Planar Lighting System Using Array of Blue LEDs to Excite Yellow Remote Phosphor Film

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

***Abstract*—This investigation demonstrates a novel light-emitting system with an array of blue light-emitting diodes (LEDs). Unlike a conventional lighting system that is constructed from white LEDs, the proposed planar lighting system uses blue LEDs to excite a YAG : Ce^{3+} yellow phosphor film remotely, yielding a high lumen efficiency with uniform and planar light-emission. The phosphor film herein acts as a wavelength converter and a light diffuser simultaneously. The optical properties of the proposed lighting system, angular color deviation and light-emitting uniformity, are studied. Eventually, a high lumen efficiency (73.0 lm/W) and thin lighting module (7.5 mm-thick) was demonstrated without the use of any conventional diffuser plate or light guiding plate (LGP). A low color deviation $(\Delta u'v' = 0.025)$ and a high light-emitting uniformity $(\mathrm{U_{niformity}} = 82\%)$ were achieved. Hence, the proposed lighting system exhibited superior optical performance using a compact module.**

***Index Terms*—Angular color deviation, indium gallium nitride (InGaN), light-emitting diodes (LEDs), phosphor, remote phosphor, yttrium aluminum garnet (YAG).**

I. INTRODUCTION

IN RECENT years, white light-emitting diodes (wLEDs) have become more important sources of illumination in TFT-LCD backlighting (BL) and general lighting applications than conventional incandescent, fluorescent (hot cathode or cold cathode) or halogen lamps, because wLEDs are compact, mercury-free, and energy-efficient [1], [2]. However, in conventional wLEDs, phosphor is dispersed in an epoxy resin that surrounds the LED die [seeFig. 1(a)]. Since the phosphor is close to the LED die in the wLEDs package, a significant proportion of the blue light is backscattered by the phosphor and lost by absorption of the LED chips [3]–[5]. Additionally, the high temperature of an operating wLEDs causes thermal quenching, which reduces the light radiation efficiency of the YAG phosphor and the InGaN blue LEDs [6], [7]. Hence, the placing phosphor away from the die, as in a remote phosphor converter (RPC), has been developed to increase lumen efficiency [Fig. 1(b)]. The RPC method enables the backscattered photons to be extracted and the effect of thermal quenching to be reduced, increasing the ultimate overall light output and lumen efficiency [8].

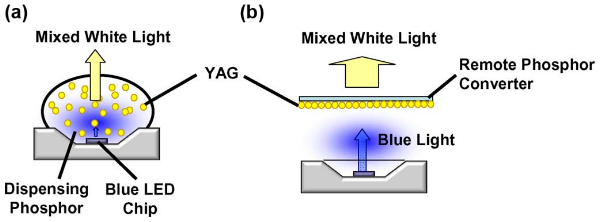

Fig. 1. Schematically depicts the packing method of LED. (a) Package of dispensing phosphor. (b) Package of remote phosphor.

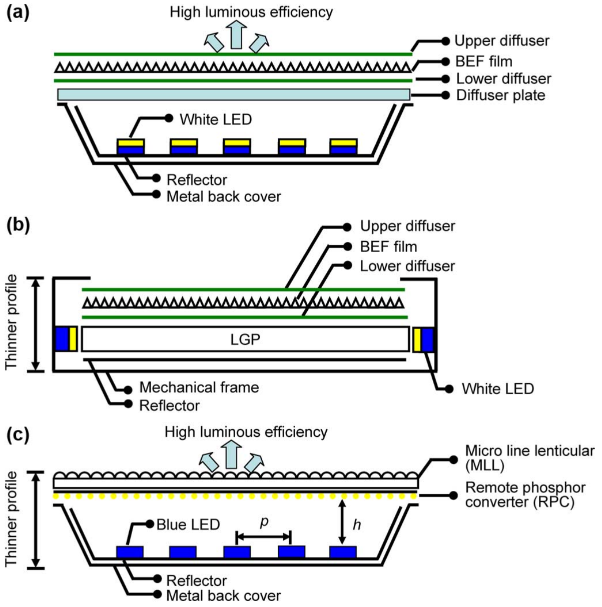

Fig. 2. LED lighting system. (a) Typical direct-emission. (b) Typical edge-emission. (c) Proposed light-emission system constructed by RPC and MLL.

Earlier studies have shown that RPC method can significantly improve the lumen efficiency of a single wLEDs package [9]–[11]. However, studies of the application using the RPC method to large-area illumination are relatively few. Conventional planar lighting herein has been developed by exploiting direct-emission using a diffuser plate [Fig. 2(a)] or edge-emission using a light guiding plate (LGP) [Fig. 2(b)]. Direct-emission yields high lumen efficiency in lighting systems, while edge-emission is more suitable for the application of thin module configurations. These approaches cannot easily support high lumen efficiency and a thin lighting module simultaneously. Therefore, the use of an array of blue LEDs to excite a remote yellow RPC film and generate an area of white light distribution is demonstrated herein. In this study, the optical characteristics of RPC lighting system are studied. Subsequently, a thin lighting module with high lumen efficiency,

