DOI: 10.1002/ijch.201400058

Synthesis, Aggregation-Induced Emission, and Electroluminescence of Dibenzothiophene- and Dibenzofuran-Containing Tetraarylethenes

Ni Xie,^[a] Yang Liu,^[b] Rongrong Hu,^[a] Nelson L. C. Leung,^[a] Mathieu Arseneault,^[a] and Ben Zhong Tang*^[a, c, d]

Abstract: Dibenzothiophene- and dibenzofuran-functionalized ethanes were synthesized by the McMurry coupling reaction. The luminogens are faintly emissive when molecularly dissolved in good solvents, but emit intensively when aggregated as nanoparticles in poor solvents or fabricated as solid thin films, demonstrating the phenomenon of aggregation-induced emission (AIE). Their organic light-emitting diode (OLED) applications were explored, utilizing the AIE effect. Electroluminescence devices with the configuration of indium tin oxide (ITO)/N,N'-di(1-naphthyl)-N,N'-diphenyl-(1,1'-biphenyl)-4,4'-diamine (NPB; 60 nm)/dye (20 nm)/ 1,3,5-tri(1-phenyl-1H-benzo[d]imidazol-2-yl)phenyl (TPBi; 10 nm)/tris(8-hydroxyquinoline)aluminum (Alq₃; 30 nm)/LiF (1 nm)/Al (100 nm) were fabricated. The OLED device emits at 510 nm with a maximum luminescence and external quantum efficiency of 10⁴ cd/m² and 2.1%, respectively. The OLED behavior of the E/Z isomers was also studied.

Keywords: aggregation · electrochemistry · isomers · luminescence · thin films

1 Introduction

Since the first report of organic light-emitting diodes (OLEDs) by Tang and VanSlyke in 1987,^[1] there have been two main methods to enhance OLED performances. One is to design new devices with multiple layers; another is to find new materials for such applications. To obtain new light-emitting materials with strong emission efficiency in the device, several requirements are needed. For example, the new material should not self-quench its luminescence in the aggregated state, but rather have a high quantum yield. However, most organic luminescent molecules have reduced emission upon aggregation, which limits their practical applications. To prevent such low efficiency, currently organic emitting materials are doped to prevent dye aggregation and prevent the reduction of emission efficiency. If there is a molecular design that can overcome the aggregation-caused quenching (ACQ) problem once and for all, it will allow the production of the next generation of light-emitting technology and save energy and costs in the fabrication of any lightemitting device, including OLED devices.

The ACQ effect has been widely studied.^[2] To solve this notorious ACQ problem, we utilized the totally opposite aggregation-induced emission (AIE) phenomenon in a series of propeller-shaped molecules. The mechanism of AIE is due to the restriction of intramolecular free rotation (RIR).^[3] These promising new AIE materials, with high quantum yields in the aggregated states, provide a solution to the ACQ problem and are candidates for nondoped OLED device applications.^[4–6] Our group has previously reported a silole-containing AIE material for OLED device fabrication,^[7] but the synthesis of the materials was rather complicated with harsh conditions. For

 [a] N. Xie, R. Hu, N. L. C. Leung, M. Arseneault, B. Z. Tang Department of Chemistry, Institute for Advanced Study Division of Biomedical Engineering, Division of Life Science State Key Laboratory of Molecular Neuroscience and Institute of Molecular Functional Materials The Hong Kong University of Science and Technology Clear Water Bay, Kowloon, Hong Kong (S.A.R. China) e-mail: tangbenz@ust.hk 	
[b] Y. Liu State Key Laboratory of Crystal Materials Shandong University, Jinan 250100 (P. R. China)	
 [c] B. Z. Tang Guangdong Innovative Research Team SCUT-HKUST Joint Research Laboratory State Key Laboratory of Luminescent Materials and Devices South China University of Technology Guangzhou 510640 (P. R. China) 	
 [d] B. Z. Tang HKUST Shenzhen Research Institute, No. 9 Yuexing 1st RD South Area, Hi-tech Park, Nanshan, Shenzhen 518057 (P. R. China) 	

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/ijch.201400058.



Scheme 1. Synthetic scheme and structures of OTPE and STPE. Inset: Chemical reactivity sites of dibenzothiophene. DCM = dichloromethane.

facile synthesis, we designed our materials based on the tetraphenylethene core (TPE).

