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Synthesis of Dithieno[2,3-*b*:3′,2′-*d*]thiophenes—Building Blocks for Cross-Conjugated *β*-Oligothiophenes

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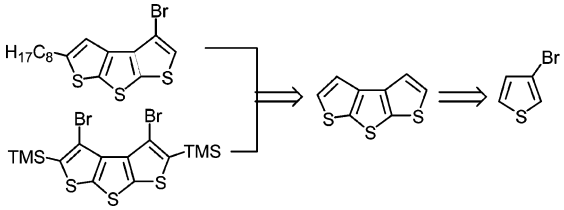

Syntheses of annelated and functionalized *β*-trithiophenes (dithieno[2,3-*b*:3′,2′-*d*]thiophenes), building blocks for the helically annelated, cross-conjugated *β*-oligothiophenes, are reported. UV−vis spectra reveal that the effect of octyl substituents on the onset of electronic absorption in annelated *β*-trithiophenes is negligible compared to the effect of helical distortion in the higher *β*-oligothiophenes.

Oligothiophenes are among the most studied organic materials.[1] It has been shown that annelated oligothiophenes provide materials with significantly improved optical and electronic properties.[2,3] Recently, quasi-linearly annelated α-heptathiophene and helically annelated, cross-conjugated *β*-undecathiophene **1** (Figure 1) have been prepared.[4,5] Syntheses of highly annelated structures such as **1** rely on iterative connections and annelations of thiophene building blocks. In this context, efficient and cost-effective syntheses of annelated *β*-trithiophenes with adequate functionalization[6−10] are a prerequisite for the preparation of higher oligothiophenes and for studies of their material properties.

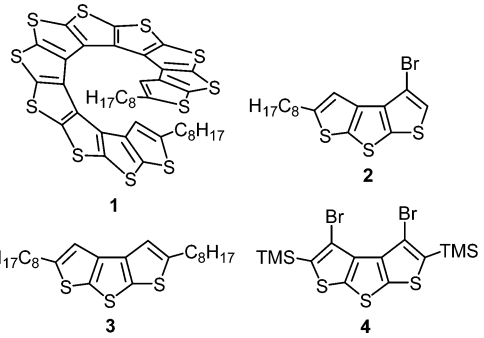

FIGURE 1. *β*-Undecathiophene **1** and functionalized dithieno-[2,3-*b*:3′,2′-*d*]thiophenes **2**−**4**.

We report on the efficient synthesis of functionalized and annelated *β*-trithiophenes (dithieno[2,3-*b*:3′,2′-*d*]thiophenes), **2**−**4**, and studies of the effect of alkyl substitutents on the UV−vis absorption spectra of annelated *β*-trithiophenes, such as **3**. Annelated *β*-trithiophene **2** may be used as the terminal building blocks for higher homologues of **1**, *β*-trithiophene **3** serves as a reference for the determination of the optical band gap in helical *β*-oligothiophenes, and *β*-trithiophene **4** provides most of the cross-conjugated carbon framework in **1** and all other longer *β*-oligothiophenes prepared to date.[5,11]

Syntheses of Annelated *β*-Trithiophenes 2−4. Starting from 3-bromothiophene, the sequence of α-connection and *β*-annelation provide annelated *β*-trithiophene **7** (Scheme 1).[6,12−14a] Optimization of the reaction conditions (solvent and temperature) for the α-connection step gives significantly improved yields compared to the reported values of 10−15%.[12] Lithiation of **7** with LDA (1.5 equiv), followed by addition of 1-bromooctane, provides a mixture of **3**, **8**, and unreacted **7**, which are readily separable by column chromatography. Bromination of **8** with NBS gives **9**. Treatment of **9** with LDA in THF, followed by a MeOH quench, provides rearranged product **2**. The overall isolated yield of **2** for five steps from 3-bromothiophene (Scheme 1) is ∼8%, without recycling of the starting material in the alkylation step.

