Correlated Color Temperature Tunable WLED for Smart Lighting

Haiwei Chen, Ruidong Zhu, Yun-Han Lee, and Shin-Tson Wu

College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA

Abstract

We proposed a new device structure to dynamically tune the correlated color temperature (CCT) of a white light-emitting-diode (WLED). The key component is a dynamic color filter, consisting of a liquid crystal (LC) cell sandwiched between two cholesteric LC films whose Bragg reflection band covers the blue wavelength of the WLED. Validated by experiment, our design exhibits several advantages, such as reasonably wide tuning range (6916K to 3253K), low operation voltage (~3.2 V), simple device configuration, and low cost. It is a strong contender for next generation smart lighting.

Keywords

White LED; Color temperature; Smart lighting.

1. Introduction

Smart solid-state lighting is emerging and has potential to become next generation lighting technology [1, 2]. A main feature of smart lighting is real-time tunable spectrum, resulting in tunable correlated color temperature (CCT). It enables the white light to be tailored according to different environments (e.g. weather, season, daytime, etc.) or by different purposes (working, relaxing, meeting, etc.). Background illumination has profound effects on human productivity, comfort and even health. For example, people's visual comfort, glare, and brightness perception are closely related to CCT [3]. Thus, there is great demand for CCT tunable white light-emitting diode (WLED).

To realize this goal, several approaches have been proposed [4-8]. A straightforward way is to use red, green, blue (RGB) LEDs and drive them independently [4-6]. However, the complexity from both optical and electrical components, and high cost limit its applications. Recently, CCT tunable LED with quantum dot (QD) has been proposed [7]. Its performance is good, but the voltage is fairly high [9]. Recently, our group tried to combine liquid crystal (LC) technology with LED to achieve tunable CCT WLEDs [10]. The device configuration is fairly simple and cost is low, but the dichroic ratio of the employed fluorescent dye is inadequate so that the tunable CCT range is limited.

In this paper, we proposed a new design to dynamically tune the CCT of a WLED. The key component is a dynamic color filter, consisting of a liquid crystal (LC) cell sandwiched between two cholesteric LC films whose Bragg reflection band covers the blue wavelength of the WLED. Validated by experiment, our design exhibits several advantages, such as reasonably wide tuning range (6916K to 3253K), low operation voltage (~3.2 V), simple device configuration, and low cost.

2. Device configuration

Color temperature is mainly determined by the spectral power distribution (SPD) of a light source. Typically, white light with higher CCT will have more lumens in short wavelength region and it appears more bluish. While, more lumens in longer wavelength (red or yellow light) will lead to lower CCT white light, looking more yellowish, like candle or sunset. Therefore, to tune the CCT of a light source, the basic idea is to change the relative intensity of blue (short wavelength) and yellow light (longer wavelength) [8, 10].

Based on this principle, we propose to use a dynamic color filter to control the blue light transmission, while keeping the longer wavelengths unchanged. Figure 1 shows the device configuration, where a dynamic color filter is placed above a conventional WLED. The color filter consists of an LC cell [here we use vertical alignment (VA)] sandwiched between two cholesteric liquid crystal (CLC) films.

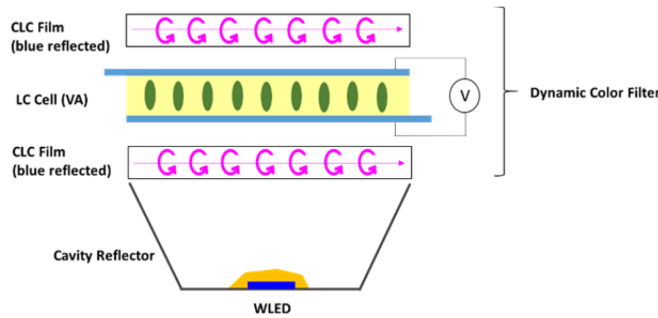

Figure 1. Device configuration of the proposed CCT tunable WLED using a dynamic color filter.