Thiophene is considered as an excellent material with an electron-rich conjugation system in its oligomer form and polymer structures.^[8-14] Dibenzothiophene (DBT) has an even more planar, fused polycyclic aromatic hydrocarbon structure than thiophene,^[15,16] and it is thus considered to have superior electronic properties than those of thiophene.^[15-18] With similar electronic affinity for sulfur and oxygen atoms, dibenzofuran (DBF) is another potential candidate for OLED applications.^[19-30]

In this work, we aimed to develop new DBF- and DBT-containing AIE-active materials. Through a twostep synthesis, new materials with AIE properties were obtained by using DBF and DBT (Scheme 1) as building blocks and their electroluminescence (EL) performance of the OLED devices are investigated.

2 Results and Discussion

Two TPE derivatives were obtained using DBT and DBF as the building blocks. The 2- and 8-positions (Scheme 1, inset) of DBT and DBF are the electrophilic positions for the Friedel–Crafts acylation reaction.^[31] The reaction was catalyzed by AlCl₃ and good yield was achieved for **1a** and **2a**, as shown in Scheme 1. The products are easily separated, owing to their relatively higher polarity than the reactants. A McMurry coupling reaction then took place and STPE and OTPE were both obtained in satisfactory yields. Surprisingly, the large planar structures do not result in byproducts with ethane structures. So far, this is the most efficient method to synthesize DBT- and DBF-containing AIE molecules.

The two compounds STPE and OTPE have good solubility in common organic solvents, such as THF, DCM, and chloroform, although they cannot dissolve in water. Mixtures of THF/water are thus chosen to study how the aggregates affect their luminescence, using a photoluminescence (PL) spectrophotometer. As shown in Figure 1A, the solution of STPE in THF is non-emissive. When the poor solvent, water, is slowly added with vigorous stirring, while keeping a fixed dye concentration of 10^{-5} M, an emission peak appears at 485 nm. Figure 1B shows the emission intensity changes with the water fraction. It is clear that, in the pure solution state (100% THF), the emission is barely detectable by the PL spectrophotometer. There is no prominent enhancement in the intensity until the water fraction reaches 70%. Intense emission of the nanoaggregates was observed afterwards and the intensity reached a maximum at a water fraction of 95%.

A similar phenomenon was observed with OTPE (Figure 2A). The trend of the intensity enhancement towards increasing water fractions is almost the same, but the maximum emission peak at 470 nm is blueshifted by 15 nm compared with STPE. The prominent enhancement of the luminescence begins at 80% water fraction (Figure 2B).

The thermal stability of both molecules was measured, as shown in Figure 3. Their decomposition temperatures, with only 5% weight loss, are both above 300°C according to TGA measurements. In particular, the decomposition temperature of STPE is as high as 357 °C. OTPE and STPE can both retain 50% of their weight, even over 370 and 430°C, respectively. In addition, elemental replacement in the two materials gives a decomposition temperature difference of about 40 °C. This is a reasonable result because the sulfur atom is larger than the oxygen atom and STPE has stronger intermolecular interactions than OTPE, which is responsible for the higher thermal stability. A more detailed analysis and explanation of the intermolecular interactions is given later in the section discussing the crystal packing of the molecules. The strong thermoresistance of the materials endows them with high



Figure 1. A) PL spectra of STPE in THF and mixtures of THF/water with different water fractions. B) Changes in PL intensity of STPE with water fraction in a mixture of THF/water. Dye concentration: 20 μM; excitation wavelength: 330 nm.



Figure 2. A) PL spectra of OTPE in THF and mixtures of THF/water with different water fractions. B) Changes in PL intensity of OTPE with water fraction in a mixture of THF/water. Dye concentration: 20 μM; excitation wavelength: 330 nm.

thermal stability for potential applications, such as in device fabrication, especially OLEDs.

