

# Planar Lighting by Blue LEDs Array with Remote Phosphor

Chung-Hao Tien\*, Chien-Hsiang Hung, Bo-Wen Xiao, Hsin-Tao Huang, Yi-Pai Huang, and Chuang-Chuang Tsai

Department of Photonics, National Chiao Tung University, Hsinchu, Taiwan 30010

## ABSTRACT

A novel direct-emitting LED backlight for LCDs was demonstrated. Unlike the conventional white LED schemes for display applications, proposed blue light excited planar lighting (BLPL) exploits blue LED chip to remotely excite the YAG-phosphor film and thus render a uniform planar source, where the YAG-phosphor acts as the diffuser film and wavelength down converter simultaneously. Based on the diffusing characterization of YAG-phosphor layer, we examined the optical properties of the BLPL system in viewpoints of uniformity, luminance and mixing capability. Consequently, a prototype 10-mm-thickness BLPL module was demonstrated with 86% uniformity and 9800 nits without using any diffuser film or light guiding plate.

**Keywords:** light-emitting diodes, backlit, LCD

## 1. INTRODUCTION

The GaN blue light-emitting diodes (LEDs) were widely used as the white backlit for liquid crystal display (LCD) applications [1]. Fig. 1(a) shows the setup of the conventional direct-emitting source with white LED scheme, where the YAG-phosphor is coated on the surface of blue LED chips and packaged inside accordingly. For general LCD uses, the requirement for spatial uniformity of a backlight should be over 80% [2,3]. Therefore, the most straightforward approach for the uniform direct-emitting scheme is to use reduce the LED intervals with the uses of the low-power chips, and to increase the mixing space. However, such approaches hinder the backlit from ultra-slim solution.

In this paper, we proposed a blue light excited planar lighting (BLPL) system, which is an alternative LEDs-based direct-emitting planar scheme. Fig. 1(b) shows the structure of BLPL, which consists of a blue LEDs array and a YAG-phosphor film. Here the YAG phosphor is coated on a remote substrate. The YAG-phosphor layer is simultaneously functioned as the diffuser film and wavelength down converter to achieve an ultra-slim LCD backlight application [4].

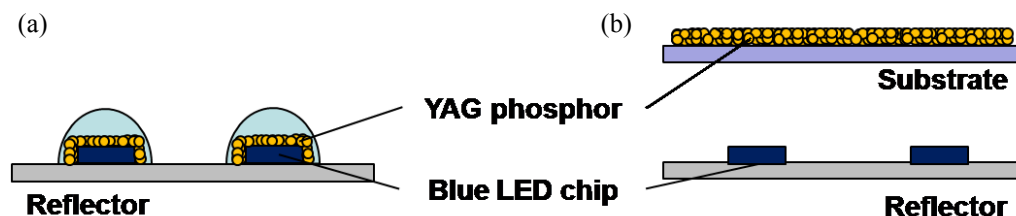


Fig. 1. Scheme of (a) conventional direct-emitting backlight using white LEDs and (b) BLPL system.

The light emitting mechanism of BLPL system includes wavelength-converting process and scattering by the flat YAG-phosphor particle, as illustrated in Fig. 2. Unlike the conventional phosphor-converted LEDs, the YAG-phosphor in BLPL system is coated on an external substrate by the roll-to-roll coating process [5]. The YAG-phosphor layer here acts as a diffuser film and a wavelength-converter at the same time. As the blue light from blue LED chips irradiate the YAG-phosphor layer, portion of the incident blue light will be diffused with high diverging angle, whereas the other part of the incident blue light will be converted to a certain bandwidth, as shown in Fig. 3. For the BLPL system, flat phosphor layer redistributes lights and converts the original point light sources to the planar light source. Thus, the proposed optical setup could perform uniform lighting and reduce module thickness of backlight systems.

Because light-emitting mechanism of BLPL involves both spectral and spatial conversion, the traditional ray-tracing computational tools are insufficient to completely treat the underlying physics. Based on the bidirectional photometric measurable data, this paper proposed a methodology to model, analyze and optimize the BLPL system. Finally, a small-size prototype will be demonstrated to validate the model.

