CHEMISTRY OF MATERIALS

Novel Blue Fluorophor with High Triplet Energy Level for High Performance Single-Emitting-Layer Fluorescence and Phosphorescence Hybrid White Organic Light-Emitting Diodes

Xiao-Ke Liu,^{†,‡} Cai-Jun Zheng,^{†,§,*} Ming-Fai Lo,[§] Jing Xiao,^{||} Zhan Chen,^{†,‡} Chuan-Lin Liu,[†] Chun-Sing Lee,^{§,*} Man-Keung Fung,[§] and Xiao-Hong Zhang^{†,‡,*}

[†]Nano-organic Photoelectronic Laboratory and Key Laboratory of Photochemical Conversion and Optoelectronic Materials, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, People's Republic of China

[‡]University of Chinese Academy of Sciences, Beijing 100039, People's Republic of China

[§]Center of Super-Diamond and Advanced Films (COSDAF) and Department of Physics and Materials Science, City University of Hong Kong, Hong Kong SAR, People's Republic of China

College of Physics, Electronic Engineering, Taishan University, Taian, Shandong 271021, People's Republic of China

Supporting Information

ABSTRACT: On the basis of a D- π -A structural strategy incorporating diphenylamine as an electron-donor and 1,3,5-triazine as an electron-acceptor with a short benzene π -conjugated feature, 4-(4,6-diphenoxy-1,3,5-triazin-2-yl)-*N*,*N*-diphenylaniline (POTA), a novel blue fluorophor with high triplet energy level has been designed and synthesized to achieve high performance single-emitting-layer (single-EML) fluorescence and phosphorescence hybrid white organic light-emitting diodes (F–P hybrid WOLEDs). POTA exhibits efficient blue electrofluorescence and excellent host features for green and red phosphorescent devices. The single-EML RGB F–P hybrid WOLED based on POTA and green/red complexes shows a maximum total power efficiency of 59.8 ± 1.0 lm W⁻¹ and a maximum total external quantum efficiency of 24.7 ± 0.7%, representing the highest efficiencies among single-EML RGB WOLEDs. Moreover, these performances are comparable with multiple-EML RGB WOLEDs even based on p-i-n structures, providing verification of the high

performance and simple structure of single-EML RGB F-P hybrid WOLEDs.



KEYWORDS: fluorescence and phosphorescence hybrid WOLEDs, blue fluorophors, single-emitting-layer, triazine

INTRODUCTION

White organic light-emitting device (WOLED) technique has attracted much attention because of its great potential in solidstate lighting and displays.¹ Many innovative device architectures have been devised using various material systems to achieve high performance WOLEDs.² Among them, the fluorescence and phosphorescence hybrid WOLED (F-P hybrid WOLED), which can separately utilize the singlet excitons with a blue fluorescent emitter and the triplet excitons with green, orange, and red phosphorescent dopants, is considered an ideal candidate.³ Compared with traditional fully phosphorescent WOLEDs, the F-P hybrid WOLEDs replace the blue phosphorescent dopant with a highly efficient blue fluorescent emitter. F-P hybrid WOLEDs are not only able to harvest 100% internal quantum efficiency due to the complete utilization of singlet and triplet excitons, but also achieve better performance since blue fluorescent emitters are typically more stable than blue phosphors.^{3b,c} They also have the potential for higher efficiency because there is nearly no exchange energy loss from the singlet excitons to the triplet excitons.^{3a} Therefore, F-P hybrid WOLEDs are considered to be the best pathway for realizing high performance WOLEDs.

Generally, white light is formed in WOLEDs by two complementary colors or three primary colors (red, green, and blue).^{2b} As the backlight of full-color displays, white light would be separated into red (R), green (G) and blue (B) color by the color filters. For solid-state lighting applications, white light with an entire visible region spectrum provides better high color-rending capability for objects.^{1c} Thus, adopting an RGBemitter system is clearly preferable to realize white light emission that has high efficiencies and high light qualities.⁴ In the past decade, great progress has been made in high performance RGB F-P hybrid WOLEDs with multiemittinglayer (EML).^{3a,b,5} For example, in 2006, Forrest's group constructed an F-P hybrid WOLED by doping a blue fluorophor and green/red phosphors into CBP in separate emitting-layers, showing a maximum total external quantum efficiency (EQE) and power efficiency (PE) of 18.7% and 37.6 lm W⁻¹, respectively.^{3a} In 2007, Leo and his co-workers reported an F-P hybrid WOLED with higher performance by

```
Received:October 9, 2013Revised:October 12, 2013Published:October 12, 2013
```

