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Carbazole modified terphenyl based high triplet energy host materials for blue phosphorescent organic light-emitting diodes

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1. Introduction

The development of high triplet energy host materials is important to improve the external quantum efficiency of blue phosphorescent organic light-emitting diodes (PHOLEDs) because the efficiency of the blue PHOLEDs mainly depends on energy transfer from host to blue triplet emitter. The triplet energy of the host material should be higher than that of dopant material for efficient energy transfer from host to dopant.

The high triplet energy host materials should be designed to include high triplet energy moieties in the molecular structure [1–20]. Common high triplet energy host materials have carbazole [1–10], fluorene [11–13] and dibenzofuran [14–17] as the high triplet energy moieties in the backbone structure, which was combined with other aromatic units to produce the high triplet energy host materials. In general, aromatic units derived from phenyl or biphenyl backbone structure were used to realize high triplet energy because a terphenyl unit reduced the triplet energy of the host materials. However, the terphenyl unit can be used to develop high triplet energy host materials by decreasing the degree of conjugation through a kink structure [18]. The merits of using the kinked terphenyl core were high triplet energy and high thermal stability.

ABSTRACT

Carbazole modified terphenyl based high triplet energy host materials were developed for application as host materials for blue phosphorescent organic light-emitting diodes. Two terphenyl based materials, 9-(5"-phenyl-[1,1':2',1":3",1"'-quaterphenyl]-3-yl)-9H-carbazole (CzTPPh) and 9-(3",5"-di(pyridin-3-yl)-[1,1:2',1"-terphenyl]-3-yl)-9H-carbazole (CzTPPy), were synthesized as the host materials with high triplet energies of 2.75 eV and 2.73 eV, respectively. The two host materials were evaluated as the host materials for blue phosphorescent organic light-emitting diodes and high quantum efficiencies of 20.2% and 15.7% were obtained in the CzTPPh and CzTPPy devices, respectively.

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A few high triplet energy host materials possessing the kinked terphenyl core structure were reported as the host materials for blue PHOLEDs [19-23].

In this work, high triplet energy host materials derived from the carbazole modified kinked terphenyl core structure, 9-(5"-phenyl-[1,1':2',1":3",1"'-quaterphenyl]-3-yl)-9*H*-carbazole (CzTPPh) and 9-(3",5"-di(pyridin-3-yl)-[1,1':2',1"-terphenyl]-3-yl)-9*H*-carbazole (CzTPPy), were synthesized as the host materials for blue PHOLEDs. A high triplet energy over 2.70 eV was obtained using the CzTPPh and CzTPPy host materials and a high quantum efficiency of 20.2% was achieved using the CzTPPh host material.

2. Experimental section

2.1. General information

All chemicals and reagents were purchased from Aldrich and TCI Chem, and were used without further purification. 3-(9*H*-carbazol-9-yl)phenylboronic acid was prepared according to the synthetic method in literature [24] and general chemical analysis were described in our previous work [25].

2.1.1. Synthesis of 9-(2'-bromo-[1,1'-biphenyl]-3-yl)-9H-carbazole

3-(9*H*-carbazol-9-yl)phenylboronic acid (12.0 g, 42.1 mmol), 1,2dibromobenzene (50.0 g, 211 mmol) and tetrahydrofuran (480 ml) were added to a two-necked flask equipped with a magnetic





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stirring bar, a septum and a reflux condenser attached to a gas-flow adapter with a stopcock. The solution was bubbled with high purity nitrogen gas for 30 min to remove oxygen and potassium carbonate (11.6 g, 84.3 mmol) dissolved in oxygen free distilled water (160 ml) was added to the solution. Tetrakis(triphenylphosphine)palladium(0) (Pd(PPh₃)₄, 2.43 g, 2.11 mmol) was added and the resulting suspension was refluxed for 24 h under nitrogen. The solution was allowed to cool and was transferred to a separatory funnel. The solution was extracted with ethyl acetate and the organic layer was combined, washed with water saturated with sodium chloride, and dried over magnesium sulfate. Solvent was removed with a rotary evaporator to yield a yellow oil, which was purified by column chromatography(dichloromethane/*n*-hexane) to give 14.0 g of 9-(2'-bromo-[1,1'-biphenyl]-3-yl)-9H-carbazole.

