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Narrow-band high-transmittance birefringent filter and its application in wide color gamut display*

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We propose a narrow-band birefringent filter and its application in wide color gamut. The birefringent filter consists of five phase retarders and two polarizers, and it has both narrow band and high transmittance. In the experiment, we fabricate the birefringent filter using quartz phase retarders and polarizers, and apply it in serval different displays. The color gamuts of displays are enhanced more than 30%NTSC (National Television System Committee), and the widest color gamuts that have been obtained are 126%NTSC in liquid crystal displays and 138%NTSC in organic light-emitting devices. Moreover, the deep blue light in spectrum of display can be reduced using the birefringent filter. The birefringent filter can be an efficient element to achieve wide color gamut display.

Keywords: narrow band filter, wide color gamut, display

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1. Introduction

Wide color gamut, which means the vivid color, is the key characteristic of next-generation displays. Wide color gamut displays have attracted much attention in the past decades, and there have been many techniques applied in displays to achieve wide color gamut.[1,2] In liquid crystal displays (LCDs), wide color gamut is achieved by using narrow-band color filters (CFs)[3,4] and improving the backlight.[5–7] Quantum-dot (QD) enhanced films (QDEFs) based on blue light-emitting diodes (LEDs) bring LCDs into the wide color gamut era. Various QDs have been employed in LCDs with different forms, from QDEFs to QD-doped CFs, then to QD LEDs, and the color gamut of LCDs is enlarged step by step.[8–12] In organic light-emitting devices (OLEDs), color gamut is continuously enlarged by developing high-performance materials.[13–15] In other kinds of displays such as QLEDs, mini-LEDs and micro-LEDs, their narrow emitting bands of three primary colors show wide color gamut.[16,17] At present, most of the researches on wide color displays are searching for novel luminescent materials. However, except for high-performance material methods, wide color gamut can also be achieved by an optical method. An optical filter, like a function reflective polarizer,[18,19] can improve the spectrum of a display and enlarge the color gamut. The optical filter changes the emission spectrum directly, and the unwanted spectrum can be eliminated. Effect of an optical filter can be predicted accurately as it follows the basic optical principle and can be calculated by a mathematical method. Optical filters have shown excellent improvement to displays' color gamut, but structure of an optical filter is usually complex. Take the function reflective polarizer as an example, there are hundreds of layers in nm scale. Another wide color display method with the similar theory is the phosphor-in-glass (PIG) filter.[20,21] The phosphor with special absorption spectrum is doped into a glass substrate, and the unwanted spectrum is absorbed by the phosphor. However, the filter effect of the PIG filter is not as good as the function reflective polarizer.

In this paper, we report a birefringent filter (BF), which consists of two polarizers and five phase retarders, the narrow bandwidth of the transmittance spectrum can be achieved, so a wide color gamut can be obtained. Moreover, it fits LCDs with any backlight and OLEDs with any emission light spectrum.

2. The birefringent filter

The BF consists of seven layers, including two polarizers and five birefringence phase retarders (Fig. 1(a)). The polarizers are placed on the outsides, and their transmission axes are parallel. The phase retarders are sandwiched by the polarizers, and their optical-axis directions are in the following older: 45°, 90°, 45°, 0°, 45°. Here the direction of the transmission axis of polarizers is determined to be 0°. In our experiment, the phase retarders are chosen as quartz with thicknesses of 286 μm, the polarizers and phase retarders are glued together for achieving the BF (Fig. 1(a)). When light transmits through the BF, the modulations of the BF to the different-wavelength lights are different because of the color dispersion of quartz, so transmittance is wavelength-dependent. The transmittance of the BF can be calculated by the Jones matrix method.[22–24] The Jones matrix of the analyzer with 0° transmission axis is

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[1 0], and Jones matrix of the linearly incident polarized light with 0° polarization direction (or polarizer with 0° transmission axis) is $[1\ 0]^{\mathrm{T}}$ with superscript T representing transposition. The Jones matrix of phase retarder is

$$R = \begin{bmatrix} \exp(\mathrm{i}\delta) & 0 \\ 0 & \exp(-\mathrm{i}\delta) \end{bmatrix}, \quad \text{with} \quad \delta = \Delta n d/\lambda, \tag{1}$$

where Δn represents the birefringence, d is thickness of the phase retarder, and λ is the wavelength of light. When a phase retarder with its optical axis is set at azimuthal angle ϕ between the two parallel polarizers, the rotational matrix is

$$\Phi(\phi) = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix}. \tag{2}$$

