White Electroluminescence with Simultaneous Three-Color Emission from a Four-Armed Star-Shaped Single-Polymer System

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A four-armed star-shaped single-polymer system with 4,7-bis(5-(4-(9*H*-carbazol-9-yl)phenyl)-4-hexylthiophen-2-yl)benzo[*c*][1,2,5]thiadiazole (FTBT) as a red emissive core, polyfluorene (PF) as blue emissive arms and 1,3-benzo thiadiazole (BT) as green emissive dopants was designed and synthesized, in which red, green, and blue (RGB) emission balance can be achieved by adjusting the doping concentration of FTBT and BT discreetly. A typical single-emissive-layer device (ITO/PEDOT:PSS/polymer/TPBI/LiF/Al) was studied and discussed, realizing a pure and stable white emission with a luminous efficiency (LE) of 1.59 cd·A⁻¹ and CIE coordinates of (0.31, 0.34). The high-color-quality white electroluminescence of the devices could be mainly attributed to the suppressed intermolecular interactions, and partial energy transfer from the blue PF arms to the red and green dopants.

Keywords white electroluminescence, hyperbranched polymers, multi-armed structures, Förster resonance energy transfer, organic light-emitting diodes

Introduction

White polymer light-emitting diodes (WPLEDs) have received particular attention due to their potential applications in low-cost, large-area and flexible devices via solution-processed fabrication,^[1-4] which are expected to become a complementary or competitive candidate to compete with other light sources such as fluorescent tubes and inorganic light-emitting diodes in the lighting markets in the near future. A conventional approach to obtain white emission is to use physical blends in a combination with red, green and blue emis-sive species,^[5-7] such as polymer-polymer blend sys-tems,^[10,11] and polymer-small molecule blend sys-tems.^[12,13] Despite promising efficiencies, this strategy may suffer from the challenge of phase separation and bias-dependent electroluminescent (EL) spectra.^[14,15] To resolve these issues, single-polymer systems have been investigated as a prospective strategy to eliminate the phase separation and obtain bias-independent EL spectra.^[16-19] At the beginning, this kind of white emission was achieved by blue emission from the blue dopant

and orange emission from the aggregation/excimer/exciplex, manifesting low efficiency. Later on, a strategy of covalently attaching various emissive components to the polymer host has been proposed to improve the efficiency. The intrinsic phase separation could thus be suppressed because of the single-polymer chemical architectures, leading to better operational stability.

Recently, intense efforts have been focused on exploring this methodology to realize white emission. For example, Woo and co-workers^[20] synthesized a linear polymer with red chromophore 4,7-bis(2-thienyl)-2,1,3-benzothiadiazole (DBT), a green dye 2,1,3-benzothiadiazole (BT) and a blue backbone of tetraoctylindenofluorene (IF), emitting white light with maximum current efficiency of 0.36 cd·A⁻¹ and CIE coordinates of (0.34, 0.32). Wang *et al.*^[21] reported a PF doped with quinacridone, showing white emission with CIE coordinates of (0.27, 0.35). Despite significant progress, it is still a great challenge to achieve highly efficient pure and stable white EL. The unsaturated white light emission from the linear polymer systems may mainly originate from the strong intermolecular interactions in the solid state due to the π - π * stacking of the linear rigid

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conjugated polymer backbones, leading to low EL quality. In this context, star-shaped single-polymer systems have attracted particular interests because of their unusual structural and optoelectronic properties.^[22-25] Hyperbranched and globular features are expected to eliminate intermolecular interactions in order to achieve high-color-quality and stable white EL. For instance, Wang *et al.*^[26] have reported star-like single-polymers through incorporating six PF arms onto a star-shaped orange core (1,3,5-tris(4-(7-(4-(*N*,*N*-diphenylamino)phenyl)-2,1,3-benzothiadiazole-4-)phenyl)benzene, TPB6), demonstrating an external quantum efficiency (EQE) of 6.36%. However, the difficulty lies in the relatively poor solubility of the TPB6 unit.

