Steric Poly(diarylfluorene-co-benzothiadiazole) for Efficient Amplified Spontaneous Emission and Polymer Light-emitting Diodes: Benefit from Preventing Interchain Aggregation and Polaron Formation

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Abstract. The effect of introducing side-chain steric hindrance on the optoelectronic properties of the well-studied green light-emitting polymer (poly(9,9-di-octylfluorene-alt-benzothiadiazole, aka F8BT) were investigated by means of replacing the 9,9-dioctylfluorene unit by two novel steric hindrance functionalized monomers, namely poly (9,9-diarylfluorene-alt-benzothiadiazole) (FDFBT) and poly (9,9-diarylfluorene-4-carbazole-alt-benzothiadiazole) (FCzBT). Bathochromic-shifts of the optical spectra concomitant with enhanced photoluminescence quantum yields (PLQY) and improved film morphologies were found on the novel copolymers compared to F8BT. Fs-transient absorption (TA) spectroscopy demonstrate how steric hindrance effect in the novel copolymers manifests into enhanced stimulated emission (SE) and longer excited state lifetimes, associated with the suppression of polaron formation, all these being favorable features for light amplifying applications. Consequently, random lasing emission was achieved in films based on these copolymers with a threshold of 3 times lower than that of F8BT (22.95 μJ cm\(^{-2}\) for F8BT, 6.36 μJ cm\(^{-2}\) for FDFBT and 8.44 μJ cm\(^{-2}\) for FCzBT). Polymer light-emitting diodes (PLEDs) based on the novel copolymers exhibited performances comparable to the best reported on fluorene-based devices. All of these results manifest the great potential of these novel copolymers for the application in the field of light emitting devices.

1. Introduction

Rational molecular design of conjugated polymers is crucial for tuning molecular self-organization behavior in the solid state and consequently for improving the performance and stability of organic light-emitting diodes (OLEDs), organic solar cells (OSCs), organic field-effect transistors (OFETs), and...
organic lasers (OLs).\textsuperscript{1-5} Interchain $\pi-\pi$ interaction plays a central role in polymer-based optoelectronic because of the dense aromatic packing leading to oriented superstructures that enable efficient exciton and charge transport,\textsuperscript{6-9} however, its effect on light emission is often detrimental due to the formation of non- / weakly- emissive intermolecular excited states such as polaron-pairs or excimers and aggregation-caused quenching (ACQ).\textsuperscript{10} What is more, multiple secondary non-covalent interactions resulting from heavy heteroatom substitution and rigid aromatic polymer backbones can facilitate compact interchain packing, which consequently effect the film morphology, energy band gap, photoluminescence (PL) color purity and light emission efficiency.\textsuperscript{11,12} In this regard, it is desirable to precisely control the interchain aggregation and film morphology of light-emitting conjugated polymers (LCPs) by rational molecular design to obtain robust and stable emission for high performance light-emitting optoelectronic devices.

Control of the interchain electronic and exciton coupling in the molecular design of LCPs is essential to suppress exciton and charge pitfalls as well as reduce optical losses in OLs and OLEDs.\textsuperscript{10,13} In respect of optical gain materials, high stimulated emission (SE) cross section ($\sigma_{\text{SE}}$), long excited state lifetimes and notable waveguiding properties in thin films are benchmark parameters.\textsuperscript{14} Among the examples of green-yellow LCPs, F8BT has been extensively exploited in light-emitting optoelectronic devices because of its relative high and balanced charge mobility. However, common to many classical LCPs, it shows undesired interchain aggregation and morphological instability in condensed state, which have propelled the research for novel LCPs with morphology stable and higher PLQY based on this notable aromatic platform.\textsuperscript{15} Up to now, isolate sulfur-contained backbone chains, such as P3HT, and inhibit interchain interactions via encapsulated or blending strategy are the common rule to suppress the polaron formation, thereby reduce the overlap of the region of photo-