The previously reported synthesis of **4**, which is the prerequisite tetrafunctional building block for all known $(C_2S)_n$-based helical oligothiophenes, is based on the connection of thiophene derivatives at their *β* positions (*β*-connection), followed by the annelation at the α positions (α-annelation) to form a new thiophene ring.[7,8] One of the problems with this route is that all carbon atoms forming the fused framework of **4** are derived from a rather inaccessible 3,4-dibromothiophene.[14] In the new

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(14) (a) *β*-Trithiophene **7** is commercially available at the cost of $60 000/mol (1-g amounts) or $190 000/mol (100-mg amounts). (b) The current cost per mol from common suppliers of organic reagents is about $2500 for 3,4-dibromothiophene (25-g amounts) compared to only $180 for 3-bromothiophene (100-mL amounts).

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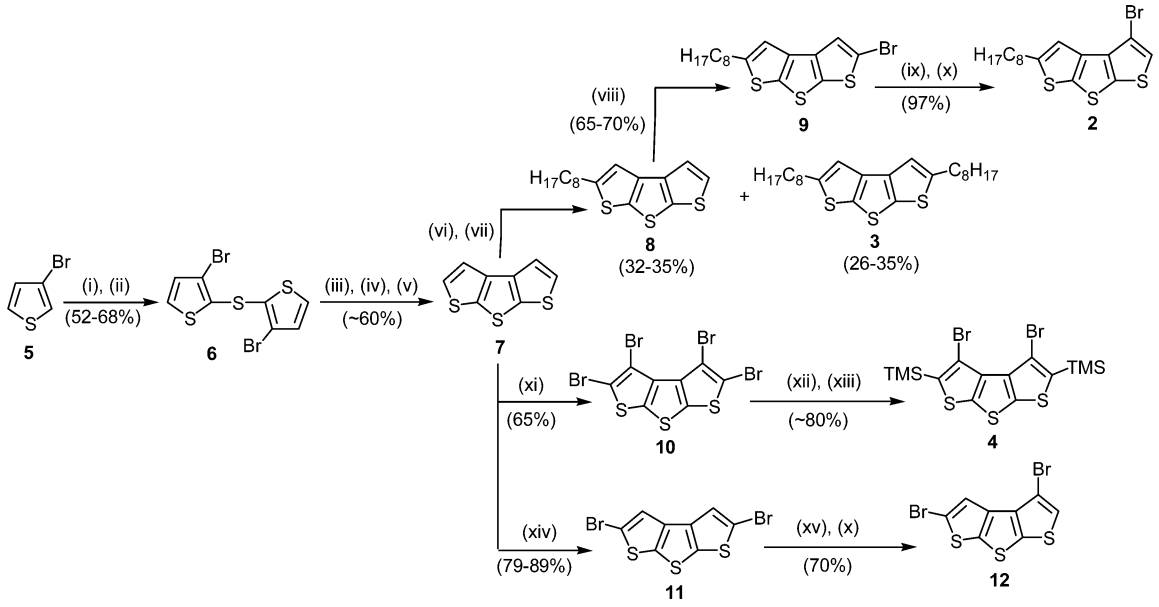
SCHEME 1. Synthesis of Annelated β-Trithiophenes 2−4[a]



[a] Reagents and conditions: (i) LDA (1.05 equiv), toluene, 0 °C, 3 h; (ii) $(PhSO_2)_2S$ (0.5 equiv), −78 °C; (iii) *n*-BuLi (2.2 equiv), THF, −78 °C, 2.5 h; (iv) $ZnCl_2$ (2.4 equiv), −78 °C, 2.5 h, then −50 °C, 2 h; (v) $CuCl_2$ (3.3 equiv), −78 °C; (vi) LDA (1.5 equiv), THF, −78 °C, 3 h; (vii) $CH_3(CH_2)_7Br$ (1.5 equiv); (viii) NBS (1 equiv), chloroform/AcOH (1:1), room temperature for 3−4 h; (ix) LDA (1 equiv), THF, −78 °C for 2.5 h; (x) CH_3OH at −78 °C; (xi) Br_2 (5 equiv), CCl_4, reflux; (xii) *n*-BuLi (2.1 equiv), THF, −78 °C, 3 h; (xiii) TMSCl (2.5 equiv), −78 °C; (xiv) NBS (2 equiv), chloroform/AcOH (1:1), room temperature, 3 h; (xv) LDA (2.1 equiv), THF, −78 °C, 2 h.

synthetic route to **4** (Scheme 1), β-trithiophene **7** is converted to its tetrabromo derivative **10**. Selective Br/Li exchange at the α positions of **10** is followed by a TMSCl quench to provide **4** in ∼50% yield for the two steps from **7**. A more atom-efficient route from **7** to **4** would rely on the double rearrangement of the dibromo derivative **11**. Although **11** can be obtained in good yield,[12] its treatment with LDA provided significant yields of the monorearranged product only; for example, **12**[12] could be isolated in 70% yield after a MeOH quench (Scheme 1).

