Research Article

Synthesis and Optical Properties of Triphenylene-Based Donor-Donor and Donor-Acceptor Conjugated Polymers: A Comparative Study

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Received 3 September 2020; Revised 20 October 2020; Accepted 24 October 2020; Published 17 November 2020

Academic Editor: Peng He

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Two new conjugated polymers (P1 and P2), containing a bithiophene donor unit coupled with either a triphenylene donor unit or an imide-functionalized triphenylene acceptor unit in the backbone, have been synthesized, structurally characterized, and comparatively studied by using 1H NMR, FT-IR, gel permeation chromatography, differential scanning calorimetry, cyclic voltammetry, ultraviolet-visible absorption, and fluorescence spectroscopy. Both polymers are amorphous in nature and thermally stable up to 450°C. The inclusion of the imide functionalization in the triphenylene unit significantly lowered the lowest unoccupied molecular orbital energy level and thus the bandgap of the donor-acceptor polymer P2 over the donor-donor polymer P1. P1 and P2 show very different optical properties in hexane and other solvents. P1 shows a broad emission in hexane but vibronically structured emissions in other solvents; in contrast, P2 exhibits a vibronically resolved emission in hexane, while exhibiting redshifted, broad, and featureless emissions in other solvents. P1 takes a random coil conformation in good solvents like p-xylene, benzene, toluene, anisole, chloroform, THF, and o-dichlorobenzene, whereas in hexane, it may adopt a helical folding conformation. In the poor solvent DMSO, interchain aggregates dominate. P2, on the other hand, adopts a random coil conformation in hexane but possibly the helical folding conformation in other good solvents. The opposite conformations of the two polymers may be responsible for their opposite solvent-dependent fluorescence properties. By virtue of the very different fluorescence properties of these two polymers in nonpolar solvents such as hexane and in polar solvents, the potential of using the polymers to detect the trace amount of ethanol content that is added to gasoline has been revealed with high sensitivity.

1. Introduction

Organic semiconductors have attracted growing interest ever since the first discovery of highly conductive organic charge-transfer complexes in the 1950s [1]. They have now emerged as an appealing, commercially viable alternative to conventional inorganic semiconductor materials and have been found to have numerous cutting-edge electronic and optoelectronic applications in, for example, photovoltaic solar cells [2–7], organic light-emitting diodes [8–10], organic field effect transistors [11–13], and organic phototransistors [14–16]. The advantages of using organic molecules instead of established inorganic materials, such as silicon or gallium arsenide, include flexibility in structural modification, ease in device fabrication, and fast recovery in energy “debt” [17, 18].

Conjugated small molecules and polymers are the major types of organic semiconducting materials. Among the myriad of conjugated molecules, polycyclic aromatic compounds (PACs) have been the most extensively investigated [19–33]. In particular, triphenylene derivatives as one of the most common discotic mesogens have exhibited some unique properties attractive for various optical and/or electronic applications due to their planar geometry and extended \( \pi \)-delocalization [34–38]. A great number of triphenylene-based small molecules and triphenylene-containing polymers have been reported in the literature; however, conjugated
polymers with triphenylene constructed as repeating units in the backbone still remain noticeably rare [39–41].

We have been interested in preparing conjugated systems containing triphenylene building blocks, including amphiphilic conjugated macrocycles, conjugated dendrimers, and conjugated polymers [41–43]. In this paper, we wish to report the synthesis and photophysical properties of two new conjugated polymers, \( \text{P1} \) and \( \text{P2} \), containing a bithiophene donor unit coupled with either a triphenylene donor unit or an imide-functionalized triphenylene acceptor unit in the backbone. It is found that these two polymers show very different optical properties in hexane and other solvents.

2. Results and Discussion

Schemes 1 and 2 depict the synthetic routes of the imide-functionalized triphenylene-based acceptor monomer \( \text{M2} \) and the two triphenylene-based conjugated polymers \( \text{P1} \) and \( \text{P2} \). The syntheses of the triphenylene-based donor monomer \( \text{M1} \), the bithiophene donor comonomer \( \text{M3} \), and 5,6-dibromo-2-dodecylisoindoline-1,3-dione (1), the starting material for the synthesis of monomer \( \text{M2} \), have been reported previously [43–45].