The proposed RIR mechanism is employed to interpret the experimental data shown above.^[6,32] Intermolecular interactions of the dye are absent in the solution state. Abundant solvent molecules surround the dye molecules and intramolecular free rotation can take place in solution. With the addition of poor solvent, water, into the solution, the hydrophobic molecules start to aggregate. This induces the formation of nanoaggregates in such THF/ water mixtures as suspensions. The internal rotations of dye molecules are restricted by the aggregates. Therefore, the excited-state non-radiative relaxation pathways are blocked, leaving the system emissive upon excitation. $^{[4,33]}$

Fortunately, although STPE and OTPE both have large, coplanar, heteroatomic, fused, aromatic conjugation systems, potential π - π stacking interactions do not affect their AIE behavior. To find out why there is no quenching of emission in the aggregated state, despite the presence of these planar structures, the intermolecular interactions in the crystalline states were inspected. Single crystals of the *E* isomer of STPE were obtained from a solution in a mixture of DCM and methanol. The *Z* isomer of STPE, which appears as insoluble precipitates, was col-



Figure 3. Thermogravimetric analysis (TGA) measurements for STPE and OTPE.

lected by filtration of a hot solution in THF. The powder was then dissolved in a large amount of DCM and single crystals of the Z isomer were obtained from a mixture in DCM/methanol, as shown in Figure 4. Although similar methods were used for OTPE, only microneedle crystals could be formed from the mixed solution of OTPE and did not qualify for single-crystal analysis. The AIE behavior of both isomers shows no difference from that of STPE.

Close inspection of the ORTEP drawings of the E and Z isomers of STPE (Figure 4) suggest that the phenyl and DBT rings are twisted away from the ethene core plane and form a propeller-shaped structure. Besides the isolated molecules, intermolecular interactions were also analyzed through molecular packing. The weak interactions found in the packing crystal cell units are shown in

Figure 5. Generally, there is one major interaction in the isomers: $CH\cdots\pi$ interactions. The $CH\cdots\pi$ interactions of the two isomers share no common points.

As shown in Figure 5A, the *E* isomers have only intermolecular CH··· π interactions. On the grey labeled molecule, protons on the sp²-carbon of the adjacent phenyl ring interact with the DBT unit in the dark gray (right side) molecule with a distance of 2.928 Å to the closest DBT phenyl ring π cloud center and 3.061 Å to the thiophene π center. For the *Z* isomer (Figure 5B), besides having an intermolecular CH··· π interaction with a distance of about 3.5 Å, there is an additional intramolecular CH··· π interaction between the adjacent DBT proton on the 2-position to the same DBT phenyl ring π center with a distance of 2.923 Å. These intramolecular CH··· π interactions are responsible for the poor solubility of the *Z* isomer in hot THF.

CH…S interactions exist in the single crystal of the *E* isomer between two neighboring DBT units from different STPE molecules (Figure 6). The fact that no π … π interactions were observed explains why STPE presents no self-quenching emission in the aggregated state, but, on the other hand, the CH… π interactions in both isomers as well as the CH…S interactions in the *E* isomer reinforce the twisted propeller-like configuration. It prevents rotation or excimer formation; thus endowing the molecules with enhanced emission in the solid or aggregated state. Because OTPE is an analogue of STPE, similar properties are expected.

The UV absorption spectra of E- and Z-STPE were studied (Figure 7). The solution of the Z isomer in THF has a major absorption peak at 268 nm with a shoulder at 334 nm. The solution of the E isomer in THF has a blue-shifted main absorption peak at 252 nm and a higher shoulder absorption at 344 nm compared with that of the Z isomer.

Calculation of the transition state of the two isomers is shown in Table 1. The calculation is set to a "zero" energy level for the E isomer. To obtain the Z isomer,





Figure 4. ORTEP drawings of E-STPE (left) and Z-STPE (right).

Isr. J. Chem. 2014, 54, 958–966

Israel Journal of Chemistry



Figure 5. Weak CH··· π interactions in A) *E*-STPE and B) *Z*-STPE.



Figure 6. Weak CH…S interactions in E-STPE.

the central double bond needs to be broken to form one single bond with two radicals at each ethene carbon atom. The molecule is excited to the excited state after absorbing energy, where the conformation can be easily turned into its Z isomer with a statistical population distribution. According to the computational calculation (Table 1), the energy difference between the E and Z isomers is 0.2226 kcal/mol and the energy of the transition state is 32.5316 kcal/mol.



Figure 7. Normalized absorption of STPE isomers in dry THF solution.

Table 1. Computational calculation for STPE isomerization.

State	<i>E</i> -STPE [kcal/	Transition state [kcal/	Z-STPE [kcal/
	mol]	mol]	mol]
ΔE [kcal/ mol]	0	32.5316	0.2226



Figure 8. LUMOs and HOMOs calculated for STPE.