In summary, dibromotrithiophene **4** is obtained in an overall ∼19% isolated yield in four steps starting from the readily available 3-bromothiophene (Scheme 1).[14b,15]

UV−Vis Spectra for Octyl-Substituted Annelated β-Trithiophenes. The electronic absorption UV−vis spectrum for di-octyl-substituted β-trithiophene **3** is used as a reference for the evaluation of electron delocalization and for an estimate of the optical band gap for the $(C_2S)_n$ helix polymer.[5] Similar di-octyl substitutions have been used for the higher $(C_2S)_n$ oligomers, including **1**, to provide adequate solubility.[5] In this context, the effect of octyl substituents on the UV−vis spectra of annelated β-oligothiophenes is evaluated using β-trithiophenes **3**, **7**, and **8** (Figure 2).

The spectra of **3**, **7**, and **8** show two major bands at $\lambda_{max} \approx$ 251−255 nm and $\lambda_{max} \approx$ 216−221 nm, for which small bathochromic shifts and small increases in molar absorbance (ϵ_{max}) with the increasing number of octyl groups at the α positions are observed.[16] Most importantly, the absorption onsets

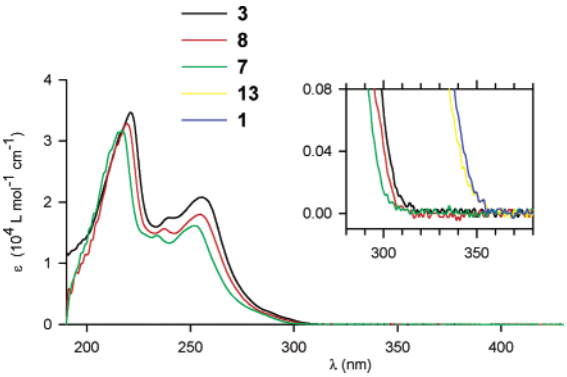


FIGURE 2. Main plot: electronic absorption UV−vis spectra for β-trithiophenes **3**, **7**, and **8** in cyclohexane at room temperature. Inset plot: onsets of absorption for β-trithiophenes **3**, **7**, and **8** and the corresponding onsets for helical β-heptathiophene **13** and β-undecathiophene **1**.

for **3**, **7**, and **8** are within <10 nm of each other, compared to the ∼50-nm bathochromic shift observed for the helically distorted di-octyl-substituted undecathiophene **1** and its heptathiophene homologue **13** (Figure 2).[5,17] Similar small bathochromic shifts were reported for alkyl α-substituted α-oligothiophenes (Table S1, Supporting Information). This result is consistent with the finding that the optical band gap in the $(C_2S)_n$ polymer is primarily determined by the cross-conjugation of the carbon−carbon π system and the helical distortion.[5]

In summary, efficient and cost-effective syntheses of annelated and functionalized β-trithiophenes were developed. This will facilitate the synthetic approaches to the $(C_2S)_n$ homologues and the optimization of their material properties.

(15) A similar isolated yield of ∼19% for dibromotrithiophene **4** is obtained after a three-step synthesis, starting from 3,4-dibromothiophene (ref 7).

(16) UV/vis, cyclohexane, λ_{max}/nm (ϵ_{max}/L mol^{-1} cm^{-1}): **3**, 255 (2.08 × 10^4), 240 (1.75 × 10^4), 221 (3.47 × 10^4); **7**, 251 (1.61 × 10^4), 233 (1.45 × 10^4), 216 (3.16 × 10^4); **8**, 254 (1.80 × 10^4), 236 (1.56 × 10^4), 218 (3.28 × 10^4).

(17) The absorption onsets for thiophene and 2-octylthiophene in cyclohexane are at 254 and 262 nm, respectively.

