

A Novel LCD Backlight with Mixed White and Colorful LEDs

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Abstract— With improved luminous efficiency, reduced cost, long lifetime, wide color gamut, fast response, LEDs are becoming a suitable solution for LCD backlight. Backlight consisting of white LEDs has the merit of high luminous efficiency while is not possible to change color temperature. Backlight with colorful LEDs of red, green, blue to form white lights can reach various color temperatures while luminous efficiency is not as high as white LED backlight. A mixed backlight combining white and colorful LEDs is presented in this paper to preserve the merits of both kinds of LED backlights. High luminous efficiency white LEDs provide most of luminance and colorful LEDs are only lightened when color temperature is to change. An implementation is realized. The experimental results show that the theoretical model is appropriated and the mixed backlight presents the high luminous efficiency with less LEDs and possibility to change color temperature.

Keywords—LED backlight; liquid crystal display; luminance; color temperature; backlight

I. INTRODUCTION

Liquid crystal display (LCD) is one of the most popular display technologies and LCD products are almost ubiquitous in our lives, e.g., grocery stores, railway station, airport, living room. A backlight unit (BLU) is necessary for LCDs since LCDs are not self-luminance. Currently cold cathode fluorescent lamps (CCFL) are the master stream of LCD BLU [1]. CCFL needs to be driven by a DC-AC inverter, requiring more space and high voltage. Moreover, CCFL is not environmental friendly as the use of mercury inside. With the merits of long life span, fast response, wide color gamut, environmental friendliness, etc., light emitting diode (LED) is becoming a most promising substitutive technology for LCD BLU [2].

Nowadays LED BLU can be categorized into two classes: 1) white LED BLU [3], 2) colorful LED BLU [4]. The first class consists of LEDs which can directly emit white lights. White LEDs are usually high power of more than 1W or 3W and luminous flux can reach more than 100lm. The second class backlight consists of LEDs emitting colorful lights of red (R), amber, green (G), cyan, blue (B), or orange that are mixed to form white lights. Most of colorful LED BLUs employ the low power LEDs, leading the amount of LEDs to as many as hundreds even thousands. Some of colorful LED BLUs don't mix the colorful lights to form white lights. Instead, the R, G, B

lights are illuminating the LC screen sequentially, which omits the use of color filters to improve LCD efficiency. Such kind of colorful LED BLU is not discussed in this paper. Comparing to a colorful LED BLU, white LED one has higher luminous efficiency, needs less number of LEDs and consequently less drivers and less complicated driving circuits. Mixing lights from one red LED, one or two green LED, and one blue LED to form white lights, a colorful LED BLU can reach various color temperatures by driving different currents to different color LEDs. To preserve the merits of tow categories, this paper presents a third class of LED BLU – a white and colorful LED mixed BLU with advantages of high luminous efficiency and possibility to reach various color temperatures. The number of colorful LEDs could be decided according to real applications. In the section III, a BLU with one white LED and one green LED are implemented. With high-luminous-efficiency white LEDs providing most needed lights, colorful LEDs are only lightened when color temperature is to change, which can save power consumption.

The paper is organized as following: the second part introduces a theoretical model of a mixed BLU. The implementation of the model is presented in the section III. The section IV shows the experimental results of the implementation, including luminance, uniformity, and color temperature. The conclusion is drawn in the final part.

II. THEORETICAL MODEL

BLU provides uniform lights to illuminate LCD. Lights from BLU have to pass several optical components to reach the eyes of an observer, as shown in Fig 1.

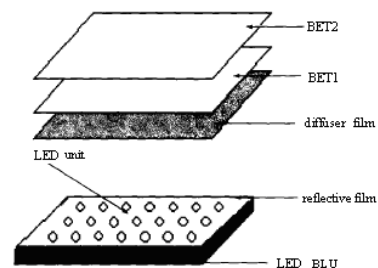


Figure 1. LED BLU structure

The LED unit in the figure could consist of one white LED and several colorful LEDs. The number and main wavelength of colorful LEDs are depending on different requirements. The LED unit with one white LED and one green LED are shown in following section as an example. The optical components may be reflective film, diffuser film, brightness enhance film (BEF), etc. The LED circuit with LED units above are put inside a cavity whose inside walls are covered by high reflectivity films.

