Highly efficient phosphorescent OLEDs with host-independent and concentration-insensitive properties based on a bipolar iridium complex†

Tai Peng,‡ Guomeng Li, Kaiqi Ye, Chenguang Wang, Shanshan Zhao, Yu Liu,*‡ Zhaomin Hou and Yue Wang*‡

A bipolar iridium complex, (ppy)2Ir(dipig), based on the ancillary ligand N,N-diisopropyl-diisopropyl-guanidinate (dipig) with well-known cycmolatated (C,N) ligand ortho-(2-pyridyl)phenyl (ppy), is applicable in phosphorescent organic light-emitting diodes (PHOLEDs) as an efficient emitter, using easily available host materials and a simple device fabrication process. The corresponding PHOLEDs are dominated by an efficient direct-exciton-formation mechanism and show very high EL efficiency together with gratifying host- and doping-concentration-independent features. EL efficiency values of more than 93 lm W⁻¹ for power efficiency (ηp) and 24% for external quantum efficiency (ηext) accompanied by little efficiency roll-off at high luminance are achieved in the (ppy)2Ir(dipig)-based devices by adopting the common materials 4,4’-bis(N-(1-naphthyl)-N-phenylamino)biphenyl (NPB) and 1,3,5-tris(N-phenylbenzimidazol-2-yl)benzene (TPBI) as the host, with rather random concentration ranges of 8–15 wt% and 15–30 wt%, respectively. To the best of our knowledge, these values are the highest efficiencies ever reported for yellow PHOLEDs, and are even comparable with the highest levels for PHOLEDs in the scientific literature. Moreover, the ηp and ηext values of the non-doped device can reach 70 lm W⁻¹ and 18% respectively. They are almost two times higher than those of the most efficient reported PHOLEDs based on a neat emitting layer (EML).

Introduction

It is well known that a 100% internal quantum efficiency (IQE) of electrophorescence can be achieved by harvesting both electrogenerated singlet and triplet excitons for emission. However, phosphorescent emitters normally have to be doped in a suitable charge-transporting host matrix due to their typically poor carrier mobility and their tendency to undergo luminescence self-quenching under neat conditions. For phosphorescent organic lighting emitting devices (PHOLEDs), there are two possible mechanisms of exciton formation and emission: energy transfer from host to guest (mechanism I) (as shown in Fig. 1a) and formation of excitons on the phosphorescent molecules through direct recombination of carriers on the guest molecule (mechanism II) (as shown in Fig. 1b). By comparison, the latter mechanism seems to be more efficient, where the guest molecules can trap and transport carriers, allowing direct exciton formation on the guest molecules. Consequently, the electrophosphorescent emission due to mechanism II can realize extremely high efficiency by potentially eliminating several energy cost processes (as shown in the following list) that exist in mechanism I in which energy transfers from host to guest. First, carrier injection for a wide band gap host often needs to overcome higher energy barriers; second, the energy transfer from a host with a high E_T to a guest with a relatively low E_T typically results in large energy loss (ΔE_T); and third, the possibility of triplet–triplet annihilation (TTA) increases due to the much shorter triplet lifetime of the fluorescent host than that of the phosphorescent guest. Therefore, for electrophosphorescent emission following mechanism I, high external quantum efficiency (ηext) and current efficiency (η_i) is usually easily achieved, but high power efficiency (η_p) is much more difficult to realize. In addition, the aforementioned high-performance PHOLEDs usually require not only some speciality additional materials to confine triplet excitons within the EML, but also precisely controlled doping concentrations (3–8 wt% and ±1%), which should be disadvantages for the preparation of reliable and reproducible commercial devices.

