A tunable lighting system integrated by inorganic and transparent organic light-emitting diodes

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A tunable surface-emitting integrated lighting system is constructed using a combination of inorganic light-emitting diodes (LEDs) and transparent organic LEDs (OLEDs). An RB two-color LED is used to supply red and blue light emission, and a green organic LED is used to supply green light emission. Currents of the LED and OLED are tuned to produce a white color, showing different Commission Internationale d'Eclairage (CIE) chromaticity coordinates and correlated color temperatures with a wide adjustable range. Such an integration can compensate for the lack of the LED's luminance uniformity and the transparent OLED's luminance intensity.

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As an electroluminance device, organic light-emitting diode (OLED) is suitable for general lighting because of its salient features, such as surface emission, flexibility and transparency[1,2]. However, the development of high-brightness OLEDs is hindered by the low luminous intensity of OLEDs. At high luminance, organic molecules are degraded significantly by Joule heating, which shortens the device lifetime[3–6]. Moreover, the applications of OLED panels for the general lighting system and color tuning are limited by their high cost. As a high-luminous-intensity light source, LED is widely used as illuminating lamp for road lighting, flood lighting and square lighting. However, within the framework of large-area surface emission, the use of LEDs as spot light source must be arrayed, which may require a heavy heat sink and complicated light distribution. Several new lighting systems, where organic and inorganic LEDs are coupled, can overcome these problems. One scheme is to deploy side-view LEDs on one side of the glass substrate of OLED panels[7]. The other scheme is to deploy an LED bar on one side of a transparent light guide plate (LGP) and an OLED panel on the rear surface of the LGP[8]. Although the methods above have obtained a high luminous efficiency and color rendering index (CRI), the structures of the systems are complicated. The luminous efficiency of OLEDs is highly reduced by the light leakage and low optical transmittance of the LGP. Acquiring different correlated color temperatures (CCTs) and Commission Internationale d'Eclairage (CIE) coordinates is difficult because white light emissions are integrated by two light emissions.

In this study, we investigate a new structure combining RB two-color LED and transparent green OLED (Fig.1). An RB two-color LED chip is mounted on the cooling plate. A reflecting shade is utilized to reflect and recycle the light from the RB two-color LED and the transparent OLED. A diffused reflection plate is used to obtain an LED with good lighting uniformity. The structure of LED is composed of a cooling plate, a reflecting shade and a diffused reflection plate. Red and blue chips could be tuned on the RB LED. Thus, different light emissions could be obtained by tuning three color light emissions. By tuning the currents on the LED and OLED, we obtain a luminous efficiency of 9.69 lm/W at a luminance intensity of 1003 cd/m^2, a color rendering index (CRI) of 87.9, and a CCT of 7761 K.

For experiment, we purchased a transparent green OLED (efficient emitting area is 30 mm×40 mm) from Visionox Technology Co., Ltd.. Although the OLED is rectangle, which is different from that shown in Fig.1 (round), discussing the function and advantages of this tunable lighting system is still effective. Fig.2 shows the images of the RB LED emission, the transparent OLED emission and the integrated lighting system. We can obtain white light emission from the lighting system (circle region) by combining the purple LED emission with the

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green OLED emission.

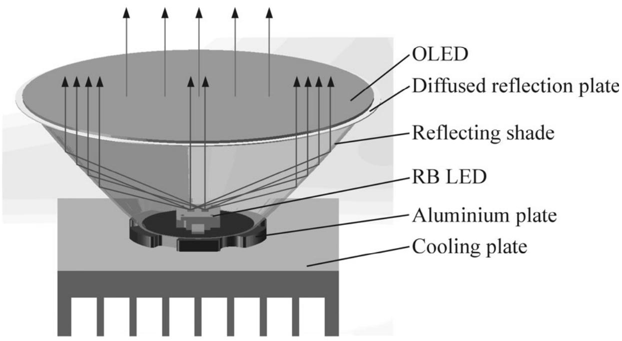
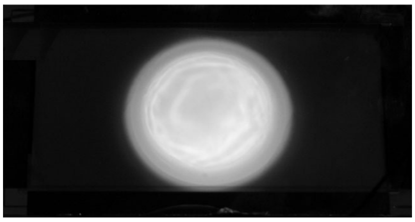
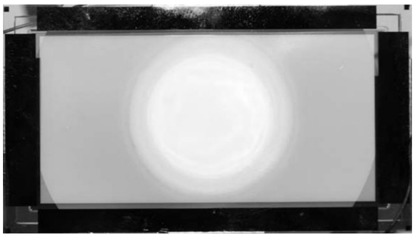


Fig.1 Structure of the integrated lighting system



(a)

(b)



(c)

Fig.2 Images of (a) the RB two-color LED emission, (b) the transparent OLED emission, and (c) the integrated lighting system emission

The measured lighting spectra of the system (LED emission, OLED emission and integrated lighting system emission) when two-color LED chips are connected in series are shown in Fig.3. The blue LED chip, green LED chip and green transparent OLED show the peak luminous intensities at 465 nm, 625 nm and 515 nm, respectively.

