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Review

Recent progress in the development of polymers for white light-emitting polymer devices

Inam ul Haq Raja[1], Jae Yeol Lee[2], In Tae Kim[3], So Ha Lee[1,4]

[1] Department of Biomolecular Science, University of Science and Technology, Daejon, Korea
[2] Research Institute for Basic Sciences and Department of Chemistry, College of Science, Kyung Hee University, Seoul, Korea
[3] Department of Chemistry, Kwangwoon University, Seoul, Korea
[4] Life Sciences Research Division, Korea Institute of Science and Technology, Cheongryang, Seoul, Korea

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Abstract Much effort has been devoted to the design and synthesis of polymers for use in flat panel display, solid state lighting, transistors, and photovoltaic devices. Especially, development of white light emitting polymeric materials has recently attracted much interest owing to their possible use in lighting application and backlights for flat panel displays. White emission has been obtained from polymeric molecules, small organic molecules, organometallic molecules, and phosphor-based or quantum dot-based inorganic molecules. Among materials used in white light emitting diodes, we summarize the white light emitting polymeric materials synthesized and published till December 2007.

Keywords Polymerization; Polycondensation; Organometallic compounds; White polymeric light emitting devices; Photoluminescence.

Introduction

White polymer light-emitting diodes (WPLEDs)* have gained increasing research interest and are considered as a new generation of light sources for backlighting of liquid crystal displays and lighting sources [1]. For WOLEDs*, efficiencies have significantly been improved in red, green, and blue emission by utilizing phosphorescent dyes [2–4], and phosphorescent WOLEDs were fabricated by several groups [5, 6] with high efficiencies of 11 lm/W at 1000 cd/m^2.

Among many applications of white light emitting diodes, lighting sources are very important because of energy problem all over the world. A tremendous amount of electricity is consumed every year all over the world. In terms of total primary energy consumption, lighting accounts for about 20% of all the electricity produced. Fluorescent tubes and incandescent lamps are the frequently used traditional light sources and account for about 40% of total electrical energy consumed. Incandescent bulbs turn

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Correspondence: In Tae Kim, Department of Chemistry, Kwangwoon University, 447-1 Wolgye-Dong, Nowon-Ku, Seoul 139-701, Korea, So Ha Lee, Life Sciences Research Division, Korea Institute of Science and Technology, P.O. Box 131, Cheongryang, Seoul 130-650, Korea. E-mail: itkim@kwangwoon.ac.kr

* These terms are used throughout the references in this field although their grammatical construction is incorrect. The devices should be termed correctly "white light-emitting polymer diodes" and "white light-emitting organic diodes", or otherwise "polymer(ic) white light-emitting diodes" and "organic white light-emitting diodes"! With respect to their common use and to avoid discrepancies with literature we retain the terms WPLED and WOLED in this review, however.

about 90% of the energy into heat; while fluorescent light does better by converting 70% of the energy they use into light. Incandescent lamps and fluorescent tubes have typical luminous efficiencies of 1320 lm/W and 90 lm/W. So, to save the world energy, low energy consuming alternate to light bulbs should be found. Compared to conventional incandescent light sources, the white light-emitting (white LED) is superior in lifetime, robustness, and efficiency. Operation cycles of 100,000 hours and an efficiency of 80–90% are today's industry standard. After red, green, and yellow LEDs have begun replacing traffic lights at intersections, white LEDs are next to substitute for light sources in other areas where low maintenance requirements are desired. How fast they will find their way to our homes and general lighting depends however on our acceptance of the yet quite unusual light of the white LED.

White emission was obtained from small organic molecules, organometallic molecule, phosphor-based or quantum dot-based inorganic molecule, and polymeric molecule. They have merit and demerit in CIE (Commission Internationale de I'Eclairage) [7], CRI (color rendering index) [8], stability, reproducibility, fabrication process, and device cost according to materials used.

Among materials used in white light-emitting diodes we tried to summarize the white light emitting polymeric materials synthesized and published till December 2007.

Polymers as white light-emitting materials

There are two major ways to achieve white light emission from polymeric materials in white polymer light-emitting diodes (WPLEDs). One of them is a polymer-blend systems, such as three-polymer blends containing red, green, and blue light-emitting polymers; two-polymer blends containing blue and orange light-emitting polymers; blends consisting of two polymers and an organometallic complex as the phosphorescent emitter, and blends consisting of two or three kinds of fluorescent dyes in an efficient blue light-emitting polymer or polymer matrix. However, WPLEDs made by polymer-blend systems usually suffer from low efficiency and color instability. A second approach is to get white emission from single polymeric materials or single component polymers. Although this approach is difficult, it gives superior results.

Single component polymer materials for white light emission

Using single component white light-emitting materials in WPLED can overcome many problems which are encountered in polymer blend systems or polymer-dopant systems. Single component polymers emitting white light are not frequently reported in literature.

Chow et al. reported the unprecedented single component white light-emitting polymeric material prepared in one step from an anthracene-fused norbornadiene derivatives through a ring-opening metathesis polymerization (ROMP) process [9]. The structure of the white light-emitting 1,3-divinyl-2,3-dihydro-1*H*-cyclopenta[*b*]anthracene polymer is shown in Fig. 1.

When the solution of this polymer was spin-coated and dried to form a thin film, the major emission band was blue-shifted about 10 nm. In addition to this band, a minor broad emission appears at $\lambda_{\max} = 550$ nm and tails to 700 nm. Electroluminescence from a single film of polymer sandwiched between two electrodes displayed white light, as a result of overlapping the short wavelength emission of anthracene with other long wavelength emissions. The latter emissions have been derived from aggregates in solid films. The device was fabricated using both polymer *a* and *b*. It was encouraging to observe that the emission spectrum of these single layer devices did not change much with respect to voltage. The CIE coordinates at different voltages stayed within a small region. However, since the long wavelength emissions are derived from aggregation, their relative intensity depended on film morphology. When the solvent used for spin-coating was changed from toluene to dichloromethane, the long wavelength emissions became even brighter than the original short wavelength anthracene emission. The CIE

