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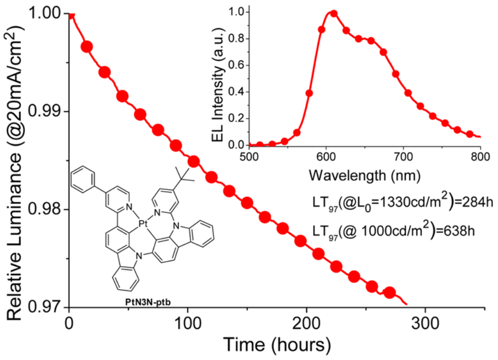
Efficient Red-Emitting Platinum Complex with Long Operational Stability

Tyler Fleetham,[†] Guijie Li,[†] and Jian Li*

Materials Science and Engineering, Arizona State University, Tempe, Arizona 85287, United States

S Supporting Information

ABSTRACT: A tetradentate cyclometalated Pt(II) complex, PtN3N-ptb, was developed as an emissive dopant for stable and efficient red phosphorescent OLEDs. Devices employing PtN3N-ptb in electrochemically stable device architectures achieved long operational lifetimes with estimated LT_{97}, of over 600 h at luminances of 1000 cd/m^2. Such long operational lifetimes were achieved utilizing only literature reported host, transporting and blocking materials with known molecular structures. Additionally, a thorough study of the effects of various host and transport materials on the efficiency, turn on voltage, and stability of the devices was carried out. Ultimately, maximum forward viewing EQEs as high as 21.5% were achieved, demonstrating that Pt(II) complexes can act as stable and efficient dopants with operational lifetimes comparable or superior to those of the best literature-reported Ir(III) complexes.



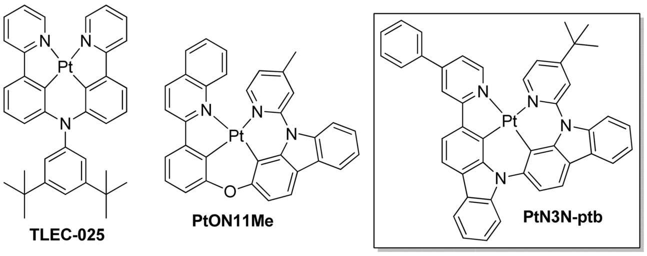
KEYWORDS: *operational lifetime, red emitter, phosphorescence, platinum complex, efficiency, OLED*

1. INTRODUCTION

Organic light-emitting diodes (OLEDs) are widely considered as the next-generation full-color displays and solid-state lighting because of their ability to demonstrate high color quality, employ low-cost fabrication methods, and have low power consumption.[1,2] In particular, phosphorescent metal complexes have attracted a great deal of attention as emissive materials for OLED applications since they can utilize all of the electrogenerated singlet and triplet excitons and achieve near-unity internal electron-to-photon conversion efficiency.[3−6] However, to meet the requirement for potential commercialization, the operational stability of phosphorescent materials in the device settings is also a critical metric for material evaluation. The bulk of the previous research efforts related to the emissive materials have focused on the cyclometalated Ir(III) complexes.[7−15] In fact, efficient and stable Ir(III) complexes emitting in the "green" and "red" region have been developed and incorporated into commercial consumer electronics products. However, a wider range of market adoption will demand the development of stable and efficient blue emitters as well as green and red phosphorescent emitters with improved optical and electrical properties. Thus, expanding the material research efforts beyond the lonely class of cyclometalated Ir(III) complexes could help to achieve such a goal.

From the stand-point of photophysicists, cyclometalated Pt(II) complexes can be considered as emissive dopants for the fabrication of efficient and stable OLEDs. In the past several years, the performance of OLEDs employing Pt-based emitters have improved significantly with reported blue, green, red, and white OLEDs with internal quantum efficiency approaching unity,[16−25] which are comparable to their Ir-analogs. Moreover, Pt-based emitters have demonstrated desirable optical properties through their unique formation of phosphorescent excimers and better control of emission spectral shape, making them more suitable for displays and lighting applications.[26−32] However, because of the lack of knowledge regarding their electrochemical stability, the development of Pt complexes has remained in the academic community and has not attracted much attention from the main-stream industries. In 2012, a red OLED utilizing Pt(II) complex, i.e., [3,5-bis(1,1-dimethylethyl)-phenylimino]bis[6-(2-pyridinyl-*κN*)-2,1-phenylene-*κC*^{1}]platinum(II) (TLEC-025), shown in Scheme 1, exhibited an external quantum efficiency (EQE) of 17.2% at 100 cd/m^2 and an estimated LT_{80}, operational lifetime at 80% of initial

