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Preparation of Shape-Persistent Macrocycles with a Single Pyridine Unit by Double Cross-Coupling Reactions of Aryl Bromides and Alkynes

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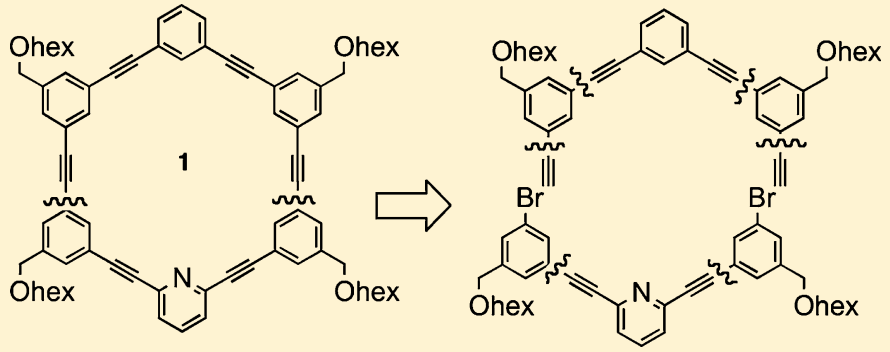
Supporting Information



ABSTRACT: A double Sonogashira-type coupling reaction between aryl bromides and alkynes using a catalytic Pd/XPhos (2-dicyclohexylphosphino-2′,4′,6′-triisopropylbiphenyl) system was introduced as an efficient method for the synthesis of shape-persistent macrocycles (SPMs). This approach is advantageous in the synthesis of SPMs with a single pyridine unit.

Shape-persistent macrocycles (SPMs), composed of arylene and ethynylene units, are versatile macromolecules and are frequently used in host–guest chemistry.[1,2] Twynsky et al. used SPMs for the formation of supramolecules mediated by Pt–bipyridine chelation outside the macrocycle cavity,[3] and Yoshida et al. reported an SPM–Sb complex which incorporated an Sb atom inside the macrocycle.[4] Crystallography has shown that SPMs with large diameters can even accommodate two Cu ions inside their cavities.[5] SPMs are also known to form aggregates in solution.[6] Recently, the control of SPM aggregation on surfaces has been intensively studied by scanning tunneling microscopy.[7]

Efficient methods for SPM synthesis have been developed since the 1990s by Moore et al.[8] and Tobe et al.[9] These strategies can be classified into three main groups. The first method involves an intermolecular coupling reaction, such as a Sonogashira coupling reaction between an aryl iodide and an alkyne, followed by an intramolecular coupling reaction under dilute conditions.[8] The second method uses a double-cyclization reaction such as Glaser coupling of alkynes[10] or a Sonogashira coupling between an aryl iodide and an alkyne.[11] Alkyne metathesis, which is very efficient, was recently introduced as the third method.[8d]

Although many characteristics and functions of SPMs have been studied, the diversity of SPM structures is not rich enough. Many SPMs have an axis of symmetry, which will facilitate synthesis and structural analysis, and most SPMs which incorporate pyridine substructures contain two and more pyridine moieties.[1] It would be difficult to analyze the properties of SPMs when two or more pyridine moieties are incorporated, so it is desirable to synthesize and analyze SPMs incorporating a single pyridine unit. In this paper, we describe the synthesis of SPMs with a single pyridine unit using a double Sonogashira-type coupling reaction, using aryl bromide as the substrate and under mild conditions. We found that by using a highly active catalyst for the Sonogashira-type coupling reaction,[12,13] various dibromides could be used as the substrate for cyclization via double Sonogashira-type coupling reactions.

The SPM precursors were prepared using conventional Sonogashira coupling reactions, as shown in Scheme 1. The Sonogashira coupling reaction between **2** (or **3**) and **4** afforded **5** (or **6**) in good yield. Compound **5** was further converted to alkyne derivative **8** by an additional Sonogashira coupling reaction with trimethylsilylacetylene and deprotection of the trimethylsilyl group. The diiodide precursor was prepared as shown in Scheme 2. Compound **3** reacted with an excess of **9** under Sonogashira coupling reaction conditions to afford diiodide hemicycle **10**. Compound **10** was reacted with trimethylsilylacetylene and subsequent deprotection gave the desired pyridine derivative **12**.[14]

With these substrates in hand, we screened the conditions for the cross-coupling reaction (Table 1). In most cases, harsh conditions are required for Sonogashira coupling using an aryl bromide as the substrate.[3c,15] Although various highly active

