Toward Conjugated Double Helical Ladder Polymers: Cyclooctatetrathiophene as a Highly Versatile Double Helical Scaffold

Michael J. Marsella,* In Tae Kim, and Fook Tham

Department of Chemistry
University of California at Riverside
Riverside, California 92521

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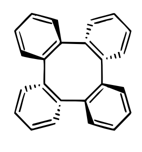
The synthetic pursuit of π-conjugated (and cross-conjugated) macromolecules possessing well-defined architectures is driven by the desire to impart specific physical properties onto materials via structural control (i.e., the structure−property relationship).[1−4] In the case of helical π-systems, the helicity of the macromolecule is a dominant factor in both optical and electronic properties,[5,6] and may ultimately provide organic materials capable of exhibiting electromagnetic properties.[7,8] Although several routes into (covalent) helical π-systems have been reported,[5,9] there exists only a single report describing the synthesis of a (covalent) conjugated ladder-type macromolecule exhibiting a double helical motif.[6] In that pioneering report, Rajca and co-workers establish tetra-*o*-phenylene (**1**) as a fragment of a double helix, and utilize this fact to synthesize a tetra-*o*-phenylene homodimer (an octaaryl double helical oligomer). Unfortunately, stereochemical issues render this homocoupling of *racemic* tetra-*o*-phenylene prone to nonproductive coupling pathways, as reflected by the low reported yield (ca. 4%). Recognizing the topological similarities between tetra-*o*-phenylene (**1**) and cyclooctatetrathiophene (**2**), we demonstrate herein an approach that renders *racemic* cyclooctatetrathiophene **3** as a versatile building block for the synthesis of conjugated double helical macromolecules (such as compounds **4**, **5**, and **6**) in very good yields (82%, 35%, and 28%, respectively). In addition, a supramolecular polymer of **5** is reported, as is a viable route into the synthesis of double helical ladder polymers.



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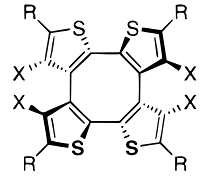

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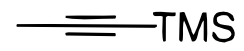
4 X = 

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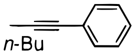
5 X = 
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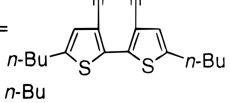
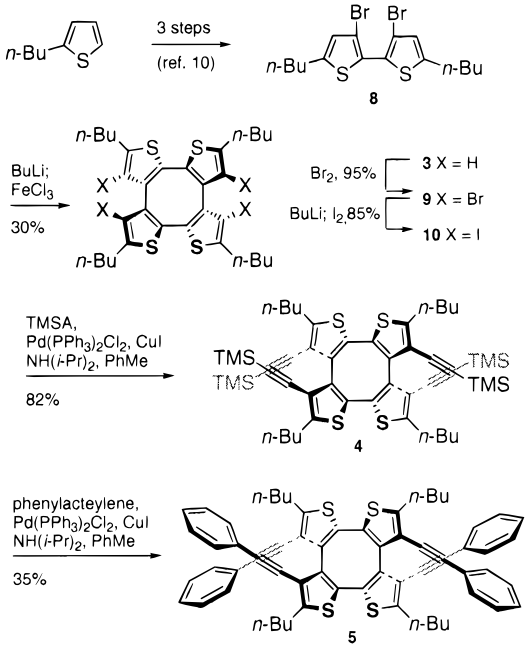
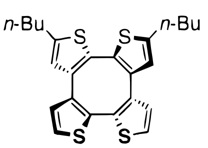
6 2X = 

R = n-Bu

We have recently established dibutylcyclooctatetrathiophene, compound **7**, as a potential helical directing group for its corresponding homopolymer, poly(**7**).[10] The facile conversion of monomer **7** to poly(**7**) is based on the higher chemical reactivity of α-thienyl versus β-thienyl positions. The transformation of **7** from a helical directing group to a *double helical scaffold* requires exclusive synthetic access to the four peripheral β-thienyl positions. This prerequisite is accomplished by preparing peripherally substituted tetrabutylcyclooctatetrathiophene, compound **3**. The synthesis of **3** is based on the original synthesis of the parent (unsubstituted) cyclooctatetrathiophene,[11] and is shown in Scheme 1.

Scheme 1





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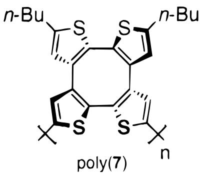

poly(**7**)

With all four α-positions of **3** deactivated toward electrophillic attack, bromination occurs exclusively at the four β-positions of **3** to afford compound **9**. Conversion from tetrabromide **9** to tetraiodide **10** is accomplished via lithium−halogen exchange, followed by quenching with iodine. Compound **10** is the key scaffold for the preparation of double helical oligomers and polymers via cross-coupling, and a 4-fold Pd/Cu mediated cross-coupling with tetramethylsilylacetylene or phenylacetylene completes the synthesis of double helical compounds **4** and **5**, respectively (Scheme 1). Room temperature ^{1}H NMR reveals that the methylene protons adjacent to the thiophene rings of **4** and **5** are diastereotopic, thus implying that interconversion of enantiomers does not occur under ambient conditions. Compound **5** is readily crystallized from benzene/ethanol and its crystal structure

