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Structures of 2,5-diaryl- and 2,3,5,6-tetra[3,2-*b*]thiophene synthesized by the palladium-catalyzed Suzuki-Miyaura cross-coupling reaction

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Abstract

The crystal structures of 2,5-di(ethoxyphenyl)-3,6-dibromothieno[3,2-*b*]thiophene (**I**) and 2,5-di(ethoxyphenyl)-3,6-diphenylthieno[3,2-*b*]thiophene (**II**) have been studied in order to evaluate the planarity of these molecules. The aromatic systems introduced to the thieno[3,2-*b*]thiophene core structure show a degree of rotation from 30.94° to 66.56°. The crystal packing of (**I**) are characterized by $\pi\cdots\pi$ stacking, while in (**II**), C-H $\cdots\pi$ and C-H \cdots O interactions are observed.

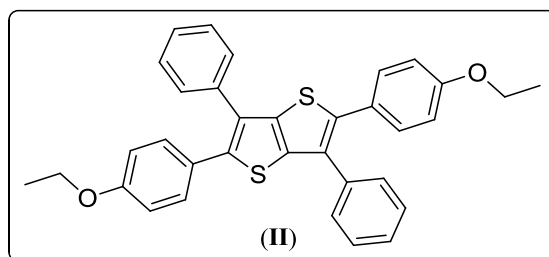
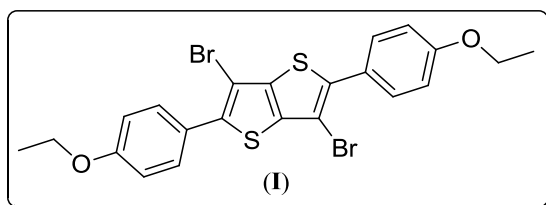
Keywords. thieno[3,2-*b*]thiophene, palladium-catalyzed, Suzuki-Miyaura, cross-coupling.

1. INTRODUCTION

Thieno[3,2-*b*]thiophene possesses a rigid structure and an extended π -conjugation. This electron-rich two annulated thiophene structure enable it to construct conjugated and low band gap organic semiconductors. Functionalized thieno[3,2-*b*]thiophene units have been incorporated into, or designed as a part of the skeleton of conjugated oligomers and polymers to improve the electronic properties of the materials [1]. These kinds of materials were applied to produce high-performance organic field-effect transistors (OFETs) [2], organic light-emitting diodes (OLEDs) [3], and photovoltaics devices [4]. In fact, the performance of a functionalized material depends heavily on its molecular structure and the stacking motif. Therefore, design of functional molecular solid-state

structures, or arrangements, through tuning of the intermolecular interactions is essential.

One of the convenient methods for fine-tuning band gaps involves the arylation which promotes a greater conjugation in the ground state. This method is also employed for adjusting the band gap of organic materials and increasing intermolecular interactions in the solid state. The objective of this work was the partial and full functionalization of the thieno[3,2-*b*]thiophene ring starting from 2,3,5,6-tetrabromothieno[3,2-*b*]thiophene [5] using the palladium-catalyzed Suzuki-Miyaura cross-coupling reaction [6]. Herein, the synthesis, the molecular and the crystal structures of the synthesized 2,5-di(ethoxyphenyl)-3,6-dibromothieno[3,2-*b*]thiophene (**I**) and 2,5-di(ethoxyphenyl)-3,6-diphenylthieno[3,2-*b*]thiophene (**II**) will be discussed.



2. EXPERIMENTAL

2.1. Chemicals

Catalysts, solvents and other chemicals were purchased from Sigma-Aldrich or Merck and were used as received unless otherwise indicated. THF

were refluxed over sodium wire in the presence of benzophenone as indicator and redistilled just before used. The Suzuki-Miyaura cross-coupling reactions were conducted under deaerated conditions.

2.2. Instrumentation

The ^1H NMR and ^{13}C NMR spectra were recorded on a Bruker Avance 500 NMR spectrometer in CDCl_3 . Chemical shift was reported in ppm units with tetramethylsilane (TMS) as internal reference. Splitting patterns are designated as s (singlet), d (doublet), t (triplet), q (quartet) and m (multiplet). X-ray measurements were performed on an Agilent SuperNova (single source at offset, Eos detector) diffractometer at the Department of Chemistry, KU Leuven, Belgium.