As shown in Scheme 1, Pd-catalyzed Suzuki coupling of compound 1 with 3-methoxyphenylboronic acid gave compound 2 in excellent yields; subsequent Scholl oxidative cyclization of 2 afforded the triphenylene compound 3 in good yields; and bromination of 3 using \( \text{NBS} \) and catalytic amount of sulfuric acid in trifluoroacetic acid (TFA) resulted in the desired monomer \( \text{M2} \) in a 56% yield [46]. The desired product of each synthetic step shown in Scheme 1 can be isolated via a simple workup followed by routine purification techniques such as recrystallization, and those reactions can be easily scaled up to a multigram scale. The \( \text{H} \) NMR spectrum of \( \text{M2} \) (Figure 1) showed three well-resolved, separated sharp signals (singlets) in the aromatic region at 7.98, 8.66, and 8.97 ppm, respectively, for three separated aromatic protons (g, h, and i) in the molecule, confirming the purity of the monomer.

Both polymers \( \text{P1} \) and \( \text{P2} \) were synthesized using the Stille polycondensation reaction with the \( \text{Pd}_{3} \) (dba),/P(o-tolyl) catalyst system. The Stille crosscoupling reaction of donor comonomer \( \text{M3} \) with another donor monomer \( \text{M1} \) yielded the donor-donor (D-D) conjugated polymer \( \text{P1} \) as a reddish brown solid in excellent yields (Scheme 2). The polymer was purified by dissolving in a minimum amount of good solvent like \( \text{CHCl}_3 \) and then precipitation in MeOH, where it had poor solubility. Similarly, the polymerization of donor comonomer \( \text{M3} \) and acceptor monomer \( \text{M2} \) was carried out following Stille coupling reaction using \( \text{THF} \) as the solvent for about 40 h to yield the donor-acceptor (D-A) conjugated polymer \( \text{P2} \) in excellent yields (Scheme 2). The synthesized polymer \( \text{P2} \) was isolated by repeated dissolution-precipitation-separation steps, giving \( \text{P2} \) as a dark red solid.

Introducing the multiple long dodecyl chains into the structure improves the solubility of the polymers \( \text{P1} \) and \( \text{P2} \) in most of the organic solvents. \( \text{P1} \) is soluble in nonpolar solvent like hexane, while \( \text{P2} \) is only partially soluble in hexane. Both \( \text{P1} \) and \( \text{P2} \) have good solubility in solvents like 1-p-xylene, benzene, toluene, anisole, chloroform, tetrahydrofuran (THF), and \( o \)-dichlorobenzene (ODCB) but very poor solubility in dimethylformamide (DMF). These two polymers are completely insoluble in dimethyl sulfoxide (DMSO) at room temperature.
the band at ~1765 cm\(^{-1}\) is assigned to the symmetrical stretching vibration of the C=O bond in the imide-functionalized triphenylene units, while the band at ~1707 cm\(^{-1}\) is attributed to C=O asymmetrical stretching. The band at ~1383 cm\(^{-1}\) corresponds to the C-N stretching, and the band around 747 cm\(^{-1}\) is designated to the C=O bending from the imide groups. These vibrations were absent in \(P_1\) as it does not contain imide groups in the structure.

Polymers \(P_1\) and \(P_2\) were characterized by gel permeation chromatography (GPC) to estimate the molecular weights using THF as an eluent and polystyrene as the standard (Figure S6). The number average molecular weight (\(M_n\)) of polymer \(P_1\) was found to be 6.23 kDa, while the weight average molecular weight (\(M_w\)) was 7.40 kDa. For polymer \(P_2\), \(M_n\) and \(M_w\) were estimated to be 4.40 and 5.09 kDa, respectively. Both polymers have narrow polydispersity indices (PDI) (1.19 and 1.16 for \(P_1\) and \(P_2\), respectively). It is worth noting that the calculated molecular weights based on polystyrene standards may not be accurate for conjugated polymers \(P_1\) and \(P_2\) especially when considering the potentially folding conformations of the polymers.