ACS Publications © 2013 American Chemical Society

doping an orange phosphor into a blue fluorophor 4P-NPD and a green phosphor into 1,3,5-tris(*N*-phenylbenzimidazol-2yl)benzene (TPBI). Their p-i-n structured white device exhibited a total PE of 57.6 lm W⁻¹ at a brightness of 100 cd m⁻².^{3b} However, these multi-EML F–P hybrid WOLEDs are complicated, expensive, and difficult to reproduce. Moreover, the solution process, the next generation process for low-cost and large-area manufacturing,^{1b,6} cannot be realized on such complicated multi-EML F–P hybrid WOLEDs. Therefore, realizing high performance single-EML RGB F–P hybrid WOLEDs has become increasingly important.^{3c,7}

In single-EML F-P hybrid WOLEDs, green/red phosphors are directly doped into a blue fluorophor, which acts as both the blue emitter and the host material for the phosphorescent dopants. With this arrangement, the blue fluorophor must simultaneously achieve an efficient blue fluorescence emission and a triplet energy level (T_1) higher than 2.4 eV for sensitizing the green phosphor. However, common blue fluorophors cannot realize such high T1 due to their large singlet-triplet splitting $(\Delta E_{\rm ST})$,^{5d} and blue fluorophors with T₁ higher than 2.4 eV are rarely reported. Considering that the singlet energy level (S_1) should be between 2.6 and 2.9 eV for blue fluorescence emission and T₁ must be higher than 2.4 eV to fit the energy level of green phosphors, the $\Delta E_{\rm ST}$ of the blue fluorophor should be smaller than 0.5 eV. To achieve such a small ΔE_{ST} , the blue fluorophor should have a minimal overlap between the HOMO/LUMO,⁸ whereas too small an overlap will reduce the fluorescence efficiency.⁹ These contradictory requirements can be appropriately managed in a molecule by using a suitable π -conjugation group to bridge an electrondonating group to an electron-accepting group (D- π -A). In such a molecule, the HOMO and LUMO would be located mainly on the electron-donating group and the electronaccepting group respectively, and the overlap between the HOMO and LUMO would be nearly equal in the π -bridging group. Thus, we can optionally adjust the bulk of the overlap by switching the bridging groups to achieve efficient blue fluorophors that have high T₁s. Compared with the similar structure D-A bipolar host materials which have been widely used in phosphorescent OLEDs recently,¹⁰ D-*π*-A compounds can not only provide balanced hole and electron flows, but also remarkably improve their poor fluorescent efficiency by appropriately increasing the overlap between the HOMO/ LUMO.⁵

According to such a design strategy, in this work we report on a novel triazine/amino-based D- π -A blue fluorophor 4-(4,6diphenoxy-1,3,5-triazin-2-yl)-N,N-diphenylaniline (POTA). The short and direct benzene π -conjugated linkage between the electron donor diphenylamine and the acceptor 1,3,5triazine endows the POTA with efficient blue fluorescent emission and a high T1 of 2.44 eV. The nondoped blue fluorescent device based on POTA exhibits a maximum EQE of $4.2 \pm 0.3\%$ and the phosphorescent devices containing POTA as host material show maximum EQEs as high as $17.1 \pm 0.2\%$ for green and $18.8 \pm 0.2\%$ for red. These excellent electroluminescent (EL) results demonstrate POTA as an excellent blue fluorophor as well as an outstanding host material for phosphorescent dopants. The single-EML RGB F-P hybrid WOLED based on POTA realizes a maximum total EQE of 24.7 \pm 0.7%, a maximum total PE of 59.8 \pm 1.0 lm , and a PE of 31.3 \pm 0.3 lm W¹⁻ at a luminance of 1000 cd W^{-1} m⁻², , representing the highest efficiencies found among single-EML RGB WOLEDs. The efficiencies are also higher than in

multi-EML RGB F–P hybrid WOLEDs even those having p-i-n structures.

EXPERIMENTAL SECTION

General Procedures. NMR spectra were determined on a Bruker Advance-400 spectrometer with chemical shifts reported as ppm. Mass spectrum data were obtained with a Finnigan 4021C GC-MS spectrometer. Absorption and photoluminescence spectra were recorded with a Hitachi UV–vis spectrophotometer U-3010 and a Hitachi fluorescence spectrometer F-4500, respectively. Cyclic voltammetry was performed on a CHI660E electrochemical analyzer.

Synthesis. Commercially available reagents were used without purification. The synthetic route of POTA is outlined in Scheme 1.

Scheme 1. Synthetic Route and Chemical Structure of POTA



2-Chloro-4,6-diphenoxy-1,3,5-triazine. Cyanuric chloride (1.840 g, 10 mmol) was dissolved in acetone (100 mL) and cooled to 0 °C. In a separate flask, phenol (1.880 g, 20 mmol) was reacted with NaOH (0.800 g, 20 mmol) in water (100 mL) to form a clear aqueous solution. Then the aqueous solution was added drop by drop to the cyanuric chloride solution. After stirring at 0 °C for 8 h, the mixture was poured into water (100 mL) to form white precipitate. The white precipitate was filtered and washed with water and then ethanol. The product was purified by recrystallization with hexane to produce a white solid. Yield: 73%. ¹H NMR (400 MHz, CDCl₃, δ): 7.43–7.36 (m, 4H), 7.28 (dd, J = 7.8, 1.4 Hz, 2H), 7.17–7.11 (m, 4H). HRMS (EI, m/z): [M] ⁺ calcd for C₁₅H₁₀ClN₃O₂, 299.0462; found: 299.0546.

