



# Highly efficient orange and white phosphorescent organic light-emitting devices with simplified structure



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## ABSTRACT

We successfully developed efficient orange and white phosphorescent organic light-emitting devices based on simplified structure. The maximum power efficiency and current efficiency of the orange device with only 5 nm emission layer are 34.1 lm/W and 38.0 cd/A. Performances of the simplified orange devices can be greatly improved to 62.6 lm/W (79.7 cd/A) by introducing one blue phosphorescent dye iridium(III)[bis(4,6-difluorophenyl)-pyridina-to-N,C2']picolinate into the orange emission layer. The emission mechanism of the above orange devices was also discussed. White light emission with Commission International de L'Eclairage coordinates of (0.36, 0.45) and efficiency of 40.6 lm/W (38.7 cd/A) was obtained by exactly adjusting the doping concentration of orange phosphorescent dye.

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## 1. Introduction

Organic light-emitting diodes (OLEDs) are considered as the ultimate technology and have already been commercialized in portable electronic display panels due to high power efficiency and low manufacturing costs. Another potential application for OLEDs is to be introduced for solid-state lighting in the near future [1–7]. In the past two decades, tremendous efforts have been spent to improve the performance of OLEDs such as developing efficient phosphorescent materials which can harvest both singlet and triplet excitons [8–13], exploiting various device configurations to efficiently utilize excitons [2–4,14]. Generally speaking, in order to obtain high efficiency, OLEDs always adopt multilayer structure including electron or hole/exciton blocking layer to avoid exciton quenching. However, such a complicated multilayer structure greatly increases the manufacturing cost and prevents their industrialization application. Thus it's a promising strategy to reduce the cost by simplifying the OLEDs structure without compromising the performance for the potential commercial use [15–18].

Recently, Wang et al. demonstrated simplified green phosphorescent OLEDs with high efficiency of 50.5 lm/W at 5000 cd/m<sup>2</sup> [16]. He et al. fabricated bi-layer blue OLEDs based on 4,40-bis(9-ethyl-3-carbazovinyleno)-1,10-biphenyl as a fluorescent emitter mixed with two charge transport hosts [17]. By using 1,1-bis[(di-4-tolylami-no)phenyl]cyclohexane and 1,3,5-tri(p-pyrid-3-yl-phenyl) benzene as mixed host system, Suh

et al. reported bi-layer green OLEDs with efficiency of 33.6 cd/A [18].

Orange OLEDs are very important in order to achieve highly efficient white OLEDs based on blue and orange complementary colors [19–21], especially for tandem white OLEDs in which the blue emission unit and orange emission unit are connected by charge generation layer [22]. Here we report efficient simplified orange OLEDs based on a common host material 4,4'-bis(N-carbazolyl)bi phenyl (CBP) acting as hole-transport layer and the host material. The optimized orange device with maximum luminance of 62100 cd/m<sup>2</sup> has maximum efficiency of 62.6 lm/W (79.7 cd/A). Moreover, efficient simplified white device with power efficiency of 40.6 lm/W is also fabricated.

## 2. Experimental

Patterned indium tin oxide (ITO) coated glass with a sheet resistance of 20 Ω/□ used as transparent anode were pre-cleaned by soaking in ultrasonic acetone, ethanol and deionized water in sequence and baking for 20 min and were then exposed to an oxygen plasma followed by UV ozone for 5 min before loading into a high vacuum thermal system. Organic layers and cathode were deposited with a base pressure of 3 × 10<sup>-4</sup> Pa by thermal evaporation at a rate of 0.1–0.2 nm/s, while the emission dyes were deposited at a rate of 0.1–5 Å/min. And Al cathode was deposited at the rate of 5 Å/s without breaking the vacuum. The organic materials used in our experiments were purchased from Luminescence Technology Corporation. The layer thickness and the deposition rate of materials were monitored in situ by an oscillating quartz

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thickness monitor. Electroluminescence (EL) spectra and Commission International de L'Eclairage (CIE) coordinates of the devices were measured by using a PR655 spectroscan spectrometer. The luminance–voltage and current–voltage characteristics were measured simultaneously with the measurement of the EL spectra by combining the spectrometer with a programmable Keithley 2400 voltage–current source. All devices were measured at room temperature under ambient conditions without encapsulated.

### 3. Results and discussion

A common host material CBP doped with iridium(III) bis(4-phenylthieno[3,2-c]pyridinato-N,C2') acetylacetonate (PO-01) was used as orange emission layer. 4,7-diphenyl-1,10-phenanthroline (Bphen) was used as electron-transport layer. 0.8 nm LiF covered by 100 nm Al was used as cathode. The detailed energy level diagram of the OLEDs and molecular structures of organic materials are shown in Fig. 1.

Firstly, four simplified orange OLEDs with the following structure were fabricated: ITO/MoO<sub>3</sub> (2 nm)/CBP [(70 – X) nm]/CBP: 5%PO-01 (X nm)/Bphen (30 nm)/LiF (0.8 nm)/Al (100 nm). And the emission layer thickness X = 5, 10, 20, 30 nm corresponding to devices O-1, O-2, O-3, O-4, respectively. The current density–voltage–luminance characteristics and the normalized EL spectra at 8 V of the four devices are shown in Fig. 2(a) and (b) respectively. The inset of Fig. 2(b) shows the EL performance of the four devices. It can be seen that the turn-on voltage increases from 2.9 V to 3.1 V while the current density markedly decreases with the thickness of doped emission layer increasing from 5 nm to 30 nm. The phenomenon is attributed to the strong holes trapping ability of PO-01 with the highest occupied molecular orbital (HOMO) level