Then we used a UV lamp to excite one of the isomers to test for photoinduced E/Z isomerization in a similar process to that of photoswitching of *cis-/trans*-azoben-

zene. The Z-STPE isomer was first dissolved in DCM and the solution was irradiated with either 254 or 365 nm UV light. The transformation from the Z to E isomer does occur, but is incomplete. Due to the large overlap of the absorption spectra of both isomers, it is difficult to identify the degree of conversion. Because of the low energy needed for isomerization, under photoexcitation the isomers can readily interconvert to create a mixture. This is different from typically photoswitchable azobenzene, which has distinct absorptions of the *cis* and *trans* forms. For azobenzene, the conversion of one pure isomer to another can be achieved by controlling the excitation wavelength.

Calculations were carried out to predict the lowest unoccupied molecular orbital (LUMO) and highest occuTable 2. Summary of the thermal and optical properties of STPE and $\mbox{OTPE}.^{[a]}$

Lumi- nogen	Τ _{95%} [°C]	λ _{em} [nm]	ΔE [eV]	$\Phi_{ extsf{F,A}}$ [%]
<i>E</i> -STPE	313	480	4.155	100
<i>Z</i> -STPE	313	483	3.867	100
OTPE	357	463	N/A	69

[a] $\lambda_{\rm em}$ = emission maximum in a mixture of THF/water (1:9 v/v); ΔE = energy gap calculated by UV/Vis spectroscopy; $\Phi_{\rm F,A}$ =thin-film absolute fluorescent quantum yield.



Figure 9. Fabricated OLED devices with OTPE and STPE: A) EL spectra; B) brightness (right axis) power efficiency (PE; left axis) versus voltage; C) external quantum efficiency (EQE; right axis) and current density (left axis) versus voltage; and D) CIE coordinates of OTPE and STPE. Configuration: indium tin oxide (ITO)/*N*,*N*'-di(1-naphthyl)-*N*,*N*'-diphenyl-(1,1'-biphenyl)-4,4'-diamine (NPB; 60 nm)/dye (20 nm)/1,3,5-tri(1-phenyl-1*H*-benzo[*d*]imidazol-2-yl)phenyl (TPBi; 10 nm)/tris(8-hydroxyquinoline)aluminum (Alq₃; 30 nm)/LiF (1 nm)/Al (100 nm).

Isr. J. Chem. 2014, 54, 958-966

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

pied molecular orbital (HOMO). As shown in Figure 8, the left column is calculated for the E isomer, while the right column is for the Z isomer. The crystal structures were used as the initial model for input into the computational calculation. The electronic cloud is located between the two sulfur atoms. The E isomer has its HOMO located in a straight chain between the two DBT units; meanwhile, the Z isomer has its HOMO showing the same electron density alignment between both DBT units, but the conformation is more twisted. The LUMO shows a similar electron cloud distribution, shifting the electron density from the sulfur atom and accumulating on the central carbon double bond. The properties of STPE and OTPE are summarized in Table 2. The quantum yield for STPE is 100%, while that for OTPE is 69%; both suggest high emission efficiency in the solid state (Table 2).

Since these two materials were stable and AIE active, OLED devices were fabricated to test their EL properties. Unlike conventional OLED devices employing a guest and host combination mixture as the emitting layer, pure organic AIE-active compounds without doping luminogens can be achieved, which are able to ideally resolve the ACQ problem. The EL data is presented in Figure 9. With the configuration of ITO/NPB (60 nm)/dye (20 nm)/TPBi (10 nm)/Alq₃ (30 nm)/LiF (1 nm)/Al (100 nm), good performances were obtained with STPE in the bluish green region. Figure 9A presents the EL spectra of STPE and OTPE at 488 and 468 nm, respectively.

In the EL study, STPE shows better a brightness of up to 10^4 cd/m², which is about one order of magnitude higher than that of OTPE (Figure 9B). The turn-on volt-



Figure 10. Fabricated OLED devices of STPE isomers: A) EL spectra; B) luminescence (right axis) and current density (left axis) versus voltage spectra; C) EQE (right axis) and PE (left axis) versus voltage; and D) CIE coordinates of *Z*- and *E*-STPE. Configuration: ITO/NPB (60 nm)/ dye (20 nm)/TPBi (10 nm)/Alq₃ (30 nm)/LiF (1 nm)/Al (100 nm).