4-(4,6-Diphenoxy-1,3,5-triazin-2-yl)-N,N-diphenylaniline (POTA). Toluene (12 mL), ethanol (6 mL), and 2 M aqueous Na₂CO₃ (9 mL) were added to a mixture of 2-chloro-4,6-diphenyl-1,3,5-triazine (0.536 g, 2 mmol), 4-(diphenylamino)phenylboronic acid (0.578 g, 2 mmol), and tetrakis(triphenylphosphine)platinum (0.234 g, 0.2 mmol). The mixture was refluxed for 8 h under a nitrogen atmosphere. When cooled to room temperature, the mixture was extracted with dichloromethane and dried over Na2SO4. After the solvent had been removed under reduced pressure, the residue was purified by column chromatography on silica gel using dichloromethane/petroleum ether (4:1) as the eluent to produce a yellow solid. Yield: 66%. ¹H NMR (400 MHz, DMSO-d₆, δ): 7.99 (d, J = 8.8 Hz, 2H), 7.45 (t, J = 4.0 Hz, 4H), 7.39 (t, J = 8.0 Hz, 4H), 7.28 (t, J = 8.4 Hz, 6H), 7.19 (t, J = 7.4 Hz, 2H), 7.15–7.13 (m, 4H), 6.96 (d, J = 8.8 Hz, 2H). ¹³C NMR (100 MHz, CDCl₃, δ): 175.81, 173.50, 153.30, 152.80, 147.35, 131.39, 130.39, 130.20, 127.34, 126.78, 126.58, 125.39, 122.49, 120.81. HRMS (EI, m/z): [M] ⁺ calcd for C₃₃H₂₄N₄O₂, 508.1899; found, 508.1793.

Quantum Calculation. Theoretical calculation of the compound was carried out using the Gaussian-03 program. Density functional theory (DFT) B3LPY/6-31G(d) was used to determine and optimize the structure.

Device Fabrication and Measurement. ITO-coated glasses with a sheet resistance of 30 Ω per square were used as substrates. The substrates were first cleaned with isopropyl alcohol and deionized water, then dried in an oven at 120 °C, treated with UV-ozone, and finally transferred to a deposition system with a base pressure of about 1×10^{-6} Torr. Thermally evaporated organic materials were sequentially deposited at a rate of 1-2 Å s⁻¹ onto the ITO substrates. The cathode was completed by thermal deposition of LiF at a deposition rate of 0.1 Å s⁻¹. EL luminescence, spectra, and CIE color coordinates were measured with a Spectrascan PR650 photometer, and the current–voltage characteristics were measured with a computer-controlled Keithley 2400 SourceMeter under ambient atmosphere.

Chemistry of Materials

RESULTS AND DISCUSSION

Synthesis. The intermediate of 2-chloro-4,6-diphenoxy-1,3,5-triazine was prepared from the reaction between cyanuric chloride and phenol with the existence of sodium hydroxide (Scheme 1).¹¹ Then, the chlorine-substituted 1,3,5-triazine unit was attached to the 4-position of triphenylamine using a palladium-catalyzed cross-coupling reaction to give POTA in good yield.^{11a,12} The chemical structure of POTA was fully characterized by ¹H NMR and ¹³C NMR spectroscopy and mass spectrometry.

Optical Properties. The UV-vis absorption and photoluminescence (PL) spectra of POTA in dilute cyclohexane solution were investigated (Figure 1 and Table 1). The



Figure 1. (a) UV-vis absorption and PL spectra of POTA in dilute cyclohexane solution at room temperature, and the fluorescence and phosphorescence spectra of POTA in 2-methyltetrahydrofuran at 77 K. (b) PL spectra of POTA in different solvents at room temperature.

absorption peak at 295 nm is associated with the diphenylamine centered n- π^* transition,¹³ while the longer wavelength peak at 378 nm can be attributed to the intramolecular charge transfer (ICT) transition from the electron-rich diphenylamine moiety to the electron-deficient 1,3,5-triazine core. POTA shows a deep blue emission in a dilute cyclohexane solution with a peak at 422 nm and a shoulder peak at 437 nm, which are attributed to the n- π^* transition and ICT transition, respectively. To prove that POTA undergoes an ICT transition, we measured the PL spectra of POTA in solvents with different polarity (Figure 1). POTA displays strong solvatochromaticity such that the emission spectrum exhibits a clear bathochromic shift from nonpolar cyclohexane to higher polar toluene, dichloromethane (DCM), acetone, and dimethylformamide (DMF).¹⁴ The fluorescent quantum yield (Φ_f) of POTA in cyclohexane solution was determined to be 0.75 using 9,10-diphenylanthracence $(\Phi_f = 0.90 \text{ in cyclohexane solution})^{15}$ as a standard.