Scheme 1. Molecular Structures of Previously Reported Stable Red Emitters TLEC-025 and PtON11Me As Well As the Structure of the Newly Developed PtN3N-ptb



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luminance, of 721 h with an initial luminance of 1000 cd/m^2,[33] which was the first significant report for the operational stability of Pt(II) complexes in the device settings. However, to meet the strict requirement of commercialization, LT$_{97}$, the operational lifetime at 97% of initial luminance, rather than LT$_{80}$ are considered as an important metric to maintain for display application, which can help to minimize the image sticking effect as well as differential aging effect on the displays. Recently, we developed a red OLED using cyclometalated Pt(II) complex, i.e., platinum(II) [(6-(quinolin-2-yl-*κN*)-1,2-phenylene-*κC*^{1}]oxy[9-(4-methylpyridin-2-yl-*κN*)-9*H*-carbazole-1,2-diyl-*κC*^{1}] (PtON11Me), demonstrated a high operational lifetime, LT$_{97}$, of 74 h at the constant current of 20 mA/cm^2,[34] which was better than its iridium analog employing a similar cyclometalating ligand, i.e. iridium(III) bis(2-phenylquinolyl-*N,C*$^{2\prime}$) acetylacetonate [(pq)$_2$Ir(acac)] in the same device settings.[35] These results, indicate that platinum complexes can have the potential for future commercialization,[33−36] although it remains a challenging task to demonstrate a stable and efficient Pt-based phosphorescent emitter to meet such a strict requirement. Moreover, because of the strong competition among all of commercial vendors of organic electronic materials, most reports regarding the OLED operational stability usually include proprietary host or transporting material with undisclosed molecular structure, which are not accessible to the general public.[33,37] In this communication, we will report a stable and efficient, commercialization ready red Pt(II) complex, i.e. platinum(II) [9-(4-*tert*-butylpyridin-2-yl-*κN*)-2′-(4-phenylpyridin-2-yl-*κN*) −2,9′-bi-9*H*- carbazole-1,1′-diyl-*κC*^{1},*κC*$^{1\prime}$] (PtN3N-ptb), which is incorporated in a device setting employing literature reported functional materials with known chemical structures. Devices employing PtN3N-ptb displayed an estimated operational lifetime, LT$_{97}$, of 638 h at an initial luminance of 1000 cd/m^2 with a low turn-on voltage and a peak EQE of 10.8%. A maximum forward viewing EQE of 21.5% was achieved for PtN3N-ptb devices by adopting different host material system, albeit with a lower operational stability.

2. RESULTS AND DISCUSSION

Recently, our group reported that PtN3N-ptb could act as an efficient red phosphorescent emitter for white OLEDs with EQEs greater than 20%,[38] indicating that PtN3N-ptb can be useful for displays and solid-state lighting applications. PtN3N-ptb employs a tetradentate cyclometalating ligand including a 4-phenylpyridyl-carbazole as a lumophore bonded to 4-*tert*-butylpyridyl-carbazole, the chemical structure of which is illustrated in Scheme 1. The room-temperature absorption and emission spectra of PtN3N-ptb in the solution of CH$_2$Cl$_2$ and low temperature (77K) emission spectrum in 2-methyl-THF are shown in Figure 1. Three characteristic types of well-resolved absorption bands are observed. The high energy, very strong absorption bands (250−400 nm, ε = 2.4−6.4 × 10^{4}cm^{-1} M^{-1}) are attributed to allowed $^1(\pi-\pi^*)$ transitions localized on the cyclometalating ligand.[39−41] The strong bands located at longer wavelength (450−550 nm, ε = 3890 cm^{-1} M^{-1}) can be assigned to metal-to-ligand-charge-transfer (MLCT) transitions.[42] The weaker, lowest energy broad absorption band between (560−650 nm, ε = 120 cm^{-1} M^{-1}) can be identified as the triplet transition (T$_1$) on the basis of the small energy difference between absorption and emission at room temperature. Compared to other literature reported tetradentate Pt complexes, e.g., PtOO$_2$, PtOO$_3$, PtOO$_7$, and PtON7,[16,43] the triplet absorption band of PtN3N-ptb has a higher extinction coefficient and is broader, which is partially overlapping with its own emission spectrum. PtN3N-ptb shows a structured emission spectrum at low temperature with a dominant emission peak at 574 nm and a small vibronic sideband at 622 nm. However, at room temperature, emission peaks at 602 nm and has a Gaussian type emission spectrum with less vibronic features compared to the 77K emission spectrum. Such a large rigidochromic shift indicates a strong mixing of ^{1}MLCT/^{3}MLCT characters into the lowest excited state, similar to other previously reported tetradentate Pt complexes like PtON1 and PtON7.[43] The photoluminescent quantum efficiency of PtN3N-ptb in a solution of dichloromethane is 34% but is expected to be much higher in thin film as has been observed for many other tetradentate Pt complexes.[43,44]

