DOI: 10.1002/ijch.201400055

A New Multifunctional Triazine—Carbazole Compound with High Triplet Energy for High-Performance Blue Fluorescence, Green and Red Phosphorescent Host, and Hybrid White Organic Light-Emitting Diodes

Xiao-Ke Liu,^[a, b] Cai-Jun Zheng,^{*[a]} Jing Xiao,^[d] Ming-Fai Lo,^[c] Zhan Chen,^[a, b] Chun-Sing Lee,^{*[c]} Chuan-Lin Liu,^[a] Xue-Mei Ou,^[a] Fan Li,^[a] and Xiao-Hong Zhang^{*[a, e]}

Abstract: A blue fluorescent compound, 9-[4-(4,6-diphenoxy-1,3,5-triazin-2-yl)phenyl]-9*H*-carbazole (POTC), the triplet energy level of which reaches 2.76 eV, has been designed and synthesized. POTC is an excellent blue emitter as well as host for green and red phosphors, and therefore, matches the requirements of the host for single-emitting-layer fluorescence and phosphorescence hybrid white organic

light-emitting diodes (OLEDs). The blue, green, red, and white devices based on POTC show maximum external quantum efficiencies (EQEs) of 2.4, 22.4, 13.0, and 8.1%, respectively. Even at a high brightness of 1000 cd m⁻², these values maintain EQEs of 2.3, 22.1, 11.1, and 7.0%, respectively, indicating less than 15% roll-offs from the maxima.

Keywords: electrochemistry · heterocycles · fluorescence · luminescence · organic light-emitting diodes

1 Introduction

Fluorescence and phosphorescence hybrid white organic light-emitting diodes (WOLEDs) have attracted considerable attention in recent years due to their unique advantages of combining the excellent stability of blue fluorophores and complete exciton utilization.^[1] Thus, hybrid WOLEDs are considered as the ideal candidates for the next generation of solid-state lighting sources and fullcolor, flat-panel displays with long lifetimes and high efficiencies.^[1a] Generally, hybrid WOLEDs can be realized by adopting multiple emitting layer (EML)^[1a-d,2] or single EML^[1e-g,3] device structures with different color emitting materials. For multi-EML hybrid WOLEDs, the film thicknesses need to be precisely controlled to effectively separate the singlet and triplet excitons. Moreover, the complicated multi-EML structure is impracticable to obtain by a solution process, which is the most ideal process for large-area, low-cost manufacturing.^[4] Correspondingly, single-EML hybrid WOLEDs undergo simple manipulation of the EML and can also achieve high electroluminescent (EL) performance.^[1f,g] Therefore, the single-EML architecture is the more appropriate strategy for hybrid WOLEDs.

In single-EML hybrid WOLEDs, the blue fluorophore has to double as the blue fluorescent emitter to utilize the singlet excitons and the host for green and red phosphorescent dopants for triplet excitons, and therefore, has become the key point of these devices. Since triplet excitons are expected to be harvested by the green phosphor

- [a] X.-K. Liu, C.-J. Zheng, Z. Chen, C.-L. Liu, X.-M. Ou, F. Li, X.-H. 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 (P. R. China) Tel: + 86-10-82543510 Fax: + 86-10-64879375 e-mail: xhzhang@mail.ipc.ac.cn zhengcaijun@mail.ipc.ac.cn
- [b] X.-K. Liu, Z. Chen University of Chinese Academy of Sciences Beijing 100190 (P. R. China)
- [c] M.-F. Lo, C.-S. Lee
 Center of Super-Diamond and Advanced Films (COSDAF)
 & Department of Physics and Materials Sciences
 City University of Hong Kong
 Hong Kong (S.A.R. China)
 e-mail: apcslee@cityu.edu.hk
- [d] J. Xiao College of Physics and Electronic Engineering Taishan University Shandong 271021 (P. R. China)
- [e] X.-H. Zhang
 Functional Nano & Soft Materials Laboratory (FUNSOM)
 Jiangsu Key Laboratory for Carbon-Based Functional Materials
 & Devices and Collaborative Innovation Center of Suzhou
 Nano Science and Technology, Soochow University
 Suzhou, Jiangsu 215123 (P. R. China)