Table 1. Physical Properties of POTA

$\lambda_{\rm abs}/\lambda_{\rm em} \ ({\rm nm})^a$	295 378/422 437
$\Phi_{ m f}^{\ b}$	0.75
$\lambda_{\rm fluo}/\lambda_{\rm phos}~({\rm nm})^c$	443/508
$S_1/T_1 (eV)^d$	2.80/2.44
$\Delta E_{\rm ST} \ ({\rm eV})^e$	0.36
$E_{1/2}^{ox}/E_{1/2}^{red} (V)^{f}$	0.67/-2.15
HOMO/LUMO (eV) ^g	-5.41/-2.59
$E_g/E_g^{opt} (eV)^h$	2.82/2.84

^{*a*}Measured in dilute cyclohexane solution at room temperature. ^{*b*}Measured in dilute cyclohexane solution, using 9,10-diphenylanthracence ($\Phi_f = 0.90$ in cyclohexane solution) as a standard. ^{*c*}Fluorescence and phosphorescence spectrum peaks measured in 2methyltetrahydrofuran at 77 K. ^{*d*}S₁, singlet energy level, calculated from the fluorescence peak at 77 K; T₁, triplet energy level, calculated from the phosphorescence peak at 77 K. ^{*e*} ΔE_{ST} , Singlet–triplet energy difference, $\Delta E_{ST} = S_1 - T_1$. ^{*f*} $E_{1/2}^{\text{cx}}$, half-wave oxidation potential vs Fc/ Fc⁺; $E_{1/2}^{\text{red}}$, half-wave reduction potential vs Fc/Fc⁺. ^{*g*}HOMO = $-E_{1/2}^{\text{ox}} - E_{SCE}$ and LUMO = $-E_{1/2}^{\text{red}} - E_{SCE}$, the energy level of SCE (E_{SCE}) is 4.74 eV vs vacuum level.²¹ ^{*h*} E_g , energy band gap, calculated from the CV; E_g^{opt} , calculated from the absorption spectrum.

The fluorescence and phosphorescence spectra of POTA in 2methyltetrahydrofuran glass at 77 K were also determined, with peaks at 443 and 508 nm, respectively (Figure 1 and Table 1). Accordingly, the S₁ and T₁ of POTA are calculated to be 2.80 and 2.44 eV, respectively, indicating that POTA has a small $\Delta E_{\rm ST}$ of 0.36 eV.^{10d} Additionally, the T₁ of POTA is higher than the triplet energy of common green phosphorescent dopants such as fac-tris(2-phenylpyridine) iridium (Ir(ppy)₃) (2.41 eV),¹⁶ ensuring that POTA can be used as a host material for green phosphors. POTA's high fluorescent quantum yield and suitable S₁ and T₁ indicate that POTA is a potential host material for single-EML RGB F–P hybrid WOLEDs.

Theoretical Calculations and Electrochemical Proper-ties. To better understand POTA's structure–property relationship at the molecular level, quantum chemical calculations were employed at the B3LYP/6-31G(d) theoretical level (Figure 2). In the ICT transition-based POTA, the



Figure 2. Calculated spatial distributions of the HOMO/LUMO of POTA.

HOMO is primarily located on the electron-rich diphenylamine unit and benzene π bridge, whereas the LUMO mostly sits on the electron-deficient 1,3,5-triazine group and benzene π bridge. The overlap in the POTA molecule between the HOMO and LUMO is limited on the benzene π bridge, which tallies with our assumption and results in a small $\Delta E_{\rm ST}$ of 0.36 eV and a high fluorescence efficiency of 0.75. To measure the experimental values of the HOMO/LUMO energy levels, we investigate the electrochemical property of POTA using a three-electrode cell (Figure S1 of the Supporting Information, SI). During the anodic scan, POTA undergoes a quasireversible oxidation curve, originating from its electron-rich diphenylamine unit. Upon the cathodic sweep, POTA also

Tal	ole	2.	Electro	luminescenc	e Pro	perties	of	the	D	evi	ces
-----	-----	----	---------	-------------	-------	---------	----	-----	---	-----	-----

