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Enlarging the color gamut of liquid crystal displays with a functional reflective polarizer

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Abstract: We propose to add a functional reflective polarizer (FRP) in the backlight unit to suppress the crosstalk between red, green and blue color filters of a liquid crystal display (LCD) panel. When incorporated with a commercial two-phosphor-converted white light-emitting diode (2pc-WLED), the color gamut of the LCD can be improved from 92% to 115% NTSC standard, which is comparable to the cadmium-based quantum dot (QD) backlight. If a narrow-band color filter is employed, the color gamut can be further enhanced to 135% NTSC. Our design offers an alternative approach to QDs, while keeping low cost and long lifetime. Such a simple yet efficient approach would find widespread applications for enlarging the color gamut of LCDs.

OCIS codes: (230.3720) Liquid-crystal devices; (230.3670) Light-emitting diodes; (310.0310) Thin films; (160.3710) Liquid crystals.

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1. Introduction

Backlight affects the color gamut, optical efficiency, dynamic range, and viewing angle of liquid crystal display (LCD) devices [1–4]. In the past two decades, backlight technology has evolved from cold cathode fluorescence lamp (CCFL) to phosphor-converted white light emitting diode (pc-WLED) [5, 6]. The latter employs a blue LED to pump YAG:Ce^{3+} yellow phosphor to generate white color. The major advantages of pc-WLED are high efficiency, long lifetime, low cost and simple optical configuration. However, its broad yellow spectrum leads to a relatively narrow color gamut (75% NTSC). To widen color gamut, quantum dot (QD)-enhanced backlight [7–10] and two phosphor-converted WLED (2pc-WLED) [11–14] have been developed. Each technology has its pros and cons. For examples, the cadmium-based QDs offer a narrow emission bandwidth (full width at half maximum FWHM ~20-30 nm) and large freedom for selecting peak wavelengths to match the transmittance of color filters. The resultant color gamut can reach 115% of the National Television Standard Committee (NTSC) standard in CIE 1976 color space, or over 90% Rec. 2020 standard [9, 15]. However, cadmium is a toxic heavy metal and its maximum allowable level is limited to 100 ppm according to the European Union's Restriction of Hazardous Substances (RoHS). Some heavy-metal-free QDs have been developed, such as InP/ZnS [16, 17], but their efficiency and bandwidth are compromised. Moreover, these QDs are often present as a film, known as quantum dot enhancement film (QDEF) [18]. For a large screen LCD TV, the QDEF should match the TV size, thus the cost issue needs to be taken into consideration as well. On the other hand, 2pc-WLED can be easily packed into a small chip and it offers advantages in low cost, high brightness, excellent stability, and long lifetime. But the bottleneck is its relatively wide emission bandwidth, e.g. the state-of-the-art green phosphor (β-sialon:Eu^{2+}) still exhibits FWHM ~55 nm [14, 19, 20]. While for red phosphor (K_2SiF6:Mn^{4+}) with five emission peaks, its individual FWHM is quite narrow but the

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effective peak wavelength centers at 625 nm [14, 21–23], which is slightly short from an ideal red color of 638 nm [9]. Therefore, red (R), green (G) and blue (B) lights still show a large crosstalk after passing through the color filters, which in turn degrades the color purity.

To enlarge color gamut, here we propose to add a functional reflective polarizer (FRP) in the backlight unit to suppress the color crosstalk. Such a FRP functions as a notch filter to reflect the unwanted spectrum, while transmitting the remaining wavelengths with high efficiency. By optimizing the FRP bandwidth, we can boost the color gamut from 92% to 115% NTSC standard, which is comparable to the Cd-based QDs. The incurred 18% optical loss results from the blocking of unwanted colors. Our design is completely compatible to the current backlight configuration; it simply replaces the conventional reflective polarizer with our new FRP. No extra modification or cost is required. This simple yet efficient approach would enable 2pc-WLED based backlight to achieve wide color gamut for future LCDs.

