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Tuning the correlated color temperature of white LED with a guest-host liquid crystal

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Abstract: We demonstrate an electro-optic method to tune the correlated color temperature (CCT) of white light-emitting-diode (WLED) with a color conversion film, consisting of fluorescent dichroic dye doped in a liquid crystal host. By controlling the molecular reorientation of dichroic dyes, the power ratio of the transmitted blue and red lights of the white light can be accurately manipulated, resulting in different CCT. In a proof-of-concept experiment, we showed that the CCT of a yellow phosphor-converted WLED can be tuned from 3200 K to 4100 K. With further optimizations, the tuning range could be enlarged to 2500 K with fairly good color performance: luminous efficacy of radiation (LER) > 300 lm/W, color rendering index (CRI) > 75, and Duv < 0.005. Besides, the operation voltage is lower than 5 V and good angular color uniformity is achieved with remote-phosphor coating. This approach is promising for next generation smart lighting.

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OCIS codes: (220.2945) Illumination design; (330.1690) Color; (230.3670) Light-emitting diodes; (160.3710) Liquid crystals; (230.2090) Electro-optical devices.

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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 real-time CCT tunable white light-emitting diode (WLED) depending on the use and time of the day in a variety of settings, such as indoor or outdoor.

To realize this goal, several approaches have been proposed. A straightforward way is to use red, green, blue (RGB) LEDs and drive them independently [4–6]. By properly mixing the RGB intensities, we can produce white light with any color temperatures. However, the complexity from both optical and electrical components, and high cost limit its applications [4, 7]. Recently, CCT tunable LED with quantum dot (QD) has been proposed [8]. Its performance is good, but the voltage is fairly high (typically, several hundred kV/cm electric field is needed to get proper CCT tuning range [9–11]) and device configuration is still complicated. It remains a big challenge to get a real-time CCT tunable white light source with simple configuration and low power consumption.

Dichroic dye has been employed in guest-host liquid crystal displays (LCDs) [12–14]. The main feature is the dichroism, which is a characteristic of the anisotropy of the molecular transition moment in either absorption or emission. Similar to phosphors, dichroic dyes function as color-conversion materials, and when they are dissolved as guest species in an LC host, they follow the alignment direction of the LC molecules. Once the applied voltage exceeds a threshold, the dichroic dyes will be reoriented with the LC directors [13].

Based on this principle, in this paper, we demonstrate a real-time CCT tunable WLED with a dichroic *fluorescent* dye. The key part is an electrically driven color conversion film, which is a guest-host LC. This film can be integrated easily with an existing WLED, and the color temperature could be tuned over a reasonably wide range. Moreover, the power consumption is really low because LC is a voltage device, and the operation voltage is lower than 5 V.

2. Device structure

In general, white light can be generated by mixing RGB lights together or using a blue LED to pump yellow phosphor. We call the latter as phosphor-converted white LED, or pc-WLED. By adjusting the ratios of each color composition, different correlated color temperatures can be obtained [8, 15]. In brief, a higher CCT white light contains relatively more lumens in the short wavelength region (blue) and relatively fewer lumens in the longer wavelength region (red). To illustrate this effect, we use three RGB LEDs as an example to produce white light with different CCT, and the simulated spectral power distribution (SPD) are shown in Fig. 1. From Fig. 1, the black line represents the SPD of white light with CCT = 6500 K whose lumens in blue region is almost twice higher than that of red. Increasing the red light component gradually decreases the CCT to 4500 K (red line), and then 2500 K (blue line). Here, green light intensity is kept almost the same.