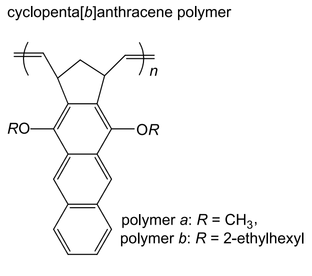
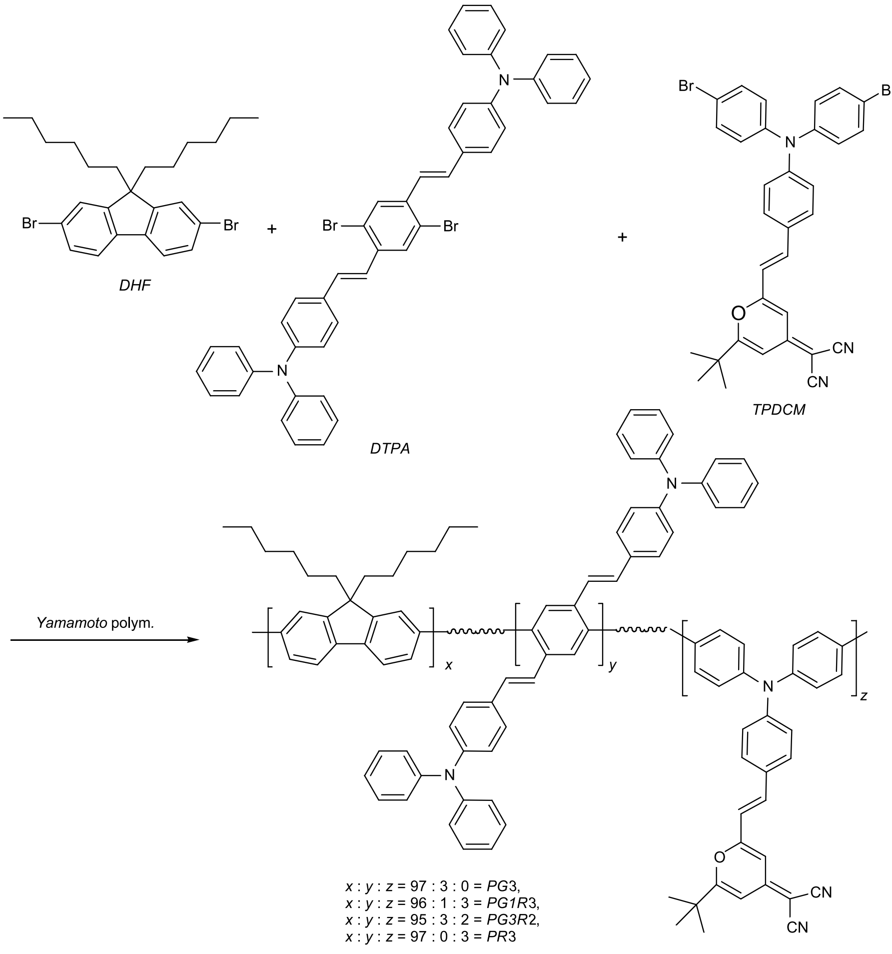


Fig. 1 4,11-Dialkoxy-1,3-divinyl-2,3-dihydro-1*H*-cyclopenta[*b*]anthracene polymer



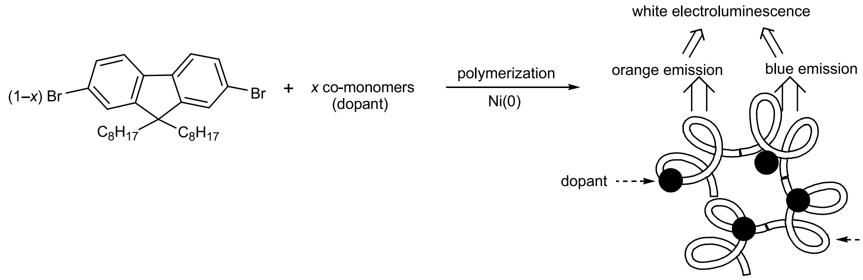
Scheme 1

coordinate for the latter device moved slightly bluish to (0.33, 0.37), yet still in the region of white light.

Also *Shim et al.* reported a series of single component white light-emitting copolymers for WPLED consisting of a polymer chain with a red-emitting unit, 2-{2-(2-[4-{bis(4-bromophenyl)amino}phenyl]vinyl)-6-*tert*-butylpyran-4-ylidene}malonitrile (*TPDCM*), a green-emitting unit, {4-(2-[2,5-dibromo-4-{2-(4-phenylaminophenyl)vinyl}phenyl]-vinyl)phenyl} diphenylamine (*DTPA*), and a blue-emitting unit, 2,7-dibromo-9,9-dihexylfluorene (*DHF*) [10]. The synthesis scheme of this copolymer is shown in Scheme 1.

It was found that emission spectra of the resulting copolymer could easily be tuned by varying the *DPTA* and *TPCDM* content. Thus, with appropriate red, green, and blue-emitting units ratio, white light emission was obtained from these copolymers. The *WPLED* fabricated by using these copolymers was found to exhibit a maximum brightness of 820 cd/m^2 at 11 V with CIE coordinates (0.33, 0.35), which are close to the standard CIE coordinate for white light emission (0.33, 0.33). The device exhibited the white-light emission that remained almost constant on varying the driving voltage.

Wang et al. reported light-emitting diodes exhibiting efficient pure white light electroluminescence by using a single polymer, polyfluorene derivatives with 1,8-naphthalimide chromophores chemically doped onto the polyfluorene backbones [11]. It is well known that a combination of blue-light and orange-light emission will generate white-light emission. Therefore, polyfluorene (*PF*) was chosen as the blue-light emitting polymer, and 1,8-naphthalimide derivatives were chosen as the orange-light-emitting components, owing to their high photoluminescence (PL) quantum yields, tunable emission colors, and their ability to be attached to the polymer main and side chains [12–15] as summarized in Scheme 2 and Fig. 2.



