OPTOELECTRONICS LETTERS Vol.11 No.1, 1 January 2015

A spectrum-adjusted white organic light-emitting diode for the optimization of luminous efficiency and color rendering index*

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(Recieved 24 September 2014)

High luminous efficiency and high color rendering index (CRI) are both the foremost factors for white organic light-emitting diodes (WOLEDs) to serve as next generation solid-state lighting sources. In this paper, we show that both luminous efficiency and CRI can be improved by adjusting the green/red spectra of WOLEDs. With green emission spectra matching with the human photopic curve, the WOLEDs exhibit higher luminous efficiency and higher CRI. Theoretical calculation shows that by tuning the white emission spectra to maximally match with the human photopic curve, the luminous efficiency can be improved by 41.8% without altering the color coordinates, the color correlated temperature (CCT) and the external quantum efficiency (EQE) of the WOLEDs.

Document code: A **Article ID:** 1673-1905(2015)01-0022-4
DOI 10.1007/s11801-015-4167-2

White organic light-emitting diodes (WOLEDs) are regarded as ideal candidates to serve as next generation solid-state lighting sources[1-4]. However, the luminous efficiency and color rendering index (CRI) of WOLEDs should be further improved. The luminous efficiency of WOLEDs can be physically characterized by quantum efficiency (QE). The internal QE can be improved by employing phosphorescent emitters which harvest both singlet and triplet excitons[5,6], while the external QE (EQE) is generally enhanced by extracting the waveguide light through adjusting the substrate/air or indium tin oxide (ITO)/substrate interfaces[7-10]. The QE, which solely reflects the electron-photon conversion efficiency of WOLEDs, tells no information of the luminous efficiency. For lighting sources, it is more practical to use the photometric quantities with unit of lm/W or cd/A, which tells how much luminance has been generated per incident power/current, to evaluate the electroluminance (EL) efficiency[1,3,4]. The photometric quantities, such as luminance, are related to the spectral sensitivity of the human eye, which is described by the luminosity function. It is well known that the eyes are more sensitive to the green/yellow emission than to the blue/red emission. For example, 1 W 555 nm green emission has a maximum luminous flux of 683 lm, which is significantly higher by 2.73 lm and 260 lm than those for 1 W 420 nm blue emission and 1 W 620 nm red emission, respectively[3,11]. At a certain power, emission spectra matching with the photopic curve result in an improved luminance. Hence, by adjusting the emission spectra of WOLEDs to match with the photopic curve, the enhanced luminance and the luminous efficiency can be achieved. However, most reports focus on improving QE[5,6,12,13] and lowering down the driving voltage[14,15] to increase the luminous efficiency of WOLEDs. Few researches have been reported on adjusting the emission spectra to improve both luminous efficiency and CRI of WOLEDs, though it is theoretically feasible and effective[16].

In this paper, we investigate the relationship between the luminous efficiency and the emission spectra of WOLEDs. By employing emitters with different emission spectra, the white spectra can be tuned in a wide range while maintain the same color purity. Theoretical calculation shows that by tuning the white emission spectra to maximally overlapping with the photopic curve, the luminous efficiency can be improved by 41.8% without altering the color coordinates, the color correlated temperature (CCT) and the EQE of WOLEDs. This work offers a valuable guideline for emitter selection, structure design and spectrum adjustment to construct WOLEDs with high luminous efficiency.

To investigate the relationship between the luminous efficiency and the emission spectra of WOLEDs, the luminous efficiency is calculated firstly. According to the conversion formula from radiometry to photometry,

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* This work has been supported by the National Natural Science Foundation of China (No.61405089), and the Innovation of Science and Technology Committee of Shenzhen (No.JCYJ20140417105742713).