2. Device configuration and working mechanism

Figure 1(a) shows the transmission spectrum of commonly employed color filters (dashed lines) and the emission spectrum of a 2pc-WLED (solid line). These RGB color filters are the same as that reported in [14]. They are highly efficient, but exhibit severe crosstalk in the blue-green and green-red spectral regions. As a result, the largest color gamut using 2pc-WLED is only 96.2% NTSC in CIE 1976 [14]. Figures 1(b) to 1(d) show the transmitted spectra after such color filters. Here, the fringe field switching (FFS) LCD with a negative dielectric anisotropy ($\Delta\varepsilon < 0$) LC mixture is employed in our simulation [24, 25] and the wavelength dependent refractive indices are considered. Clearly, there is some light leakage for each channel, especially for blue, where a large bump leaks through the green color filters, deteriorating the final color purity.

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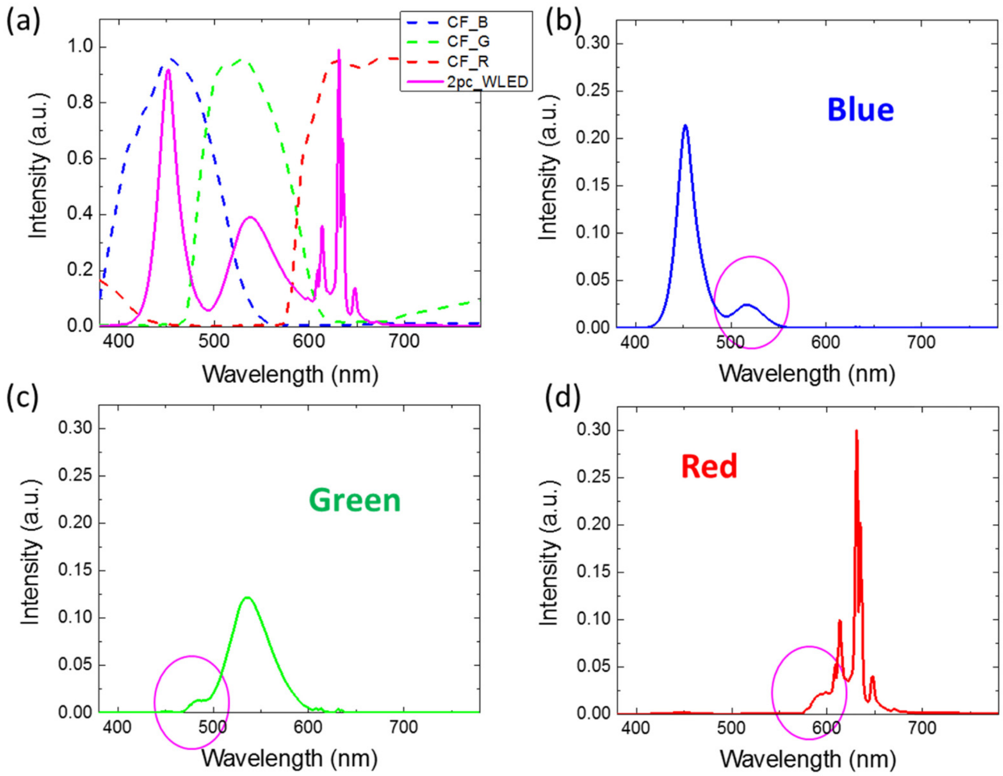

Fig. 1. (a) Transmission spectrum for commercial color filters and 2pc-WLED with green (β-sialon:Eu^{2+}) and red (K_2SiF_6:Mn^{4+}) phosphors; (b)-(d) Output spectrum for the blue, green and red sub-pixels, respectively.

To suppress the color crosstalk, we propose to replace the conventional reflective polarizer [26, 27] with a functional reflective polarizer [28] in the backlight unit. Figure 2 shows the panel configuration with an edge-lit 2pc-WLED as an example. Different from QDEF or QD rail-based backlight, the 2pc-WLED can be packed into a chip without thermal stability issue. Therefore, the whole system is compact. The functional light guide plate (LGP) together with an inverted prism film forms a directional backlight [29], and a front diffuser spreads the incident light to achieve wide viewing angle [30]. The employed functional LGP is specially designed that there are micro prism lines on both back and front surfaces (not shown here). Detailed design can be found in [29]. Such a system possesses advantages in wide view and negligible color shift and gamma shift [31]. Our FRP is laminated on top of LGP. The design principles and working mechanisms of FRP are discussed as follows.