Scheme 2

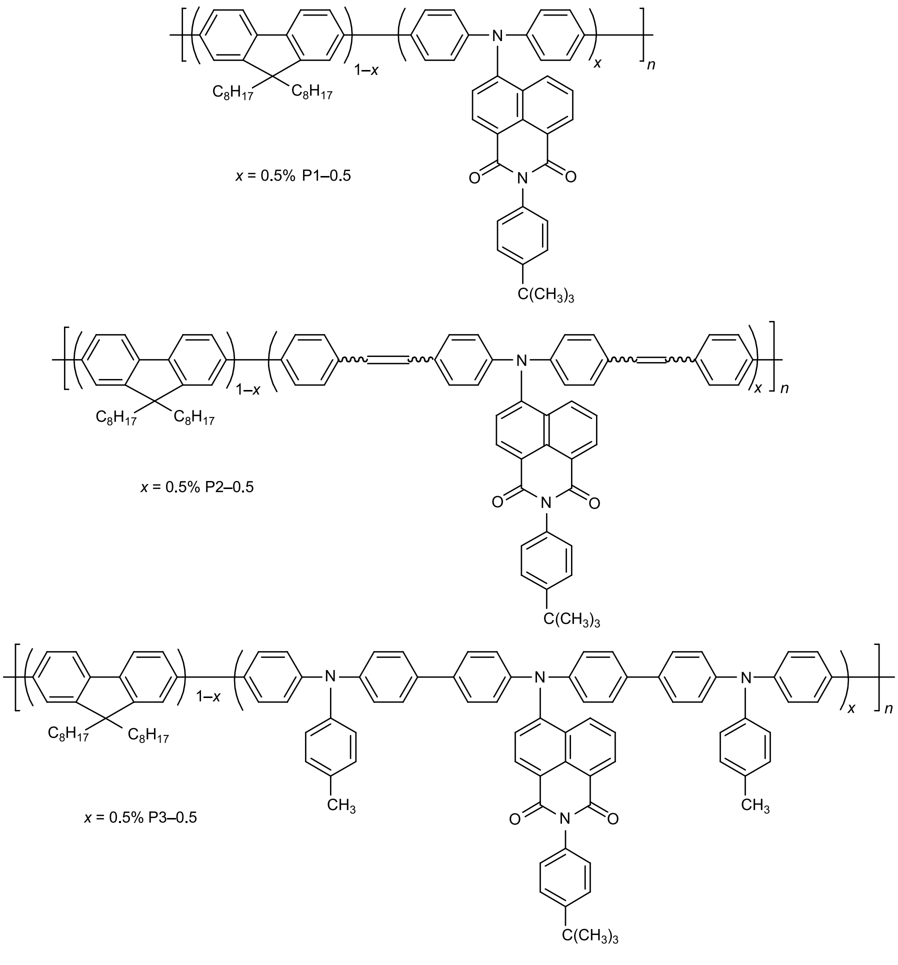
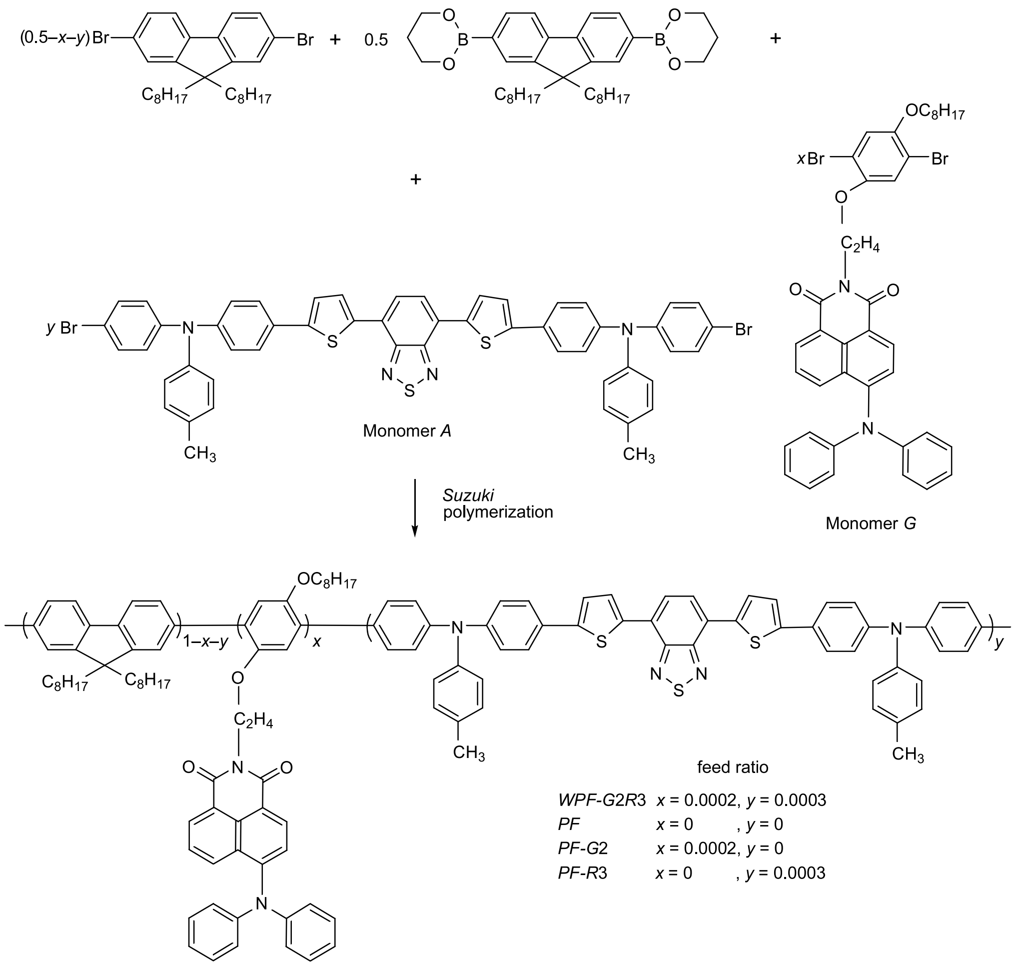


Fig. 2 Structures of white light emitting polyflourene polymers (*PF*s)

A highly efficient pure white-light emission was obtained from a single polymer, by using PF as a blue light-emitting component and a small amount of 1,8-naphthalimide derivative with different emission wavelengths as an orange light-emitting component. By adjusting the emission wavelength of the orange/red light-emitting component and optimizing the relative content of the 1,8-naphthalimide derivatives in the resulting polymers, highly efficient and nearly pure white light electroluminescence with CIE coordinates of (0.32, 0.36), a current efficiency of 3.8 cd/A, a power efficiency of 2.0 lm/W, and an external quantum efficiency of 1.50% was achieved. The CIE coordinates were almost insensitive to the driving voltage for the un-encapsulated devices under ambient conditions. The efficiencies of WPLEDs, so far, have been improved up to 16 lm/W, approaching practical application. On the other hand, colour control of WPLEDs is an important issue. Because WPLEDs normally possess one active layer, the electroluminescence (EL) process of the WPLEDs with blend or doping emitters follows the mechanism of both energy transfer between different emitters and traps by guests, resulting in complicated optimization in the concentration of guests.

Xu et al. reported white light emission from single doped WPLEDs with only a trap mechanism without an energy transfer process [16]. The device comprised emitters of poly(9,9-dioctylfluorenyl-2,7-diyl) end-capped with dimethylphenyl (*PFO*) emitting blue light, and the phosphorescent dye of iridium(III) bis(2,4-diflurophenyl-2-pyridine-4-phenyl-*p*-carbarzole)(2-(4*H*-1,2,4-triazol-3-yl)pyridine)-[*Ir*(*CzBPPF*)$_2$(*PZ*)] with yellow light. The emission colour of the device is easily controlled to get pure white light. The efficient device exhibits high EL efficiency of 5.6 cd/A and luminance of 7565 cd/m^2 at driving voltages of 9.5 V and 14 V.

