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Solid-Phase Synthesis of *m*-Phenylene Ethynylene Heterosequence Oligomers

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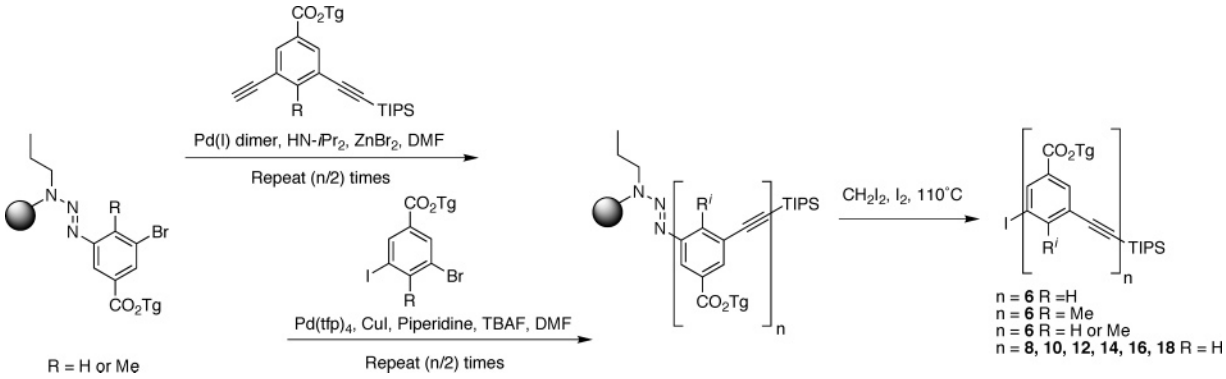
Received April 4, 2006



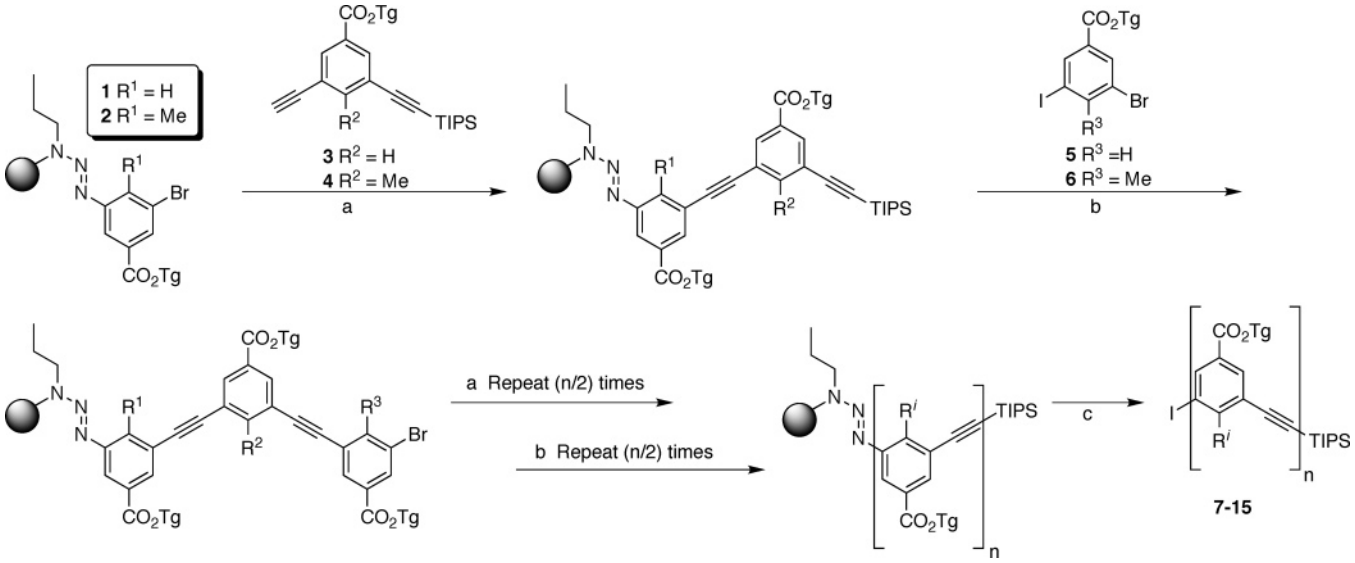
Both homo- and heterosequence *m*-phenylene ethynylene oligomers are synthesized using a conceptually simple iterative solid-phase strategy. Oligomers are attached to Merrifield's resin through a known triazene-type linkage. The phenylene ethynylene molecular backbone is constructed through a series of palladium-mediated cross-coupling reactions. The strategy employs two types of monomers that bear orthogonal reactivity, one being a monoprotected bisethynyl arene and the other being a 3-bromo-5-iodo arene. The catalyst conditions are tailored to the requirements of each monomer type. The monoprotected bisethynyl arene is coupled to the growing chain in 2 h at room temperature using a Pd(I) dimer precatalyst (^{t}Bu$_3$P-(Pd(μ-Cl)(μ-2-methyl allyl)Pd)P^{t}Bu$_3$) in conjunction with $ZnBr_2$ and diisopropylamine. In alternate steps, the resin is deprotected in situ with TBAF and coupled to the 3-bromo-5-iodo arene using the iodo selective Pd(tri-2-furylphosphine)$_4$ catalyst in conjunction with CuI and piperidine; this reaction is also completed in 2 h at room temperature. These cross-coupling events are alternated until an oligomer of the desired length is achieved. The oligomer is then cleaved from the resin using CH_2I_2/I_2 at 110 °C and purified using preparatory GPC. Using this method, a series of homo- and heterosequence oligomers up to 12 units in length in excellent yield and purity were synthesized on the 100 mg scale. Longer oligomers were attempted; however, deletion sequences were found in oligomers longer than 12 units.

Introduction

Phenylene ethynylene oligomers of discrete length have been investigated intensely in the past decade because of their interesting solution[1] and solid-phase[1m,n,2] properties and for their utility as precursors to shape-persistent macrocycles.[3] It has been shown that both *meta*-[4] and *ortho*-[1b,c]phenylene ethynylene oligomers have the ability to adopt a solvophobically driven helical conformation. Meta-substituted foldamers have been extensively examined, and their ability to function as a molecular host has been well documented.[5] Fully conjugated *para*-phenylene ethynylene oligomers have been investigated for their use as organic molecular wires[1j−l,n,o] and nonlinear optical materials.[1h,i] Also, hybrids, containing ortho-, meta-, and para-substituted oligomers, have been investigated for their electroluminescence properties.[1m] Because of the widespread interest in the phenylene ethynylene molecular framework, a number of different syntheses have been explored. The solution-phase synthesis of these molecules typically involves a series of deprotection and palladium-mediated Sonogashira coupling steps.[1a−n,o,2d,6] Our own laboratory[7] as well as that of Tour,[8] Wang,[1o] and Anderson[1m] have independently investigated the solid-phase synthesis of *meta*-, *para*-, mixed, and *para*-

10.1021/jo0607212 CCC: $33.50
Published on Web 06/13/2006

SCHEME 1. Iterative Solid-Phase Heterosequence Synthesis[a]



[a] Reagents: (a) Pd(I) dimer, HN^iPr_2, $ZnBr_2$, DMF, 2 h; (b) TBAF, $Pd(tfp)_4$, CuI, piperidine, 2 h; (c) CH_2I_2, I_2, 110 °C, 12 h. tfp = tri-2-furylphosphine; Tg = $-(CH_2CH_2O)_3CH_3$.

phenylene alternating with 2,5-thiophene phenylene ethynylene oligomers, respectively.[9] Despite the typical advantages offered by solid-phase synthesis, such as minimal purification, the syntheses that have been described until now involve a large time investment. Moreover, they are rooted in convergent/divergent strategies and thus are not amenable to the synthesis of heterosequence libraries.

Herein, we describe a new and improved solid-phase synthesis of *m*-phenylene ethynylene oligomers that utilizes the previously developed 3-propyl-3-(benzyl-supported) triazene linkage[7] but introduces an iterative coupling strategy based on two different monomers bearing functional groups that have orthogonal reactivity. New catalyst conditions are also described, which can perform the desired coupling steps in 2 h at room temperature to produce aryl iodide terminated oligomer fragments. We report the preparation, purification, and characterization of a series of oligomers of up to 18 units in length. We also compare this new method to previously developed solid-phase methods for preparing phenylene ethynylene oligomers.