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the output luminance for 1 ampere input current can be calculated by[17]

$$\int nh\nu\times\frac{s(\lambda)}{\int s(\lambda)\mathrm{d}\lambda}\times R(\lambda)\mathrm{d}\lambda=$$

$$\int\eta\times\frac{1}{e}\times\frac{hc}{\lambda}\times\frac{s(\lambda)}{\int s(\lambda)\mathrm{d}\lambda}\times R(\lambda)\mathrm{d}\lambda\,, \qquad (1)$$

where n is the number of the generated photons, h is the plank constant, v and λ are the frequency and the wavelength of the emission spectra, respectively, η is the EQE of the devices, $s(\lambda)$ is the emission spectrum or the spectral power distribution, and $R(\lambda)$ is the photopic luminosity function. According to the equation, the luminance output is proportional to the area under the curve of $s(\lambda)\times R(\lambda)$. The larger the overlap area between emission spectra and luminosity function, the higher the luminance output is. Therefore, for enhancing the luminous efficiency of WOLEDs, the white spectra should be tuned to maximally overlap with the luminosity function.

Fig.1 shows the spectra of the blue, green and red emissions which are selected to create the white spectra for evaluation. As shown in Fig.1, the luminosity function has smaller response in the blue region than that in the green/yellow/orange region, so the variation of the blue spectrum has smaller impact on the luminous efficiency compared with that of the green/yellow/orange spectrum. Therefore, we fix the blue spectrum, and only change the green/yellow/orange spectrum to examine their impacts on the luminous efficiency. The blue spectrum is chosen to be the emission of BcZVBi. For the green/yellow emission, three typical spectra with Gaussian shape, full width at half maximum (FWHM) of 73 nm and central wavelengths of 515 nm, 535 nm and 555 nm are mathematically generated. The generated 515 nm green spectrum is similar with that of conventional green emitter Ir(ppy)$_3$. For the orange/red emission, two spectra with central wavelengths of 600 nm and 620 nm are adopted, which originate from the emissions of Ir(2-phq)$_3$ and Ir(btp)$_2$acac, respectively. These blue, green and red spectra are used to create the white spectra for luminous efficiency evaluation.

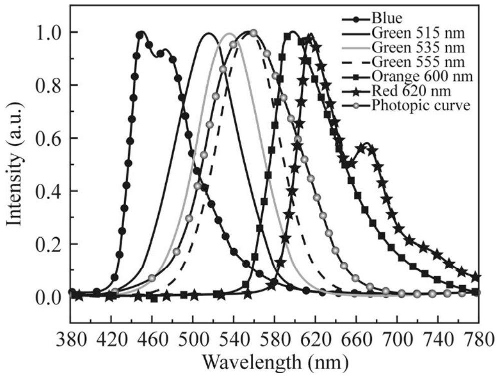
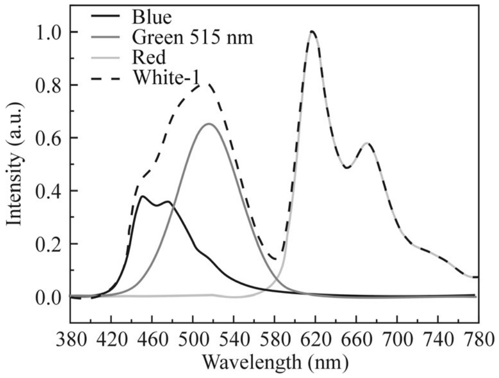


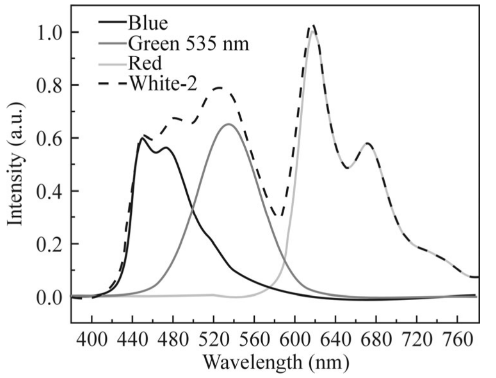
Fig.1 The red, green and blue emission spectra and the human photopic curve