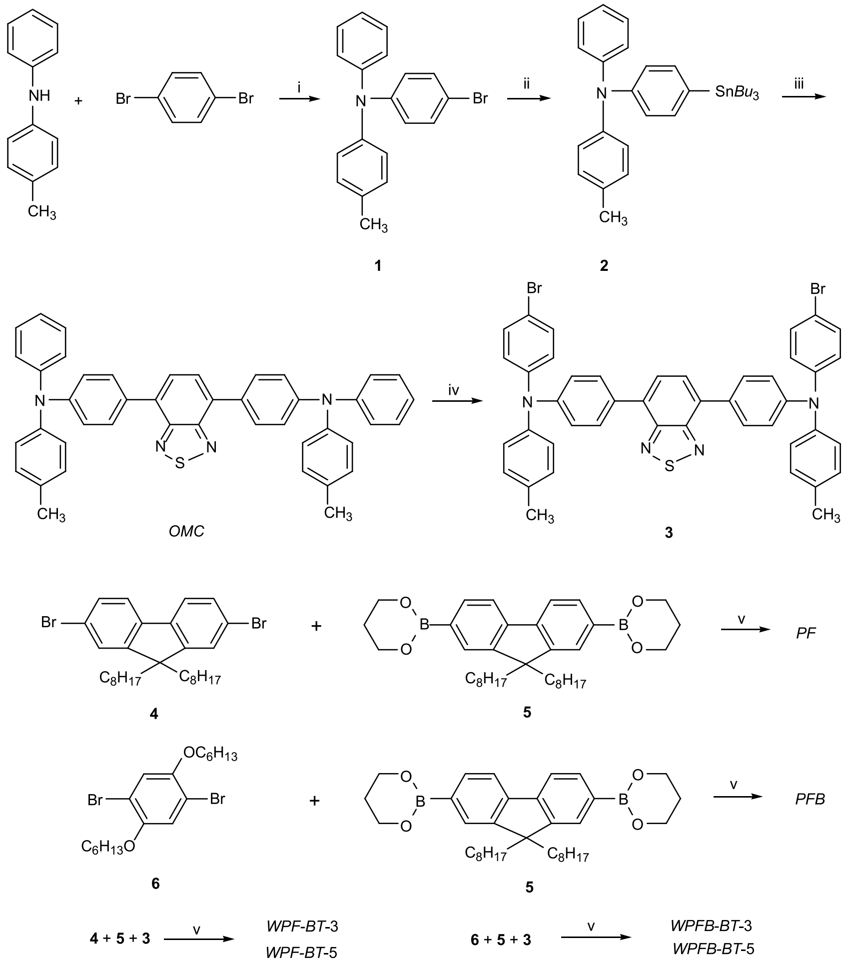
As it was mentioned before, white EL from a single polymer is extremely desirable because it has a great advantage over blend systems in terms of no phase separation [9, 17–22]. This approach has been demonstrated in several white light-emitting polymers, such as an anthracene-containing polymer [9], an oxadiazole-containing poly (phenylenevinylene) (*PPV*) with a non-conjugated spacer [17], polyaniline [18], and platinum-functionalized random copolymers [22]. In these polymers, the blue emission from the polymer itself and the orange emission from aggregation/excimer/electroplex/electromer makes the emission color white. However, white EL of this kind suffers from low efficiency and bias dependent EL spectra.



Scheme 3

A novel strategy was reported to realize white EL with simultaneous blue, green, and red emission from a single polymer [23]. This is achieved by attaching a small amount of a green-emissive component to the pendant chain and incorporating a small amount of a red-emissive component into the main chain of the macromolecule, which itself has a blue emission. The resulting single polymer can be considered as a system with two individual chromophores (green dopant and red dopant) molecularly dispersed in a blue-emissive polymeric host [14]. That is, one macromolecule includes three emissive species. Thus, individual emission from three emissive species for generating white emission with simultaneous emission from three primary colors was realized. All the polymers were synthesized by *Suzuki* polymerization and were thoroughly purified. The chemical structures of monomers and polymer synthesized is shown in Scheme 3.

Using single-layer devices of the polymers emitted white light with simultaneous blue ($\lambda_{\max} = 421\,\text{nm}/445\,\text{nm}$) and orange emission ($\lambda_{\max} = 564\,\text{nm}$). Moreover, the EL spectra exhibited no bias dependence. It was also demonstrated that the EL efficiency of a white electroluminescent polymer can be improved by enhancing the PL quantum efficiency of either the blue host or the orange dopant unit. For a thermally annealed single-layer device utilizing the polymers, a turn-on voltage of 3.5 V, luminance efficiency of 8.99 cd/A, and power efficiency of 5.75 lm/W, with CIE coordinates of (0.34, 0.35), were achieved. This performance is roughly



i) CuI, 18-crown-6, 1,3-dimethyl-3,4,5,6-tetrahydro-2(1*H*)-pyrimidinone (*DMPU*),
K_2CO_3, ii) a) *n-Bu*Li, *THF*, b) Bu_3SnCl, iii) $Pd(PPh_3)_4$, toluene,
4,7-dibromo-2,1,3-benzothiadiazole, iv) Bu_4NBr_3, CH_2Cl_2, v) $Pd(PPh_3)_4$, K_2CO_3
(aq, 2 *M*), toluene, Aliquat 336.

Scheme 4

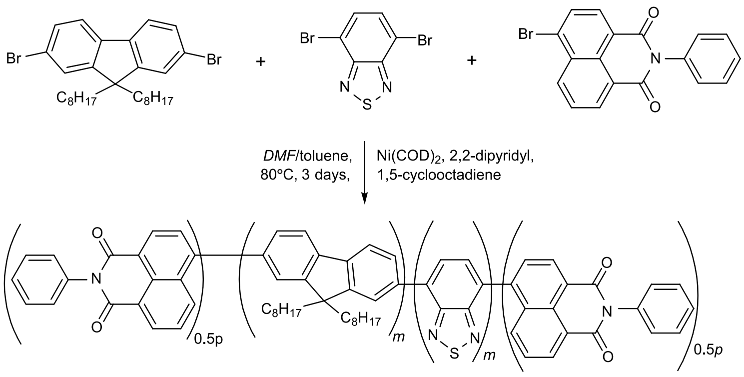
comparable to that of white organic light-emitting diodes with multilayer device structures and complicated fabrication processes. Connecting to his previous work, *Wang et al.* recently reported a new single-polymer electroluminescent systems containing two individual emission species, polyfluorenes as a blue host and 2,1,3-benzothiadiazole derivative units as an orange dopant on the main chain [24]. A synthesis route to the monomers and polymers is outlined in Scheme 4.

So, a white light-emitting single-polymer system was developed by incorporating 7-bis(4-(*N*-phenyl-*N*-(4-methylphenyl)amino)phenyl)-2,1,3-benzothiadiazole as an orange dopant unit in the main chain of PF as the blue host. Single-layer devices of the polymers emitted white light with simultaneous blue ($\lambda_{\max} = 421\,\text{nm}/445\,\text{nm}$) and orange emission ($\lambda_{\max} = 564\,\text{nm}$). For a thermally annealed single-layer device utilizing this polymers, a turn-on voltage of 3.5 V, luminance efficiency of 8.99 cd/A, and power efficiency of 5.75 lm/W, with CIE coordinates of (0.34, 0.35), were achieved. This performance is roughly comparable to that of white organic light-emitting diodes with multilayer device structures and complicated fabrication processes.

Recently, *Hsu et al.* developed a new method to achieve white-light emission from a single polymer [25]. A green-emission dye, *N*-phenyl-1,8-naphthalimide (*NTI*), was incorporated into a blue and orange light-emitting copolymer backbone, poly(fluorene-*co*-benzothiadiazole), by an end-capping approach. The molar ratio of these three composition units was adjusted to balance the light color and achieve white light emission, but with the fluorine unit as the main part of the copolymer backbone. A synthesis scheme for these polymers is shown in Scheme 5.