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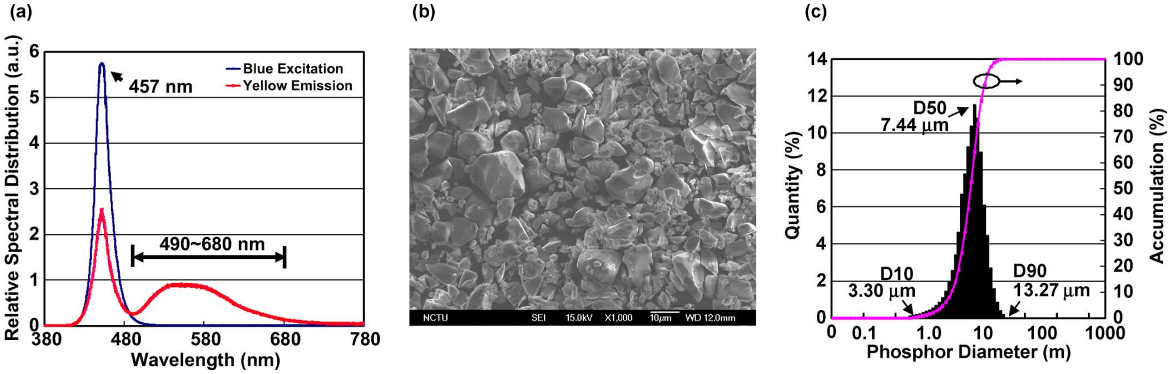

Fig. 3. (a) Spectral properties of the blue excitation and yellow emission. (b) SEM morphology of YAG : Ce^{3+} phosphor. (c) Size distribution of phosphor particles.

high brightness, uniform luminance and low color deviation is proposed, providing as a planar lighting system. It can be used in a wide range of TFT-LCD BL applications.

II. EXPERIMENTS

This section elucidates the experimental component of a remote phosphor converter (RPC), the manufacturing method and the configuration of proposed lighting module.

A. *Remote YAG Phosphor Film*

The phosphor powder that was used in this experiment was a cerium-doped yttrium aluminum garnet ($\mathrm{YAG}:\mathrm{Ce}^{3+}$) with a wavelength distribution (irradiating wavelengths of 490 $\sim$ 680 nm). [Fig. 3(a)]. As show in Fig. 3(b), phosphor powder has an irregular morphology. The mean size of phosphor particles (D50) is 7.44 μm [Fig. 3(c)]. An indium gallium nitride (InGaN)-based blue LED, which emits a wavelength of 457 nm, is applied to excite $\mathrm{YAG}:\mathrm{Ce}^{3+}$ phosphor and white light is generated by mixing these complementary colors.

B. *Phosphor Film Coating Process*

Fig. 4(a) schematically depicts the process of phosphor coating by conventional dispensing method. Firstly, pulverized phosphor powder is blended, using a formulation mixer, with a silicone binder and an organic solvent to form a uniform phosphor suspension slurry. After that, this slurry is applied to the cavity of an LED package. It drops onto the surface of a blue nitride LED chip.

However, the RPC film is prepared by slot die coating method [12]–[14]. Fig. 4(b) displays a simplified film preparing process. Firstly, the slurry of phosphor is applied to a polyethylene terephthalate (PET) film. The thickness of the applied phosphor layer can be varied from 10 to 40 μm to control the color temperature (Tc) of white light from 9500 to 3000 K. Next, the phosphor film adheres to a plastic substrate to form a RPC. Properly positioning the RPC in the lighting module can reduce the heating by the light source, such that the phosphor coating has a high lumen efficiency and long lifetime.

Fig. 5(a) shows the phosphor film that was prepared by the slot die coating method. Fig. 5(b) reveals that the morphology of phosphor film is irregular and full of voids. Table I presents the optical characteristics of the RPC film. This structure, with a high haze ratio, is especially effective at scattering incident light. Hence, it can be used for simultaneous wavelength conversion and light diffusion.

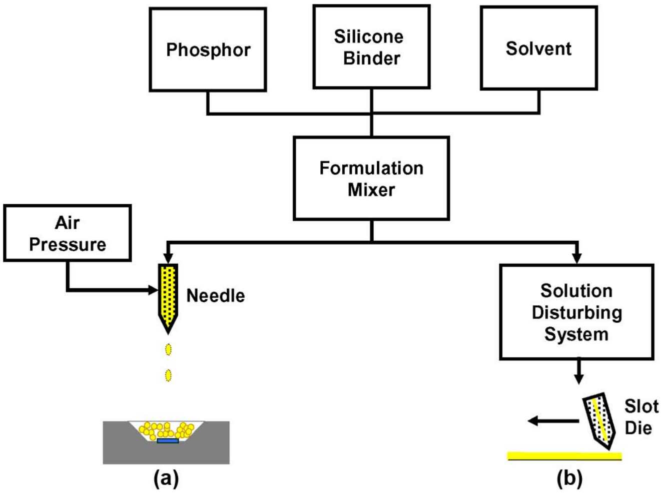

Fig. 4. Schematic diagram of the phosphor coating process. (a) Conventional dispensing method. (b) Slot die coating on film.

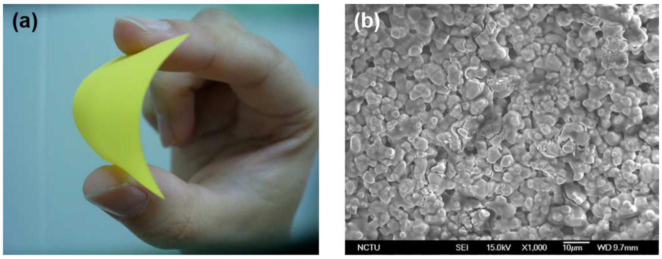

Fig. 5. Views of phosphor film coated by slot die coating. (a) Appearance. (b) SEM micrograph.