Generally, the contribution of mechanism II to the efficiency of PHOLEDs is very limited due to the insufficient
charge-transporting ability of the reported phosphorescent emitters. To address this issue, the phosphorescent emitter should possess good bipolar charge-transporting abilities, which can ensure the direct formation of excited phosphors based on mechanism II (Fig. 1b). Although many organic hosts or host emitting materials with excellent carrier transporting properties have been reported, the design and synthesis of phosphorescent materials with good carrier transporting properties is still a challenge. In this context, we chose an ancillary ligand of \( N,N' \)-diisopropyl-diisopropyl-guanidinate (dipig) to construct phosphorescent material \( (ppy)_2{Ir(dipig)} \) with the well-known \( (ppy)_2{Ir} \) \( (ppy = \text{ortho}-\text{2-pyridyl} \text{phenyl}) \) species. We present a comprehensive investigation that encompasses the crystal structure, photophysical properties, theoretical calculations, charge-transporting properties as well as the detailed electroluminescent (EL) characteristics of this complex. The luminescent material \( (ppy)_2{Ir(dipig)} \), which possesses relatively high and balanced hole and electron transport properties, has been used to fabricate highly efficient PHOLEDs dominated by the direct-exciton-formation mechanism. The corresponding PHOLEDs exhibit obviously host-independent and doping-concentration-independent features.

Maximum EL efficiencies of more than 93 lm W\(^{-1}\) for \( \eta_p \) and 24% for \( \eta_{ext} \) accompanied by little efficiency roll-off at high luminance were achieved in \( (ppy)_2{Ir(dipig)} \)-based devices adopting the common materials 4,4’-bis(N-(1-naphthyl)-N-phenylamino)biphenyl (NPB) and 1,3,5-tris(N-phenyl-benzimidazol-2-yl)benzene (TPBI) as the host, with rather random concentration ranges of 8–15 wt% and 15–30 wt%, respectively. To the best of our knowledge, they are the highest efficiencies ever reported for yellow PHOLEDs, and are even comparable with the highest known values for PHOLEDs. Moreover, the \( \eta_p \) and \( \eta_{ext} \) values of the non-doped device can reach 70 lm W\(^{-1}\) and 18% respectively. They are almost two times higher than those of the most efficient reported PHOLEDs based on a neat EML.

**Experimental section**

**General information**

Materials obtained from commercial suppliers were used without further purification. Anhydrous hexane was distilled with sodium benzophenone ketyl under nitrogen atmosphere and degassed by the freeze–pump–thaw method. All glassware, syringes, magnetic stirring bars and needles were dried in a convection oven for at least 4 h. Reactions were monitored with thin layer chromatography (TLC). Commercial TLC plates (Silica gel 60 F254, Merck Co.) were developed and the spots were seen under UV light at 254 and 365 nm. Silica column chromatography was carried out using silica gel 60 G (particle size 5–40 μm, Merck Co.). \(^1\)H NMR spectra were recorded on a Bruker AVANCE 300 MHz spectrometer with tetramethylsilane as an internal standard. Mass spectra were measured on a GC/MS mass spectrometer. Elemental analyses were performed on a flash EA 1112 spectrometer. Absorption spectra were obtained using a Shimadzu UV-2550 UV-vis spectrometer. PL spectra were recorded on a Perkin-Elmer LS-55 fluorescence spectrometer with a Xe arc lamp excitation source. All solvents were degassed via three freeze–pump–thaw cycles. Emission lifetime experiments were performed using a time-correlated single-photon counting (TCSPC) system under right-angle sample geometry. A 379 nm picosecond diode laser (Edinburgh Instruments EPL375, repetition rate 20 MHz) was used to excite the samples. PL emissions were collected with a photomultiplier tube (Hamamatsu H5783p) connected to a TCSPC board (Becker&Hickel SPC-130). The time constant of the instrument response function (IRF) is about 220 ps. Electrochemical measurements were performed with a BAS 100 W Bioanalytical electrochemical work station, using a Pt working electrode, platinum wire as an auxiliary electrode, and a porous glass wick Ag/Ag\(^+\) as the reference electrode. Voltammograms were referenced to a ferrocene/ferroacenium couple and the scan rate was 100 mV S\(^{-1}\). Due to the limitations in measuring reduction potentials in the range of \(-2.7\) V to \(-3.5\) V in CH\(_2\)Cl\(_2\), we obtained only the oxidation potential for \( (ppy)_2{Ir(dipig)} \), and no reduction wave was detected within the electrochemical window of dichloromethane. The highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO)
energy levels of the complex were calculated from the cyclic voltammetry (CV) data together with the absorption spectrum.

