Dithienothiophene (DTT)-based dyes for dye-sensitized solar cells: synthesis of 2,6-Dibromo-DTT

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Abstract
A one-pot synthesis of 2,6-dibromodithieno[3,2-b;2′,3′-d]thiophene (dibromo-DTT, 4) was developed. A key step was bromodecarboxylation of DTT-2,6-dicarboxylic acid, obtained by saponification of the diester 1. The donor-acceptor dye DAHTDTT (13), based on a central 2,6-bis[2′-(3′-hexylthienyl)]dithieno[3,2-b;2′,3′-d]thiophene core (9), was prepared and incorporated in a dye-sensitized solar cell (DSC), which exhibited an energy conversion efficiency of 7.3% with Voc of 697 mV, Jsc of 14.4 mA/cm², and ff of 0.73 at 1 sun.

Keywords
cells, solar, sensitized, dye, dyes, dithienothiophene, dtt, dibromo, 6, 2, synthesis

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Dithienothiophene (DTT)-based Dyes for Dye-Sensitized Solar Cells: Synthesis of 2,6-Dibromo-DTT.

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A one-pot synthesis of 2,6-dibromo-DTT 4 was developed. A key step was bromodecarboxylation of DTT-2,6-dicarboxylic acid, obtained by saponification of the diester 1. The donor-acceptor dye DAHTDTT (13) based on a central 2,6-bis[2′-(3′-hexylthienyl)]dithieno[3,2-b;2′,3′-d]thiophene core (9), was prepared and incorporated in a dye-sensitized solar cell (DSC), which exhibited an energy conversion efficiency of 7.3% with Voc of 697 mV, Jsc of 14.4 mA/cm², and ff of 0.73 at 1 sun.

Recently, organic dye-sensitized solar cells (DSCs) have received considerable attention owing to their wide variety, high molar extinction coefficients of dyes and potentially low cost of fabrication compared with those based on ruthenium dye sensitizers.1-17 Most organic sensitizers consist of a donor fragment (D), a π-conjugated linking segment and an acceptor fragment (A) to achieve broad and intense absorption within the visible to near IR spectrum. When designing dyes for high efficiency DSCs, it is preferable to (i) employ a non-planar structure to prevent self-aggregation, (ii) incorporate appropriate conjugation length for a broad absorption, (iii) use long alkyl chain substituents to minimize electron recombination, (iv) aim for chemical and structural stability.

In this study, we employ a 2,6-bis[2′-(3′-hexylthienyl)]dithieno[3,2-b;2′,3′-d]thiophene core unit 9 for the π-conjugated linking segment. This is due to the relatively high hole mobility exhibited by the fused thiophene core18 in a variety of electronic and optical applications,4-7,19 such as organic thin film transistors18,20-22 and polymer solar cells.21 Owing to the various useful applications of dithieno[3,2-b;2′,3′-d]thiophene (DTT) in the optoelectronic field, the synthesis of DTT derivatives has received much attention.23,24 However many approaches still require multiple steps and harsh conditions.23,25 For the purpose of a convenient synthesis and scale up of the DTT unit, we developed a synthesis of 2,6-dibromo-DTT 4 by one-pot bromodecarboxylation reaction of the DTT-diacid 5.

SCHEME 1. Routes to dibromo-DTT 4 from the diester 1.

recombination from the TiO₂ nanoparticle to the radical cation of the dye owing to the presence of the hexyl substituents. The final components of the light harvesting dye DAHTDTT 13 are the nonplanar triphenyl amine (TPA) donor unit (D) and an α-cyanoacrylic acid group as the electron acceptor (A) to form a D-π-A structure.