C. *Lighting Module Configuration*

As shown in Fig. 6(a), the lighting module size in this experiment is 7 inch-diagonal and the thickness is variable for evaluation. Blue LEDs are directly mounted on the substrate. The total input power of this lighting system is 28 $\mathrm{V_{DC}}$ at 150 mA and the power consumption is 4.2 W. Next, optical sheets using micro line lenticular (MLL) structure (Fig. 7) are exploited to integrate with the RPC film and blue LEDs light source in this experiment. As presented in Fig. 6(b), MLL structure along the

TABLE I
OPTICAL CHARACTERISTICS OF RPC

HZ[1]	**TT**[2]	**DF**[3]	**PT**[4]
99.29	**68.5**	**68.02**	**0.49**

unit: (%)

[1] HZ: haze ratio, $\mathrm{HZ} = (\mathrm{DF}/\mathrm{TT}) \times 100\%$

[2] TT: transmittance of total output light;

[3] DF: transmittance of diffused light;

[4] PT: transmittance of parallel light;

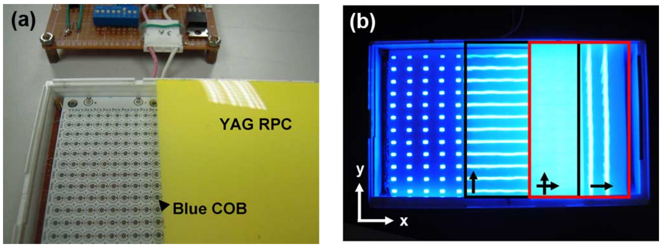

Fig. 6. (a) The lighting module integrates an array of blue LEDs with YAG RPC layer; (b) the obverse view of RPC coupled with two sheets of micro line lenticular (MLL) array (arrow marked the structural direction on MLL).

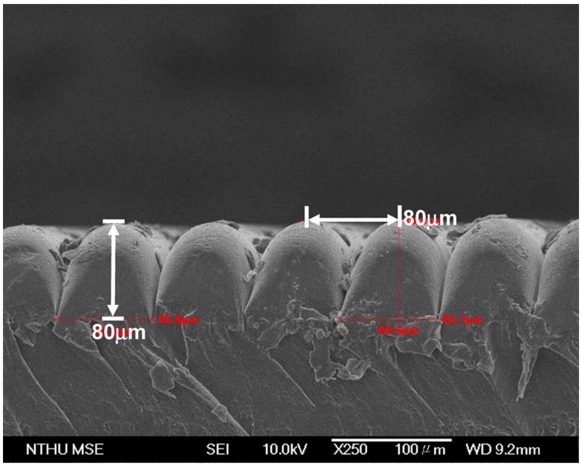

Fig. 7. The SEM picture of the plastic substrate with micro line lenticular (MLL) arrays. (pitch: 80 μm, height: 80 μm).

y-axis can convert the light from an array of point LEDs into horizontal light. MLL along the x-axis can yield vertical light; crossed MLL can yield planar blue light to excite the assembled YAG RPC. In Fig. 6(b), the arrow-mark indicates the direction of the MLL structure. MLL arrays are not only functional for the improvement of on-axis luminance, but also contribute to luminous distribution in this lighting module configuration.

III. THEORETICAL MODELING AND OPTIMIZATION

The optical mechanism of the RPC method will be modeled as it differs from that of illumination by conventional wLEDs. Because of the complexity of the experiments, theoretical calculations will be made and a simulation model established to determine the values of the parameters LED gap (h) and LED pitch (p) [refer to Fig. 2(c)], that optimize an RPC lighting system. Subsequently, a mockup sample that uses the RPC method will be demonstrated to achieve high lumen efficiency when applied in an ultra-slim lighting module.

A. Measurement of Light-Emission in RPC Method

In the RPC lighting system, light scattering and light converting occur simultaneously, as presented in Fig. 8. The diffused blue light and the excited yellow light were measured separately in this experiment to identify the optical mechanism of RPC method, owing to these two kinds of lights with different light distribution. The optical characteristics of the RPC lighting system are described using bidirectional scatter distribution functions (BSDFs). The BSDFs is typically split into reflected and transmitted components, which are treated separately as the bidirectional transmittance distribution functions (BTDFs) and the bidirectional reflectance distribution functions (BRDFs) [15], [16].

When the blue light radiated from LEDs to excite the RPC, some of the incident blue light are converted to yellow light with Lambertian distribution [Fig. 8(b)]. The rest of the incident blue light is diffused [Fig. 8(a)], and Fig. 8(d) and (e) represents the reflective distribution of blue light and yellow light, respectively. Finally, these rays are mixed to generate a white light distribution with broad angular distribution (Fig. 9, blue line). By these measured BTDFs and BRDFs results, the RPC method could be characterized to develop the light-emitting mechanism.