The thermal properties of the two polymers were investigated by using differential scanning calorimetry (DSC) in \(N_2\) with a heating and cooling rate of 10°C min\(^{-1}\). As can be seen from Figure 4, both polymers happened to be amorphous in nature with no obvious thermal transitions and they are both thermally stable up to 450°C.

The electrochemical properties of the two triphenylene-containing conjugated polymers were studied as thin films using cyclic voltammetry (CV) measurements. For polymer \(P_1\), one irreversible reduction wave was observed during the cathodic scan, and three irreversible oxidation waves were shown during the anodic scan as seen in Figure 5. In the case of polymer \(P_2\), two reversible reduction waves were observed during the cathodic scan, and two semireversible oxidation waves were seen during the anodic scan. By making use of the first oxidation onset potential during the anodic scan (\(E_{\text{ox}}^{\text{onset}} = 0.13\) V for \(P_1\) and 0.14 V for \(P_2\)) and the first reduction onset potential in the cathodic scan (\(E_{\text{red}}^{\text{onset}} = -2.24\) V for \(P_1\) and –1.28 V for \(P_2\)), the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) energy levels of the polymers \(P_1\) and \(P_2\) were estimated to be –4.92/–2.56 and –4.94/–3.52 eV, respectively. In a D-A conjugated polymer, the HOMO energy level is controlled by the D unit, while the LUMO energy level is controlled by the A unit. In the cases of both polymers \(P_1\) and \(P_2\), their donor comonomers are the same, and their HOMO
Figure 1: $^1$H NMR spectrum of monomer M2 in CDCl₃ (signals labeled with "∗" are solvent peaks).

Figure 2: $^1$H NMR spectra of the two polymers P1 and P2.

Figure 3: FT-IR spectra of polymers P1 and P2.
levels are very close to each other, while their LUMO levels are very different. The LUMO energy level in the case of polymer P2 was lowered substantially due to the presence of imide functionalization, and that in turn lowered the effective band-gap. The bandgaps of polymers P1 and P2 were found to be 2.36 and 1.42 eV, respectively.

Figure 6 shows the absorption spectra of the polymers P1 and P2 as dilute solutions in different solvents with their absorption maxima compiled in Table 1. As can be seen, polymer P1 exhibit one broad absorption band centered at 436~440 nm in the visible region in good solvents like p-xylene, benzene, toluene, anisole, chloroform, THF, and ODCB. In hexane and the two solvents (DMF and DMSO) in which both polymers exhibit poor solubility, one notices a prominent shoulder peak around 500 nm besides the major absorption band. There is about 10 nm redshift for the maximum absorption wavelength in the visible range for P1 in DMSO as compared to the other solvents. In hexane and DMSO, P1 also shows an absorption tail longer than that in the other solvents, extending to ~750 nm. The absorption shoulder/long tail in DMSO is likely due to the stronger interchain aggregation and/or interchain π-π overlap resulting from the poor solubility of P1. In hexane, however, P1 exhibits good solubility. The redshifted shoulder band and the long tail are attributed likely to an intrachain π-π stacking interaction. In other words, P1 in hexane likely adopts a folding conformation, which is consistent with its fluorescence properties discussed later. In the case of polymer P2, there is only one broad absorption band in the visible region in the same variety of solvents. A redshift of 18 nm is observed for the absorption maximum in the visible range when the solvent is changed from hexane to DMSO. An absorption tail extending to longer wavelengths is observed for P2 in all three poor solvents (hexane, DMF, and DMSO).

These two polymers are moderately to weakly fluorescent in different organic solvents, and their fluorescence behaviors were found to be strongly dependent on the type of the organic solvents. Figure 7 shows the absorbance-corrected fluorescence emission spectra of polymers P1 and P2 as dilute solutions in different solvents with their emission maxima and fluorescence quantum yields summarized in Table 2 and detailed excitation/emission spectra illustrated in Figures S2 and S3 in the supporting information. In all good solvents studied with the exception of hexane, polymer P1 exhibits very similar vibronically structured fluorescence emissions, indicating that P1 adopts a random coil conformation in those solvents. In the poor solvent

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Figure 4: DSC thermograms of the polymers P1 and P2 with a heating and cooling rate of 10°C min⁻¹. Note that the DSC thermograms of successive scans were offset for clarity.