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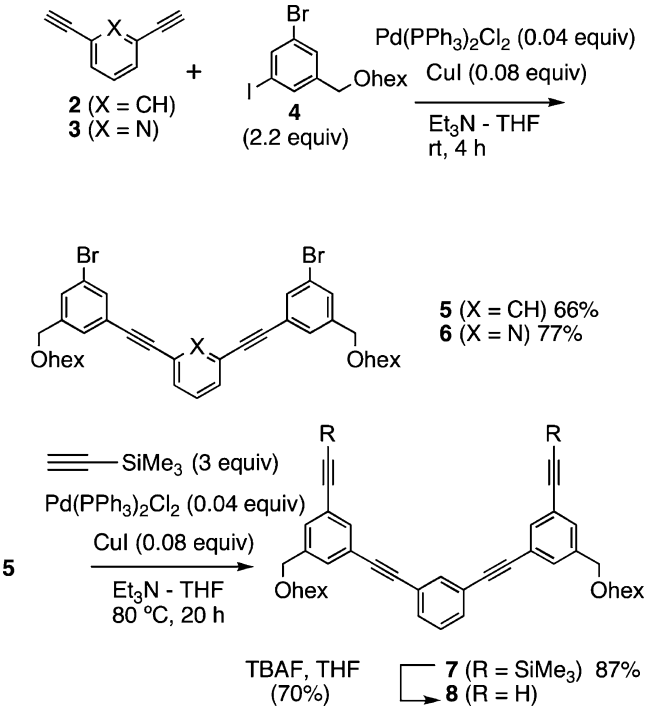
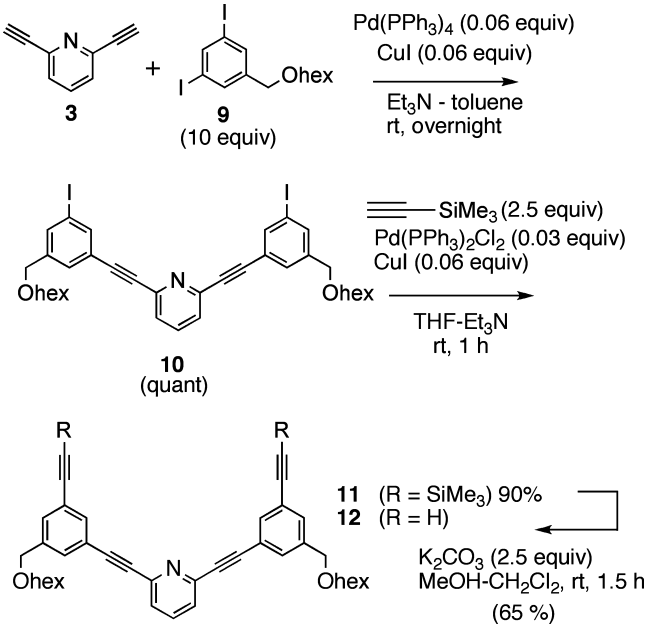
Scheme 1. Synthesis of Cyclization Precursors (1)



Scheme 2. Synthesis of Cyclization Precursors (2)



catalysts for Sonogashira-type coupling reactions were examined, we found that the Cu-free Sonogashira-type coupling reactions with Pd/XPhos (2-dicyclohexylphosphino-2′,4′,6′-triisopropylbiphenyl, see Table 1), originally reported by Buchwald et al.,[12] worked well for the coupling reaction of **6** and **8**. This catalytic system is relatively stable and easy to handle. To prevent intermolecular oligomerization, we carried out the coupling reaction under pseudodilute conditions. Thus, **8** (0.054 mmol, 1 equiv) in 1,4-dioxane (0.54 mL) was added to a mixture of 0.1 equiv of $Pd(CH_3CN)_2Cl_2$, 0.3 equiv of XPhos, $CsCO_3$ (6 equiv), and **6** (0.054 mmol, 1 equiv) in 1,4-dioxane (4.86 mL) via a syringe pump over 10 h at 60 °C. Compound **1** was easily purified by silica gel chromatography and was obtained in 24% yield (Table 1, entry 1). It is noteworthy that neither the cyclized trimer nor tetramer was isolated in this reaction.[16] The higher temperature (60 °C) allowed the reaction to finish in a shorter period of time, without reducing the product yield (entry 2). The product yield did not improve when the reaction was carried out at an even higher temperature (80 °C) or when the catalyst loading was increased or decreased (entries 3−5). With regard to substrate concentration, the best result was observed when the concentration, based on the total amount of solvent and **6** (or **8**), was set at 10 mM; the product yield decreased when half or twice the amount of solvent was used (entries 6 and 7). The yield did not improve when the addition time was extended to 20 h (entry 8). In contrast, the yield of **1** improved marginally when the addition of **8** was completed in 5 h (entry 9). This result implies that catalyst decomposition occurred when the reaction was continued for a longer period of time. Further reduction of the injection time (3 h) resulted in a slightly lower yield of the product (entry 10). The conditions listed in entry 9 gave the best results for coupling reactions of these substrates.