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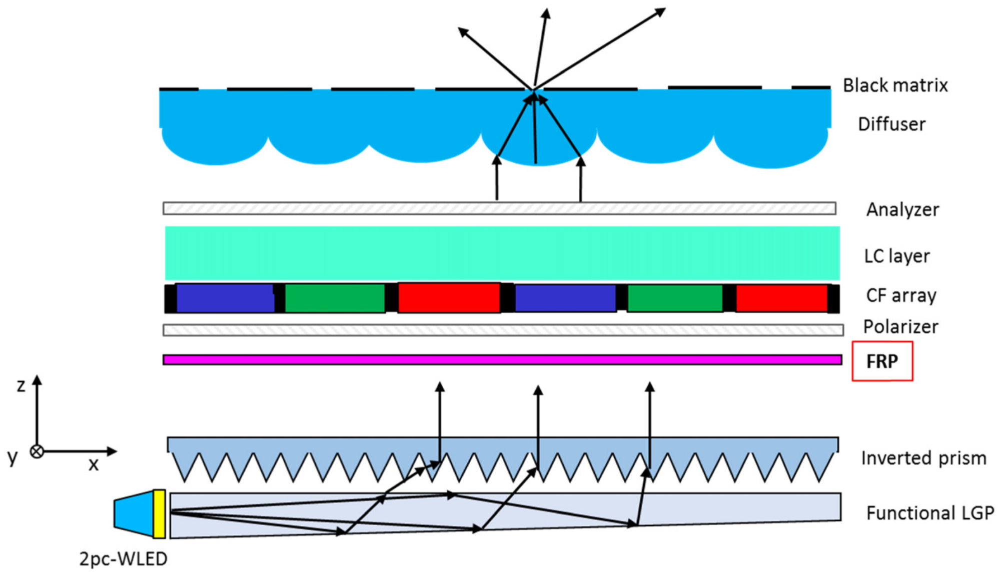

Fig. 2. Schematic diagram of the system design with a functional reflective polarizer. (LC: liquid crystal, CF: color filter, FRP: functional reflective polarizer, and LGP: light guide plate).

Figure 3(a) shows the schematic diagram of a conventional reflective polarizer [27], where in *x*-axis the refractive index alternates between n_1 and n_2. This multi-layered structure exhibits broadband reflection due to the constructive/destructive interferences. While in *y*-axis, there is no change in refractive index, enabling 100% transmittance for the *y*-polarized backlight [Fig. 3(b)]. Such a reflective polarizer has been widely used in LCD backlight system to enhance the optical efficiency by recycling the disallowed polarization. Here, we modify this structure slightly. As Fig. 3(c) depicts, it is a multi-layered structure in both axes. In *x*-axis, it works as a broadband reflector, but in *y*-axis it is designed to function as a notch filter. The transmission spectrum is shown in Fig. 3(d), where the reflection bands could be tuned to block the unwanted spectrum. The detailed design principle of FRP has been reported in [28]. Generally speaking, transfer matrix is employed to calculate the transmission and reflection spectra based on multi-layer constructive/destructive theory. This can be done using a commercial software TFCalc (Software Spectra, Inc.).

Regarding device fabrication, for conventional reflective polarizers two polymeric materials are commonly used: one is an isotropic film with refractive index n_1 (e.g. NOA81; $n_1 = 1.57$) and another is a uniaxial film with $\Delta n = n_2 - n_1$ (e.g. BL038 LC polymer; $n_2 = 1.82$ and $n_1 = 1.57$) [27, 28]. For the proposed FRP, we need one more isotropic material with refractive index n_2. In our calculations, we choose polyferrocenes with $n = 1.82$ [28, 32]. The optimized FRP consists of 791 layers and the total film thickness is 27.18 μm [28]. The detailed parameters of each specific layer are not shown here due to space limit. Based on our analysis, our FRP performs reasonably well as the thickness of each layer varies within ± 3 nm. Of course, the final performance is determined by the real fabrication capability.