B. Optimized Configuration of Lighting Module

The optimal parameters of RPC configuration like LED gap (h) and LED pitch (p) are difficult to determine the relationship with luminous distribution. Therefore, we setup an optical simulation model used light-emitting mechanism of RPC method to predict the optimal configuration. Firstly, the light-emitting properties of RPC could be characterized by the measured BTDFs and BRDFs. In order to simplify the analysis, we restrict the discussion to the transmitted type (BTDFs). Certainly, the study can be easily applied to the reflective type (BRDFs) without loss of generality. The BTDFs is defined as

$$\mathrm{BTDFs}(\theta_\mathrm{i}, \phi_\mathrm{i}, \theta_\mathrm{t}, \phi_\mathrm{t}) = \frac{\mathrm{L_t}(\theta_\mathrm{t}, \phi_\mathrm{t})}{\mathrm{E_i}(\theta_\mathrm{i}, \phi_\mathrm{i})} \tag{1}$$

where E_i is the illuminance on the sample plane due to the incident blue-light; L_t stands for the luminance of emitted light from the sample surface. The incident and emitted angles are represented by the coordinates of (h, θ_i, ϕ_i) and (h, θ_t, ϕ_t), where h, θ and ϕ denote the radius, zenith angle, and azimuthal angles in spherical coordinate, respectively. Since the scattering characteristics of RPC caused by the randomly distributed phosphor are rotationally symmetric, the data processing of BTDFs can be simplified by merely considering the variance of zenith angle θ along a constant azimuthal angle, $\phi = 90°$.

There are four parameters of the RPC lighting configuration regarding the theoretical calculation: 1) the BTDFs of RPC; 2) the intensity distribution (I_s) of LED chips; 3) the LED gap (h); and 4) the LED pitch (p). Through the definition of photometric (Fig. 10), the illuminance (E_i) of the RPC at point P excited by the blue light can be calculated as

$$\mathrm{E_i}(\theta_\mathrm{i}, \phi_\mathrm{i}) = \frac{\mathrm{I_s}(\theta_\mathrm{i}, \phi_\mathrm{i}) \cdot \cos^3 \theta_\mathrm{i}}{\mathrm{h}} \tag{2}$$

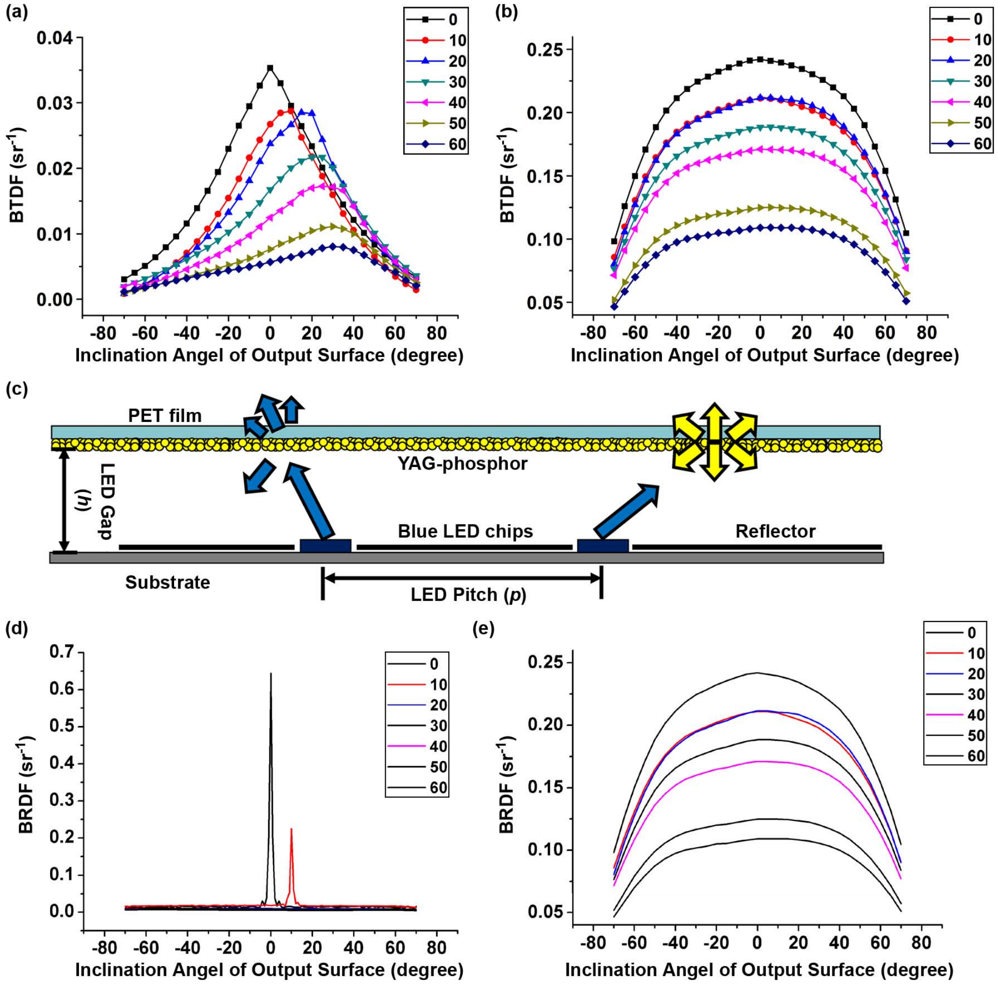

Fig. 8. Measured BTDFs result of: (a) diffused blue light; (b) up-converted yellow light; and (c) light-emitting mechanism of RPC lighting system. Measured BRDFs result of: (d) reflective blue light and (e) down-converted yellow light.