Isr. J. Chem. 2014, 54, 958-966

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

age to 1 cd/m² for both materials is about 5 V. The PE and EQE are separately plotted in Figure 9B and C. STPE displays good EL performance with an EQE value of about 2%, which is more than twofold higher than that of OTPE. The PE of the STPE device is about 3.0 mA/W, while that of OTPE is less than 1.0 mA/W. Due to the high thermal stability of STPE, the device shows strong resistance to high-voltage conditions, while functioning stably. However, OTPE is less stable under high-voltage conditions when compared with STPE. The PE and EQE of OTPE drops to 0 mA/cm² and 1 cd/m², respectively, above 10 V.

By recalculating the EL spectrum, we obtain the chromaticity diagram coordinates from the Commission Internationale de l'Éclairage (CIE) 1931,^[34] which is (0.1935, 0.3188) for STPE and (0.1697, 0.2189) for OTPE (Figure 9D). With the CIE 1931 standard chart, it is possible to ascertain that the color, regardless of the ambient brightness, because the luminance intensity is not considered in this xy coordinate, but only the chromaticity. According to the CIE 1931 standard, red (R), green (G), blue (B), and white (W) are defined as (0.64, 0.33), (0.30, 0.60), (0.15, 0.06), and (0.3127, 0.3290), respectively. From these chromaticity coordinates, x and y values represent the red emission fraction and the green emission fraction of measured light, respectively. In this case, the OTPE molecule shows an x value of 0.1697, which is close to the standard blue color x value (0.15), but its y value (0.2189)is much higher than the standard blue y value of 0.06. Thus, it gives a green light mixed with blue emission that matches the emission from the PL and EL measurements. The OTPE spectrum thus has a tail in the bluish green region.[35,36]

The same trend is observed for STPE, which is redshifted from OTPE, as an emitter in an OLED device. The CIE 1931 coordinates values calculated for STPE show that the y value is 0.3188. This is a net enhancement compared with 0.2189 of OTPE. It nears the standard red color y value of 0.33, while the x value was not changed much by exchanging oxygen for sulfur.

The E/Z isomers of STPE were successfully isolated on a large scale and their EL behavior was tested, as shown in Figure 10. According to the EL spectrum, the emission of Z isomer is redshifted from that of the E isomer. It matches the calculation results that the E isomer has the most overlapped electron cloud, which enhances the conjugation, whereas the Z isomer has a highly twisted backbone of each large, planar DBT moiety. Therefore, a small redshift in the EL spectra of the Z isomer is thus observed. In addition, better EL performance is observed for the Z isomer with crowded electrons when fabricated into a device, in terms of both the brightness and efficiency (Figure 10B). This is the first EL device study based on E/Z isomers as the emitting layer material.

3 Conclusions

DBT- and DBF-containing TPE derivatives, STPE and OTPE, were first synthesized by the McMurry reaction in high yields. Both TPE derivatives were faintly emissive in solutions. The two heteroatomic polycyclic compounds could emit intensely in the aggregated state due to interactions, such as $CH \cdots \pi$ and $CH \cdots S$, which restricted the intramolecular rotation processes, and hence, promoted radiative decay of the excited-state molecules. Both STPE and OTPE emitted efficiently in the solid state and enjoyed high morphological and thermal stabilities. Their large polycyclic structures adopted twisted conformations, avoiding intramolecular π - π stacking, which allowed them to be highly fluorescent in the aggregation state. STPE, with a sulfur atom, exhibited better EL properties than those of OTPE. The brightness, PE, and EQE are up to 10⁴ cd/m², 3.0 cd/A, and 2.0%, respectively. Additionally, the E isomer of STPE could be separated by a thermal method and offered even better electronic performance in a fabricated EL device, as summarized in Table 3. Such attributes make the DBT-containing luminogens promising materials for optoelectronic devices.

