



Full-Wavelength White Organic Light Emitting Diodes with Blue Fluorescence and Phosphorescent Iridium Complexes

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A highly efficient white organic light emitting diode (WOLED) was fabricated and possible emission mechanisms of a WOLED configured with blue fluorescence and phosphorescent iridium complexes are proposed. The white light emitting layer is comprised of a blue fluorescent emitting layer anthracene and a green and red phosphorescent emitting layer TPBI:11% Ir(ppy)₃: 0.5% Ir(piq)₂(acac). The device exhibits white emission with a Commission Internationale de l'Eclairage coordinate of ($x = 0.33$, $y = 0.33$) and the luminance and luminous efficiency was 6389 cd/m² and 6.4 cd/A, respectively, at 100 mA/cm². Evidence indicates that the good energy overlap between the absorption spectrum of Ir(ppy)₃ and Ir(piq)₂(acac) and the emission spectrum of TPBI results in an effective energy transfer from TPBI to Ir(ppy)₃ and Ir(piq)₂(acac). The optimal thickness of the green and red emitting layer promotes the injection and emitting of carriers in that layer.

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White organic light-emitting diodes (WOLEDs) are commercial OLEDs, because they have potential applications as backlights for liquid-crystal displays and as general solid-state light sources.^{1,2} A WOLED is based on an additive mixture of the three primary colors or two complementary colors. Many approaches have been proposed for developing WOLEDs with high luminance and high stability.³⁻⁷ When WOLEDs are fabricated by vacuum evaporation, using red, green, and blue colors, making the pixels of the WOLED uniform is difficult because of the difficulty in the alignment of the shadow masks. Additionally, when WOLEDs are fabricated using color filters, the luminance intensity of the light sources is degraded and a pure white emission with a broad wavelength is required. Therefore, systematic investigations of the fabrication and the characteristics of full-wavelength WOLEDs with high luminance and good color balance must be conducted to identify potential applications of high-efficiency backlight sources in full-color displays. Unfortunately, numerous full-wavelength WOLEDs have the shortcomings that the luminescent efficiency is very poor and the chromaticity coordinate changes significantly with the operating voltage.^{8,9} Moreover, only a few WOLEDs with high luminescent performance, using three primary-color emitters, have been reported because of the complexity of the device fabrication process.¹⁰ For example, Huang et al. fabricated a full-wavelength WOLED using a dual-doped method, where the luminous efficiency was 4.8 cd/A at 100 mA/cm² and the electroluminescence (EL) spectra of this device only covered the range of 400–700 nm.¹¹ Although blue phosphorescent dyes were reported to exhibit an external quantum efficiency of 7.5%, their dependency on host materials with very large bandgaps represents a barrier to the design of WOLEDs.¹² Therefore, the high efficiency and color stability of WOLEDs depends on the use of blue fluorescence with green and red phosphorescent dyes.

This study reports a full-spectrum and highly efficient WOLED and establishes the possible emission mechanisms of WOLED configured with blue fluorescence and phosphorescent iridium complexes.

Experimental

WOLEDs are fabricated by vacuum vapor deposition at a pressure of 5×10^{-6} Torr. Figure 1a presents the WOLED structure with a hole-transporting layer *N*, *N'*-diphenyl-*N*, *N'*-bis (1-naphthylphenyl)-(1, 1'-biphenyl)-4, 4'-diamine (NPB) (400 Å), a blue emitting layer anthracene (300 Å), a green and red emitting layer TPBI: *fac* tris (2-phenylpyridine) iridium (Ir(ppy)₃): bis[1-

(phenyl)isoquinoline] iridium (III) acetylacetonate [Ir(piq)₂(acac)], and the cathode Mg/Ag alloy with an atomic ratio of 10:1. TPBI is an efficient host material for phosphorescent dopant and hole-blocking material, due to the wide energy gap and suitable emission spectrum.¹³ The white emission comes from the anthracene blue fluorescence and the TPBI host doped with Ir(ppy)₃ green phosphorescent iridium complexes and Ir(piq)₂(acac) red phosphorescent iridium complexes. The thickness of the film was measured using an oscillating quartz thickness monitor (Sycon STM-100) and the active area of the devices, defined by the size of the overlap between the indium tin oxide (ITO) and Mg/Ag electrodes, was 0.3