Figure 5: Cyclic voltammograms of the polymer thin films. Note that these curves are both first scans of cyclic voltammetry.
Figure 6: UV-Vis absorption spectra of P1 and P2 as dilute solutions in different solvents. Note that P2 has poor solubility in hexane, and the upper, clear portion of a saturated P2 solution in hexane was collected and used for measurement. Also, note that due to the very poor solubility of P1 and P2 in DMF and the insolubility of P1 and P2 in DMSO, these solutions were prepared by adding a very small amount of concentrated CHCl3 stock solution of P1 or P2 to respective solvents.

Table 1: Absorption maxima of P1 and P2 as dilute solutions in different solvents.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Hexane (1.9)</th>
<th>p-Xylene (2.268)</th>
<th>Benzene (2.27)</th>
<th>Toluene (2.38)</th>
<th>Anisole (4.33)</th>
<th>CHCl3 (4.81)</th>
<th>THF (7.58)</th>
<th>ODCB (9.93)</th>
<th>DMF (36.7)</th>
<th>DMSO (46.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>440</td>
<td>440</td>
<td>438</td>
<td>440</td>
<td>442</td>
<td>436</td>
<td>438</td>
<td>440</td>
<td>442</td>
<td>458</td>
</tr>
<tr>
<td>P2</td>
<td>468a</td>
<td>476</td>
<td>474</td>
<td>478</td>
<td>476</td>
<td>474</td>
<td>472</td>
<td>482</td>
<td>472</td>
<td>486</td>
</tr>
</tbody>
</table>

P2 has poor solubility in hexane, and the upper, clear portion of a saturated P2 solution in hexane was collected and used for measurement. Due to the very poor solubility of P1 and P2 in DMF and the insolubility of P1 and P2 in DMSO, these solutions were prepared by adding a very small amount of concentrated CHCl3 stock solution of P1 or P2 to respective solvents. The numbers in brackets are the dielectric constants of the solvents.

DMSO, P1 shows extremely weak fluorescence barely discernable by the instrument (Figure S2). The weak emission is broad with a significantly redshifted emission maximum $\lambda_{\text{max}}$ at 585 nm. The weak, broad, and significantly redshifted emission of P1 in DMSO is attributed to the strong interchain $\pi$-$\pi$ stacking interaction of P1 in poor solvent. In hexane, the emission of P1 is again broad and lacks vibronic bands. However, the maximum emission wavelength ($\lambda_{\text{max}}$ 543 nm) in hexane is higher than those in the other good solvents but lower than that in DMSO, indicating that P1 in hexane does not adopt a random coil conformation as in other good solvents nor exist as interchain aggregates as it does in DMSO. As alluded to earlier, we suggest that P1 in hexane adopts a helical folding conformation driven by intrachain $\pi$-$\pi$ stacking interactions that gave rise to its unique fluorescence emissions. The strong interdigitation of long alkyl side chains in P1 with the solvent hexane likely plays a significant role in driving P1 helical folding since folding exposes long alkyl chains towards the solvent.