2.3. Synthesis and crystallization

2.3.1. Synthesis of 2,5-di(ethoxyphenyl)-3,6-dibromothieno[3,2-*b*]thiophene (**I**)

Toluene (4 ml) was deoxygenated and saturated with argon by exchanging between vacuum and a stream of argon (3 times). 2,3,5,6-Tetrabromothieno[3,2-*b*]thiophene (230 mg, 0.5 mmol, 1.0 equiv) and $\text{Pd}(\text{Ph}_3\text{P})_4$ (57.7 mg, 0.05 mmol, 0.10 equiv) were dissolved in this solvent at 60-70 °C. To the obtained solution was added H_2O (1 ml), K_3PO_4 (212 mg, 1.0 mmol, 2.0 equiv), and 4-ethoxyphenylboronic acid (182.6 mg, 2.2 equiv). The reaction was vigorously stirred under argon atmosphere at 110 °C until TLC (100 % *n*-hexane) showed the complete consumption of the starting material (about 8 hours). The reaction mixture was cooled by ice water. The white solid separated was filtered, washed several times with toluene and recrystallized from hot *n*-hexane:ethyl acetate (1:1, v/v) to give (**I**) (155.5 mg, yield 58 %) as white needles; mp 230-231 °C. ^1H NMR (CDCl_3 , 500 MHz): δ (ppm) 7.36 (t, $J = 8.0$ Hz, 1 H, *aromatic*), 7.27 (m, 2 H, *aromatic*), 6.95 (m, 1 H, *aromatic*), 4.10 (q, $J = 7.0$ Hz, 2 H, CH_2), 1.45 (t, $J = 7.0$ Hz, 3 H, CH_3); ^{13}C NMR (CDCl_3 , 125 MHz): δ (ppm) 159.1 ($\text{C}-\text{O}$), 139.4, 138.8, 134.0, 129.8, 121.3, 115.2, 114.9, 100.1, 63.6 ($\text{O}-\text{CH}_2$), 14.8 (CH_3).

2.3.2. Synthesis of 2,5-di(ethoxyphenyl)-3,6-diphenylthieno[3,2-*b*]thiophene (**II**)

(**I**) (108 mg, 0.2 mmol) and $\text{Pd}(\text{Ph}_3\text{P})_4$ (24 mg, 0.02 mmol, 0.10 equiv) were dissolved in toluene (4 ml) that was degassed and saturated with argon. To the mixture were added phenylboronic acid (47 mg,

0.44 mmol), K_3PO_4 (170 mg, 4.0 equiv) and distilled water (1 ml). The resulting mixture was refluxed at 110 °C, during which the progress of the reaction was monitored by TLC (100 % *n*-hexane). After 8 h, phenylboronic acid (21 mg, 0.2 mmol) and $\text{Pd}(\text{Ph}_3\text{P})_4$ (12 mg, 0.01 mmol, 0.05 equiv) were added; the mixture was further refluxed for 12 h. After the reaction was completed, the reaction mixture was diluted with 20 ml toluene, washed with water (3 times) and dried over anhydrous Na_2SO_4 . (**II**) was isolated by column chromatography (*n*-hexane:ethyl acetate 95:5, v/v) as a white solid (64 mg, yield 60 %); mp 231-233 °C. (**II**) was further purified by recrystallized from *n*-hexane:ethyl acetate (3:1, v/v) solution. ^1H NMR (CDCl_3 , 500 MHz): δ (ppm) 7.48 (dd, $J = 8.0$ Hz and 1.0 Hz, 2 H, *aromatic*), 7.37 (dt, $J = 8.0$ Hz and 1.0 Hz, 2 H, *aromatic*), 7.33 (d, $J = 8.5$ Hz, 1 H, *aromatic*), 7.16 (t, $J = 8.0$ Hz, 1 H, *aromatic*), 6.92 (td, $J = 7.5$ Hz and 0.5 Hz, 1 H, *aromatic*), 6.86 (m, 1 H, *aromatic*), 6.79 (m, 1 H, *aromatic*), 3.86 (q, $J = 7.0$ Hz, 2 H, CH_2), 1.13 (t, $J = 7.0$ Hz, 3 H, CH_3). ^{13}C NMR (CDCl_3 , 125 MHz): δ (ppm) 158.9 ($\text{C}-\text{O}$), 139.0, 138.9, 135.7, 135.2, 130.8, 129.5, 129.1, 128.8, 127.7, 121.6, 114.8, 114.6, 63.3 ($\text{O}-\text{CH}_2$), 14.7 (CH_3).