Firstly, the impact of the variation of green spectrum on the luminous efficiency is examined. As shown in Fig.2(a)-(c), by adjusting the ratio of the red, green and blue emissions, the balanced white emissions with similar color purity can be obtained. For example, white-1 with 515 nm green emission exhibits Commission Internationale de l'Eclairage (CIE) coordinates of (0.35, 0.36) and CCT of 5 004 K, which are nearly the same with (0.35, 0.37) and 5 021 K for the white-2 with 535 nm green emission and (0.35, 0.37) and 5 023 K for the white-3 with 555 nm green emission. However, the luminous efficiencies for these white devices are quite different. When the green spectrum shifts from 515 nm to 555 nm, the overlap area between the green spectrum and the photopic curve gradually increases, which results in an improved luminous efficiency as predicted by Eq.(1). To simplify the analysis, we assume all white devices have the same EQE of 100% and turn-on voltage of 3 V, though in reality, the white-1 may have higher QE due to the less amount of needed blue emission, as compared in Tab.1. It should be noted that in general, the higher EQE and the lower turn-on voltage result in a higher luminous efficiency with unit of lm/W. However, as we focus on investigating the impacts of the emission spectra on the luminous efficiency, it is appropriate to assume that all devices have the same QE and turn-on voltage, so that the calculation results solely reflect the main focus. Under such an assumption, the luminous efficiency is improved from 521.1 lm/A for the white-1 to 578.5 lm/A for the white-2 and 655.4 lm/A for the white-3, which represent the improvements of 11% and 26%, respectively. Moreover, by shifting the green emission from 515 nm to 555 nm, the red, green and blue emissions become evenly distributed, therefore the CRI is remarkably improved from 56 for white-1 to 92 for white-3[18]. Through calculation, it is clear that the green spectra play a significant role on the luminous efficiency as well as the CRI. It is suggested that the green emission with central wavelength of 555 nm should be used for simultaneously achieving high luminous efficiency and high CRI.

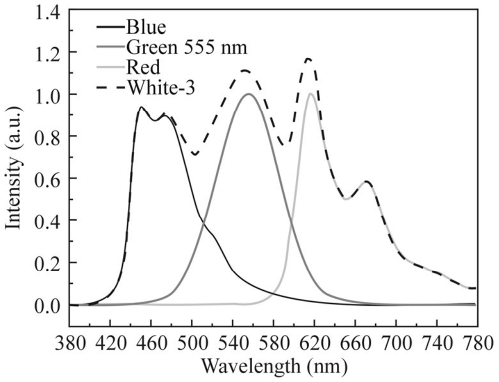
The impacts of the orange and red spectra on the luminous efficiency are then evaluated. As shown in Fig.2(d), by using the orange spectra with central wavelength of 600 nm, the optimized white-4 exhibits an improved luminous efficiency of 738.7 lm/A compared with 655.4 lm/A for the white-3 with 620 nm red spectrum, and this luminous efficiency represents an improvement of 41.8% compared with that of white-1 while maintaining the same color purity. The improved luminous efficiency is clearly attributed to the larger overlap area between the orange spectra and the photopic curve. Through the comparisons, it is clear that both green and orange spectra play a significant role on the luminous efficiency, because the human can perceive high luminance to the green/orange emission. Hence, to maximize the luminous efficiency, the green and orange emitters should be carefully selected for their emission spectra matching with the luminosity function. Assuming the shortest emission wavelength is 410 nm (3 eV), which correspondingly requires a turn-on voltage of 3 V, the theoretical efficiency limit for the white-4 is 246.2 lm/W which is far beyond the currently reported highest value of 100 lm/W[19]. The key parameters of the four devices are listed and compared in Tab.1.