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induced absorption (PA) with SE.\textsuperscript{9,16,17} However, there are numerous significant unresolved issues remaining in those insulated or blended LCPs systems, such as the complicated steric congestion and serious phase separation.\textsuperscript{18,19} The preparation of “encapsulated layer” functionalized F8BT with reduced interchain interactions and polaron formation, which simultaneously possess relatively high charge carrier mobility, emission stability and efficiency, is one of the most fascinating and challenging current research goals. Consequently, unraveling the relationships between molecular structure and materials property is critical to shedding light on the rational design and development for high-performance light-emitting optoelectronic devices. Steric hindrance strategy was an ideal method to avoid polaron formation and achieve amplified spontaneous emission (ASE) with low-threshold.\textsuperscript{20} In this context, we constructed two novel “self-encapsulated” polydiarylfluorene copolymers named as FDFBT and FCzBT, with orthogonally arranged diaryl substituents specifically designed to induce steric hindrance and polymer backbone insulation in the solid state (Figure 1a). The sterically-functionalized FDFBT and FCzBT exhibited a stable emission with the PLQY of 40.6% and 36.0%, respectively, higher than 32.8% of F8BT. Insights into the excited-state dynamics of these copolymers are provided by TA spectroscopy and fluorescent lifetime analysis and confirm an overall slow-down of the exciton dynamics compatible with a reduction in the non-radiative decay rates. These properties of the novel copolymers were favorable for achieving better optical gain properties. Films of FDFBT and FCzBT exhibit random lasing at the low pump thresholds of 6.26 $\mu$J cm$^{-2}$ and 8.44 $\mu$J cm$^{-2}$, about 3 times lower than that of F8BT (22.59 $\mu$J cm$^{-2}$) under the same measured conditions. Finally, PLEDs based on these novel copolymers exhibited better performance than F8BT, confirming the effectiveness of our strategy and a wide prospective for optoelectronics applications in the future.
2. Preparation and structural characterization of steric F8BT.

Novel diarylfluorene monomers with aryl substituents at 9-position and pendant solubilizing alkoxy chains at 4-position are synthesized according to procedures reported elsewhere.\textsuperscript{21,22} All copolymers were prepared via Suzuki polymerization (Scheme S1) following a procedure which is described in the supporting information. The chemical structure of three copolymers were determined by \textsuperscript{1}H-NMR measurements (Figure S1). Gel permeation chromatography (GPC) measurements revealed the number-average molecular weight ($M_n$) and polydispersity index (PDI) of these copolymers, as shown in Figure S2 and Table 1. Thermogravimetric (TG) analysis demonstrated the decomposition temperatures ($T_d$) of the three copolymers were above 420 °C (Figure S3a). The glass transition temperature ($T_g$) of copolymers provided by the differential scanning calorimetry (DSC) analysis were 203 °C in FDFBT and 192 °C in FCzBT, well above the 99 °C of F8BT, thus indicating the higher thermal stability and lower crystallization tendency in the novel copolymers (Figure S3b). With a view of conducting a comparative evaluation of the thermal stability of thin films, tapping mode atomic force microscopy (AFM) was carried out to investigate the film nanostructure of these copolymers before and after annealing at 220 °C for 20 min (Figure S4). The measured roughness-mean-square (RMS) of as-cast films was 0.3 nm in FDFBT and FCzBT, and 0.8 nm in F8BT. After thermal annealing at 220 °C for 20 min, it is obvious that the F8BT morphology becomes rough and the RMS increases up to 1.7 nm, comparably larger than the 0.3 nm found in annealed films of FDFBT and FCzBT. Therefore, these topography images of FDFBT and FCzBT revealed a smoother and more stable surface morphology than F8BT in general.