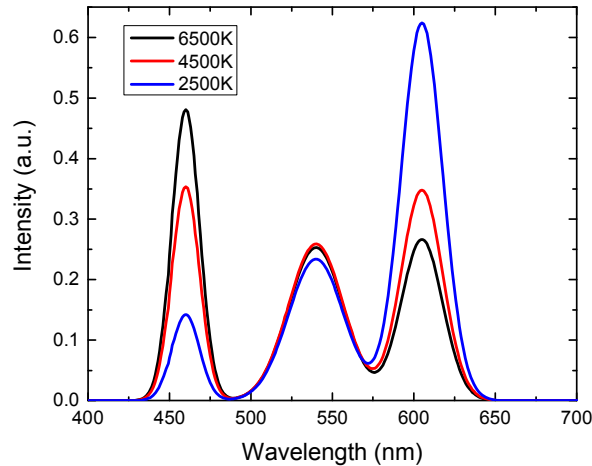


Fig. 1. Spectral power distribution of white source with three different correlated color temperatures. The three primary wavelengths are centered at R = 605 nm, G = 540 nm, B = 460 nm. (6500 K: LER = 346.9 lm/W, Duv = 0.9e-5, CRI = 82.7; 4500 K: LER = 380.5 lm/W, Duv = 1.0e-4, CRI = 81.8; 2500 K: LER = 421.3 lm/W, Duv = 4.4e-4, CRI = 76.0)

To tune the color temperature, we can adjust the blue/red power ratio. A conventional approach is to change the power of R/G/B LEDs independently. However, the required electronic circuits and algorithms are rather complicated [4–6]. Here we propose to use a color conversion film, which absorbs blue light and emits red light. Figure 2 shows the device configuration. It combines a WLED and a switchable guest-host LC cell. The LC cell is placed on top of a remote phosphor WLED to tune the blue/red ratio. With the advanced LCD

manufacturing technology, this film could be pixelated and integrated with a patterned WLED array easily.

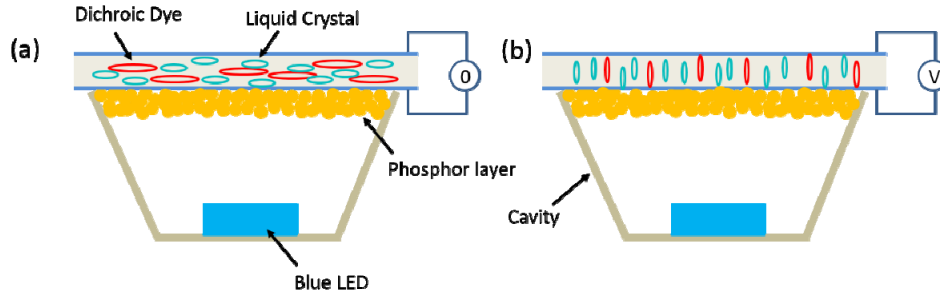


Fig. 2. Device configuration of the proposed CCT-tunable white light source with a remote phosphor WLED and a switchable guest-host LC cell as color conversion layer.

When the voltage is below a threshold ($V < V_{th}$) [Fig. 2(a)], the dichroic dyes are aligned parallel in the LC cell, resulting in a higher absorption. In this case, more blue light will be absorbed, which is converted to red light through fluorescence of the dichroic dyes. As a result, a lower CCT is obtained. When $V \gg V_{th}$, the dichroic dyes are reoriented perpendicular to the substrates by the electric field [Fig. 2(b)]. Here, we assume the employed LC has a positive dielectric anisotropy ($\Delta\epsilon > 0$). Accordingly, the white light emitted from WLED will experience a fairly low absorption by the short axis of dichroic dyes. This means less blue light component is absorbed and CCT is higher. Through the applied voltage, the blue/red ratio can be tuned precisely, leading to white light with tunable CCT. The major advantage of our device is that it works for an unpolarized white light source. For other LC-based approaches, polarizers are required in order to control the transmittance of blue light [16], thus its optical efficiency is reduced by at least 2X. Moreover, different from our design the blue light is absorbed without emission of longer wavelength in red region, which further decreases the efficiency. In contrast, our approach has advantages in simple device structure, polarization independency, high efficiency, low power, and low cost.