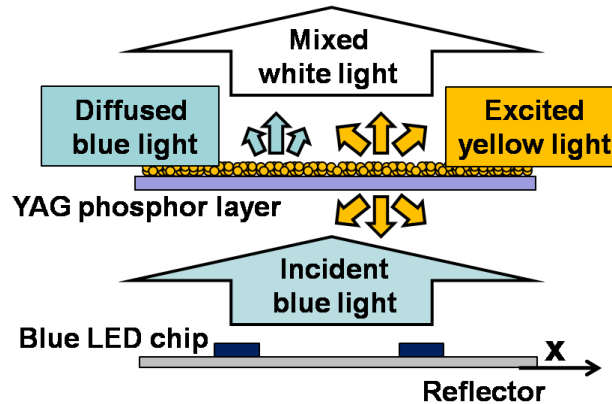


Fig. 2 The scheme of the BLPL system with light-emitting mechanism.

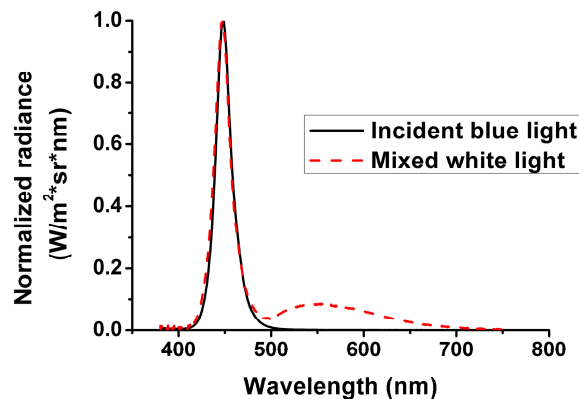


Fig. 3. Spectrum of the incident blue light and the mixed white light.

## 2. OPTICAL CHARACTERISTICS OF YAG-PHOSPHOR

The optical properties of YAG-phosphor layer could be characterized by the measured bidirectional transmittance distribution functions (BTDFs), which is defined as [6-8]:

$$BTDF(\theta_i, \phi_i, \theta_t, \phi_t) = \frac{L_t(\theta_t, \phi_t)}{E_i(\theta_i, \phi_i)}, \quad (1)$$

where  $E_i$  is the illuminance on the sample plane due to the incident light,  $L_t$  is the luminance of transmitted light from the sample surface. Here the incident and emit angles are represented by the polar coordinates  $(\theta_i, \phi_i)$  and  $(\theta_t, \phi_t)$ ,

respectively. Since the scattering characteristics of YAG-phosphor layer caused by the randomly distributed phosphor are rotationally symmetric. The measurement and data processing of BTDFs can be simplified by merely considering the variance of polar angle  $\theta_i$  with a fixed azimuthal angle  $\phi_i$ .

BTDFs represent the angular spread function of the diffusing specimen, which have a variety of optical features due to various manufacturers' recipes about the refractive index, the size of scattering particles, the density of the phosphor distribution, and so on. The major advantage of this study lies in that there is no need to formulate the complex physical mechanism of the phosphor scattering in a microscopic viewpoint. Instead, as long as the LED chip is available, the proposed characterizing method can assist the simulation of the optical radiance and the efficiency.

Differing from the traditional definition of the BTDFs, the BTDFs we defined can represent the scattered light and the emitted light by the spectrally filtered measurements. Owing to the two kinds of optical mechanisms under the blue light illumination, the diffused blue light and the emitted yellow light were measured separately. Fig. 4 (a) and (b) show the BTDF measured results of the YAG-phosphor. The angular distribution of the excited yellow light is close to lambertian and has a wider full width at half maximum (FWHM) than the diffused blue light. By these two measured BTDF results, the YAG-phosphor layer could be characterized to develop the BLPL model.