to generate intense green emission, the triplet energy (T₁) of the blue fluorophore needs to be higher than 2.44 eV (which is the T_1 of commercial green phosphor $Ir(ppy)_3$; ppy=2-phenylpyridine)^[5] to guarantee effective energy transfer from the host to the guest. However, blue fluorophores with such a high T₁ are rarely reported, which limits the development of single-EML hybrid WOLEDs. Recently, we proposed a molecular design strategy for developing such efficient blue fluorophores with high T_1 , and reported a multifunctional compound, 4-(4,6-diphenoxy-1,3,5-triazin-2-yl)-N,N-diphenylaniline (POTA), for high-performance single-EML hybrid WOLEDs accordingly.^[1g] However, the T₁ of POTA is still no more than 2.44 eV and energy transfer from the guest back to the host occurs, resulting in a low external quantum efficiency (EQE) of 17.1% for the POTA-based green phosphorescent device. Thus, it is still challenging to develop blue fluorophores with T_1 higher than 2.44 eV.

Herein, we report a new multifunctional blue emitter with a high T_1 of 2.76 eV. This compound, namely, 9-[4-(4,6-diphenoxy-1,3,5-triazin-2-yl)phenyl]-9H-carbazole (POTC), is an excellent blue emitter and phosphor host. Despite the high T_1 of 2.76 eV, stable blue emission can still be achieved based on POTC. The blue device exhibits blue emission with CIE coordinates of (0.16, 0.16) and a 2.3% EQE at a high brightness of 1000 cd cm^{-2} . The Ir(ppy)₃-doped green phosphorescent OLED based on POTC shows a high current efficiency (CE) of 71.9 cd A^{-1} and an EQE of 22.1 % at 1000 cd cm⁻². A red phosphorescent OLED has also been constructed by using POTC as the host and $Ir(MDQ)_2(acac)$ (MDQ = 2-methyldibenzo-[f,h] quinoxaline, acac = acetylacetonate) as the dopant. The red device shows high EQEs of 13.0, 11.9, and 11.1% at maximum, 100, and 1000 cdm^{-2} , respectively. Finally, a single-EML hybrid WOLED has been fabricated. The device has a forward-viewing CE of $17.8 \text{ cd } \text{A}^{-1}$ and an EQE of 7.0% at a brightness of 1000 cdm^{-2} , corresponding to total efficiencies^[1a,2b,4] of $30.3 \text{ cd } \text{A}^{-1}$ and 11.9%, respectively.

2 Results and Discussion

The compound POTC was readily prepared in good yield by using a palladium-catalyzed Suzuki cross-coupling reaction of 4-(9*H*-carbazol-9-yl)phenylboronic acid with 2chloro-4,6-diphenoxy-1,3,5-triazine^[1g] (Scheme 1). The chemical structure of this new compound was character-



Scheme 1. Synthetic route and molecular structure of POTC.

ized by ¹H and ¹³C NMR spectroscopy and mass spectrometry.

Room-temperature absorption and emission spectra of POTC in ethyl acetate are shown in Figure 1. The broad absorption spectrum with a peak surrounding 342 nm and the emission band with a maximum at 457 nm are ascribed to the donor-acceptor charge-transfer transition. The fluorescent quantum yield (Φ_f) of POTC was measured to be 0.48 in cyclohexane by using an integrated sphere method. These results indicate that POTC is a promising candidate as a blue emitter. The fluorescence and phosphorescence spectra at 77 K of POTC were also investigated (Figure 1). POTC has a fluorescence spec-



Figure 1. Room-temperature UV/Vis absorption and photoluminescence (PL) spectra of POTC in ethyl acetate as well as fluorescence and phosphorescence spectra in 2-MeTHF at 77 K.

trum with a single peak of about 412 nm. In contrast, the phosphorescence spectrum exhibits an extra characteristic vibrational structure for carbazole, indicating that the T_1 state is a ${}^3\pi\pi^*$ state located mostly on the electron-donating moiety. For a ${}^3\pi\pi^*$ state, its zero–zero energy is identified by the highest-energy peak of its emission.^[6] Thus, from the highest-energy phosphorescence peak, the T_1 of POTC is estimated at 2.76 eV. Such a high T_1 is rare for blue fluorophores. The high T_1 can be attributed to the high- T_1 1,3,5-triazine and carbazole moieties as well as short π conjunction over the molecule.