**Fabrication of the OLEDs and EL measurements**

The general architecture of the complex multilayer diodes used in this study is as follows: ITO (indium-tin oxide) coated glass substrates (20 Ω per square) were first cleaned in ethanol, acetone, and soap ultrasonic baths. All organics were purified by gradient sublimation and thermally evaporated at a rate of 1.0 Å s⁻¹ at a base pressure of around 3.5 × 10⁻⁸ Pa. A LiF layer (0.5 nm) was deposited at a rate of 0.2 Å s⁻¹. The finishing Al electrode (cathode) was deposited at a rate of 10 Å s⁻¹ in another chamber. The active area of the diode segments was 2 × 3 mm². EL spectra and brightness–current density–voltage characteristics of the devices were measured by combining a Spectrascan PR-650 spectrophotometer with a computer-controlled direct-current power supply Keithley model 2400 voltage–current source under ambient conditions at room temperature.

**Synthesis**

The synthetic route to \((ppy)_2\text{Ir(dipig)}\) is shown in Scheme 1.¹¹

\[
[\text{ppy}]_2\text{Ir(μ-Cl)}_2 : [\text{ppy}]_2\text{Ir(μ-Cl)}_2 \text{was synthesized according to a modified version of the Nonoyama procedure,}^{14} \text{by refluxing } \text{IrCl}_3 \cdot n\text{H}_2\text{O} (7 \text{ mmol}, 2.5 \text{ g}) \text{ with 2.5 equiv. of the ligand } (2.8 \text{ g} \text{ of phenylpyridine}) \text{ in a } 3 : 1 \text{ mixture of 2-methoxyethanol and water for } 6–7 \text{ h}. \text{ The reaction mixture was cooled to room temperature, and more water was added to precipitate the product. The resulting mixture was subsequently filtered through a Buchner funnel and then washed with hexane and diethyl ether several times to provide the crude product, } [\text{ppy}]_2\text{Ir(μ-Cl)}_2 : 85\% \text{ yield.}
\]

\((\text{ppy})_2\text{Ir(dipig)}\). In a 50 mL flask, a hexane solution of n-ButLi (0.2 mL × 2.5 M) was added to diisopropylamine (50 mg, 0.5 mmol) in hexane (15 mL) at −78 °C under argon. The reaction mixture was stirred at room temperature for 30 min, and then added dropwise to N,N-diisopropylcarbodiimide (63 mg, 0.5 mmol). The colorless solution was stirred for another 30 min, and then added dropwise to \([\text{ppy}]_2\text{Ir(μ-Cl)}_2 (267 mg, 0.25 mmol) in hexane solvent (20 mL). After being stirred at 80 °C for 8 h, the reaction mixture was cooled to room temperature. The solvent was evaporated under vacuum, and the product was washed with Et₂O (20 mL) three times to give a yellowish green powder \((\text{ppy})_2\text{Ir(dipig)} (70\%). MS: m/z 726.99 (M⁺). Anal. calcd for C₃₅H₄₄IrN₅: C, 57.83; H, 6.10; N, 9.63; Found: C, 57.83; H, 5.97; N, 9.65%. ¹H NMR (300 MHz, CDCl₃) δ 9.16 (d, J = 6 Hz, 2H), 7.81 (d, J = 7.8 Hz, 2H), 7.65 (t, J = 7.5 Hz, 2H), 7.53 (d, J = 7.8 Hz, 2H), 7.09 (t, J = 6.9 Hz, 2H), 6.74 (t, J = 7.8 Hz, 2H), 6.63 (t, J = 7.5 Hz, 2H), 6.30 (d, J = 7.8 Hz, 2H), 3.81–3.73 (m, 2H), 3.53–3.40 (m, 2H), 1.22 (d, J = 6.6 Hz, 6H), 1.17 (d, J = 6.6 Hz, 6H), 0.83 (d, J = 6.0 Hz, 6H), −0.05 (d, J = 5.7 Hz, 6H).