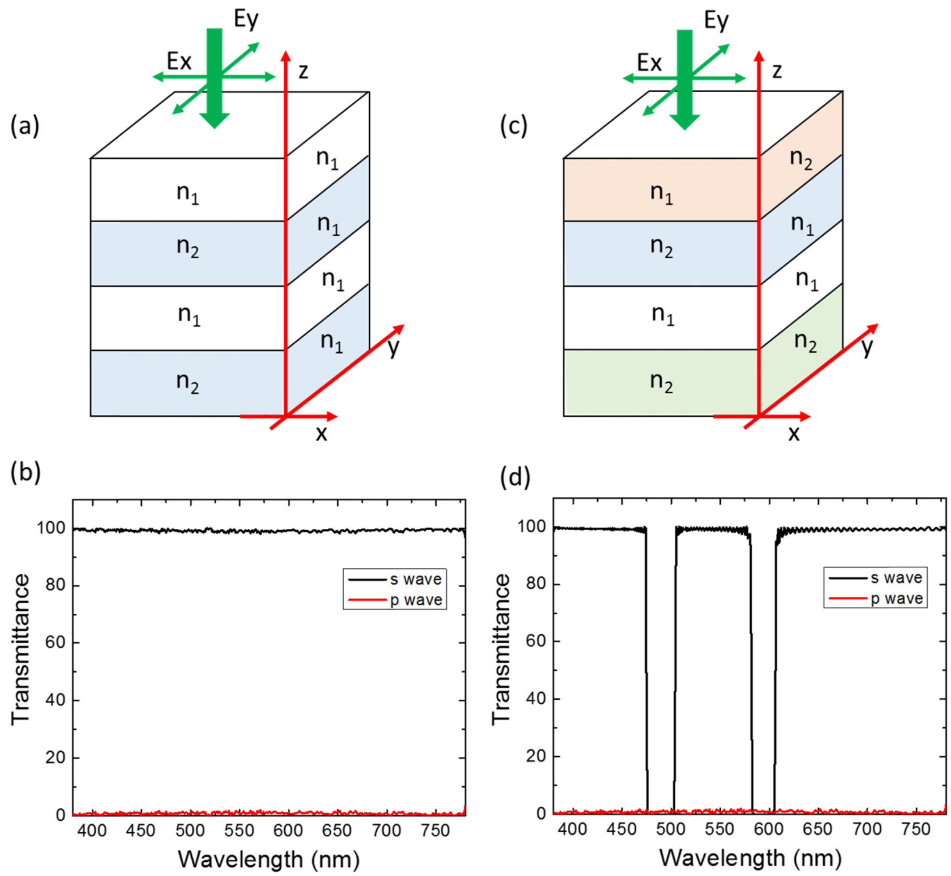

Fig. 3. Schematic diagram of (a) conventional reflective polarizer and (c) functional reflective polarizer; Transmission spectrum of (b) conventional reflective polarizer and (d) functional reflective polarizer.

3. Simulation results

Next, we integrate our FRP with 2pc-WLED backlight, and their transmission spectra are plotted in Fig. 4(a). The reflection band of FRP is specifically designed to block the crosstalk regions originated from 2pc-WLED and RGB color filters. For simplicity, here we assume the bandwidth of two reflection bands is equal, i.e. $\Delta\lambda_1 = \Delta\lambda_2 = 30$ nm. Of course, they can be different for practical applications, depending on the 2pc-WLED spectrum employed. After passing through FRP, the red, green and blue lights are well separated [Fig. 4(b)]. Then we calculate the output spectrum considering the LC layer dispersion and color filter absorption [8, 9], the obtained results are plotted in Figs. 4(c) to 4(e). As expected, the crosstalk for each color is greatly reduced; especially for green and red, the light leakage is almost completely eliminated. Even for blue light, the crosstalk bump in the green region is partially blocked. It could be further improved by tuning the reflection band or enlarging the reflection bandwidth. As will be discussed later, the trade-off is lower transmittance.