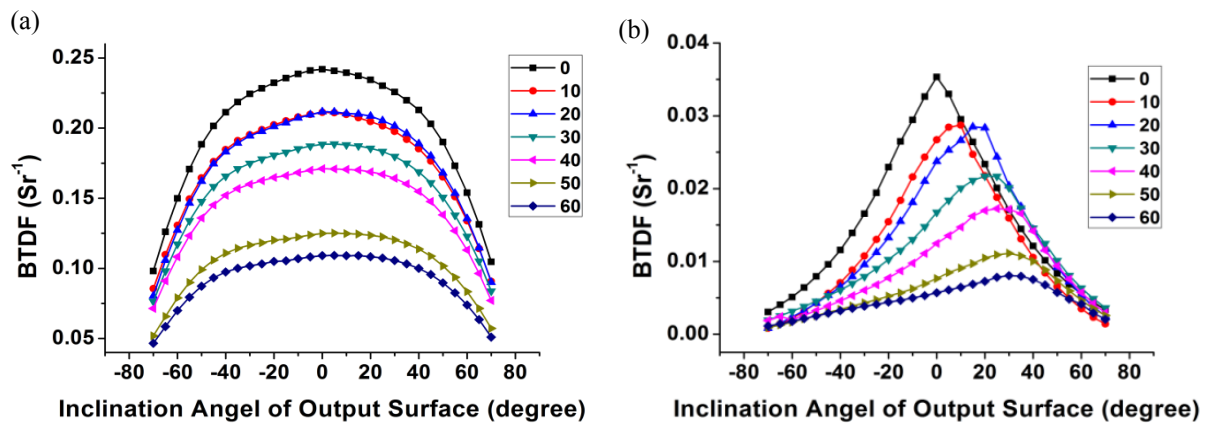


Fig. 4. The measured BTDF of (a) the emitted yellow-light radiance and (b) the scattered blue-light radiance

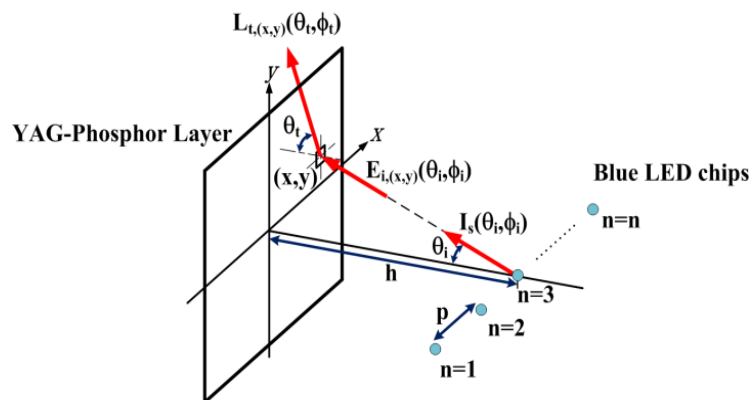


Fig. 5. Scheme of theoretical calculation.

### 3. THEROTICAL CALCULATION

By using the characterizations of the YAG-phosphor layer, a theoretical model was developed to calculate the transmitted luminance distribution of BLPL system. First of all, the four major parameters of the BLPL configuration should be obtained for the theoretical calculation: (1) the BTDF of the YAG-phosphor layer, (2) the intensity distribution  $I_s$  of the LED chips, (3) the distance  $h$  between LED chips and YAG-phosphor layer, and (4) the interval  $p$  of the LED arrangement. Through the definition of photometric, the illuminance  $E$  illuminating the YAG phosphor layer at the point  $(x, y)$  from the incident direction  $(\theta_i, \phi_i)$  of single blue LED can be calculated by

$$E_{(x,y)}(\theta_i, \phi_i) = \frac{I_s(\theta_i, \phi_i) \cdot \cos^3 \theta_i}{h}. \quad (2)$$

Here the geometric relation is schematically shown in Fig. 5. Then, the transmitted luminance distribution  $L_t$  from the YAG-phosphor layer at point  $(x, y)$  can be transferred by the BTDFs

$$\begin{aligned} L_{t,(x,y)}(\theta_t, \phi_t) &= \int_{\Omega_i} BTDF_{(x,y)}(\theta_i, \phi_i, \theta_t, \phi_t) \cdot E_{i,(x,y)}(\theta_i, \phi_i) d\omega_i \\ &= \int_{\Omega_i} BTDF_{(x,y)}(\theta_i, \phi_i, \theta_t, \phi_t) \cdot \frac{I_s(\theta_i, \phi_i) \cdot \cos^3 \theta_i}{h} d\omega_i. \end{aligned} \quad (3)$$