		PE/CE/EQE ^b [lm	$\operatorname{CIE}(x, y)^c$		
	$V_{\rm on}^{\ a} [{\rm V}]$	maximum	@1000 cd m ⁻²		
device B	3.1	$5.0 \pm 0.3/5.9 \pm 0.4/4.2 \pm 0.3$	$2.6 \pm 0.3/4.8 \pm 0.3/3.4 \pm 0.2$	(0.15, 0.26)	
device G	3.0	$52.3 \pm 0.1/57.6 \pm 0.8/17.1 \pm 0.2$	$38.4 \pm 0.4/51.9 \pm 0.1/15.2 \pm 0.2$	(0.28, 0.63)	
device R	2.9	$28.1 \pm 0.2/36.7 \pm 0.3/18.8 \pm 0.2$	$26.8 \pm 0.4/36.7 \pm 0.3/18.8 \pm 0.2$	(0.55, 0.44)	
device W1	2.8	$59.8 \pm 1.0/57.2 \pm 0.9/24.7 \pm 0.7$	$31.3 \pm 0.3/40.6 \pm 0.3/18.3 \pm 0.2$	(0.41, 0.46)	
device W2	2.9	$60.5 \pm 0.9/60.4 \pm 0.9/25.1 \pm 0.5$	$32.3 \pm 2.0/44.3 \pm 0.9/20.0 \pm 0.6$	(0.34, 0.45)	
⁴ Turn-on voltage. ^b Maximum power efficiency, current efficiency and external quantum efficiency. ^c Estimated at 1000 cd m ⁻² .					

exhibits a quasi-reversible reduction curve, which can be attributed to electron-deficient 1,3,5-triazine moiety. The reversible oxidation and reduction behavior of POTA implies that it has potential for efficient hole and electron transport.¹³ The HOMO/LUMO energy levels of POTA are estimated from the half-wave potentials of the oxidation and reduction curves (relative to vacuum level),^{10d} which are -5.41 eV and -2.59 eV, respectively. Calculated from the HOMO/LUMO energy levels, the energy band gap (E_g) value of 2.82 eV is obtained for POTA, similar to the result estimated from the optical absorption edges of solid film on quartz substrate (Table 1). The rather narrow E_g with its suitable HOMO/LUMO energy levels is beneficial for lessening the driving voltage and augmenting the PE of the OLEDs.¹⁷

Electroluminescence Performance. A nondoped blue fluorescent OLED (device B) was first fabricated with a device structure of ITO/NPB (30 nm)/TCTA (10 nm)/POTA (30 nm)/TPBI (30 nm)/LiF (1.5 nm)/Al. In this device, ITO (indium tin oxide) and LiF/Al are the anode and the cathode, respectively; NPB (4,4'-bis[N-(1-naphthyl)-N-phenyl amino]biphenyl) is the hole-transporting layer (HTL); TCTA (4,4',4"-tris(N-carbazolyl)triphenylamine) is the exciton-blocking layer; and TPBI serves as the electron-transporting layer (ETL), the hole-blocking layer and the exciton-blocking layer. The nondoped blue device based on POTA exhibits stable blue fluorescent spectra at different luminance with peaks at 472 nm and CIE coordinates of (0.15, 0.26) (SI Figure S2 and Table 2). The maximum PE, current efficiency (CE) and EQE of device B are 5.0 \pm 0.3 lm W⁻¹, 5.9 \pm 0.4 cd A⁻¹ and 4.2 \pm 0.3%, respectively (Figure 3 and Table 2). Considering the 5% theoretical limit in fluorescent devices,¹⁸ POTA is deemed to be an outstanding blue fluorophor.

Green and red phosphorescent devices based on POTA were then constructed to testify the host properties of POTA for green and red phosphors. They have a configuration of ITO/ NPB (30 nm)/TCTA (10 nm)/POTA: 2 wt % Ir(ppy)₃ or 6 wt % Ir(2-phq)₃ (30 nm)/TPBI (30 nm)/LiF (1.5 nm)/Al (device G and R). Herein, Ir(2-phq)₃ is tris(2-phenylquinoline)iridium. Device G exhibits a maximum EQE of 17.1 ± 0.2%, a maximum PE of 52.3 \pm 0.1 lm W⁻¹ and a maximum CE of 57.6 \pm 0.8 cd A⁻¹ (Figure 3 and Table 2). Similarly, device R also gives a high performance with a maximum PE of 28.1 ± 0.2 Im W^{-1} , a maximum CE of 36.7 \pm 0.3 cd A^{-1} and a maximum EQE of 18.8 \pm 0.2%. Considering the 20% theoretically limit for EQE in phosphorescent devices, 18,19 both devices exhibit extremely high EQEs, indicating that POTA can not only sensitize a triplet emission of green phosphor, but also achieve excellent host performance for phosphors.