Results

Oligomers **7**−**15** were synthesized using the iterative strategy outlined in Scheme 1. Oligomers were grown from Merrifield's solid-phase resin tethered to the support through a triazene-type linkage. Two different types of monomers that bear orthogonal reactivity, one being a monoprotected bisethynyl arene (**3** or **4**) and the other being a 3-bromo-5-iodo arene (**5** or **6**), were used for this solid-phase method and are illustrated in Scheme 1.

The first reaction on resin involves the coupling of the terminal acetylene of **3** or **4** to the exposed bromide of the resin-bound monomer utilizing a Pd(I) dimer precatalyst (Figure 1), developed in our laboratory,[10] in combination with HN^iPr_2 and $ZnBr_2$. After the appropriate washing steps to remove unreacted

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(10) Unpublished results. For an example of its use, see: Denmark, S. E.; Baird, J. D. *Org. Lett.* **2006**, *8*, 793−795.

TABLE 1. Characterization Data for Oligomers 7−15

Compound Number	Sequence[b]	Yield[c] (%)	Purity[d] (%)	PDI[f]	Mass Prepared (mg)	MALDI [M+Na$^+$] (calcd.)	MALDI [M+Na$^+$] (found)
7	I-◆◆◆◆◆◆-TIPS	86	94	1.02	184.6	2133.27	2132.59
8	I-◇◆◇◇◆◇-TIPS	88	93	1.03	141.5	2077.16	2076.92
9	I-◇◇◇◇◇◇-TIPS	87	96	1.03	137.2	2049.11	2049.83
10	I-(◇)$_8$-TIPS	89	93	1.03	180.4	2629.73	2627.55
11	I-(◇)$_{10}$-TIPS	75	91	1.04	187.0	3210.35	3208.71
12	I-(◇)$_{12}$-TIPS	73	89	1.04	213.2	3790.98	3789.60
13[a]	I-(◇)$_{14}$-TIPS	50	NA[e]	1.04	170.5	4371.60	4369.30
14[a]	I-(◇)$_{16}$-TIPS	47	NA[e]	1.05	181.6	4952.22	4948.40
15[a]	I-(◇)$_{18}$-TIPS	42	NA[e]	1.04	180.6	5532.84	5530.67

[a] Contains deletion product. [b] Oligomer with repeat units represented by ◇ (R = H monomer) and ◆ (R = Me monomer) at each position. [c] Purified yields; yields based on loading of the linker on resin. [d] Determined from HPLC of the purified sequence. [e] NA = not available. [f] Polydispersity index (PDI) of the purified sequence measured by gel permeation chromatography (GPC), calibrated with polystyrene standards.

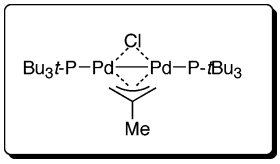

FIGURE 1. Structure of the Pd(I) dimer precatalyst.

monomer and catalyst components, the next step involves the in situ deprotection of the triisopropylsilyl group with TBAF and the subsequent cross-coupling of **5** or **6** to the growing oligomer chain using the iodide selective Pd(tri-2-furylphosphine)$_4$ catalyst[11] in conjuction with an amine base and copper iodide. The steps are alternately repeated until the desired oligomer length is obtained, at which point the oligomer is cleaved from the solid-phase resin using either CH_2I_2 and I_2 or CH_3I at 110 °C.[12] Upon cleavage from the resin, the oligomers are purified using preparatory GPC. This iterative strategy was successful in synthesizing phenylene ethynylene oligomers up to 18 units in length on the 100 mg scale. As is evident from Table 1, the oligomer yield decreases as the length increases. In addition, oligomers with lengths greater than 12 units contained deletion sequences two units shorter than the target oligomer. Nonetheless, this method can provide hexameric oligomers in a start-to-finish time of only 48 h whereas using the previously developed solid-phase method for the same length oligomer requires more than 6 days to complete. Oligomers prepared by this method have been characterized by ^{1}H NMR spectroscopy, MALDI mass spectrometry, GPC, and HPLC and have been found to be of similar purity to those reported by previous methods.

Discussion

Linking Strategy. A triazene unit was chosen as an appropriate solid-phase linker because of its stability to the basic conditions necessary for the palladium cross-coupling reactions utilized for constructing the oligomer backbone.[13] The triazene linker (**1** or **2**) contains the first monomer of the oligomer chain; from the exposed bromide, the oligomer can be grown through a series of palladium-mediated cross-coupling reactions. When cleaved with diiodomethane or methyl iodide at 110 °C, the triazene moiety affords an iodide end group on the oligomer.[12] This is significant as it was desired to produce a terminally functionalized oligomer which could undergo further manipulation to produce longer oligomer chains or desired end groups. Triazene linkers **1** and **2** are identical to the one utilized in our original solid-phase synthesis of phenylene ethynylene oligomers.[7] The linker synthesis is based on modifying chloromethylated Merrifield's resin with propylamine. This secondary amine is then reacted with a tetrafluoroborate salt to produce triazene linker **1** or **2**. The extent of loading of the linker on the resin is most accurately calculated through gravimetric analysis, the details of which can be found in our previous report.[7] ArgoGel resin was also tested as the solid support, as it is known to produce a more solution-like environment for the reacting substrates because of the grafted poly(ethylene glycol) chains.[14] However, the conditions required for linker cleavage caused significant resin decomposition. Merrifield's resin was found to be superior.

Monomer Rationale and Preparation. Analysis of the phenylene ethynylene backbone by the disconnection method yielded two types of monomers: 3-bromo-5-iodo arene monomers **5** or **6** and 3,5-bisethynyl arene monomers **3** or **4**. These monomers were chosen because when they were added sequentially to the growing oligomer chain an average of one phenylacetylene unit was appended per synthetic step. The synthesis is highly efficient in this regard. The H-series monomer **5** is easily synthesized by the diphenylammonium triflate[15] acid-catalyzed esterification of commercially available 3-bromo-5-iodobenzoic acid with tri(ethylene glycol) monomethyl ether. The synthesis of the Me-series counterpart **6** is more involved because the starting point is the commercially available 3-bromo-4-methylbenzoic acid. The benzoic acid is

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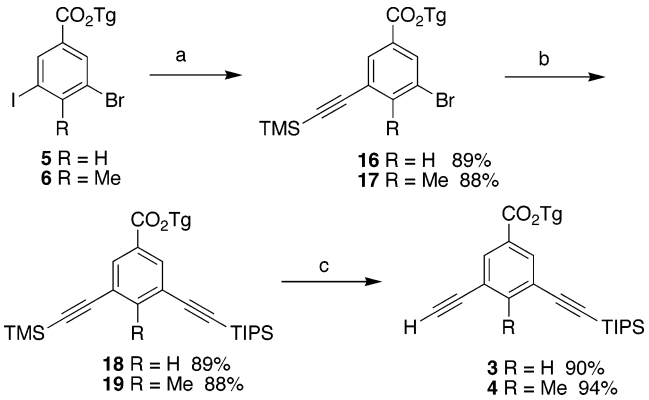
SCHEME 2. Synthesis of Bisethynyl Monomers 3 and 4[a]



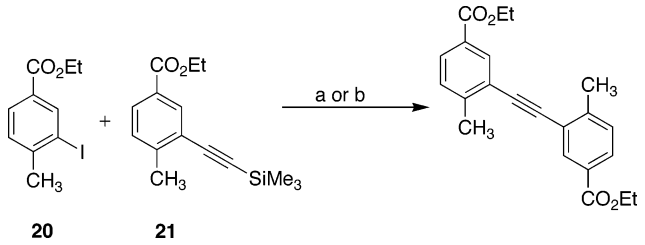
[a] Reagents: (a) $Pd(PPh_3)_2Cl_2$ (1.5 mol %), CuI, THF, NEt_3, TMSA; (b) Pd(I) dimer (3%), $ZnBr_2$, HN^iPr_2, toluene, TIPSA; (c) 4-chlorophenol, potassium 4-chlorophenolate, THF.

first converted to its methyl ester via acid-catalyzed esterification to increase its solubility. Methyl 3-bromo-4-methylbenzoate is then functionalized with an iodo group using *n*-iodosuccinamide in sulfuric acid. Transesterification using tri(ethylene glycol) monomethyl ether and K_2CO_3 yields the desired monomer **6**. Unexpectedly, the gram-scale synthesis of bisethynyl monomers **3** and **4** (Scheme 2) was significantly more challenging because of limitations imposed by the chemical lability of the ester functionality.