Yield: 84%. ¹H NMR (500 MHz, CDCl₃): δ 7.23 (t, 1H, *J* = 6.0 Hz), 7.29 (t, 2H, *J* = 4.8 Hz), 7.37–7.44 (m, 4H), 7.49 (d, 1H, *J* = 4.0 Hz), 7.52 (d, 2H, *J* = 4.0 Hz), 7.60 (d, 1H, *J* = 4.0 Hz), 7.63 (s, 1H), 7.66 (t, 1H, *J* = 5.2 Hz), 7.70 (d, 1H, *J* = 4.0 Hz), 8.15 (d, 2H, *J* = 4.0 Hz), Mass (FAB): *m/z* 397 [M⁺].

2.1.2. Synthesis of 9-(3",5"-dichloro-[1,1':2',1"-terphenyl]-3-yl)-9H-carbazole

9-(2'-Bromo-[1,1'-biphenyl]-3-yl)-9H-carbazole (10.0)g, 25.1 mmol), 3,5-dichlorophenylboronic acid (6.23 g, 32.6 mmol) and tetrahydrofuran (240 ml) were added to a two-necked flask and was bubbled with nitrogen for 30 min. Potassium carbonate (8.68 g, 62.8 mmol) dissolved in oxygen free distilled water (80 ml) was added to the solution followed by adding $Pd(PPh_3)_4$ (1.45 g. 1.26 mmol). The resulting suspension was refluxed for 24 h under nitrogen. The reaction was allowed to cool and was extracted with ethyl acetate. The organic layer was combined, washed with water saturated with sodium chloride, and dried over magnesium sulfate. Solvent was removed with a rotary evaporator to yield a brown powder, which was purified by column chromatography using a dichloromethane/n-hexane eluent to give 9-(3",5"-dichloro-[1,1':2',1''-terphenyl]-3-yl)-9H-carbazole (9.0 g) as a white powder.

Yield: 77%. ¹H NMR (500 MHz, CDCl₃): δ 7.01 (d, 2H, *J* = 4.0 Hz), 7.13 (s, 2H), 7.23 (s, 1H), 7.26 (t, 1H, *J* = 4.8 Hz), 7.33–7.51 (m, 10H), 7.59 (t, 1H, *J* = 5.2 Hz), 8.10 (d, 2H, *J* = 4.0 Hz). Mass (FAB): *m*/*z* 463 [M⁺].

2.1.3. 9-(5"-Phenyl-[1,1':2',1":3",1'''-quaterphenyl]-3-yl)-9H-carbazole (CzTPPh)

A solution of 9-(3",5"-dichloro-[1,1':2',1"-terphenyl]-3-yl)-9*H*-carbazole (3.00 g, 6.46 mmol), phenylboronic acid (3.15 g, 25.8 mmol), K₃PO₄ (8.23 g, 38.8 mmol), 2-dicyclohexylphosphino-2',6'-dimethoxybiphenyl (S-Phos, 0.53 g, 1.29 mmol), tris(dibenzylideneacetone)dipalladium (Pd₂(dab)₃, 0.30 g, 0.34 mmol), toluene (210 ml) and distilled water (21 ml) was refluxed for 48 h. The solution was cooled down to room temperature, diluted with 100 ml water and extracted with ethyl acetate. The organic extracts were dried over anhydrous magnesium sulfate, filtered, and evaporated to yield a brown solid. The crude product was purified by column chromatography on silica gel using dichloromethane/*n*-hexane as an eluent. Additional purification by sublimation (250 °C. at 10^{-5} mmHg) resulted in 1.5 g of pure glassy solid.

Yield: 42%. *T*_g: 90 °C, *T*_m: 176 °C. FT-IR (ATR): 3053, 1592, 1476, 1450, 1412, 1312, 1228, 1164, 1081, 1028, 880, 802, 749, 697 cm^{-1. 1}H NMR (500 MHz, CDCl₃): δ 7.03 (d, 2H, *J* = 4.3 Hz), 7.18 (t, 4H, *J* = 8.3 Hz), 7.32 (t, 2H, *J* = 4.8 Hz), 7.39 (t, 4H, *J* = 5.0 Hz), 7.42–7.50 (m, 11H), 7.54–7.61 (m, 3H), 7.78 (s, 1H), 8.04 (d, 2H, *J* = 4.3 Hz). ¹³C NMR (125 MHz, CDCl₃): δ 109.6, 119.8, 120.1, 123.3, 124.4, 125.0, 125.9, 127.3, 127.5, 127.8, 128.0, 128.1, 128.6, 128.8, 129.7, 130.6, 137.5, 140.0, 140.3, 140.7, 140.9, 141.9, 142.0, 143.9. Mass (FAB): *m/z* 547 [(M)⁺]. Elemental analysis Calcd. for C₄₂H₂₉N: C, 92.11%; H, 5.34%; N, 2.56%. Found: C, 92.11%; H, 5.33%; N, 2.58%.