3. Optical property and morphology analysis of three polymers in various states.
To disentangle the effects of the steric hindrance effect on the photophysical properties, here we combined the analysis of UV-vis absorption, PL spectra and Raman spectra. The absorption and PL spectra of the copolymers in dilute chlorobenzene (CB) solution and spin-coated films are illustrated in Figure 1b, whereas the peak values are summarized in Table 1. FDFBT and FCzBT exhibited broad absorption bands centered at 460 nm and 458 nm in solution and at 475 nm and 470 nm in film respectively, showed a 4 nm red shift either in solution or films compared to the absorption spectra of F8BT. In turn to the PL spectra of copolymers in solution and films, the novel copolymers showed a red shift of ca. 15 nm in solution and ca. 22 nm in films respect to that of F8BT. The origin of this discrepancy was ascribed to the chain conformation changes which stem from the steric hindrance effect in diarylfluorene units. The electron-donating effect of alkoxy substitution at 4-postion also induced the red-shifted emission spectrum. Besides, the emission of all the three copolymers either in solution or films were dominated by the singlet transition ($S_0$-$S_1$). The optical bandgaps ($E_{opt}^{\text{on}}$) evaluated from the onset of the absorption are 2.30 eV for FDFBT and 2.29 eV for FCzBT, slightly lower than 2.34 eV of F8BT. Combining the results analyzed from the cyclic voltammetry (CV) and ionization energy measurements, we observed the highest occupied molecular orbital (HOMO) level is lifted up upon incorporation of the diarylfluorene unit, thus leading to a narrow bandgap and red-shift of optical spectra (Figure S5). What’s more, A superior feature of FDFBT and FCzBT is that they showed unaffected PL spectra similar to F8BT after thermal annealing at 220°C for 20 min in air, an indication of superior photophysical stability (Figure S6). In order to investigate the changes of vibrational modes that coupled to the conjugated backbone associated to the change of monomer, we made the comparison of Raman spectra in films, as depicted in Figure S7. Raman spectra of F8BT film is consistent with that reported elsewhere and the novel copolymers exhibit similar Raman
spectra characteristic. All of these spectra manifest two pronounced peaks at 1545 cm\(^{-1}\) corresponds to the BT ring stretching mode and at 1610 cm\(^{-1}\) corresponds to fluorene ring stretching mode. It is evident that there is no difference about the BT ring stretching mode, and the peaks of the novel fluorene ring stretching mode shifted to 1606 cm\(^{-1}\). We attribute this shift mainly to the steric hindrance effect stems from the diarylfluorene substituents, since the electron-donor effect afforded by the aryl substituents and ether bond can lead to lower energy of molecular vibrations. Besides this reason, according to the red shift of optical spectra in the FDFBT and FCzBT films, we believe the enhancement of effective conjugation length resulted from the decrease of dihedral angle between novel diarylfluorene and BT units also accounts for the Raman shift. Furthermore, the PLQY in solutions showed negligible difference, and in films showed slight enhancement in the novel copolymers respect to that of F8BT (Figure 1c), increased from 32.8% in F8BT to 40.6% in FDFBT and 36% in FCzBT. We ascribed this to the diminution of aggregation-induced quenching thanks to the steric hindrance encapsulation. To gain further insights into the luminescent properties at local scale, 2D time-resolved fluorescence images (10 µm × 10 µm) of spin-coated films are shown in Figure 1d, while the corresponding detailed distribution histogram of average lifetimes and decay curves in the selected spots are shown in Figure S8. The PL lifetimes obtained from the selected spots are 1.19 ns for FDFBT and 1.16 ns for FCzBT, an almost two-fold increase respect to 0.69 ns found in F8BT. This result is consistent with the measurements by time-correlated single photon counting (TCSPC), as shown in Figure S8. Based on these values and the corresponding PLQYs, we calculated the radiative and non-radiative decay rates of these copolymers, (see Table S1). We observed the radiative decay rates (k\(_r\)) of these copolymers show negligible difference either in solution or in films. Noteworthily, the non-radiative decay rate (K\(_{nr}\)) of FCzBT in solution is 8 \times 10^7 s\(^{-1}\), which is the highest in three
copolymers. In contrast, the $K_{nr}$ for F8BT in film amounts to $7.3 \times 10^8$ s$^{-1}$, which is significantly higher than that of FDFBT ($4.7 \times 10^8$ s$^{-1}$) and FCzBT ($5.6 \times 10^8$ s$^{-1}$), highlights how the steric substituents have an impact on the exciton de-activation pathways in film. We infer that the carbazole group at the end of alkoxy chains influenced the solubility in solution, however, the substituents of aryl and alkoxy chains can enlarge the chain spaces and reduce the chain interactions after spin-coated to films. In order to elucidate differences in polymer chain packing in films, we performed grazing-incidence wide-angle X-ray diffraction (GIWAX) using a synchrotron X-ray beam with a 2D detector (Figure S9). The out-of-plane diffraction patterns of the films show a peak at $q$ vector around 1.5 Å$^{-1}$, commonly observed in amorphous conjugated polymers. The $\pi-\pi$ stacking distances calculated from the $q$ values at the peaks are 3.82 Å in FDFBT and FCzBT, and 3.76 Å in F8BT. We further calculated the interchain distances of copolymer films from the spectra of X-ray diffraction (XRD) (Figure S9c). The lamellar packing distances are 20.3 Å for F8BT, 20.6 Å for FDFBT and 21.1 Å for FCzBT. In light of these results, we conclude that the aryl substituents at the fluorene 9-position are favorable for separating polymer chains through enlarge the distances of interchain and $\pi-\pi$ stacking by the steric hindrance effect. Moreover, FDFBT and FCzBT exhibit a weaker intensity than F8BT at $q$ vector position of around 1.5 Å$^{-1}$ and at 2$\theta$ value of 4.5°, indicating that the novel copolymers films show slightly higher amorphous degree state than F8BT, in line with the prospection from the higher $T_g$ values observed in the DSC thermograms (Figure S3b). These results suggest that the novel copolymers will be one kind of superior LCPs for their application as active layers into light-emitting optoelectronic devices.