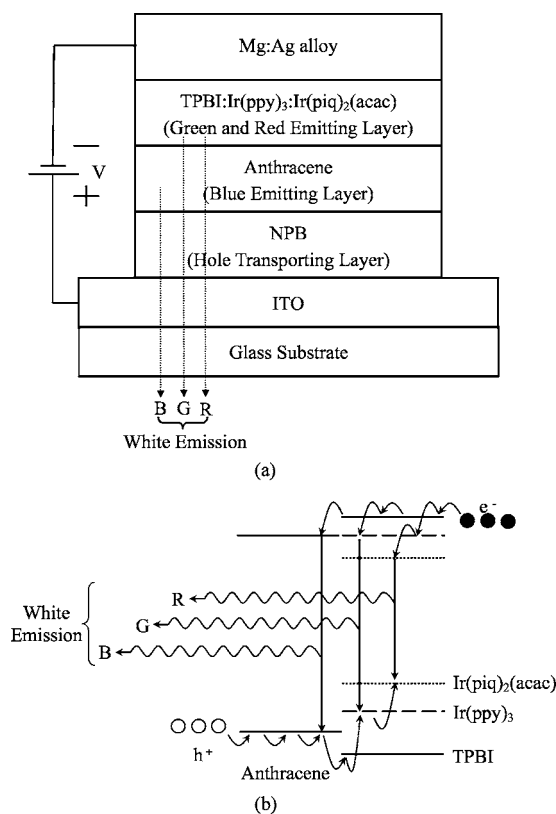


Figure 1. (a) Configuration and (b) energy band diagram of WOLED, comprising blue fluorescence and phosphorescent iridium complexes.

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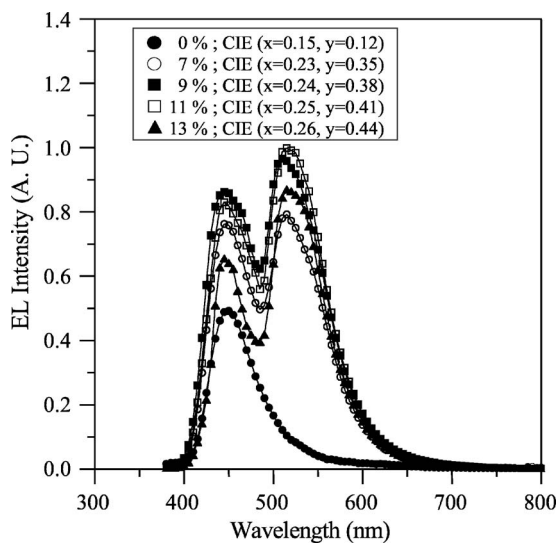


Figure 2. EL spectra of ITO/NPB/anthracene/TPBI:Ir(ppy)₃/Mg:Ag WOLED with 0, 7, 9, 11, and 13% Ir(ppy)₃ in TPBI layer whose thickness is 300 Å and current density is 20 mA/cm².

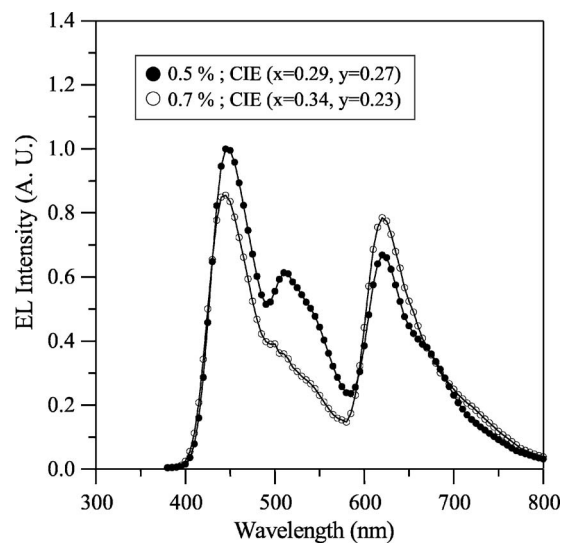


Figure 3. EL spectra of ITO/NPB/anthracene/TPBI:11%Ir(ppy)₃:Ir(piq)₂(acac)/Mg:Ag WOLED with 0.5 and 0.7% Ir(piq)₂(acac) in TPBI layer whose thickness is 300 Å and current density is 20 mA/cm².

× 0.3 cm². All devices were encapsulated in a dry nitrogen glove box.

EL spectra and Commission Internationale de l'Eclairage (CIE) coordinates of the devices were measured using a PR650 spectroscan spectrometer and the luminance vs current density (*L*-*J*) characteristics were determined simultaneously from the EL spectra by using the spectrometer with a Keithley 2400 programmable voltage-current source. Photoluminescence (PL) spectra of the organic films were obtained using the 325 nm line from an He-Cd laser. Fluorescence was collected through a window and directed into a 1/4 m spectrograph with a cooled photodiode array detector.