3. Experiment

In experiment, we used 4-(dicyanomethylene)-2-methyl-6-[p-(dimethylamino)styryl]-4H-pyran (DCM) as fluorescence dichroic dye and 4-n-pentyl-4'-cyanobiphenyl (5CB) as LC host, whose chemical structures are drawn in Fig. 3(a) and 3(b), respectively. DCM is a commonly used fluorescent dye with high quantum efficiency [17–20]. Its peak absorption wavelength is at 460 nm and emission wavelength at 610 nm [17]. We doped 1.5 wt% DCM into 5CB and filled the mixture into a homogeneous cell made of indium tin oxide (ITO) glass substrates. The inner surface of the ITO-glass was over-coated with a thin polyimide (PI) alignment layer. Silica spacers with 5 μm in diameter were evenly sprayed on top of the PI layer to maintain a uniform gap between the glass substrates. To enable widespread applications, in our experiment we employed a most commonly used WLED (blue LED with yellow phosphor) as the light source, and the transmitted spectrum was recorded by HR2000 CG-UV-NIR high-resolution spectrometer (Ocean Optics).

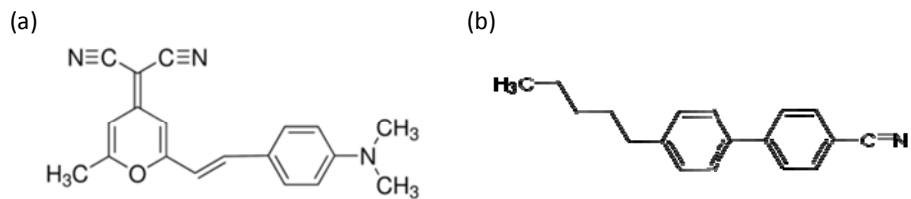


Fig. 3. Chemical structures of (a) DCM and (b) 5CB.

Figure 4(a) depicts the measured results. As expected, the blue and red (more precisely, yellow) spectra can be tuned continuously with voltage. Black line is the recorded spectral power distribution of WLED alone. At $V = 0$ (red line), a large portion of blue light is absorbed and converted to red light. Since the peak emission wavelength of DCM is in the red region (~ 610 nm) [17], the emission spectrum slightly shifts toward the longer wavelength side. As the voltage increases, the absorption of DCM gradually decreases. As a result, blue light component increases and red decreases. As plotted in Fig. 4(b), the resulted CCT increases from 3218 K to 4090 K as the voltage increases from 0 to 4.1 V. The tuning range is about 900 K. For practical applications, especially for indoor illumination, this tuning range (~ 3200 K to 4100 K) is insufficient, thus more optimizations are needed. To increase CCT and widen the tuning range, we have to employ a high-CCT white LED and increase the dichroic ratio of the dye as will be discussed in Sec. 4. The measured response time of the 5- μm guest-host LC cell is ~ 20 ms at 23°C . To shorten response time, we can choose a lower viscosity LC host [21].

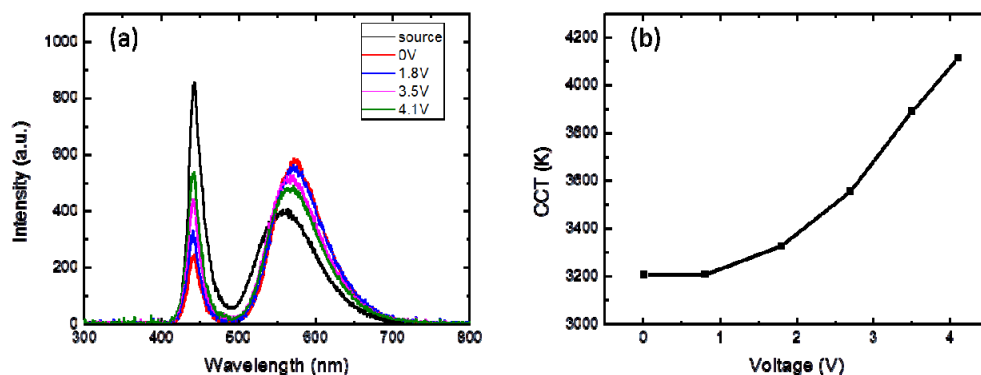


Fig. 4. (a) Measured spectral power distribution of white light with different voltages, (b) relationship between CCT and applied voltage.