2.4. Structure solution and refinement

The X-ray diffraction data were collected on an Agilent SuperNova diffractometer using mirror-monochromated MoK_α radiation ($\lambda = 0.71073$ Å). Using Olex2 [7]. The structure was solved with the SHELXS [8] structure solution program using Direct Methods and refined by full-matrix least-squares methods based on F^2 using SHELXL [9]. All non-hydrogen atom parameters were refined anisotropically. All hydrogen atoms were placed in idealized positions and refined in riding mode with U_{iso} values assigned as 1.2 times those of the parent atoms (1.5 times for methyl groups), with a C-H distance of 0.95 (aromatic), 0.98 (methyl) or 0.99 Å (methylene). The crystal data, the data collection, and the structure refinement details are summarized in table 1.

3. RESULTS AND DISCUSSION

The molecular structures of the diaryl (**I**) and tetraaryl (**II**) derivatives of thieno[3,2-*b*]thiophene are shown in Fig. 1. The bond lengths and angles are in good agreement with the average values in the Cambridge Structure Database (CSD, version 5.37, November 2015) [10].

In order to enlarge the π -conjugated system of

the thieno[3,2-*b*]thiophene, aromatic rings were introduced into the thieno[3,2-*b*]thiophene skeleton by Suzuki-Miyaura cross-coupling reactions. In

these reactions, the site-selectivity at the C2 and C5 positions was observed due to the effect of the sulphur heteroatom [10].

Table 1: Crystal data, data collection and structure refinement parameters for (I) and (II)

	(I)	(II)
CSD code	CSD 1497991	CSD 1497992
Chemical formula	C ₂₂ H ₁₈ Br ₂ O ₂ S ₂	C ₃₄ H ₂₈ O ₂ S ₂
<i>M_r</i>	538.30	532.68
Crystal system, space group	Monoclinic, <i>P</i> 2 ₁ / <i>n</i>	Triclinic, <i>P</i> -1
Temperature (K)	100	100
<i>a</i> , <i>b</i> , <i>c</i> (Å)	3.9155(3), 14.7861(11), 17.4836(14)	5.7894(5), 9.3851(11), 13.4001(14)
α , β , γ (°)	90, 91.395(7), 90	82.144(9), 84.093(8), 75.788(9)
<i>V</i> (Å ³)	1011.92(13)	697.35(13)
<i>Z</i>	2	1
Radiation type	MoK α	MoK α
μ (mm ⁻¹)	4.23	0.22
Crystal size (mm ³)	0.3 × 0.1 × 0.1	0.45 × 0.12 × 0.08
Data collection		
<i>T_{min}</i> , <i>T_{max}</i>	0.679, 1.000	0.638, 1.000
No. of measured, independent and observed [<i>I</i> > 2σ(<i>I</i>)] reflections	10583, 2054, 1917	14116, 2842, 2541
<i>R_{int}</i>	0.033	0.047
(sinθ/λ) _{max} (Å ⁻¹)	0.625	0.625
Refinement		
<i>R</i> [<i>F</i> ² > 2σ(<i>F</i> ²)], <i>wR</i> (<i>F</i> ²), <i>S</i>	0.020, 0.048, 1.07	0.040, 0.104, 1.07
No. of reflections	2054	2842
No. of parameters	128	173
Δρ _{max} , Δρ _{min} (e Å ⁻³)	0.36, -0.25	0.47, -0.27

Compound (I) crystallizes in space group *P*2₁/*n*, while (II) crystallizes in space group *P*-1. Both compounds have an inversion centre located in the middle of the C1-C1ⁱ bond in (I) and C2-C2ⁱⁱ bond in (II) (Symmetry codes: (i) -*x*, -*y* + 1, -*z* + 1; (ii) -*x* + 1, -*y* + 1, -*z*; Fig. 1). As a result, the asymmetric unit consists of one half of the molecule, the second half being generated by an inversion centre. The fused thiophene rings in both structures are planar (r.m.s. deviation = 0.002 Å for (I) and 0.001 Å for (II)). The introduced phenyl rings are non-planar with the core structure. In (I), the dihedral angle between the thieno[3,2-*b*]thiophene ring and the ethoxyphenyl ring is 46.93(8)°. The rotation is to reduce the repulsion between Br1...H5 and S1...H9, that is in good agreement with the case of 3,6-dibromo-2-(4-*tert*-butylphenyl)-5-(4-methylstyryl)thieno[3,2-*b*]thiophene [12]. In (II), the dihedral angles between the thieno[3,2-*b*]thiophene ring and the two