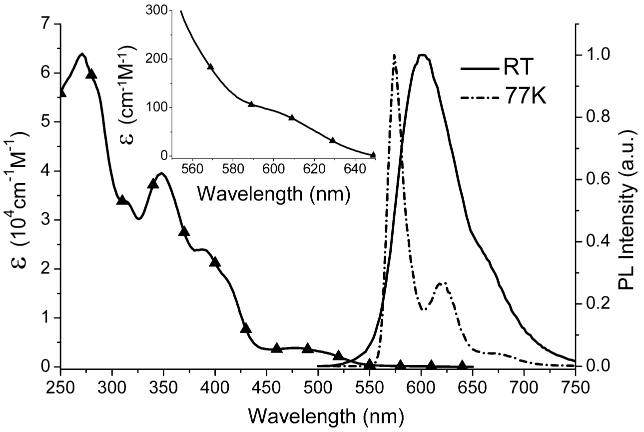

Figure 1. Absorption spectrum of PtN3N-ptb measured in CH$_2$Cl$_2$ at room temperature and emission spectra measured in CH$_2$Cl$_2$ at room temperature (solid line) and in 2-methyl-THF at 77K (dash-dot line). The T_1 absorption transition is shown in the inset.

To evaluate the operational stability and electroluminescent (EL) properties of PtN3N-ptb, we fabricated and tested a device using a known stable device structure,[35] ITO/HATCN-(10 nm)/NPD(40 nm)/10% PtN3N-ptb:CBP(25 nm)/Balq-(10 nm)/Alq$_3$(40 nm)/LiF(1 nm)/Al(100 nm), denoted as Structure 1, where HATCN was 1,4,5,8,9,12-hexaazatriphenylene-hexacarbonitrile, NPD is N,N′-diphyenyl-N,N′-bis(1-naphthyl)-1,1′-biphenyl-4,4″-diamine, CBP is 4,4′-bis(N-carbazolyl) biphenyl, BAlq is bis(2-methyl-8-quinolinolato) (biphenyl-4-olato)aluminum, and Alq$_3$ is tris(8-hydroxyquinoline) aluminum. The EL spectrum, current density−voltage (*J*−*V*) characteristics, forward viewing external quantum efficiency-luminance curve and relative luminance−operational time characteristics of this device are plotted in Figure 2a−d. The operational stability of the OLED (Figure 2d) was assessed in an accelerated condition at a constant driving current of 20 mA/cm^2. This device showed a broad orange-red emission spectrum peaking at 606 nm, which is broader than the PL spectrum of PtN3N-ptb in the solution. The EL spectrum also includes a small portion of detected emission in the range between 450 and 550 nm, which was also observed in the similar devices employing PtON11Me as emissive dopant.[34] The origin of blue luminescence in the device Structure 1 is possibly associated with the emission of NPD at the interface of HTL/EML[35] indicating some degree of electron or exciton transfer between the two layers. This device demonstrated a maximum forward viewing EQE of 8.2%, and an EQE of 7.8% at a luminance of 100 cd/m^2, which is lower than that of many