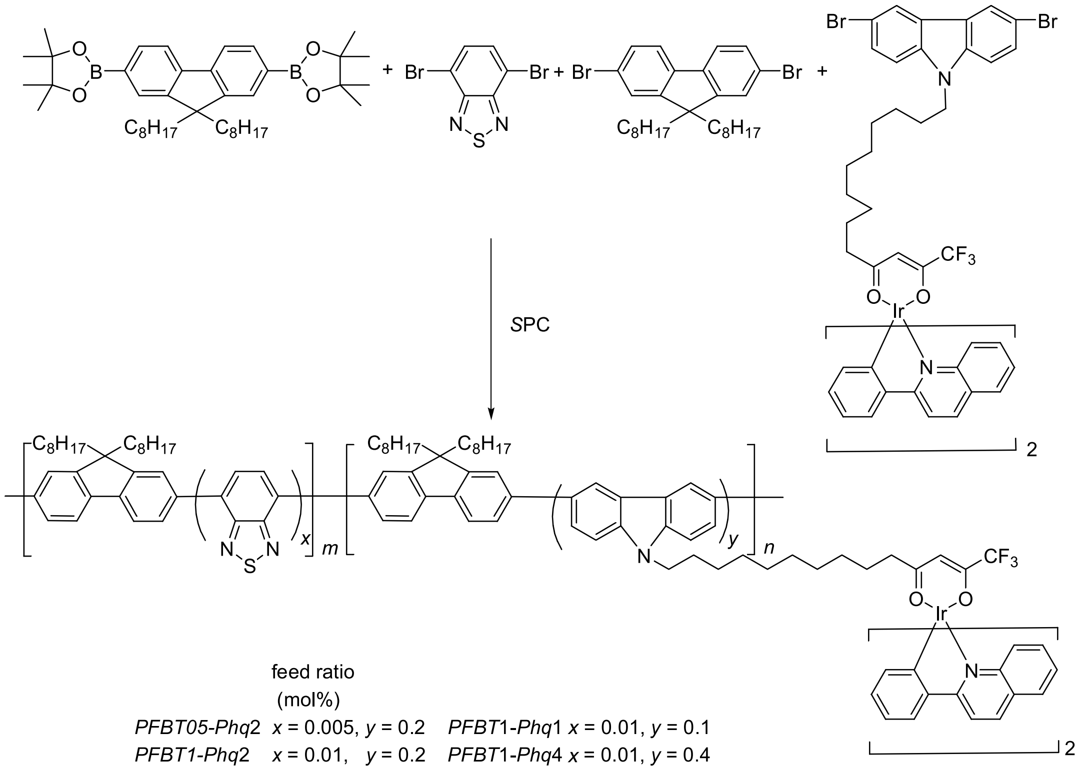
The highest brightness in an EL device is $251\,\text{cd/m}^2$ at a current density of $400\,\text{A/m}^2$ with CIE coordinates of (0.31, 0.39). The EL spectra show color stability over different operating voltages. The approach is proved to be a useful way to prepare efficient white light-emitting diodes.

Cao et al. reported a new strategy to realize efficient white light emission from a single polymer, which simultaneously consists of fluorescence- and phosphorescence-emitting species [26]. By introducing a small number of benzothiadiazole (*BT*) units into the polyfluorene backbone and by attaching a small number of iridium complexes onto the side chain, white light emission was obtained from three individual emission species. Large band-gap fluorene was used as the host for the blue light-emitting species, and *BT* was selected as the green light emitter. An iridium complex was used as the triplet red-light emission species because of its high quantum efficiency owing to strong spin orbit coupling of the heavy-metal ions. By adjusting the contents of *BT* and/or the iridium complex, simultaneous emission of three species can be obtained and further combined to form white light. It was expected that the incorporation of singlet-emission *BT* units into the polyfluorene backbone and attachment of triplet emission iridium complexes onto the side chain can increase the luminance efficiency. A synthesis route



	molar ratio(%)
PF-2% BT-3% end*NTI*	*m* = 95, *n* = 2, *p* = 3
PF-3% BT-2% end*NTI*	*m* = 95, *n* = 3, *p* = 2
PF-2% BT-1% end*NTI*	*m* = 97, *n* = 2, *p* = 1
PF-2% BT-0.5% end*NTI*	*m* = 97.5, *n* = 2, *p* = 0.5

Scheme 5



feed ratio
(mol%)
*PFBT05-Phq*2 x = 0.005, y = 0.2 *PFBT*1-*Phq*1 x = 0.01, y = 0.1
*PFBT1-Phq*2 x = 0.01, y = 0.2 *PFBT*1-*Phq*4 x = 0.01, y = 0.4
*PFBT3-Phq*2 x = 0.03, y = 0.2 *PFBT*1-*Phq*5 x = 0.01, y = 0.5
*PFBT5-Phq*2 x = 0.05, y = 0.2 *PFBT*3-*Phq*3 x = 0.03, y = 0.3

*S*PC: *Suzuki* polycondensation; *PFBT-Phq*: the copolymer from fluorene(*F*),*BT*, and the 2-phenylquinoline iridium complex (*Phq*).

Scheme 6

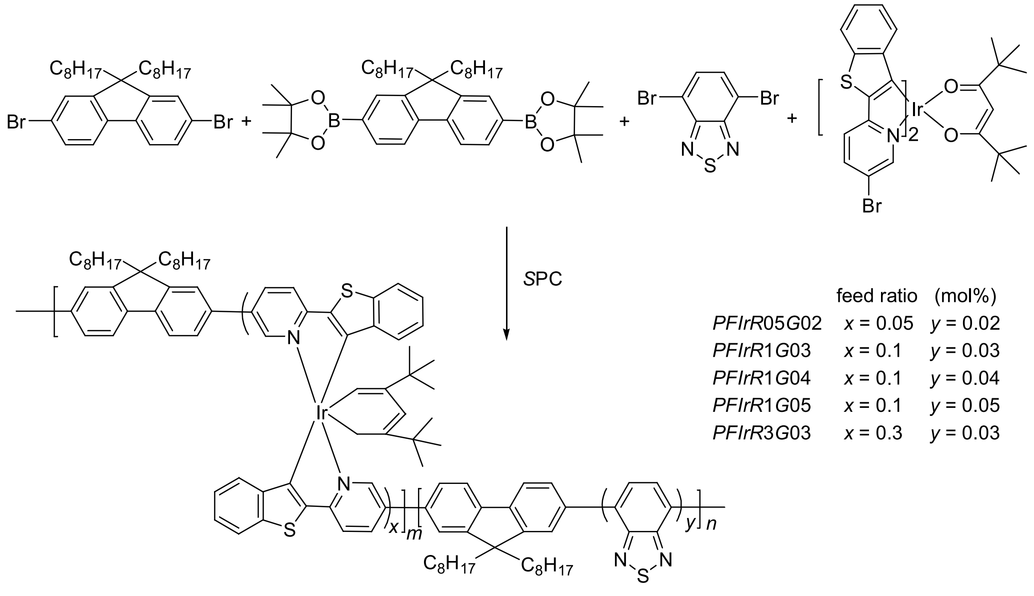
to the copolymers and the feed ratio of the comonomers is shown in Scheme 6.

