

# Synthesis and Chiroptical Properties of Optically Active, Regioregular Oligothiophenes

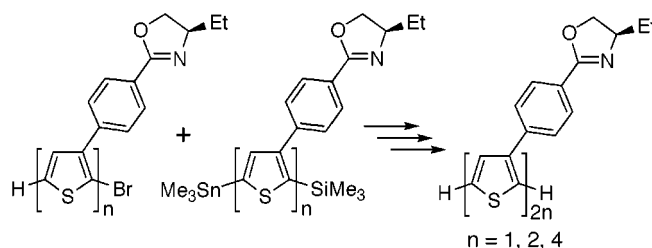
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## ABSTRACT



A series of regioregular oligothiophenes bearing chiral oxazoline residues have been synthesized in high yields by a stepwise synthesis using the Stille cross-coupling reaction. The chiroptical properties of the oligothiophenes up to the octamer were investigated with UV–visible and CD spectroscopies. The octamer showed split-type Cotton effects in chloroform as a good solvent in the presence of a poor solvent such as acetonitrile, while the lower molecular weight oligomers exhibited almost no induced CD.

The design and synthesis of chiral  $\pi$ -conjugated polymers and oligomers with a well-defined structure has attracted considerable interest in the past decade<sup>1</sup> due to their potential applications not only in optoelectronic devices<sup>2</sup> but also in enantioselective sensors, catalysts, and adsorbents.<sup>1a,b,3</sup> The chiral  $\pi$ -conjugated polymers and oligomers that have been

most intensively studied in this respect are the chiral regioregular (head-to-tail, HT) polythiophenes (PTs).<sup>4</sup> Chiral PTs are significantly different from other optically active polymers,<sup>5</sup> and they exhibit optical activity in the  $\pi$ – $\pi^*$  transition region derived from the main chain chirality when they are aggregated to form a  $\pi$ -stacked supramolecular aggregate through intermolecular interactions in a poor solvent, at low temperature, or in a film, whereas they show no optical activity in this region in a good solvent or at high temperatures.<sup>4</sup> Nevertheless, a complete structural interpretation on the origin of the optical activity in the aggregated chiral PTs still remains unclear. Langeveld et al. proposed

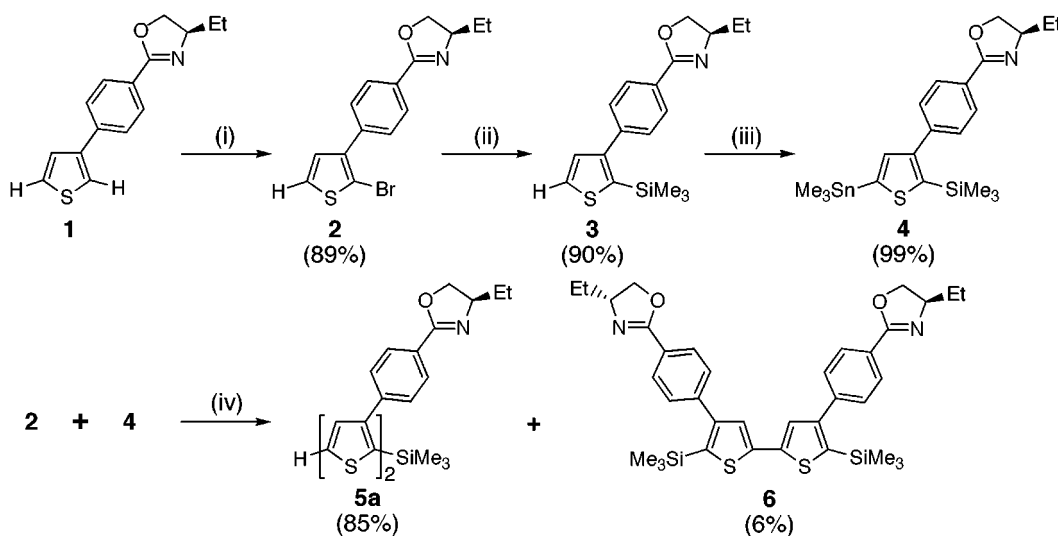
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Scheme 1<sup>a</sup>