phenyl rings are 31.24(6)° and 66.61(7)°, respectively. In addition, in this compound, the ethoxyphenyl ring is almost perpendicular to the phenyl ring (the dihedral angle between both rings is 64.09(8)°). Only one tetra-substituted thieno[3,2-*b*]thiophene structure similar to (II) is present in the CSD: 2,3,5,6-tetraphenylthieno[3,2-*b*]thiophene (refcode WEXBOS, [12]). In that case, the 2,5-phenyl rings and the 3,6-phenyl rings are rotated out of the plane of the thieno[3,2-*b*]thiophene ring by dihedral angles of 35.31(7) and 59.38(6)°, respectively. Possibly, the ethoxy-substituted phenyl groups force the un-substituted ones to rotate less from the core structure, while they themselves are twisted more. The packing of (I) shows π-π stacking between the 4-ethoxyphenyl rings [Cg1...Cg1ⁱ = 3.9155(3) Å; Cg1 is the centroid of the C4-C9 ring; symmetry code: (i) *x* + 1, *y*, *z*; Fig. 2a]. A weak C-Br...π interaction is observed [C2-Br1...Cg1ⁱⁱ;

$\text{Br1}\cdots\text{Cg1}^{\text{ii}} = 3.9290(9) \text{ \AA}$; symmetry code: (ii) $-x + 1, -y + 1, -z + 1$].

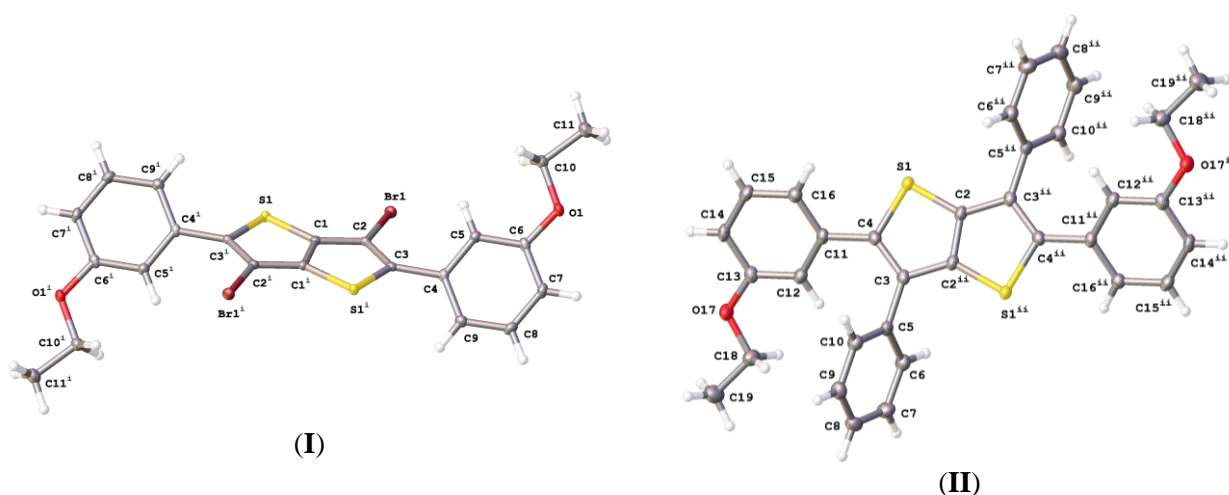


Figure 1: Molecular structures of **(I)** and **(II)**, showing the atom-labelling schemes. Displacement ellipsoids are drawn at the 50% probability level. [Symmetry codes: (i) $-x, -y + 1, -z + 1$; (ii) $-x + 1, -y + 1, -z$]

Due to the presence of the four bulky substituents, the packing of **(II)** shows no π - π stacking (Fig. 2b), which is in agreement with the analogous structure 2,3,5,6-tetraphenylthieno[3,2-*b*]thiophene [12]. C-H \cdots O interactions are present in the crystal packing resulting in a chain of molecules in the (204) plane. Parallel chains of the molecules

are linked by C-H \cdots π interactions with the ethoxy-substituted phenyl groups (table 2, Fig. 2b).

Possible intermolecular S \cdots S interactions which could increase the electronic transport between neighboring molecules are not observed in the crystal packing of both **(I)** and **(II)**.

Table 2: Hydrogen bond geometry (\AA , $^\circ$) for **(II)**

D-H \cdots A	D-H	H \cdots A	D \cdots A	D-H \cdots A
C14-H14 \cdots O17 ⁱ	0.95	2.54	3.476(2)	168
C6-H6 \cdots Cg1 ⁱⁱ	0.95	2.67	3.515(2)	148
C19-H19C \cdots Cg2 ⁱⁱⁱ	0.98	2.87	3.697(2)	143

Symmetry codes: (i) $-x - 1, -y - 1, -z - 1$; (ii) $x + 1, y, z$; (iii) $-x, -y + 1, -z + 1$.