Interestingly, the fluorescence emissions of P2 show solvent dependence that is almost opposite to that of P1. As can be seen in Figure 7, P2 in all solvents except for hexane shows one broad structureless emission. It seems that, contrary to P1, P2 adopts a folding conformation in all good solvents studied. The stronger folding tendency of P2 is likely due to the stronger $\pi$-$\pi$ stacking interaction among the imide-functionalized triphenylene units. The emission of P2 in hexane, however, is blueshifted and vibronically structured. The emission intensity of P2 is significantly lower in hexane than in the other three nonpolar solvents (p-xylene, benzene, and toluene) but higher than in the rest of the solvents which all happen to have higher dielectric constants than hexane. The blueshifted and vibronically structured emission may indicate a random coil conformation of P2 in hexane. The fluorescence emission spectra of P2 as dilute solutions in mixed hexane/toluene solvents with varied volume ratios were studied and are shown in Figure 8. Note that the same amount of saturated hexane stock solution was used for the preparation of all these solutions, and the overall concentration of P2 was kept constant. As can be seen from Figure 8, when the volume percentage of toluene increases from 0 to 80% in a gradual manner, P2 shows a clear and continuous transition from the vibronically resolved emission in pure hexane with maximum emission wavelength at 519 nm towards a redshifted, broad, and featureless emission.
portion of a saturated di as very dilute solutions (maximum absorbance: ca. 0.1) in hexane, and the upper, clear portion of a saturated and cates that the di ff the one in pure toluene solvent (Figure 7). This result indi- centered at ~580 nm in the mixed solvent containing 20% hexane and 80% toluene, the latter of which is similar to the one in pure toluene solvent (Figure 7). This result indicates that the different fluorescent properties of P2 in hexane from those in the other solvents are not due to molecular weight difference of dissolved P2 polymers but rather the result of P2 polymers taking a different conformation (random coil instead of folded helices).

Noticing the varied fluorescence intensities and shifting of emission bands of P1 and P2 in the different solvents, we further compared the absorbance-corrected, integrated fluorescence intensity and maximum emission wavelength of P1 and P2 as very dilute solutions as a function of the dielectric constant of the solvent (Figure 9 and Figure S4). Due to the very different fluorescence behavior in hexane and the extremely weak fluorescence intensities in DMF and DMSO, these three solvents are excluded from the plots in Figure 9. For P1, when the polarity of the solvent increases, its fluorescence intensity first decreases and then increases, while no clear trend can be seen for its emission maximum. For P2, when the polarity of the solvent increases, its fluorescence intensity generally decreases, and its emission maximum shifts to longer wavelength with small fluctuations. P2 is highly fluorescent in the three good nonpolar solvents (benzene, p-xylene, and toluene). The fluorescence intensity drops significantly when the dielectric constant of the solvent is changed slightly from toluene to anisole, accompanied by a sizable redshift in emission wavelengths.

It is interesting to note the significant differences in the solvent-dependent emission properties of polymers P1 and P2 in chloroform and hexane. For P1, the polymer is more fluorescent in CHCl3 and the emission $\lambda_{\text{max}}$ is blueshifted by 19 nm compared to that in hexane. For P2, the observation is exactly opposite: polymer P2 has significantly less fluorescence emission in chloroform and the emission $\lambda_{\text{max}}$ in chloroform is significantly redshifted by 92 nm compared to that in hexane. In order to further understand the effect of solvent composition on the emission of the polymers, a

**Table 2: Emission maxima (excited at the corresponding absorption maximum) and fluorescence quantum yields of P1 and P2 as very dilute solutions (maximum absorbance: ca. 0.1) in different solvents.**

<table>
<thead>
<tr>
<th>Solvent</th>
<th>$\lambda_{\text{max}}$ (nm)</th>
<th>$\phi$</th>
<th>$\lambda_{\text{max}}$ (nm)</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexane (1.9)</td>
<td>543</td>
<td>0.021</td>
<td>519</td>
<td>0.070</td>
</tr>
<tr>
<td>p-Xylene (2.268)</td>
<td>525</td>
<td>0.093</td>
<td>585</td>
<td>0.121</td>
</tr>
<tr>
<td>Benzene (2.27)</td>
<td>526</td>
<td>0.091</td>
<td>590</td>
<td>0.103</td>
</tr>
<tr>
<td>Toluene (2.38)</td>
<td>524</td>
<td>0.073</td>
<td>588</td>
<td>0.090</td>
</tr>
<tr>
<td>Anisole (4.33)</td>
<td>526</td>
<td>0.039</td>
<td>604</td>
<td>0.007</td>
</tr>
<tr>
<td>CHCl3 (4.81)</td>
<td>524</td>
<td>0.052</td>
<td>611</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>THF (7.58)</td>
<td>522</td>
<td>0.092</td>
<td>606</td>
<td>0.013</td>
</tr>
<tr>
<td>ODCB (9.93)</td>
<td>530</td>
<td>0.112</td>
<td>612</td>
<td>0.004</td>
</tr>
<tr>
<td>DMF (36.7)</td>
<td>524$^b$</td>
<td>0.015$^b$</td>
<td>612$^b$</td>
<td>&lt;0.001$^b$</td>
</tr>
<tr>
<td>DMSO (46.7)</td>
<td>585$^b$</td>
<td>0.001$^b$</td>
<td>647$^b$</td>
<td>&lt;0.001$^b$</td>
</tr>
</tbody>
</table>