Experimental Section

5-Octyldithieno[2,3-*b*:3′,2′-*d*]thiophene (8). *n*-BuLi (2.53 M in hexane, 3.0 mL, 7.59 mmol) was added to diisopropylamine (1.2 mL) in THF (12 mL) at 0 °C ($[c]_{LDA}$ = 0.469 M). After 2 h at 0 °C, the LDA solution (12 mL, 5.68 mmol, 1.5 equiv) was added to dithieno[2,3-*b*:3′,2′-*d*]thiophene **7** (743.6 mg, 3.79 mmol, 1 equiv) in THF (25 mL) at −78 °C. The reaction mixture (pale red suspension) was stirred for 3 h at −78 °C, and then 1-bromooctane (1.0 mL, 5.68 mmol, 1.5 equiv) was added at −78 °C. The reaction mixture was kept at −78 °C and then allowed to attain ambient temperature. The usual aqueous extraction with ether gave the crude product as pale yellow oil. Purification by column chromatography (silica, hexane) gave the three fractions: fraction 1, 5,5′-dioctyldithieno[2,3-*b*:3′,2′-*d*]thiophene (**3**) (R_f = 0.78); fraction 2, 5-octyldithieno[2,3-*b*:3′,2′-*d*]thiophene (**8**) (R_f = 0.69); and fraction 3, dithieno[2,3-*b*:3′,2′-*d*]thiophene (**7**) (R_f = 0.59). From three reactions on 740-, 500-, and 500-mg scales, 929 mg (32−35%) of **8**, 1.123 g (26−35%) of **3**, and 301.5 mg (12−21%) of **7** were obtained from 1.753 g of **7**.

8: mp 28−29 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.367 (AB, J = 5.2, 1H, LB = −0.8, GB = 0.5), 7.317 (AB, J = 5.2, 1H, LB = −0.8, GB = 0.5), 7.073 (t, J = 1.2, 1H, LB = −0.8, GB = 0.5), 2.914 (td, J = 7.2, 1.2, 2H, LB = −0.8, GB = 0.5), 1.722 (quin, J = 7.6, 2H), 1.45−1.21 (m, 10H), 0.890 (t, J = 6.8, 3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ aromatic region, expected 8 resonances, found 8 resonances at 148.9, 138.6, 138.2, 137.7, 136.0, 127.3, 118.7, 115.9; aliphatic region, expected 8 resonances, found 8 resonances at 31.8, 31.7, 31.1, 29.3, 29.2, 29.0, 22.7, 14.1. IR (cm^{-1}): 2954, 2926, 2890, 2852 (C−H). LR/HR FABMS (3-NBA matrix): *m*/*z* (ion type, % RA for *m*/*z* = 300−400, deviation for the formula): 308.0732 ([M]$^+$, 100%, −1.4 ppm for $^{12}C_{16}{}^1H_{20}{}^{32}S_3$).

3: liquid at room temperature. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.005 (t, J = 1.2, 2H, LB = −1.0, GB = 0.6), 2.882 (td, J = 7.6, 1.2, 4H, LB = −1.0, GB = 0.6), 1.722 (quin, J = 7.6, 4H), 1.45−1.21 (m, 20H), 0.890 (t, J = 6.8, 6H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ aromatic region, expected 4 resonances, found 4 resonances at 148.6, 138.0, 135.2, 115.8; aliphatic region, expected 8 resonances, found 8 resonances at 31.9, 31.7, 31.1, 29.3, 29.2, 29.0, 22.7, 14.1. IR (cm^{-1}): 2953, 2925, 2853 (C−H). LR/HR FABMS (3-NBA matrix): *m*/*z* (ion type, % RA for *m*/*z* = 350−500, deviation for the formula): 420.1990 ([M]$^+$, 100%, −2.7 ppm for $^{12}C_{24}{}^1H_{36}{}^{32}S_3$), 421.2044 ([M + H]$^+$, 56%, 3.2 ppm for $^{12}C_{24}{}^1H_{37}{}^{32}S_3$).