4. CONCLUSION

In conclusion, the crystal structures of a 2,5-diaryl- and a 2,3,5,6-tetraaryl derivatives of thieno[3,2-*b*]thiophene were recorded and analyzed. The results showed that the phenyl rings introduced into the thieno[3,2-*b*]thiophene core structure undergo a degree of rotation from 30.94° to 66.56° . In addition, π \cdots π stacking is the dominant arrangement in the crystal packing of **(I)**. On the other hand, C-H \cdots π and C-H \cdots O interactions are observed in the crystal structure of **(II)**. Intermolecular S \cdots S interactions which could increase the electronic transport between neighboring molecules are not found in the crystal packing of both **(I)** and **(II)**. Attempts to planarize the introduced aromatic rings with the thieno[3,2-*b*]thiophene by the FeCl_3 -oxidation reaction are in

progress in our laboratory and will be reported in near future.

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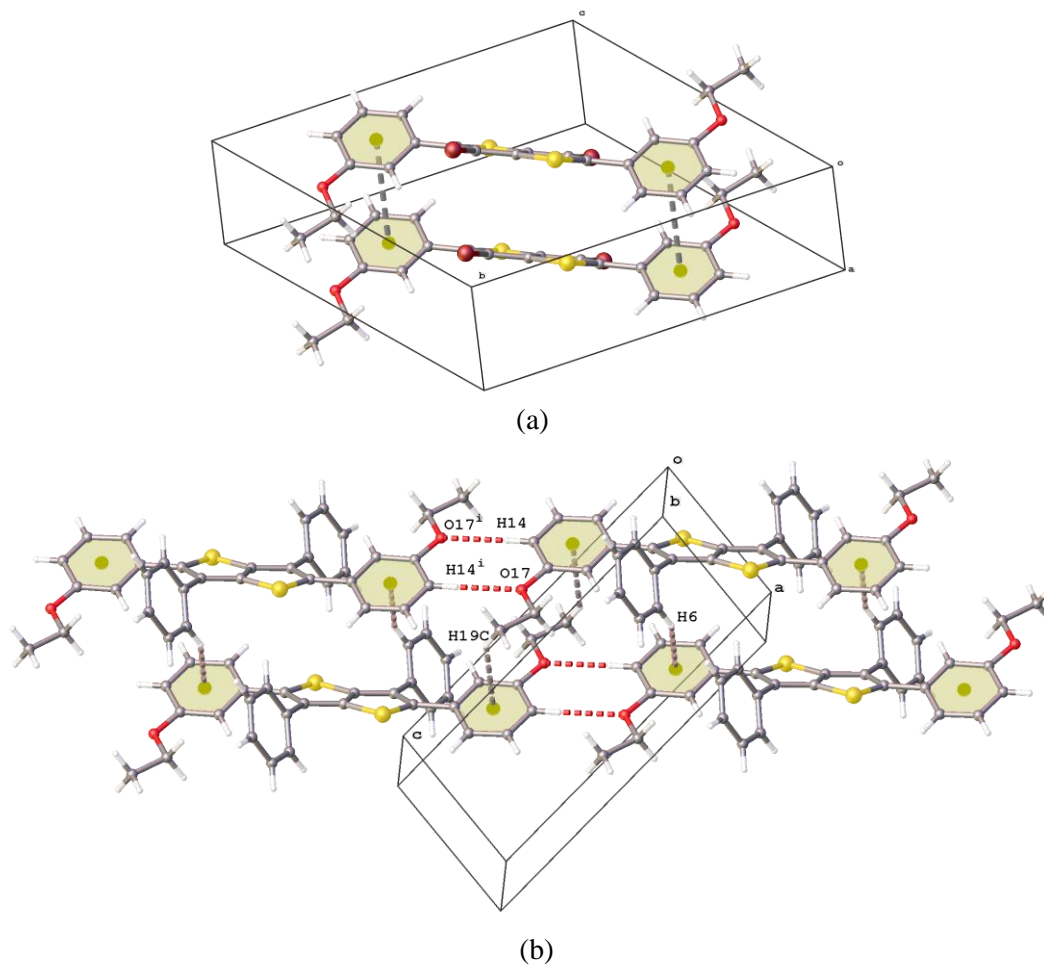


Figure 2: (a) π - π stacking in (I); (b) partial crystal packing of (II) showing C-H... π (grey) and C-H...O (red) interactions

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