Another way to visualize the device performance is to plot the chromaticity in CIE 1960 chromaticity diagram, as Fig. 5 shows. The CCT variation track is roughly a straight segment, which ranges from 3200 K to 4100 K. Because the LC directors can be controlled continuously by the applied voltage, the CCT can be tuned precisely. However, we could not obtain CCT of the original WLED (6600 K) because there is always absorption loss for the blue light even the dichroic dyes are completely reoriented perpendicular to the substrates. But this is not a big issue because we can always choose a high-CCT WLED (a thinner yellow phosphor layer) as the light source. The other concern from Fig. 5 is that the CCT variation track is deviated from the black-body locus, which may cause the light no longer be “white”. This characteristic could be quantified by the CIE chromaticity coordinates deviation (Duv), as will be discussed later.

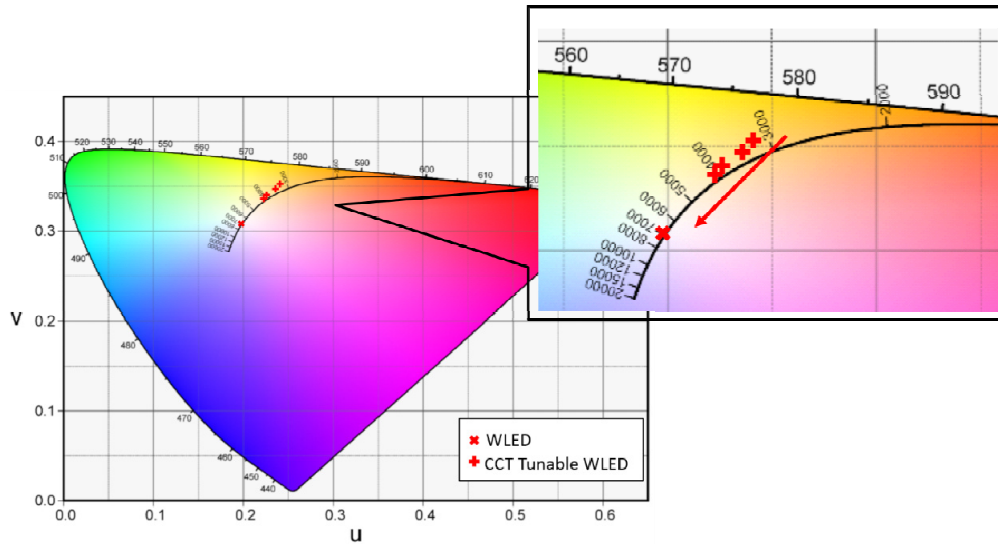


Fig. 5. CCT in C.I.E. 1960 chromaticity diagram obtained by different applied voltages.

Apart from the correlated color temperature, for general lighting, other parameters are also important, like color rendering index (CRI), luminous efficacy of radiation (LER), and CIE chromaticity coordinates deviation (Duv). All these properties are evaluated and summarized in Table 1. By comparison, the LER of our CCT tunable WLED is reasonably high, as least 50 lm/W higher than that of original WLED. But color rendering property is fairly poor, less than 50, which is too low for practical applications. Such a low CRI is mainly originated from the underperformance of original WLED with CRI = 60. Another reason is the mismatch between the emission spectrum of fluorescent dye and the SPD of WLED. For the same reasons, Duv is much larger than the typical value for practical applications ($Duv < \pm 0.005$) [22, 23]. Obviously, our device has to be optimized further to meet the standard for practical use. In Sec. 4, more details of optimizations will be discussed and one example of CCT tunable WLED with fairly good performance is given.