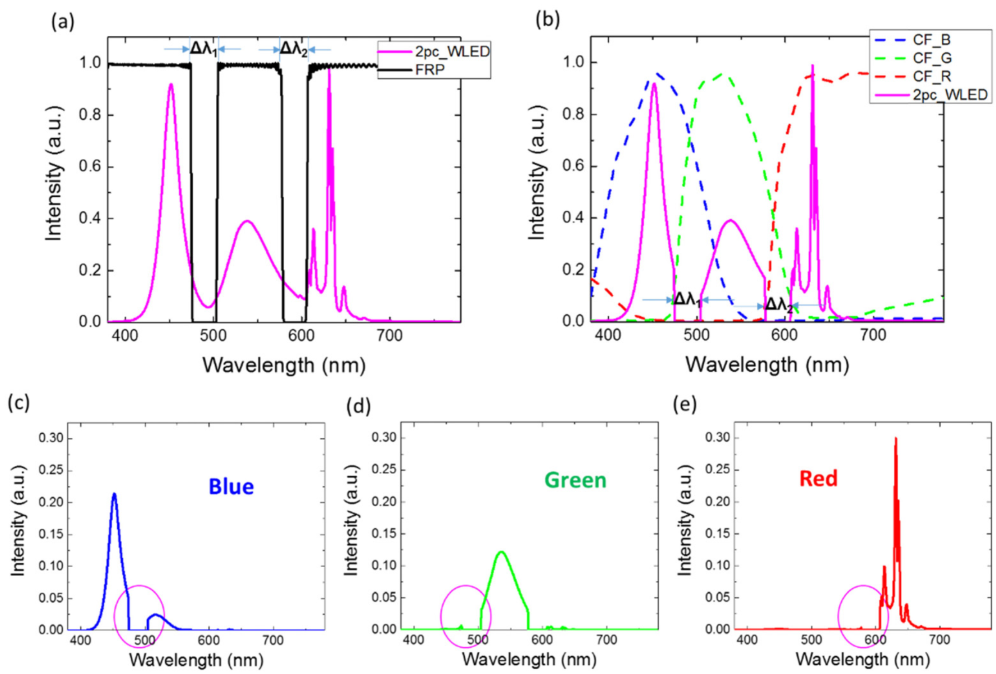

Fig. 4. (a) Spectrum for 2pc-WLED and FRP; (b) Output spectrum after FRP; (c)-(e) Output spectrum for blue, green and red sub-pixels, respectively.

Figures 5(a) and 5(b) show the simulated color gamut at CIE 1931 and CIE 1976 color space, respectively. From these two figures, we can see clearly that color gamut is widened because of purer three primary colors. As usual, NTSC is adopted as the evaluation metric, and the calculated color gamut increases from 84.4% to 93.1% in CIE 1931 color space, and from 91.9% to 105.0% in CIE 1976 color space. This is a record high color gamut for the 2pc-WLED based backlight [14]. However, the optical efficiency is decreased by 8.8% because our FRP blocks some unwanted spectrum.

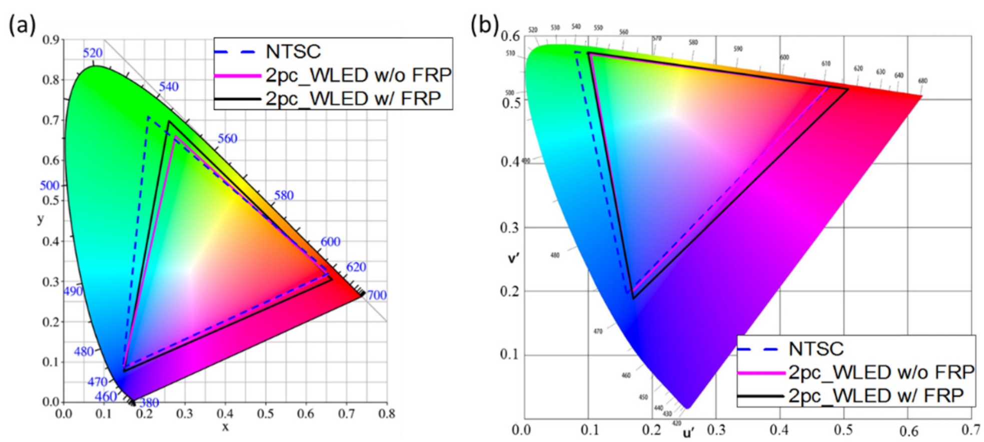

Fig. 5. Simulated color gamut for 2pc-WLED with and without FRP in (a) CIE 1931 and (b) CIE 1976 color space.