Both Me- and H-series bisethynyl monomers were constructed from monomers **5** and **6**. Trimethylsilylacetylene was appended to **5** or **6** through a Sonogashira cross-coupling reaction utilizing the Pd(II) precatalyst $Pd(PPh_3)_2Cl_2$ in conjunction with CuI acting as a cocatalyst and triethylamine as the base. This reaction is complete in 30 min at room temperature and gives the desired product in excellent yield. Triisopropylsilylacetylene can then be attached to the monomer core through another excellent yielding palladium-mediated Sonogashira-type coupling reaction which employs the more active $^tBu_3P(Pd(\mu\text{-}Cl)(\mu\text{-}2\text{-methyl allyl})Pd)P^tBu_3$ (Pd(I) dimer) precatalyst in combination with $ZnBr_2$ and diisopropylamine. The use of this Pd(I) dimer precatalyst will be discussed further in the following section. To obtain a terminal acetylene, the TMS moiety must be deprotected selectively over the TIPS functionality. The known synthetic protocol for this transformation involves treatment of the substrate with K_2CO_3 in MeOH.[16] However, these conditions lead to transesterification. Therefore, a new method was required. A variety of reagents were explored, and it was found that potassium 4-chlorophenolate in combination with 4-chlorophenol offers a mild environment in which the trimethylsilyl group is selectively deprotected in the presence of the triisopropylsilyl group without affecting the ester functionality. This procedure furnished **3** and **4** in excellent yield.

Reaction Conditions for Palladium-Mediated Cross-Coupling Reactions. Traditional methods for the construction of phenylene ethynylene backbones involve a series of palladium cross-coupling reactions separated by deprotection events.[1a−n,2d,6] Our previously developed solid-phase method involved an iterative strategy where a monomer unit was coupled to the growing oligomer chain in one step and then deprotected in the next. This cycle was then repeated until the target oligomer length was reached.[7] In the newly developed synthetic sequence, monomers were chosen that would limit the number of synthetic manipulations on the solid support. It was envisioned that, using one set of reaction conditions, the resin-bound protected acetylene could be deprotected and then selectively cross-coupled with the iodide of **5** or **6**. The other set of reaction conditions to be developed would involve the cross-coupling of the resin-bound bromide to the terminal acetylene of **3** or **4**. To increase the applicability of this method for the preparation of longer oligomers, it was also desired that all cross-couplings be done at room temperature in less than 2 h. The development of the two different types of cross-coupling conditions needed to meet these target criteria are described next.

SCHEME 3. Model Reaction to Determine Necessary Reaction Conditions for Selective Aryl Iodide Coupling[a]



[a] Reagents: (a) **20** (2 equiv), **21** (1 equiv), 4-chlorophenol (5 equiv), potassium 4-chlorophenolate (6 equiv), $Pd(tfp)_4$ (10 mol %), DMF-*d*-7; (b) **20** (2 equiv), **21** (1 equiv), 4-chlorophenol (5 equiv), potassium 4-chlorophenolate (6 equiv), $Pd(tfp)_4$ (10 mol %), CuI (20 mol %), DMF-*d*-7.

A catalyst system that was selective for an aryl iodide over aryl bromide, which could be combined with an in situ TIPS acetylene deprotection agent that would not affect the ester side chains, was desired. If this could be achieved, then the TIPS moiety of the growing oligomer chain could be removed to reveal a terminal acetylene in situ which could then be coupled with the aryl iodide of monomer **5** or **6**. Through model studies, it was found that Pd(tri-2-furylphosphine)$_4$ was able to selectively couple aryl iodides with terminal acetylenes in the presence of aryl bromides. To determine the activity of this catalyst with a sterically and electronically demanding substrate, model reactions were performed in solution (Scheme 3). It was found that when copper-free conditions[17] were employed in the presence of 4-chlorophenol and potassium 4-chlorophenolate (deprotection agent) the reaction took nearly 2 days. It is well-known that the rate of palladium-mediated Sonogashira reactions can be dramatically increased by utilizing a catalytic amount of a Cu(I) salt.[18] When CuI was added to the model reaction, the desired transformation was achieved in 1 h at room temperature.

The optimal conditions were then tested on resin-bound substrates. The test case chosen was similar to the second transformation shown in the iterative oligomer sequence in Scheme 1. To monitor the test case reaction, a small amount of resin was removed and analyzed using infrared spectroscopy.[7] It was found that the characteristic carbon−carbon stretch of the terminal acetylene with the trimethylsilyl group (2156 cm^{-1}) was absent. The reaction was permitted to proceed for another hour, and the product was then cleaved from the resin. As the

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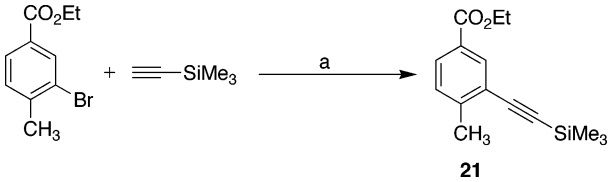
SCHEME 4. Model Reaction Used to Determine Appropriate Reaction Conditions for Aryl Bromide Coupling[a]



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[a] Reagents: (a) Ethyl 3-bromo-4-methylbenzoate (1 equiv), TMSA (2 equiv), Pd(0)(P-*t*-Bu_3)$_2$ (10 mol %), $ZnBr_2$ (4 equiv), HN^{i}Pr$_2$.

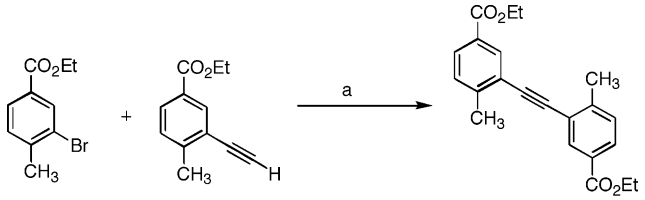
cross-coupling was found to be incomplete under these conditions, the catalyst loading was increased to 20 mol % and TBAF was instead used as the deprotection agent (details are provided in Scheme 1). The amount of catalyst might seem excessive, but considering the small scale of the reaction, the quantity utilized is not significant. The reaction would reach completion with lower catalyst loading, but the high loading was necessary to achieve our target of 2 h per coupling cycle. Using these conditions, the reaction reached completion, as evidenced by the cleaved product producing a monomodal peak in the GPC. Any excess TBAF or TBA salts can easily be removed from the resin using a DMSO washing cycle.

The other set of reaction conditions involved the room-temperature coupling of an on-resin aryl bromide with the terminal acetylene from monomer **3** or **4**. A more active catalyst than Pd(tfp)$_4$ was necessary because of the less-reactive aryl bromide substrate. It has been shown that palladium catalysts with bulky electron-donating ligands, such as Fu's catalyst Pd(0)(P^{t}Bu$_3$)$_2$, can accomplish aryl bromide couplings in a reasonable time at room temperature in solution.[19] A set of model reactions involving a sterically and electronically demanding substrate (Scheme 4) were attempted in solution.

With 10 mol % of Fu's catalyst, the reaction took 4 h to reach completion, which is considerably longer than our initial goal of 2 h. Recent reports have suggested that the catalytically active form of these catalysts possesses a 1:1 ratio of phosphine to palladium.[20] To guarantee that the correct metal/ligand ratio was obtained, a new catalyst precursor ^{t}Bu$_3$P(Pd(μ-Cl)(μ-2-methyl allyl)Pd)P^{t}Bu$_3$ was utilized. Werner et al.[21] previously described this palladium complex in the literature, but there had been no reports describing its use as a precatalyst for cross-coupling. The catalytic behavior of a related Pd(I) dimer has been reported by Hartwig.[22] The catalytic activity of ^{t}Bu$_3$P(Pd(μ-Cl)(μ-2-methyl allyl)Pd)P^{t}Bu$_3$ was found to be useful in solution for the room-temperature coupling of aryl bromides.[10] Moreover, the Pd(I) dimer's solubility in a variety of solvents such as DMF and toluene was also a very attractive property for its use as a catalyst for solid-phase synthesis. As a result, a model study was again performed on an electronically and sterically demanding substrate in solution (Scheme 5).