**Results and discussion**

**Single crystal structure, and photophysical properties**

A single crystal X-ray diffraction study revealed that the distance between two nearest ppy planes is 3.45 Å and there is no overlap between these two planes in \((\text{ppy})_2\text{Ir(dipig)}\) (Fig. 2a). This indicates there is no significant intermolecular π–π interaction between the ppy groups, which could effectively depress the undesired self-quenching problems in the solid state. The UV-vis absorption and photoluminescence (PL) spectra of \((\text{ppy})_2\text{Ir(dipig)}\) in degassed dilute CH₂Cl₂ solution and neat thin film are also shown in Fig. 3. Intense absorption bands were observed in the ultraviolet part of the spectrum between 240 and 350 nm, assignable to the spin-allowed \(1(\pi–\pi^*) \) transitions of the ppy or/and aromatic moieties. The absorption bands observed at lower energies extending into the region of 350–450 nm, assignable to the spin-allowed \(3(\pi–\pi^*) \) transitions of the Ir[μ] and aromatic moieties. These \(3\text{MLCT}\) bands have been attributed to an effective mixing of charge transfer transitions with higher lying spin-allowed transitions on the cyclometalated ligand.¹⁵ This mixing is facilitated by the strong spin–orbit coupling of the Ir[μ] center. The weak shoulder peaks extending into the region of 450 to 540 nm were assigned associated with both spin–orbit coupling enhanced \(3(\pi–\pi^*) \) and spin-forbidden

![Scheme 1](image)  
**Scheme 1** Synthesis of iridium complex \((\text{ppy})_2\text{Ir(dipig)}\).

![Image](image)  
**Fig. 2** (a) Crystal packing diagram of \((\text{ppy})_2\text{Ir(dipig)}\). (b) Contour plots of the HOMO and LUMO in \((\text{ppy})_2\text{Ir(dipig)}\) from DFT calculations.
MLCT transitions, which are inevitable in nature for phosphorescent materials. The corresponding phosphorescent quantum yield of \((ppy)_2\text{Ir} \text{(dipig)}\) in solution is 0.43, which is generally comparable to those of the well-known complex of \(\text{Ir(ppy)}_3\) (0.4) and the amidinate-supported analogue of \((ppy)_2\text{Ir(dipba)}\) (0.3).\(^13\) Indeed, the neat solid film of \((ppy)_2\text{Ir} \text{(dipig)}\) also displayed strong PL emission in air (Fig. 3, inset) with a quantum yield of 0.11, which has almost the same profile and maximum emission at 558 nm as that in solution, implying the absence of any appreciable aggregates in the solid state. The phosphorescence lifetime of \((ppy)_2\text{Ir} \text{(dipig)}\) in toluene solution is found to be as short as 0.13 ms, suggesting that there is spin–orbit coupling leading to intersystem crossing from the singlet to triplet state in this guanidinate complex.\(^14\) The relatively shorter lifetime was expected to increase spin-state mixing and delay the roll-off of electroluminescent (EL) efficiency.\(^15\)

### Theoretical calculations and time-of-flight (TOF) measurements

To understand the influence of the guanidinate ligand on the electronic characteristics of \((ppy)_2\text{Ir} \text{(dipig)}\), density functional theory (DFT) calculations were carried out and electron-density distributions of the HOMO (highest occupied molecular orbital) and LUMO (lowest unoccupied molecular orbital) are shown in Fig. 2b. The HOMO of \((ppy)_2\text{Ir} \text{(dipig)}\) mainly consists of the N atoms of the dipig ligand and d-orbitals of the Ir atom, while the LUMO is largely located on the ppy ligand. This electronic structure is remarkably different from those of the well-known analogous Ir complexes \(\text{Ir(ppy)}_3\) and \((ppy)_2\text{Ir(acac)}\), where both the HOMO and LUMO are distributed on the \(\pi\) orbitals of the ppy ligands in addition to the Ir d orbitals.\(^17\) Since the HOMO and LUMO of \((ppy)_2\text{Ir} \text{(dipig)}\) are situated on different groups of the molecule, this may be conductive to promote bipolar charge-transporting ability,\(^18\) as holes and electrons can realize intermolecular hopping smoothly along the respective transporting channels. Time-of-flight (TOF) measurements (see Fig. S2, ESI†) revealed that the hole and electron mobilities of \((ppy)_2\text{Ir} \text{(dipig)}\) are \(1.2 \times 10^{-3}\) and \(3.5 \times 10^{-3}\) cm² V⁻¹ s⁻¹, respectively. Both are rather high values for phosphorescent emitters, and are even similar to or much higher than those of typical hole and electron transporting materials such as NPB and TPBI.\(^9\) Therefore, \((ppy)_2\text{Ir} \text{(dipig)}\) is expected to be an efficient EL emitter that also plays another important role in conducting both holes and electrons.