2.1.4. 9-(3",5"-di(pyridin-3-yl)-[1,1':2',1"-terphenyl]-3-yl)-9Hcarbazole (CzTPPy)

A solution of 9-(3",5"-dichloro-[1,1':2',1"-terphenyl]-3-yl)-9*H*carbazole (3.00 g, 6.46 mmol), 3-pyridinylboronic acid (3.18 g, 25.8 mmol), K₃PO₄ (8.23 g, 38.8 mmol), S-Phos (0.53 g, 1.29 mmol), Pd₂(dab)₃ (0.30 g, 0.34 mmol), toluene (210 ml) and distilled water (21 ml) was refluxed for 48 h. The solution was cooled down to room temperature, diluted with 100 ml water and extracted with ethyl acetate. The organic extract was dried over anhydrous magnesium sulfate, filtered, and evaporated to yield a brown solid. The crude product was purified by column chromatography on silica gel using dichloromethane/*n*-hexane as an eluent. Additional purification by sublimation (250 °C. at 10⁻⁵ mmHg) resulted 1.7 g of pure glassy solid.



Scheme 1. Synthetic scheme of CzTPPh and CzTPPy.

Yield: 48%. *T*_g: 98 °C, *T*_m: N.D. FT-IR (ATR): 3046, 1594, 1477, 1450, 1393, 1314, 1228, 1166, 1118, 1022, 885, 801, 750, 710 cm⁻¹. ¹H NMR (500 MHz, CDCl₃): δ 6.95 (d, 2H, *J* = 1.5 Hz), 7.16 (t, 4H, *J* = 8.7 Hz), 7.30–7.34 (m, 3H), 7.49–7.52 (m, 6H), 7.58 (t, 2H, *J* = 5.2 Hz), 7.65 (t, 1H, *J* = 5.2 Hz), 7.73–7.75 (m, 3H), 8.04 (d, 2H, *J* = 4.5 Hz), 8.60 (d, 2H, *J* = 3.0 Hz), 8.75 (s, 2H). ¹³C NMR (125 MHz, CDCl₃): δ 109.4, 119.9, 120.2, 123.3, 123.6, 124.2, 125.3, 125.8, 128.2, 128.3, 128.6, 128.7, 128.7, 129.9, 130.5, 130.8, 134.4, 136.0, 137.5, 139.0, 139.4, 139.9, 140.6, 142.9, 143.6, 148.3, 149.0. Mass (FAB): *m/z* 550 [(M + H)⁺]. Elemental analysis Calcd. for C₄₀H₂₇N₃: C, 87.40%; H, 4.95%; N, 7.64%. Found: C,87.24%; H, 4.98%; N, 7.67%.

3. Device fabrication and measurement

The device structure of the blue PHOLEDs fabricated in this work was indium tin oxide (ITO, 50 nm)/poly(3,4-ethylenedioxy thiophene): poly(styrenesulfonate) (PEDOT:PSS, 60 nm)/4,4'-cyclohexylidenebis[N,N-bis(4-methylphenyl)aniline] (TAPC, 20 nm)/1,3bis(N-carbazolyl)benzene (mCP, 10 nm)/CzTPPh or CzTPPy:iridium(III) bis[(4,6-difluorophenyl)-pyridinato-*N*,*C*²]picolinate (FIrp ic) (25 nm, 10%)/diphenylphosphine oxide-4-(triphenylsilyl)phenyl (TSPO1, 35 nm)/LiF (1 nm)/Al (200 nm). Doping concentration of FIrpic were 5% and 10%. PEDOT:PSS and TAPC were used as a hole injection layer and hole transport layer, respectively. TSPO1 and mCP were exciton blocking layers. A control device with mCP host instead of CzTPPh and CzTPPy was also fabricated. Device structure of electron only device was ITO (50 nm)/Ca (5 nm)/CzTPPh or CzTPPy (25 nm)/TSPO1 (35 nm)/LiF (1 nm)/Al (200 nm). Device evaluation was carried out using CS 1000 spectroradiometer and Keithley 2400 source measurement unit.