Results and Discussion

Because Ir(ppy)₃ and Ir(piq)₂(acac) were adopted as the green and red guest phosphorescent iridium complexes, respectively, the optimal concentrations of these two dopants added to the host material TPBI must be determined. Figure 2 presents the EL spectra of ITO/NPB/anthracene/TPBI:Ir(ppy)₃ (300 Å)/Mg/Ag with various Ir(ppy)₃ doping concentrations of between 0 and 13%. As shown in Fig. 2, at doping concentrations of Ir(ppy)₃ of between 7 and 11%, the intensity of green emission at a wavelength of approximately 520 nm [contributed by Ir(ppy)₃] was observed to increase with the doping concentration of Ir(ppy)₃ up to 11%. However, at doping concentrations of Ir(ppy)₃ of over 11%, the intensity of the green emission dropped as the doping concentration of Ir(ppy)₃ increased. This is due to triplet-triplet (T-T) annihilation between the Ir(ppy)₃ and host triplets.¹⁴ Therefore, the host material of TPBI doped with 11% Ir(ppy)₃ exhibits an energy transfer at the appropriate rate, optimally emitting green light from Ir(ppy)₃.

The effect of doping TPBI with Ir(ppy)₃ and Ir(piq)₂(acac) on the balance between the green and red emission intensities was also studied. Figure 3 shows the EL spectra of ITO/NPB/anthracene/TPBI:11% Ir(ppy)₃/Ir(piq)₂(acac) (300 Å)/Mg/Ag with various doping concentrations of Ir(piq)₂(acac) of between 0.5 and 0.7%. The analytical results in Fig. 3 indicated that the device with 0.5% Ir(piq)₂(acac) in the host material TPBI exhibited not only balanced green and red emission intensities but also relatively high energy transfer from TPBI to Ir(piq)₂(acac).

The thickness of the blue, green, and red emissive layers as well as the doping concentration of each fluorescent and phosphorescent material strongly affects the EL spectrum of the white light emitting device. The thickness of the green and red emitting layer was varied

and the doping concentrations of Ir(ppy)₃ and Ir(piq)₂(acac) maintained at 11 and 0.5%, respectively, to obtain a bright and high-purity WOLED. Figure 4 shows the EL spectra of the WOLEDs with green and red emitting layers of various thicknesses and reveals that the luminescent performance was strongly related to the thickness of the green and red emitting layer. The EL spectra of the devices are full-spectrum and cover the range 400–800 nm, with three major emissions at 440 nm (from anthracene), 520 nm [from Ir(ppy)₃], and 620 nm [from Ir(piq)₂(acac)]. Figure 5 plots the luminance-current density-luminous efficiency characteristics of WOLEDs with green and red emitting layer of various thicknesses. Evidence shows that green and red emitting layer of suitable thickness (400 Å) can be used to yield white emission with relatively high color purity and a CIE coordinate of (*x* = 0.33, *y* = 0.33). The luminance and luminous efficiency was 6389 cd/m² and 6.4 cd/A,

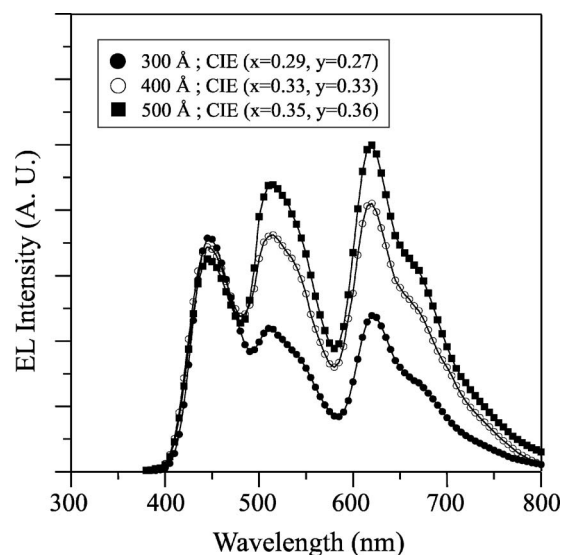


Figure 4. EL spectra of the WOLEDs with green and red emitting layers of various thicknesses.