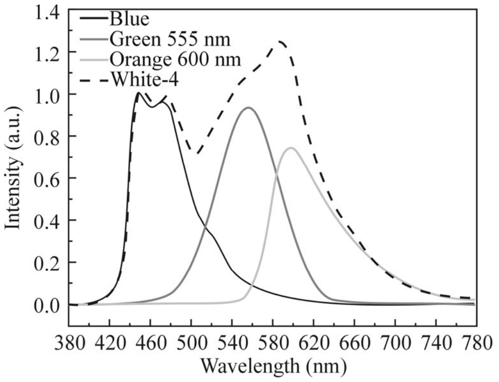
(a) White-1 with 515 nm green spectrum



(b) White-2 with 535 nm green spectrum



(c) White-3 with 555 nm green spectrum



(d) White-4 with 600 nm orange spectrum

Fig.2 The white spectra and their corresponding red, green and blue components

Tab.1 Key parameters of the white-1–white-4

Device	Blue (%)	Green (%)	Red (%)	CCT (K)	CIE (x, y)	CRI	EQE (%)	Efficiency (lm/A)	Voltage (V)	Efficiency (lm/W)
White-1	18.42	32.02	49.96	5 004	(0.35, 0.36)	56	100	521.1	3	173.7
White-2	26.67	28.89	44.44	5 021	(0.35, 0.37)	81	100	578.5	3	192.8
White-3	32.43	33.78	33.78	5 023	(0.35, 0.37)	92	100	655.4	3	218.5
White-4	37.93	34.48	27.59	5 127	(0.34, 0.37)	76	100	738.7	3	246.2

To verify the calculation, two WOLEDs were fabricated with structures of white-5: ITO/NPB/CBP:Ir(btp)$_2$(acac)/ CBP:compound-1/ CBP / CBP: BcZVBi / TPBi/LiF /Al and white-6: ITO / NPB / CBP: Ir(btp)$_2$acac / CBP:Ir(ppy)$_3$ / CBP/ CBP:BcZVBi / TPBi / LiF / Al. The only difference of these two devices is that white-6 uses Ir(ppy)$_3$ with central emission wavelength of 515 nm as green emitter, while white-5 uses compound-1 with central emission wavelength of 544 nm as green emitter. The chemical structures of Ir(ppy)$_3$ and compound-1 are shown in the inset of Fig.3(a) and (b), respectively. The thickness of each layer was carefully tuned so that the resulted white spectra have similar color purity. As shown in Fig.3, white-5 exhibits CIE coordinates of (0.31, 0.35) and high CRI of 92 due to the even distribution of red, green and blue emissions, and white-6 exhibits similar CIE coordinates of (0.34, 0.32) but remarkably lower CRI of 51 due to the weak rendition of the yellow color. The white-5 is expected to have higher luminous efficiency since its spectra are more matched with the luminosity function. Indeed, at the current density of 10 mA/cm^2, white-5 exhibits a higher luminance of 1 000 cd/m^2 and a higher luminous efficiency of 3.26 lm/W, compared with 837 cd/m^2 and 2.66 lm/W for the white-6. It is worth to note that white-5 exhibits a lower EQE of 4.7% compared with 5.29% for white-6, but its luminous efficiency is 19.67% higher than that of white-6. One may intuitionally think that higher EQE yields the higher luminous efficiency by providing that the white spectra have the same CIE coordinates. It is indicated that for WOLEDs with the same color purity, even the QE is low, higher luminous efficiency can still be achieved by simply adjusting the spectra. For fair comparison, the influence of EQE on the luminous efficiency should be deducted. Therefore, the luminous efficiency with unit of lm/W and driving voltage versus the EQE are shown in Fig.4(a), and the luminous efficiency with unit of lm/A versus EQE is shown in Fig.4(b). As shown in Fig.4, at the EQE of 5%, white-5 exhibits a luminous efficiency of 3.67 lm/W at 9.1 V (corresponding to 33.34 lm/A), which is substantially higher than 2.33 lm/W at 10.7 V (corresponding to 24.93 lm/A) for white-6. By deducting the influence of EQE and driving voltage on the luminous efficiency, the luminous efficiency with unit of lm/A is improved by 33.73%. The key parameters of white-5 and white-6 are compared in Tab.2. It is now theoretically and experimentally confirmed that by adjusting the emission spectra to match with the luminosity function, an improved luminous efficiency can be achieved.