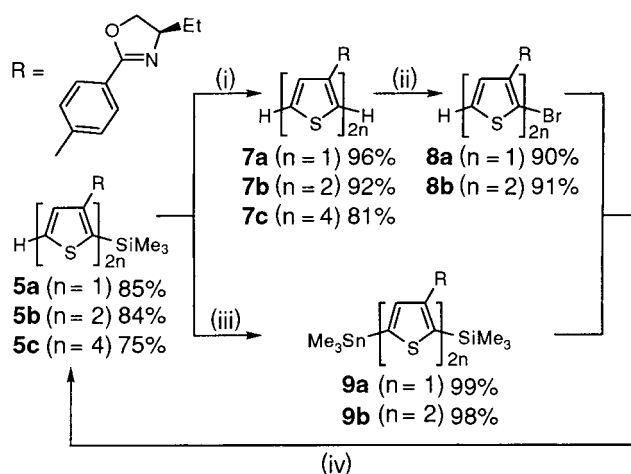
<sup>a</sup> Reagents and conditions: (i) NBS, DMF, rt, 4 days; (ii) *n*-BuLi, Me<sub>3</sub>SiCl, THF, -98 °C, 20 min; (iii) LDA, Me<sub>3</sub>SnCl, THF, -78 °C, 20 min; (iv) Pd<sub>2</sub>(dba)<sub>3</sub>, P(PhO)<sub>3</sub>, CuO, DMF, 100 °C, 15 h.

the helical packing of predominantly planar chains for the chiral aggregated PTs rather than a helical cisoidal conformation.<sup>6</sup>

We have previously shown that an optically active HT-PT, poly[(*R*)-3-(4-(4-ethyl-2-oxazolin-2-yl)phenyl)thiophene] (PEOPT), exhibited a unique induced circular dichroism (ICD) upon complexation with metal ions in a good solvent, chloroform, for PEOPT, accompanied by negligible changes in the UV–visible spectra, which indicates that chirality induction may not be derived from the chiral  $\pi$ -stacked aggregations of PEOPT but from the main chain chirality such as a predominantly one-handed helical structure induced by intermolecular coordination of the oxazoline groups to the metal ions.<sup>7</sup> We also found dramatic changes in the ICDs of PEOPT depending on the nature of the solvent; the addition of a poor solvent such as methanol or acetonitrile to the chloroform solution of PEOPT induced a conformational change in PEOPT which caused chiral aggregations with different handedness.<sup>8</sup> Here, we report the synthesis and chiroptical study of a series of optically active oligothiophenes with well-defined structures as the model oligomers of PEOPT. The present model studies will serve to elucidate the origin of the optical activity in chiral PTs.

The regioregular oligomers (**7a–7c**) were prepared starting from optically pure (*R*)-3-(4-(4-ethyl-2-oxazolin-2-yl)phenyl)thiophene monomer (**1**)<sup>7</sup> according to Schemes 1 and 2. The regioselective bromination at the 2-position of **1** using *N*-bromosuccinimide (NBS), followed by transmetalation with *n*-BuLi and then quenching with trimethylsilyl chloride afforded **3** in high yield. Regioselective stannylation at the 5-position of **3** quantitatively gave **4**. Subsequent Pd-

catalyzed, CuO-modified Stille cross-coupling<sup>9</sup> with **2** afforded HT-**5a** in 85% yield together with the head-to-head (HH) byproduct **6** (6%), which could be easily separated by silica gel chromatography. In the Stille coupling reaction, P(PhO)<sub>3</sub> was superior to PPh<sub>3</sub> as the palladium ligand. When PPh<sub>3</sub> was used as the ligand under the same conditions in the Stille coupling reaction, the yield (45%) and selectivity of HT-**5a** (**5a**:**6** = 10:1) decreased.<sup>10</sup> The trimethylsilyl protecting group was removed with tetrabutylammonium fluoride (TBAF) in THF to give the HT-dimer (**7a**) in 96% yield. In the same way, the HT-tetramer (**7b**) and HT-octamer (**7c**) were prepared in high yields without difficulty. **7a** is a colorless solid (mp 45 °C), while **7b** and **7c** are pale yellow

Scheme 2<sup>a</sup>

<sup>a</sup> Reagents and conditions: (i) TBAF, THF, rt, 20 min; (ii) NBS, DMF, rt, 3 days; (iii) LDA, Me<sub>3</sub>SnCl, THF, -78 °C, 20 min; (iv) Pd<sub>2</sub>(dba)<sub>3</sub>, P(PhO)<sub>3</sub>, CuO, DMF, 100 °C, 6 h.

