Pure RGB Emissions Based on a White OLED Combined with Optical Colour Filters *

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We report on a white organic light emitting device (OLED) with a single light emitting layer consisting of a greenish-white emitting host bis-(2-(2-hydroxyphenyl) benzothiazole)zinc ($Zn(BTZ)_2$) and an orange-red dopant 5,6,11,12-tetraphenylnaphthacene (rubrene). The Commission Internationale De L'Eclairage (CIE) coordinates, external quantum efficiency, and brightness of the white OLED are (0.341, 0.334), 0.63% and 4000 Cd/m^2 at the bias of 20 V, respectively. Pure red-green-blue (RGB) emissions have been successfully achieved from the white OLED combined well with several built-in optical colour filters (CFs). The CIE coordinates of the white mixture calculated in theory are very close to the coordinates of the white mixture which recorded with spectrophotometer in practice.

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Since the efficient organic light emitting devices (OLEDs) were reported in 1987, an appreciable amount of research has been carried out in different fields of electroluminescence such as emitting mechanism, development of materials, application techniques and so on. During recent years, tremendous attention is highly being paid to full-colour OLED displays. Diversiform prototypes have been demonstrated by several different research organizations which took various approaches to the fabrication of displays. For example, white OLEDs combined with colour filters (CFs), stacked OLEDs with multi-emission layers and other methods.[1−3] Among these approaches, we adopt the first one to make a white OLED exhibiting pure RGB colours.

In this Letter, firstly we obtain a bright and pure white light emission from a white OLED based on a greenish-white emitting host bis-(2-(2-hydroxyphenyl) benzothiazole)zinc ($Zn(BTZ)_2$) and an orange-red dopant 5,6,11,12-tetraphenylnaphthacene (rubrene) in which the optimum doping concentration (0.05 wt.%) has been determined. Secondly, several built-in optical CFs are particularly selected to be nice match for the white OLED which regards as a white backlight. Then, the corresponding optical CFs are used in conjunction with the white OLED to achieve the pure RGB emissions. Thirdly, based on the colour mixture principles, we discuss how to obtain the white light emission mixed by the pure RGB colours from the corresponding emitting cells which are accurately controlled by the different bias. Moreover, chromaticity coordinates of a white mixture calculated in theory are very close to the coordinates of the white mixture recorded with spectrophotometer in practice.

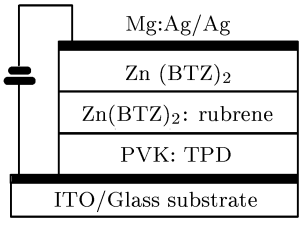

Fig. 1. The device configuration.

Poly(*N*-vinylcarbazole) (PVK) and N,N′-bis(3-methylphenyl)-1,1′-biphenyl-4,4′diamine (TPD) are purchased from TCI, while 2-(2-hydroxyphenyl) benzothiazole (HBT) and rubrene are purchased from Acros Chemicals. The chelate metal complex $Zn(BTZ)_2$ is synthesized from complex reaction between zinc acetate dihydrate and HBT in our laboratory.[4] The final powder is purified by the sublimation. The white OLED is fabricated on a pretreatment glass substrate coated with ITO (sheet resistance about 60 Ω/sq) using the conventional spin-coating and vacuum vapor deposition methods. The device configuration shown in Fig. 1 is ITO/PVK:TPD(40 nm)/$Zn(BTZ)_2$:rubrene(110 nm)/$Zn(BTZ)_2$(30 nm)/Mg:Ag(100 nm)/Ag(50 nm), where the structure consists of PVK:TPD as the hole transport layer (HTL), $Zn(BTZ)_2$:rubrene as the emitting

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layer (EML), $Zn(BTZ)_2$ as the electron transport layer (ETL), and finally Mg:Ag/Ag alloy as the cathode. The emission area is $3 \times 5\,mm^2$. In addition, the electroluminescence (EL) spectra, brightness and CIE coordinates are all recorded with a PR-650 Spectrophotometer (Photo Research). The characteristics of quantum efficiency-current density of the device are measured by the OLED quantum efficiency testing system which mainly composed of Keithley 2400 (Sourcemeter) and Keithley 485 (Picoammeter).