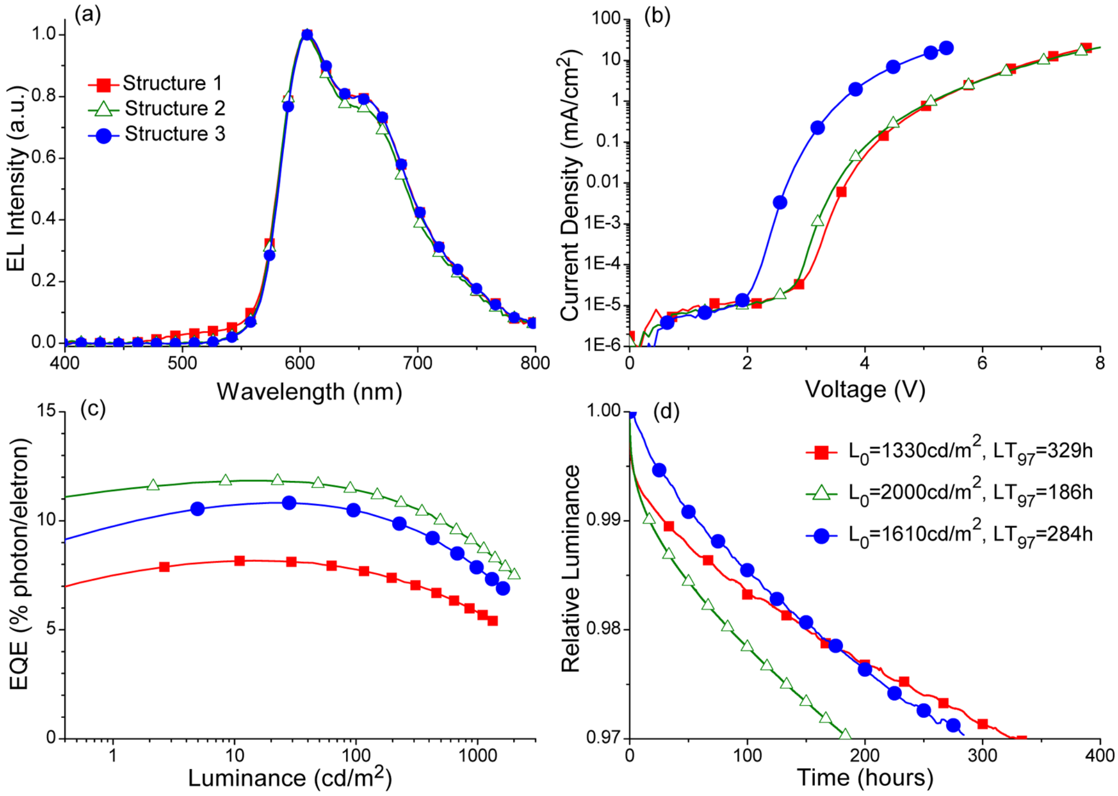

Figure 2. (a) EL spectra, (b) current density−voltage characteristics, (c) EQE vs luminance, and (d) relative luminance vs operation time at constant current of 20 mA/cm^2: Structure 1, ITO/HATCN/NPD/10% PtN3N-ptb:CBP/Balq/Alq$_3$/LiF/Al; Structure 2, ITO/HATCN/NPD/TrisPCz/10% PtN3N-ptb:CBP/Balq/Alq$_3$/ LiF/Al; Structure 3, ITO/HATCN/NPD/TrisPCz/10% PtN3N-ptb:CBP/Balq/BPyTP/LiF/Al.

Table 1. Summary of Device Performance Data

	emitting layer		EQE (%)						
structure[a]	host	dopant conc. (%)	peak	100 cd/m^2	1000 cd/m^2	CIE (x,y)[b]	L_0 (cd/m^2)	LT_{97} (h) at L_0	LT_{97}[c)] (h) 1000 cd/m^2
1	CBP	10	8.2	7.8	5.8	(0.61,0.38)	1330	329	534
2	CBP	10	11.8	11.4	8.9	(0.63,0.37)	1875	186	542
3	CBP	10	10.8	10.4	7.8	(0.63,0.37)	1610	284	638
3	TrisPCz	10	12.1	11.9	9.8	(0.63,0.37)	1980	128	408
3	Bebq$_2$	10	16.3	14.4	10.4	(0.61,0.39)	2394	37	163
3	Bebq$_2$	6	18.0	15.3	10.5	(0.60,0.40)	2656	14	68
3	Bebq$_2$	2	21.5	19.2	13.5	(0.58,0.42)	3743	2.7	25