The synthesis of the dye DAHTDTT 13 is shown in Scheme 2. 2,6-Dibromo-DTT 4 can be prepared by bromination of DTT 3, itself obtained by decarboxylation of the diacid 2 (overall yield 40% for three steps). However, this classical method, although it gave a good yield, still required a three step process and included the harsh preliminary decarboxylation step as outlined in Scheme 1. We now report an improved synthesis of the dibromo-DTT 4 by a one-pot bromo-decarboxylation of the DTT-2,6-diacid 5 (Scheme 1). This method, followed standard saponification of the diester 6 (heat to reflux in aqueous THF containing NaOH), dilution of the cooled product slurry to dissolve the carboxylate salt, and addition of an excess of NBS (over 6 eq) followed by stirring overnight. Standard extraction with CH₂Cl₂ and basic work-up produced the dibromo-DTT 4 in over 80% yield.

Without column purification, the dibromo-compound 4 was coupled under Suzuki conditions with 3-hexylthiophenyl)PF₆ and 2M K₃PO₄, to afford bis(3-hexylthiophenyl)-DTT 9 in 79% yield. Vilsmeier formylation gave the dialdehyde 10 which underwent a mono-Wittig-Horner chain extension in 53% yield with the ylide derived from the known triarylamine-based phosphonium salt 11. Knoevenagel-type condensation of the resulting aldehyde 12 with cyanoacetic acid (> 20 equiv.) in a microwave reactor gave the required dye 13 in 87% yield after purification by column chromatography.

The UV/VIS absorption spectrum of the dye DAHTDTT 13 in CH₂Cl₂ (0.02 mM) showed a strong broad absorption maximum around 650 nm (εₘₓₓ > 30,000), with the PL emission maximum at 613 nm as shown in Figure 1.

Cyclic voltammetry measurements of the dye 13 in CH₂Cl₂ solutions (0.5 mM) with 0.1 M tetra-n-butylammonium hexafluorophosphate (TBAPF₆) as the supporting electrolyte are summarized in Table 1. Also included are the observed UV/VIS and PL emission spectra and the DFT-calculated HOMO and LUMO energies.

![FIGURE 1. UV/VIS and PL spectra of dye 13 in CH₂Cl₂ (0.02 mM).](image)

The oxidation potential of the dye 13 (0.98 V versus NHE) is sufficiently positive compared with the reduction potential of iodine/iodide, (0.4 V versus NHE) that the photooxidized dye could be expected to be reduced efficiently by the iodine/iodide redox couple. The reduction potential of the dye (−1.29 V vs NHE) was calculated from E_{red}−E_{0-0}(V). As this is more negative value than the level of the TiO₂ conduction band (CB) edge, (−0.5 V vs NHE) we can expect that the photoexcited state of the dye 13 can effectively inject electrons into the conduction band (CB) of TiO₂.

![FIGURE 2. DFT-calculated electron densities of HOMO (bottom) and LUMO (top) orbitals of 13.](image)

Optimized Density Functional Theory (DFT) calculations were carried out utilizing Gaussian09 at the B3LYP/6-31G(d) level of theory. As shown in Figure 2, the electron densities in the HOMO and LUMO of the dye are well separated. The HOMO is generally located on the triphenyl amine unit while the LUMO is on the cyanoacetic acid group; this is a desirable feature for the required charge separation in dye-sensitized solar cells.

DSCs were constructed using a sandwich configuration with an electrolyte composed of 0.6 M 1,2-dimethyl-3-propylimidazoliodide, 0.025 M lithium iodide, 0.04 M iodine, 0.05 M guanidinium thiocyanate (GuSCN), and 0.28 M tert-butylpyridine (TBP) in a dry acetonitrile/valeronitrile solvent mixture (v/v = 85/15). For the titanium oxide different film thicknesses of the transparent and scattering layer were used as follows: 6 μm (6), 6 + 6 scattering layer μm (6 + 6s), 12 μm (12), and 12 + 6 scattering layer μm (12 + 6s) were studied as well as the effect of the co-adsorbent (DCA=3α, 7α-dihydroxy-5β-cholic acid).