The transmittance of few phase retarders between the parallel polarizers can be calculated by

$$T = \left| \begin{bmatrix} 1 & 0 \end{bmatrix} \prod_{i}^{N} \left(\Phi(-\phi) R \Phi(\phi)\right)_i \begin{bmatrix} 1 \\ 2 \end{bmatrix} \right|^2, \tag{3}$$

where i means the ith-layer phase retarder. The normalized transmittance of the BF is

$$T = \cos^2\delta \cdot \cos^4(2\delta). \tag{4}$$

From the transmittance equation, the light can transmit the BF with the maximum when the wavelength satisfies the condition of $\lambda = \Delta n d/k$ (k is an integer), and with the minimums when $\lambda = \Delta n d/(k+\frac{1}{2})$ and $\lambda = \Delta n d/(k\pm\frac{1}{4})$. In the experiment, the transmittance spectrum of the BF has three peak wavelengths corresponding to 445 nm, 524 nm and 649 nm, and the full width at half maximums (FWHMs) are 11 nm, 17 nm and 28 nm in the visible light range (Fig. 1(b)). As the light emission from the display is polarized, there is only one polarizer that is needed in the BF. The less polarizer means the higher transmittance at peak wavelength, and the transmittance of peaks is more than 80%. If we put the BF between the backlight unit and the liquid crystal panel, the DBEF in the backlight unit and the rear polarizer in the liquid crystal panel will replace the polarizers in the BF, and the peak transmittance will be about 100%. When the BF is applied in displays, the spectra of the three primary colors can be improved (Fig. 1(c)). The three primary color's photos in an LCD without/with the BF exhibit the improvement, the yellowish-green (for the green color) and orange-red (for the red color) can be seen in the normal display, and the purer primary colors can be seen in the enhanced display (Fig. 1(d)).