4. Exciton and polaron behavior of three polymers in film states.
In order to elucidate the effect of steric hindrance on the ultrafast exciton dynamic of novel copolymers, we performed femtosecond transient absorption (fs-TA) experiments in F8BT, FDFBT and FCzBT films. Figure 2 shows the TA contour plot together with the \( \Delta T/T \) spectra at 0.2, 2, 20 and 202 ps delay time. The contour plots depict the dominance of positive \( \Delta T/T \) band in the 300-350 nm and 400-650 nm range (Figure 2a). \( \Delta T/T \) spectra at different delays confirm (starting from F8BT) two spectrally separated photobleach (PB) bands with maxima at 334 and 450 nm (in correspondence with the absorption peaks at 321 and 454 nm), followed by a stimulated emission (SE) (featuring as a shoulder of the long wavelength PB band) with a maximum around 565 nm (Figure 2b). The longer wavelength part of the \( \Delta T/T \) spectrum is characterized by photoinduced absorption (PA). At the longest time delay (202 ps) the SE band vanishes and the residual PB confirms the presence of long-lived polarons with PA above 600 nm in line with previous findings. The \( \Delta T/T \) spectra of FDFBT is similar to F8BT: two PB bands at 339 and 462 nm and a SE bands at 535 nm and tail down to 600 nm dominates the 0.2 ps delay spectrum with the PA proceeds beyond 650 nm. They both show a slight red-shift compared to F8BT in line with similar shifts observed in the absorption and PL spectra, which can be ascribed to the isolated chains because of strong steric hindrance effect. The \( \Delta T/T \) spectra of FCzBT resembles the corresponding one of FDFBT, showing two PB bands (at 341 and 464 nm), two structureless SE bands (at 537 and 612 nm) and a PA band at 650 nm. Spectral relaxation is more important in FDFBT and FCzBT than in F8BT as confirmed by the red-shift of the \( \Delta T/T \) zero crossing point (18 nm in the novel copolymers compared to 5 nm in F8BT).

A comparison of the normalized SE dynamics in the three films pumped with different pump fluences confirms a slower SE decay in FDFBT and FCzBT respect to F8BT, as shown in Figure 3. Remarkably, there are no significant changes in the SE decay dynamics of FDFBT and FCzBT with
increasing the pump energy up to 80 and 160 nJ, which in stark contrast with the acceleration of the
decay kinetics of F8BT. The appearance of ps and sub-ps decay components on the TA dynamics of
conjugated polymer films pumped with high fluences is a common feature which has been generally
ascribed to exciton-exciton annihilation.\textsuperscript{25,26} In particular, the effects of exciton-exciton annihilation
on the TA dynamics of F8BT were previously investigated by Stevens et al.\textsuperscript{27} Based on a detailed
analysis of decay rates measured at different pump fluences they concluded that this process is
driven by Förster resonance energy transfer between different energy sites in the density of states,
in stark contrast with diffusion-limited annihilation ascribed to its blue-emitting relative poly(9,9-
dicocytfluorene). They explained this distinctive behaviour as due to the large spectral overlap
between F8BT stimulated emission and singlet excited-state absorption yielding a Förster radius of 4
nm.\textsuperscript{27} In light of the pump-independent SE kinetics of FDFBT and FCzBT it follows that exciton-
exciton annihilation is to certain extent hindered in these copolymers, which points towards a
scenario where excitons are less mobile. This scenario has a positive impact on the light emitting
properties bearing in mind that many dynamic quenching processes are fueled by exciton diffusion
(annihilation processes, singlet oxygen quenching, exciton dissociation).\textsuperscript{28} Indeed, the lower PLQY
found in F8BT is associated to a larger non-radiative PL decay rate which exceeds by 1.6 and 1.3 that
of FDFBT and FCzBT.