POTA was finally applied in a single-EML RGB F–P hybrid WOLED (device W1) with a configuration of ITO/NPB (30 nm)/TCTA (10 nm)/POTA: $Ir(ppy)_3$: $Ir(2-phq)_3$ (30 nm)/TPBI (30 nm)/LiF (1.5 nm)/Al. In the EML, the



Figure 3. PE-EQE-luminance plots of (a) device B, (b) device G, and (c) device R.

concentrations of $Ir(ppy)_3$ and $Ir(2-phq)_3$ have been optimized to 0.2 and 0.3 wt %, respectively. At such low doping concentrations, it is likely that some blue fluorophor molecules will find no phosphorescent molecules within their 3 nm vicinity (the diffusion length of a singletexciton); while phosphorescent dopant molecules will exist within 100 nm (the diffusion length of a triplet exciton).^{3a,c} Therefore, singlet excitons will be reserved on the blue fluorophors and utilized for blue fluorescence; whereas the triplet excitons will transfer to the dopant molecules for green and red phosphorescence, resulting in white emission. Owing to the suitable HOMO/ LUMO and singlet/triplet energy levels (SI Figure S4), small injection barriers exist between the HTL/ETL and EML, and excitons are effectively limited in the EML. Thus, the device W1 has a low turn-on voltage of 2.8 V (Figure 4a and Table 2).



Figure 4. (a) Current density-luminance-voltage characteristics, (b) the EL spectra, and (c) PE-EQE-luminance plots of device W1.

As shown in Figure 4b and SI Table S1, warm light emission was realized in this device, and the CIE coordinates show moderate blue-shift from (0.44, 0.48) to (0.36, 0.44) when the luminance increases from 100 to 10 000 cd m⁻², which may due to the triplet-triplet annihilation at high current densities. As illumination sources are generally characterized by their total emitted power,^{3a,20} device W1 realizes a maximum total PE of 59.8 ± 1.0 lm W⁻¹, a maximum total CE of 57.2 ± 0.9 cd A⁻¹ and a maximum total EQE of 24.7 ± 0.7%. The total efficiencies maintain at 31.3 ± 0.3 lm W¹⁻, 40.6 ± 0.3 cd A⁻¹ and 18.3 ± 0.2% even at brightness of 1000 cd m⁻².

POTA-based single-EML RGB F–P hybrid WOLED represents the highest efficiencies among single-EML RGB WOLEDs with hybrid emitters or all phosphors. Furthermore, such high performance is also comparable with the multiple-EML RGB F–P hybrid WOLEDs even based on p-i-n structures (Table 3).

Table 3. Summary of Recently Reported High Performance RGB WOLEDs

	maximum	@1000 cd m ⁻²		
	PE/CE/EQE [lm W ⁻¹ / cd A ⁻¹ / %]	$\frac{\text{PE/CE/EQE}}{[\text{lm W}^{-1}/\text{ cd A}^{-1}/\text{ \%}]}$		
ref 5a ^a	_/_/_	$14.8/25.0/10.7^d$		
ref 5b ^a	46.8/-/16.5	_/_/_		
ref 21 ^a	57.3/-/21.8	24.4/-/-		
ref 4b ^b	$52.3/-/-^{e}$	35.2/-/-		
ref 3b ^c	$57.6/-/20.3^{e}$	37.5/-/16.1		
ref 3a. ^c	37.6/-/18.7	$23.8/-/18.4^{d}$		
ref 5c ^c	32.0/30.2/13.4 ^e	27.1/30.8/13.7		
ref 21 ^f	28.6/-/21.0	22.1/-/-		
device W1	$59.8 \pm 1.0/57.2 \pm 0.9/24.7 \pm 0.7$	$\begin{array}{c} 31.3 \pm 0.3/40.6 \pm 0.3/\\ 18.3 \pm 0.2 \end{array}$		
device W2	$\begin{array}{r} 60.5 \pm 0.9/60.4 \pm 0.9/\\ 25.1 \pm 0.5 \end{array}$	$\begin{array}{r} 32.3 \pm 2.0/44.3 \pm 0.9 \\ 20.0 \pm 0.6 \end{array}$		

^aSingle-EML F–P hybrid WOLEDs. ^bSingle-EML fully phosphorescent WOLEDs. ^cMultiple-EML F–P hybrid WOLEDs with p-i-n structures. ^dAt 500 cd m⁻². ^eAt 100 cd m⁻². ^fMultiple-EML F–P hybrid WOLEDs.

To further prove that the performance of this single-EML device structure could keep up with the multi-EML for F-P hybrid WOLEDs, we fabricated a POTA-based multiple-EML RGB F-P hybrid WOLED (device W2) with a structure of ITO/NPB (30 nm)/TCTA (10 nm)/POTA (8 nm)/POTA: 2 wt % Ir(ppy)₃ (6 nm)/POTA: 2 wt % Ir(2-phq)₃ (8 nm)/ POTA (8 nm)/TPBI (30 nm)/LiF (1.5 nm)/Al, which is a typical device structure in multi-EML F-P hybrid WOLEDs.^{3a,21} Device W2 also shows warm white light emission (SI Table S1) with a maximum total CE of 60.4 \pm 0.9 cd A⁻¹, a maximum total PE of 60.5 \pm 0.9 lm W^{1-} and a maximum total EQE of 25.1 \pm 0.5% (SI Figure S5 and Table 2). The efficiencies of device W1 are equally matched with device W2. The single-EML F-P hybrid WOLED based on POTA performs as highly as the multiple-EML, while the former has a simpler structure and better economy.