In our previous contributions, a novel series of monodisperse conjugated starburst macromolecules has been developed.^[27-35] These monodisperse multibranched molecules combine significant advantages of well-de-fined chemical structures, good solution processibility, high purity, suppressed intermolecular interactions and excellent optoelectronic properties. Highly efficient blue and red emission have been demonstrated. Thus, there are some possibilities that we could build up a unique platform to achieve white EL by means of adjusting the central core and conjugated arms to construct multi-armed structures.

In this contribution, we reported a set of four-armed star-like single-polymer system by introducing 4,7-bis-(5-(4-(9H-carbazol-9-yl)phenyl)-4-hexylthiophen-2-yl)benzo[c][1,2,5]thiadiazole (FTBT) as a red emissive core, polyfluorene (PF) as blue emissive arms and 1,3-benzo thiadiazole (BT) as green emissive dopants into a star-shaped architectures (Scheme 1). By selecting the proper concentration of the dopants, [36,37] partial Förster resonance energy transfer (FRET) and charge trapping from the blue arms to green and red dopants are accomplished to ensure white EL, exhibiting simultaneous blue emission (λ_{max} =430/450 nm), green emission (λ_{max} =519 nm), and red emission (λ_{max} =571 nm). A single-emissive-layer device based on this four-armed single-polymer achieved pure and stable white light with Commission Internationale d'Eclairage (CIE) coordinates of (0.31, 0.34) and a luminous efficiency (LE) of 1.59 cd \cdot A⁻¹ at 5.8 V.

Experimental

Synthesis of 4,7-bis(5-(4-(3,6-dibromo-9*H*-carbazol-9-yl)phenyl)-4-hexylthiophen-2-yl)benzo[*c*][1,2,5]thia-diazole (FTBT4Br)

N-Bromosuccinimide (NBS) (0.39 g, 2.25 mmol) was added to a solution of 4,7-bis(5-(4-(9*H*-carbazol-9-yl)phenyl)-4-hexylthiophen-2-yl)benzo[c][1,2,5]thiadiazole (FTBT; 0.47 g, 0.5 mmol) in CH₂Cl₂ (20 mL). The resulting mixture was kept stirred at room temperature for 6 h. After workup, the mixture was poured into aqueous NaHSO₃. The organic layer was washed with water and then dried with anhydrous Na₂SO₄. After filtration and evaporation of the solvent, the residue was purified by silica column chromatography to give the title compound as a red solid. Yield: 0.51 g (80%). ¹H NMR (CDCl₃, 400 MHz) δ: 8.19-8.27 (m, 4H), 7.19-8.13 (m, 4H), 7.76 - 7.80 (dd, J = 5.9, 9.9 Hz, 4H), 7.59 - 7.66 (m, 4H), 7.51 - 7.56 (t, J = 9.0 Hz, 4H), 7.34-7.39 (dt, J=4.9, 8.3 Hz, 4H), 2.85-2.88 (m, 4H), 1.72-1.82 (m, 4H), 1.34-1.44 (m, 12H), 0.89 (s, 6H); ¹³C NMR (CDCl₃, 100 MHz) δ: 153.96, 152.29, 141.04, 140.54, 139.76, 139.69, 139.37, 134.30, 133.57, 132.31, 130.88, 130.79, 130.69, 129.53, 129.50, 128.73, 127.08, 127.03, 126.97, 124.15, 124.11, 123.34, 123.32, 120.62, 120.59, 120.57, 120.55, 113.38, 113.37, 113.29, 112.98, 111.58, 111.53, 31.94, 31.69, 31.42, 29.71, 29.67, 29.37, 22.70, 22.64, 14.13. Anal. calcd for C₆₂H₅₀Br₄N₄S₃: C 58.78, H 3.98, N 4.42, S 7.59; found C 58.34, H 3.84, N 4.49, S 7.19. MALDI-TOF (m/z): Anal. calcd for $C_{62}H_{50}Br_4N_4S_3$: 1262.0; found: 1264.3 [M⁺].