### Characterization of phosphorescent OLEDs

To evaluate the EL performance of \((ppy)_2\text{Ir} \text{(dipig)}\), a series of PHOLEDs with a uniform and simple configuration of [ITO/NPB (35 nm)/emitting layer (25 nm)/TPBI (30 nm)/LiF (0.5 nm)/Al] were fabricated (Fig. 4a). NPB and TPBI were not only employed as the hole transport layer (HTL) and electron transport/
hole-blocking layer (ETL and HBL), respectively, but also as the host of \((ppy)_2\text{Ir(dipig)}\). Films of \((ppy)_2\text{Ir(dipig)}\) doped in NPB or TPBI with concentrations of 8, 15 and 30 wt% as well as a neat \((ppy)_2\text{Ir(dipig)}\) film were adopted as emitting layers (EML) to fabricate devices \(\text{N8, N15, N30, T8, T15, T30 and Ir100}\). All the devices present bright yellow emission with maximum at 556–560 nm and Commission Internationale de L’Eclairage (CIE) coordinates of \((0.48, 0.51)\) at a brightness of 10 000 cd m\(^{-2}\) (Fig. 5). The EL spectra are consistent with the PL spectra of \((ppy)_2\text{Ir(dipig)}\) and no additional emission from the host was observed.

The current density–voltage–luminance \((J–V–L)\) characteristics of the devices are shown in Fig. 6, and the EL performance data are summarized in Table 1. All the devices displayed low driving voltages, and the corresponding current density and luminance exhibited more speedy increase upon increasing the doping concentration. Since the HTL and host in the N-series devices or the ETL and the host in the T-series devices are the same material, the rather low driving voltages can be partly attributed to a minimum injection/transport barrier for the holes from the HTL (NPB) to the EML (NPB doped with emitter) and for the electrons from the ETL (TPBI) to the EML (TPBI doped with emitter), respectively. On the other hand, according to the energy diagram (see Fig. 4b), holes and electrons tend to directly inject into \((ppy)_2\text{Ir(dipig)}\) molecules. This hypothesis was further supported by the \((J–V–L)\) characteristics of two reference devices \(\text{N15N and TT15}\) shown in Fig. 6a and b. The two devices were fabricated by inserting 5 nm thick layers of NPB and TPBI into devices \(\text{N15 and T15}\) with the structures of \([\text{ITO/NPB/EML/NPB (5 nm)/TPBI/LiF/Al}]\) \((\text{N15N})\) and \([\text{ITO/NPB/TPBI (5 nm)/EML/TPBI/LiF/Al}]\) \((\text{TT15})\), respectively. The current density and luminance of \(\text{N15N and TT15}\) are much lower than those of all the N- and T-series devices. This implies that the processes of both electron injection/transport through NPB molecules and hole injection/transport through TPBI molecules are almost impossible, due to the typical “mono-polar” carrier transporting properties of NPB and TPBI\(^1\) together with the large energy barriers between them. Apparently, in the doped devices shown in Fig. 4a, the \((ppy)_2\text{Ir(dipig)}\) molecules serve as an advanced charge-transporting channel in addition to NPB and TPBI, which facilitates hole and/or electron injection and transport across the EML by hopping between the adjacent emitting molecules. This is consistent with the \((J–V)\) characteristics of the corresponding electron- and hole-only single-carrier devices (see Fig. S3, ESI\(^\ddagger\)). As a result, increasing the \((ppy)_2\text{Ir(dipig)}\) concentration will reduce the hopping distance, further enhancing the charge transport and exciton formation.\(^4\) This gives a reasonable explanation for the dependence of the current density and luminance on the doped concentration in the N- and T-series devices.

**Fig. 6** Current density–voltage–luminance curves of (a) devices N8, N15, N15N, N30, Ir100 and (b) devices T8, T15, TT15, T30, Ir100.