CONCLUSIONS

In summary, a novel blue fluorophor POTA has been designed and synthesized by using a D- π -A structural strategy incorporating diphenylamine as an electron-donor and 1,3,5triazine as an electron-acceptor with a short benzene π conjugated feature. POTA simultaneously exhibits an efficient blue fluorescence emission, a high T₁ of about 2.44 eV, and appropriate HOMO/LUMO energy levels. The excellent EL performances demonstrate that POTA is an excellent blue fluorophor as well as an outstanding host material for phosphorescent dopants. The single-EML RGB F–P hybrid WOLED based on POTA shows a maximum total PE of 59.8 ± 1.0 lm W⁻¹ and a maximum total EQE of 24.7 ± 0.7%, the highest efficiencies among the single-EML RGB WOLEDs. These performances are also comparable with multiple-EML RGB WOLEDs, even those with p-i-n structures. Moreover,

Chemistry of Materials

this work provides verification of the high performance and simple structure of single-EML RGB F-P hybrid WOLEDs.

ASSOCIATED CONTENT

S Supporting Information

Cyclic voltammograms, EL spectra, energy level diagrams, current density-luminance-voltage characteristics, PE-EQE-luminance plots and CIE coordinates. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*E-mail: xhzhang@mail.ipc.ac.cn (X.-H.Z.); zhengcaijun@mail. ipc.ac.cn (C.-J.Z.); apcslee@cityu.edu.hk (C.-S.L.).

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (No. 51373190, 51033007, 51103169, and 51128301), the Beijing Natural Science Foundation (No. 2111002), the National High-tech R&D Program of China (863 Program) (Grant No. 2011AA03A110) and the Instrument Developing Project of the Chinese Academy of Sciences (Grant No. YE201133), P. R. China.

REFERENCES

(1) (a) Wang, R. J.; Liu, D.; Ren, H. C.; Zhang, T.; Yin, H. M.; Liu, G. Y.; Li, J. Y. *Adv. Mater.* **2011**, *23*, 2823. (b) Zhang, B. H.; Tan, G. P.; Lam, C. S.; Yao, B.; Ho, C. L.; Liu, L. H.; Xie, Z. Y.; Wong, W. Y.; Ding, J. Q.; Wang, L. X. *Adv. Mater.* **2012**, *24*, 1873. (c) Chen, S.; Tan, G.; Wong, W.-Y.; Kwok, H.-S. *Adv. Funct. Mater.* **2011**, *21*, 3785.

(2) (a) Wang, Q.; Ma, D. G. Chem. Soc. Rev. 2010, 39, 2387.
(b) Farinola, G. M.; Ragni, R. Chem. Soc. Rev. 2011, 40, 3467.
(c) Gather, M. C.; Kohnen, A.; Meerholz, K. Adv. Mater. 2011, 23, 233. (d) Kamtekar, K. T.; Monkman, A. P.; Bryce, M. R. Adv. Mater. 2010, 22, 572.

(3) (a) Sun, Y. R.; Giebink, N. C.; Kanno, H.; Ma, B. W.; Thompson, M. E.; Forrest, S. R. *Nature* **2006**, *440*, 908. (b) Schwartz, G.; Pfeiffer, M.; Reineke, S.; Walzer, K.; Leo, K. *Adv. Mater.* **2007**, *19*, 3672. (c) Ye, J.; Zheng, C. J.; Ou, X. M.; Zhang, X. H.; Fung, M. K.; Lee, C. S. *Adv. Mater.* **2012**, *24*, 3410.

(4) (a) Jou, J.-H.; Chou, Y.-C.; Shen, S.-M.; Wu, M.-H.; Wu, P.-S.; Lin, C.-R.; Wu, R.-Z.; Chen, S.-H.; Wei, M.-K.; Wang, C.-W. J. Mater. Chem. 2011, 21, 18523. (b) Zou, J.; Wu, H.; Lam, C.-S.; Wang, C.; Zhu, J.; Zhong, C.; Hu, S.; Ho, C.-L.; Zhou, G.-J.; Wu, H.; Choy, W. C. H.; Peng, J.; Cao, Y.; Wong, W.-Y. Adv. Mater. 2011, 23, 2976.