[a]Structure 1: ITO/HATCN/NPD/EML/BAlq/Alq$_3$/ LiF/Al; Structure 2: ITO/HATCN/NPD/TrisPCz/EML/BAlq/Alq$_3$/ LiF/Al; Structure 3: ITO/HATCN/NPD/TrisPCz/EML/BAlq/BPyTP/LiF/Al. [b]Spectral data collected at 1 mA/cm^2. [c)]Estimated from the equation $LT(L_1) = LT(L_0)(L_0/L_1)^n$, where n is chosen to be 1.7 for comparative purposes.

previously reported phosphorescent red OLEDs. However, this device demonstated a very good operational lifetime, = 329 h, with an initial luminance (L_0) of 1330 cd/cm^2. Lifetime at different luminances can be estimated using the formula $LT(L_1) = LT(L_0)(L_0/L_1)^n$ where L_1 is the desired luminance and the exponent n is typically reported to be in the range of 1.55−1.9.[45−47] For the purpose of comparison, LT_{97} at 1000 cd/m^2 is roughly approximated to be 534 h using a moderate value of n = 1.7. The operational lifetime of this device was superior to that of the reported green emitting *fac*-tris(2-phenylpyridine)iridium [Ir(ppy)$_3$] and orange-red emitting iridium(III) bis(2-phenylquinolyl-*N*,$C^{2'}$)acetylacetonate [(pq)$_2$Ir(acac)] doped OLEDs in the silimar device settings,[35] which demonstrated that PtN3N-ptb can be employed as a stable phosphorescent dopant for OLED applications.

To eliminate the residual NPD emission and improve the device efficiency, we added a 10 nm TrisPCz layer as an electron blocking layer (EBL), ITO/HATCN(10 nm)/NPD-(40 nm)/TrisPCz (10 nm)/10% PtN3N-ptb:CBP(25 nm)/Balq(10 nm)/Alq$_3$(40 nm)/LiF(1 nm)/Al(100 nm), denoted as Structure 2, where TrisPCz is 9,9′,9″-triphenyl-9H,9′H,9″H-3,3′:6′3″-tercarbazole).[47] Because TrisPCz has a higher lowest unoccupied molecular orbital (LUMO) level (−2.1 eV) than that of host material CBP (−3.0 eV), as well as a higher triplet energy (2.7 eV vs. 2.6 eV), it helps to confine the exciton formation inside of the emissive layer effectively and results in an exclusive EL spectrum from PtN3N-ptb.[47] Thus, the device efficiency was improved to a peak EQE of 11.8% (Figure 2c). This device exhibited an operational lifetime, LT_{97}, of 186 h at an initial luminance of 1875 cd/cm^2, corresponding to an approximate LT_{97} of 542 h at 1000 cd/cm^2 (Table 1). These results demonstrate that TrisPCz could act as a stable electron blocking material to improve the device efficiency and operational stability.

Besides efficiency and operational lifetime, turn-on voltage is also an important device performance parameter to consider for display and lighting applications. A low driving voltage results in a low power consumption and has a potentially positive effect on the device operational stability. Electrofluorescent devices with reduced driving voltage using triphenylene derivertives as electron transporting materials have been previously reported.[48] In Structure 3, ITO/HATCN(10 nm)/NPD(40 nm)/TrisPCz (10 nm)/10% PtN3N-ptb:CBP(25 nm)/BAlq(10 nm)/BPyTP(40 nm)/LiF(1 nm)/Al(100 nm), BPyTP (2,7-Di(2,2′-bipyridin-5-yl)triphenylene) was incorporated into the device as an electron transport layer (ETL). It is very encouraging to report that this device in the Structure 3 exhibited a significant lower driving voltage compared with previous devices with Alq_3 as an ETL. To pass a current density of 1 mA/cm^2, the driving voltages were 5.2 V for both of the devices in Structure 1 and 2; however, just 3.6 V for the device in Structure 3 (Figure 2b). This enhancement was largely attributed to the high electron mobility, since the BPyTP molecules tend to adopt a fairly parallel orientation on the substrate while Alq_3 packs randomly.[48] Additionally, it should be noted that this device demonstrated an operational lifetime, LT_{97}, of 284 h at an initial luminance of 1610 cd/cm^2, and an approximate LT_{97} of 638 h at 1000 cd/cm^2, which is much better than previously reported red emitting Pt complexes.[33] Such operational lifetime performance is very close to the desirble parameters for OLED display industry, although the maximum EQE of around 10% is still far below the real potential of the state-of-the art phosphorescent materials.