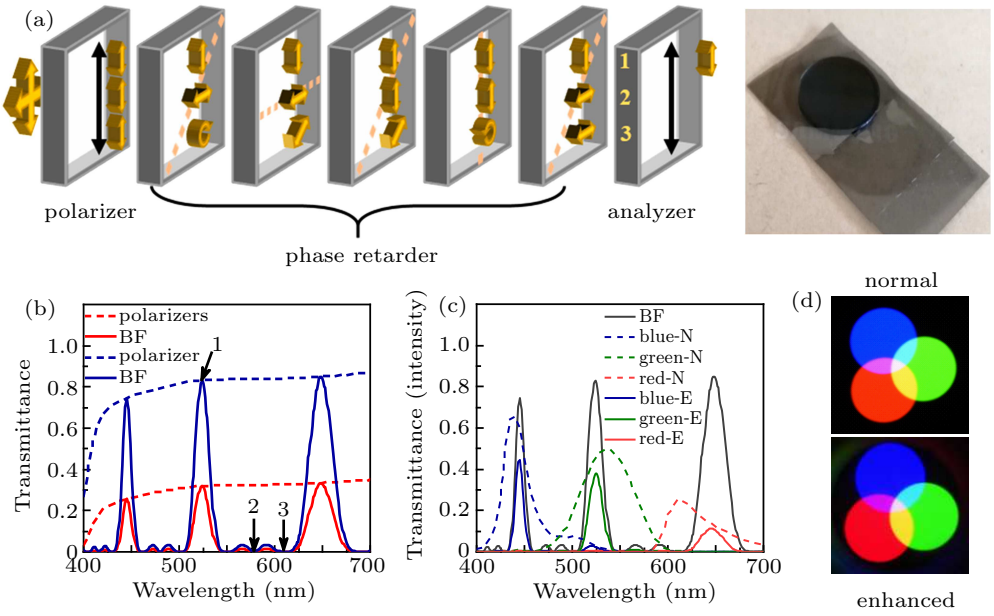


Fig. 1. The schematic diagram and the filter effect of the BF. (a) Schematic diagram of the BF which consists of two polarizers and five phase retarders. The arrows show the different changes of polarized state of three wavelengths signed by 1, 2, 3. (b) The transmittance spectrum of the BF. The blue and red dashed lines are the transmittances of two parallel polarizers, and the blue and red solid lines are the transmittances of the BF under the polarized and natural incident light, respectively, and the numbers 1, 2, 3 are for the three wavelengths in (a). (c) Effect of the BF on display. The dashed lines are the blue, green and red spectra of a display, and the colored solid lines are the enhanced spectra. (d) The photos of the three primary colors' figures in an LCD without (upper)/with (lower) the BF.

3. Wide color gamut display

3.1. Experiment measurement

We have measured five displays, including three LCDs and two OLEDs, and the original color gamuts of these displays are in the range from 85%NTSC to 104%NTSC. We number these displays as sample A (Honor 6Plus cell phone, LCD with YAG-LED backlight), sample B (Honor V9 cell phone, LCD with KSF-LED backlight), sample C (Samsung C27H711QEC monitor, LCD with QD-LED backlight), sample D (Huawei Mate 20Pro cell Phone, OLED) and sample E (Samsung S10 cell phone, OLED). We measured the spectra and color gamuts of these displays and the displays with the BF (BF-display) (Table 1).

Table 1. The spectra and the color gamut of the displays and the BF displays.

Displays			Sample A	Sample B	Sample C	Sample D	Sample E
Original	B	PW (nm)	451	451	449	457	460
		FWHM (nm)	19	19	21	21	20
	G	PW (nm)	540	540	539	530	523
		FWHM (nm)	61	45	40	38	37
	R	PW (nm)	612	/	630	621	624
		FWHM (nm)	59	/	44	37	35
	CG/%NTSC		85	91	87	94	104
Enhanced	B	PW (nm)	447	447	447	448	449
		FWHM (nm)	10	9	9	9	9
	G	PW (nm)	525	525	525	525	525
		FWHM (nm)	16	16	15	14	15
	R	PW (nm)	644	/	643	644	640
		FWHM (nm)	26	/	23	25	22
	CG/%NTSC		126	126	122	133	138