A. BLU LUMINANCE

Usually the luminance measured before LCD is given as a system parameter, which has to be conversed to the luminance of a BLU. With the given luminance before LCD, The luminous flux of a BLU can be calculated with the following equation [5]:

$$\phi_{LED} = \frac{L_{FOS} \times A \times 2\pi \times (1 - \cos \varphi_{1/2})}{\eta_{LCD} \times \prod \tau_i} \quad (1)$$

Where, ϕ_{LED} is the total required luminous flux of a LED BLU, L_{FOS} is the luminance before LCD, η_{LCD} is the transmissivity of LCD, A is the display area of LCD, $\varphi_{1/2}$ is the off-axis viewing angle at the 50% peak luminance between BEF and diffuser, $\prod \tau_i$ is the cross product of transmissivity of each optical films.

With white LEDs contributing to the most of luminance, the involvement of high luminous flux white LEDs could lead to less number of LEDs and less power consumption. White LEDs with 1W power and 120lm luminous flux are available on market now. According to NTSC standard shown in the equation 2 [6], the final luminance of white lights formed by colorful lights is not the linear sums of the luminance of each color lights, which means more powers are needed for colorful LED BLU of R, G, B than white LED BLU to create same luminance.

$$W = 0.299R + 0.587G + 0.114B \quad (2)$$

Where, W , R , G , B are the luminance of white lights, red lights, green lights, blue lights, respectively.

As LED manufactures provide several choices about basic white point of white LEDs, the practical BLU could employ LEDs whose white point is same or close to required color temperature. For example, 6500K is a color temperature defined by China national standard GB936-89 [7], which is implemented in color TVs. In this case, white LEDs with cool white color (6500K) could be directly used and colorful LEDs could be only lightened when the white point of white LEDs is deviated from 6500K after long time operation or the color temperature is required to change.

B. COLOR TEMPERATURE

After the luminance requirement is satisfied, color temperature has to be considered. There are several possibilities to change color temperature: 1) white point of

white LEDs have to be stabilized, 2) different operation environment, for example, white point of color TVs in Europe is lower than Chinese standard. In addition, it is better for a display installed on an airplane to change to higher color temperature when flying at high altitude.

For a certain color temperature, luminous flux of each basic color of R, G, B could be determined by the equation 3 [8].

$$\begin{pmatrix} \Phi_R \\ \Phi_G \\ \Phi_B \end{pmatrix} = \Phi_{LED} \begin{pmatrix} \frac{x_R}{y_R} & \frac{x_G}{y_G} & \frac{x_B}{y_B} \\ 1 & 1 & 1 \\ \frac{1-x_R-y_R}{y_R} & \frac{1-x_G-y_G}{y_G} & \frac{1-x_B-y_B}{y_B} \end{pmatrix}^{-1} \begin{pmatrix} \frac{x_w}{y_w} \\ 1 \\ \frac{1-x_w-y_w}{y_w} \end{pmatrix} \quad (3)$$

Where, ϕ_{LED} is the luminous flux of a LED BLU, ϕ_R , ϕ_G , ϕ_B are the luminous flux of R, G, B LEDs. x_R , y_R , x_G , y_G , x_B , y_B are chromaticity coordinates of R, G, B lights, which is decided by R, G, B LEDs. x_w , y_w are chromaticity coordinates of required white point.

If BLU is only consisting of white LEDs, the color temperature is decided by white LEDs. In the case that a BLU consists of colorful LEDs of red, green, and blue, the needed color temperature could be reached with each color LEDs providing required luminous flux according to equation 3. As to white and colorful LED mixed BLU presented in this paper, the needed luminous flux of R, G, B LEDs have to recalculate due to the reason that white lights emitting from white LEDs have already included R, G, B lights. It is also why that there are some color temperatures that the mixed BLU can not reach. Reasonably, the range of available color temperatures is bigger than white LED BLU and smaller than colorful LED BLU.

For colorful LED BLU, it is quite easy to change color temperature. With the definition of required luminous flux ϕ_R , ϕ_G , ϕ_B of each color light and spectrum characteristics of each color LEDs, the ratio of each color lights could be changed by providing different driving currents to different color LEDs, leading to the change of color temperature. For mixed BLU, spectrum characteristics of both white and colorful LEDs have to be consideration.