Table 3. EL properties of STPE and OTPE.^[a]

Emitting layer	λ _{εL} [nm]	L _{max} [cd/ m²]	η _{Ρ,max} [lm/ W]	$\eta_{ m ext,max}$ [%]	CIE (<i>x</i> , γ)
STPE ^[b]	488	9102	3.1	2.1	0.19,
OTPE ^[b]	464	1033	0.97	0.96	0.32 0.17,
	504	5572	12	1.0	0.22
Z-STPL"	504	5525	1.5	1.0	0.23, 0.40
E-STPE ^[c]	492	6626	2.0	1.7	0.20, 0.34

[a] $\lambda_{EL} = EL$ maximum, $V_{on} = turn-on voltage at 1 cd/m^2$, $L_{max} = maximum luminance$, $\eta_{P,max} = maximum power efficiency$, $\eta_{ext,max} = maximum external quantum efficiency, and CIE = CIE 1931 color space coordinate. [b] Device configuration: First time ITO/NPB (60 nm)/emitter (20 nm)/TPBi (10 nm)/Alq₃ (30 nm)/LiF (1 nm)/Al (100 nm). [c] Device configuration: Second time ITO/NPB (60 nm)/emitter (20 nm)/TPBi (10 nm)/Alq₃ (30 nm)/LiF (1 nm)/Al (100 nm). [c] Device (10 nm)/Alq₃ (30 nm)/LiF (1 nm)/Al (100 nm).$

Acknowledgements

B. Z. T. would like to thank the support of crystallographer Herman H. Y. Sung and Professor Ian D. William. This work was partially supported by the National Basic Program Research of China (973 Program; 2013CB834701), the Research Grants Council of Hong Kong (HKUST2/CRF/10, N_HKUST620/11, 604711 and 604913), and the University Grants Committee of HK (AoE/P-03/08). B. Z. T. also thanks the support of the Guangdong Innovative Research Team Program (201101C0105067115).

References

- [1] C. W. Tang, S. A. VanSlyke, Appl. Phys. Lett. 1987, 51, 913.
- [2] Y. N. Hong, J. W. Y. Lam, B. Z. Tang, Chem. Commun. 2009, 4332.
- [3] Y. N. Hong, J. W. Y. Lam, B. Z. Tang, Chem. Soc. Rev. 2011, 40, 5361.
- [4] W. Z. Yuan, S. M. Chen, J. W. Y. Lam, C. M. Deng, P. Lu, H. H. Y. Sung, I. D. Williams, H. S. Kwok, Y. M. Zhang, B. Z. Tang, *Chem. Commun.* **2011**, *47*, 11216.
- [5] W. Z. Yuan, P. Lu, S. M. Chen, J. W. Y. Lam, Z. M. Wang, Y. Liu, H. S. Kwok, Y. G. Ma, B. Z. Tang, *Adv. Mater.* **2010**, *22*, 2159.
- [6] J. Huang, N. Sun, P. Chen, R. Tang, Q. Li, D. Ma, Z. Li, *Chem. Commun.* 2014, 50, 2136.
- [7] J. Luo, Z. Xie, J. W. Y. Lam, L. Cheng, H. Chen, C. Qiu, H. S. Kwok, X. Zhan, Y. Liu, D. Zhu, B. Z. Tang, *Chem. Commun.* 2001, 1740.
- [8] E. L. Ratcliff, J. L. Jenkins, K. Nebesny, N. R. Armstrong, *Chem. Mater.* 2008, 20, 5796.
- [9] H. Peeters, T. Verbiest, G. Koeckelberghs, J. Polym. Sci. Part A Polym. Chem. 2009, 47, 1891.
- [10] E. Lim, S. Lee, K. K. Lee, Mol. Cryst. Liq. Cryst. 2011, 538, 157.
- [11] E. Lim, K. K. Lee, S. Lee, J. Nanosci. Nanotechnol. 2012, 12, 3483.
- [12] U. Giovanella, C. Botta, A. Bossi, E. Licandro, S. Maiorana, J. Appl. Phys. 2006, 100.
- [13] C. B. Fan, P. Yang, X. M. Wang, G. Liu, X. X. Jiang, H. Z. Chen, X. T. Tao, M. Wang, M. H. Jiang, *Sol. Energy Mater. Sol. Cells* **2011**, *95*, 992.
- [14] C. Carach, M. J. Gordon, J. Phys. Chem. B 2013, 117, 1950.
- [15] M. G. Choi, R. J. Angelici, Organometallics 1992, 11, 3328.
- [16] C. Bianchini, M. V. Jimenez, A. Meli, S. Moneti, F. Vizza, V. Herrera, R. A. Sanchezdelgado, *Organometallics* 1995, 14, 2342.
- [17] M. Norval, A. P. Cullen, F. R. de Gruijl, J. Longstreth, Y. Takizawa, R. M. Lucas, F. P. Noonan, J. C. van der Leun, *Photochem. Photobiol. Sci.* 2007, 6, 232.
- [18] M. Norval, R. M. Lucas, A. P. Cullen, F. R. de Gruijl, J. Longstreth, Y. Takizawa, J. C. van der Leun, *Photochem. Photobiol. Sci.* 2011, 10, 199.
- [19] H. P. Xiao, L. Yu, Y. H. Li, W. Yang, B. Zhang, H. B. Wu, Y. Cao, *Polymer* **2012**, *53*, 2873.