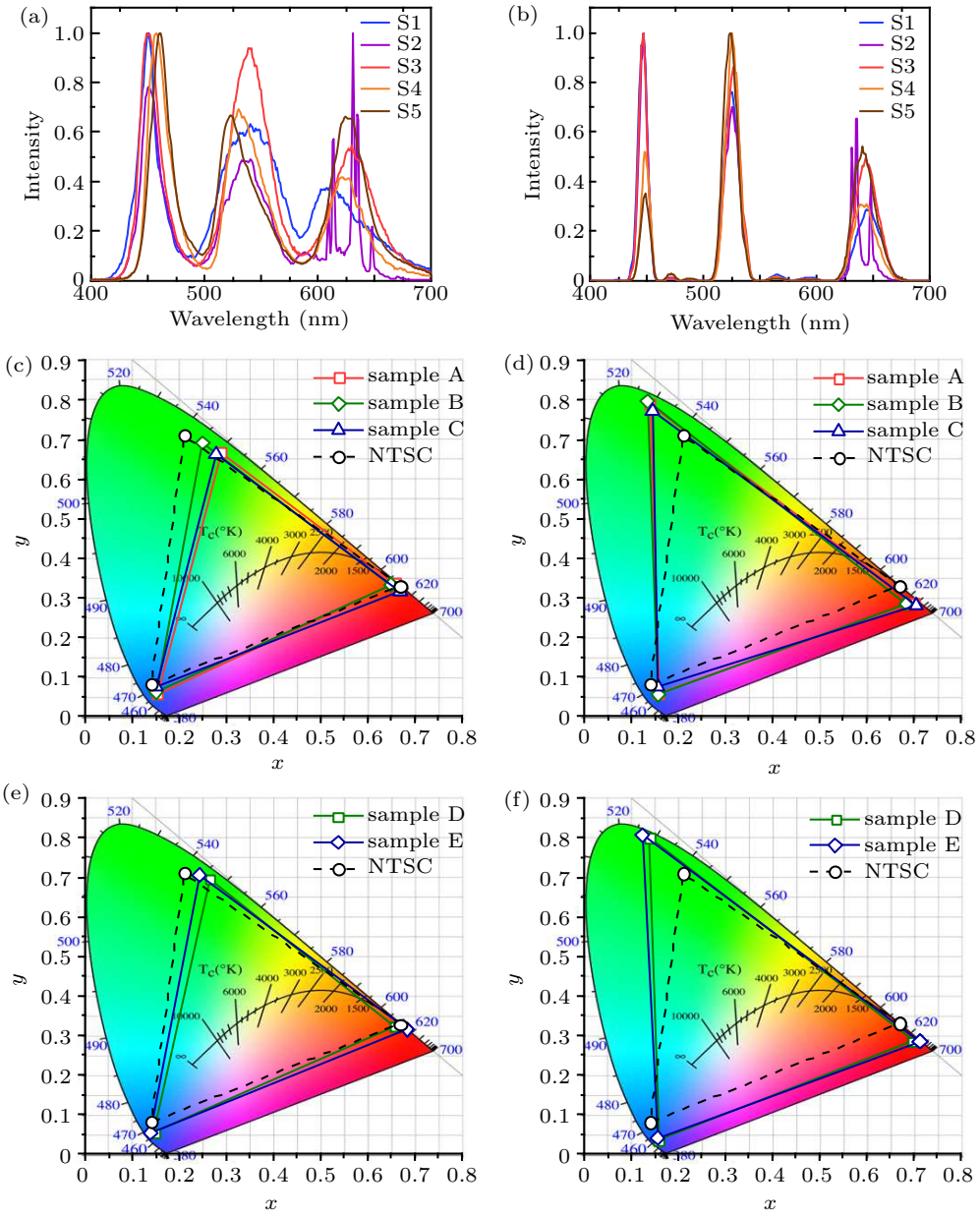


Fig. 2. The spectra and color gamut of the sample displays without/with BF. (a) The spectra of five samples without the BF. (b) The spectra of five samples with the BF. (c) The original color gamuts of these LCDs. (d) The enhanced color gamuts of the BF LCDs. (e) The original color gamuts of these OLEDs. (f) The enhanced color gamuts of the BF OLEDs.

In the LCD with the BF (BF-LCD), the first polarizer can be canceled because the light emitted from the LCD is linear polarized light. The original color gamuts of samples A, B and C were 85%NTSC, 91%NTSC and 87%NTSC, and the enhanced color gamuts were 126%NTSC, 126%NTSC and 122%NTSC, respectively. The original and enhanced color gamuts of these LCDs were shown in the CIE1931 color space (Figs. 2(a) and 2(b)), the difference among these displays was caused by the different backlight spectra and CFs. In the OLED with the BF (BF-OLED), the first polarizer was also taken off because a polarizer was in the outermost layer of an OLED. The original color gamuts of samples D and E were 94%NTSC and 104%NTSC, and the enhanced color gamuts were 133%NTSC and 138%NTSC, respectively. The original and enhanced color gamuts of these OLEDs were shown in CIE1931 color space (Figs. 2(c) and 2(d)).