For a certain color temperature, the needed luminous flux for each color of R, G, B are ϕ_R , ϕ_G , ϕ_B . With both white and colorful LEDs providing lights, ϕ_R , ϕ_G , ϕ_B could be described as follows:

$$\begin{cases} \phi_R = \int_{\lambda_1}^{\lambda_2} (\tau_w(\lambda) + \tau_R(\lambda)) \Delta \lambda \\ \phi_G = \int_{\lambda_3}^{\lambda_4} (\tau_w(\lambda) + \tau_G(\lambda)) \Delta \lambda \\ \phi_B = \int_{\lambda_5}^{\lambda_6} (\tau_w(\lambda) + \tau_B(\lambda)) \Delta \lambda \end{cases} \quad (4)$$

Where, $\tau_w(\lambda)$, $\tau_R(\lambda)$, $\tau_G(\lambda)$, $\tau_B(\lambda)$ are spectrum characteristics of white, red, green, blue LEDs. λ_1 and λ_2 are

the wavelength range of red light, λ_3 and λ_4 are the wavelength range of green light, λ_5 and λ_6 are the wavelength range of blue light. Mathematically, the needed luminous flux of colorful LEDs ϕ_{R-LED} , ϕ_{G-LED} , ϕ_{B-LED} in a mixed BLU are shown in the equation 5.

$$\begin{cases} \phi_{R-LED} = \phi_R - \int_{\lambda_1}^{\lambda_2} \tau_W(\lambda) \Delta \lambda \\ \phi_{G-LED} = \phi_G - \int_{\lambda_3}^{\lambda_4} \tau_W(\lambda) \Delta \lambda \\ \phi_{B-LED} = \phi_B - \int_{\lambda_5}^{\lambda_6} \tau_W(\lambda) \Delta \lambda \end{cases} \quad (5)$$

With ϕ_{R-LED} , ϕ_{G-LED} , ϕ_{B-LED} and the electro-optical characteristics of colorful LEDs, the driving current can be decided to achieve a certain color temperature.

From above description, to design a mixed BLU, the total luminous flux ϕ_{LED} should be first calculated according to the equation 1. White LEDs are then chosen, with the consideration of white point and numbers. When color temperature is required to change, ϕ_{R-LED} , ϕ_{G-LED} , ϕ_{B-LED} are calculated to decide the driving currents of each color LEDs according to the equation 3 and 5.

III. IMPREMENTATION

This section will introduce an implementation of the mixed BLU. The luminance of a 21-inch LC TV is required to reach 400cd/m². The BLU consists of 2 diffusers and 2 BEFs. The transmissivity of each optical film is 80%. The transmissivity of LCD is set to be the worst case of 3%. $\psi_{1/2}$ is 50 degree. According to the equation 1, the required luminous flux of the BLU is

$$\begin{aligned} \phi_{LED} &= \frac{400}{0.03} \times (21 \times 0.0254 \times 0.8) \times (21 \times 0.0254 \times 0.8) \\ &\times 2 \times 3.14 \times (1 - \cos 50) \times \frac{1}{0.8 \times 0.8 \times 0.8 \times 0.8} \\ &= 9967 \text{ lm} \end{aligned} \quad (6)$$

According to Chinese national standard, the color temperature of white point of color TVs is 6500K. In this case, cool-white LEDs from PHILIPS LUMILEDS Co. are chosen. The luminous flux of PHILIPS white LEDs is 100lm and the power is 1W. To satisfy the requirement of luminous flux calculated by the equation 6, the BLU will consist of an array of more than 100 white LEDs. If the length-width ratio of LC screen is 4:3, the disposition of LEDs should be consistent with this ratio as 4:3, leading to an array of 12:9. PHILIPS also supplies R, G, B LEDs with various luminous flux. The spectrum characteristics of white LED and colorful LEDs from PHILIPS are shown in Fig. 2 and Fig 3, respectively [9].

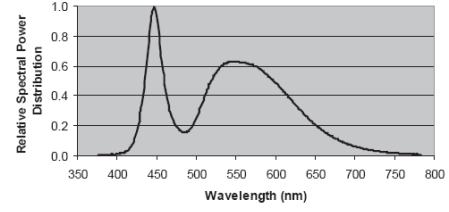


Figure 2. Cool-white LED spectrum

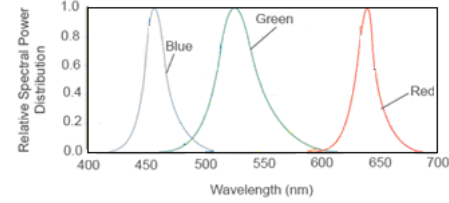


Figure 3. Colorful LED spectrum.