The thermal properties of POTC were determined by thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). The DSC and TGA curves are displayed in Figure 2. The decomposition temperature $(T_d$, corresponding to 5% weight loss), melting point (T_m) , and glass transition temperature (T_g) are 357, 109 and 79 °C, respectively. The T_g of POTC is high enough for the formation of a uniform amorphous film, which is favorable for use in OLEDs.

The electrochemical properties of POTC were investigated in dimethylformamide (DMF) by using a threeelectrode cell with ferrocene (Fc) as a standard. As shown in Figure 3, POTC shows a quasi-reversible reductive curve and irreversible oxidative wave, originating from its electron-deficient 1,3,5-triazine moiety and elec-



Figure 2. a) DSC and b) TGA curves of POTC.



Figure 3. Cyclic voltammetry plots of POTC in DMF.

tron-rich carbazole moiety, respectively. From the onsets of the oxidative and reductive curves, the HOMO and LUMO energy levels were estimated to be -5.58 and -2.80 eV, respectively. All physical properties data of POTC are summarized in Table 1.

To gain insight into the structure-property relationship of POTC at the molecular level, density functional theory (DFT) calculations were performed at the B3LYP/6-31G (d) level (Figure 4). The HOMO of POTC is mainly lo-



Figure 4. Calculated spatial distributions of the LUMO and HOMO of POTC.

cated at the electron-donating carbazole moiety and partly in the benzene π bridge, whereas the LUMO sits on the electron-deficient 1,3,5-triazine core and the benzene π bridge. Such orbital distributions could lead to excellent hole- and electron-transporting properties. The introduction of an oxygen atom interrupts π conjugation between the 1,3,5-traizine ring and its adjacent benzene ring. Such a design narrows the π -electron delocalization zone of POTC and contributes to a high T_1 .^[7] In addition, separation between the HOMO and LUMO can be clearly observed, which indicates an intramolecular chargetransfer (ICT) transition from the donor to the acceptor. ICT molecules commonly have small singlet-triplet splitting; in other words, ICT blue fluorophores may show high T_1 .^[1c] On the other hand, there is still overlap between the HOMO and LUMO, giving efficient ICT emission demonstrated by the $\Phi_{\rm f}$.

The EL properties of POTC were investigated in a device with a structure of indium tin oxide (ITO)/1,4bis-[(1-naphthylphenyl)amino]biphenyl (NPB; 30 nm)/ 4,4',4"-tris(*N*-carbazolyl)triphenylamine (TCTA; 10 nm)/ EML (30 nm)/1,3,5-tris(*N*-phenylbenzimidazol-2-yl)benzene (TPBI; 30 nm)/LiF (1.5 nm)/Al. ITO and LiF/Al are the anode and cathode, respectively; NPB is the holetransporting layer; TCTA is the exciton-blocking layer; and TPBI serves as the electron-transporting layer, the hole-blocking layer, and the exciton-blocking layer. The blue fluorescent device (device A) was fabricated by using POTC as the EML, while the EML of the green and red phosphorescent devices (devices B and C) were

 Table 1. Summary of the physical properties of POTC.

$\lambda_{\max,abs}^{[a]}$	$\lambda_{\max, em}^{[a]}$ [nm]	$arPsi_{f}^{[b]}$	$\lambda_{ ext{max,fluo}}{}^{[c]}$ [nm]	λ _{max,phos} ^[c] [nm]	Τ ₁ ^[d] [eV]	HOMO ^[e] [eV]	LUMO ^[e] [eV]	$T_{\rm g}/T_{\rm m}/T_{\rm d}$			
342	457	0.48	412	450, 473	2.76	-5.58	-2.80	79/109/357			

[a] Absorption and emission maxima, measured in ethyl acetate at room temperature. [b] Measured in cyclohexane by using the integrated sphere method. [c] Fluorescence and phosphorescence spectrum peaks measured in 2-MeTHF at 77 K. [d] Estimated from the phosphorescence maxima at 77 K. [e] Determined from the onset oxidation/reduction potentials of the cyclic voltammetry curve in DMF.