3.2. Spectrum analysis

In the traditional analysis, the color gamut is connected to the peak wavelength and FWHM in the spectrum, especially when color gamut is wider than 120%NTSC for the LCD and 125%NTSC for the OLED. We have observed the narrow FWHMs (9 nm at 447 nm, 14 nm at 525 nm and 22 nm at 640 nm) in the spectra when the BF is applied in the displays. Comparing the spectrum of the BF display with that of the QD LCD or OLED which has wide color gamut, the BF displays have the better performance in the green, so we compare the green emission spectra of the BF LCD (sample A) and a QD LCD with the color gamut of 107%NTSC (Fig. 3(a)). The differences of the peak wavelengths and FWHMs in the spectra lead to the different colors, and the green chromaticity coordinates of the BF LCD and the QD LCD are (0.1374, 0.7814) and (0.2186, 0.7114), respectively (Fig. 3(b)). While the blue and red colors of the BF LCD and the QD LCD are the same, the color gamuts are 126%NTSC and 108%NTSC, respectively (Fig. 3(b)). Furthermore, we make some optimizations to the emission spectrum of the QD LCD to reduce the effect of peak wavelength and FWHM. We scale down the FWHM of the spectrum of the QD LCD by half to achieve the same FWHM to the BF LCD, and we move the peak wavelength to 525 nm (Fig. 3(a)), defined as an ideal QD LCD. The chromaticity coordinates corresponding to the improvement spectrum are (0.1649, 0.7190) (Fig. 3(b)), and color gamut is 113%NTSC (Fig. 3(b)). The tail in the spectra causes the difference in the color performances corresponding to the emission spectra with the same peak wavelength and FWHM. In the normal display, FWHM of each color is wide, so the tails' effect is very small compared with the effect of peak wavelength and crosstalk of the colors. In the ultra-wide color gamut display, the FWHM of emission peak is very small, and the tails' effect is large when the peak wavelength is the same (comparing the ideal QD LCD and BF LCD in Fig. 3(b)). Here we define the spectrum with the intensity less than half the maximum value as the tail, and we calculate the ratios of the tail in the green emission spectra of the BF LCD, QD LCD and ideal QD LCD. The ratios of the tail in the green emission spectra of the BF LCD, QD LCD and ideal QD LCD are 28%, 35% and 47%, respectively, and the results explain the difference of chromaticity coordinates corresponding to the spectra with the same peak wavelength and FWHM. The luminescent property of luminescent materials shows the high ratio of the tail, it not only affects the chromaticity coordinate of each color but also leads to the crosstalk between colors, so the tail must be reduced to achieve the ultra-wide color gamut.

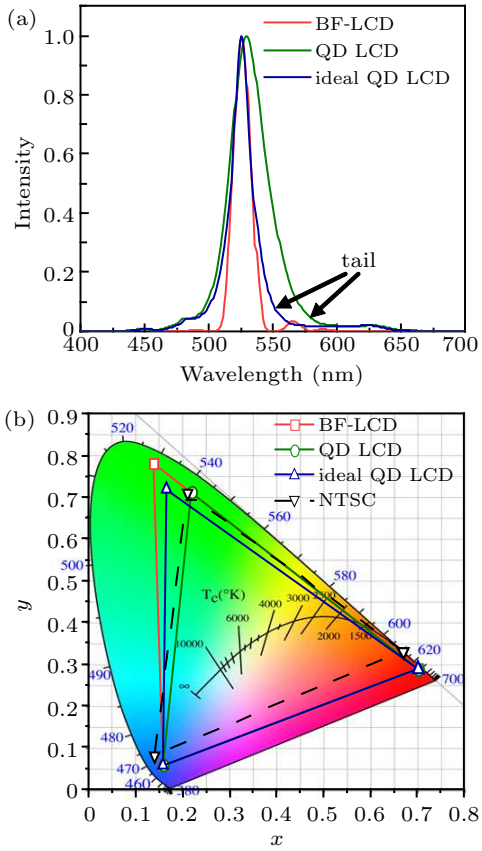


Fig. 3. The spectral characteristics of the BF displays. (a) The spectra of the green emission peaks of the BF LCD, QD LCD and ideal QD LCD. (b) The green chromaticity coordinates and color gamut of the BF LCD, QD LCD and ideal QD LCD with the same blue and red color.