It was noticed that changing the contents of the *BT* and/or iridium complex, the EL spectra can be adjusted to achieve white light emission. The devices from *PFBT*1-*Phq*2 and *PFBT*3-*Phq*2 emit white light with CIE coordinates of (0.34, 0.33) and (0.32, 0.33), respectively. The device from *PFBT*5-*Phq*2 exhibits a maximum luminance efficiency of 6.1 cd/A at a current density of 2.2 mA/cm^2. A maximum luminance of 10110 cd/m^2 was achieved at a current density of 345 mA/cm^2. The white light emission of devices from the copolymers is stable over the whole white light region at different applied voltages, and the EL efficiencies decline slightly with increasing current density. Connecting to this approach, *Peng et al.* also reported a new strategy to realize white light emission from a single polymer by introducing a small amount of *BT* and the bicyloiridium complex, iridium(III)bis(2-(2′-benzo[4,5-α]thienyl)pyridinato-*N*,$C^{3'}$)-2,2,6,6-tetramethyl-3,5-heptanedione [(*btp*)$_2$Ir(*tmd*)] into a polyfluorene backbone [27]. Fluorene, *BT*, and the iridium complex are blue-, green-(G) and red (R)-emissive species, respectively. By adjusting the contents of *BT* or/and (*btp*)$_2$Ir(*tmd*), simultaneous emission of the three species can be obtained and can be further combined to form white light. Chemical structures and synthesis route of copolymers is shown in Scheme 7.

The device from *PFIrR*1*G*03 shows a maximum external quantum efficiency of 3.7% and a maximum luminous efficiency of 3.9 cd/A at a current density of 1.6 mA/cm^2 with CIE coordinates of (0.33, 0.34). The maximum luminance of 4180 cd/m^2 is achieved at a current density of 268 mA/cm^2 with CIE coordinates of (0.31, 0.32).

Polymer blend system for white light emitting

As mentioned before, there are two major approaches to get white emission from WPLEDs. One is to use a single component white light emitting polymer or a single white light-emitting poly-



Scheme 7

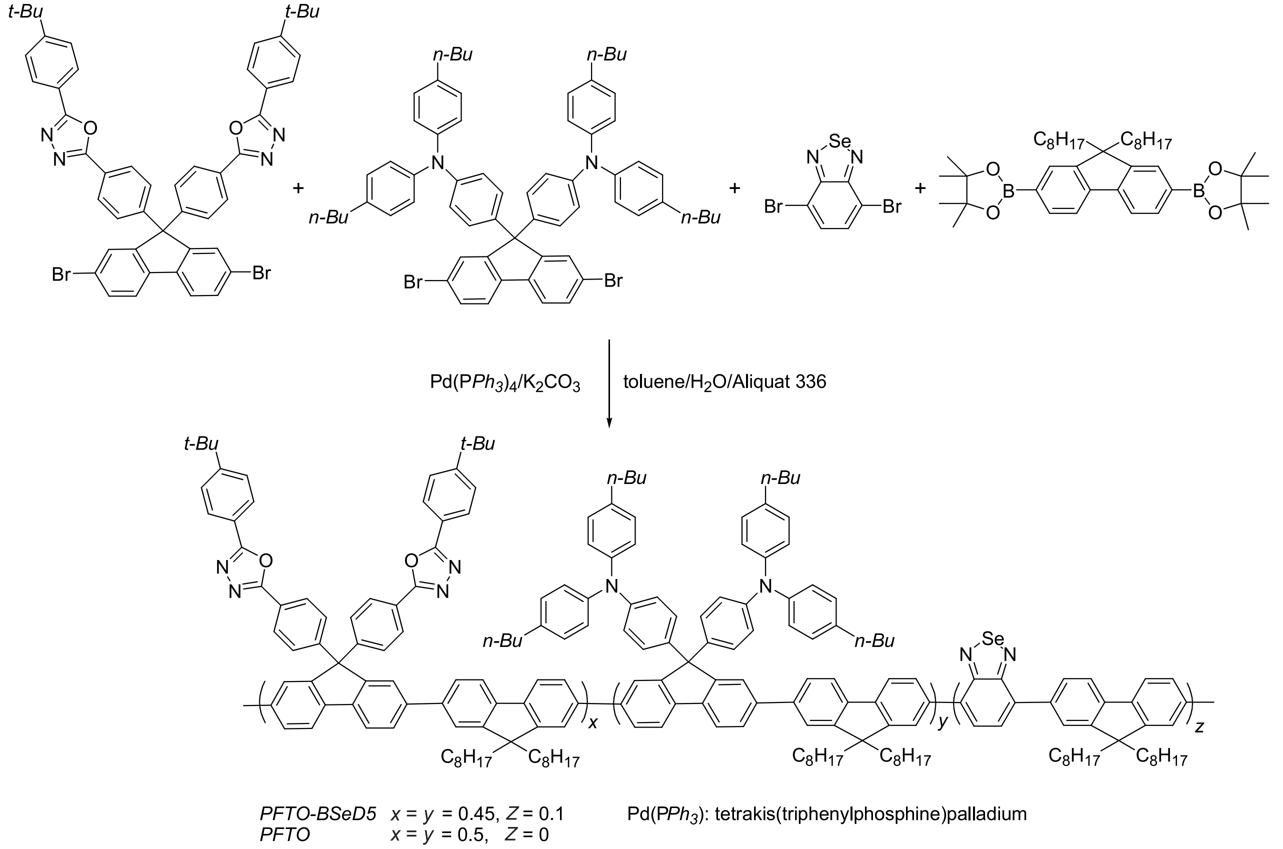
mer as emitting layer, which has been discussed in details in previous section. The second approach is to use polymer blend system. There are different ways to use polymer blend system in WPLED *e.g.*, blending red, green, and blue light-emitting polymers or blending blue and orange light-emitting polymers [28–31], and blending fluorescent or phosphorescent dyes into a polymer matrix, *etc.* [32–38].

It is well known that polyfluorenes (*PF*s) are very promising candidates for blue light-emitting materials because of their high photoluminescence (PL) and electroluminescence (EL) efficiencies, high thermal stabilities, and ready color tuning through the introduction of low-band-gap comonomers [14, 39–43]. In addition, the facile process of functionalizing the C-9 position of the fluorine unit provides the opportunity to tune the optoelectronic properties of these materials [37, 44]. Moreover, *PF*s can be used as host materials to generate other colors through energy transfer to lower energy emitters in blends with other conjugated polymers, fluorescent dyes, and organometallic triplet emitters [30, 35, 45–51]. Consequently, *PF*s can function as both the host and the blue emitter in white light-emitting PLEDs.