Several OLEDs with different doping concentrations of rubrene (1.2%, 0.15%, 0.08% and 0.05% by weight) have been fabricated. Figure 2 shows the electroluminescence (EL) spectra and the corresponding CIE coordinates of these devices. Also from Fig. 2, it is obvious that $Zn(BTZ)_2$ has a blue emission peak at approximately 464 nm and rubrene has orange-red emission peaks at approximately 552 and 602 nm. While the blue emission peak of $Zn(BTZ)_2$ decreases along with the increase of rubrene concentration from the 0.05% to 1.2%. This indicates that we can successfully achieve the pure white light emission by changing the doping concentration of rubrene in $Zn(BTZ)_2$.

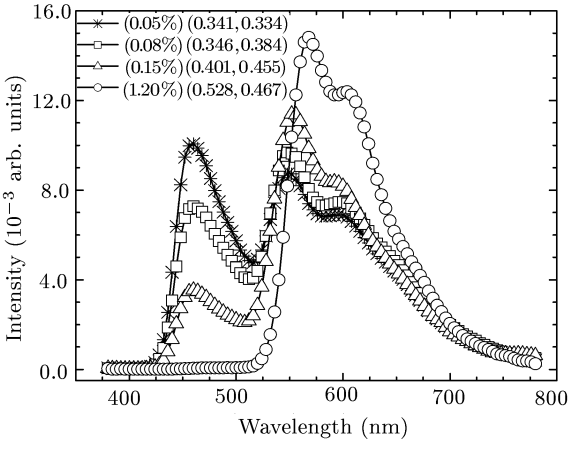

Fig. 2. EL spectra of devices with different rubrene amounts.

When the device with doping concentration of rubrene reaches at 1.2%, the OLED has an external quantum efficiency of 0.91%, a brightness of $8300\,Cd/m^2$ at the driving voltage of 20 V. However, the orange emission with CIE coordinates of (0.528, 0.467) can not satisfy our requirements. In this case, the doping concentration of rubrene decreases from 1.2% to 0.15%, further to 0.08%, and finally to 0.05%. Ultimately, the pure white emission is successfully achieved and the optimum doping concentration of rubrene is determined to be 0.05%. The external quantum efficiency versus current density curve and current versus voltage characteristics of the white OLED are shown in Fig. 3. The maximum external quantum efficiency is approximately 0.63% at 20 V. Simultaneously, the CIE coordinates and the brightness are (0.341, 0.334) and $4000\,Cd/m^2$, respectively.

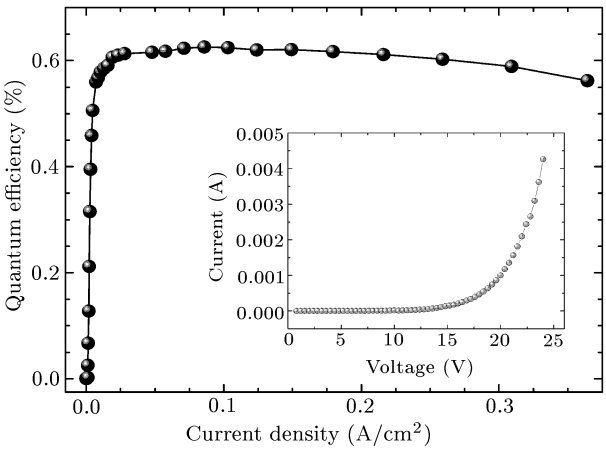

Fig. 3. Quantum efficiency versus current density curve of the white OLED. The insert shows the current versus voltage characteristics of the device.

On the other hand, several built-in optical CFs (optimized thickness approximately $500\,\mu m$) which are manufactured under our special requirements are utilized to combine with the white backlight to achieve the pure RGB emissions. In order to achieve the good colour representation, these optical CFs are selected based upon sharp spectrum eliminating unnecessary wavelengths and retaining only the necessary light. Meanwhile, the high transmission could enable the light intensity to fall slightly when the light passes through the colour filters resulting in a satisfying emission efficiency. These optical CFs also exhibit high stability against heat, light and chemical.[5] Other optimized optical characteristics also contribute to the better display such as high contrast, low reflection, and so on.

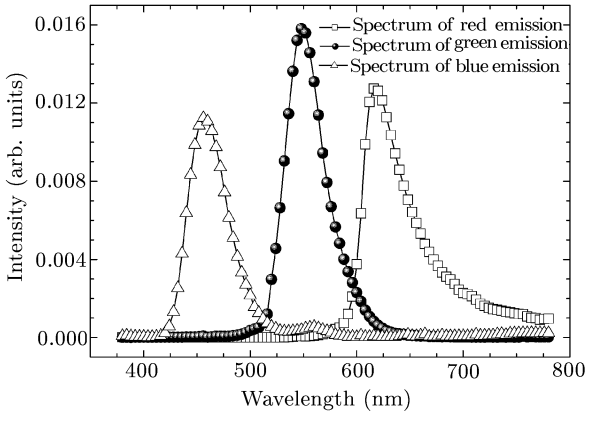

Fig. 4. Spectra of the pure RGB emissions.