Different from commonly used rod-like nematic liquid crystals for flat panel displays, CLC is formed by rod-like molecules whose directors are self-organized in a helical structure [11, 12]. In the planes perpendicular to the helical axis, the LC directors are continuously rotated along the helical axis. Due to the helical structure, CLC exhibits Bragg reflection with central wavelength (λ_0) and reflection bandwidth ($\Delta\lambda$) as [11]:

$$p = \frac{1}{HTP \cdot c\%}, \tag{1}$$

$$\lambda_0 = \langle n \rangle \cdot p = \frac{n_e + n_o}{2} \cdot p, \tag{2}$$

$$\Delta\lambda = \Delta n \cdot p = (n_e - n_o) \cdot p, \tag{3}$$

where p is the pitch length, HTP the helix twisting power of chiral dopant, c the concentration of chiral dopant, $\langle n \rangle$ the average refractive index of LC host, n_e the extraordinary refractive index, n_o the ordinary refractive index, and Δn the LC birefringence.

From Eqs. (1) – (3), the reflection band of CLC could be controlled easily by the pitch length. Besides, to reduce the number of substrates and weight for practical applications we can use polymeric CLC films instead of cells [13]. In our design, these two CLC films reflect right-handed circularly polarized (RCP) blue light. Thus, at the voltage-off state (V = 0), only left-handed circularly polarized (LCP) blue light passes through the first CLC film, VA cell, and then the second CLC film. In this case, all the blue light goes out, leading to a high CCT. Please note that the reflected RCP blue light by the first CLC film will be reflected back by the metal cavity and converted to LCP, which means the blue light is recycled and high efficiency is obtained. At the voltage exceeds a threshold ($V > V_{th}$), the LC directors (whose dielectric anisotropy is negative, $\Delta\varepsilon < 0$) in the VA cell will be reoriented to be parallel to the substrate. In this case, the VA cell functions as a half-wave plate. It converts the transmitted LCP blue light from first

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CLC film into RCP, which is in turn blocked by the second CLC film. Thus, little blue light transmits through the dynamic filter, resulting in a low CCT.

In the whole process, the VA cell serves as a switch to convert LCP blue light into RCP, thus controlling the transmittance of the blue light. The resultant CCT can be controlled by the applied voltage.

3. Experimental results

In experiment, we doped 3.3 wt% chiral compound R5011 (HCCH, China) into LC host BL-038 (Merck, Germany) whose $n_e = 1.799$ and $n_o = 1.527$ [14]. Then we filled the mixture into two commercial homogeneous cells with cell gap $d = 8$ μm. Due to the effect of chiral dopant, LC directors are rotated helically in the CLC cell, resulting in circularly polarized reflection band, as Fig. 2 shows. As expected, the reflection band is centered at $\lambda_o \approx 450$ nm and bandwidth is $\Delta\lambda \approx 80$ nm. This band covers most of the blue light emitted from commercial blue LEDs. Please note that to prove concept, here we used two CLC cells with glass substrates, but for real applications we should use CLC polymeric films, as demonstrated in [13] in order to reduce device thickness and weight.

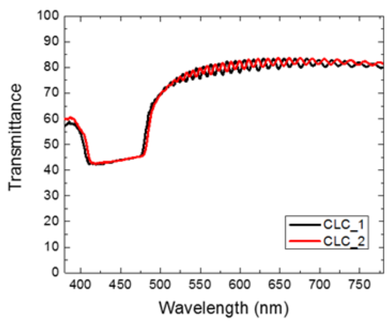

Figure 2. Measured transmission spectra of two cholesteric liquid crystal films.

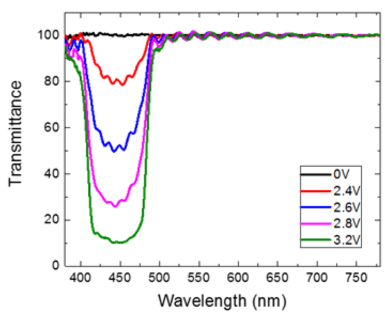

Figure 3. Measured transmission spectra of the dynamic color filters under different voltages.