To further improve the device efficiency, we also tested various host materials in a general device Structure 3: ITO/HATCN(10 nm)/NPD(40 nm)/TrisPCz (10 nm)/10% PtN3N-ptb:host (25 nm)/BAlq(10 nm)/BPyTP(40 nm)/LiF(1 nm)/Al(100 nm), including TrisPCz and $BeBq_2$. The EQE-luminance curves and luminance-time characteristics of the devices were presented in Figure 3a, b. The device employing TrisPCz as a host displayed an enhanced peak EQE of 12.1% with a low roll off to 11.9% at 100 cd/m^2 (Figure 3a). Additionally, an estimated LT_{97} of 408 h at 1000 cd/cm^2 was comparable to the best PtN3N-ptb:CBP based device. The device employing the $Bebq_2$ as a host achieved an even higher peak EQE value of 16.3%, which could be attributed to the improved charge balance in the emissive layer, resulting in a wider and more efficient recombination zone, since $Bebq_2$ is ambipolar and has a high electron mobility (2×10^{-5} cm^2/(V s) at an electric field of 6.4×10^5 V/cm).[49] However, this enhancement came at the expense of device operational lifetime which dropped to an estimated LT_{97} of 163 h at 1000 cd/m^2.

To probe the effects of the dopant concentrations on both device efficiency and device operational lifetime, we fabricated various dopant concentrations in the PtN3N-ptb:$Bebq_2$-based devices following a general device Structure 3: ITO/HATCN(10 nm)/NPD(40 nm)/TrisPCz (10 nm)/x% PtN3N-ptb:$Bebq_2$ (25 nm)/BAlq(10 nm)/BPyTP(40 nm)/LiF(1 nm)/Al(100 nm) (x = 10, 6, or 2). As seen in Figure 4a, the EQE increases with decreasing dopant concentration. For the 2% PtN3N-ptb-doped device, a peak EQE of 21.5% was achieved, which was decreased to 19.2% at 100 cd/m^2 and 13.5% at 1000 cd/m^2, respectively. The high roll-off of device efficiency is similar to the performance observed in many lightly doped devices due to poor charge balance and the higher concentration of excitons on a smaller number of dopant molecules. For low dopant concentrations, the EL spectra is much narrower than that of the 10% doped devices, but similar to the PL spectrum observed in a dilute solution of PtN3N-ptb. This indicates a strong self-absorption of PtN3N-ptb inside of the 10% doped devices, resulting in a decreased device efficiency with increased dopant concentrations. The operational lifetimes of devices also droped quickly with decreasing dopant concentration (Figure 4b). They exhibited estimated LT_{97} of 163, 68, and 25 h for 10, 6, and 2%-doped devices at 1000 cd/m^2, respectively (Table 1). Although lower than those for the PtN3N-ptb:CBP-based device, these operational lifetimes are still among the best reported in literatures for lifetimes to 97% initial luminance, and are expected to be in the range of many hundreds to thousands of hours if tested to LT_{80} or lower as has been typically reported previously in the literatures. The reason for the decrease in lifetime with decreasing dopant concentration could be due to charges and exitons residing mostly on the suspected unstable $Bebq_2$ material, but more study into the exact degradation mechanism in these devices is needed. A summary of the key device characteristics and the operational lifetime values for the EL devices in this study are listed in Table 1. To demonstrate a long-lived phosphorescent OLED with 100% internal quantum efficiency, more comprehensive and systematic work is needed beyond our existing effort, which is an insurmountable task for any acdamic lab due to limited resources. However, it is our strong belief that the operational lifetime and efficiency of PtN3N-ptb based OLEDs can be further improved with the