Synthesis of 2,2'-(9,9-dihexyl-9*H*-fluorene-2,7-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (2)

A solution of 2,7-dibromo-9,9-dioctylfluorene (1) (15.54 g, 28.3 mmol) in dry THF (250 mL) at –78 $^\circ\!\mathrm{C}$ was added to n-BuLi (17.7 mL). After stirring for 1 h, trimethlyborate (4.2 mL, 37.1 mmol) was added and the mixture was kept stirred for another 24 h, followed by the addition of 2 mol \cdot L⁻¹ hydrochloric acid (100 mL). The mixture was extracted with ether and the combined extracts were evaporated to give a white solid, 7-bromo-9,9-dioctylfluoren-2-yl boric acid. The boric acid was mixed with 1,3-propanediol (2.5 mL, 34.5 mmol) and toluene (150 mL), and the resulting mixture was refluxed overnight. Evaporation of the solvent under reduced pressure gave the crude product, which was recrystallized in ethanol twice to afford the title compound as a white solid. Yield: 5.81 g (37%). ¹H NMR $(CDCl_3, 400 \text{ MHz}) \delta$: 7.80–7.82 (d, J=8.1 Hz, 2H), 7.71-7.75 (m, 4H), 1.98-2.02 (m, 4H), 1.39 (s, 24H), 0.99 - 1.10 (m, 12H), 0.73 - 0.76 (t, J = 7.1 Hz, 6H), 0.50 - 0.56 (dd, J = 7.3, 15.5 Hz, 4H); ¹³C NMR (CDCl₃, 100 MHz) δ: 150.47, 143.93, 133.66, 128.92, 119.38, 83.72, 55.19, 40.10, 31.45, 29.63, 24.95, 23.57, 22.58, 14.02.

General procedures for synthesis of the polymers

To a mixture of 2,7-dibromo-9,9-dihexyl-9*H*-fluorene (1) (quantities given below), 2,2'-(9,9-dihexyl-9*H*-fluorene-2,7-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (2), and Pd(PPh₃)₄ (11.5 mg, 0.01 mmol) under N₂ was added a drop of Aliquat 336, 2 mol·L⁻¹ aqueous potassium carbonate (2.5 mL), and degassed toluene (5 mL). Solutions of 4,7-bis(5-(4-(3,6-dibromo-9*H*-carbazol-9-yl)phenyl)-4-hexylthiophen-2-yl)benzo-[*c*][1,2,5]thiadiazole (FTBT4Br) and solutions of 4,7-dibromobenzo[*c*][1,2,5]thiadiazole (4) were also added. The mixture was stirred at 90 °C for 48 h and then poured into methanol. The precipitate was collected by using filtration, dried, and then dissolved in dichloro-

methane. The solution was washed with water and dried over anhydrous Na_2SO_4 . After most of the solvent had been removed, the residue was poured into stirred methanol to give a fiber-like solid. The polymer was further purified by extracting with acetone for 24 h. The reprecipitation procedure in THF/methanol was then repeated several times. The final product, a light orange-colored fiber, was obtained after drying in a vacuum with a yield of 80%-90%.

PF: 1 (0.25 g, 0.50 mmol) and 2 (0.30 g, 0.50 mmol) were used in the polymerization. Gel-permeation chromatography (GPC): $M_n=2.47\times10^4$, polydispersity index (PDI)=2.09 (polystyrene as standard).

PFB: **1** (0.25 g, 0.50 mmol) and **2** (0.30 g, 0.50 mmol), BT2Br (0.40 mL 5×10^{-4} mol·L⁻¹ solution in toluene, 2×10^{-4} mmol) were used in the polymerization. Gel-permeation chromatography (GPC): $M_n = 1.19 \times 10^4$, polydispersity index (PDI)=1.96 (polystyrene as standard).