Shu et al. reported white PLEDs formed from polymer blends consisting of blue and orange polyfluorene copolymers. Poly{[9,9-bis(4-(5-(4-*tert*-butylphenyl)-[1,3,4]-oxadiazol-2-yl)-phenyl)-9′,9′-di-*n*-octyl-[2,2′]-bifluoren-7,7′-diyl]-stat-[9,9-bis(4-(*N*,*N*-di(4-*n*-butylphenyl)amino)phenyl)-9′,9′-di-*n*-octyl-[2,2′]-bifluoren-7,7′-diyl]}(*PFTO*) exhibits good spectral stability and a high-efficiency blue emission upon either optical or electrical excitation [29]. Accordingly, *PFTO* was chosen as the polymeric host and blue emitter, which was doped with *PFTO-B*Se*D*5, a new orange-emitting polymer that incorporates 5 mol% of narrow bandgap benzoselenadiazole (*B*Se*D*) units into the polyfluorene backbone, to realize white PLEDs. Synthesis of polymers is shown in Scheme 8.

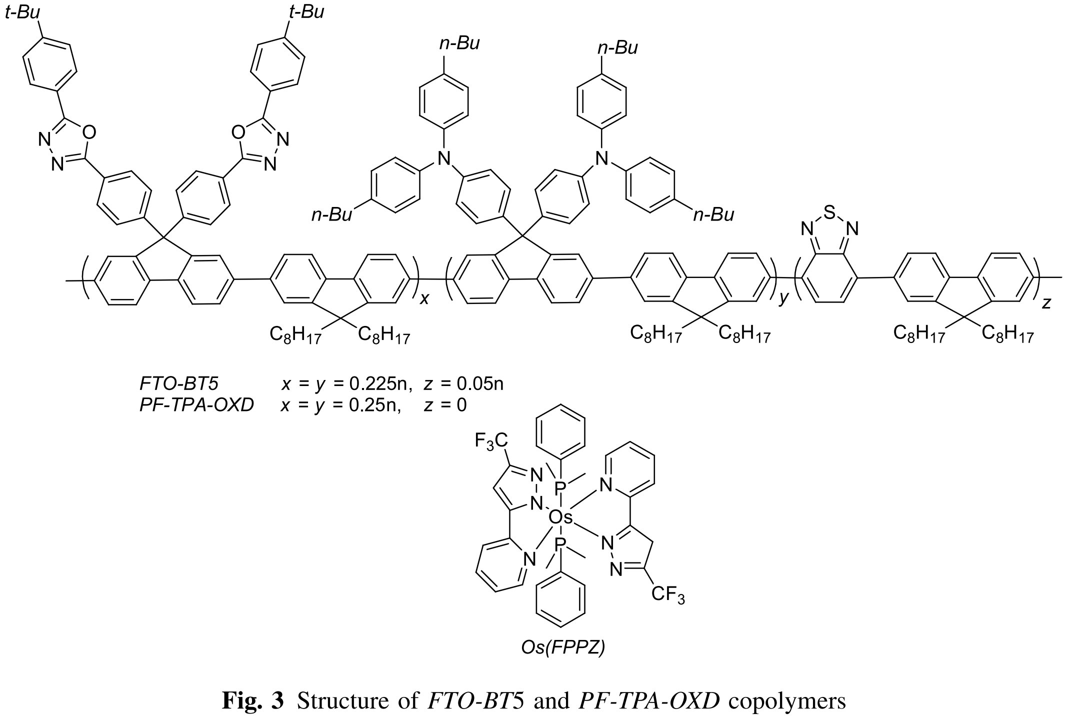
Bright white light-emitting diodes based on the above-mentioned single-layer polymer blends were fabricated readily through spin-casting of a solution containing *PFTO* and *PFTO-B*Se*D*5 (7–11 wt%). For the 9 wt% doped device, a pure white light emission having CIE coordinates of (0.32, 0.33) was achieved with a high external quantum efficiency and brightness of 1.64% (4.08 cd/A) and 7328 cd/m^2. Even when the brightness was increased to 103 cd/m^2 (at ca. 25 mA/cm^2), the EL efficiency remained above 1.58% (3.93 cd/A). Extending this work, *Shu et al.* further synthesized a green-emitting copolymer (*FTO-BT*5) by incorporating low bandgap *BT* moieties into a blue light-emitting polyfluorene copolymer (*PF-TPA-OXD*) [52]. The structure of copolymer and the red light-emitting phosphor is shown in Fig. 3.

A highly efficient and color-stable white electrophosphorescent device based on this single-layer polymer blend was fabricated readily through spin-



PFTO-BSeD5 *x* = *y* = 0.45, *Z* = 0.1
PFTO *x* = *y* = 0.5, *Z* = 0
Pd(P*Ph*3): tetrakis(triphenylphosphine)palladium

Scheme 8



FTO-BT5 *x* = *y* = 0.225n, *z* = 0.05n
PF-TPA-OXD *x* = *y* = 0.25n, *z* = 0

Os(FPPZ)