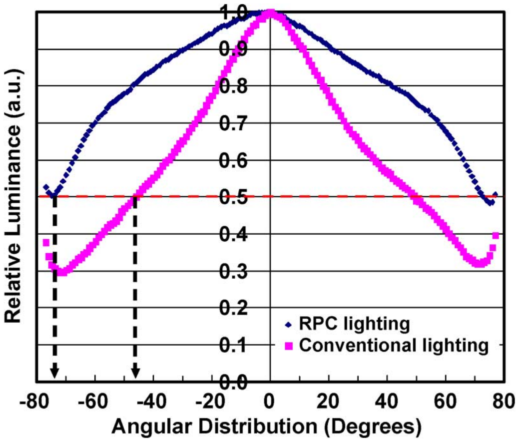

Fig. 9. Comparison of luminance in angular distribution between conventional wLEDs lighting and RPC lighting.

Then, the emitted luminance (L_t) from the RPC at the point P can be transferred from (1) as

$$\mathrm{L_t}(\theta_\mathrm{t},\phi_\mathrm{t}) = \int_{\Omega_\mathrm{i}} \mathrm{BTDFs}(\theta_\mathrm{i},\phi_\mathrm{i},\theta_\mathrm{t},\phi_\mathrm{t})\cdot \mathrm{E_i}(\theta_\mathrm{i},\phi_\mathrm{i})\mathrm{d}\omega_\mathrm{i}$$

$$= \int_{\Omega_\mathrm{i}} \mathrm{BTDFs}(\theta_\mathrm{i},\phi_\mathrm{i},\theta_\mathrm{t},\phi_\mathrm{t})\frac{\mathrm{I_s}(\theta_\mathrm{i},\phi_\mathrm{i})\cdot\cos^3\theta_\mathrm{i}}{\mathrm{h}}\mathrm{d}\omega_\mathrm{i}. \tag{3}$$

Finally, the total radiating luminance (L_{output}) from the RPC lighting system can be calculated by the convolution between the single LED luminance (L_t) and a two-dimensional comb function as

$$\mathrm{L_{output}}(\theta_\mathrm{t},\phi_\mathrm{t}) = \sum_\mathrm{n}\sum_\mathrm{m}\left[\int_{\Omega_\mathrm{i}} \mathrm{BTDFs}(\theta_\mathrm{i},\phi_\mathrm{i},\theta_\mathrm{t},\phi_\mathrm{t}) \cdot\frac{\mathrm{I_s}(\theta_\mathrm{i},\phi_\mathrm{i})\cdot\cos^3\theta_\mathrm{i}}{\mathrm{h}}\mathrm{d}\omega_\mathrm{i} * \delta(\mathrm{a}-\mathrm{np},\mathrm{b}-\mathrm{mp})\right] \tag{4}$$

where the counting number n and m indicate the nth and mth LED along a and b direction, respectively. In this case, the summation and integration were performed by Monte Carlo simulation [17].

Then, we import the measured BSDFs into the commercial software LightTools to accomplish the optical simulation of RPC lighting system. In order to keep the luminous uniformity of lighting system as the first merit, the ratio (h/p) of LED gap

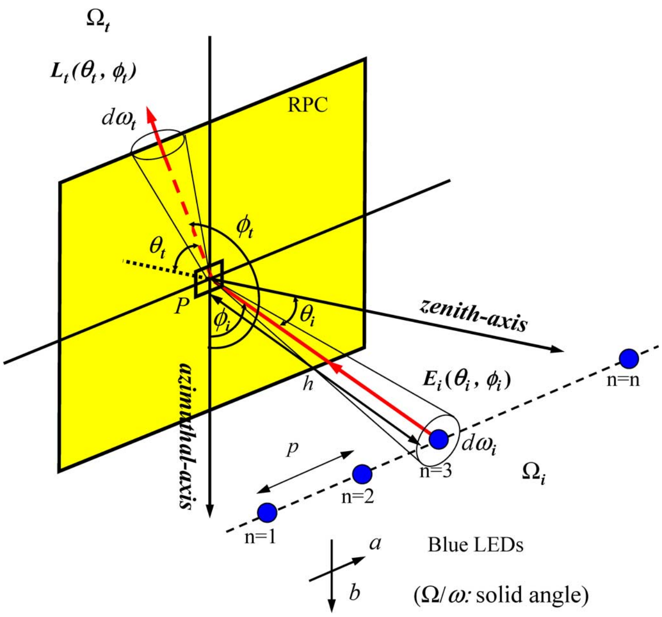

Fig. 10. Definition of photometric in this theoretical calculation.

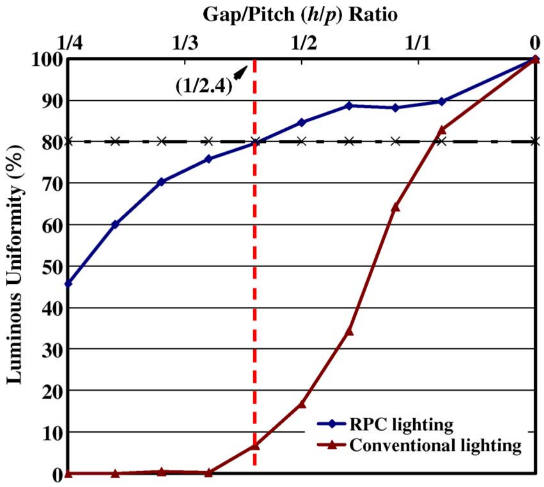

Fig. 11. Comparison of luminous uniformity ($\mathrm{U_{niformity}}$) with (h/p) ratio.