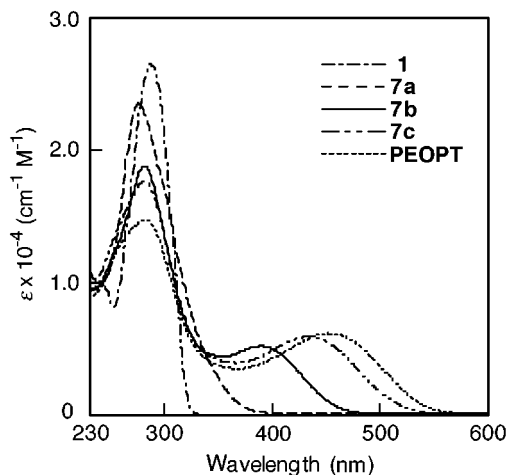
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(mp 112 °C) and orange solids (decomposition at 165 °C), respectively. All the oligomers were purified by silica gel chromatography or by preparative, recycle HPLC and characterized and identified using  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectroscopies, elemental analyses, and mass measurements (see Supporting Information).

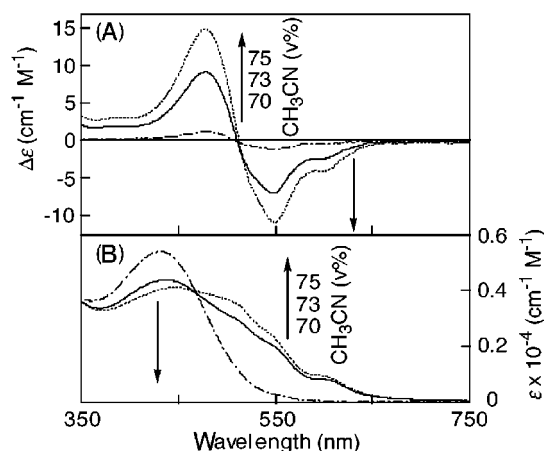
The chiroptical properties of these optically active oligomers were investigated using UV–visible and CD spectroscopies. The UV–visible spectra of the oligothiophenes in chloroform exhibit a tendency well correlated with the number of repeating units ( $n$ ) of the oligomers (Figure 1).



**Figure 1.** UV–visible spectra of oligothiophenes and HT-PEOPT in chloroform in a 0.10 cm quartz cell at rt with a concentration of 0.25 mg/mL.

The absorbance maximum ( $\lambda_{\text{max}}$ ) for the  $\pi$ – $\pi^*$  transition nonlinearly increases as  $n$  increases ( $\lambda_{\text{max}}$ : **7a** (275), **7b** (390), and **7c** (435 nm)). A similar tendency was observed for the maximum emission wavelength ( $\lambda_{\text{em}}$ : **7a** (447), **7b** (510), and **7c** (561)), although HT-PEOPT having an extended  $\pi$ -conjugation ( $n = \text{ca. } 20$ ) has red-shifted absorption ( $\lambda_{\text{max}} = 452$  nm; Figure 1) and emission maximum ( $\lambda_{\text{em}} = 573$  nm). The oligomers exhibit an emission with different colors from blue (**7a**) to green (**7b**) and yellow (**7c**) both in chloroform solution and in the solid and are correlated with the emission maximum.