Fig. 3 Structure of *FTO-BT*5 and *PF-TPA-OXD* copolymers

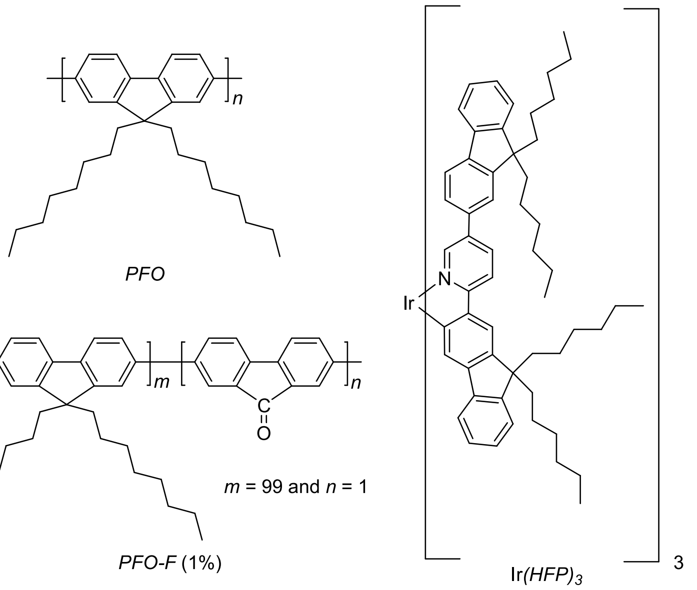


Fig. 4 Molecular structure of *PFO* and *PFO-F* (1%), and Ir(*HFP*)$_3$

casting a solution containing *PF-TPA-OXD*, *FTO-BT*5 and a red-emitting Os(*FPPZ*) complex. In addition to being the host matrix, *PF-TPA-OXD* plays the role of an emitter. It offers its efficient fluorescence to the blue emission region of the resulting white light emission. This situation not only reduces the number of dopants required but also simplifies the fabrication process. This approach should be valuable for solid-state lighting applications because of the simple device architecture and the promise of low-cost manufacture ability. Without physically co-doping any charge transporting molecules into the host matrix, a device efficiency of 4.1% (8.3 cd/A at 402 cd/m^2 for the resulting white light) was obtained, the spectrum of which covered the entire visible region. When luminance was increased from 30 to 5×10^3 cd/m^2, the corresponding CIE coordinates exhibited only a slight shift from (0.36, 0.32) to (0.33, 0.31) and the value of EQE remained above 3%. White electrophosphorescent devices based on a single polyfluorene emitter, chemically doped with *BT* units and red phosphor, have been demonstrated with a maximum LE of 6.1 cd/A in comparison with them, polymer-blend-based device shows comparably decent color stability with relatively higher EL efficiency. Single layer polymer blends or hybrid inorganic conjugated polymer structures are advantageous because they can be fabricated by solution processing at room temperature [53–54]. White light-emiting PLEDs fabricated by spin casting luminescent from solution would result in a simpler and therefore potentially less expensive manufacturing process. Keeping this in view, *Moses et al.* reported white light emission from the devices fabricated using luminescent semiconducting polymer blended with organometallic emitters. The luminescent phosphorescent mixture is spin cast directly from solution [36]. Structures of polymers and the iridium complex is shown in Fig. 4.

The type-1 device was fabricated from poly(9,9-dioctylfluorene) (*PFO*) with tris(2,5-bis-2′-(9′,9′-dihexylfluorene)pyridine)iridium(III) (Ir(*HFP*)$_3$). The type II device was fabricated from blends of *PFO* with poly(9,9-dioctylfluourene-*co*-fluorenone) with 1% fluorenone (*PFO-F*(1%)) and Ir(*HFP*)$_3$. The CIE

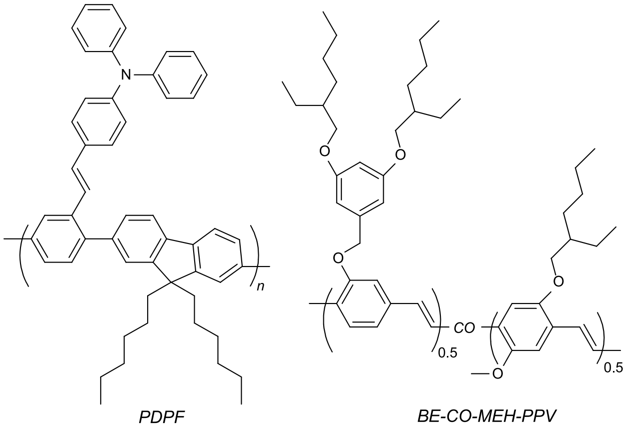


Fig. 5 Chemical structure of *PDPF* and *BE-CO-MEH-PPV*

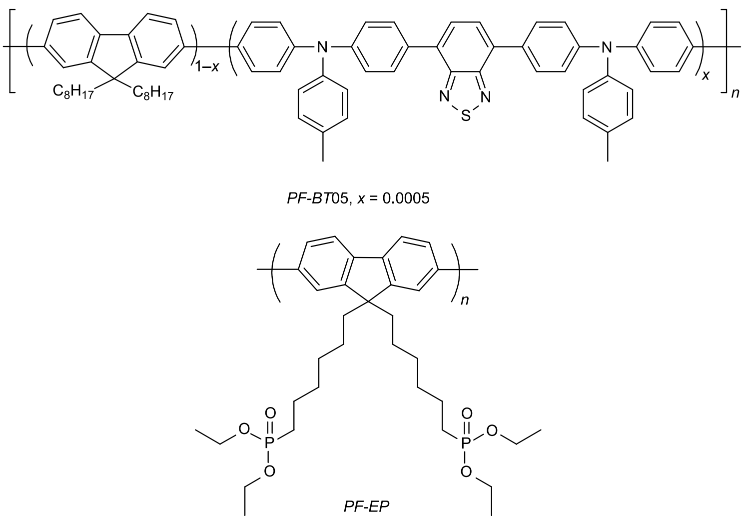


Fig. 6 Chemical structure of *PF-BT*05 and *PF-EP*

coordinates, CT and CRI for the type I and the type II device are (0.329, 0.321), 6400 K, 92, and (0.352. 0.388), 4600 K, 86. All these values are close to pure white light.

Li et al. reported white emission based on the homogeneous blend of a greenish blue-light emitting polyfluorene derivative, poly(2-(4′-diphenylamino)-phenylenevinyl)-1,4-phenylene-*alt*-9,9-*n*-dihexyl-fluorene-2,7-diyl) (*PDPF*) doped with a reddish orange-light emitting copolymer, poly{2-[3′,5′-bis(2″-ethylhexyloxy)benzyloxy]-1,4-phenylenevinlene}-*co*-poly(2-methoxy-5-(2′-ethylhexyloxy)-1,4-phenylenevinylene (*BE-CO-MEH-PPV*). Stable white light emission was achieved with the dopant concentration of 0.194‰, and the EL spectra are less sensitive to the applied voltages in a wide operation voltage range. With the voltage varying from 6 V to 15 V, the CIE coordinates slightly shift from (0.369, 0.328) to (0.320, 0.358), which are all in the region of white light and very close to the pure white coordinates (0.333, 0.333) (Fig. 5) [55]. Also, *Li et al.* reported pure white emission on the basis of three kinds of luminescent polymer, the red emitting material, poly{2-[3′,5′-bis(2″-ethylhexyloxy)benzyloxy]-1,4-phenylenevinylene}-*co*-poly(2-methoxy-5-(2′-ethylhexyloxy)-1,4-phenylenevinylene (*BE-CO-MEH-PPV*), the green emitting material, poly(6,6′-bis(9,9′-dihexylfluorene)-*co*-(9,9′-dihexylfluorene-3-thiophene-5′-yl))(*PFT*), and the blue emitting material, poly(9,9′-dioctylfluorene-2,7-diyl) (PFO) [56].

Xie et al. reported good white color stability emitted by poly[9,9-*di*-*n*-octylfluorene-*co*-4,7-bis(4-[*N*-phenyl-*N*-(4-methylphenyl)amino]phenyl)-2,1,3-benzothiadiazole] (*PF-BT*05) and poly[9,9-bis(6′-diethoxyphosphoryl-hexyl)fluorene] (PF-EP) (Fig. 6) [57].

Except for the abovementioned examples, many researches have been progressed by changing emitting polymer or small molecule [58], hole transport layer and a lot of variable with quantum dot [59] or metal-chelated method [60] for white light-emitting.

Conclusions

We discussed the synthesis of polymeric materials used in white LEDs as the main subject reported up to December 2007. White polymer light-emitting diodes (WPLEDs) made from polymer blend system suffer from low efficiency and color instability, so, single polymers emitting white light are extremely desirable as they have great advantage over the polymer blend system in terms of no phase separation. Many single component white light-emitting materials have been developed so far and the CIE values obtained from WPLEDs are closer to ideal values as compared to those obtained by WOLEDs. There is also a new approach to blend quantum dots in polymer to achieve purer white emission. More research is needed in this area yet to improve the efficiency, stability, and fabrication process.

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