Finally, the total radiating luminance  $L_{output}$  from the YAG-phosphor layer by LED-array illumination can be calculated by the convolution between the single-LED luminance distribution  $L_{t,(x,y)}$  and a two-dimensional comb function

$$L_{output}(\theta_t, \phi_t; x, y) = \sum_n \sum_m \left[ \int_{\Omega_i} BTDF_{(x,y)}(\theta_i, \phi_i, \theta_t, \phi_t) \cdot \frac{I_s(\theta_i, \phi_i) \cdot \cos^3 \theta_i}{h} d\omega_i * \delta(x - np, y - mp) \right], \quad (4)$$

where the counting number  $n$  and  $m$  indicate the  $n$ -th and  $m$ -th LED along  $x$  and  $y$  direction, respectively. In this case, the summation and integration were performed by Monte Carlo simulation [9]. In addition to the transmitted luminance distribution, the recycled light which is multi-reflected by the YAG-phosphor film and the bottom reflector can be identically calculated by the bidirectional reflection distribution functions (BRDFs).

### 4. SIMULATION

For the LED backlit use, a 5x5 blue LED chips array was placed above a reflector and covered with the YAG-phosphor layer, as shown in Fig. 6. We import the measured BSDFs into the commercial software LightTools<sup>TM</sup> to accomplish the influence of YAG-phosphor on the whole BLPL system. In order to keep the uniformity and luminance as the first merit, the module gap ( $h$ ) and the interval of blue LED chips ( $p$ ) were modulated from 4 to 20 mm. Here the luminance uniformity is defined as

$$Uniformity = \frac{L_{output, \min}}{L_{output, \max}} \bigg|_{\theta_t=0}, \quad (5)$$

which is the luminance ratio of the positions with the minimum luminance and the maximum luminance at the normal viewing direction. The simulated luminance uniformity is shown in Fig. 7 in comparison with a conventional white LED direct-emitting backlit (covered by diffuser plate).

It is found that the operating region is much wider in BLPL system than the conventional backlit due to BLPL structure includes a strong scattering function conducted by YAG-Phosphor layer in the optical path. Even without additional diffuser or diffusing plate, high uniformity is able to be achieved under ultra-slim configuration. As shown in Fig. 8, as spacing between the LED chip and diffusing structure is reduced to 10 mm (cross line (b) and (e) in Fig. 7), the optimized light-redistributed mechanism on the flat YAG-phosphor layer makes BLPL system achieved 82% uniformity associated with 10-mm LED interval, whereas the conventional white LED backlight with 20% uniformity with the

identical LED interval, the results exhibit the advantage of remote phosphor for uniformity issue in large-area backlit applications.

