# Ultraviolet excitation of remote phosphor with symmetrical illumination used in dual-sided liquid-crystal display

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The UV-excited flat lighting (UFL) technique differs from conventional fluorescent lamp or LED illumination. It involves using a remote phosphor film to convert the wavelength of UV light to visible light, achieving high brightness and planar and uniform illumination. In particular, UFL can accomplish compact size, low power consumption, and symmetrical dual-sided illumination. Additionally, UFL utilizes a thermal radiation mechanism to release the large amount of heat that is generated upon illumination without thermal accumulation. These characteristics of the UFL technique can motivate a wide range of lighting applications in thin-film transistor LCD backlighting or general lighting. © 2010 Optical Society of America

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The great diversity of future display applications, such as digital signage and public information displays, cannot all be based on single-sided LCDs. Dual-sided displays can create added value in public spaces, such as shopping centers, stations, and airports, by way of running two displays synchronously [1]. Conventionally, two sets of single-sided LCDs are installed back to back to display in two directions, as presented in Fig. 1(a). The occupied volume is very large; the system is heavy, thermal release is poor, and power consumption is high. Therefore, an LCD system with dual-sided screens has been studied by several research teams [2,3]. As presented in Fig. 1(b), this work constructs a novel lighting inside a dual-sided LCD system with symmetrical illumination. To reach uniform display performance, this illumination should irradiate light in two opposite surfaces brightly and uniformly.

When conventional light sources [such as fluorescent lamps (FLs) or LEDs] are used in a dual-sided illumination system, the elimination of a metal back holder and an optical reflector [compare Figs. 1(a) and 1(b)] from a single-sided backlight (BL) affect not only the uniformity of light distribution but also the dissipation of the large amount of heat that is generated by plural light sources. The elimination of the optical reflector causes a lack of reflected light, such that a dark area exists between the light sources. Accordingly, the light is not distributed uniformly. Additionally, removal of a metal back holder leads to the loss of thermal release by the thermal conduction mechanism. Hence, UV-excited flat lighting (UFL) is employed in this work as a solution to these problems of dual-sided lighting systems.

In this experiment, UV was applied to a UFL lighting system to ensure satisfactory dual-sided display. Because UV LED light sources cannot be produced efficiently, mercury vapor lamps was used to produce UV radiation in this work. The lamp was chosen to ensure the efficient conversion of UV rays with a wavelength of 254 nm. For UFL with a remote phosphor converter (RPC), Huang *et al.* revealed the experimental procedure related to the manufacturing of the samples [4]. To form the RPC plate, trichromatic phosphors were blended and then applied on a poly(methyl methacrylate) substrate by the slot die coating method.

In the proposed dual-sided lighting system [Fig. 1(b)], UV irradiates two opposite RPC plate surfaces and is converted into visible light. Moreover, the phosphor compound eliminates irradiation at wavelengths of 590 and 490 nm, achieving high color rendering, at 92% of the National Television System Committee (NTSC) standard [5] for digital signage applications with vivid color distributions. Additionally, UFL lighting reportedly yields high luminance uniformity, high brightness, compact configuration, low power consumption, and a long lifetime [4].

The optical characteristics of the dual-sided display are verified using 42 in. configurations of UFL lighting and FL lighting. The angular-luminance distribution was measured using the conoscopic [6] approach [Fig. 2(a)]. First, measurements were made at position A, the area above the lamp, and then the conoscope was moved to position B, in the area halfway between the lamps. Figures 2(b) and 2(c) trace the rays and plot the luminous distribution of FL lighting in a dual-sided illumination sample. Figures 2(d) and 2(e) present the optical behavior of a UFL-illuminated sample.