FTBT-R5G8: **1** (0.25 g, 0.50 mmol), **2** (0.30 g, 0.50 mmol), BT2Br (0.80 mL 5×10^{-4} mol•L⁻¹ solution in toluene, 4×10^{-4} mmol) and FTBT4Br (2.50 mL 5×10^{-4} mol•L⁻¹ solution in toluene, 1.25×10^{-3} mmol) were used in the polymerization. GPC: $M_n = 6.35 \times 10^4$, PDI=1.69.

FTBT-R5G12: **1** (0.25 g, 0.50 mmol), **2** (0.30 g, 0.50 mmol), BT2Br (1.20 mL 5×10^{-4} mol·L⁻¹ solution in toluene, 6×10^{-4} mmol) and FTBT4Br (2.50 mL 5×10^{-4} mol·L⁻¹ solution in toluene, 1.25×10^{-3} mmol) were used in the polymerization. GPC: M_n =3.34×10⁴, PDI=2.00.

FTBT-R5G15: **1** (0.25 g, 0.50 mmol), **2** (0.30 g, 0.50 mmol), BT2Br (1.50 mL 5×10^{-4} mol•L⁻¹ solution in toluene, 8×10^{-4} mmol) and FTBT4Br (2.50 mL 5×10^{-4} mol•L⁻¹ solution in toluene, 1.25×10^{-3} mmol) were used in the polymerization. GPC: M_n =5.46×10⁴, PDI=1.65.

FTBT-R2G4: **1** (0.25 g, 0.50 mmol), **2** (0.300 g, 0.50 mmol), BT2Br (0.40 mL 5×10^{-4} mol·L⁻¹ solution in toluene, 1×10^{-4} mmol) and FTBT4Br (1.00 mL 5×10^{-4} mol·L⁻¹ solution in toluene, 7.50×10^{-4} mmol) were used in the polymerization. GPC: M_n =3.77×10⁴, PDI=1.71.

FTBT-R4G4: **1** (0.25 g, 0.50 mmol), **2** (0.30 g, 0.50 mmol), BT2Br (0.40 mL 5×10^{-4} mol·L⁻¹ solution in toluene, 2×10^{-4} mmol) and FTBT4Br (2.00 mL 5×10^{-4} mol·L⁻¹ solution in toluene, 7.50×10^{-4} mmol) were used in the polymerization. GPC: M_n =4.54×10⁴, PDI=1.77.

All these polymers showed similar ¹H NMR spectra and elemental analysis results. For example, PF: ¹H NMR (CDCl₃, 400 MHz) δ : 7.85 (d, *J*=7.8 Hz, 2H), 7.72-7.65 (m, 4H), 7.53-7.29 (m, 1H), 2.13 (s, 4H), 1.57 (s, 1H), 1.14 (s, 16H), 0.87-0.73 (m, 12H). Anal. calcd: C 89.76, H 10.24; found C 89.41, H 9.87. The contents of green- and red-light-emitting dopant units in these polymers were too low to be detected using ¹H NMR and elemental analysis.

Device fabrication and characterization

OLEDs were fabricated on pre-patterned indium-tin oxide (ITO) with the sheet resistance of $10-20 \Omega/sq$. The substrate was ultrasonic cleaned with acetone, detergent, deionized water, and 2-propanol. Oxygen plasma treatment was made for 4 min as the final step just before the film coating. Onto the ITO glass was spin-coated a layer of polyethylenedioxythiophenepolystyrene sulfonic acid (PEDOT:PSS) film with thickness of 40 nm from its aqueous dispersion. PEDOT: PSS film was dried at 80 °C for 3 h in the vacuum oven. The solution of FTBT-RxGy polymers in chloroform was prepared under nitrogen atmosphere and spin-coated onto the PEDOT:PSS layer. The typical thickness of the emitting layer was 80 nm. Then a thin layer of TPBI as an electron injection cathode and the subsequent 30 nm thick LiF/aluminum protection layers were thermally deposited by vacuum evaporation through a mask at a base pressure below 2×10^{-4} Pa. The cathode area was defined as the active area of the device. The typical active area of the devices in this study was 0.15 cm^2 . The spin coating process of the EL layer and the device performance tests were carried out within a glovebox under nitrogen atmosphere. The luminance of the device was measured with a calibrated photodiode. External quantum efficiency was verified by the measurement of the integrating sphere, and luminance was calibrated after the encapsulation of devices with UV-curing epoxy and thin cover glasses. The Commission Internationale d'Eclairage (CIE) coordinates have been calculated using 1931 observer parameters.