When a fresh solution of the Pd(I) dimer precatalyst was utilized at the 10 mol % level, the reaction reached completion in 2 h at room temperature. When the Pd(I) dimer precatalyst was first combined with ethyl 3-bromo-4-methylbenzoate and

SCHEME 5. Model Reaction to Determine the Suitability of the Pd(I) Dimer Catalyst Precursor for Room-Temperature Aryl Bromide Coupling[a]



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[a] Reagents: (a) Ethyl 3-bromo-4-methylbenzoate (1 equiv), **22** (2 equiv), Pd(I) dimer (10 mol %), $ZnBr_2$ (4 equiv), HN^{i}Pr$_2$, DMF.

allowed to equilibrate for 11.5 h before addition of other reaction components, there was a significant decrease in catalyst activity, suggesting that catalyst solutions should not be combined with arene halides in advance. Optimal reaction conditions were then tested on resin using the formation of the dimer (first step of Scheme 1) as the test case. Three reactions were performed simultaneously and were allowed to proceed for 2, 3, and 4 h. At the appropriate times, the reactions were stopped and the products were cleaved from the resin and analyzed by TLC to qualitatively determine if the reactions had gone to completion. In all three cases, the reactions were not complete. Therefore, the catalyst loading was increased to 20 mol %; however, the reaction still took approximately 4−6 h to complete. Fortunately, this unusually long coupling time was not general to any of the subsequent steps. The slow kinetics in this first step is presumed to be due to the electron-donating effect of the triazene linker and the inaccessibility of the resin. When these coupling conditions are applied in the next reaction cycle, a unit that is further from the linker, the reaction takes only 2 h to complete.

Oligomer Synthesis. On-resin reactions were performed using a Quest-210 parallel synthesizer which allows up to 20 oligomer sequences to be prepared simultaneously. The resin is loaded into Teflon reaction vessels which are placed into the synthesizer, and the solutions of catalyst and monomer are prepared in a glovebox under an inert atmosphere and stored in gastight syringes. On-resin reactions are then carried out according to Scheme 1. The first step, as mentioned previously, involves the coupling of the resin-bound aryl bromide with the terminal acetylene of **3** or **4** and requires 4−6 h to reach completion. Because of the length of this reaction, it is usually set up the night before the remaining on-resin reactions are performed. Upon completion of this reaction, the resin is then washed sequentially three times with DMF, DMSO, and CH_2Cl_2 and then dried. The next reaction involves the in situ deprotection of the TIPS-protected acetylene and subsequent coupling to the aryl iodide monomer **5** or **6** which takes 2 h to complete. Following another washing and drying sequence, the bromo-terminated oligomer is treated with the Pd(I) dimer precatalyst, $ZnBr_2$, HN^{i}Pr$_2$, and monomer **3** or **4**. This reaction only requires 2 h to reach completion. These alternating steps are repeated until the desired oligomer length is achieved. After a final washing and drying sequence, the resin is placed in a sealed tube with either CH_2I_2 and I_2 or CH_3I and heated to 110 °C for 8−12 h. If the oligomer is in any way water sensitive, the CH_3I cleavage method is preferred because of the absence of water in its workup. Finally, the isolated oligomer is purified using preparatory GPC.

To demonstrate that different monomers could easily be incorporated into any position of the phenylene ethynylene

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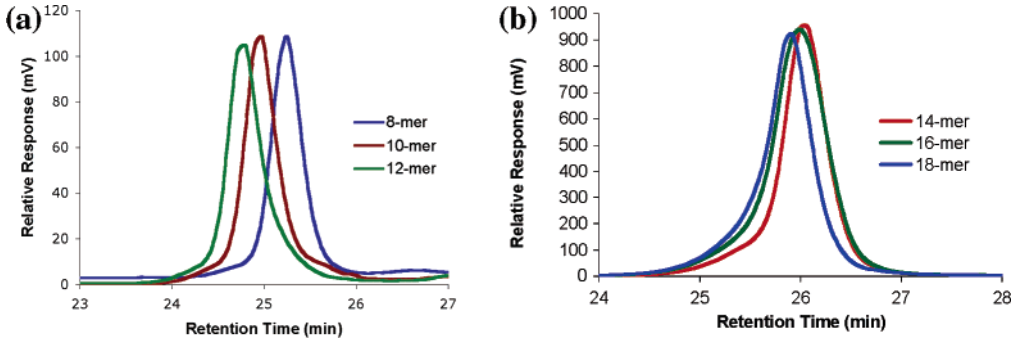

FIGURE 2. Purified gel permeation chromatograms of **10**−**15**. (a) Eluting solvent: THF. (b) Eluting solvent: 89 THF:10 MeOH:1 NEt_3.

sequence, a series of hexamers were synthesized using this methodology. These heterosequence hexamers were produced in excellent yields and high purity in less than 48 h. It was then of interest to synthesize longer length oligomers to test the limitations of the method. Results showed that as the length of the oligomer increases the amount of high molecular weight impurities increases resulting in a decrease in yield of the purified oligomer. The most likely cause of high molecular weight impurities is either resin decomposition or on-resin chain−chain coupling. Simple resin decomposition due to the cleavage conditions was ruled out by a control experiment which involved cleavage of the monomer from the resin. However, the resin could also decompose over the course of the repeated coupling reactions. Typical solutions to these problems include the use of a more robust resin with a higher degree of cross-linking or a decrease in the loading of the linker on the resin.[23] Both of these solutions were attempted but did not reduce the amount of higher MW byproduct formed. However, using preparatory GPC, the removal of the higher MW byproduct was successful in oligomers up to 12 units in length.

During the synthesis of oligomers greater than 12 units, the resin was left overnight, usually after 8 or 10 units were appended to the solid support. In all cases, when the dry or wet resin was left for extended times, a deletion sequence two units shorter than the target was produced as a minor contaminant as indicated by MALDI mass spectrometry. Because of the GPC's size-based method of separation, it is difficult to resolve these deletion sequences from the target product. Therefore, as noted in Table 1, oligomers with 14, 16, and 18 units are all contaminated with a small amount of 12-, 14-, or 16-mer that could not be removed (Figure 2). Therefore, the method reported here is most suitable for the synthesis of oligomers up to 12 units in length.

Comparison to the Previous Solid-Phase Method. The original solid-phase method developed for phenylene ethynylene oligomers took 11 synthetic steps and 6 days to construct an oligomer six units in length in 58% yield.[7] Each coupling step was performed at high temperature and required the 2 h preparation of a precatalyst solution for each cross-coupling step.[7] In contrast, this newly developed solid-phase method requires only five synthetic steps and takes less than 48 h to complete a hexameric oligomer in 87% yield on the 100 mg scale. All cross-coupling steps can be performed in 2 h at room temperature and do not require excessive preparation of catalyst solutions. This method is now a quick and efficient route for the synthesis of phenylene ethynylene oligomer fragments. The phenylene ethynylene oligomers thus produced have many potential applications. For example, a pair of oligomer fragments formed from this method can be coupled to a bisethynyl arene monomer unit to form longer oligomers. Also, functionality can be incorporated sequence specifically in the phenylene ethynylene chain thus producing fragments that can be cyclized to form monofunctional shape-persistent macrocycles or selectively functionalized foldamer cavities. This level of control was not possible in the previous methods based on convergent−divergent oligomer growth strategies.

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Conclusion

An iterative solid-phase synthetic method was devised which allowed for the synthesis of both homo- and heterosequence oligomers up to 18 units in length. This was achieved using monomer pairs that possess orthogonal reactive groups. A novel deprotection method, using 4-chlorophenol and potassium 4-chlorophenolate, which selectively removes a TMS group in the presence of TIPS and the ester functionality, was devised and utilized to synthesize bisethynyl monomer units **3** and **4**. The linking of monomer units was achieved using two sets of Sonogashira cross-coupling conditions. One involved the in situ TBAF deprotection of a TIPS group to reveal a solid-supported terminal acetylene which was then coupled selectively using $Pd(tfp)_4$ with the aryl iodide of monomer **5** or **6**. The other set of cross-coupling conditions involved reaction of resin-bound aryl bromide with the terminal acetylene of **3** or **4** using a Pd-(I) dimer precatalyst. In general, both of these cross-coupling reactions can be completed in 2 h at room temperature. This oligomer synthesis is most suitable for preparing sequences up to 12 units in length because of the presence of deletion sequences in the synthesis of longer oligomers. The development of this solid-phase method considerably reduces the time required for the construction of phenylene ethynylene oligomers and thus will allow for a more in-depth investigation into their sequence variations.

Experimental Section

General Procedure for the Synthesis of Potassium 4-Chlorophenolate. A 2 L round-bottom flask was charged with 4-chlorophenol (456.68 g, 3.55 mol) and potassium methoxide (249.16 g, 3.55 mol) in 1.5 L of methanol. The solution was allowed to stir until all reagents were dissolved. The solvent was then removed under reduced pressure to reveal a dark oil. THF (300 mL) and ether (1.2 L) were added to the dark oil and cooled in the freezer. A white precipitate formed (78 g, 0.47 mol, 13%) which was filtered and dried under vacuum at 110 °C for 12 h. The filtrate was concentrated to again produce a dark oil. THF (300 mL) and ether (1.2 L) were again added to the dark oil and cooled in the freezer.