Two-component cyclizations by double Sonogashira-type coupling reactions using aryl bromides as the substrates are rare.[17] The only example we could find in the literature was reported by Lee et al., who used Sonogashira coupling reactions with such substrates to obtain an SPM in 54% yield [$(PdCl_2(PPh_3)_2$, CuI, *i*-Pr_2NH, 70 °C, 16 h].[3c] Although the yields in our reactions were not very high, the yields are comparable to those in other examples which used aryl iodides as the substrates for the synthesis of similar SPMs.[17]

We used these optimized conditions in the coupling reaction of aryl iodide (**10**) and diyne (**8**), but the product yield was low (Scheme 3). This result tells us that more reactive substrates do not necessarily give better yields of the product. The reversed pair of diyne (**12**) and dibromide (**5**) were also subjected to cyclization, and this combination gave a slightly lower yield of **1**.

With these optimized conditions in hand, we used this strategy to synthesize various SPMs and related compounds (Figure 1). An *N*,*N*-dimethylaminopyridine (DMAP) moiety was introduced into the SPM structure by cyclization of a dibromide bearing a DMAP moiety with **8**; **13** was isolated in 20% yield. An SPM with two pyridine moieties (**14**) was also prepared, albeit in low yield. We assume that the low yield of **14** was partially a result of purification difficulties. Cyclization using a starting material containing a flexible linker was also examined under these conditions, and the macrocycle **15** was obtained in 11% yield. This result implies that the preordered molecular structures of **6** and **8** are beneficial in this double coupling strategy. The larger SPM **16**, linked with a butadiyne unit, was obtained in 7% yield. The lower yield of **16** might be a result of the instability of the butadiyne unit.

In summary, we have reported an efficient synthesis of SPMs with a single pyridine unit by successive inter- and intramolecular Sonogashira-type coupling reactions between aryl bromides and alkynes, catalyzed by Pd/XPhos. We optimized the conditions for the coupling reaction with aryl bromide as the substrate; this enabled synthesis of an SPM from 1,3-diethynylpyridine (**3**) in short steps. The use of aryl bromides in place of aryl iodides is rare, and usually requires harsh condition. The use of aryl bromides, however, facilitates SPM

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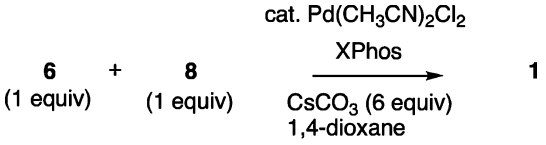
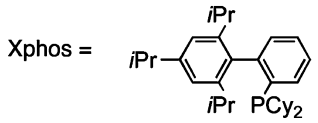
Table 1. Coupling Reactions of 6 and 8

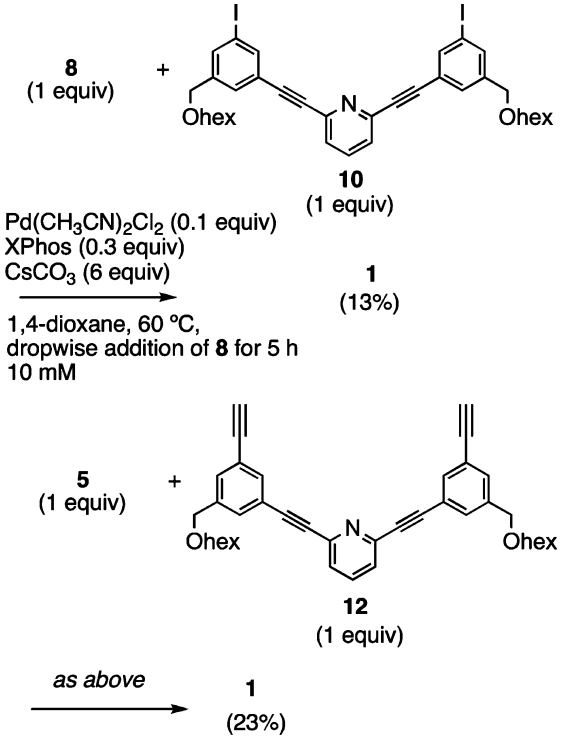




entry	$Pd(CH_3CN)_2Cl_2$ (equiv)	XPhos (equiv)	conc (mM)[a]	T (°C)	time[b] (h)	yield (%)
1	0.1	0.3	10	40	40 (10)	24
2	0.1	0.3	10	60	14 (10)	24
3	0.1	0.3	10	80	15 (10)	21
4	0.2	0.6	10	60	15 (10)	19
5	0.05	0.15	10	60	72 (10)	0
6	0.1	0.3	20	60	15 (10)	10
7	0.1	0.3	5	60	48 (10)	0
8	0.1	0.3	10	60	26 (20)	7
9	0.1	0.3	10	60	6.5 (5)	28
10	0.1	0.3	10	60	5 (3)	24

[a]Estimated concentration, which was defined as follows: (the amount of **6** used for the reaction)/(total amount of the solvent). [b]Total reaction time, including the addition time of **8**. The addition time of **8** is indicated in parentheses.