Ray tracing for FL illumination [Fig. 2(b)] reveals that the normally transmitted beam (L1), which is in the direction of the incident beam, is the strongest ray at position

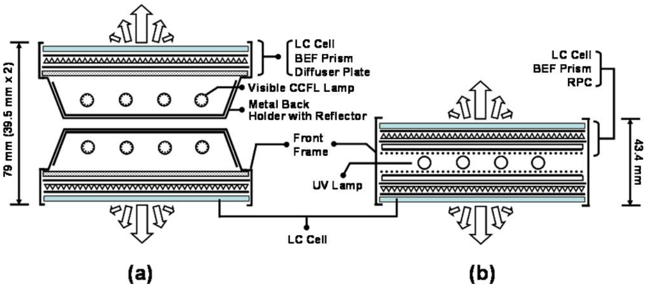

Fig. 1. (Color online) Dual-sided application constructed by (a) a conventional pair of single-sided displays applied back to back and (b) a UFL dual-sided display.

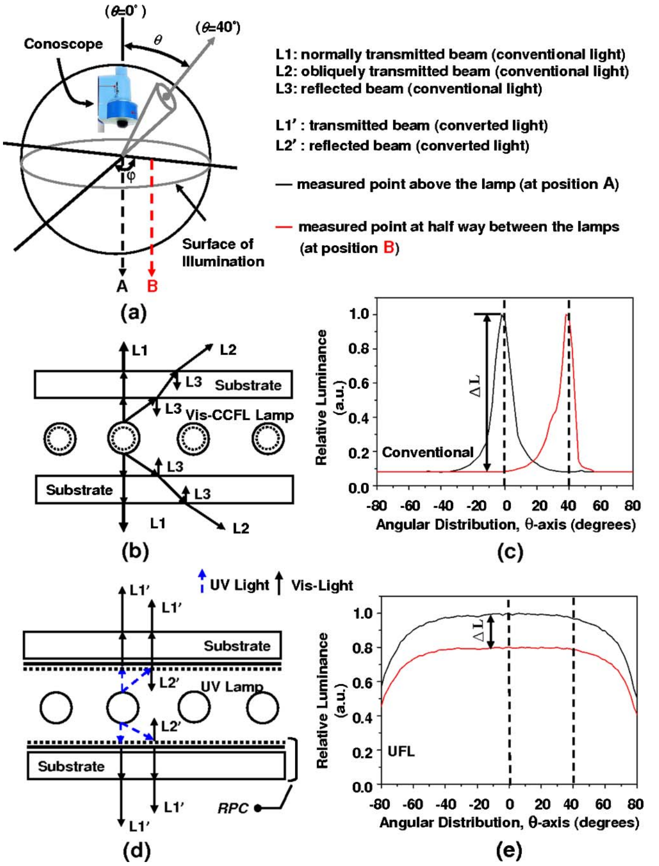

Fig. 2. (Color online) (a) Construction of angular-luminance distribution measurement. (b) and (c) show the ray tracing and luminous distribution of FL dual-sided illumination, and (d) and (e), of UFL illumination.

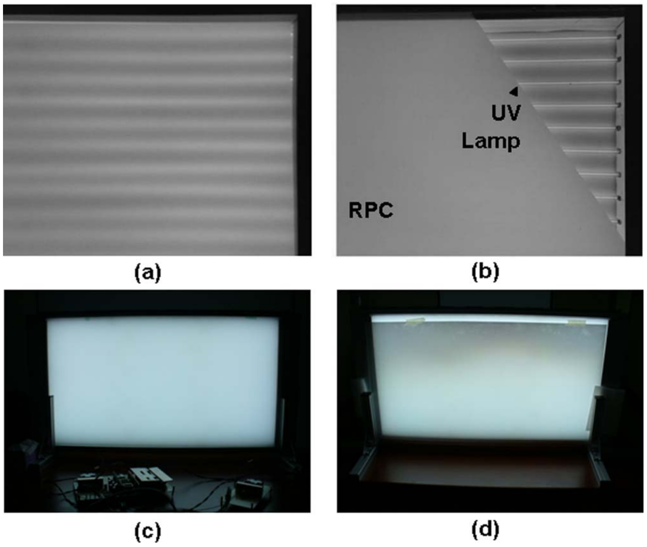

Fig. 3. (Color online) Luminous distribution of dual-sided illumination: (a) FL lighting, (b) UFL lighting; (c) UFL front view, (d) UFL back view.