Table 1. Color performance of the proposed CCT tunable WLED.

Applied voltage (V)	CCT (K)	LER (lm/W)	Duv	CRI
0	3218	432.6	0.0125	41.5
1.8	3361	412.4	0.0072	43.8
3.5	3862	409.0	0.0106	45.8
4.1	4090	387.6	0.0028	47.6
Original WLED	6632	334.0	2.8e-6	59.8

For most lighting applications, good angular color uniformity is a critical requirement, which is affected by several factors, such as the placement and method of the phosphor coating of a pc-WLED [24, 25]. In our design, a guest-host LC layer is integrated into WLED chip, which will undoubtedly change the light emission pattern. However, this effect can be mitigated by the specific remote phosphor coating, as Fig. 2 depicts, since the phosphor layer and color conversion film are laminated together and they exhibit quite similar emission pattern. Then we try to examine the color uniformity of our proposed structure. This technique is similar to that described in Ref [16]. Briefly speaking, the detector was moved to

different positions, and spectral power distribution was recorded every 5 degrees. The obtained results are shown in Fig. 6. For a WLED without color conversion film, the angular CCT deviation (ACCTD) is about 1100 K, which is typical for pc-WLED without any optimization [26, 27]. When a color conversion film is inserted, the color temperature is decreased from 6600 K (black line) to 4100 K (red line), because of the absorption of blue light. Meanwhile, the obtained ACCTD is shrunk to 800 K, originating from the reduced color temperature [26]. To reduce ACCTD, the approaches employed in conventional WLED will also work for our design, like silicone lens structure [26], patterned remote phosphor structure [27], and the so-called truncated cone structure [28]. With these techniques, it is fairly easy to achieve ACCTD less than 100 K.

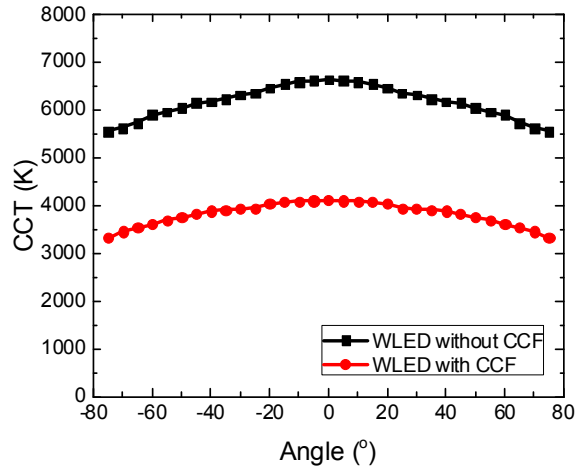


Fig. 6. Angular color uniformity of the proposed CCT tunable light source. CCF stands for color conversion film.

4. Discussion

4.1 WLEDs

In the above experiments, a WLED consisting of blue LED and yellow phosphor was employed as the light source. Obviously, other kinds of WLED, e.g. RGB LEDs, or UV-LED with RGB phosphors, are also applicable. For practical applications, the original WLED needs to be chosen carefully and be optimized in order to get a proper tuning range of CCT. Here, we did some simulations to optimize the device performance based on our experimental results. The simulated spectral power distribution is shown in Fig. 7. The employed WLED (black line) is still the simplest configuration (blue LED + yellow phosphor), but the performance is greatly improved (see data in Table 2). In our simulation, the fluorescence of dichroic dye is optimized with the central wavelength $\lambda_0 = 610$ nm, the total quantum efficiency $\Phi_F = 0.2$, and dichroic ratio $R = 10:1$ [29]. The detailed properties are evaluated and results summarized in Table 2.