Isr. J. Chem. 2014, 54, 952–957

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

POTC/6 wt % Ir(ppy)₃ and POTC/4 wt % Ir(MDQ)₂-(acac), respectively. The single-EML hybrid WOLED (device D) was constructed by controlling the concentrations of the phosphorescent dopants, and the optimized EML was POTC/0.2 wt% Ir(ppy)₃/0.5 wt% Ir(MDQ)₂-(acac). Figure 5 demonstrates current density-voltage and luminance-voltage plots of these devices. Figure 6 exhibits current efficiency-luminance curves of these devices and their EL properties data are summarized in Table 2. Among all devices, device A shows the largest current density versus the same voltage, while device B shows the smallest one. This finding may be explained by the ratios of excitons used. All singlet and triplet excitons in device B are believed to be utilized for emission because the EQE of device B is greater than 20% (the theoretical limit). In contrast, device A shows approximately one-tenth the EQE of device B, indicating that only a small part of excitons is harvested. The unemployed excitons mostly contribute to current density. The turn-on voltages (observed at the brightness of 1 cd m⁻²) of the devices range from 3.2 to 3.5 V. The doped devices show slightly lower turn-on voltages than that of device A due to the charge-trap effect of phosphors.^[8] The devices with blue, green, red, and white color show maximum EQEs of 2.4, 22.4, 13.0, and 8.1%, respectively. Even at a high brightness of 1000 cd m⁻², these values are maintained at 2.3, 22.1, 11.1, and 7.0%, respectively, indicating less than 15% roll-offs from the maxima. The EQE of OLEDs can be expressed by Equation (1):

$$EQE = \gamma \chi \eta_{PL} \eta_{oc} \tag{1}$$

in which γ is the recombination efficiency of injected holes and electrons, χ is the fraction of excitons that can potentially radiatively decay, η_{PL} is the intrinsic PL efficiency of the EML, and η_{oc} is the light out-coupling factor, which is about $(20\pm2)\%$.^[9] Based on the maximum EQE (22.4% for device B) and the estimated outcoupling factor ($(20\pm2)\%$), γ , χ , and η_{PL} can reach unity for device B. This result demonstrates balanced hole and electron flows and complete energy transfer from the POTC host to Ir(ppy)₃ dopant. Since the charge balance, charge confinement, and optical out-coupling effects by ITO and organic materials are similar in devices A, B, C, and D, the parameters γ and η_{oc} are approximately equal

Table 2. EL properties of the devices.



Figure 5. a) Current density-voltage and b) luminance-voltage plots of the devices.



Figure 6. Current efficiency–luminance curves of the devices.

for these devices. Thus, devices A, C, and D show balanced hole and electron flows as well, which are responsible for the high efficiencies and slight efficiency roll-offs.

Device	V _{on} [V] ^[a]	CE ^[b]	PE ^[b]	EQE ^[b]	CIE ^[c]				
A	3.5	2.9/2.6/2.8	1.8/1.7/1.5	2.4/2.1/2.3	(0.16, 0.16)				
В	3.3	72.2/68.4/71.9	54.3/53.8/47.7	22.4/21.7/22.1	(0.26, 0.62)				
С	3.2	25.4/23.4/21.4	22.7/18.7/14.1	13.0/11.9/11.1	(0.58, 0.41)				
D	3.3	20.4/19.9/17.8	16.5/15.1/11.0	8.1/7.9/7.0	(0.43, 0.45)				

[a] Turn-on voltage (at the luminance of 1 cd m⁻²). [b] CE (current efficiency), PE (power efficiency), and EQE (external quantum efficiency) at maximum, 100, and 1000 cd m⁻². [c] At 1000 cd m⁻².