From Fig. 3, the main wavelength of red, green, and blue LED are 625nm, 525nm, and 450nm, respectively. If the color temperature is required to change to 9300K (Chinese are more used to this color temperature), the required luminous flux of each color lights of R, G, B could be calculated by the equation 3 and shown in table 1.

TABLE 1: REQUIRED LUMINOUS FLUX FOR 9300K

	Luminous flux at 9300K
(x,y)	(0.287,0.287)
ϕ_R (lm)	2816.28
ϕ_G (lm)	10302.89
ϕ_B (lm)	1024.01

The total luminous flux of R, G, B provided by 12*9 cool-white LEDs are

$$\begin{cases} \int_{\lambda_1}^{\lambda_2} \tau_W(\lambda) \Delta \lambda \times 108 = \int_{600}^{700} \tau_W(\lambda) \Delta \lambda = 3019 \text{ lm} \\ \int_{\lambda_3}^{\lambda_4} \tau_W(\lambda) \Delta \lambda \times 108 = \int_{475}^{600} \tau_W(\lambda) \Delta \lambda = 6966 \text{ lm} \\ \int_{\lambda_5}^{\lambda_6} \tau_W(\lambda) \Delta \lambda \times 108 = \int_{400}^{475} \tau_W(\lambda) \Delta \lambda = 1026 \text{ lm} \end{cases} \quad (7)$$

According to the equation 5, the needed luminous flux of colorful LEDs ϕ_{R-LED} , ϕ_{G-LED} , ϕ_{B-LED} are

$$\begin{cases} \phi_{R-LED} = \phi_R - \int_{\lambda_1}^{\lambda_2} \tau_W(\lambda) \Delta \lambda = 2816.28 - 3019 = -192.72 \text{ lm} \\ \phi_{G-LED} = \phi_G - \int_{\lambda_3}^{\lambda_4} \tau_W(\lambda) \Delta \lambda = 10302.89 - 6966 = 3336.89 \text{ lm} \\ \phi_{B-LED} = \phi_B - \int_{\lambda_5}^{\lambda_6} \tau_W(\lambda) \Delta \lambda = 1024.01 - 1026 = -1.99 \text{ lm} \end{cases} \quad (8)$$

We can see that when the color temperature of BLU is required to change from 6500K to 9300K, more green lights are needed. However the amount of red lights provided by

cool-white LEDs are too much, which means the color temperature could not reach 9300K.

To satisfy the requirement of uniformity, it is better to apply one or two green LEDs disposed closely to each white LED so that white lights and green lights can fully mix. In the case of one green LED, the luminous flux of green LED is $3336.89/108=30.9\text{lm}$. According to Fig. 4, the driving current to green LEDs can be decided [9]. For a 1W and 80lm green LED, the relative luminous flux is $30.9/80=38.6\%$, corresponding to about 130mA driving current. The Fig. 5 shows the disposition of mixed BLU with the LED unit consisting of one white LED and one green LED.

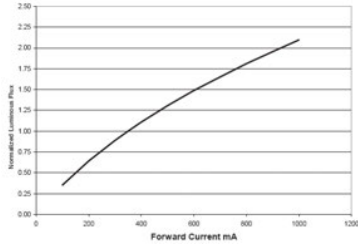


Figure 4. Electro-optical characteristic of green LED

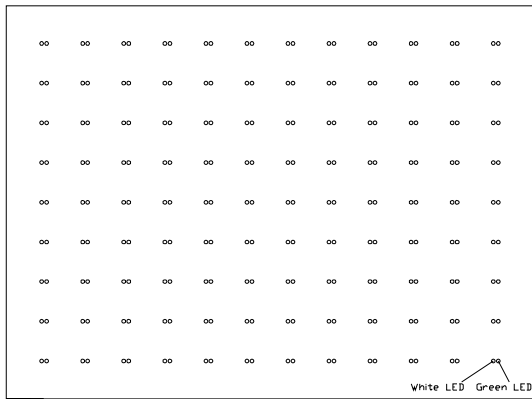


Figure 5. White and green LED mixed BLU

IV. EXPERIMENTAL RESULTS

The schematic diagram of the test system is shown in Fig. 6. A BLU is the type of direct-light. The BLU consists of 12×9 LED units with each unit comprising one white LED and one green LED. 2 diffusers and 2 BEFs are employed in the BLU to improve uniformity and brightness. The transmissivity of the LC is measured to be 4%. The luminance before the LC is measured with the luminance colorimeter of BM-7A.