A. In contrast, the reflected beam (L3) is weak at position B, when observed at the $\theta = 0°$ direction. By the same rules as were applied to the case of UFL dual-sided illumination [Fig. 2(d)], the transmitted beams (L1′) are all normal to the illuminated surface at both positions A and B. The L1′ are also associated with reflected beams (L2′), which illuminate the dark area at position B.

The luminous distribution at positions A and B when $\theta = 0°$ (normal view) is compared with that at $\theta = 40°$ (oblique view). Under FL illumination [Fig. 2(c)], the relative luminance at position A is higher and that at position B is lower when observed at $\theta = 0°$. Similarly, the relative luminance is lower at position A and higher at position B when observed at $\theta = 40°$. Large luminance difference ($\Delta L$) causes the nonuniform luminance distribution (lamp mura). However, in UFL dual-sided illumination [Fig. 2(e)], a slight $\Delta L$ between positions A and B exist at both $\theta = 0°$ and 40°. Therefore, dual-sided UFL illumination can eliminate undesired lamp mura by light conversion over a complete RPC surface with Lambertian distribution. Uniform luminance is achieved without the use of optical reflectors. Figure 3 demonstrates the luminous distribution of dual-sided illumination by FL lighting [Fig. 3(a)] and by UFL lighting [Fig. 3(b)].

Figures 3(c) and 3(d) show a construction of 42 in. dual-sided UFL illumination. When this illumination is combined with two thin-film transistor LCD panels with 4.5% transmittance, the dual-sided display can provide an average luminance of 567 cd/m$^2$. The total power consumption is 245 W. Table 1 summarizes the UFL dual-sided display features and compares them with those of a conventional pair of single-sided displays applied back to back. The UFL dual-sided display has luminous uniformity of 92% at a small module thickness of as low as 43.4 mm. It reduced the volume by 45% and the weight by 50% because of the removal of the metal back holders and its simple optomechanical construction. The power consumption is reduced by 30% because a smaller number of lamps is used (40 to 22 pieces). Additionally, the resulting color gamut reaches 92% of the NTSC standard.

In a UFL dual-sided display, the metal back holder that is used in a single display is removed. In conventional single-sided FL BL, the metal back holder was considered to release the heat from the lamps by a thermal conduction mechanism. The most popular metal back holder material is aluminum, which has a thermal conductivity of 237 W/m·K. This material is, therefore, a good thermal conductor. However, in our proposed structure, there is no metal back holder. Two RPC plates,

**Table 1. Comparison of Different Dual-Sided Displays**

| | Dual-Sided Display (Back-to-Back Installation) | UFL Dual-Sided Display | Improvement |
|---|---|---|---|
| LCD weight | 30 kg | 15 kg | 50% |
| LCD thickness | 79.0 mm | 43.4 mm | 45% |
| Power consumption | 350 W | 245 W | 30% |
| Lamp number (piece) | 40 | 22 | — |
| Luminance | 527 cd/m$^2$ | 567 cd/m$^2$ | 8% |

**Table 2. Comparison of Measured Temperature of Conventional Single-Sided Display with UFL Dual-Sided Display**[a]

| | $\Delta T$ | Top Surface of Display | Metal Back Holder | Inside the Illumination |
|---|---|---|---|---|
| Single-sided display | 2.8 °C | 40.0 °C | 47.0 °C | 53.9 °C |
| UFL dual-sided display | 2.0 °C | 38.9 °C | — | 52.2 °C |

[a] Power consumption, 245 W; ambient temperature, 25 °C.