4. Results and discussion

The two carbazole modified terphenyl compounds, CzTPPh and CzTPPy, were designed to have high triplet energy by combining high triplet energy carbazole and ortho connected terphenyl unit. The carbazole modified terphenyl moiety was further substituted with phenyl or pyridinyl unit to increase the glass transition temperature and to manage charge transport properties of the host materials. The phenyl and pyridyl units were attached to meta position of the carbazole modified terphenyl core to suppress the increase of the degree of conjugation.

Synthetic scheme of CzTPPh and CzTPPy is shown in Scheme 1. The carbazole modified terphenyl core was prepared from 3-(9*H*-carbazol-9-yl)phenylboronic acid. The 3-(9*H*-carbazol-9-yl)phenylboronic acid intermediate was reacted with 1,2-dibromobenzene to produce the 9-(2'-bromo-[1,1'-biphenyl]-3-yl)-9*H*-carbazole intermediate, which was combined with 3,5-



Fig. 1. HOMO and LUMO distribution of CzTPPh and CzTPPy.



Fig. 2. UV-Vis, solution PL, solid PL and low temperature PL spectra of CzTPPh and CzTPPy.

dichlorophenylboronic acid to prepare functionalized carbazole modified terphenyl intermediate. The Cl functionalized terphenyl core was substituted with phenyl and pyridine using phenylboronic acid and 3-pyridinylboronic acid.

Molecular orbital simulation of the CzTPPh and CzTPPy host materials was performed to study the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) distribution. The HOMO and LUMO distribution calculated from Gaussian 09 program using density functional of B3LYP with 6-31G* basis sets is shown in Fig. 1. The HOMO of the two host materials was localized on the carbazole unit of the host materials due to electron donating character of the amine unit of carbazole. There was little difference of the HOMO distribution between the two host materials. However, the LUMO distribution was different depending on the substituent of the carbazole modified terphenyl core. The LUMO of CzTPPh was uniformly distributed over the terphenyl core and the phenyl substituent because of relatively weak electron donating character of the aromatic unit compared to the carbazole unit. However, the LUMO of CzTPPy was localized on the pyridine unit due to strong electron deficiency of the pyridine unit. The different electron deficiency of the phenyl and pyridinyl substituents induced the different LUMO distribution. The



Fig. 3. Oxidation and reduction cyclic voltammetry curves of CzTPPh and CzTPPy.

Table T		
Physical	properties	of materials.

Material	UV–Vis	Solution PL	Solid PL	HOMO	LUMO	Bandgap	Triplet energy
	(nm) ^a	(nm) ^a	(nm)	(eV) ^b	(eV) ^b	(eV) ^c	(eV) ^d
CzTPPh	241	366	370	-6.04 -6.03	-2.51	3.53	2.75
CzTPPy	239	364	373		-2.68	3.35	2.73

^a Data were measured in tetrahydrofuran solution.

^b HOMO and LUMO were measured by CV.

^c Bandgap was calculated from the difference of HOMO and LUMO.

^d Triplet energy was calculated from the first phosphorescent emission peak of low temperature delayed PL spectra.

calculated HOMO/LUMO levels of CzTPPh and CzTPPy were -5.28/-1.03 eV and -5.24 eV/-1.30 eV, respectively. As the HOMO was localized on the same carbazole unit, the calculated HOMO levels were similar.

Photophysical properties of the CzTPPh and CzTPPy host materials were measured using ultraviolet-visible (UV-Vis) and photoluminescence (PL) spectrometers. Fig. 2 shows UV-Vis and PL spectra of CzTPPh and CzTPPy host materials. The two host materials showed similar UV-Vis absorption spectra irrespective of the substituents. Weak $n-\pi^*$ absorption of the carbazole moiety was observed between 310 nm and 350 nm and strong $\pi - \pi^*$ absorption of the carbazole modified terphenyl was detected below 300 nm. The substituent had little influence on the UV-Vis absorption of the two host materials. Solution PL emission of CzTPPh and CzTPPy was observed at 366 nm and 364 nm, respectively. There was little difference of solution PL emission between the two host materials. Solid PL peak positions of CzTPPh (370 nm) and CzTPPv (373 nm) were also similar, but the solid PL emission above 400 nm was guite different. The long wavelength emission was significant in CzTPPy, while it was weak in CzTPPh. This indicates that strong intermolecular interaction between CzTPPy molecules induces excimer formation or charge transfer complex formation.