Results and Discussion

The chemical structures of the polymers are depicted in Scheme 1. FTBT was selected as the core structure due to its efficient red emission and good solubility in common solvents because of the alkyl chains on the thiophene units that facilitate the subsequent synthesis and purification. PF was utilized as the branching arms because of its high energy blue emission, high fluorescence quantum yields in the solid state, and good charge transport properties. BT units were employed as the green dopants with the aim to modulate the balance of RGB emission to achieve saturated white light emission. The synthesis of FTBT is detailed in Supporting Information. Bromination of FTBT with NBS afforded A₄(arm-four)-type monomer FTBT4Br. Star-shaped polymers were synthesized by Suzuki polycondensation with 9,9-dioctylfluorene monomer, BT monomer and a A4(arm-four)-type red dopant monomer FTBT4Br. After polymerization, these polymers were end-capped with phenyl groups. Since the polymer was prepared by polycondensation, the length of the arms in the star-shaped polymers was uniform. In order to obtain the blue, green and red emission balance, the doping concentration of FTBT and BT was adjusted to be (0.05%, 0.08%),

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(0.05%, 0.12%), (0.05%, 0.15%), (0.02%, 0.04%), and (0.04%, 0.04%) to modulate the corresponding intensity of blue, green and red emission. The polymers are denoted as FTBT-RxGy, where x identifies the contents of FTBT as red fluorescents and y means the contents of BT as green fluorescents. All the polymers are readily soluble in common organic solvents, such as toluene, chloroform, terahydrofuran (THF), *etc.*

The thermal properties are investigated by thermo-

Table 1Thermal, electrochemical and photophysical propertiesof FTBT

Sample	$T_{\rm g}/{}^{\circ}\!{ m C}$	$T_{\rm d}/{\rm ^{\circ}C}$	$E_{\rm HOMO}/{\rm eV}$	$E_{\rm LUMO}/{\rm eV}$	E_{g}/eV	λ_{abs}/nm	λ_{em}/nm
FTBT	134	410	-5.55	-2.81	2.74	342/503	632

gravimetric analysis (TGA) and differential scanning calorimetry (DSC). FTBT is thermally stable with 5% weight loss temperature (T_d) at 410 °C. Glass transition

Scheme 1 Schematic illustration, chemical structures and synthetic routes of the polymers



temperature (T_g) was observed at 134 °C. The resulting excellent thermal stability is believed to be able to improve the morphological stability and reduce the possibility of phase separation upon heating.

The absorption spectra of the polymers in THF are shown in Figure 1a. All the polymers exhibit a strong absorption band at 390 nm, which is attributed to the fluorene segments. The absorption of red dopants at about 503/342 nm is negligible because of the low doping concentration. PL spectra of the polymers recorded in dilute THF (Figure 1b) at room temperature are similar to that of PF, originating from the π - π * transition of the PF arms. Meanwhile, PL spectra in films of the polymers consist of not only the blue emission from the



Figure 1 (a) Normalized absorption and (b) PL spectra of FTBT-RxGy recorded in dilute THF at room temperature; (c) normalized PL spectra of FTBT-RxGy in films. PL spectra were obtained upon excitation at the absorption maxima.

PF arms but also the red emission from the cores and green emission from the dopants (Figure 1c). The green emission can be ascribed to the partial FRET from the PF arms to the green BT units as mentioned above.