which are plastic with a low thermal conductivity of $6\ \mathrm{W/m \cdot K}$, were placed on both sides of the UV lamps. Therefore, the thermal releasing mechanism from the RPC plates has to be analyzed. According to a prior report [7], the thermal emissivity ($\varepsilon$) of a plastic plate is 0.94 and that of a metal is 0.22. The equation of thermal radiation power, $P_{\mathrm{RAD}}$, is expressed as follows:

$$P_{\mathrm{RAD}} = \sigma \varepsilon (A) T^4, \tag{1}$$

where $\sigma$ denotes the Stefan–Boltzmann constant, $\varepsilon$ denotes the thermal emissivity, $(A)$ denotes the radiation area, and $T$ denotes the absolute temperature. From Eq. (1), thermal radiation dominates the thermal release from a UFL dual-sided display because the radiation area $(A)$ is double that of a conventional single-sided display.

A computational fluid dynamic tool, FloTHERM, and a thermal IR camera, FLIR, are adopted to analyze the thermal distribution of experimental displays. As Figs. 4(a) and 4(b) show, the variation in color represents the thermal distribution of the display. A low and uniform thermal distribution was expected across the display. Afterward, the temperature variation ($\Delta T$) is defined as

$$\Delta T = T_{\max} - T_{\min}. \tag{2}$$

The thermal radiation mechanism from a UFL dual-sided BL yields a lower temperature variation ($\Delta T = 2.0$ °C) compared with the thermal conduction mechanism in a conventional single-sided BL ($\Delta T = 2.8$ °C). Moreover, the single-sided BL also reveals a higher metal back holder temperature (47.0 °C). Table 2 presents the temperature measured in practice using T-type thermocouples at an ambient temperature of 25 °C. (Power supplies to both BLs were 245 W). The data indicate that the UFL dual-sided display has a lower top surface temperature (38.9 °C) than that of conventional single-sided display (40.0 °C), and the temperatures inside of the UFL lighting are also lower (52.2 °C < 53.9 °C). These data indicate that the thermal radiation mechanism can efficiently release heat from the UFL dual-sided display when compared with the thermal conduction mechanism of conventional single-sided display.

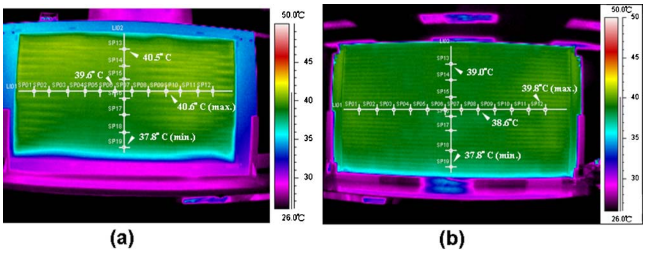

Fig. 4. (Color online) Thermal distribution regarding (a) FL dual-sided BL, (b) UFL dual-sided BL.

In summary, the UFL dual-sided technique effectively eliminates the dark area between lamps, yielding a symmetrical, dual-sided illumination without the need for conventional optical reflectors. The UFL dual-sided display can yield a brightness of $567\ \mathrm{cd/m^2}$, with a luminous uniformity of 92% and a color gamut of 92% NTSC. It perfectly satisfies the optical requirement for display applications. The thickness is 45% lower (79.0 to 43.4 mm); the weight is 50% lower (30 to 15 kg), and the power consumption is 30% lower (350 to 245 W) than those of a conventional pair of single-sided displays applied back to back. The mechanism of thermal radiation from the UFL dual-sided system can replace the conventional thermal conduction mechanism, lowering the temperature both on the surface (38.9 °C) and inside (52.2 °C) the illumination system without thermal accumulation. Consequently, the proposed UFL dual-sided illumination was successfully demonstrated for dual-sided display applications with high optical, thermal, and mechanical performance.

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