Next, we further explore the stimulated emission properties of the copolymers according to
\[ \sigma_{SE} = \left( \frac{\Delta T}{T} \right) \times (N_e d)^{-1} \]
and taking into account the maximum $\Delta T/T$ value, the film thickness ($d$) and the initial exciton density ($N_e$) estimated from the pump fluence and the absorbance of each film
at the pump wavelength. The SE cross sections ($\sigma_{SE}$) at the 0-1 SE peak were calculated to be
2.47×10\textsuperscript{-16} cm\textsuperscript{2} for F8BT, 6.15×10\textsuperscript{-17} cm\textsuperscript{2} for FDFBT and 1.12×10\textsuperscript{-16} cm\textsuperscript{2} for FCzBT. The values are
comparable to that have reported elsewhere for F8BT. Taken together with these results, we infered that the improvement comes mainly from reduced exciton mobility which hinders losses by for instance annihilation, which may also explain the larger PLQY in films.

5. Organic laser and PLEDs based on three polymers.

These findings above encourage us to further investigate the optical gain properties of the novel steric copolymers. As the polymer refractive index is larger than that of the substrate and air, this configuration form waveguides between air and the quartz substrate. Above a certain pump fluence we observe linewidth narrowing ascribed to ASE. Interestingly, superposed with ASE appear a sequence of narrow, coherent spectral lines which we ascribe to random lasing (RL). The spectral narrow lines and their dependence on the excitation density were shown in Figure 4. RL in conjugated polymer films has bee previosly reported and explained as the result of multiple scattering at aggregates in the film, leading to random cavities in the gain medium. Based on the PL spectra measured at 77K (Figure S10), we confirm that all the random lasing peaks of these samples are spectrally locate within the 0-1 PL spectral range, in agreement with a 4-level laser system. The linewidth of discrete emission peaks are about 1 nm. We determined the excitation thresholds for ASE ($E_{th}$) by slowly increasing the pump density and monitoring the full width at half maximum (FWHM) and output intensities (Figure 4, bottom). The $E_{th}$ of FDFBT and FCzBT were 6.26 $\mu l/cm^2$ and 8.44 $\mu l/cm^2$ respectively, about 3 times lower than that of F8BT (22.95 $\mu l/cm^2$). These results confirm that other than having improved PL properties, FDFBT and FCzBT are outperforming materials for lasers respect to F8BT.

Inspired by the high PLQY of the novel copolymers, we fabricated light-emitting diodes with ITO/PEDOT:PSS (40 nm)/PVK (40 nm)/EML (30~40 nm)/TPBi (20 nm)/LiF (0.8 nm)/Al (100nm)

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configuration where F8BT, FDFBT and FCzBT served as emitting layer. As shown in the energy levels diagram (Figure 5a), the HOMO levels of novel copolymers better matched the corresponding of hole transport layer served by PVK, leading to an efficient hole injection, and thus the novel copolymers endowed the devices with a reduced turn on voltage of 3.9 V, 0.3 V lower than that of F8BT (Figure 5b). The maximum luminance of FDFBT and FCzBT based devices reached 13000 cd/m$^2$ and 10000 cd/m$^2$, respectively, well above the 7500 cd/m$^2$ found in F8BT-based devices. We ascribed this enhancement to the high PLQY of the novel copolymers. The EL spectra of the devices under 300 mA/cm$^2$ show peaks at 542 nm for F8BT, 565 nm for FDFBT and 573 nm for FCzBT (Figure 5c), and the Commission International de L’Eclairage (CIE) coordinates respectively are (0.42, 0.57) for F8BT, (0.47, 0.51) for FDFBT, (0.49, 0.50) for FCzBT, which are consistent with their corresponding PL spectra. It is worthy to comment on the highest efficiencies found in these devices (Figure 5d). Devices based on F8BT showed a maximum current efficiency of 3.2 cd/A and EQE of 0.94%, which were higher than that obtained in FDFBT and FCzBT, whose maximum current efficiency respectively were 2.3 cd/A, 1.96 cd/A and EQE were 0.75%, 0.67%. We noted the maximum values of current efficiency and EQE based on the novel copolymers were lower than that based on F8BT, but were comparable to that have reported devices based on F8BT or the derivatives.$^{24,32,33}$ Furthermore, when we compared the property of PLEDs at high current density, it is obvious that the performances based on the novel copolymers were better than that based on F8BT. That’s to say, the novel copolymers are more resistant to higher voltage and current density than F8BT, which is also critical to the practical application of PLEDs. Therefore, these steric hindrances functionalized copolymers showed potential application in light-emitting devices.