Phosphorescent emission of the two host materials was observed in low temperature PL spectra and triplet energies calculated from the first phosphorescent emission peak were 2.75 eV and 2.73 eV for CzTPPh and CzTPPy, respectively. There was little difference of the triplet energy between CzTPPh and CzTPPy because the phenyl and pyridinyl substituents did not affect the triplet energy of the carbazole modified terphenyl core. As both phenyl and pyridinyl substituents were attached to the metaposition of the terphenyl unit, the triplet energy of the carbazole modified terphenyl was not degraded. The triplet energy of the CzTPPh and CzTPPy was higher than that of common Flrpic dopant and efficient energy transfer from the host materials to the Flrpic dopant is expected. The HOMO and LUMO levels of the host materials were measured by cyclic voltammetry from oxidation and reduction curves of CzTPPh and CzTPPy (Fig. 3). The HOMO/LUMO levels of CzTPPh and CzTPPy were -6.04/-2.51 eV and -6.03/-2.68 eV, respectively. As shown in the molecular orbital distribution, the HOMO of CzTPPh and CzTPPy was localized on the same phenyl-carbazole unit, which resulted in similar HOMO levels in CzTPPh and CzTPPy. However, the LUMO level was stabilized in the CzTPPy host because of electron deficient pyridine substituent. All energy levels of the host materials are summarized in Table 1.

Thermal properties of the host materials were analyzed with differential scanning calorimeter (DSC). Fig. 4 shows DSC thermograms of CzTPPh and CzTPPy. Glass transition temperature (T_g) of CzTPPy was higher than that of CzTPPh by 8 °C due to strong intermolecular interaction by the pyridine substituent. The pyridine unit was effective to improve the T_g of carbazole modified terphenyl derivatives.

As the CzTPPh and CzTPPy had different electron transport moieties in the molecular structure, electron current density of the device was compared. Fig. 5 shows current density–voltage curves of CzTPPh and CzTPPy devices. The electron current density of CzTPPy was higher than that of CzTPPh and the voltage at the same current density was reduced by 1.8 V. The high electron current density of the CzTPPy device is due to the pyridine substituent. Electron deficiency of the pyridine unit improved electron transport properties of the CzTPPy device, resulting in high electron current density.

Blue PHOLEDs were fabricated based on the high triplet energy of CzTPPh and CzTPPy host materials. FIrpic was doped as a blue triplet emitter and doping concentrations of FIrpic were 5% and 10%. Current density–voltage–luminance curves of CzTPPh and CzTPPy blue PHOLEDs are shown in Fig. 6. The current density of the blue PHOLED was high in the CzTPPy device because of high electron current density as shown in electron only device data. The driving voltages at 1000 cd/m² were 6.7 V and 6.2 V for CzTPPh and CzTPPy devices. The doping concentration of FIrpic also affected the



Fig. 4. DSC thermograms of CzTPPh and CzTPPy.



Fig. 5. Current density-voltage curves of electron only device of CzTPPh and CzTPPy.



Fig. 6. Current density-voltage-luminance curves of CzTPPh and CzTPPy blue PHOLEDs.



Fig. 7. Energy level diagram of CzTPPh and CzTPPy blue PHOLEDs.

current density of the blue PHOLEDs and high current density was obtained at 10% doping concentration. As shown in the energy level diagram in Fig. 7, there was large difference of LUMO levels between host materials and FIrpic. The large LUMO level difference induces electron trapping by FIrpic, which dominates electron transport of the blue PHOLEDs. In the case of the electron trapped devices, electron transport properties are improved at high doping concentration due to electron hopping between dopant materials. Therefore, high current density was obtained at high doping concentration. The luminance followed the same tendency as the current density.

Quantum efficiency–luminance curves of the CzTPPh and CzTPPy blue PHOLEDs are shown in Fig. 8. The quantum efficiency



Fig. 8. Quantum efficiency-luminance curves of CzTPPh and CzTPPy blue PHOLEDs.



Fig. 9. EL spectra of CzTPPh and CzTPPy blue PHOLEDs.

of the blue PHOLEDs was optimized at high doping concentration and high quantum efficiency was achieved at 10% doping concentration in both devices. Maximum quantum efficiencies of the CzTPPh and CzTPPy blue PHOLEDs were 20.2% and 15.7%, respectively. The high quantum efficiency was maintained even at high luminance and high quantum efficiencies of 19.0% and 15.3% were obtained at 1000 cd/m² in the CzTPPh and CzTPPy blue PHOLEDs, respectively. The quantum efficiency of the CzTPPy host was lower than that of the CzTPPh host in spite of high electron current density. The relatively low quantum efficiency of the CzTPPy host can be explained by long wavelength solid PL emission of the CzTPPy host (Fig. 2). The long wavelength emission of the CzTPPy host could not contribute to the energy transfer to FIrpic, which degraded the quantum efficiency of the CzTPPy blue PHOLEDs. The CzTPPh host showed better quantum efficiency than common mCP host.