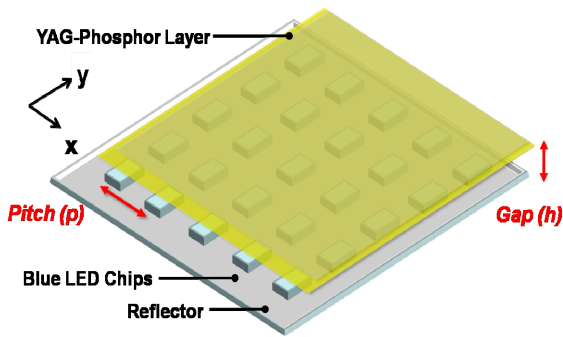


Fig. 6. The scheme of the BLPL structure for simulation

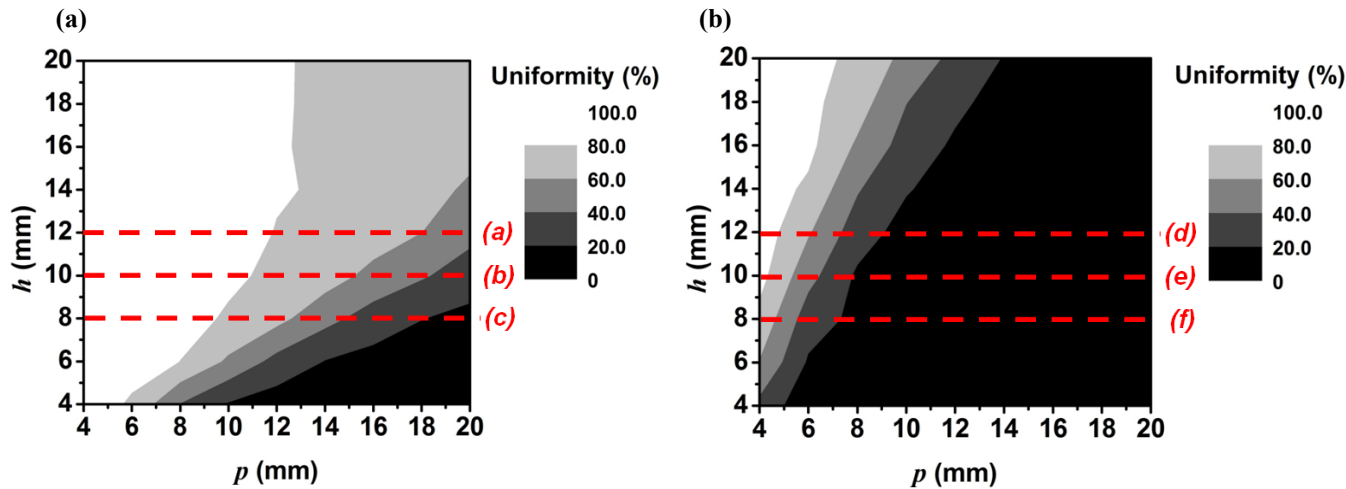


Fig. 7. The simulated uniformity of (a) the BLPL system and (b) LEDs array with varied LED pitch and system gap.

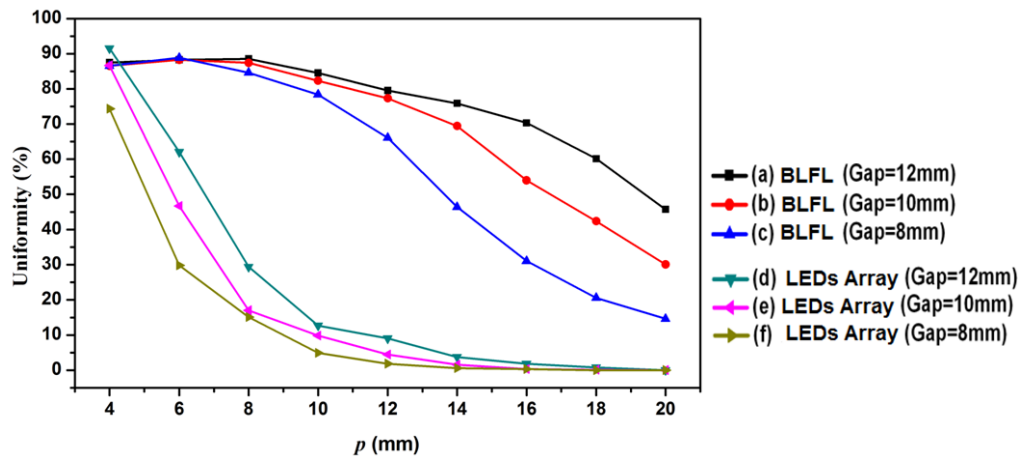


Fig. 8. The comparison of the uniformity between the BLFL and the LEDs array

Off-axis color deviation, which is a major optical issue of a backlight system, was considered in the BLPL system. Based on the uniformity optimization, the 10-mm mixing gap was chosen as the appropriate parameters for the slim backlight design. Thus, the chromaticity at the center of the simulation model (as shown in Fig. 9) was obtained, and the color differences ( $\Delta u'$ ,  $\Delta v'$ ) versus different viewing inclinations  $\theta$  were evaluated. Fig. 10 represents the color deviations  $\Delta u'v'$  of the  $0^\circ$ - $30^\circ$  and  $0^\circ$ - $60^\circ$  viewing inclinations, respectively. According to the results, the LED arrangements with 8-10 mm interval have relatively low color difference.

