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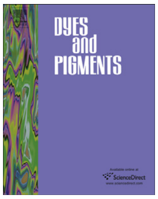

Highly efficient pure red organic light-emitting devices based on tris(1-phenyl-isoquinoline) iridium(III) with another wide gap iridium(III) complex as sensitizer

Yunlong Jiang, Liang Zhou*, Rongzhen Cui, Yanan Li, Xuesen Zhao, Hongjie Zhang**

State Key Laboratory of Rare Earth Resource Utilization, Changchun Institute of Applied Chemistry, Chinese Academy of Sciences, Renmin Street 5625, Changchun 130022, People's Republic of China

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In this work, we report the realization of highly efficient pure red organic co-doped electroluminescent device with tris(1-phenyl-isoquinoline) iridium(III) ($Ir(piq)_3$) and iridium(III) bis(4,6-(difluorophenyl) pyridinato-*N*,$C^{2'}$)picolinate (FIrpic) as emitter and sensitizer, respectively. By selecting 4,4′,4″-Tri(9-carbazoyl)triphenylamine and 2,6-bis(3-(9*H*-carbazol-9-yl)phenyl)pyridine as host materials, a series of devices with single or double light-emitting layer(s) were fabricated and investigated. The well-known wide gap blue emitter FIrpic, which possesses low-lying energy levels, was co-doped minutely into electron dominant light-emitting layer. Compared with reference devices, co-doped devices displayed significant improvement of device performances attributed to improved carriers' balance and broadening recombination zone. Finally, the 0.3 wt% co-doped double light-emitting layers device obtained the maximum brightness, current efficiency, power efficiency and external quantum efficiency up to 28,031 cd/m^2, 14.89 cd/A, 12.99 lm/W and 9.0%, respectively. Even at the certain brightness of 1000 cd/m^2, EL efficiency as high as 12.06 cd/A can be retained by the same device.

1. Introduction

Organic light-emitting devices (OLEDs) have attracted great interest throughout the world owing to their potential application in solid-state lighting and in full-color flat panel displays [1–5]. Although the performances of OLEDs have been developed prosperously in recent years, further improvement is still necessary for practical application. Transition metal complexes, which are widely utilized as therapeutic agents or phosphorescent probes for biomolecules [6–13], have been extensively studied as the electroluminescent materials because both singlet and triplet excitons can be harvested and thus 100% internal quantum efficiency was expected [14–16]. For commercial application, especially for full-color display, three primary colors of blue, green and red are basically required [17,18]. Up to now, the major performances of green OLEDs are high enough for industrial application, while red and blue OLEDs remain to be optimized in color purity, efficiency and brightness [19–23].

In the past decades, many groups have devoted their efforts to the design of novel transition metal complexes and the optimization of device structures [24–26]. To realize high performance OLEDs, highly efficient transition metal complexes with matched energy levels, short excited state lifetime, and excellent thermal stability were required. For example, Z. B. Wang et al. have obtained the phosphorescent OLED with external quantum efficiencies above 20% based on a cyclometalated platinum(II) (Pt^{II}) complex with a triarylboron group [24]. Chi et al. have realized the orange-red device with the maximum external quantum efficiency, current efficiency and power efficiency of up to 18.3%, 61.0 cd/A and 53.8 lm/W, respectively, by utilizing a novel Os(II) complex $Os(pz2py)(PPh_2Me)_2(CO)$ (pz2py = 2,6-di(5-trifluoromethylpyrazol-3-yl) pyridine, PPh_2Me = diphenylmethylphosphine) as the dopant [25]. F. Dumur et al. utilized heteroleptic cyclometalated iridium(III) (Ir^{III}) complex bis(1-phenylisoquinoline)(acetylacetonate)iridium(III) ($Ir(piq)_2(acac)$) as red dopant and achieved the maximum power efficiency of 7.2 lm/W, the maximum current efficiency of 10.0 cd/A as well as the CIE coordinate of (0.67, 0.33) [26]. Although significant improvement of maximum EL efficiencies has been realized, EL

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* Corresponding author. Tel.: +86 43185262855; fax: +86 43185698041.
** Corresponding author. Tel.: +86 43185262127; fax: +86 43185685653.
E-mail addresses: zhoul@ciac.ac.cn (L. Zhou), hongjie@ciac.ac.cn (H. Zhang).

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efficiencies of most reported devices dropped rapidly attribute to various reasons such as triplet–triplet annihilation, triplet–polaron annihilation, and electric field induced dissociation of excitons [27,28]. The roll-off of efficiency is quite severe in phosphorescent OLEDs due to the relatively long lifetime of triplet excitons, and it detrimentally degrades the device performances for practical applications particularly at high brightness. Therefore, further investigation on how to suppress the roll-off of EL efficiency are most important for the development of red OLEDs based on transition metal complexes.

Previously, C.-M. Che et al. have demonstrated an efficient device design strategy to improve the EL performances of red Pt^{II} complex by co-doping wide energy gap Ir^{III} complex into electron dominant light-emitting layer (EML) as sensitizer [29]. Experimental results revealed the co-doped Ir^{III} complex molecules function as deeper electron trappers, thus broadening the recombination zone and facilitating the balance of holes and electrons on Pt^{II} complex molecules. Due to the matched triplet energies of host material, Ir^{III} complex and Pt^{II} complex, the co-doped Ir^{III} complex molecules function as also the energy transfer ladders between host material and Pt^{II} complex. Consequently, higher EL performances were obtained by the co-doped devices. Recently, we have significantly enhanced the EL performances of red Ir^{III} complex iridium(III) bis(2-phenylquinoly-*N*,$C^{2'}$)dipivaloylmethane (PQ_2Ir(dpm)) by utilizing the classical wide band gap trivalent europium complex $Eu(TTA)_3phen$ (TTA = thenoyltrifluoroacetone, phen = 1,10-phenanthroline) as sensitizer [30]. Experimental results demonstrated the co-doped $Eu(TTA)_3phen$ molecules act as electron trappers and energy transfer ladders, which result in higher EL efficiencies, slower efficiency roll-off, higher brightness, and even higher color purity. Interestingly, wider recombination zone and faster energy transfer of the co-doped devices cause even lower necessary doping concentration of emitter.