3.3. Simulated calculation

In LCDs, different backlight sources and CFs show different color gamuts because of distinct emission spectra of backlight source and transmittance of CFs. Three kinds of backlights (Fig. 4(a)) and two kinds of CFs (Fig. 4(b)) are used in the calculation to analyze the effect of backlights and CFs to color gamut, color gamuts are 73.8%NTSC, 93.6%NTSC and 107.3%NTSC for the three backlight sources when CF1 is used, and color gamuts are 86.1%NTSC, 101.2%NTSC and 110.9%NTSC when CF2 is used (Fig. 4(c)). There are noticeable differences between the different backlights and CFs. When the BF is used in the LCD, color gamuts are 120.4%NTSC, 127.4%NTSC and 131.9%NTSC for CF1, and the color gamut are 121.7%NTSC, 128.7%NTSC and 132.1%NTSC for CF2. There is no obvious difference be-

tween these two CFs for one backlight source, and the differences among the three backlight sources are smaller than those without the BF (Fig. 4(c)). Application of the BF in displays not only widens color gamut to a higher level but also weakens the choice of luminescent material and CF. As a result, the material with long lifetime and high luminescent efficiency, but without good spectrum, can also be used to obtain wide color gamut.

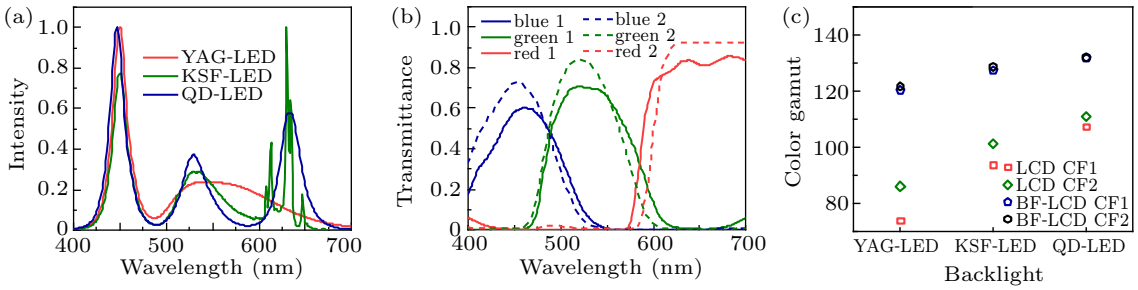


Fig. 4. The data and result of calculation. (a) The spectra of the backlights. (b) The transmittance spectra of the CFs. (c) The calculated color gamuts.

3.4. Reducing of deep blue light

The deep-blue light in the wavelength range of 400–440 nm is harmful to the human eyes,[25] and it exists in various displays because the similar blue-LEDs are used as the excitation light sources for obtaining green and red colors. The peak wavelength of blue-LEDs is nearby 450 nm to ensure the color performance, and the ratio of the deep-blue light (less than 440 nm) is at a high level because of the wide FWHM (about 20 nm). Taking a blue spectrum of an LCD as an example, the ratio of deep-blue light in the blue spectrum is 41.9%. When the BF is applied, the FWHM of blue color is reduced to about 10 nm, and the ratio of deep-blue light is reduced to 16.5%, less than half the value in the traditional display (Fig. 5). If we consider the deep-blue light in the wavelength range of 400–430 nm, the ratio of deep-blue light is reduced from 17% to 0.7%.

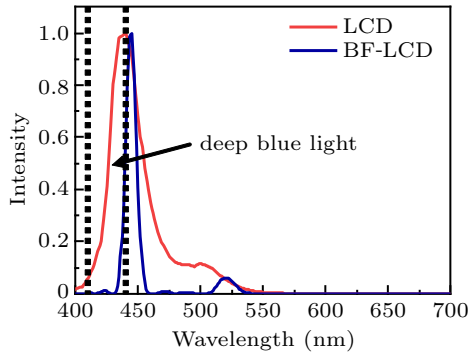


Fig. 5. The blue emission spectra of an LCD and a BF LCD.

4. Conclusion and perspectives

In summary, the BF proposed here is an effective element to obtain wide color gamut in display. In experiment, we obtain a color gamut of 126%NTSC in commercial LCDs, and we get a color gamut of 138%NTSC in commercial OLEDs, which is over the Rec.2020 standard. The enhancement of the BF to the color gamut of the commercial displays is more than 30%NTSC, and we have achieved an 41%NTSC enhancement in an LCD with YAG-LED backlight and a normal CF. When the BF is used in display, the requirement of luminescent material and CF can be reduced, and the ratio of deep-blue light can be reduced. Moreover, the phase retarder can be produced by an organic material, so the Cd-based QD or other harmful technologies can be avoided in wide color gamut display.

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