Considering the stability of the above white OLED, we use the white OLED as a backlight com-

bined well with several custom-built optical CFs to achieve pure RGB emissions under the relative low driving voltages of about 10 V. The spectra of the pure RGB emissions from the backlight combined with optical CFs are shown in Fig. 4. Meanwhile, we also provide with a photograph of a white OLED exhibiting pure RGB colours in Fig. 5. The corresponding EL peaks, CIE coordinates and brightness of RGB colours are listed in Table 1.

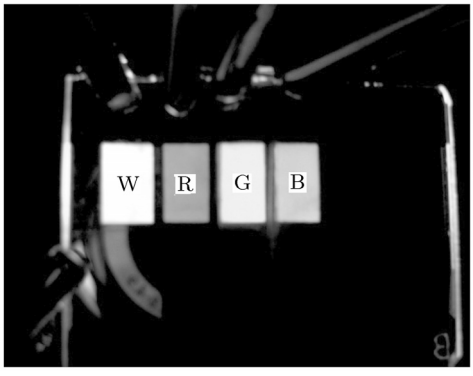

Fig. 5. Photograph of the white OLED combined with RGB optical CFs. W: white, R: red, G: green, B: blue.

Table 1. EL performance of pure WRGB emissions at 10.5 V.

Emitting colours	EL peaks (nm)	CIE coordinates	Brightness (Cd/m^2)
Red	616	(0.676, 0.322)	136
Green	556	(0.335, 0.573)	174
Blue	456	(0.147, 0.082)	121
White	460, 552 and 600	(0.335, 0.334)	550

Next, we utilize the pure RGB emissions from the white OLED whose emitting cells are driven by different biases to produce pure white emission though additive colour mixture methods in which the pure RGB colours are mixed. For example, the brightness and chromaticity of the RGB colours are known from Table 1. The tristimulus values of every colour can be computed by use of the formulae,

$$\begin{aligned} X &= \frac{x}{y}Y, \\ Y &= Y, \\ Z &= \frac{1-x-y}{y}Y, \end{aligned} \tag{1}$$

where X, Y, and Z are the tristimulus values of one colour, and x and y are chromaticity coordinates. Particularly, tristimulus value Y is equal to brightness of corresponding colour.[6] Furthermore, if three colours of light whose tristimulus values are X_1, Y_1, Z_1, X_2, Y_2, Z_2, and X_3, Y_3, Z_3, the tristimulus values X_s, Y_s, and Z_s of the mixture would be expressed as[7]

$$\begin{aligned} X_s &= X_1 + X_2 + X_3, \\ Y_s &= Y_1 + Y_2 + Y_3, \\ Z_s &= Z_1 + Z_2 + Z_3. \end{aligned} \tag{2}$$

Thus the chromaticity coordinates of the mixture could be obtained. Here, based upon Eqs. (1) and (2), we can calculate the CIE coordinates and brightness of white mixture which are (0.343, 0.332) and 265 Cd/m^2 when the RGB emitting cells driven by the different biases are 6.5 V, 11.2 V and 6 V respectively. From Table 2, the CIE coordinates of the white mixture calculated in theory are very close to the coordinates of white mixture measured by PR-650. Especially, not only the white mixture, but other mixture colours would be achieved as long as the RGB emitting cells based on different biases could accurately controlled by the driver circuit.

Table 2. EL performance of white emissions obtained by different approaches.

White emission	CIE coordinates	Brightness (Cd/m^2)
White mixture calculated in theory	(0.343, 0.332)	265
White mixture measured by PR-650	(0.338, 0.331)	252

In summary, we have presented a novel white OLED fabricated with a greenish-white emitting host $Zn(BTZ)_2$ and an orange-red dopant rubrene (optimum loading level is 0.05 wt.%). The stable white OLED is used in conjunction with several custom-built optical CFs to achieve the pure RGB emissions. Based upon the colour mixture principles, white mixture can be successfully obtained from the RGB emitting cells driven by different biases. Moreover, our experiments indicate that white and other mixture colours would be possibly achieved which will contribute to applications of a white OLED combined with optical CFs to produce a full-colour display.

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