The optical parameters of the integrated lighting system are tested when the currents of LED and OLED are tuned. The emitting spectrum, luminous efficiency, CCT[9] and CRI[10] of the lighting source are measured by a spectrum analysis system (PMS-80, Everfine Co., Ltd.). The luminance uniformity and intensity are measured using a source imaging goniometer (SIG-400, Radiant Zemax Corporation) and a luminance meter (LM-3, Everfine Co., Ltd.), respectively.

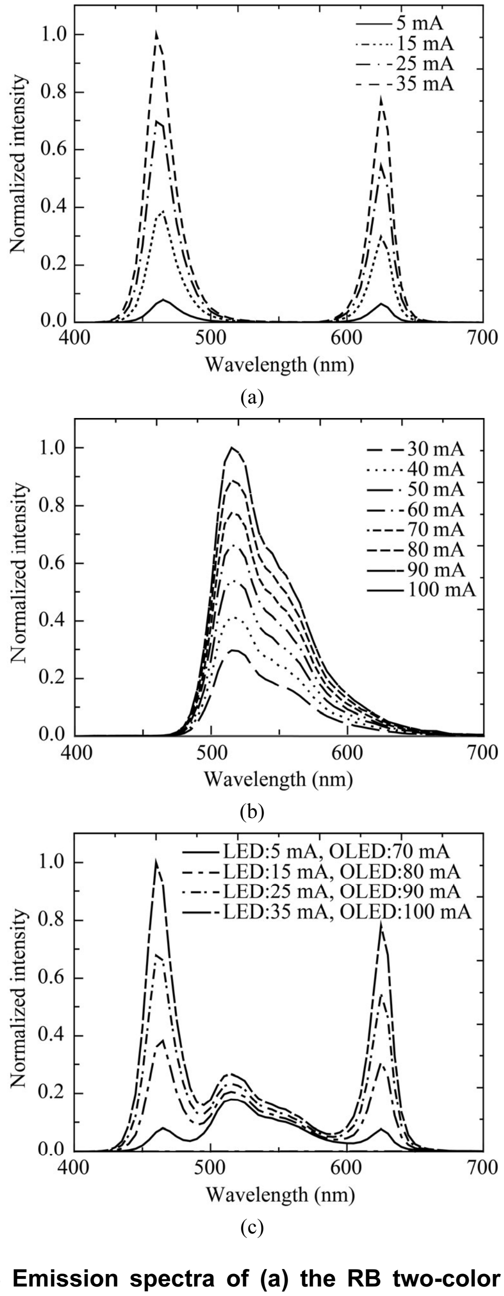


Fig.3 Emission spectra of (a) the RB two-color LED (series connected) emission, (b) the transparent green OLED emission, and (c) the integrated lighting system emission

The red LED chip, blue LED chip and green OLED are driven by three power supply systems to obtain different CCTs and CIE coordinates. Tab.1 shows the CIE coordinates, CCTs and CRIs of the combined white light after adjusting the currents of the LED and OLED. The CIE coordinates of the blue LED, red LED and green transparent OLED are (0.14, 0.04), (0.69, 0.31) and (0.19, 0.72), respectively. When the OLED current is maintained at 100 mA and the red and blue LED chips are tuned, CIE x can be tuned from 0.19 to 0.46, CIE y can be tuned from 0.21 to 0.43, and CCT changes from 2862 K to 100000 K (Tab.1). The CIE coordinates of the three-color light emissions are shown as circle, and those of the integrated system are shown as star in Fig.4. When the LED current is maintained at 20 mA and the green OLED current is tuned from 40 mA to 90 mA, CIE x is almost 0.29, CIE y can be tuned from 0.22 to 0.31, and CCT changes from 8726 K to 100000 K (Tab.1). Thus, the integrated system can be used to obtain different CIE coordinates and different CCTs with a wide adjustable range. A high CRI can also be acquired by setting the LED and OLED currents at 15 mA and 100 mA, respectively.