For practical applications, both color gamut and optical efficiency need to be optimized. The optical efficiency is mainly governed by the output spectra power density (SPD). The SPD directly determines the luminous efficacy of radiation (*LER*) of the system [9]:

$$LER = \frac{K_m \int S_{out}(\lambda) V(\lambda) d\lambda}{\int S_{out}(\lambda) d\lambda}, \tag{1}$$

where $S_{out}(\lambda)$ is the SPD of the output light, $V(\lambda)$ is the standard luminosity function, and K_m = 683 lm/W is the *LER* of the ideal monochromatic 555-nm source. As the *LER* is only determined by the light spectra, it sets the theoretical limit for the total efficiency of a display.

For a non-emissive display such as LCD, the SPD of the backlight ($S_{in}(\lambda)$) and the actual output light ($S_{out}(\lambda)$) can be modulated dramatically, depending on the transmission characteristics of the system. To quantify the transmission characteristics of the system, we introduce the transfer efficiency (*TE*) of the system as:

$$TE = \frac{\int S_{out}(\lambda) d\lambda}{\int S_{in}(\lambda) d\lambda}. \tag{2}$$

Then the total light efficiency (*TLE*) of the system is:

$$TLE = LER \cdot TE = \frac{K_m \int S_{out}(\lambda) V(\lambda) d\lambda}{\int S_{in}(\lambda) d\lambda}. \tag{3}$$

In our analysis, *TLE* is used as the main evaluation metric to quantify the optical efficiency. To make it more representative, all the efficiencies are normalized to the original 2pc-WLED backlight without FRP. It is worth mentioning that the decreased optical efficiency is mainly from blocking the unwanted light. The main red, green and blue spectra remain unchanged.

Table 1. Simulated color gamut and optical efficiency for the 2pc-WLED based LCDs with different FRPs

$\Delta\lambda_1 = \Delta\lambda_2$	Color Gamut (NTSC)		Efficiency
	CIE 1931	CIE 1976	
Original 2pc-WLED	84.4%	91.9%	100%
10 nm	87.5%	96.7%	96.4%
20 nm	91.3%	102.6%	92.8%
30 nm	93.1%	105.0%	91.2%
40 nm	98.5%	115.0%	82.2%
50 nm	101.2%	120.4%	74.3%
QD*	109.6%	115.6%	NA

*Here, QD spectrum is obtained using blue InGaN LED to pump CdSe-based QD nanoparticles. The RGB peak wavelengths are λ_B = 452 nm, λ_G = 535 nm, and λ_R = 632 nm, respectively. The corresponding FWHMs are $\Delta\lambda_B$ = 20 nm, $\Delta\lambda_G$ = 25 nm, and $\Delta\lambda_R$ = 25 nm.

Next, we investigate how the reflection bandwidth of FRP affects color gamut and optical efficiency. Table 1 lists the simulated results. In our calculations, we assume the same reflection bandwidth, i.e. $\Delta\lambda_1 = \Delta\lambda_2$. As the bandwidth increases, the RGB colors are separated farther, leading to less crosstalk and wider color gamut. When $\Delta\lambda_1 = \Delta\lambda_2$ = 40 nm, a color gamut of 115% NTSC can be realized, which is comparable to that of Cd-based QD. However, the incurred optical loss is about 18%. This is because the FRP blocks some unwanted spectrum from the 2pc-WLED. From Table 1, $\Delta\lambda_1 = \Delta\lambda_2$ = 30 nm seems to be a good compromise.

4. Discussion

For all the multi-layered films using constructive/destructive interferences, angular dependence is a big issue. Our FRP shares the same concern [27,28]. As the incident light deviates from normal, the transmission spectrum of FRP would shift toward the shorter wavelength region, as Fig. 6 shows. Thus, it is preferred to use a directional backlight in our design. Such a backlight (with FWHM~20°, i.e. ± 10°) has been developed and commercialized successfully [29]. The backlight power is confined within ± 20°. From Fig. 6, the reflection band shifts ~2 nm when the incident angle is 10°, and it increases to 9 nm as the incident angle increases to 20°. Such a small band shift is still tolerable for a directional backlight.