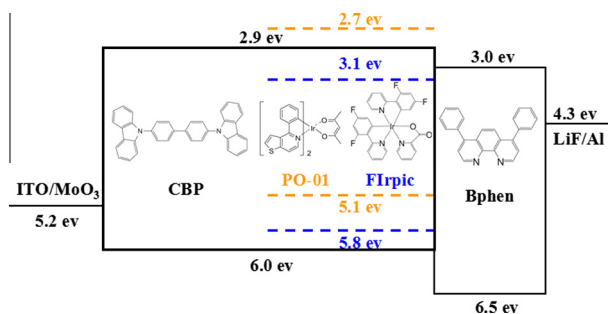


Fig. 1. The detailed energy level diagram of OLEDs and molecular structures for organic materials.

of 5.1 eV which is 0.9 eV lower than that of CBP. For simplified orange OLEDs with thicker emission layer, more holes are trapped by PO-01 and fewer excitons are generated at CBP/Bphen interface, which leads to worse efficiency and higher turn-on voltage. The maximum efficiency of 34.1 lm/W (38.0 cd/A) is achieved for device O-1 with only 5 nm emission layer.

In order to investigate the position of exciton recombination zone for such device structure, we fabricated three devices with the structures of ITO/MoO<sub>3</sub> (2 nm)/CBP (70 nm)/PO-01 (0.2 nm)/Bphen (30 nm)/LiF (0.8 nm)/Al (100 nm) (device T1); ITO/MoO<sub>3</sub> (2 nm)/CBP (65 nm)/PO-01 (0.2 nm)/CBP (5 nm)/Bphen (30 nm)/LiF (0.8 nm)/Al (100 nm) (device T2); ITO/MoO<sub>3</sub> (2 nm)/CBP (65 nm)/PO-01 (0.2 nm)/CBP (5 nm)/Bis(2-methyl-dibenzof[*f,h*]quinoxaline)(acetylacetonate)iridium(III) [Ir(MDQ)<sub>2</sub>(acac)] (0.1 nm)/Bphen (30 nm)/LiF (0.8 nm)/Al (100 nm) (device T3).

Fig. 3(a) shows the normalized EL spectra at 4 V of the three devices. The spectra of devices T1 and T2 show a primary emission peak at ~560 nm originating from PO-01. While device T3 shows a pure red emission peak from Ir(MDQ)<sub>2</sub>(acac). Fig. 3(b) shows the current efficiency–voltage characteristics of the three devices. It is clearly to see device T1 shows much higher current efficiency than device T2. For device T2, the lower efficiency and the strong host emission at ~390 nm means the PO-01 thin layer is away from the main exciton combination zone and the orange emission is mainly attributed to triplet excitons diffusion from the main exciton recombination zone. The absence of orange emission in device T3 indicates that no excitons are generated in the position 5 nm away from the interface of CBP/Bphen. For the system of PO-01 doped in CBP, the large interfacial energy barriers at the interface of CBP/Bphen indicates electrons and holes accumulated at the interface, resulting in the recombination zone locating at the narrow interface of CBP/Bphen as shown in Fig. 4(a). Then the excitons could be transferred to Ir(MDQ)<sub>2</sub>(acac) via the Dexter mechanism. Moreover, as the strong electron trapping characteristic of Ir(MDQ)<sub>2</sub>(acac) [23,24], direct excitons recombination on Ir(MDQ)<sub>2</sub>(acac) could also happen.

Considering the good electron transport character of Flrpic, we doped it with PO-01 into CBP to facilitate the injection of electron into the emission layer and expand the exciton recombination zone. Another four orange devices with the structure of ITO/MoO<sub>3</sub> (2 nm)/CBP [(70 – Y) nm]/CBP: 10%Flrpic: 5%PO-01 (Y nm)/Bphen (30 nm)/LiF (0.8 nm)/Al (100 nm) were fabricated. And Y = 5, 10, 20, 30 nm for devices O-5, O-6, O-7, O-8, respectively. The current density–voltage–luminance and the power efficiency–luminance characteristics are shown in Fig. 5(a) and (b) (inset summarizes the EL performances and the normalized EL spectra at 5000 cd/m<sup>2</sup>). The maximum efficiency increases from

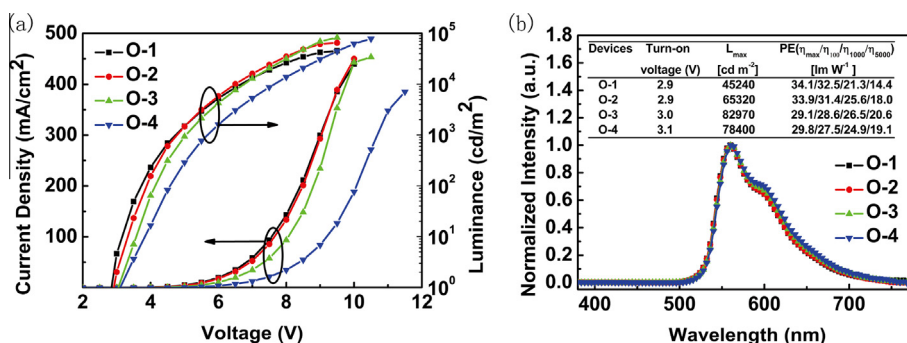


Fig. 2. The current density–voltage–luminance characteristics of the orange devices O-1, O-2, O-3, O-4 (a); the normalized EL spectra and the performance (inset) of the devices O-1, O-2, O-3, O-4.  $L_{max}$ : maximum luminance; PE: power efficiency (lm/W);  $\eta_{max}$ ,  $\eta_{100}$ ,  $\eta_{1000}$ ,  $\eta_{5000}$ : maximum efficiency, efficiency at 100 cd/m<sup>2</sup>, efficiency at 1000 cd/m<sup>2</sup>, efficiency at 5000 cd/m<sup>2</sup> (b).

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