**Fig. 7** Power efficiency–luminance–external quantum efficiency curves of (a) devices N8, N15, N30, Ir100 and (b) devices T8, T15, T30, Ir100.
Additionally, device Ir100 with a non-doped EML based on a neat (ppy)2Ir(dipig) film exhibited a more rapid increase in current and luminance than all the other doping devices (Fig. 6). Ir100 achieved brightness values of 100, 1000 and 96 500 cd m⁻² at low driving voltages of 2.6, 3.2 and 8.0 V, respectively, and its turn-on voltage is as low as 2.2 V (Table 1). These values are even lower than those of the reported devices based on a p–i–n structure, the most effective low-driving-voltage technology for OLEDs.\(^\text{100}\) Here, direct charge injection/transport followed by exciton formation on (ppy)2Ir(dipig) molecules without the need of a host, should be a unique mechanism in EML. It is also direct proof for this emitter possessing multifunctional character.

Desired EL efficiencies have been achieved for all the (ppy)2Ir(dipig)-based devices as showed in Fig. 7 and Table 1. Among them, the \(\eta_{\text{ext}}\) values are calculated based on the corresponding current density, luminance and the EL spectra that depend on the driving voltages.\(^\text{19}\) The optimized concentration range is from 8 to 15 wt% for the N-series devices. Very high efficiencies were observed with \(\eta_p, \eta_{\text{max}}, \eta_{\text{ext}}, \eta_{\text{ext,max}}\) for N8 and \(\eta_{\text{ext}}, \eta_{\text{ext,max}}\) for N15, respectively. For the T-series devices, T15 and T30 exhibited higher efficiencies \(\eta_{\text{ext}}, \eta_{\text{ext,max}}\) compared to the N-series. Moreover, the maximum efficiency of Ir100 is more than 70 lm W⁻¹ for \(\eta_p\) and 18% for \(\eta_{\text{ext}}\), which are also the highest levels for non-doped devices reported in the literature.\(^\text{19}\) All of the (ppy)2Ir(dipig)-based doped devices exhibited rather low efficiency roll-off upon increasing brightness. The \(\eta_{\text{ext}}\) Roll-off values are less than 5% at a luminance of 1000 cd m⁻², and still lower than 20% at the extremely high luminance of 10 000 cd m⁻². Such high EL performance should be attributed to the (ppy)2Ir(dipig) molecules that perform the main function of hole/electron transport in the EML due to their bipolar charge transporting abilities and well-matched energy levels with the HTL/ETL. These procedures could lead to balanced charge fluxes and broader recombination zones within the EML, which could suppress the TTA process especially at high luminance levels. In addition, the EL efficiencies of those devices with doped ETL were almost insensitive to doping concentrations within the range from 8 to 15 wt% for the N-series and 15 to 30 wt% for the T-series. The fluctuation in efficiency values (for both \(\eta_p\) and \(\eta_{\text{ext}}\)) between N8/N15 and T15/T30 induced by different (ppy)2Ir(dipig) contents within the very wide current density range of 0.01–100 mA cm⁻² (corresponding to the practical luminance from 10 to 50 000 cd m⁻²), remains less than 3% (Fig. 8). Such a characteristic as the EL performance being almost independent of the doping concentration within a certain range, will lead to an easily controlled process for the fabrication of highly efficient PHOLEDs. It is greatly helpful for improving the product yield of commercial mass production in the future.

**Conclusions**

In summary, a bipolar phosphorescent iridium complex (ppy)2Ir(dipig) has been employed as an emitter to fabricate highly efficient PHOLEDs. The balanced carrier transporting ability of (ppy)2Ir(dipig) ensured that the performance of (ppy)2Ir(dipig)-based PHOLEDs possessed host-independent and doping-concentration-insensitive as well as low efficiency roll-off characteristics. Therefore, we no longer need to specially develop new ingenious hosts by complex synthetic processes to match the photoelectric properties of (ppy)2Ir(dipig). More importantly, the