5-Bromo-5′-octyldithieno[2,3-*b*:3′,2′-*d*]thiophene (9). NBS (297.3 mg, 1.67 mmol, 1 equiv) was added to a solution of **8** (515.4 mg, 1.67 mmol, 1 equiv) in chloroform/AcOH (1:1, 10 mL) at room temperature and protected from light. After 3−4 h at room temperature, the usual aqueous extraction with chloroform gave the crude product as a pale yellow solid. Purification by column chromatography (silica, hexane) and recrystallization from ethanol gave **9** (452.3 mg, 70%) as needle crystals. From two other reactions on 130- and 500-mg scales, 541.8 mg of **9** (65−68%) was obtained from 643.1 mg of **8**. Mp 53−54 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.325 (s, 1H), 7.004 (t, J = 0.8, 1H, LB = −1.0, GB = 0.5), 2.881 (td, J = 8.0, 0.8, 2H), 1.716 (quin, J = 7.6, 2H), 1.43−1.20 (m, 10H), 0.878 (t, J = 7.2, 3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ aromatic region, expected 8 resonances, found 8 resonances at 149.4, 137.6, 137.5, 136.8, 135.6, 122.0, 115.6, 112.4; aliphatic region, expected 8 resonances, found 8 resonances at 31.8, 31.6, 31.1, 29.3, 29.2, 29.0, 22.7, 14.1. IR (cm^{-1}): 2954, 2927, 2851 (C−H). LR/HR FABMS (3-NBA matrix) *m*/*z* (ion type, % RA for *m*/*z* = 350 − 450, deviation for the formula): 385.9826 ([M]$^+$, 100%, 1.7 ppm for $^{12}C_{16}{}^1H_{19}{}^{32}S_3{}^{79}Br$), 387.9798 ([M + 2]$^+$, 99%, 3.5 ppm for $^{12}C_{16}{}^1H_{19}{}^{32}S_3{}^{81}Br$).

4-Bromo-5′-octyldithieno[2,3-*b*:3′,2′-*d*]thiophene (2). *n*-BuLi (2.60 M, 0.4 mL, 1.04 mmol) was added to diisopropylamine (0.16 mL, 1.13 mmol) in THF (3 mL) at 0 °C ($[c]_{LDA}$ = 0.292 M). The LDA solution (2.67 mL, 0.780 mmol, 1 equiv) was added to 5-bromo-5′-octyldithieno[2,3-*b*:3′,2′-*d*]thiophene (**9**; 302.2 mg, 0.780 mmol) in THF (25 mL) at −78 °C (clear yellow solution). After 2.5 h at −78 °C, methanol (excess) was added. The usual aqueous extraction with ether gave the crude product as a pale yellow solid. This crude product was combined with the crude products from two other reactions on 100- and 300-mg scales and was purified by a short column (silica, hexane) to provide 4-bromo-5′-octyldithieno[2,3-*b*:3′,2′-*d*]thiophene (**2**; 687.6 mg, 97%) from 706.4 mg of **9**. A 366-mg sample was further recrystallized from ethanol to give analytically pure **2** (322 mg). M.p. 51−52 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.376 (t, J = 0.8, 1H, LB = −1.0, GB = 0.5), 7.263 (s, 1H), 2.913 (td, J = 7.2, 0.8, 2H), 1.739 (quin, J = 7.6, 2H), 1.48−1.23 (m, 10H), 0.882 (t, J = 6.8, 3H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ aromatic region, expected 8 resonances, found 8 resonances at 149.3, 138.0, 137.12, 137.04, 136.7, 123.6, 115.5, 102.5; aliphatic region, expected 8 resonances, found 8 resonances at 31.8, 31.7, 31.2, 29.3, 29.2, 29.1, 22.6, 14.1. IR (cm^{-1}): 3110, 2950, 2912, 2850 (C−H). LR/HR FABMS (3-NBA matrix) *m*/*z* (ion type, % RA for *m*/*z* = 350−600, deviation for the formula): 385.9827 ([M]$^+$, 89%, −1.5 ppm for $^{12}C_{16}{}^1H_{19}{}^{32}S_3{}^{79}Br$), 387.9808 ([M + 2]$^+$, 100%, 0.9 ppm for $^{12}C_{16}{}^1H_{19}{}^{32}S_3{}^{81}Br$).

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Supporting Information Available: Experimental details and NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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