- [20] Z. J. Ren, D. M. Sun, H. H. Li, Q. Fu, D. G. Ma, J. M. Zhang, S. K. Yan, *Chem. Eur. J.* 2012, 18, 4115.
- [21] X. F. Li, Z. G. Chi, B. J. Xu, H. Y. Li, X. Q. Zhang, W. Zhou, Y. Zhang, S. W. Liu, J. R. Xu, J. Fluoresc. 2011, 21, 1969.
- [22] S. M. King, I. I. Perepichka, I. F. Perepichka, F. B. Dias, M. R. Bryce, A. P. Monkman, *Adv. Funct. Mater.* **2009**, *19*, 586.
- [23] E. Q. Jin, C. Du, M. Wang, W. W. Li, C. H. Li, H. D. Wei, Z. S. Bo, *Macromolecules* **2012**, *45*, 7843.
- [24] S. H. Jeong, J. Y. Lee, J. Mater. Chem. 2011, 21, 14604.
- [25] C. L. Ho, S. Y. Poon, P. K. Lo, M. S. Wong, W. Y. Wong, J. Inorg. Organomet. Polym. Mater. 2013, 23, 206.
- [26] R. F. He, S. J. Hu, J. Liu, L. Yu, B. Zhang, N. Li, W. Yang, H. B. Wu, J. B. Peng, J. Mater. Chem. 2012, 22, 3440.
- [27] C. M. Han, Z. S. Zhang, H. Xu, S. Z. Yue, J. Li, P. R. Yan, Z. P. Deng, Y. Zhao, P. F. Yan, S. Y. Liu, *J. Am. Chem. Soc.* 2012, 134, 19179.
- [28] R. Grisorio, G. Melcarne, G. P. Suranna, P. Mastrorilli, C. F. Nobile, P. Cosma, P. Fini, S. Colella, E. Fabiano, M. Piacenza, F. Della Sala, G. Ciccarella, M. Mazzeo, G. Gigli, J. *Mater. Chem.* 2010, 20, 1012.
- [29] S. C. Dong, C. H. Gao, X. D. Yuan, L. S. Cui, Z. Q. Jiang, S. T. Lee, L. S. Liao, Org. Electron. 2013, 14, 902.
- [30] J. K. Bin, J. Yang, J. I. Hong, J. Mater. Chem. 2012, 22, 21720.
- [31] J. E. McMurry, Organic Chemistry, 8edth edBrooks Cole, Belmont CA, 2011.
- [32] W. Z. Yuan, F. Mahtab, Y. Y. Gong, Z. Q. Yu, P. Lu, Y. H. Tang, J. W. Y. Lam, C. Z. Zhu, B. Z. Tang, J. Mater. Chem. 2012, 22, 10472.
- [33] W. Z. Yuan, Y. Y. Gong, S. M. Chen, X. Y. Shen, J. W. Y. Lam, P. Lu, Y. W. Lu, Z. M. Wan, R. R. Hu, N. Xie, H. S. Kwok, Y. M. Zhang, J. Z. Sun, B. Z. Tang, *Chem. Mater.* 2012, 24, 1518.
- [34] CIE, Commission Internationale de l'Eclairage Proceedings, Cambridge University Press, Cambridge, 1931.
- [35] W. G. Quirino, R. D. Adati, S. A. M. Lima, C. Legnani, M. Jafelicci, M. R. Davolos, M. Cremona, *Thin Solid Films* 2006, 515, 927.
- [36] K. McLaren, J. Soc. Dyers and Colour. 1976, 92, 338.

Received: February 28, 2014 Accepted: April 17, 2014 Published online: July 8, 2014