<table>
<thead>
<tr>
<th>Device</th>
<th>(V_{\text{on}}) (V)</th>
<th>(V_{\text{at}}) (V)</th>
<th>(L_{\text{max}}) (cd m⁻²)</th>
<th>(\eta_{p,\text{max}}) (lm W⁻¹)</th>
<th>(\eta_{\text{ext,\text{max}}}) (%)</th>
<th>(\eta_p) (lm W⁻¹)</th>
<th>(\eta_{\text{ext}}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N8</td>
<td>2.5</td>
<td>3.4, 4.4, 6.4</td>
<td>97 500 (9.5)</td>
<td>95.5</td>
<td>24.8</td>
<td>80.5, 59.2, 36.5</td>
<td>24.8, 23.9, 21.5</td>
</tr>
<tr>
<td>N15</td>
<td>2.4</td>
<td>2.9, 3.7, 5.5</td>
<td>92 430 (9.0)</td>
<td>95.9</td>
<td>25.1</td>
<td>83.5, 60.5, 36.5</td>
<td>24.7, 24.0, 20.3</td>
</tr>
<tr>
<td>N30</td>
<td>2.3</td>
<td>2.8, 3.5, 5.1</td>
<td>10 094 (8.5)</td>
<td>79.3</td>
<td>19.7</td>
<td>71.5, 56.8, 34.2</td>
<td>19.6, 19.1, 16.5</td>
</tr>
<tr>
<td>T8</td>
<td>2.8</td>
<td>3.7, 5.1, 7.2</td>
<td>56 810 (10)</td>
<td>77.5</td>
<td>19.6</td>
<td>63.6, 45.4, 28.6</td>
<td>19.5, 18.9, 17.4</td>
</tr>
<tr>
<td>T15</td>
<td>2.5</td>
<td>3.5, 4.6, 6.4</td>
<td>110 400 (9.5)</td>
<td>93.6</td>
<td>25.3</td>
<td>80.4, 59.5, 38.7</td>
<td>25.3, 24.8, 23.2</td>
</tr>
<tr>
<td>T30</td>
<td>2.3</td>
<td>3.0, 4.1, 6.1</td>
<td>124 800 (9.0)</td>
<td>95.3</td>
<td>24.6</td>
<td>82.2, 59.8, 35.9</td>
<td>24.3, 23.6, 21.8</td>
</tr>
<tr>
<td>Ir100</td>
<td>2.2</td>
<td>2.5, 3.2, 4.6</td>
<td>96 500 (8.0)</td>
<td>73.8</td>
<td>18.5</td>
<td>57.6, 40.5, 21.6</td>
<td>16.5, 14.6, 11.8</td>
</tr>
</tbody>
</table>

\(^\text{a}\) Applied voltage required for luminance of 1 cd m⁻²; \(^\text{b}\) Driving voltage at 100, 1000 and 10 000 cd m⁻², respectively. \(^\text{c}\) Power efficiency at 100, 100 and 10 000 cd m⁻², respectively. \(^\text{d}\) External quantum efficiency at 100, 1000 and 10 000 cd m⁻², respectively.
high-performance PHOLEDs could be constructed based on a simple device configuration and a reproducible fabrication process, suggesting the possibility of realizing cost-effective EL display and lighting source technology. Furthermore, this result demonstrated that imparting good bipolar transport properties on a phosphorescent emitter is an ideal strategy for realizing the optimum performance of PHOLEDs. Studies on the application of this (guanidinate) and related ancillary ligands to other C:N ligands of the existing phosphorescent metal complexes, and the development of more novel phosphorescent emitters with further improved EL performance are in progress.

Acknowledgements

This work was supported by the National Basic Research Program of China (973 Program 2013CB834805 and 2009CB623600), Natural Science Foundation of China (51173065 and 51173064) and Provincial Science and Technology Bureau of Jilin Province (201105010).

Notes and references


10 Improvements in the performance of the Ir(ppy)$_3$ or (ppy)$_2$Ir(acac)-doped devices were observed by modification of the device structures (e.g., employing a p-i-n structure or utilizing a more efficient exciton-block layer, a higher-mobility electron-transport material or a host material with superior charge mobility, etc.). For examples, see: (a) G. F. He, M. Pfeiffer, K. Leo, M. Hofmann, J. Birnstock, R. Pudzich and J. Salbeck, Appl. Phys. Lett., 2004, 85, 3911; (b) Y. Z. Li, W. J. Xu, G. Z. Ran and G. G. Qin, Appl. Phys. Lett., 2009, 95, 033307; (c) Y. T. Tao, Q. Wang, C. L. Yang, C. Chong, J. G. Qin and D. G. Ma, Adv. Funct. Mater., 2010, 20, 2923; (d) S. J. Su, H. Sasabe, Y. J. Pu, K. i. Nakayama and J. Kido, Adv. Mater., 2010, 22, 3311.