(5) (a) Yang, X. H.; Zheng, S. J.; Bottger, R.; Chae, H. S.; Tanaka, T.;
Li, S.; Mochizuki, A.; Jabbour, G. E. J. Phys. Chem. C 2011, 115, 14347.
(b) Chen, Y.; Zhao, F.; Zhao, Y.; Chen, J.; Ma, D. Org. Electron. 2012, 13, 2807. (c) Zhao, F. C.; Zhang, Z. Q.; Liu, Y. P.; Dai, Y. F.; Chen, J. S.; Ma, D. G. Org. Electron. 2012, 13, 1049. (d) Zheng, C.-J.; Wang, J.;
Ye, J.; Lo, M.-F.; Liu, X.-K.; Fung, M.-K.; Zhang, X.-H.; Lee, C.-S. Adv. Mater. 2013, 25, 2205.

(6) (a) Xue, S.; Yao, L.; Shen, F.; Gu, C.; Wu, H.; Ma, Y. *Adv. Funct. Mater.* **2012**, *22*, 1092. (b) Ge, Z.; Hayakawa, T.; Ando, S.; Ueda, M.; Akiike, T.; Miyarnoto, H.; Kajita, T.; Kakimoto, M. A. *Chem. Mater.* **2008**, *20*, 2532.

(7) (a) Peng, T.; Yang, Y.; Bi, H.; Liu, Y.; Hou, Z. M.; Wang, Y. J. *Mater. Chem.* **2011**, *21*, 3551. (b) Hung, W. Y.; Chi, L. C.; Chen, W. J.; Chen, Y. M.; Chou, S. H.; Wong, K. T. J. Mater. Chem. **2010**, *20*, 10113.

(8) Endo, A.; Sato, K.; Yoshimura, K.; Kai, T.; Kawada, A.; Miyazaki, H.; Adachi, C. *Appl. Phys. Lett.* **2011**, *98*, 083302.

(9) Schwartz, G.; Reineke, S.; Rosenow, T. C.; Walzer, K.; Leo, K. Adv. Funct. Mater. 2009, 19, 1319.

(10) (a) Duan, L. A.; Qiao, J. A.; Sun, Y. D.; Qiu, Y. Adv. Mater.
2011, 23, 1137. (b) Chaskar, A.; Chen, H. F.; Wong, K. T. Adv. Mater.
2011, 23, 3876. (c) Tao, Y.; Wang, Q.; Yang, C.; Wang, Q.; Zhang, Z.; Zou, T.; Qin, J.; Ma, D. Angew. Chem., Int. Ed. 2008, 47, 8104.
(d) Brunner, K.; van Dijken, A.; Borner, H.; Bastiaansen, J. J. A. M.; Kiggen, N. M. M.; Langeveld, B. M. W. J. Am. Chem. Soc. 2004, 126, 6035. (d) Su, S. J.; Cai, C.; Kido, J. Chem. Mater. 2011, 23, 274.

(11) (a) Liu, X.-K.; Zheng, C.-J.; Xiao, J.; Ye, J.; Liu, C.-L.; Wang, S.-D.; Zhao, W.-M.; Zhang, X.-H. *Phys. Chem. Chem. Phys.* **2012**, *14*, 14255. (b) Rothmann, M. M.; Haneder, S.; Da Como, E.; Lennartz, C.; Schildknecht, C.; Strohriegl, P. *Chem. Mater.* **2010**, *22*, 2403.

(12) Janietz, D.; Bauer, M. Synthesis 1993, 33.

(13) Tao, Y. T.; Wang, Q. A.; Yang, C. L.; Zhong, C.; Qin, J. G.; Ma, D. G. Adv. Funct. Mater. **2010**, 20, 2923.

(14) Zheng, M.; Bai, F. L.; Zhu, D. B. Polym. Advan. Technol. 2003, 14, 292.

- (15) Eaton, D. F. Pure Appl. Chem. 1988, 60, 1107.
- (16) Finkenzeller, W. J.; Yersin, H. Chem. Phys. Lett. 2003, 377, 299.
- (17) Gao, Z. Q.; Luo, M.; Sun, X. H.; Tam, H. L.; Wong, M. S.; Mi,

B. X.; Xia, P. F.; Cheah, K. W.; Chen, C. H. Adv. Mater. 2009, 21, 688.

(18) Zhen, C. G.; Dai, Y. F.; Zeng, W. J.; Ma, Z.; Chen, Z. K.; Kieffer, J. Adv. Funct. Mater. 2011, 21, 699.

(19) Adachi, C.; Baldo, M. A.; Thompson, M. E.; Forrest, S. R. J. Appl. Phys. 2001, 90, 5048.

(20) D'Andrade, B. W.; Holmes, R. J.; Forrest, S. R. Adv. Mater. 2004, 16, 624.

(21) Wan, J.; Zheng, C. J.; Fung, M. K.; Liu, X. K.; Lee, C. S.; Zhang, X. H. J. Mater. Chem. **2012**, *22*, 4502.