Again, a white precipitate formed (514 g, 3.08 mol, 87%) which was filtered and dried under vacuum at 110 °C for 12 h. The combined precipitate was then transferred to the glovebox because of its hygroscopic nature.

General Procedure for Coupling Resin-Bound Aryl Bromide with Monoprotected Diethynyl Monomer 3 or 4. A 10 mL Teflon reaction vessel containing an agitator (Argonaut Quest 210 parallel synthesizer) was loaded with resin-bound aryl bromide (200 mg, 0.082 mmol) and purged with nitrogen. Stock solutions of Pd(I) dimer precatalyst (5.8 mg, 0.016 mmol Pd-L) in DMF (1.2 mL), $ZnBr_2$ (73.40 mg, 0.33 mmol) and HN^iPr_2 (515 μL, 3.60 mmol) in DMF (1.1 mL), and monomer **3** or **4** (0.16 mmol) in DMF (1.1 mL) were prepared in the glovebox in gastight syringes protected by silicon stoppers. These solutions were then added to the reaction vessel in the order listed above. The concentration of the entire solution within the reaction vessel after all three stock solutions have been added must not be less than 0.024 M. Upon addition of the final stock solution, agitation was carried out for 12 h (first coupling) or 2 h (all subsequent couplings). At the conclusion of the reaction, the catalyst solution was filtered off and the resin was washed for 1 min with DMF (3 × twice the resin volume) and then with DMSO (3 × twice the resin volume) and CH_2Cl_2 (3 × twice the resin volume) and dried for 5 min under a stream of dry nitrogen.

General Procedure for Coupling Resin-Bound Aryl TIPS-Protected Acetylene and Bifunctional Aryl Monomer 5 or 6. A 10 mL Teflon reaction vessel containing an agitator (Argonaut Quest 210 parallel synthesizer) was loaded with the resin-bound triisopropylsilyl-protected acetylene monomer (0.15 mmol) and purged with nitrogen. Stock solutions of TBAF (290 μL, 1.0 M in THF) in DMF (2.0 mL), bifunctional aryl monomer **5** or **6** (0.29 mmol) and $Pd(tfp)_4$ (31.4 mg, 0.03 mmol) in DMF (2.0 mL), and piperidine (287.0 μL, 2.90 mmol) and CuI (1.60 mg, 0.008 mmol) in DMF (2.0 mL) were prepared in the glovebox in gastight syringes protected by silicon stoppers. These solutions were then added to the reaction vessel in the order listed above. The concentration of the entire solution within the reaction vessel after the three stock solutions have been added must not be less than 0.024 M. Upon addition of the final stock solution, agitation was carried out for 2 h. At the conclusion of the reaction, the catalyst solution was filtered off and the resin was washed for 1 min with DMF (3 × twice the resin volume) and then with DMSO (3 × twice the resin volume) and CH_2Cl_2 (3 × twice the resin volume) and dried for 5 min under a stream of dry nitrogen.

General Procedure for the Cleavage of an Oligomer from Resin. A thick-walled sealed tube was charged with a resin-bound oligomer (294.2 mg, 0.120 mmol), I_2 (30.5 mg, 0.120 mmol), and CH_2I_2 (2.5 mL), evacuated (3× with N_2 backfill), sealed, and placed into a 110 °C oil bath. The reaction was allowed to proceed for 8−12 h after which time the contents were cooled to room temperature. The contents were then poured into a saturated solution of $Na_2S_2O_3$ (10 mL) and extracted with CH_2Cl_2 (3 × 10 mL). The combined organic layers were dried over $MgSO_4$ and filtered, and the solvent was removed to give a dark oil which was placed in a Kugelrohr apparatus and distilled at 90 °C under vacuum (10 mTorr) to remove any excess CH_2I_2 to give a dark wax which can be purified by preparative-scale GPC to yield pale yellow waxy solids.

1-(2-[2-(2-Methoxyethoxy)ethoxy]ethyl-3-bromo-phenyl)-3-propyl-3-(benzyl-supported) Triazene (1). A 100 mL round-bottom flask fitted with a magnetic stir bar was charged with propylamine-modified Merrifield's resin (5.00 g, 3.50 mmol), K_2CO_3 (0.967 g, 7.00 mmol), and DMF (58 mL) and stirred at 0 °C for 10 min. To this was added 3-bromo-5-[2-(2-methoxyethoxy)-ethoxy]ethyl benzene diazonium tetrafluroborate (2.1 g, 4.55 mmol), and the reaction was allowed to stir for 1 h at which point the ice bath was removed and the reaction was allowed to stir for another hour. The contents of the flask were then transferred to a frit and washed with DMF (3 × 250 mL), THF (3 × 250 mL), H_2O (3 × 250 mL), CH_2Cl_2 (3 × 250 mL), H_2O (3 × 250 mL), and CH_2Cl_2 (3 × 250 mL). The resin was then allowed to dry under vacuum overnight to give **1** (5.4805 g, 0.26 mmol/g, 37%) as a light orange resin.

1-(2-[2-(2-Methoxyethoxy)ethoxy]ethyl-3-bromo-4-methyl-phenyl)-3-propyl-3-(benzyl-supported) Triazene (2). Using the procedure for **1**, we obtained **2** (5.6416 g, 0.34 mmol/g, 49%) as a light orange resin.

2-[2-(2-Methoxyethoxy)ethoxy]ethyl-3-ethynyl-5-[(triisopropylsilanyl)-ethynyl]-benzoate (3). In a glovebox under an inert atmosphere of argon, a 100 mL round-bottom flask was fitted with a magnetic stir bar and charged with 2-[2-(2-methoxyethoxy)ethoxy]-ethyl-3-[(triisopropylsilanyl)-ethynyl]-5-trimethylsilanylethynyl-benzoate **18** (5.7386 g, 10.53 mmol) and dry THF (30 mL). To this solution was added 4-chlorophenol (4.06 g, 31.6 mmol) and potassium 4-chlorophenolate (4.39 g, 26.33 mmol). Upon addition of the reagents the reaction turned a darker yellow color and evolved some heat. The reaction was allowed to proceed for 3 h and was then quenched by pouring into saturated NH_4Cl (30 mL) and extracted with CH_2Cl_2 (3 × 30 mL). The organic layers were combined, dried over $MgSO_4$, and filtered, and the solvent was removed to give a dark yellow oil that was purified by silica gel column chromatography (2:1 hexane/EtOAc) to give **3** (4.7 g, 9.94 mmol, 90%) as a light yellow oil which solidified when stored below 0 °C: ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.00 (m, 1H), 7.69 (m, 1H), 7.70 (s, 1H), 4.42−4.40 (m, 2H), 3.77−3.75 (m, 2H), 3.63−3.55 (m, 6H), 3.45−3.43 (m, 2H), 3.27 (s, 3H), 3.12 (s, 1H), 1.05 (s, 21H); ^{13}C NMR (125 MHz, $CDCl_3$) 165.1, 139.5, 133.2, 132.9, 130.9, 124.4, 123.0, 104.9, 93.0, 81.9, 79.2, 72.0, 70.81, 70.76, 70.7, 69.2, 64.6, 59.1, 18.8, 11.3; MS (FD) ($C_{27}H_{40}O_5Si$) calcd 472.69, found 473.3. Anal. calcd for $C_{27}H_{40}O_5Si$: C, 68.61; H, 8.53. Found: C, 68.61; H, 8.30.

2-[2-(2-Methoxyethoxy)ethoxy]ethyl-3-ethynyl-4-methyl-5-[(triisopropylsilanyl)-ethynyl]-benzoate (4). Using the procedure for **3**, we obtained **4** (3.11 g, 7.73 mmol, 94%) as a light yellow oil which crystallized after being stored below 0 °C: ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.07 (s, 2H), 4.48−4.46 (m, 2H), 3.84−3.82 (m, 2H), 3.72−3.70 (m, 2H), 3.68−3.64 (m, 4H), 3.54−3.42 (m, 2H), 3.36 (s, 3H), 3.32 (s, 1H), 2.64 (s, 3H), 1.13 (s, 21H); ^{13}C NMR (125 MHz, $CDCl_3$) δ165.5, 148.3, 133.8, 133.5, 127.9, 124.6, 123, 104.3, 96.7, 82.2, 81.4, 72.1, 70.9, 70.84, 70.81, 69.3, 64.6, 59.2, 19.8, 18.9, 11.4; MS (FD) ($C_{28}H_{42}O_5Si$) calcd 486.2802, found 487.5 ([M + H]+); HRMS (ESI) found 487.2892 ([M + H]+). Anal. calcd for $C_{28}H_{42}O_5Si$: C, 69.10; H, 8.70. Found: C, 69.07; H, 8.74.