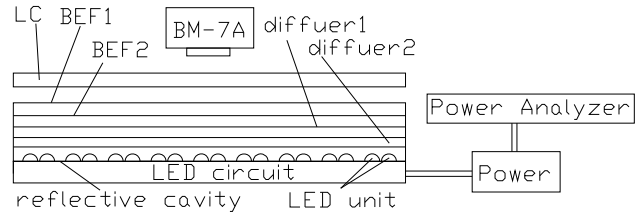


Figure 6. Schematic diagram of the test system

There are several standards to measure LCD luminance: 5 points, 9 points, 13 points, etc. The measurement results of 9 points are shown in table 2. Not able to measure luminous flux (lm), BM-7A measures the luminance of each point (cd/m^2). BM-7A can only give the chromaticity coordinates of measured points. The color temperature T_c is reckoned with the following equations [10]:

$$\begin{cases} T_c = 437n^3 + 360n^2 + 683n + 5517 \\ n = \frac{x - 0.3320}{y - 0.1858} \end{cases} \quad (9)$$

TABLE 2: MEASUREMENT RESULTS OF LUMINANCE

	x	y	Luminance(cd/m^2)	Tc(K)
1	0.2908	0.2854	450.77	8996
2	0.2883	0.2892	487.09	9128
3	0.2899	0.2848	473.12	9098
4	0.2871	0.2877	485.76	9270
5	0.2924	0.2809	492.05	9065
6	0.2889	0.2851	462.08	8801
7	0.2910	0.2838	453.17	9038
8	0.2887	0.2872	486.45	9113
9	0.2916	0.2820	452.11	9021

From the table 2, the average luminance before LCD is

$$\bar{L} = \frac{\sum_{i=1}^9 L_i}{9} = 471.4 \text{ cd}/\text{m}^2 \quad (10)$$

The luminance uniformity of the BLU is

$$\bar{P}_L = 1 - \frac{L_{\max} - L_{\min}}{\bar{L}} = 87.6\% \quad (11)$$

The average color temperature is

$$\bar{T} = \frac{\sum_{i=1}^9 T_i}{9} = 9058.9 \text{ K} \quad (12)$$

The color uniformity of the BLU is

$$\bar{P}_T = 1 - \frac{T_{\max} - T_{\min}}{\bar{T}} = 5.2\% \quad (13)$$

The uniformity is better than the common requirement of 80%. The practical luminance is a little more than the design luminance of 400cd/m². One possible reason is the test LC has higher transmissivity. The color temperature is a little bit lower than 9300K, which is consistent with above analysis that the cool-white LEDs provide too much red lights.

The further system could be designed as closed-loop with the color sensor measuring the amounts of R, G, B lights to realize the precise control on color temperature. The power consumption is about 147W, which is comparable to a CCFL backlight of similar size.

For a mixed BLU presented above, the luminance provided by white LEDs are fixed, which means that there are some color temperatures not able to reach. The gamut of a mixed BLU is not continual, which is better than a white BLU and worse than a colorful BLU. With same power consumption, the luminance of a mixed BLU would be bigger than a colorful BLU and smaller than a white BLU. The number of drivers for a mixed BLU is also between a white and colorful BLU. When a display is required to be high luminance and to work in several modes (different color temperatures), a mixed BLU could be better applied.

V. CONCLUSIONS

LED is becoming a promising substitutive technology for LCD backlight. Nowadays white LEDs on market have much higher light efficiency than colorful LEDs. However a backlight with colorful LEDs could reach various color temperatures comparing to the certain color temperature decided by white LEDs. This paper presents a white and colorful LED mixed backlight which preserves the merits of two kinds of LED backlights. High luminous efficiency white LEDs provide most of luminance and colorful LEDs are only lightened when color temperature is to change. The paper presents the theoretical design model of the mixed backlight. The experimental results of an implementation show that the

theoretical model is appropriate. The number of LEDs and drivers are quite low and consequently the cost of BLU is reduced. As the reason that lights of R, G, B provided by white LEDs are certain, there are some color temperatures that the mixed BLU can't reach. The designers have to balance the pros and cons according to requirements and make a decision which kind of BLU to be used, white, colorful, or mixed.

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