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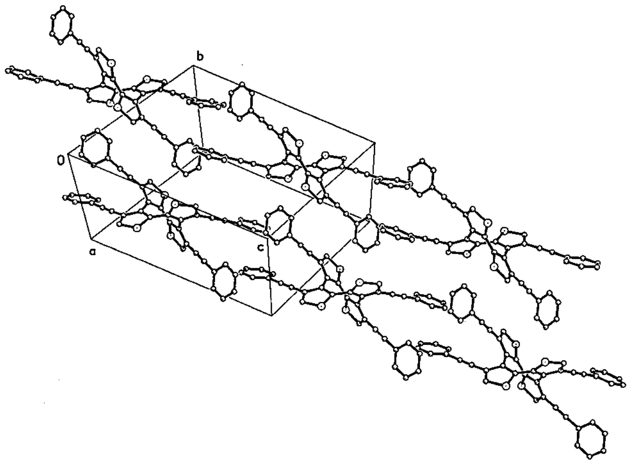
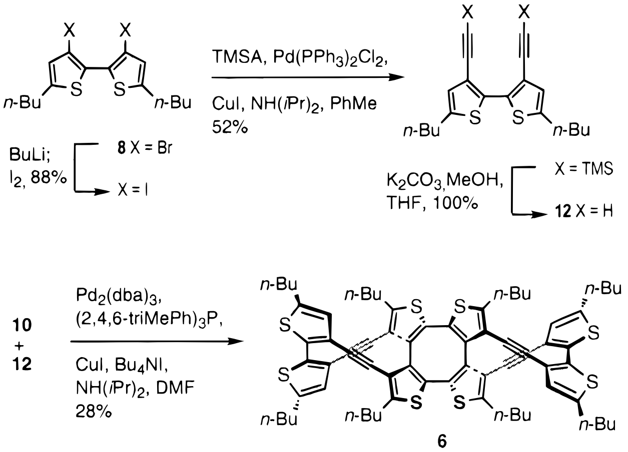


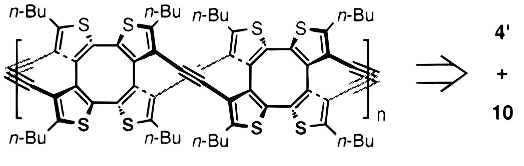
Figure 1. X-ray crystal structure (hydrogens and butyl groups omitted for clarity) of compound **5** showing three repeat units of two neighboring supramolecular polymer chains that form along the crystallographic *c*-axis (note phenyl−phenyl edge-to-face stacking interactions).

Scheme 2



is shown in Figure 1. *Note that edge-to-face phenyl−phenyl stacking interactions contribute to the formation of a solid-state supramolecular polymer of* ***5*** *along the crystallographic c-axis* (Figure 1). Such self-assembly is reminiscent of that reported for the self-aggregation of helicenes[12]

The cross-coupling of TMS deprotected **4** (denoted **4′**) and **10** allows, in theory, the production of double helical ladder polymer **11** (eq 1). However, this polymerization is subject to the same



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(1)

stereochemical issues found in the aforementioned synthesis of tetra-*o*-phenylene homodimers; homochiral **4′** and **10** are required to permit a theoretically quantitative yield of polymer **11**. As with the aforementioned synthesis of compounds **4** and **5**, the cross-coupling polymerization of **4′** and **10** would be promoted by Pd/Cu catalysis. Since this type of cross-coupling reaction is highly sensitive to perturbations in substrates and reaction conditions,[13] optimization would be essential for the production of high molecular weight polymer. Realizing this fact, we wished to establish a control reaction that would allow us to optimize the cross-coupling of **4′** and **10** without the necessity of first isolating homochiral materials. Such a control reaction can be established by cross-coupling 2 equiv of compound **12**, an achiral analogue of one hemisphere of **4′**, with racemic **10** to yield the ladder-type octaaryl oligomer, compound **6**.

Compound **12** is readily synthesized from compound **8** (Scheme 2). Free rotation about the thiophene−thiophene bond of **12** allows for the requisite tandem cross-coupling reaction to occur between **12** and either enantiomer of **10**. Unfortunately, this same free rotation also makes available nonproductive intermolecular polymerization pathways. To minimize undesirable intermolecular reactions, Pd/Cu cross-couplings were performed under pseudo-high-dilution conditions.[14] *Remarkably, the desired tandem Pd/Cu catalyzed cross-coupling between 2 equiv of* ***12*** *and 1 equiv of* ***10*** *(four total couplings, two of which are intramolecular cyclizations) provides* ***6*** *in 28% isolated yield.* Thus, the *productive* coupling reaction proceeds, on average, at 73% yield per reaction site (four sites per monomer **10**). However, since no starting materials are recovered in this reaction, the aforementioned *nonproductive* coupling pathways must also be considered when predicting the reactivity of monomers **10** and **4′** (via **12**). Thus, it can be inferred from this control reaction that cross-coupling polymerization of homochiral **4′** and **10** should occur with efficiency much greater than 73% yield per reaction site (noting that the rigidity of **4′** and **10** makes unproductive coupling pathways unlikely). Although further optimization of reaction conditions may be required, this result indicates that the synthesis of polymer **11** is attainable. Such efforts will be the subject of future reports. We also note that a polymerization approach utilizing alkyne metathesis of **4′** to yield polymer **11** is also a viable synthetic option that will be investigated.[15]

The synthetic approach described herein illustrates the first examples of conjugated octaaryl double helical oligomers that utilize achiral building blocks to extend the length of a racemic double helical scaffold. The advantage of this approach is reflected by the very good yields of double helical oligomers **4**, **5**, and **6**. Furthermore, the X-ray crystal structure of **5** reveals a novel supramolecular double helical polymer extending along the crystallographic *c*-axis. The success of the control reaction between **12** and **10** to yield **6** sets the groundwork for access to conjugated double helical ladder polymers, and may thus establish a facile approach into materials for potential use as molecular electromagnets. Both synthetic and materials-related investigations into these double helical macromolecules are ongoing, and will be the topic of future reports.

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Supporting Information Available: Synthetic procedures, characterization data for new compounds, and details of the X-ray determination of **5** (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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