$^a$Fluorescence quantum yield. $^b$Due to the very poor solubility of P1 and P2 in DMF and insolubility of P1 and P2 in DMSO, these solutions were prepared by adding a very small amount of concentrated CHCl3 stock solution of P1 or P2 to respective solvents. P2 has poor solubility in hexane, and the upper, clear portion of a saturated P2 solution in hexane was collected and diluted for measurement. The numbers in brackets are dielectric constants of the solvents.

Fluorescence emission in chloroform and the emission $\lambda_{\text{max}}$ for P2 in DMSO was collected and diluted for measurement. Also, note that due to the very poor solubility of P1 and P2 in DMF and the insolubility of P1 and P2 in DMSO, these solutions were prepared by adding a very small amount of concentrated CHCl3 stock solution of P1 or P2 to respective solvents.

**Figure 7: Absorbance-corrected fluorescence emission (excited at the corresponding absorption maximum) spectra of P1 and P2 as very dilute solutions (maximum absorbance: ca. 0.1) in different solvents. Note that P2 has poor solubility in hexane, and the upper, clear portion of a saturated P2 solution in hexane was collected and diluted for measurement. Also, note that due to the very poor solubility of P1 and P2 in DMF and the insolubility of P1 and P2 in DMSO, these solutions were prepared by adding a very small amount of concentrated CHCl3 stock solution of P1 or P2 to respective solvents.**
that P2 solutions in pure hexane and mixed hexane/toluene solvents. Note indicate that the polymers adopt di

density. The drastic changes in the emission spectra observed, for

Results are compiled in Figure 10 and Figure S5. As can be

emission in hexane, while exhibiting redshifted, broad, and

other solvents; in contrast, 

emission in hexane but vibronically structured emissions in

As can be seen, both polymers respond to the ethanol content

changes but to a different extent. The fluorescence intensity

of P1 dropped slowly until the ethanol percentage reached

50% and then dropped much faster passing 60%. In contrast,

polymer P2 is ultrasensitive to the trace amount of ethanol

content added, with its fluorescence intensity experiencing a fast decrease when the ethanol volume percentage increases. When 10 vol% of ethanol is added to hexane, the fluorescence intensity dropped to only 3.5% of its original value in pure hexane.

In summary, we have successfully synthesized two triphenylene-based conjugated polymers: P1 containing a triphenylene donor unit and a thiophene donor unit and P2 containing an imide-functionalized triphenylene acceptor unit and the same thiophene donor unit. The structures of the D-D and D-A polymers were characterized by 1H NMR and FT-IR, and their molecular weights were determined by gel permeation chromatography. Both polymers are amorphous in nature and thermally stable up to 450°C. The inclusion of the imide functionalization in the triphenylene unit significantly lowered the LUMO energy level and thus the bandgap of the D-A polymer P2 over the D-D polymer P1. P1 and P2 show very different optical properties in hexane and other solvents, indicating that the polymers adopt different conformations in the solvents. P1 shows a broad emission in hexane but vibronically structured emissions in other solvents; in contrast, P2 exhibits a vibronically resolved emission in hexane, while exhibiting redshifted, broad, and featureless emissions in other solvents. It is likely that P1 takes a random coil conformation in good solvents like p-xylene, benzene, toluene, anisole, chloroform, THF, and ODCB, whereas in hexane, it takes an intrachain folding conformation. In the nonpolar hexane solvent, P2 adopts a random coil conformation with blueshifted monomeric fluorescence emissions, while in other good solvents, it adopts the intrachain folding conformation with redshifted, featureless emissions. By virtue of the very different fluorescence properties of these two polymers in hexane and other solvents, the potential of using the polymers to detect the trace amount of ethanol content that is added to gasoline has also been revealed with high sensitivity.