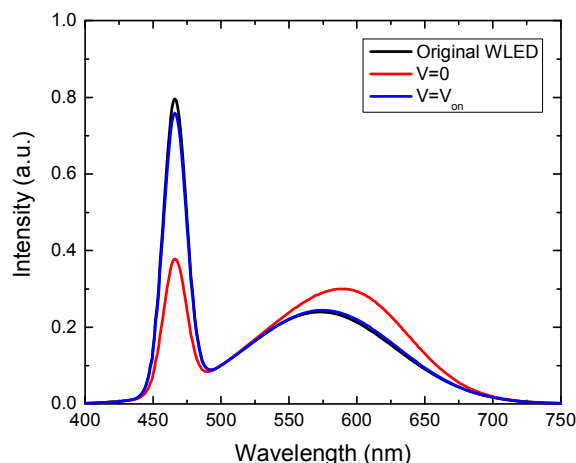


Fig. 7. Simulated spectral power distribution of white light with different voltages.

As expected, a wider CCT tuning range (>2500 K) is obtained with a larger dichroic ratio (10:1). What's more, with better choice of pc-WLED and emission spectrum of fluorescent dye, other performances are improved significantly, compared to the experimental results, which are fairly good to meet the requirements of real applications. For example, the u-v chromaticity offset (D_{uv}) is less than 0.005 to enable a “white” light, and CRI is larger than 75. For this feasibility demonstration, we used a yellow phosphor-converted WLED. If RGB LEDs or UV-LED with RGB phosphors are employed, higher CRI can be achieved [24].

Table 2. Simulated color performance based on the spectral power distribution of Fig. 7.

Applied voltage (V)	CCT (K)	LER (lm/W)	D_{uv}	CRI
0	3835	349.4	0.0034	76.7
V_{on}	6406	300.5	-0.0044	78.4
Original WLED	6991	295.8	-0.0045	77.9

4.2 Dichroic dyes

Numerous fluorescent dyes with different absorption and emission wavelengths, and dichroic ratios have been developed. To prove the concept, we chose DCM (a common dichroic dye) as the color conversion material. DCM has some drawbacks, e.g., its dichroic ratio is only ~ 2.5 [19], because its chemical structure is not linear, as shown in Fig. 3(a). In contrast, some advanced materials have dichroic ratio over 10:1 [12, 14]. When dichroic ratio is 10:1, over 2500 K CCT tuning range could be obtained easily with a 7000 K WLED. Moreover, the absorption and emission spectra of DCM are not optimal, leading to a large deviation of CCT from the black-body locus (black line in Fig. 5). By optimizing the WLED and dichroic dye's spectrum, the color performances are greatly enhanced, as shown in Table 2. In fact, non-fluorescent dichroic dyes can also be used, but the trade-off is lower efficiency than the fluorescent ones.

4.3 Liquid crystal hosts

For feasibility demonstration, in our experiment we used 5CB as the LC host, whose order parameter is relatively small because of its low clearing temperature ($T_c = 35.4$ °C). For practical applications, an LC host with a higher T_c is preferred because a higher order parameter leads to a higher dichroic ratio, which in turn widens the tuning range. Besides, we

can also optimize the fluorescent dye concentration and LC layer thickness to fine-tune the CCT for different applications. Other guest-host LC modes [30], such as vertical alignment, twisted nematic, or mixed-mode twisted nematic, can also be considered in our configuration.

5. Conclusion

We have demonstrated a real-time CCT-tunable WLED. The device configuration is quite simple where the key component is a color conversion film composed of dichroic fluorescent dye doped in liquid crystal. By adjusting the molecular reorientation of dichroic dyes, the intensity of the blue and red lights can be accurately manipulated, resulting in different CCT. In a proof-of-concept experiment, the CCT of a conventional phosphor-converted WLED can be tuned from 3200 K to 4100 K, while the operation voltage is less than 5 V. With further optimization, the tuning range could be enlarged to 2500 K with fairly good color performance: LER > 300 lm/W, CRI > 75, and Duv < 0.005. Also, good angular color uniformity is achieved with remote-phosphor coating. Different from other LC approaches, our device works well for an unpolarised white light source. Our design integrates two existing mature technologies together: LCD and LED. It holds promising applications for next generation smart lighting.

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