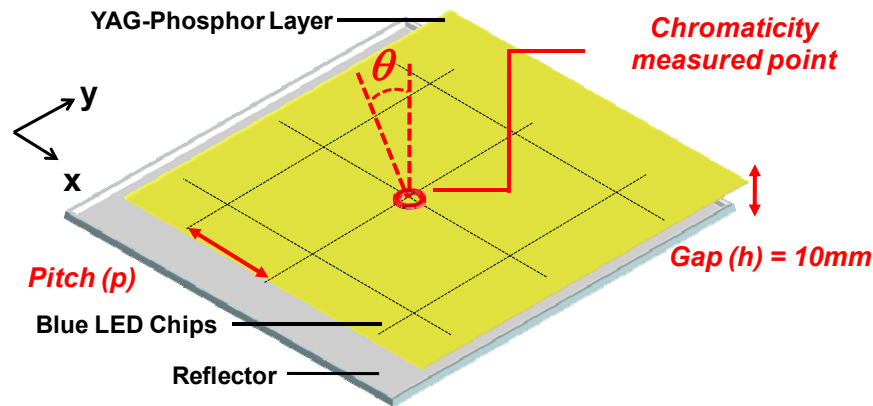


Fig. 9. Setup of the BFL system in the simulated environment.

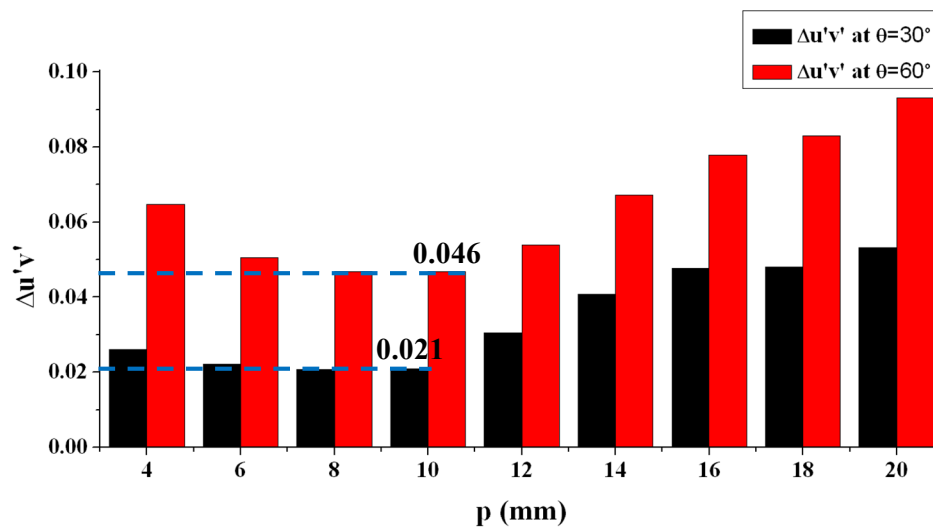


Fig. 10 The color difference ( $\Delta u'v'$ ) with a fixed module gap (10mm) and varied LED pitches (4-20mm).

From the previous simulation, the 10-mm light mixing space with 8-10 mm LED interval were chosen as the appropriate geometrical parameters of the BLPL system for the purpose of the slim backlight design. However, the radiated blue light has a relatively narrower angular distribution than the radiated yellow light. Therefore, the BLFL system exhibits a yellowish phenomenon in large viewing direction. This issue can be suppressed by using the commercial optical films with a lenticular configuration.

## 5. EXPERIMENT

Based on the BTDFs of YAG-Phosphor layer and optimized LED layout, a 7-inch slim BLPL system was demonstrated. Compared with a conventional backlight with a commercial diffuser (80% Haze) under the same LED interval and mixing space, the experimental results are shown in Fig. 11. The emitted luminance of BLPL system achieved 9800 nits and the 86% uniformity, whereas the conventional backlight had only 5600 nits and 18% uniformity. Thus, BLPL system indeed showed the potential for fabricating the ultra-slim backlight system for the large-sized LCD-TV applications.