Cyclic voltammetry (CV) is employed to estimate the lowest unoccupied molecular orbital (LUMO) and highest occupied molecular orbital (HOMO) energy levels of the model compound. As shown in Figure S1c, cyclic voltammogram of FTBT shows two oxidation peaks with the onset potentials at 0.77 and 0.85 V (vs. SCE), respectively. The first peak is attributed to the 9-phenyl-9H-carbazole unit and the second one is ascribed to the benzothiadiazole backbone. According to the first onset oxidation potential and the empirical formula, $E_{\text{HOMO}} = -(E_{\text{ox}} + 4.8)$ [eV], the HOMO energy level of FTBT is estimated to be -5.55 eV. The LUMO energy level is thus calculated to be -2.81 eV. The absorption spectra of FTBT and emission spectra of FTBT, BT, PF and PFB in solid films, are shown in Figure S1d. In terms of the obvious overlap of the emission spectra of PF, BT and the absorption spectra of the core structure FTBT, FRET from the blue emissive fluorene segments to the red emissive FTBT core units and green emissive BT units could be achieved.

To investigate the EL properties of the resulting polymers, single-emissive-layer devices with configuration of indium-tinoxide(ITO)/poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) (40 nm)/polymer (80 nm)/1,3,5-tris(1-phenyl-1H-benzimidazol-2-yl)benzene (TPBI) (30 nm)/LiF (1 nm)/Al (80 nm) were fabricated. The devices were thermally annealed at 120 °C for 10 min in a vacuum box before the LiF/Al cathode was evaporated. The EL spectra are shown in Figure 2a. The corresponding CIE coordinates are summarized in Table 2. All the EL spectra show simultaneous blue, green and red emission bands with peaks at 425/446 nm, 517 nm, and 566 nm, respectively. In order to achieve balance of blue, green and red emission, the doping concentration of FTBT and BT was adjusted carefully. By increasing the content of BT dopant to 0.04 mol% and the content of FTBT core to 0.04 mol%, the EL spectrum of FTBT-R4G4 exhibits simultaneous blue, red and green emission with comparable intensity. The CIE coordinates calculated from the EL spectra of FTBT-R4G4 are (0.31, 0.34), which are very close to the value of standard white emission (0.33,0.33). When the FTBT content further decreases to 0.02 mol%, the EL spectrum of FTBT-R2G4 exhibits negligible red emission from FTBT unit, dominant green emission from BT segments and dominant blue emission from fluorene segments. The CIE coordinates calculated from the EL spectra of FTBT-R2G4 are (0.28, 0.34). When the content of FTBT core unit is fixed as 0.05 mol%, and the content of BT dye unit increases to 0.08 mol%, 0.12 mol%, and 0.15 mol%, the green emission bands of FTBT-R5G8, FTBT-R5G12 and FTBT-R5G15 increase much higher than those of FTBT-R 2G4 and FTBT-R4G4. Meanwhile, the EL spectra of

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FTBT-R5G8, FTBT-R5G12 and FTBT-R5G15 exhibit dominant green emission from the BT unit and relatively low blue emission from fluorene segments. The CIE coordinates calculated from the EL spectra of FTBT-R5G8, FTBT-R5G12 and FTBT-R5G15 are (0.34, 0.40), (0.33, 0.41), and (0.30, 0.40), respectively. With the increment of FTBT and BT contents, the intensity of the red and green emission increases and the intensity of the blue emission decreases in the EL spectra, suggesting that a complete FRET from the fluorene segments to the FTBT unit and the BT dye emerges in this process. Significantly, its EL spectral shape of the device based on FTBT-R4G4 keeps almost unchanged with increasing the bias voltage from 7 to 10 V (Figure 2b).



Figure 2 (a) EL spectra of the devices based on FTBT-RxGy at 7 V. (b) EL spectra of the device based on FTBT-R4G4 under various bias voltages.

On the basis of the results, the EL spectrum of FTBT-R4G4 exhibits a balance of blue (425/446 nm from the fluorene segments), green (517 nm from the green BT segments) and red (566 nm from the red FTBT core) emission. The red and green emission bands of FTBT-R4G4 are much stronger in the EL spectra compared to those in PL spectra, resulting from the charge-trapping effect of the red FTBT unit in the EL process. As shown in Figure 3, the LUMO and HOMO energy levels of FTBT lie between those of PF. In addition to the FRET process from the PF host to red and green dopants, direct charge trapping may also play an important role in enhancing the red emission during the EL process.