Figure 7 exhibits the EL spectra of devices A and D under different luminances. The CIE coordinates of device A is (0.16, 0.16), which scarcely changes under different luminances. For the warm white emission of device



Figure 7. EL spectra of a) device A and b) device D under different luminances.

D, the CIE coordinates change slightly from 100 to 10000 cdm⁻², with (0.42, 0.48) at 100 cdm⁻², (0.43, 0.45) at 1000 cdm⁻², and (0.43, 0.44) at 10000 cdm⁻². In the spectra, the blue emission is strengthened with increasing luminance, whereas the green emission is weakened, primarily resulting from T_1 - T_1 interactions at high current densities.

3 Conclusions

A new multifunctional triazine–carbazole hybrid compound, POTC, has been designed and synthesized. POTC shows efficient blue emission, a high T_1 of 2.76 eV, and can be used as a blue emitter as well as the host for green and red phosphors. Devices with blue, green, and red colors show maximum EQEs of 2.4, 22.4, and 13.0%, respectively. Moreover, these values are maintained at 2.3, 22.1, and 11.1%, respectively, at a high brightness of 1000 cdm⁻², indicating less than 15% roll-offs. Furthermore, a single-EML hybrid WOLED, in which POTC doubles as the blue emitter and host for green and red dopants, shows a forward-viewing CE of $17.8 \text{ cd } A^{-1}$ and an EQE of 7.0% at a brightness of $1000 \text{ cd } m^{-2}$, corresponding to total efficiencies of $30.3 \text{ cd } A^{-1}$ and 11.9%, respectively.

4 Experimental Section

4.1 General Information

Commercially available reagents were used without purification. NMR spectra were recorded on a Bruker Advance-400 spectrometer with chemical shifts reported as ppm. Mass spectra were obtained with a Finnigan 4021C GC-MS spectrometer. Elemental analysis (C, H, N) was carried out with an Elementar Vario ELIII element analyzer. Absorption and PL spectra were recorded with a Hitachi UV/Vis spectrophotometer U-3010 and a Hitachi fluorescence spectrometer F-4500, respectively. Quantum fluorescence yield was measured by the integrating sphere method with an Edinburgh Instruments FLS920 spectrometer. TGA and DSC measurements were performed on a TA instrument TGA2050 and TA instrument DSC2910, respectively, with a heating rate of 10°Cmin⁻¹ under a nitrogen atmosphere. Cyclic voltammetry was performed on a CHI660E electrochemical analyzer with 0.1 M Bu₄NPF₆ as a supporting electrolyte, a saturated calomel electrode (SCE) as a reference electrode, a Pt disk as a working electrode, and a scan rate of 100 mV s^{-1} .

4.2 Device Fabrication and Measurement

ITO-coated glass with a sheet resistance of 30Ω per square was used as the substrate. The substrates were first cleaned with isopropanol and deionized water, then dried in an oven at 120°, 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 Ås⁻¹ onto the ITO substrates. The cathode was completed by thermal deposition of LiF at a deposition rate of 0.1 Ås^{-1} , and then capped with Al metal deposited at a rate of 10 Ås⁻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 an ambient atmosphere. EQE was calculated from the current density, luminance, and EL spectrum, assuming a Lambertian distribution.

4.3 Synthetic Details

9-[4-(4,6-Diphenoxy-1,3,5-triazin-2-yl)phenyl]-9H-carbazole (POTC)

Toluene (12 mL), ethanol (6 mL), and 2 M aqueous Na₂CO₃ (9 mL) were added to a mixture of 2-chloro-4,6-