For the tunable LC cell, we chose MLC-6882 ($\Delta n = 0.097$, and $\Delta\varepsilon = -3.1$) and filled it into a vertical-alignment (VA) cell made of indium tin oxide (ITO) glass substrates. The cell gap was controlled at 5 μm by spacer balls. Combining with two CLC test cells, the dynamic color filter for blue light was fabricated successfully. The transmission spectra of such a color filter were recorded by HR2000 CG-UV-NIR high-resolution spectrometer (Ocean Optics), as depicted in Fig. 3 with respect to different applied voltages. Clearly, the transmittance of blue light decreases gradually as the voltage increases. Meanwhile, the longer wavelength region remains unchanged. In the on-state voltage ($V_\pi \approx 3.2V_{rms}$) where the VA cell works as a half-wave plate, only about 10% of the blue light is transmitted. The reasons for this 10% light leakage will be discussed later. In brief, the VA cell is a half-wave plate only for a laser beam, but not achromatic for the entire blue band.

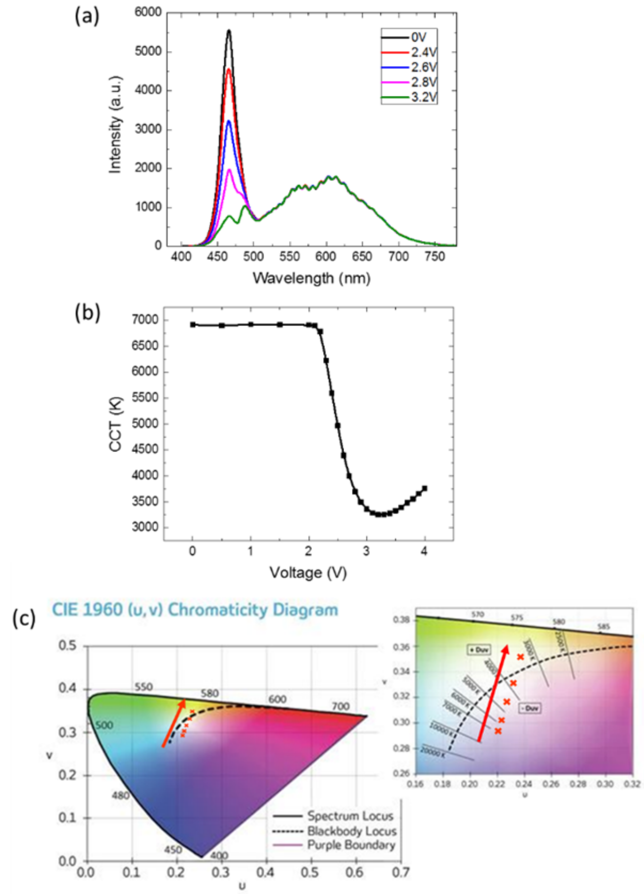

Figure 4. (a) Measured spectral power distribution of white light with different voltages, (b) relationship between CCT and applied voltage, and (c) CCT in C.I.E. 1960 chromaticity diagram obtained by different applied voltages.

In our experiment, we adopted a commercial pc-WLED (blue LED with yellow phosphor) as the light source and the measured results are shown in Fig. 4(a). Same as the results shown in Fig. 3, the intensity of blue light (405 nm ~ 485 nm) decreases as the voltage increases. The remaining part (longer wavelengths) doesn't change at all. As a result, the corresponding CCT decreases gradually, as illustrated in Fig. 4(b). Initially, the CCT of the WLED is 6916K, which is fairly high and is a cold light source. As the voltage increases, the CCT remains unchanged when V< 2 V_{rms}. This voltage is called Fréedericksz transition threshold [11], below which the LC directors won't be reoriented. Above 2V, the LCs start to bend. The polarization of the output blue light after the VA cell (Fig. 1) gradually changes from LCP to RCP so that the transmittance after the second CLC cell decreases. During this process, the CCT decreases because of less blue light. When $V = V_\pi$ (~ 3.2 V), the VA cell becomes a half-wave plate, and CCT reaches the lowest (3253K). The tuning range is about 3700K, which is wide enough for most lighting applications. If we keep increasing the voltage, the effective phase of VA cell will increase as well; then CCT will bounce back since VA cell is no longer a half-wave plate.