CD measurements were performed in order to study the molecular weight dependent, chiral aggregation formation in solution in the presence of poor solvents or Cu ions. The oligomers showed no ICD in chloroform in the  $\pi$ – $\pi^*$  transition region as anticipated for the chiral PTs in random conformations.<sup>4</sup> In sharp contrast, the octamer exhibited an apparent, split-type ICD at longer wavelengths (350–650 nm) upon the addition of a poor solvent such as methanol (87.5–97.5%, v/v) or acetonitrile (Figure 2A; 70–75%, v/v) to the chloroform solution, and the solution spontaneously



**Figure 2.** CD (A) and UV–visible (B) spectral changes of the octamer (**7c**) in acetonitrile–chloroform mixtures in a 1.0 cm quartz cell at rt just after the preparation of the sample solutions. The concentration of **7c** is 0.025 mg/mL.

changed from yellow-orange to purple. These significant changes in the ICDs were accompanied by a gradual red-shift in the absorption with a clear isosbestic point (Figure 2B). However, the ICD intensity was reduced to one-half compared to that of PEOPT and almost twice as much poor solvent by volume was required for the appearance of the ICD for the octamer. The dimer and tetramer showed almost no ICD even in the presence of excess poor solvents (99%, v/v). Similar ICDs with solvatochromism have been observed for PEOPT, but the Cotton effect signs were significantly dependent on the solvents; the addition of methanol and acetonitrile to the chloroform solution of the PEOPT induced a conformational change in the PEOPT which caused opposite chiral aggregations, thus showing mirror image ICDs.<sup>8</sup>

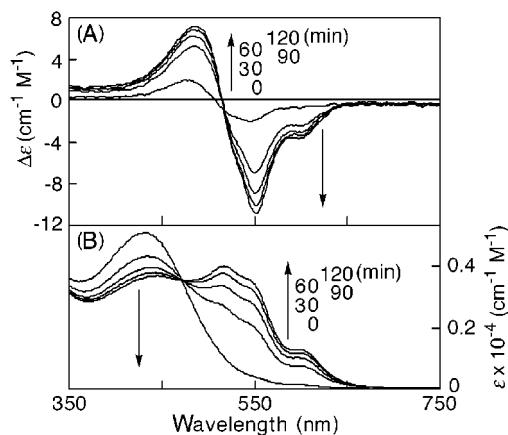
However, as for the octamer, the ICD signs were the same and independent of the solvents. The reason is not clear at the present. The CD and absorption of the octamer in the mixtures of chloroform and poor solvents were found to be highly time dependent, and the ICD intensities increased with time (Figure 3). These results are in contrast to PEOPT,<sup>8</sup> indicating that the intermolecular  $\pi$ -stacked aggregation formations that strongly depend on the  $\pi$ -conjugation length and polymers tend to aggregate in a short time for the chirality induction on the main chain. Similar time-dependent folding was reported by Moore and co-workers for chiral, apolar *m*-phenylene ethynylene oligomers.<sup>11</sup>

In the presence of Cu ions (copper(I) triflate ( $\text{Cu}(\text{OTf})$ ) and  $\text{Cu}(\text{OTf})_2$ ), the octamer also exhibited a weak ICD in the main chain in chloroform accompanied by slight changes in the UV–visible spectra. The ICD patterns were much different from those of the PEOPT–Cu complexes in chloroform (see Supporting Information). These results suggest that the octamer is not long enough to form a chiral complex such as the PEOPT–Cu complexes.

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**Figure 3.** Changes in CD (A) and UV–visible (B) spectra of **7c** with time in an acetonitrile–chloroform mixture (72.5%, v/v) in a 1.0 cm quartz cell at 25 °C. The concentration of **7c** is 0.025 mg/mL.

In summary, we have synthesized a series of oligothiophenes with well-defined regiospecificity (HT), chirality, and molecular weights. Although achiral HT-oligo(3-substituted thiophene)s up to a 12-mer<sup>12</sup> and isomerically

pure, achiral oligothiophenes up to a 48-mer<sup>13</sup> are known, the optically active octamer prepared in this study may be among the longest class of oligomers with optical activity. Further studies including the synthesis of longer oligomers, X-ray structure determinations, and scanning tunneling microscopic analyses<sup>14</sup> of the optically active oligomers will be useful to elucidate the origin of the optical activity in chiral PTs. This work is now in progress.

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**Supporting Information Available:** Experimental procedures, analytical data of the oligomers, and CD spectra of **7c** and PEOPT with Cu ions. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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