2-[2-(2-Methoxyethoxy)ethoxy]ethyl-3-bromo-5-iodo-4-methyl-benzoate (6). A 500 mL round-bottom flask was charged with methyl-3-bromo-5-iodo-4-methyl-benzoate (20.09 g, 56.6 mmol), K_2CO_3 (800 mg, 5.79 mmol), and tri(ethylene glycol) monomethyl ether (100 mL, 625 mmol) and attached to a Kugelrohr apparatus. The reaction was then heated to 35 °C overnight under vacuum (10 mTorr) after which time the temperature was raised to 80 °C to drive off excess tri(ethylene glycol) monomethyl ether, leaving a dark brown oil which was purified by silica gel column chromatography (2:1 hexane/EtOAc) to give **6** (16.87 g, 34.6 mmol, 61.1%) as a clear oil that crystallized to a white solid upon standing at below 0 °C: ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.41 (d, J = 1.7 Hz, 1H), 8.18 (d, J = 1.7 Hz, 1H), 4.47−4.45 (m, 2H), 3.83−3.81 (m, 2H), 3.71−3.64 (m, 6H), 3.55−3.53 (m, 2H), 3.37 (s, 3H), 2.69 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 163.8, 145.5, 139.4, 133.7, 130.4, 123.3, 100.5, 71.9, 70.64, 70.59, 69.0, 64.6, 59.0, 29.6; MS (LR−FD) 487.9. Anal. calcd for $C_{15}H_{20}BrIO_5$: C, 36.98; H, 4.14; N, 0. Found: C, 36.90; H, 4.15; N, 0.

(I)-Me-Me-Me-Me-Me-Me-(TIPS) (7). A reaction vessel designed for the Quest 210 parallel synthesizer was loaded with **2** (300 mg, 0.34 mmol/g) and reacted as described in the general procedures to give a dark oil that was purified by preparative scale GPC to give **7** (184.6 mg, 0.087 mmol, 86%) as a yellow waxy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.45−8.44 (m, 1H), 8.21−8.17 (m, 9H), 8.14−8.13 (m, 1H), 8.09−8.08 (m, 1H), 4.53−4.47

(m, 12H), 3.88−3.82 (m, 12H), 3.74−3.61 (m, 36H), 3.52−3.50 (m, 12H), 3.334 (s, 3H), 3.328 (s, 3H), 3.321 (s, 12H), 2.82 (s, 3H), 2.80 (s, 3H), 2.79 (s, 3H), 2.78 (s, 3H), 2.75 (s, 3H), 2.74 (s, 3H), 1.13 (s, 21H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.6, 165.5, 165.4, 164.7, 148.1, 147.6, 147.07, 147.06, 147.03, 140.5, 133.7, 133.43, 133.37, 133.03, 129.4, 128.39, 128.37, 128.1, 124.7, 124.19, 124.11, 124.09, 124.07, 124.06, 123.9, 123.8, 123.6, 104.3, 101.1, 96.9, 92.6, 92.4, 92.2, 92.18, 92.15, 91.9, 72.1, 70.91, 70.89, 70.83, 70.80, 69.4, 69.33, 69.28, 64.7, 64.63, 64.57, 59.24, 59.22, 27.6, 20.18, 20.17, 20.15, 18.9, 11.4; GPC PDI = 1.02; MS (MALDI) ($C_{111}H_{141}IO_{30}Si$) calcd 2133.27 ([M + Na^+]), found 2132.59 ([M + Na^+]). HPLC (1.0 mL/min, 98:2 $CHCl_3$/^{i}PrOH for 10 min, 93:7 $CHCl_3$/^{i}PrOH for 20 min, retention time 21.907 min) indicated >94% purity.

(I)-H-Me-H-H-Me-H-(TIPS) (8). Using the procedure for **7**, we obtained **8** (141.5 mg, 0.069 mmol, 88%) as a yellow waxy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.34 (t, J = 1.6 Hz, 1H), 8.20−8.15 (m, 9H), 8.14 (t, J = 1.6 Hz, 1H), 8.09 (t, J = 1.6 Hz, 1H), 8.07 (t, J = 1.6 Hz, 1H), 7.91 (t, J = 1.6 Hz, 2H), 7.80 (t, J = 1.6 Hz, 1H), 4.53−4.49 (m, 12H), 3.88−3.84 (m, 12H), 3.73−3.62 (m, 36H), 3.53−3.50 (m, 12H), 3.339 (s, 3H), 3.331 (s, 3H), 3.327 (s, 9H), 3.324 (s, 3H), 2.77 (s, 3H), 2.75 (s, 3H), 1.12 (s, 21H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.5, 165.4, 165.35, 165.3, 164.6, 147.4, 144.3, 139.0, 138.7, 138.6, 133.7, 133.6, 133.5, 133.2, 132.96, 132.92, 132.5, 132.22, 132.18, 131.3, 131.0, 128.37, 128.33, 125.3, 124.7, 124.07, 124.03, 123.84, 123.81, 123.79, 123.75, 123.71, 123.63, 108.1, 105.0, 93.6, 93.3, 92.8, 92.7, 92.6, 91.8, 89.26, 89.24, 89.23, 88.76, 88.68, 88.46, 72.1, 70.85, 70.81, 70.79, 69.32, 69.30, 69.28, 69.24, 67.8, 64.90, 64.82, 64.76, 64.63, 64.61, 59.25, 59.22, 29.3, 24.1, 18.5, 11.4; GPC PDI = 1.03; MS (MALDI) ($C_{107}H_{133}IO_{30}Si$) calcd 2077.16 ([M + Na^+]), found 2076.92 ([M + Na^+]). HPLC (1.0 mL/min, 98:2 $CHCl_3$/^{i}PrOH for 10 min, 93:7 $CHCl_3$/^{i}PrOH for 20 min, retention time 21.810 min) indicated >93% purity.

(I)-H-H-H-H-H-H-(TIPS) (9). Using the procedure for **7**, we obtained **9** (137.2 mg, 0.068 mmol, 87%) as a yellow waxy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.35 (t, J = 1.6 Hz, 1H), 8.21−8.17 (m, 9H), 8.14 (t, J = 1.6 Hz, 1H), 8.10 (t, J = 1.6 Hz, 1H), 8.07 (t, J = 1.6 Hz, 1H), 7.90−7.88 (m, 4H), 7.81 (t, J = 1.6 Hz, 1H), 4.54−4.49 (m, 12H), 3.88−3.85 (m, 12H), 3.74−3.63 (m, 36H), 3.54−3.52 (m, 12H), 3.35 (s, 3H), 3.343 (s, 3H), 3.341 (s, 3H), 3.338 (s, 9H), 1.12 (s, 21H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.4, 165.3, 165.2, 144.4, 139.2, 138.8, 138.6, 133.2, 133.10, 133.05, 133.0, 132.99, 132.5, 132.3, 132.2, 131.3, 131.3, 131.0, 125.0, 124.7, 123.9, 123.83, 123.81, 123.80, 123.79, 123.66, 123.4, 105.0, 93.6, 93.3, 89.7, 89.4, 89.28, 89.25, 89.22, 89.18, 88.98, 88.49, 72.12, 72.10, 70.87, 70.85, 70.83, 69.30, 69.28, 69.24, 64.88, 64.81, 64.74, 59.25, 59.23, 18.9, 11.4; GPC PDI = 1.03; MS (MALDI) ($C_{105}H_{129}IO_{30}Si$) calcd 2049.11 ([M + Na^+]), found 2049.83 ([M + Na^+]). HPLC (1.0 mL/min, 98:2 $CHCl_3$/^{i}PrOH for 10 min, 93:7 $CHCl_3$/^{i}PrOH for 20 min, retention time 21.976 min) indicated >96% purity.