Next, we plot the chromaticity in CIE 1960 color space to visualize the device performance more clearly. As can be seen from Fig. 4(c), the CCT variation track from 3200K to 6900K is roughly a straight segment. Because the LC directors can be controlled continuously by the applied voltage, the CCT can be tuned precisely. But there is a concern that the CCT variation track is deviated from the blackbody locus, which may cause the light not "white". This characteristic could be quantified by the CIE chromaticity coordinates deviation (*Duv*). For real applications, *Duv* should be less than 0.005 [15, 16]. But in our case, this value is larger than 0.02 for some CCTs. To improve this, the spectrum of original WLED should be chosen carefully and some optimizations are needed. In next section, we will give one example of WLED with optimized SPD for achieving better performance.

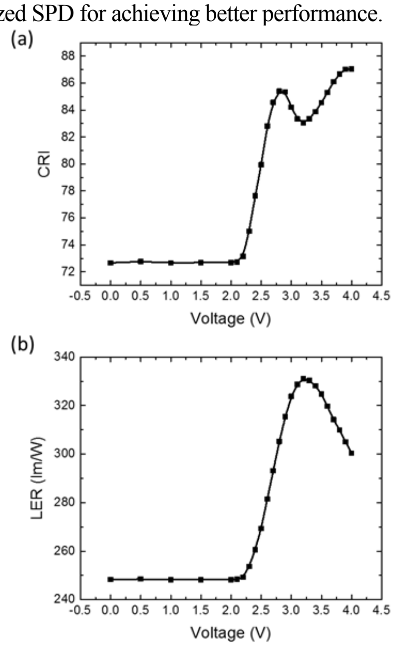

Figure 5. Measured (a) CRI and (b) LER of the light source with different voltages.

In addition to CCT, for general lighting, other parameters like color rendering index (CRI) and luminous efficacy of radiation (LER) [17] are equally important. All these properties are summarized and plotted in Fig. 5. Because of the varied spectral power distribution, the CRI and LER are tuned accordingly. Similar to CCT, there is a threshold voltage, above which, CRI and LER start to change. During the whole process, the CRI increases from 72 to 85. To boost CRI to over 90, other light sources should be employed, such as blue LED with green and red phosphors.

4. Discussion

(a) Light source

To prove concept, in our experiment we employed a commercial pc-WLED as the light source. The performance is fairly good in terms of CCT tuning range (6916K to 3253K), but the chromaticity coordinate deviation (*Duv*) is far from satisfaction because of the mismatched SPD of original WLED. To get better performance, in simulation, we slightly tuned the SPD of light source, as Fig. 6(a) depicts. The central wavelength of the blue band moves from ~465 nm (Fig. 4(a)) to 475 nm. As the voltage increases, the CCT decreases from 7500K to 3100K. At the same time, *Duv* keeps lower than 0.005, which is quite acceptable for real applications. Figure 6(b) depicts the simulated CCT in CIE 1960 chromaticity diagram. The magnified chart shows how closely the CCT follows the blackbody locus. In addition to pc-WLED, our design is also compatible to other existing light sources, including light bulbs, R/G/B WLED, emerging organic LED [18, 19], and quantum-dot LED [20-21].