The device performances are summarized in Table 2, with optimal results shown in Figure 3 and 4. The dye 13 was adsorbed onto the titania from different solvents. The choice of solvent is crucial, and the device performance varied significantly according to the solvent system chosen. The difference in performance could be due to the interaction of the dye with the solvent, which can affect the photophysical and chemical properties of the dye on the TiO₂ surface. The binding mode and the number of dye molecules adsorbed onto the TiO₂ depend on the solvents. Adsorption of the dye 13 in
CHCl₃ and EtOH solvent mixtures (1:1) yielded the highest device efficiency compared with CHCl₃, CH₂Cl₂, CH₃Cl/EtOH, chlorobenzene, and chlorobenzene/EtOH (see ESI). Optimum devices were obtained using the dye (0.2 mM) in CHCl₃/EtOH (1/1) solutions with overnight soaking on titania. Thus all devices were prepared in 0.2 mM CHCl₃/EtOH (1/1) solutions after overnight soaking.

<table>
<thead>
<tr>
<th>Dye 13</th>
<th>HOMO (Exp)</th>
<th>LUMO (Exp)</th>
<th>Abs (ε × 10^4 cm⁻¹ mol⁻¹)</th>
<th>PL (λmax)</th>
<th>Eₘₒ (V) vs NHE</th>
<th>Eₘₒ/Eₘₐₓ (V) vs NHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry</td>
<td>(eV)</td>
<td>(eV)</td>
<td>(nm)</td>
<td>(nm)</td>
<td>(V)</td>
<td>(V)</td>
</tr>
<tr>
<td>1</td>
<td>-4.67</td>
<td>-2.75</td>
<td>301 (2.0)</td>
<td>613</td>
<td>0.98</td>
<td>2.27</td>
</tr>
<tr>
<td>2</td>
<td>(−5.15)</td>
<td>(−2.88)</td>
<td>(489 (3.0),</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*HOMO = (Eₘₒ vs Fe⁺⁺/Fe⁻⁻ − 4.8 eV), LUMO = HOMO + Eₘₒ. Eₘₒ of the dye were measured in dry CH₂Cl₂ containing 0.1 M tetrabutylammonium hexafluorophosphate (TBAPF₆) as supporting electrolyte, Ag/AgCl as a reference electrode, and glassy carbon as working electrode. Potentials calibrated with Fe⁺⁺/Fe⁻⁻ were converted normal hydrogen electrode (NHE) by addition of +0.63 V. The Eₘₒ transition energy was estimated from the intersection of the absorption and emission spectra.

Using a 6 μm titania film without any co-adsorbent, a device fabricated with dye 13 gave a short-circuit photocurrent density (Jₛ𝑐) of 11.01 mA/cm², an open-circuit voltage (Vₒ𝑐) of 700 mV, and a fill factor (ff) of 0.73, corresponding to an overall conversion efficiency (η) of 5.6%. With 10 mM DCA as co-adsorbent, the device efficiency was increased up to 6.5% (Vₒ𝑐 = 718 mV, Jₛ𝑐 = 12.2 mA/cm², ff = 0.74). These results indicate that the co-adsorbent prevents dye-aggregation thus improving electron injection yield. Adsorption of DCA usually leaves protons on the TiO₂ surface and hence positively charges the surface. Thus the conduction band is shifted, resulting in low Vₒ𝑐. However, in the present case an increase of 20 mV was observed, indicating that charge recombination was suppressed by DCA. With a 6 μm scattering layer (6 + 6s), an increase in Jₛ𝑐 from 12.2 to 12.6 mA/cm² was obtained. However, with a concomitant decrease in the fill factor from 0.74 to 0.71, the device efficiency with a 6 + 6s film (6.4%) was not significantly different from that of a 6 μm film (6.5%). Using a 12 μm film thickness, an increase of Jₛ𝑐 to 13.3 mA/cm² was observed as well as a loss in Vₒ𝑐 and a reduction in fill factor, resulting in a small increase in performance of the cells (6.6%). Using a 12 μm transparent film with a 6 μm scattering layer, 12 + 6s, Jₛ𝑐 significantly increased to 14.7 mA/cm² while Vₒ𝑐 remained the same (698 mV) and the fill factor was 0.70, leading to device efficiency improving to 7.1%. The Jₛ𝑐 of devices made with the dye 13 is slightly higher than that achieved for N719 (14.5 mA/cm²) under the same conditions. Through further optimization, via an increase of co-adsorbent (20 mM), the performance of the cell increased to 7.3% with Vₒ𝑐 of 697 mV, Jₛ𝑐 of 14.4 mA/cm² and fill factor was 0.73.
reached 7.0% and 7.3%, respectively. The increase of short circuit current density with different film thickness is confirmed using the incident photon-to-current conversion efficiency (IPCE) spectrum; the spectrum becomes broader in the sequence $6 < 6 + 6 < 12 < 12 + 6$. The IPCE spectrum of a device using dye 13 with $12 + 6$ exhibits the broad absorbance range starting from the 800 nm and a higher plateau at 67% ($\lambda = 495$ nm) (Figure 4).