Tab.1 CIE coordinates and CCTs of the integrated white light source

LED		OLED	Integrated system				
Red chip current (mA)	Blue chip current (mA)	Current (mA)	CIE x	CIE y	CCT (K)	CRI	S/P ratio
40	5	100	0.46	0.43	2862	57.3	1.68
35	10	100	0.40	0.38	3577	57.8	2.06
30	15	100	0.35	0.34	4779	59.2	2.47
25	20	100	0.31	0.31	7015	62.2	2.89
20	25	100	0.27	0.28	13465	72.5	3.40
15	30	100	0.23	0.25	54800	80.9	3.86
10	35	100	0.21	0.23	100000	75.7	4.34
5	40	100	0.19	0.21	100000	56.0	4.81
15	15	100	0.28	0.35	7761	87.9	3.22
20	20	40	0.29	0.22	28930	12.8	3.75
20	20	50	0.29	0.24	15694	28.9	3.55
20	20	60	0.29	0.26	12321	42.3	3.42
20	20	70	0.29	0.27	10783	53.1	3.31
20	20	80	0.29	0.28	9820	62.1	3.21
20	20	90	0.29	0.30	9159	69.2	3.14
20	20	100	0.29	0.31	8726	75.2	3.07

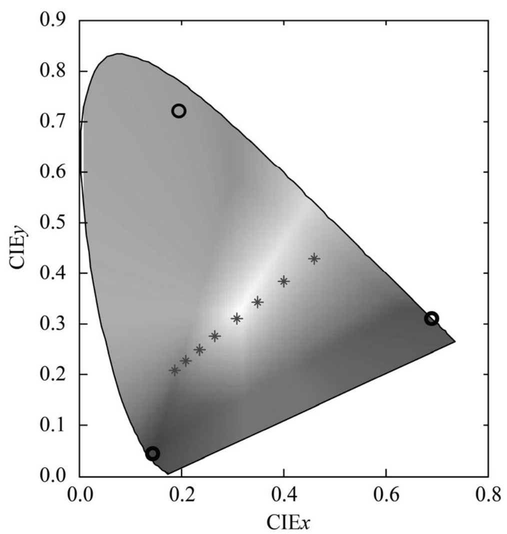


Fig.4 CIE coordinates for different tuning currents

The scotopic/photopic (S/P) ratio is a criterion that is related to eye vision and energy saving[11–13]. A light source possessing a higher S/P ratio yields better perception of brightness and better visual acuity[12]. Under the same luminous level, the higher the S/P ratio becomes, the more the eye pupils shrink. The S/P ratio can be calculated as follows[11]:

$$S/P=\frac{K'}{K}=\frac{1700\times\int_{380}^{780}S(\lambda)V'(\lambda)\mathrm{d}\lambda}{683\times\int_{380}^{780}S(\lambda)V(\lambda)\mathrm{d}\lambda}\quad,\tag{1}$$

where K' denotes the luminous flux of a light source according to the CIE scotopic spectral luminous efficiency function, K stands for the luminous flux related to the CIE photopic spectral luminous efficiency function, $S(\lambda)$ is the spectral power distribution of a light source, $V(\lambda)$ is the normalized CIE photopic spectral luminous efficiency function, and $V'(\lambda)$ is the normalized CIE scotopic spectral luminous efficiency function. The corresponding S/P ratios of the integrated system are also shown in Tab.1. Thus, the integrated lighting system can acquire different S/P ratios.

Then, the two-color RB chips are connected in series. We test the luminous efficiencies of the two-color RB LED and the transparent OLED at different installations. The measured luminous efficiencies of the two-color RB LED and the transparent OLED are shown in Fig.5. The RB LED shows a luminous efficiency of 35.12 lm/W at 20 mA. A reflecting shade and a diffused reflection board are used as a secondary optics design to obtain the surface emission. After the secondary optics design, the luminous efficiency is reduced to 23.76 lm/W. The reduction can be attributed to the incapacity of the reflecting shade to completely recycle the LED light. It can also be attributed to the diffused reflection board that acts as a light attenuator. When covered with the OLED, the luminous efficiency is reduced to 13.26 lm/W. This reduction in luminous efficiency is induced by OLED reflex and absorption.

The transparent OLED itself shows the luminous efficiency of 13.38 lm/W at 50 mA. With LED structure, the luminous efficiency of OLED is reduced to 9.53 lm/W. This reduction is caused by the absorption of the LED structure. The luminous efficiency of the LED is higher than that of the OLED. Therefore, OLED's low luminous efficiency can be improved by integrating LED and OLED.