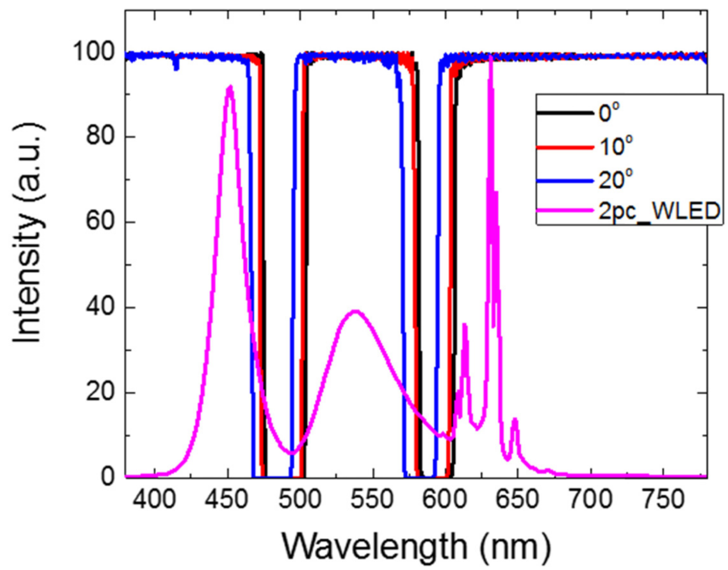

Fig. 6. Transmission spectrum of FRP for different incident angles.

Figure 7(a) depicts the color gamut as a function of incident angle. In the CIE 1931 color space, color gamut increases by 2% (from 93% to 95% NTSC) as the incident angle increases from 0° to 20°. While in CIE 1976, it is slightly decreased from 105% to 102% NTSC. As for the efficiency, it decreases slightly from 91% to 89% [Fig. 7(b)]. Therefore, our FRP works quite well for a directional backlight. If a front diffuser is employed [30], wide viewing angle, and unnoticeable color shift and gamma shift can be achieved [31].

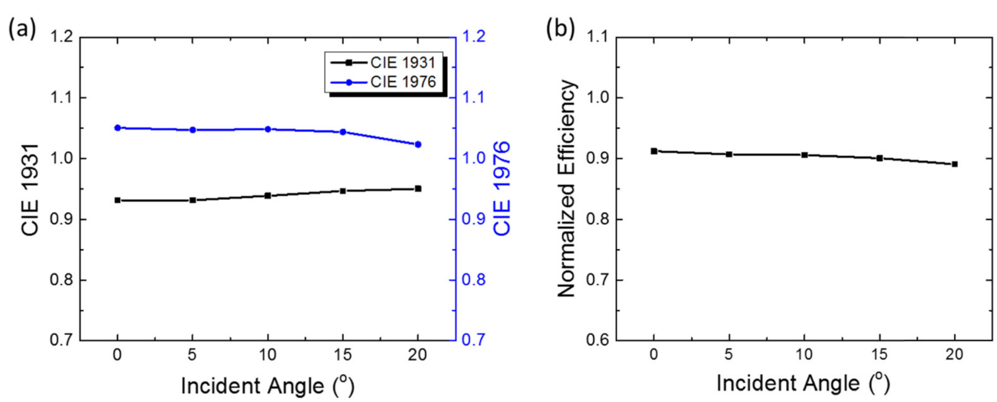

Fig. 7. (a) Color gamut and (b) optical efficiency as a function of incident angle.

So far, all the calculations are based on the high-efficiency color filters shown in Fig. 1(a). It is good for reducing the total power consumption, but the relatively large crosstalk between blue-green and green-red regions significantly shrinks the color gamut. To improve that, other narrow-band color filters can be used. For example, when we choose CF-1 in [9] and perform the calculations discussed above, the color gamut is boosted to 135% NTSC in CIE 1976. Of course, it can be further enhanced to 145% NTSC using a thicker color filter, e.g. CF-2 in [9], but the optical efficiency would be compromised. In practical applications, a delicate balance should be taken into consideration.

5. Conclusion

We propose a simple yet efficient approach to widen the color gamut of an LCD using 2pc-WLED backlight. The proposed functional reflective polarizer acts as a notch filter to block the light which would leak through the color filters, while transmitting the rest wavelength at high efficiency. When integrated with a commercial 2pc-WLED, the color gamut of the LCD can be improved from 92% to 115% NTSC standard, which is comparable to the cadmium-based quantum dot backlight. If a narrow-band color filter is employed, the color gamut can be further enhanced to 135% NTSC. Our design offers an alternative approach to quantum dots, while keeping low cost, long lifetime, and high brightness. Useful application for vivid color LCDs is foreseeable.

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