3. Experimental Section

Dichloromethane (DCM) was distilled from CaH2 immediately before use. THF was purified by distillation over sodium/benzophenone prior to use. Acetonitrile was freshly distilled from CaH2 under nitrogen. Unless otherwise stated, all other chemicals were used as received from Sigma-Aldrich or Fisher Scientific without further purification. All reactions were carried out under nitrogen using the standard Schlenk
techniques. $^1$H and $^{13}$C NMR spectra were collected on a Varian Inova 400 MHz NMR spectrometer in deuterated solvents. Chemical shifts are internally referenced to the residual solvent resonance signal. DSC thermograms were recorded on a PerkinElmer DSC 8000 differential scanning calorimeter. FT-IR spectra were recorded with a Shimadzu IRAfinity-1 Fourier transform infrared spectrophotometer. UV-visible absorption spectra were measured with a Hewlett-Packard 8452A diode array spectrophotometer. Fluorescence spectra were recorded on a Shimadzu RF-5301PC spectrofluorophotometer. The GPC measurements were performed at 30°C on a Tosoh EcoSEC HLC-8320GPC system equipped with a differential refractometer, a UV detector, and a styragel column with THF as the eluent. The calibration curve was determined by the use of a set of four polystyrene standards (from 474 to 549000).

CV measurements of the polymer thin films were carried out under argon using a BAS Epsilon EC electrochemical station employing a Pt working electrode, a silver wire reference electrode, and a Pt wire counter electrode. A 0.1 M [Bu$_4$N]PF$_6$ solution in acetonitrile was used as the supporting electrolyte, and the scan was 20 mVs$^{-1}$. Fe/Fe$^+$ was used as the reference and assigned an absolute energy of $-4.80$ eV versus vacuum. The HOMO and the LUMO energy levels were calculated by HOMO = $-(E_{\text{ox onset}} + 4.80)$ (eV) and LUMO = $-(E_{\text{red onset}} + 4.80)$ (eV), respectively.

Monomer M1 and comonomer M3, as well as compound 1, were synthesized following previously reported procedures [43–45].

3.1. Compound 2. Compound 1 (0.50 g, 1.06 mmol) and 3-methoxyphenylboronic acid (0.39 g, 2.53 mmol) were added to a Schlenk flask, and the mixture was subjected to three cycles of pumping and purging with N$_2$. Toluene (50 mL) and ethanol (20 mL) were then added to the flask, followed by the addition of tetrakis(triphenylphosphine)palladium (0) (0.06 g, 0.05 mmol) and sodium bicarbonate (0.67 g, 6.33 mmol). The reaction mixture was stirred under reflux for 16 h. It was then cooled to room temperature and neutralized with 10% HCl. It was then washed with deionized (DI) water, and the aqueous layer was extracted with DCM ($3 \times 30$ mL). The organic layers were combined and dried over magnesium sulfate. The solvent was removed to give thick yellow liquid as the crude product. It was purified by column chromatography on a silica gel with ethyl acetate/hexane (30/70) as the eluent, affording 2 as a yellow solid (0.54 g, 1.02 mmol, 96%). $^1$H NMR (400 MHz, CDCl$_3$, $\delta$ (ppm)): 9.02 (s, 2H, Ar-H), 8.51 (dd, $J = 8$ Hz, 2H, Ar-H), 8.04 (s, 2H, Ar-...
H), 7.37 (d, J = 4 Hz, 2H, Ar-H), 7.35 (d, 2H, Ar-H), 4.05 (s, 6H, -O-CH3), 3.77 (t, J = 8 Hz, 2H, -N-CH2-), 1.73 (m, 2H, -CH2-), 1.23 (m, 18H, -CH2-), 0.84 (t, J = 6 Hz, 3H, -CH3).