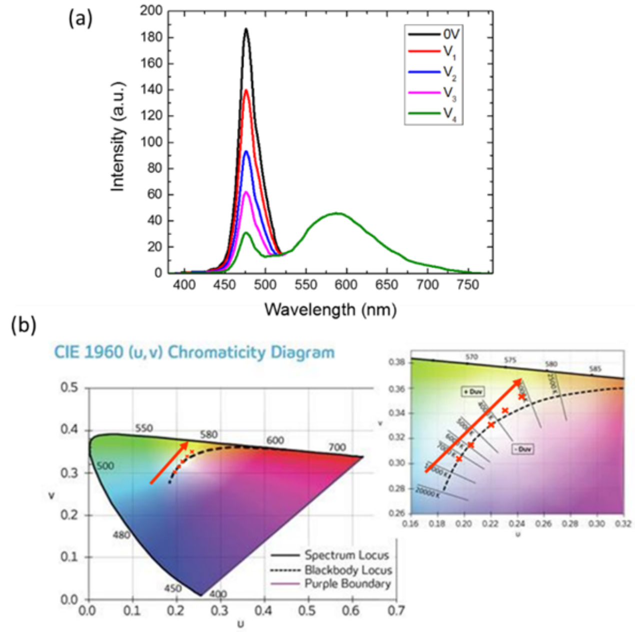

Figure 6. (a) Simulated spectral power distribution of white light with different voltages, and (b) CCT in C.I.E. 1960 chromaticity diagram with different voltages. In (b), the magnified chart shows how closely the CCT follows the blackbody locus.

(b) LC cell

Here we use vertical-alignment LC cell as the tuning part in the dynamic color filter. For practical applications, other LC modes like homogeneous (HG) LC cell can also be considered. The difference is that HG cell can be designed to work as a half-wave plate at $V = 0$. As $V > V_{th}$, the LC directors will tilt up so that the effective phase retardation decreases. In this case, blue light will be blocked initially and warm light is obtained. The CCT of the light source will increase as the voltage increases. Another parameter of LC cell is response time, which is ~5 ms in our VA cell. To get faster response, low viscosity LC materials could be used [22, 23].

Next, we investigate the dispersion effect of the VA cell. Theoretically speaking, all the blue light should be blocked if the LC cell can convert LCP to RCP completely. But due to wavelength and birefringence dispersion, our VA cell is not an ideal achromatic half-wave plate. This accounts for the ~10% blue light leakage in our experiment at $V = V_\pi$. We simulated the voltage-transmittance (VT) curves of our VA cell for three blue LED wavelengths (440 nm ~ 480 nm), and the results are depicted in Fig. 7. Clearly, for different wavelengths, half-wave plate condition is satisfied at different voltages (i.e. voltage with peak transmittance). Overall speaking, a shorter wavelength has a lower V_π. From Fig. 7, the difference in V_π for the three blue LED wavelengths is merely ~ 0.2 V.

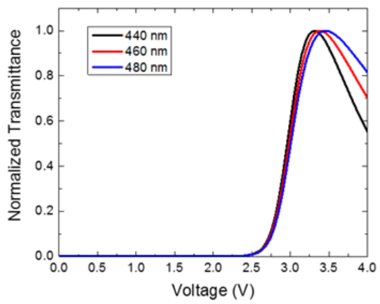

Figure 7. Voltage-transmittance curves for VA cell at three specified blue LED wavelengths.

(c) Cholesteric LC films

Based on Eqs. (1) – (3), the reflection band of CLC films could be tuned easily. Here we controlled the band to cover the blue region (405 nm ~ 485 nm). For different purposes, other reflection band could also be obtained, like green or red. If we combine several dynamic color filters together for different reflection bands (e.g. R/G/B), then the whole SPD of light source can be tuned. In this case, better performance is expected and such devices will have multiple applications other than lighting.

5. Conclusion

We have proposed a CCT tunable WLED using a dynamic color filter. This filter is comprised of a voltage-tunable LC cell sandwiched between two CLC films. By applying a voltage to the LC cell, the transmittance of blue light could be tuned precisely, and the resultant CCT changed accordingly. In experiment, we obtained about 3700K CCT tuning range, which is wide enough for most lighting applications. Meanwhile, by optimizing the SPD of a light source, we can achieve better color performances (e.g. *Duv*). Our design utilizes two mature technologies: LCD and LED. It is a strong candidate for next generation smart lighting.

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