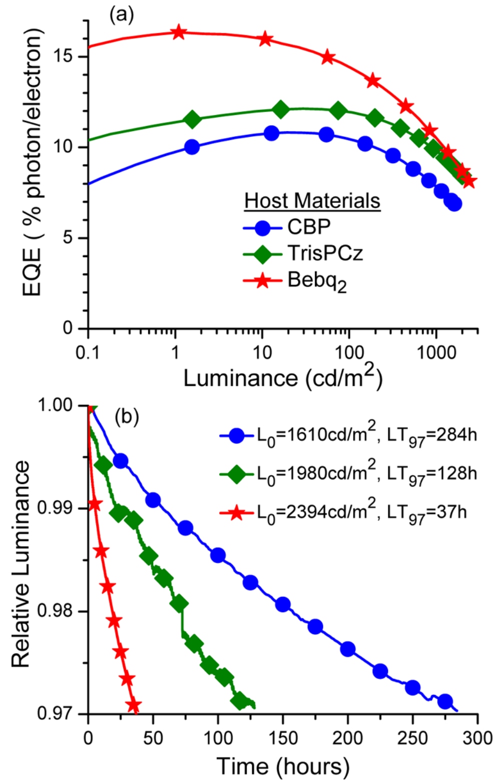

Figure 3. (a) EQE vs luminance; (b) relative luminance vs operation time at constant current of 20 mA/cm^2 for PtN3N-ptb devices with host materials of CBP (spheres), TrisPCz (diamonds), and $Bebq_2$ (stars) in Structure 3: ITO/HATCN/NPD/TrisPCz/10% PtN3N-ptb:Host/Balq/BPyTP/LiF/Al.

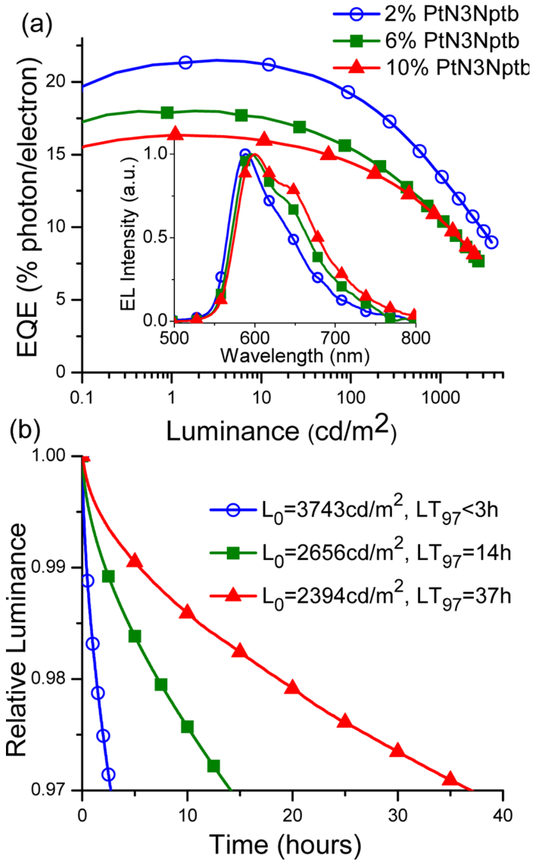

Figure 4. (a) EQE vs luminance and EL spectra (inset); (b) relative luninance vs operation time at constant current of 20 mA/cm^2 for different concentrations of PtN3N-ptb doped in Bebq$_2$ in Structure 3: ITO/HATCN/NPD/TrisPCz/x% PtN3N-ptb:Bebq$_2$/Balq/BPyTP/LiF/Al, where x = 2, 6, or 10.

incorporation of more advanced host, blocking and transporting materials that can balance the excitons in the EML and enhance the electron-to-photon conversion efficiency without compromising the device operational lifetime.

3. CONCLUSION

In summary, we demonstrated a series of stable and efficient red phosphorescent OLEDs employing tetradentate cyclometalated Pt(II) complex, PtN3N-ptb, as an emissive dopant and literature reported host, transporting and blocking materials with known molecular structures. By implementing PtN3N-ptb in the electrochemically stable device architectures, long operational lifetimes were achieved with estimated LT$_{97}$, of over 600 h at luminance of 1000 cd/m^2, which are superior to that of its platinum analog, TLEC-025 which achieved only 720 h to 80% initial luminance while still employing proprietary materials. A significantly improved maximum forward viewing EQE of 21.5% was achieved for device in Structure 3 at a low dopant concentration employing Bebq$_2$ as a host material. Additionally, it was clarified that BPyTP can act as a stable electron transport material and lower turn-on voltage significantly because of its high electron mobility. Our results confirm that Pt(II) complexes can act as stable and efficient dopants with operational lifetimes comparable or superior to those of the best literature reported Pt(II) and Ir(III) complexes, depending on the host and transporting materials. Thus, our study should provide a viable method for molecular and device design in the development of stable and efficient Pt-based phosphorescent OLEDs for commercial solid-state lighting and display applications.