 Table 2
 EL performance of FTBT-RxGy WPLEDs

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Polymer	$V_{\rm on}/{\rm V}$	$CE_{max}/(cd \cdot A^{-1})$	$L_{\rm max}/({\rm cd}{\scriptstyle \bullet}{\rm m}^{-2})$	EQE/%	$\operatorname{CIE}\left(x,y\right)$
R5G8	7.5	2.74	2630	1.10	(0.34, 0.40)
R5G12	7.0	2.23	3360	0.84	(0.33, 0.41)
R5G15	6.0	1.56	2700	0.58	(0.30, 0.40)
R2G4	5.0	1.32	1250	0.57	(0.28, 0.34)
R4G4	5.0	1.59	1675	0.70	(0.31, 0.34)
blended	5.0	0.69	1566	0.29	(0.26, 0.25)



Figure 3 LUMO and HOMO energy levels of FTBT and PF.

The EL performances of the devices of FTBT-RxGy are also demonstrated in Table 2. The brightness-voltage characteristics, current efficiency-density characteristics and EOE-voltage characteristics of the WPLEDs are illustrated in Figure 4. The CIE coordinates calculated from the EL spectra of FTBT-R4G4 are (0.31, 0.34), which are very close to the values of standard white emission (0.33, 0.33). When the BT content increases, the blue emission band in the EL spectra becomes very weak in the case of FTBT-R5G8. When it comes to FTBT-R5G15, the blue emission becomes negligible under the same circumstance. By increasing the FTBT content and decreasing the BT content, the blue, green and red emission bands in the EL spectra become balanced in the case of FTBT-R4G4 and a red emission band in the EL spectra becomes negligible in the case of FTBT-R2G4. This phenomenon can be explained by the fact that more complete FRET and charge trapping from the blue emissive fluorene segments to the red emissive FTBT unit and the green emissive BT dye have occurred in the process.

For comparison, we have physically blended 0.04 mol% FTBT into PFB and fabricated a device with the blend as the emissive layer. The EL spectra exhibit bias dependence, and the CIE coordinates of devices based on the blended layer change from (0.26, 0.25) to (0.36, 0.41) with the driving voltage increasing from 5 to 12 V. The corresponding device is realized with a luminous efficiency of 0.69 cd•A⁻¹, a power efficiency of 0.31 lm•W⁻¹, a maximum brightness of 1566 cd•m⁻² and a maximum EQE of 0.29% (Figure S2, Table 2), which are all inferior to those of a star-shaped single-polymer system. These results imply that covalently attaching red and green chromophores into a blue host has played a key role in bias-independent EL spectra of WPLEDs

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based on star-shaped single-polymer systems.



Figure 4 EL characteristics of FTBT with the configuration of ITO/PEDOT:PSS/Polymer/TPBI/LiF/Al. (a) Brightness-voltage characteristics; (b) current efficiency-density characteristics; (c) EOE-voltage characteristics.

Conclusions

In conclusion, white EL from a star-like singlepolymer system with simultaneous three emissive species (blue PF units, red FTBT fluorescent cores and green BT dyes) is achieved. The proper doping concentration of FTBT and BT can ensure the balance of blue, red and green emission, realizing high-quality white EL with simultaneous blue (λ_{max} =430/450 nm), green (λ_{max} =519 nm), and red (λ_{max} =571 nm) emission. As a result, a LE of $1.59 \text{ cd} \cdot \text{A}^{-1}$ and a maximum brightness of 1675 cd $\cdot \text{m}^{-2}$ are achieved for FTBT-R4G4. In addition, the CIE coordinates calculated from the EL spectra of FTBT-R4G4 are (0.31, 0.34), which are very close to the values of standard white emission (0.33, 0.33). Further optimization regarding the materials and the device structures is in progress.

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