(h) to the LED pitch (p) were modulated as parameter to simulate the relationship with luminous uniformity ($\mathrm{U_{niformity}}$). The definition of $\mathrm{U_{niformity}}$ is as

$$\mathrm{U_{niformity}} = \left.\frac{\mathrm{L_{output,min}}}{\mathrm{L_{output,max}}}\right|_{\theta_t=0} \times 100\% \tag{5}$$

which is the luminous ratio of the positions with the minimum luminance and the maximum luminance at the normal viewing direction ($\theta_t = 0^\circ$) of lighting system.

The simulated results are shown in Fig. 11 to compare the conventional wLEDs lighting with the RPC lighting. The target of luminous uniformity is set at 80% to keep an acceptable vision quality [18], [19]. The smaller LED gap (h) and larger LED pitch (p), the luminous uniformity is worse. The acceptable ratio (h/p) of RPC lighting by simulated result is (1/2.4).

IV. Display Performance and Applications

The RPC method reportedly has a higher lumen efficiency than conventional phosphor coating methods when applied to individual LED packages [9]–[11]. However, the applications at TFT-LCD backlighting and display performance of the RPC method have not been comprehensively explored. Therefore, the factors that affect the color temperature (Tc), angular color deviation ($\Delta u'v'$) and luminous uniformity of an ultra-slim RPC lighting system are analyzed herein.

A. Color Temperature

This study will investigate such parameters as the thickness of the phosphor layer, the LED gap (h) and the LED driving current to elucidate their relationships with color temperature (Tc) of using the RPC method.

Experimental results [Fig. 12(a)] reveal that adjusting the thickness of the phosphor coating can change the ratio of yellow to blue light intensities. Point C corresponds to a thick phosphor layer (38 μm) with a high percentage of yellow light, and a Tc of 3765 K. Point A corresponds to the low phosphor thickness (11 μm) with a high percentage of blue light, and a Tc of 9487 K. The LED driving current is also investigated. Fig. 12(b) indicates that Tc is unrelated to the LED driving current when the tested current is less than the maximum LED current rating (320 mA).

As presented in Fig. 12(c), the LED gap (h) affects the Tc of an RPC lighting system. When the LED gap (h) increases, the converted yellow light decreases greatly than the excited blue light. Hence, the lower proportion of yellow light results in Tc to increase. As the LED gap (h) increases, the lumen flux declines exponentially (Fig. 12(d)). Therefore, the LED gap (h) in this study was kept under 10 mm to maintain a high lumen flux. A small LED gap (h) also avails the design of ultra-slim modules too.

B. Ultra-Slim and Luminous Uniformity

As a result of the phosphor particles inside the RPC are stacked with voids during coating [Fig. 5(b)], the air contained in the voids is easily to cause the light scattering. Therefore, the function of RPC is similar to a diffuser with a high haze value (Table I) and contributes to thin the thickness of lighting system. Fig. 8(a) shows the light distribution of transmitted blue light with diffusing characteristics. Moreover, the converted yellow light reveals a Lambertian distribution [Fig. 8(b)]. Then, the mixing rays display a broader angle of full-width at half-maximum, $\theta_{\mathrm{FWHM}} = \pm 74^\circ$, subsequently contributing to reduce the lighting module thickness than with conventional lighting system by wLEDs, $\theta_{\mathrm{FWHM}} = \pm 48^\circ$ (Fig. 9).

Additional, the cross MLL sheets integrates with RPC also contributes to luminous uniformity too [Fig. 6(b)]. A cross MLL sheets can achieve a planar and uniform blue light-emitting before exciting the RPC. Eventually, a broader θ_{FWHM} associated with planar blue light-emitting can contribute to the luminous uniformity of RPC lighting system.

Finally, the RPC lighting system is verified by a sample and reveals a uniform luminous quality perfectly under ultra-slim lighting configuration (7.5 mm thick, h/p ratio of 1/2.4) without the use of conventional diffuser plate or light guide plate (LGP). The luminous uniformity of conventional lighting at the same