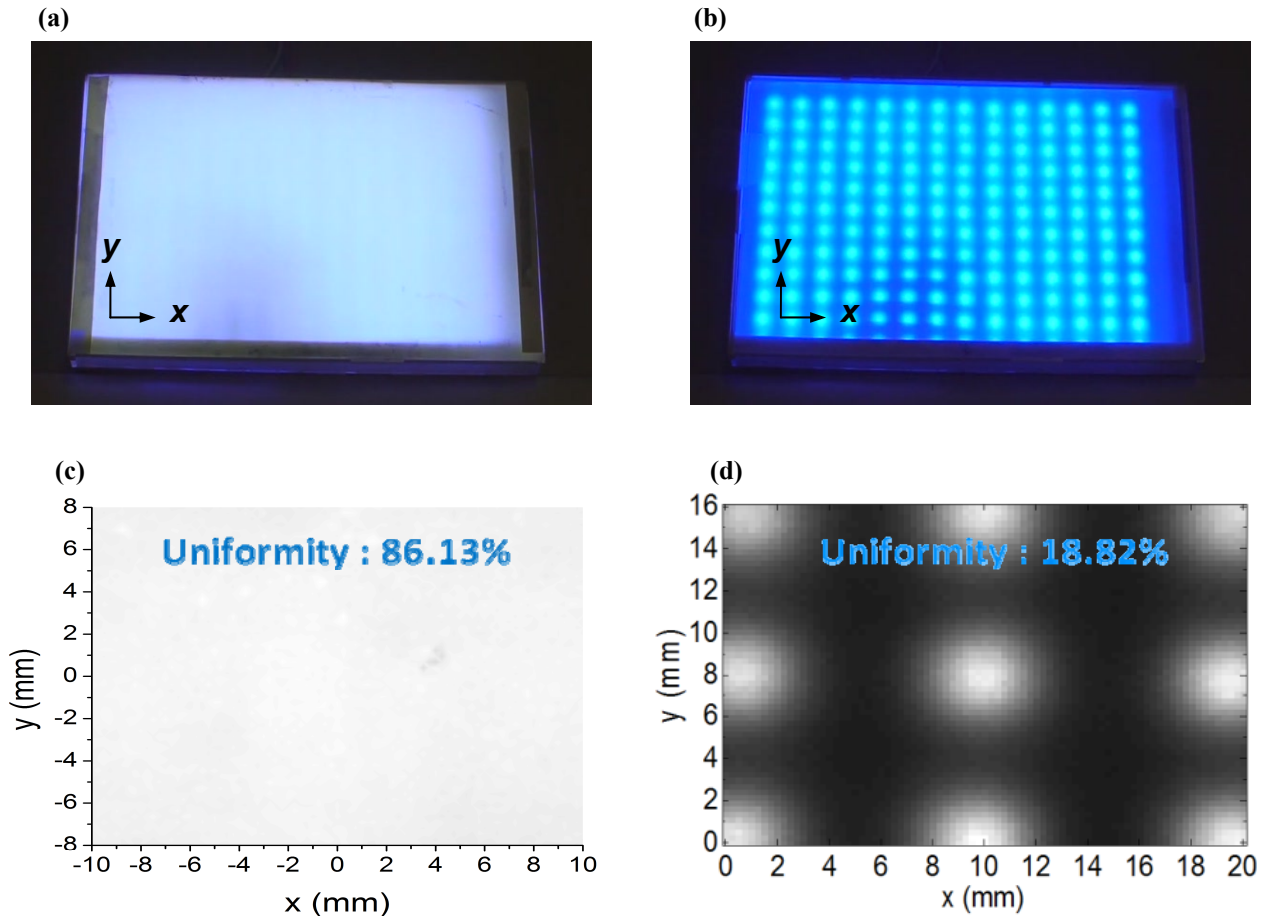


Fig. 11. The experimental results of (a) (c) the BLPL system and (b) (d) the direct LEDs array

## 6. CONCLUSIONS

The optical properties of the blue light excited planar lighting (BLPL) system had been discussed in this paper. In BLPL system, the YAG-phosphor acts as a diffuser film and the wavelength converter simultaneously. Thus the BLPL system generated flat lighting and performed higher uniformity than the conventional direct-emitting backlight with white LEDs. However, such specific optical property makes BLPL system hard to be simulated by conventional simulation software. By using the characterization of the YAG-phosphor layer, a methodology for the purpose of modeling the BLPL system was proposed. According, a prototype slim format BLPL system had been demonstrated. The small-sized BLPL system achieved 86% uniformity and 9800nits with 10-mm backlight module thickness and without using any diffuser film or plate, while the conventional backlight system had only 20% uniformity and 5600nits with the same

backlight module thickness. Consequently, BLPL system is indeed the potential technology for developing the future backlight system with high brightness and ultra-slim module thickness.

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