diphenoxy-1,3,5-triazine (0.598 g, 2 mmol), 9-phenyl-9Hcarbazol-3-ylboronic acid (0.574 g, 2 mmol), and tetrakis(triphenylphosphine)platinum (0.234 g, 0.2 mmol). With stirring, the suspension was heated at 90° for 15 h under a nitrogen atmosphere. When cooled to room temperature, the mixture was extracted with CH2Cl2 and dried over Na₂SO₄. After the solvent had been removed under reduced pressure, the residue was purified by column chromatography on silica gel using CH₂Cl₂/petroleum ether (4:1) as the eluent to give a white solid (0.820 g,81%). ¹H NMR (400 MHz, CDCl₃): $\delta = 8.52$ (d, J =8.5 Hz, 2H), 8.14 (d, J=7.7 Hz, 2H), 7.67 (d, J=8.4 Hz, 2H), 7.49–7.40 (m, 8H), 7.33–7.28 ppm (m, 8H); ¹³C NMR $(100 \text{ MHz}, \text{ CDCl}_3): \delta = 175.09, 173.07, 152.07, 142.40,$ 140.37, 133.21, 130.92, 129.51, 126.54, 126.18, 125.98, 123.93, 121.62, 120.57, 120.42, 109.81 ppm; HRMS (EI): m/z calcd for C₃₃H₂₂N₄O₂: 506.1743; found: 506.1749; elemental analysis calcd (%) for C₃₃H₂₂N₄O₂: C 78.25, H 4.38, N 11.06; found: C 78.29, H 4.41, N 11.01.

Acknowledgements

We acknowledge financial support from the National Natural Science Foundation of China (nos. 51373190, 51033007, and 51103169), the Instrument Developing Project of the Chinese Academy of Sciences (grant no. YE201133), and the Collaborative Innovation Center of Suzhou Nano Science and Technology.

References

- a) Y. R. Sun, N. C. Giebink, H. Kanno, B. W. Ma, M. E. Thompson, S. R. Forrest, *Nature* 2006, 440, 908–912; b) G. Schwartz, S. Reineke, T. C. Rosenow, K. Walzer, K. Leo, *Adv. Funct. Mater.* 2009, 19, 1319–1333; c) C.-J. Zheng, J. Wang, J. Ye, M.-F. Lo, X.-K. Liu, M.-K. Fung, X.-H. Zhang, C.-S. Lee, *Adv. Mater.* 2013, 25, 2205–2211; d) N. Sun, Q. Wang, Y. Zhao, Y. Chen, D. Yang, F. Zhao, J. Chen, D. Ma, *Adv. Mater.* 2014, 26, 1617–1621; e) X. H. Yang, S. J. Zheng, R. Bottger, H. S. Chae, T. Tanaka, S. Li, A. Mochizuki, G. E. Jabbour, *J. Phys. Chem. C* 2011, 115, 14347–14352; f) J. Ye, C.-J. Zheng, X.-M. Ou, X.-H. Zhang, M.-K. Fung, C.-S. Lee, *Adv. Mater.* 2012, 24, 3410–3414; g) X.-K. Liu, C.-J. Zheng, M.-F. Lo, J. Xiao, Z. Chen, C.-L. Liu, C.-S. Lee, M.-K. Fung, X.-H. Zhang, *Chem. Mater.* 2013, 25, 4454–4459.
- [2] a) C. L. Ho, W. Y. Wong, Q. Wang, D. G. Ma, L. X. Wang,
 Z. Y. Lin, *Adv. Funct. Mater.* 2008, *18*, 928–937; b) G.
 Schwartz, M. Pfeiffer, S. Reineke, K. Walzer, K. Leo, *Adv.*