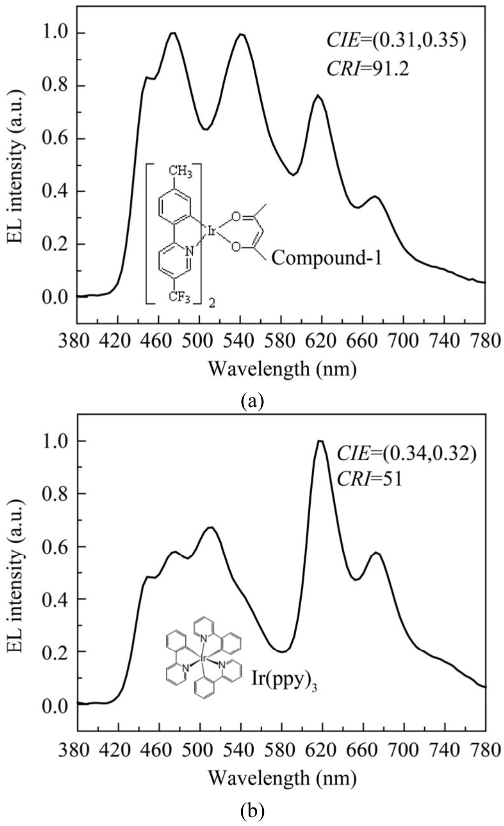


Fig.3 The spectra of (a) white-5 with compound-1 as 544 nm green emitter and (b) white-6 with Ir(ppy)$_3$ as 515 nm green emitter

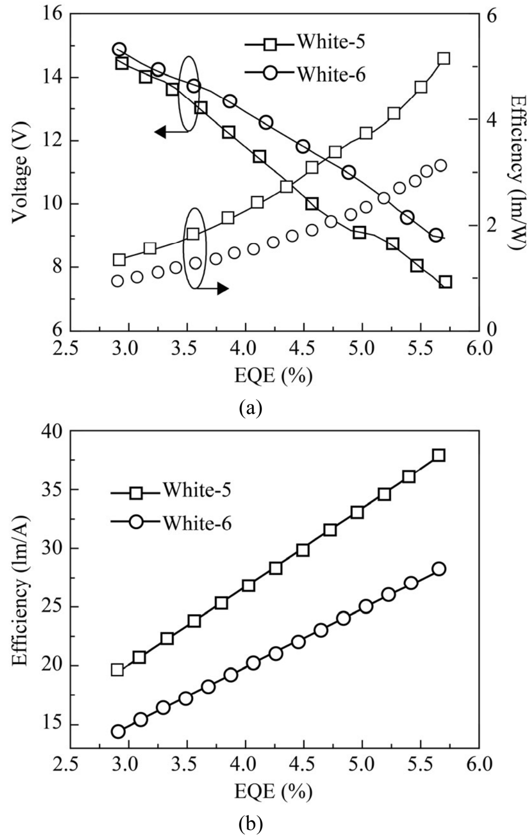


Fig.4 (a) Luminous efficiency with unit of lm/W and voltage versus EQE; (b) Luminous efficiency with unit of lm/A versus EQE

Tab.2 Key parameters of white-5 and white-6

Device	Current (mA/cm^2)	EQE (%)	Voltage (V)	Luminance (cd/m^2)	Efficiency (cd/A)	Efficiency (lm/W)	Efficiency (lm/A)	Enhancement (%)
White-5	10	4.70	9.63	1 000	10.00	3.26	31.39	19.67
White-6	10	5.29	9.86	837	8.37	2.66	26.23	-
White-5	6.89	5	9.1	732	10.65	3.67	33.34	33.73
White-6	17.81	5	10.7	1 405	7.89	2.33	24.93	-

In conclusion, due to human perception sensitivity, the spectra play an important role on the luminous efficiency, so they have to be adjusted for an improved luminous efficiency. The study in this paper points out that for maximizing the luminous efficiency, the white spectra should be adjusted to maximally match with the luminosity function. It is suggested to employ green emission with central wavelength of 555 nm and orange emission with central wavelength of 600 nm for the optimization of luminous efficiency and CRI.

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