In summary, we have developed a simple one-step synthesis of dibromo DTT (4) from diester DTT (1) over 80% yield using one-pot bromo-decarboxylation for the DSCs dyes core unit. The organic DSCs dye DAHTDTT (13) consisted of TPA and DTT coupled with hexylthiophene showing high efficiency of 7.3% with $V_{oc}$ of 697 mV, $J_{sc}$ of 14.4 mA/cm², and $ff$ of 0.73.

EXPERIMENTAL SECTION
Preparation of DAHTDTT (13). A solution of aldehyde 12 (80 mg, 0.09 mmol) in a mixture of acetonitrile (10 mL) and CHCl₃ (10 mL) with an excess of cyanoacetic acid (153 mg, 1.8 mmol) and piperidine (0.1 mL) was heated to 100 °C for 1 h. The reaction mixture was extracted with CH₂Cl₂ and the combined organic extracts were washed with 1N HCl, water, and brine solution. The organic layer was dried over MgSO₄. After removal of the solvent, the residue was purified by column chromatography on silica gel eluting with dichloromethane/methanol/acetic acid (in the volume proportions 10/1/0 to 10/1/0). 1) to give the organic dye 13 (70 mg, 87% yield) as a dark solid, m. p. 144 °C, δ (1H) in CDCl₃ (400 MHz, δ 8.36 (1 H, s), 7.66 (6 H, s), 7.91 (1 H, s), 8.36 (1 H, s), δ C NMR (125 MHz, DMSO-d₆): δ 8.00-8.45 (12 H, br m), 1.37 (4H, br m), 1.62-1.67 (4 H, br m), 2.75 (2 H, t, $J = 7.5$ Hz), 2.83 (2 H, t, $J = 7.5$ Hz), 6.88-6.93 (3 H, m) 7.02-7.07 (6 H, m), 7.11 (1 H, s), 7.24 (1 H, d, $J = 16$ Hz), 7.32 (4 H, t, $J = 7.5$ Hz), 7.47 (4 H, d, $J = 8.5$ Hz), 7.66 (6 H, s), 7.89 (1 H, s), 9.01 (1 H, s), 9.01 (1 H, s), 8.36 (1 H, s), δ C NMR (125 MHz, DMSO-d₆) at 50 °C: 14.6, 17.7, 22.7, 29.1, 29.2 29.3, 29.6, 30.1, 30.4, 31.7, 31.8, 117.5, 121.2, 120.4, 122.6, 123.3, 124.1, 125.0, 128.3, 128.8, 128.9, 129.7, 130.3, 130.7, 131.2, 131.7, 134.0, 135.2, 138.1, 141.0, 141.3, 142.0, 142.8, 142.9, 143.0, 143.7, 147.5, 147.6, 146.4, 164.0; m/z (EI) [rel. intensity] 892.2 [100, (M+)²], 893.2 [60, (M+H)]², 894.2 [20, (M+2H)]². m/z (EI): 892.2310. [M']

Calcld. for C₃₃H₃₄N₄O₁₉S₄, 892.2319. FT-IR (neat cm⁻¹): 2921, 1684, 1569, 1507, 1492, 1392, 1276, 1173, 696.

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Supporting Information Available: Syntheses and spectra of 4, 9, 10, 12, and 13; device fabrication; DFT calculations. This material is available free of charge via the internet at http://pubs.acs.org.