Electroluminescence (EL) spectra of the CzTPPh and CzTPPy blue PHOLEDs are shown in Fig. 9. The two devices exhibited typical Flrpic emission with a peak maximum at 469 nm. The EL spectra were maintained stable irrespective of the luminance of the device. The color coordinates of CzTPPh and CzTPPy blue devices were (0.14, 0.28) and (0.14, 0.30) at all luminance range from 10 cd/m² to 2000 cd/m².

5. Conclusions

In conclusion, carbazole modified terphenyl based host materials, CzTPPh and CzTPPy, were synthesized as high triplet energy host materials and showed high quantum efficiency in blue PHO-LEDs. The CzTPPh host was better than CzTPPy host in terms of quantum efficiency and showed high quantum efficiency of 20.2%. Therefore, the carbazole modified terphenyl core can be effectively used as the core structure of blue triplet host materials in future development.

References

- [1] Su S, Gonmori E, Sasabe H, Kido J. Adv Mater 2008;20:4189.
- [2] Holmes RJ, Forrest SR, Kwong RC, Brown JJ, Garon S, Thompson ME. Appl Phys Lett 2003;82:2422.
- [3] Tokito S, lijima T, Suzuri Y, Kita H, Tsuzuki T. Appl Phys Lett 2003;83:569.
 [4] Tsai MH, Lin HW, Su HC, Ke TH, Wu CC, Tang FC, et al. Adv Mater 2006;18:
- 1216.
- 5] Jeon SO, Jang SE, Son HS, Lee JY. Adv Mater 2011;23:1436.
- [6] Ding J, Wang Q, Zhao L, Ma D, Wang L, Jing X, et al. J Mater Chem 2010;20: 8126.

- [7] Lai M-Y, Chen C-H, Huang W-S, Lin JT, Ke T-H, Chen L-Y, et al. Angew Chem Int Ed 2008;47:581.
- [8] Lee CW, Lee JY. Adv Mater 2013;25:596.
- [9] Inomata H, Goushi K, Masuko T, Konno T, Imai T, Sasabe H, et al. Chem Mater 2004;16:1285.
- [10] Chou H-H, Cheng C-H. Adv Mater 2010;22:2468.
- [11] Shih P-I, Chien C-H, Chuang C-Y, Shu C-F, Yang C-H, Chen J-H, et al. J Mater Chem 2007;17:1692.
- [12] Ye S, Liu Y, Di C, Xi H, Wu W, Wen Y, et al. Chem Mater 2009;21:1333.
- [13] Shih P-I, Chiang C-L, Dixit AK, Chen C-K, Yuan M-C, Lee R-Y, et al. Org Lett 2006:8:2799.
- [14] Jeong SH, Seo CW, Lee JY, Cho NS, Kim JK, Yang JH. Chem Asia J 2011;6:2895.
- [15] Vecchi PA, Padmaperuma AB, Qiao H, Sapochak LS, Burrows PE. Org Lett 2006:8:4211.

- [16] Han C, Xie G, Li J, Zhang Z, Xu H, Deng Z, et al. Chem Eur J 2011;17:8947.
 [17] Hanm C, Xiw G, Xu H, Zhang Z, Xie L, Zhao Y, et al. Adv Mater 2011;23: 2491.
- [18] Yan M, Tao Y, Chen R, Zheng C, An Z, Huang W. RSC Adv 2012;2:7860.
- [19] Agata Y, Shimizu H, Kido J. Chem Lett 2007;36:316.
- [20] Lee CW, Lee JY. Org Electron 2013;14:1602.
- [21] Jiang W, Duan L, Qiao J, Zhang D, Dong G, Wang L, et al. J Mater Chem 2010;20:6131.
- [22] Jiang W, Duan L, Qiao J, Zhang D, Dong G, Wang L, et al. Dyes Pigment 2012;92:891.
- [23] Sasabe H. Pu Y. Nakavama K. Kido J. Chem Commun 2009:43:6655.
- [24] Su SJ, Cai C, Kido J. Chem Mater 2011;23:274.
- [25] Lee CW, Yook KS, Lee JY. Org Electron 2009;14:2013.