Tabs.2 and 3 show the test electrical and luminous parameters of the integrated light source when the red LED chip, blue LED chip and green OLED are driven separately. When the OLED luminous efficiency is 8.75 lm/W at 100 mA, combined with the LED (currents of the red chip and blue chip are 40 mA and 5 mA, respectively), the luminous efficiency of the integrated system can reach 10.3 lm/W (Tab.2).

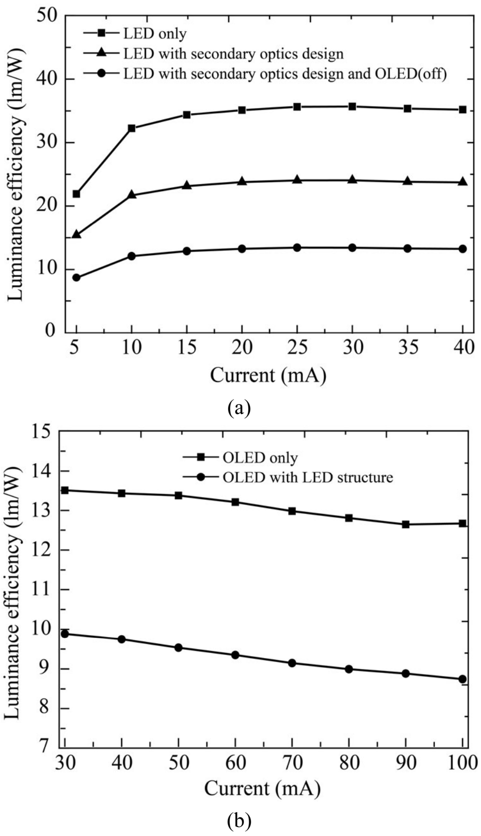


Fig.5 Luminous efficiencies of (a) the RB LED and (b) the green transparent OLED panels

Tab.2 Luminous efficiencies of the light sources

LED		OLED		Integrated system
Current (red, blue) (mA)	Luminous efficiency (lm/W)	Current (mA)	Luminous efficiency (lm/W)	Luminous efficiency (lm/W)
(40, 5)	11.73	100	8.75	10.3
(35, 10)	11.34	100	8.75	10.15
(30, 15)	11.35	100	8.75	10.03
(25, 20)	11.24	100	8.75	9.88
(20, 25)	11.50	100	8.75	9.73
(15, 30)	11.31	100	8.75	9.56
(10, 35)	11.17	100	8.75	9.39
(5, 40)	10.86	100	8.75	9.21

As shown in Tab.3, the luminance intensity of the green OLED is only 303.1 cd/m^2 under a constant current of 100 mA. However, after integration of the high-luminance-intensity LED (currents of red and blue LED chips are 40 mA and 5 mA, respectively), the luminance intensity reaches 1787.3 cd/m^2, which is almost equal to the LED's luminance intensity (1502.5 cd/m^2) added with the OLED's luminance intensity (303.1 cd/m^2). Therefore, the combination can be used to make up for the lack of the transparent OLED's luminance intensity.

The luminance uniformity is an important factor for evaluating a surface-emitting light source. When the red and blue LED chip currents are 40 mA and 5 mA, respectively, the LED's luminance uniformity is almost 70.4% after a secondary optics design. As a surface emission source, the transparent OLED has a high luminance uniformity of 93.9% at 100 mA. After the integration, the luminance uniformity of the lighting source can reach 80.2%.

Tab.3 Tested electrical and luminous parameters of the light sources

	LED		OLED (100 mA)		Integrated system	
Current (red, blue) (mA)	Luminance (cd/m^2)	Luminance uniformity (%)	Luminance (cd/m^2)	Luminance uniformity (%)	Luminance (cd/m^2)	Luminance uniformity (%)
(40, 5)	1502.5	70.4	303.1	93.9	1787.3	80.2
(35, 10)	1423.1	72.2	303.1	93.9	1716.5	81.8
(30, 15)	1345.2	73.6	303.1	93.9	1646.2	83.2
(25, 20)	1258.8	75.0	303.1	93.9	1564.7	84.4
(20, 25)	1151.3	76.0	303.1	93.9	1461.3	85.6
(15, 30)	1059.3	76.4	303.1	93.9	1371.1	86.2
(10, 35)	961.5	76.2	303.1	93.9	1276.2	86.5
(5, 40)	870.3	75.5	303.1	93.9	1185.7	86.6

The integration of the RB two-color LED and green OLED provides a solution to obtain a white light emission and color tuning. The red and blue light LED currents and the green light OLED current are tuned to obtain different CCTs and CIE coordinates. Such an integration can compensate for the lack of the transparent OLED's luminance intensity and LED's luminance uniformity.

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