Mater. 2007, 19, 3672-3676; c) U.S. Bhansali, H.P. Jia, M. A. Q. Lopez, B. E. Gnade, W. H. Chen, M. A. Omary, Appl. Phys. Lett. 2009, 94, 203501; d) J. Wan, C. J. Zheng, M. K. Fung, X. K. Liu, C. S. Lee, X. H. Zhang, J. Mater. Chem. 2012, 22, 4502-4510; e) J. Yu, H. Lin, F. Wang, Y. Lin, J. Zhang, H. Zhang, Z. Wang, B. Wei, J. Mater. Chem. 2012, 22, 22097-22101; f) T. Y. Zhang, M. Liu, T. Li, J. A. Ma, D. L. Liu, W. F. Xie, C. L. Wu, S. W. Liu, S. C. Yeh, C. T. Chen, J. Phys. Chem. C 2011, 115, 2428-2432; g) Y. Chen, F. Zhao, Y. Zhao, J. Chen, D. Ma, Org. Electron. 2012, 13, 2807-2815; h) M. E. Kondakova, J. C. Deaton, T. D. Pawlik, D. J. Giesen, D. Y. Kondakov, R. H. Young, T. L. Royster, D. L. Comfort, J. D. Shore, J. Appl. Phys. 2010, 107, 014515; i) Y. Divayana, S. W. Liu, A. K. K. Kyaw, X. W. Sun, Org. Electron. 2011, 12, 1-7; j) F. Zhao, Z. Zhang, Y. Liu, Y. Dai, J. Chen, D. Ma, Org. Electron. 2012, 13, 1049-1055; k) P. Chen, W. F. Xie, J. Li, T. Guan, Y. Duan, Y. Zhao, S. Y. Liu, C. S. Ma, L. Y. Zhang, B. Li, Appl. Phys. Lett. 2007, 91, 023505; 1) C. L. Ho, M. F. Lin, W. Y. Wong, W. K. Wong, C. H. Chen, Appl. Phys. Lett. 2008, 92, 083301; m) J. H. Seo, I. H. Park, G. Y. Kim, K. H. Lee, M. K. Kim, S. S. Yoon, Y. K. Kim, Appl. Phys. Lett. 2008, 92, 183303; n) G. Schwartz, K. Fehse, M. Pfeiffer, K. Walzer, K. Leo, Appl. Phys. Lett. 2006, 89, 083509; o) K. S. Yook, S. O. Jeon, J. Y. Lee, K. H. Lee, Y. S. Kwon, S. S. Yoon, J. H. Yoon, Org. Electron. 2009, 10, 1378-1381; p) C. Wu, S. Tao, M. Chen, H.-W. Mo, T. W. Ng, X. Liu, X. Zhang, W. Zhao, C.-S. Lee, Dyes Pigm. 2013, 97, 273-277.

- [3] a) Y. T. Tao, Q. Wang, Y. Shang, C. L. Yang, L. Ao, J. G. Qin, D. G. Ma, Z. G. Shuai, *Chem. Commun.* 2009, 77–79;
 b) W. Y. Hung, L. C. Chi, W. J. Chen, Y. M. Chen, S. H. Chou, K. T. Wong, *J. Mater. Chem.* 2010, 20, 10113–10119;
 c) V. K. M. Au, K. M. C. Wong, D. P. K. Tsang, M. Y. Chan, N. Y. Zhu, V. W. W. Yam, *J. Am. Chem. Soc.* 2010, 132, 14273–14278;
 d) T. Peng, Y. Yang, H. Bi, Y. Liu, Z. M. Hou, Y. Wang, *J. Mater. Chem.* 2011, 21, 3551–3553.
- [4] B. H. Zhang, G. P. Tan, C. S. Lam, B. Yao, C. L. Ho, L. H. Liu, Z. Y. Xie, W. Y. Wong, J. Q. Ding, L. X. Wang, *Adv. Mater.* 2012, 24, 1873–1877.
- [5] W. J. Finkenzeller, H. Yersin, Chem. Phys. Lett. 2003, 377, 299–305.
- [6] Q. Zhang, J. Li, K. Shizu, S. Huang, S. Hirata, H. Miyazaki, C. Adachi, J. Am. Chem. Soc. 2012, 134, 14706–14709.
- [7] X.-K. Liu, C.-J. Zheng, J. Xiao, J. Ye, C.-L. Liu, S.-D. Wang, W.-M. Zhao, X.-H. Zhang, *Phys. Chem. Chem. Phys.* **2012**, 14, 14255–14261.
- [8] B. Chen, Y. Li, Y. Chu, A. Zheng, J. Feng, Z. Liu, H. Wu, W. Yang, Org. Electron. 2013, 14, 744–753.
- [9] C. G. Zhen, Y. F. Dai, W. J. Zeng, Z. Ma, Z. K. Chen, J. Kieffer, Adv. Funct. Mater. 2011, 21, 699-707.

Received: February 26, 2014 Accepted: March 15, 2014 Published online: May 23, 2014