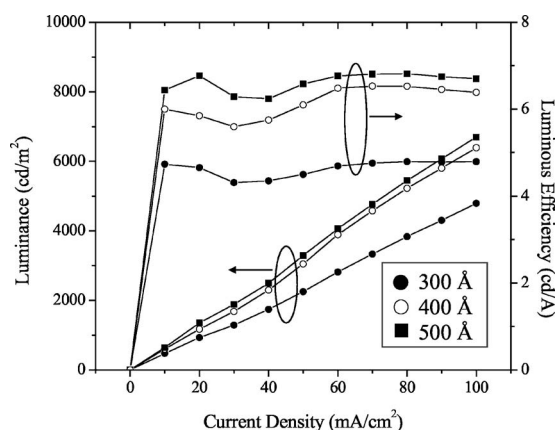


Figure 5. Luminance-current density characteristics of WOLEDs with green and red emitting layers of various thickness.

respectively, at 100 mA/cm². The optimal thickness of the green and red emitting layers promotes the injection and emission of carriers in the green and red emitting layers.

To understand the energy transfer mechanisms between the TPBI and phosphorescent dopants, we examine the PL spectrum of TPBI and the absorption spectra of Ir(ppy)₃ and Ir(piq)₂(acac), as shown in Fig. 6, elucidating the real emission mechanisms for Ir(ppy)₃ and Ir(piq)₂(acac) doped into TPBI. The similarity overlap between the absorption spectra of Ir(ppy)₃ and Ir(piq)₂(acac) and the emission of TPBI and that of the energy transfer process probably represents the dominant emission mechanism in our WOLED. The energy transfer pathways between host material of TPBI and guest materials of

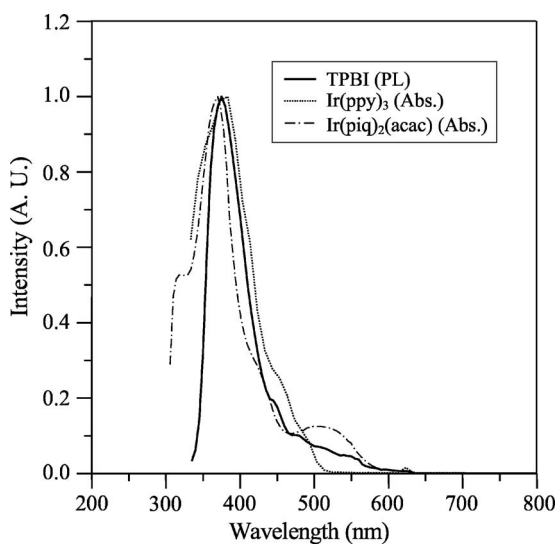


Figure 6. PL spectrum of TPBI and absorption spectra of Ir(ppy)₃ and Ir(piq)₂(acac).

Ir(ppy)₃ and Ir(piq)₂(acac) in full-wavelength WOLED are shown in Fig. 1b. In general, the white emission was generated at the interface between the blue emitting layer of anthracene and the green and red emitting layers of Ir(ppy)₃ and Ir(piq)₂(acac). The energy bandgap of TPBI is larger than Ir(ppy)₃ and Ir(piq)₂(acac). Therefore, injected holes and electrons in TPBI are transferred easily into Ir(ppy)₃ and Ir(piq)₂(acac), and excitons were formed in Ir(ppy)₃ and Ir(piq)₂(acac), respectively. Besides, an efficient T-T energy transfer from Ir(ppy)₃ to Ir(piq)₂(acac) can occur through their adjoining positions.^{15,16} The T-T energy transfer reduces the green light emission of Ir(ppy)₃ and enhances the red light emission of Ir(piq)₂(acac) as shown in Fig. 3. For this reason, in order to balance green and red emission intensities, the doping concentration of Ir(piq)₂(acac) should be lower than Ir(ppy)₃.

Conclusions

In conclusion, we have demonstrated a high-efficiency full-wavelength WOLED with blue fluorescence and phosphorescent iridium complexes. The device exhibits white emission with a CIE coordinate of ($x = 0.33$, $y = 0.33$) and the luminance and luminous efficiency was 6389 cd/m² and 6.4 cd/A, respectively, at 100 mA/cm². The possible emission mechanisms of WOLED configured with blue fluorescence and phosphorescent iridium complexes were investigated. Evidence shows that the good energy overlap between the absorption spectrum of Ir(ppy)₃ and Ir(piq)₂(acac) and the emission spectrum of TPBI results in an effective energy transfer from TPBI to Ir(ppy)₃ and Ir(piq)₂(acac). Additionally, a green and red emitting layer of an appropriate thickness (400 Å) increases the luminance of WOLEDs. The optimal thickness of the green and red emitting layer suggests the injection and emission of carriers in that layer.

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