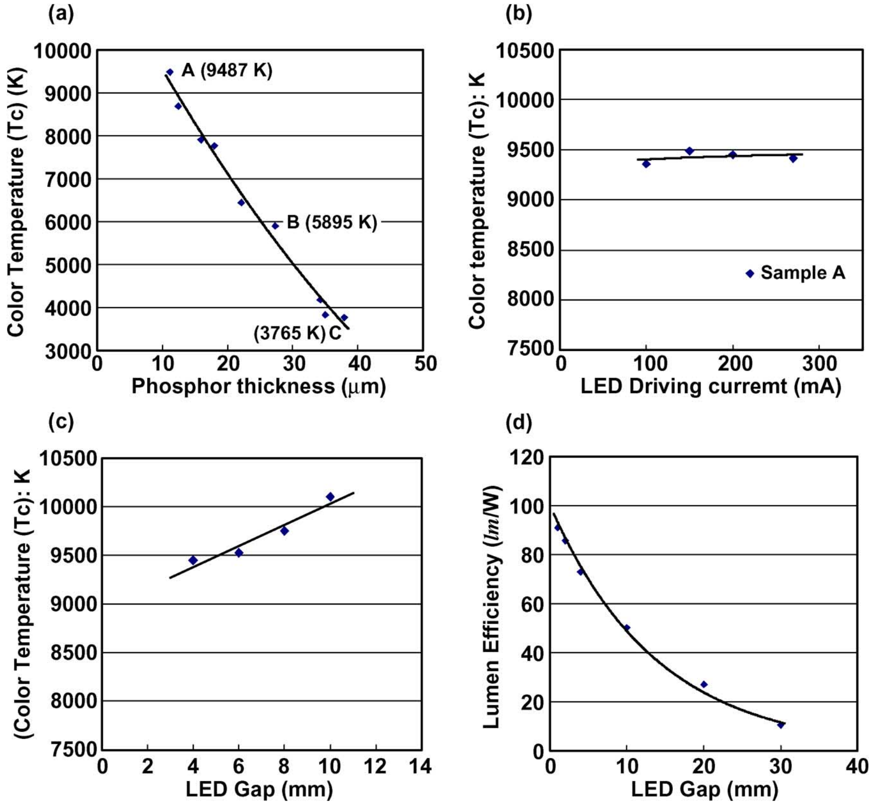

Fig. 12. Relationship between Tc and (a) phosphor thickness; (b) LED driving current; (c) LED gap; and (d) Relationship of lumen efficiency with LED gap.

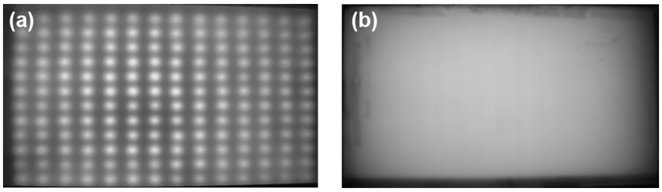

Fig. 13. The comparison of luminous uniformity at thin lighting module (7.5 mm thick, h/p ratio equals to 1/2.4). (a) Conventional wLEDs lighting and (b) RPC lighting integrated with MLL sheets.

condition demonstrates a luminous uniformity $(U_{niformity}) = 12\%$ (Fig. 13(a)). At the same situation, the RPC lighting can reach $U_{niformity} = 82\%$ [Fig. 13(b)].

C. Angular Color Deviation

To evaluate the angular color deviation of an RPC lighting system, the conoscopic approach is applied to measure the optical characteristics from varied viewing angle [Fig. 14(a)]. The zenith-axis is assumed to be the surface normal. The zenith angle θ) and the azimuthal angle (ϕ) are varied from $\theta = -60°$ to $+60°$ and $\phi = 0°$ to $360°$ in measurement, respectively. For the compared of conventional wLEDs lighting system with RPC lighting system, Fig. 14(b) and (c) plots the color distribution over the angular distribution in diagram of CIE 1976, respectively. The color deviation of a lighting system, $\Delta u'v'$, is limited to 0.015 for commercial display applications, which must have no perceptible color deviation.

For conventional wLEDs lighting, the color deviation at various viewing angles is serious [Fig. 14(b)]. It comes from the dispensing of phosphor slurry onto the LED surface is easily delaminated by gravity before cured. The experimental $\Delta u'v'$ value reveals that the conventional wLEDs lighting yields a worse color spatial uniformity (Fig. 14(b), $\Delta u'v' = 0.098$) than does the RPC lighting system $(\Delta u'v' = 0.025)$. Meanwhile, Fig. 14(d)-(f) compared the spectral properties between point X $(\theta = 0°, \phi = 0°)$ and point Y, Y' $(\theta = 60°, \phi = 0°)$ of tested lighting system.

For conventional lighting, the portion of yellow light increase when the zenith angle (θ_i) increase from $\theta = 0°$ to $\theta = 60°$ [compared Fig. 14(d) and (e)]. It causes the illuminated white light with a yellow ring at large light-emitting angle. Comparatively, RPC method indicates less increase of yellow portion [compared Fig. 14(d) & (f)] and revealed a low color deviation [Fig. 14(c)]. Therefore, the proposed RPC lighting system allows the accurate control of color distribution for high-quality illumination applications.

D. Display Application

Eventually, Table II makes an optical comparison of these two types lighting system at Tc around 9500 K. While the RPC lighting system combines with TFT-LCD panel (4.5% transmittance), a high-quality display can be achieved (Fig. 15(a)). It integrates the slim feature into the direct-emission backlighting with high lumen efficiency. The volume of the TFT-LCD configuration can be reduced to 7.5 mm thick without deteriorating the optical behavior (Fig. 15(b)), the lumen efficiency is 12.8% higher (64.7–73.0 lm/W) than those of a conventional wLEDs lighting system, the color deviation is under $\Delta u'v' = 0.025$, and

