continually. After the test, the color deviation ($\Delta u'v'$) of white point is smaller than 0.006. Moreover, the luminance decay is only 8.03% ($573 \rightarrow 527$ cd/m^2), as shown in Fig. 12.

The experimental results proved the proposed UFL lighting system achieved a planar and uniform luminous distribution, low color deviation as well as high luminance, high color saturation, along with the configuration thickness reduced to 14.5 mm. Meanwhile, the test result ensured the proposed system can satisfy for commercial application.

VI. CONCLUSION

This work presents a novel planar lighting scheme that uses 254-nm wavelengths of UV light to excite a remote phosphor converter (RPC). This UFL LCD can yield a luminance of 573 cd/m^2, accompanied by 92% luminous uniformity with $\theta_{\mathrm{FWHM}} = \pm 46^\circ$, 92% NTSC with a color deviation of $\Delta u'v' < 0.002$. Additionally, the LCD thickness decreases to 14.5 mm, whereas LCD thickness with conventional direct-view BL is 30 mm. Moreover, the lifetime of UFL LCD has already been certified by a 6000 hrs lifetime test. The color deviation ($\Delta u'v'$) of white point is smaller than 0.006, and the luminance decay is only 8.03% after testing.

For fabrication, adopting slot die coating to prepare phosphor films is also an inexpensive means of achieving a high manufacturing speed for economical mass production. The slot die coating can be scaled up to other sizes by adjusting the coating film dimensions conveniently.

In conclusion, UFL LCD satisfies the requirements of large-size displays in terms of its high uniformity, low color deviation, slim configuration, high luminance, high color rendering ability, easy scalability for manufacturing and long lifetime performance.

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