6. Conclusion

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In summary, we have demonstrated and applied a novel LCPs design principle to the synthesis of novel polydiarylfluorenes-alt-benzothiadiazole with enhanced PLQY and improved film morphologies. The aryl and alkoxy substituents at the fluorene monomer can sufficiently enlarge the chain separation and inhibit the exciton-exciton annihilation resulted from interchain aggregation. Bathochromic-shifts of the optical spectra resulted from the electron-donor effect of the substituents and conformation changes were found on the novel copolymers compared to F8BT. Consequently, we achieved lower threshold random lasing in spin-coated films of these novel copolymers respect to F8BT. Moreover, EL performance of the novel copolymers based devices are comparable to the state-of-the-art devices based on the fluorene copolymers or the derivatives. The primary purpose of this work is to provide a general principle for the molecular design of LCPs, which is applicable to other optoelectronic materials, that may extend the realm of application in high performance flexible electronics.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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References


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Figure 1. Design principle of our model steric polyfluorene, together with the corresponding optical properties. (a) Schematic representation of the encapsulated copolymer chain with steric hindrance effect afforded by the aryl substituents, and the molecular structures investigated in this work. (b) UV-vis absorption and PL spectra of copolymers in dilute CB solution ($10^{-5}$ M) and in spin-coated film. (c) Photoluminescence quantum yields (PLQY) in spin-coated films and the photographs of these films (from top to down: F8BT, FDFBT and FCzBT). (d) 2D time-resolved fluorescence images ($10 \mu m \times 10 \mu m$) of F8BT, FDFBT and FCzBT measured in spin-coated films.
Figure 2. (a) TA contour plots of (from top to bottom) F8BT, FDFBT and FCzBT showing differential transmission ($\Delta T/T$) as a function of wavelength and pump-probe delay. (b) Corresponding $\Delta T/T$ spectra of (from top to bottom) F8BT, FDFBT and FCzBT (vertical cuts in (a)) at different pump-probe delays. The pump wavelength and pump fluence were 387 nm and $6.8 \times 10^{-2}$ mJ cm$^2$ respectively.
Figure 3. Normalized $\Delta T/T$ kinetics of F8BT at 569 nm, FDFBT at 590 nm and FCzBT at 594 nm at three pump fluences: 40 nJ, 80 nJ and 160 nJ. The pump wavelength was 387 nm. The probe wavelengths correspond to the amplified spontaneous emission (ASE) peaks of each film depicted in Figure 4.

Figure 4. Random-lasing emission from spin-coated films of (a) F8BT, (b) FDFBT and (c) FCzBT, obtained by pumping at 387.5 nm with increasing pump energy. Bottom are the full-width at half-
maximum (FWHM) and random-laser output intensity versus input pump energy density for (d) F8BT, (e) FDFBT and (f) FCzBT, respectively.

Figure 5. (a) Energy levels of the different layers in polymer light-emitting diodes investigated in this work. (b) Current density-luminance-voltage characteristics of the devices. (c) Comparison of EL spectra of the devices at 300 mA/cm$^2$ based on the three copolymers. (d) Current efficiency and external quantum efficiencies (EQE) versus current density curves of the devices.
Table 1. The thermal, photophysical and electrochemical properties of polymers

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</table>

\(^a\) Measured in CB solution. \(^b\) Measured in spin-coated films. \(^c\) Calculated from the absorption onset in film. \(^d\) Measured with ionization energy measurement system. \(^e\) Calculated by LUMO = HOMO + \( E_g \).
Lubing Bai, Chen Sun, Yamin Han, Xiang An, Chuanxin Wei, Lili Sun, Ning Sun, Mengna Yu, Kangning Zhang, Jinyi Lin*, Man Xu, Linghai Xie, Haifeng Ling, Juan Cabanillas-Gonzalez*, Xiaotao Hao and Wei Huang*

Steric Poly(diarylfluorene-co-benzothiadiazole) for efficient Amplified Spontaneous Emission and Polymer Light-emitting Diodes: Benefit from Preventing Interchain Aggregation and Polaron Formation

ToC figure (Please choose one size: 55 mm broad × 50 mm high or 110 mm broad × 20 mm high. Please do not use any other dimensions)
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