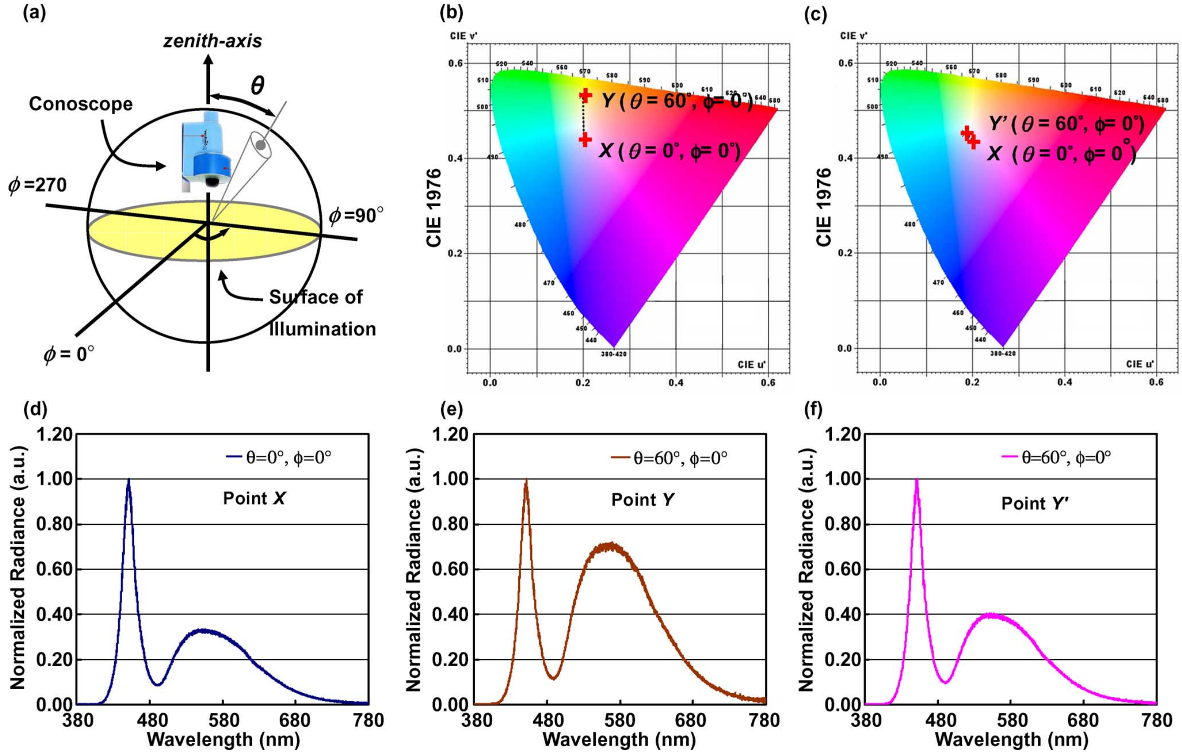

Fig. 14. (a) Measurement of optical characteristics by conoscopic approach. The color distribution of (b) conventional wLEDs lighting system; (c) RPC lighting system when view angle varies from $\theta = 0^\circ$ to $\theta = 60^\circ$ at fixed $\phi = 0^\circ$. (d) The spectral properties of both conventional and RPC lighting at view point of $\theta = 0^\circ$, $\phi = 0^\circ$. The spectral properties of (e) conventional wLEDs lighting system; (f) RPC lighting system at $\theta = 60^\circ$, $\phi = 0^\circ$.

TABLE II

OPTICAL COMPARISON OF TFT-LCD DISPLAYS USING CONVENTIONAL LIGHTING AND RPC LIGHTING[a,b,c]

	Color Index		Color Temperature	Color Deviation	Luminous Uniformity	Average Luminance	Lumen Efficiency
	Cx	*Cy*	(T_c: K)	*Δu'v'*	$\mathrm{U}_{\text{niformity}}$	(cd/m^2)	*(lm* /W)
Display using RPC lighting	0.280	0.300	9487	0.025	82%	504	73.0
Display using conventional wLEDs lighting	0.287	0.286	9364	0.098	12%	474*	64.7

[a] Display size: 7″ diagonal, 7.5 mm thick (backlighting: direct-emission type).

[b] Power consumption: 4.2 W; TFT-LCD panel with 4.5% transmittance, color gamut: 72% NTSC.

[c] Conventional lighting system and RPC lighting system use the same specifications of blue LEDs and phosphor.

*474 cd/m^2 refers to the central luminance only as luminous uniformity of display using conventional wLEDs lighting is low.

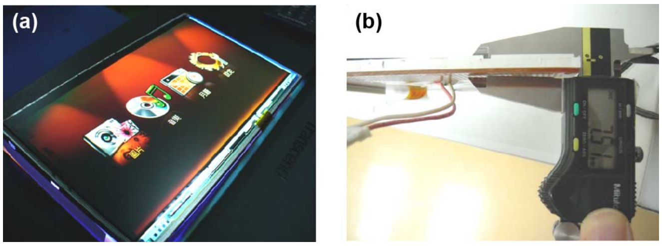

Fig. 15. (a) RPC lighting system combines with TFT-LCD panel. (b) Volume of proposed display can be reduced to 7.5 mm-thick.

the average luminance is 504 cd/m^2. Additionally, the power consumption is 4.2 W (the display size is 7-in diagonal).

V. CONCLUSION

This work presents a novel lighting system that is constructed from a yellow YAG : Ce^{3+} phosphor film and placed away from the blue LED light source. Unlike a conventional wLEDs lighting system, the proposed configuration can yield higher lumen efficiency (73.0 lm/W), less angular color deviation $(\Delta u'v' = 0.025)$ and uniform luminous distribution $(\mathrm{U}_{\text{niformity}} = 82\%)$ at an ultra-slim structure for TFT-LCD backlighting applications (the display thickness is 7.5 mm). Most importantly, the configuration is without the use of conventional diffuser plate or light guide plate (LGP). Meanwhile, the optical simulation by Monte Carto is used to predict an optimal LED gap (h) to LED pitch (p) ratio of $(h/p = 1/2.4)$ and successfully been demonstrated by the RPC backlighting. Additional, this lighting system assembled with TFT-LCD panel (7-in diagonal with 4.5% transmittance) can achieve a display with average luminance of 504 cd/m^2 at power consumption of 4.2 W. Therefore, an RPC lighting system with strong optical performance in a compact module can be obtained. Furthermore, the use of slot die coating to prepare RPC is also an inexpensive process with high manufacturing throughput, thus can be possible for an economical mass production.

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