In this work, we aim to improve the EL performances of red emitter tris(1-phenyl-isoquinoline) iridium(III) ($Ir(piq)_3$) by utilizing the well-known wide gap blue emitter iridium(III) bis(4,6-(difluorophenyl)pyridinato-*N*,$C^{2'}$)picolinate (FIrpic) as sensitizer. Based on hole transporting host material 4,4′,4″-Tri(9-carbazoyl) triphenylamine (TcTa) and electron transporting host material 2,6-bis(3-(9H-carbazol-9-yl)phenyl)pyridine (26DCzPPy), a series of single EML or double-EMLs devices were firstly fabricated and compared in order to optimize the doping concentration of $Ir(piq)_3$. Single-EML and double-EMLs devices realized the maximum brightness, current efficiencies, power efficiencies and external quantum efficiencies of 20,378 and 24,931 cd/m^2, 14.85 and 13.96 cd/A, 13.10 and 12.18 lm/W, 8.9% and 8.7%, respectively. Then, a series of co-doped devices with FIrpic at different co-doping concentrations were fabricated and measured. Experimental results demonstrated that co-doping FIrpic as sensitizer is efficient in delaying the roll-off of EL efficiency thus in realizing higher brightness. Finally, the 0.3 wt% co-doped double-EMLs device obtained the maximum brightness, current efficiency, power efficiency and external quantum efficiency up to 28,031 cd/m^2, 14.89 cd/A, 12.99 lm/W and 9.0%, respectively. At the certain brightness of 1000 cd/m^2, the same device retained the EL efficiency as high as 12.06 cd/A.

2. Experimental

All the organic materials used in this study were obtained commercially and used as received without further purification. ITO coated glass with the sheet resistance of 10 Ω/sq was used as the anode substrate. Prior to film deposition, patterned ITO substrates were cleaned with detergent, rinsed in de-ionized water, dried in an oven and finally treated with oxygen plasma for 10 min at a pressure of 10 Pa to enhance the surface work function of ITO anode (from 4.7 to 5.1 eV) [31]. All organic layers were deposited with the rate of 0.1 nm/s under high vacuum ($\leq 3.0 \times 10^{-5}$ Pa). The doped and co-doped EMLs were prepared by co-evaporating dopant(s) and host material from two or three individual sources, and the doping concentration was modulated by controlling the evaporation rate of dopant(s). LiF and Al were deposited in another vacuum chamber ($\leq 8.0 \times 10^{-5}$ Pa) with the rates of 0.01 and 1.0 nm/s, respectively, without being exposed to the atmosphere. The thicknesses of these deposited layers and the evaporation rate of individual materials were monitored in vacuum with quartz crystal monitors. A shadow mask was used to define the cathode and to make ten 9 mm^2 devices on each substrate. Current density–voltage–brightness (*J*–*V*–*B*) characteristics were measured by using a programmable Keithley source measurement unit (Keithley 2400 and Keithley 2000) with a silicon photodiode. The EL spectra were measured with a calibrated Hitachi F-7000 fluorescence spectrophotometer. The external quantum efficiency of EL device was calculated based on the photo energy measured by the

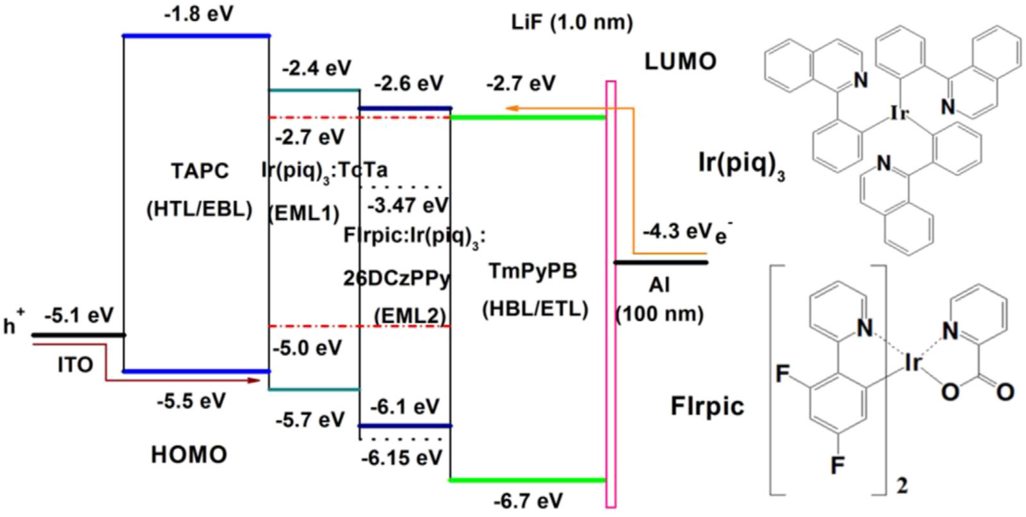

Fig. 1. Proposed energy levels diagram of the designed OLEDs in this study (left). Molecular structures of $Ir(piq)_3$ and FIrpic (right).