3.2. Compound 3. To a Schlenk flask was added compound 2 (0.90 g, 1.71 mmol), and the flask was subjected to three cycles of pumping and purging with N2. To this flask was added freshly distilled DCM (90 mL), followed by the addition of iron (III) chloride (1.38 g, 8.55 mmol) in nitromethane (20 mL). The resulting reaction mixture was stirred at room temperature for approximately 20 min. Methanol (60 mL) was then added, and the mixture was stirred for another 1 h. It was then poured into DI water and was extracted with DCM. The organic layers were combined and dried over MgSO4. It was passed through a filtration column, and the solvent was evaporated to give the orange crude product. It was then recrystallized from DCM/methanol to give compound 3 as yellow solids (0.72 g, 1.37 mmol, 80%).

1H NMR (400 MHz, CDCl3, δ (ppm)): 9.42 (s, 2H, Ar-H), 8.48 (d, J = 12 Hz, 2H, Ar-H), 8.04 (s, 2H, Ar-H), 7.64 (d, J = 8 Hz, 2H, Ar-H), 7.37 (t, J = 8 Hz, 2H, -N-CH2-), 1.73 (m, 2H, -CH2-), 1.22 (m, 18H, -CH2-), 0.84 (t, J = 6 Hz, 3H, -CH3).

13C NMR (400 MHz, CDCl3, δ (ppm)): 168.7, 158.7, 133.9, 129.5, 129.2, 124.9, 124.8, 119.0, 118.7, 105.6, 55.9, 38.6, 32.1, 29.9, 29.8, 29.6, 28.9, 27.2, 14.4.

3.3. Monomer M2. To a RB flask containing compound 3 (0.50 g, 0.95 mmol) and TFA (22.5 mL) was added conc. H2SO4 (5 mL) dropwise. NBS (0.42 g, 2.38 mmol) was then added to the above solution to yield a dark red colored soln. The resulting mixture was stirred at room temperature overnight and was then diluted with DI water. The solution was extracted with DCM. The organic layers were collected and dried over MgSO4. The solvent was evaporated to give reddish solids as the crude product which was purified by recrystallization from DCM/CH3OH to yield monomer M2 as a pale yellow solid (0.36 g, 0.53 mmol, 56%).

1H NMR (400 MHz, CDCl3, δ (ppm)): 8.97 (s, 2H, Ar-H), 8.66 (s, 2H, Ar-H), 7.98 (s, 2H, Ar-H), 4.16 (s, 6H, -O-CH3), 3.76 (t, J = 8 Hz, 2H, -N-CH2-)
3.5. Polymer P2. Polymer P2 was synthesized following the same procedure as for polymer P1. The reaction time was approximately 40 h. Yield: 0.14 g, 0.13 mmol, 86%. 1H NMR (400 MHz, CDCl3, δ (ppm)): 8.99 (br, 2H, Ar-H), 8.83 (br, 2H, Ar-H), 8.05 (br, 2H, Ar-H), 6.84 (1H, thiopene H), 6.75 (1H, thiophene H), 4.20 (br, 4H, -O-CH2-), 4.20 (br, 6H, -O-CH3), 3.82-3.73 (br, 2H, -N-CH2-), 1.75-2.02 (br, 6H, -CH2-). Molecular weights from GPC measurements: Mn 4.40 kDa, Mw 5.09 kDa, PDI 1.16.

Data Availability

Data are included in supplementary information files.

Disclosure

Part of this study is based on Dr. Kuldeep Shetye’s dissertation (Shetye, Kuldeep C. “Synthesis, Characterization and Device Studies of Conjugated Foldamers,” Ph.D. Dissertation, Chemistry and Pharmaceutical Science, University of Missouri-Kansas City, Kansas City, Missouri, USA, 2017).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work is supported by the National Science Foundation (DMR1308577).

**Supplementary Materials**

1H NMR spectrum of monomer M1. Detailed fluorescence spectra and GPC traces of the polymers. (Supplementary Materials)

**References**