I-$(H)_8$-(TIPS) (10). Using the procedure for **7**, we obtained **10** (180.4 mg, 0.069 mmol, 89%) as a yellow waxy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.34 (t, J = 1.6 Hz, 1H), 8.20−8.16 (m, 13H), 8.13 (t, J = 1.6 Hz, 1H), 8.09 (t, J = 1.6 Hz, 1H), 8.06 (t, J = 1.6 Hz, 1H), 7.90−7.87 (m, 6H), 7.81 (t, J = 1.6 Hz, 1H), 4.53−4.47 (m, 16H), 3.87−3.83 (m, 16H), 3.73−3.62 (m, 48H), 3.53−3.50 (m, 16H), 3.332−3.329 (m, 24H), 1.13 (s, 21H); GPC PDI = 1.03; MS (MALDI) ($C_{137}H_{165}IO_{40}Si$) calcd 2629.73 ([M + Na^+]), found 2627.55 ([M + Na^+]). HPLC (1.0 mL/min, 98:2 $CHCl_3$/^{i}PrOH for 10 min, 93:7 $CHCl_3$/^{i}PrOH for 20 min, retention time 24.558 min) indicated >93% purity.

I-$(H)_{10}$-(TIPS) (11). Using the procedure for **7**, we obtained **11** (187.0 mg, 0.059 mmol, 75%) as a yellow waxy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.35 (t, J = 1.6 Hz, 1H), 8.21−8.17 (m, 17H), 8.14 (t, J = 1.6 Hz, 1H), 8.10 (t, J = 1.6 Hz, 1H), 8.07 (t, J = 1.6 Hz, 1H), 7.91−7.87 (m, 8H), 7.81 (t, J = 1.6 Hz, 1H), 4.53−4.49 (m, 20H), 3.88−3.84 (m, 20H), 3.74−3.63 (m, 60H), 3.54−3.52 (m, 20H), 3.35−3.34 (m, 30H), 1.13 (s, 21H); GPC PDI = 1.04; MS (MALDI) ($C_{137}H_{165}IO_{40}Si$) calcd 3210.35 ([M + Na^+]), found 3208.71 ([M + Na^+]). HPLC (1.0 mL/min, 98:2 $CHCl_3$/^{i}PrOH for 10 min, 93:7 $CHCl_3$/^{i}PrOH for 20 min, retention time 25.296 min) indicated >91% purity.

I-$(H)_{12}$-(TIPS) (12). Using the procedure for **7**, we obtained **12** (213.2 mg, 0.057 mmol, 73%) as a yellow waxy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.33 (t, J = 1.6 Hz, 1H), 8.19−8.12 (m, 21H), 8.11 (t, J = 1.6 Hz, 1H), 8.08 (t, J = 1.6 Hz, 1H), 8.04 (t, J = 1.6 Hz, 1H), 7.89−7.85 (m, 10H), 7.79 (t, J = 1.6 Hz, 1H), 4.51−4.48 (m, 24H), 3.86−3.84 (m, 24H), 3.72−3.61 (m, 72H), 3.51−3.49 (m, 24H), 3.326−3.315 (m, 36 H), 1.11 (s, 21H); GPC PDI = 1.04; MS (MALDI) ($C_{137}H_{165}IO_{40}Si$) calcd 3790.98 ([M + Na^+]), found 3789.6 ([M + Na^+]). HPLC (1.0 mL/min, 98:2 $CHCl_3$/^{i}PrOH for 10 min, 93:7 $CHCl_3$/^{i}PrOH for 20 min, retention time 30.570 min) indicated >89% purity.

I-$(H)_{14}$-(TIPS) (13). Using the procedure for **7**, we obtained **13** (170.5 mg, 0.039 mmol, 50%) as a yellow waxy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.34 (t, J = 1.6 Hz, 1H), 8.23−8.16 (m, 25H), 8.13 (t, J = 1.6 Hz, 1H), 8.09 (t, J = 1.6 Hz, 1H), 8.06 (t, J = 1.6 Hz, 1H), 7.90−7.87 (m, 12H), 7.80 (t, J = 1.6 Hz, 1H), 4.53−4.51 (m, 28H), 3.87−3.85 (m, 28H), 3.73−3.62 (m, 84H), 3.52−3.51 (m, 28H), 3.34−3.33 (m, 42H), 1.12 (s, 21H); GPC PDI = 1.04; MS (MALDI) ($C_{233}H_{273}IO_{70}Si$) calcd 4371.60 ([M + Na^+], found 4369.30 ([M + Na^+]).

I-$(H)_{16}$-(TIPS) (14). Using the procedure for **7**, we obtained **14** (181.6 mg, 0.037 mmol, 47%) as a yellow waxy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.34 (t, J = 1.6 Hz, 1H), 8.17−8.14 (m, 29H), 8.13 (t, J = 1.6 Hz, 1H), 8.08 (t, J = 1.6 Hz, 1H), 8.05 (t, J = 1.6 Hz, 1H), 7.89−7.86 (m, 14H), 7.80 (t, J = 1.6 Hz, 1H), 4.52−4.50 (m, 32H), 3.87−3.85 (m, 32H), 3.73−3.63 (m, 96H), 3.52−3.50 (m, 32H), 3.33−3.32 (m, 48H), 1.12 (s, 21H); GPC PDI = 1.05; MS (MALDI) ($C_{265}H_{309}IO_{80}Si$) calcd 4952.22 ([M + Na^+]), found 4948.40 ([M + Na^+]).

I-$(H)_{18}$-(TIPS) (15). Using the procedure for **7**, we obtained **15** (180.6 mg, 0.032 mmol, 42%) as a yellow waxy solid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.33 (t, J = 1.6 Hz, 1H), 8.21−8.15 (m, 33H), 8.12 (t, J = 1.6 Hz, 1H), 8.08 (t, J = 1.6 Hz, 1H), 8.05 (t, J = 1.6 Hz, 1H), 7.89−7.86 (m, 16H), 7.80 (t, J = 1.6 Hz, 1H), 4.52−4.50 (m, 36H), 3.86−3.85 (m, 36H), 3.73−3.63 (m, 108H), 3.52−3.50 (m, 36H), 3.33−3.32 (s, 54), 1.12 (s, 21H); GPC PDI = 1.04; MS (MALDI) ($C_{297}H_{345}IO_{90}Si$) calcd 5532.84 ([M + Na^+]), found 5530.67 ([M + Na^+]).

2-[2-(2-Methoxyethoxy)ethoxy]ethyl-3-bromo-5-trimethylsilanylethynylbenzoate (16). 2-[2-(2-Methoxyethoxy)ethoxy]-ethyl-5-bromo-3-iodobenzoate (**5**) (10 g, 21.18 mmol) was added to a 250 mL round-bottom flask fitted with a stir bar and $Pd(PPh_3)_2Cl_2$ (0.222 g, 0.32 mmol) and CuI (0.225 g, 1.18 mmol). A solution of THF (14 mL) and triethylamine (45 mL) was then added to the reaction mixture. Subsequently, trimethylsilylacetylene (30 mL, 211 mmol) was added to the reaction mixture. Within 10 min, the reaction darkened and salts precipitated. The suspension was then filtered, transferred with ether into a separatory funnel, washed with saturated ammonium chloride (2 × 70 mL), and then dried over magnesium sulfate. The solvent was removed under vacuum to produce a dark brown oil which was purified by silica gel column chromatography (3:1 hexanes/EtOAc) to give **16** (8.4 g, 8.9 mmol, 89%) as a light orange oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.04 (s, 1H), 7.98 (s, 1H), 7.70 (s, 1H), 4.42−4.41 (m, 2H), 3.77−3.76 (m, 2H), 3.64−3.57 (m, 6H), 3.47−3.46 (m, 2H), 3.30 (s, 3H), 0.19 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 164.7, 138.7, 132.6, 132.1, 131.8, 125.5, 122.2, 102.4, 97.3, 72.1, 70.81, 70.78, 70.77, 69.2, 64.8, 59.2, −0.02; MS (FD) ($C_{19}H_{27}BrO_5Si$) calcd 443.4, found 444.1. Anal calcd for $C_{19}H_{27}BrO_5Si$: C, 51.47; H, 6.14. Found: C, 51.28; H, 6.40.

2-[2-(2-Methoxyethoxy)ethoxy]ethyl-3-bromo-4-methyl-5-trimethylsilanylethynylbenzoate (17). Using the procedure for **16**, we obtained **17** (2.04 g, 4.47 mmol, 87.8%) as a light yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.15 (d, J = 1.5 Hz, 1H), 8.05 (d,

J = 1.7 Hz, 1H), 4.48−4.45 (m, 2H), 3.84−3.81 (m, 2H), 3.73−3.70 (m, 2H), 3.69−3.64 (m, 4H), 3.55−3.53 (m, 2H), 3.37 (s, 3H), 2.59 (s, 3H), 0.27 (s, 9H); MS (LR−FD) 458.1. Anal. calcd for $C_{20}H_{29}BrO_5Si$: C, 52.51; H, 6.39; N, 0. Found: C, 52.21; H, 6.37; N, 0.