4. EXPERIMENTAL SECTION

4.1. Synthesis of PtN3N-ptb. PtN3N-ptb was synthesized according to our previously reported methods[34] (see Supporting Information about the details of the synthesis).

The absorption spectra were recorded on an Agilent 8453 UV−visible Spectrometer. Room temperature emission spectra experiments were performed on a Horiba Jobin Yvon FluoroLog-3 spectrometer in a solution of dichloromethane. For low temperature (77 K) emission spectra, the solute was dissolved in 2-MeTHF and cooled to 77K with liquid nitrogen. The photoluminescent quantum efficiency of PtN3N-ptb was measured in a solution of dichloromethane. A solution of rhodamine B (Φ = 0.70, excited at 510 nm) in ethanol was used as references for PtN3N-ptb. The equation $\Phi_s = \Phi_r((\eta_s^2 A_r I_s)/(\eta_r^2 A_s I_r))$ was used to calculate the quantum yields where Φ_s is the quantum yield of the sample, Φ_r is the quantum yield of the reference, η is the refractive index of the solvent, A_s and A_r are the absorbance of the sample and the reference at the wavelength of excitation and I_s and I_r are the integrated areas of emission bands.

4.2. Device Fabrication and Characterization. Devices were fabricated by vacuum thermal evaporation in the following structures: ITO/HATCN(10 nm)/ NPD(40 nm)/ EML/Balq(10 nm)/ Alq$_3$(40 nm)/ LiF(1 nm)/ Al(100 nm) (Structure 1), ITO/HATCN(10 nm)/ NPD(40 nm)/ TrisPCz(10 nm)/ EML/Balq(10 nm)/ Alq$_3$(40 nm)/ LiF(1 nm)/ Al(100 nm) (Structure 2), ITO/HATCN(10 nm)/ NPD(40 nm)/ TrisPCz(10 nm)/ EML/BAlq(10 nm)/ BPyTP(40 nm)/ LiF(1 nm)/ Al(100 nm) (Structure 3), Where the EML consisted of a host (either CBP, TrisPCZ, or Bebq$_2$) and PtN3N-ptb doped to 2%, 6%, or 10%, where HATCN is 1,4,5,8,9,12-hexaazatriphenylene-hexacarbonitrile, NPD is N,N′-diphyenyl-N,N′-bis(1-naphthyl)-1,1′-biphenyl-4,4″-diamine, CBP is 4,4′-bis(N-carbazolyl) biphenyl, BAlq is bis(2-methyl-8-quinolinolato) (biphenyl-4-olato)aluminum, Alq$_3$ is tris(8-hydroxyquinoline) aluminum, Bebq$_2$ is bis(benzo[*h*]quinolin-10-olato-*κN*,*κO*)beryllium(II),[33] TrisPCz is 9,9′,9″-triphenyl-9H,9′H,9″H-3,3′:6′3″-tercarbazole,[48] and BpyTP is 2,7-di(2,2′-bipyridin-5-yl)triphenylene.[48] Prior to deposition, the prepatterned ITO coated glass substrates were cleaned by subsequent sonication in deionized water, acetone, and isopropanol. Organic layers were deposited at rates of 0.5 to 1.5 Å/s, monitored by quartz crystal microbalances, in a custom-made vacuum thermal evaporation chamber built by Travato Man. Inc. The Al cathode was deposited through a shadow mask without breaking vacuum, defining device areas of 0.04 cm^2. The current−voltage-luminance characteristics were measured using a Keithley 2400 SourceMeter in conjunction with a Newport 818 Si Photodiode. Electroluminescent spectra were measured with an Ocean Optics USB2000 spectrometer. Device operational lifetime measurements were carried out by driving the device at a constant current of 20 mA/cm^2. Extrapolated lifetimes were approximated using the formula $\mathrm{LT(L_1)=LT(L_0)(L_0/L_1)^{1.7}}$.[45] All devices were tested in a nitrogen filled glovebox without encapsulation.

■ ASSOCIATED CONTENT

Supporting Information

Detailed synthetic procedures, NMR data for the ligand and complex, current−voltage−luminance characteristics, and supplemental device data. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.5b01596.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: jian.li.1@asu.edu.

Author Contributions

[†]T.F. and G.L. contributed equally.

Notes

The authors declare no competing financial interest.

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