2-[2-(2-Methoxyethoxy)ethoxy]ethyl-3-[(triisopropylsilanyl)-ethynyl]-5-trimethylsilanylethynylbenzoate (18). In a glovebox under an inert atmosphere of argon, a 250 mL round-bottom flask was fitted with a stir bar and charged with **16** (5.22 g, 11.77 mmol) and dry toluene (86 mL). To this solution was added Pd(I) dimer precatalyst (0.42 g, 1.18 mmol), diisopropylamine (8.25 mL, 58.9 mmol), $ZnBr_2$ (5.30 g, 23.5 mmol), and triisopropylsilylacetylene (13 mL, 58.85 mmol). Upon addition of the reagents, the solution darkened and salts precipitated from the reaction mixture. TLC analysis revealed that the reaction was complete within 30 min. The precipitate was removed by filtration, and the filtrate was transferred into a separatory funnel with Et_2O at which time the solution was washed with saturated NH_4Cl (2 × 100 mL). The organic layer was then dried over $MgSO_4$ and filtered, and the solvent was removed under vacuum to give a brown oil that was purified by silica gel column chromatography (3:1 hexane/EtOAc) to yield **18** (5.7 g, 10.46 mmol, 89%) as a yellow oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.88 (m, 1H), 7.55 (m, 1H), 7.70 (s, 1H), 4.31−4.29 (m, 2H), 3.65−3.63 (m, 2H), 3.52−3.42 (m, 6H), 3.32−3.30 (m, 2H), 3.15 (s, 3H), 0.95 (s, 21H), 0.09 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 164.9, 139.0, 132.8, 132.6, 130.8, 124.2, 124.0, 105.0, 103.0, 96.1, 92.6, 70.68, 70.66, 70.60, 69.1, 64.4, 58.9, 18.7, 11.3, −0.2; MS (FD) ($C_{19}H_{27}BrO_5Si$) calcd 544.87, found 545.3115 (M^{+1}).

2-[2-(2-Methoxyethoxy)ethoxy]ethyl-4-methyl-3-[(triisopropylsilanyl)-ethynyl]-5-trimethylsilanylethynylbenzoate (19). Using the procedure for **18**, we obtained **19** (5.51 g, 9.85 mmol, 88%) as a yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.01 (s, 2H), 4.45−4.43 (m, 2H), 3.81−3.79 (m, 2H), 3.69−3.67 (m, 2H), 3.65−3.60 (m, 4H), 3.50−3.48 (m, 2H), 3.32 (s, 3H), 2.61 (s, 3H), 1.10 (s, 21H), 0.23 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 165.2, 147.8, 133.1, 132.8, 127.4, 124.1, 123.7, 104.1, 102.4, 99.5, 96.1, 71.8, 70.5, 70.48, 70.42, 69.1, 64.2, 58.9, 19.6, 18.5, 11.1, −0.2; MS (FD) ($C_{31}H_{50}O_5Si_2$) calcd 558.3197, found 559.4 ([M + H$^+$]); HRMS (ESI) found 558.3282 ([M + H]).

Ethyl 3-Iodo-4-methylbenzoate (20). A 1 L round-bottom flask was charged with 3-iodo-4-methyl-benzoic acid (15.22 g, 58.08 mmol), ethanol (260 mL), and sulfuric acid (20 mL) and heated to reflux overnight. Upon completion of the reaction, the contents were cooled to room temperature and poured into a separatory funnel containing water (500 mL). The contents were then extracted with $CHCl_3$ (3 × 100 mL). The $CHCl_3$ fractions were combined and washed with brine (2 × 100 mL), combined, and dried over $MgSO_4$. After concentration of the solvent, a dark oil resulted. This oil was then distilled under vacuum to produce **20** as a yellow oil (14.83 g, 51.12 mmol, 88%): ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.43 (d, J = 1.5 Hz, 1H), 7.88 (d, J = 1.7 Hz, 1H), 7.87 (d, J = 1.7 Hz, 1H), 4.34 (q, J = 7.08 Hz, 2H), 2.44 (s, 3H), 1.37 (t, J = 7.08 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 165.3, 146.8, 140.1, 129.8, 129.7, 129.5, 100.7, 61.4, 28.5, 14.5; MS (EI) ($C_{10}H_{11}IO_2$) calcd 290.10, found 290.0. Anal. calcd for $C_{10}H_{11}IO_2$: C, 41.40; H, 3.82. Found: C, 41.48; H, 3.74.

Ethyl 3-(Trimethylsilanylethynyl)-4-methylbenzoate (21). A 0.5 L round-bottom flask was charged with $Pd_2(dba)_3$ (0.38 g, 0.41 mmol), CuI (0.16 g, 0.83 mmol), PPh_3 (0.21 g, 0.81 mmol), and a stir bar and evacuated and refilled with argon (×3). Ethyl 3-iodo-4-methylbenzoate (4.01 g, 13.82 mmol) was placed in a 250 mL round-bottom flask and evacuated and refilled (×3) with argon. A solution of piperidine (60 mL, 606 mmol) and TMSA (9 mL, 63.7 mmol) was also placed in a 100 mL round-bottom flask and evacuated and refilled (×3) with argon. The flask containing the piperidine/TMSA mixture was then transferred to the round-bottom containing **20**. This mixture was then transferred via cannula to the 0.5 L flask containing the catalyst, CuI, and PPh_3. The resultant solution turned green and produced salts almost immediately. The reaction was stirred overnight, and the reaction color darkened. At this time, the reaction mixture was poured into a separatory funnel containing 250 mL of water. The product was then extracted with CH_2Cl_2 (3 × 100 mL). The combined organic fractions were then washed with saturated NH_4Cl (3 × 200 mL) and brine (1 × 200 mL) and then dried over $MgSO_4$. After filtration, the solvent was removed to produce a dark oil. This residue was purified by silica gel column chromatography (2:1 hexane/$CHCl_3$) to produce **21** as an orange solid (2.15 g, 8.26 mmol, 60%): ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.09 (d, J = 1.8 Hz, 1H), 7.87 (d, J = 1.6 Hz, 1H), 7.86 (d, J = 1.8 Hz, 1H), 4.35 (q, J = 7.1 Hz, 2H), 2.47 (s, 3H), 1.38 (t, J = 7.1 Hz, 3H), 0.26 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 166.2, 145.9, 133.5, 129.7, 129.6, 128.3, 123.5, 103.1, 99.4, 61.2, 21.1, 14.5, 0.2; MS (EI) ($C_{15}H_{20}O_2Si$) calcd 260.40, found 260.1. Anal. calcd for $C_{15}H_{20}O_2Si$: C, 69.19; H, 7.74. Found: C, 69.16; H, 7.83.

Ethyl 3-(Ethynyl)-4-methylbenzoate (22). A scintillation vial was charged with ethyl 3-(trimethylsilanylethynyl)-4-methylbenzoate **21** (0.32 g, 1.23 mmol), THF (1.8 mL), and a stir bar. In another scintillation vial, TBAF (2.3 mL, 2.30 mmol) and acetic acid (0.13 mL, 2.30 mmol) were mixed together and then added to the scintillation vial containing **21** and THF. It was determined by TLC analysis that the reaction was completed in 13 min. At this point, the reaction mixture was passed through a plug of silica gel and then concentrated to a dark oil. This oil was then purified by silica gel column chromatography (5:1 hexane/EtOAc) to produce **22** as a yellow oil (0.17 g, 0.92 mmol, 75%): ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.12 (d, J = 1.9 Hz, 1H), 7.90 (d, J = 1.8 Hz, 1H), 7.89 (d, J = 1.8 Hz, 1H), 4.35 (q, J = 7.2 Hz, 2H), 3.31 (s, 1H), 2.49 (s, 3H), 1.38 (t, J = 7.2 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 166.1, 146.1, 133.9, 129.9, 129.8, 128.4, 122.5, 82.0, 81.7, 61.2, 21.0, 14.5; MS (EI) ($C_{12}H_{12}O_2$) calcd 188.22, found 188.11.

Acknowledgment. This work was supported by the National Science Foundation (CHE 03-45254) and the U.S. Department of Energy (DEFG02-91ER45439).

Supporting Information Available: Detailed procedure describing the solid-phase method, experimental procedures for the synthesis of monomer **6** and tetrafluoroborate salts, and characterization data such as MALDI mass spectra, NMR spectra, crude and purified GPC spectra, and HPLC spectra for oligomers **7**−**15**. This material is available free of charge via the Internet at http://pubs.acs.org.

JO0607212