Scheme 3. Synthesis of 1 with Other Cyclization Precursors



synthesis. This method provides new and rapid access to SPMs with single pyridine unit, and related compounds.

EXPERIMENTAL SECTION

General Information. Reagents were commercially available and used without further purification unless otherwise noted. Compounds **2**,[18] **3**,[19] **4**,[20] and **9**[20] were prepared as reported. Chemical shifts were reported in delta units (δ) relative to chloroform (7.24 ppm for ^{1}H NMR and 77.2 ppm for ^{13}C NMR). Multiplicity is indicated by s (singlet), d (doublet), t (triplet), q (quartet) or m (multiplet).

Preparation of Dibromides 5 and 6. General Procedure. To a mixture of CuI (46 mg, 0.24 mmol), $Pd(PPh_3)_2Cl_2$ (84 mg, 0.12 mmol), and **4** (2.62 g, 6.6 mmol) were added Et_3N (4.7 mL) and dry THF (4.7 mL). The mixture was stirred for 10 min at room temperature under Ar. After addition of diyne (**2** or **3**) (3.0 mmol), the mixture was stirred for 1 h at room temperature. The solvent was evaporated, filtered through a pad of Celite (washed with CH_2Cl_2), diluted with CH_2Cl_2, and washed with brine. The organic layer was dried over $MgSO_4$ and evaporated. The crude product was purified by silica gel column chromatography to give the desired product. **5** (66%, pale yellow solid): mp 45−46 °C; ^{1}H NMR (300 MHz, $CDCl_3$) 7.66 (s, 1H), 7.56 (s, 2H), 7.47−7.45 (m, 4H), 7.40 (s, 2H), 7.32 (t, J = 7.5 Hz, 1H), 4.44 (s, 4H), 3.46 (t, J = 6.6 Hz, 4H), 1.66−1.57 (m, 4H) 1.39−1.29 (m, 12H), 0.89 (t, J = 6.9 Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) 141.4, 134.9, 133.4, 131.8, 130.6, 129.2, 128.7, 125.0, 123.4, 122.4, 89.8, 88.7, 71.7, 71.1, 31.9, 29.9, 26.0, 22.8, 14.3; IR (KBr) 2930, 2856, 1598, 1561, 1479, 1442, 1354, 1213, 1182, 1114, 992, 892, 858, 828, 792, 732, 683, 533 cm^{-1}. Anal. Calcd for $C_{36}H_{40}Br_2O_2$: C, 65.07; H, 6.07. Found: C, 65.28; H, 6.15.

6 (77%, pale yellow solid): mp 58.0−58.2 °C; ^{1}H NMR (300 MHz, $CDCl_3$) 7.65 (t, J = 4.5 Hz, 1H), 7.61−7.59 (m, 2H), 7.46−7.41 (m, 6H) 4.41 (s, 4H), 3,44 (t, J = 6.6 Hz, 4H), 1.61−1.54 (m, 4H) 1.36−1.23 (m, 12H) 0.86 (t, J = 6.9 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) 143.6, 141.5, 136.7, 133.7, 131.3, 129.6, 126.7, 124.0, 122.4, 89.3, 88.1, 71.6, 71.1, 31.8, 29.8, 26.0, 22.8, 14.2; IR (KBr) 2931, 2857, 2218, 1596, 1559, 1455, 1355, 1201, 1159, 1115, 907, 860, 807, 787, 731, 679, 551 cm^{-1}. Anal. Calcd for $C_{35}H_{39}Br_2NO_2$: C, 63.17; H, 5.91; N, 2.10. Found: C, 63.10; H, 5.77; N, 2.04.

Preparation of Diyne 7. To a mixture of CuI (0.06 g, 0.314 mmol), $Pd(PPh_3)_2Cl_2$ (0.112 g, 0.16 mmol), and dibromide **5** (3.48 g, 5.23 mmol) were added Et_3N (8.7 mL) and dry THF (8.7 mL), and the mixture was stirred for 10 min at 80 °C under Ar. Trimethylsilylacetylene (2.2 mL, 15.7 mmol) was added, and the mixture was stirred overnight. The solvent was evaporated, filtered through a pad of Celite (washed with CH_2Cl_2), diluted with CH_2Cl_2, and washed with brine. The organic layer was dried over $MgSO_4$ and evaporated. The crude product was purified by silica gel column chromatography (hexane/CH_2Cl_2 5:1) to give **7** (3.18 g, 87%) as yellow oil. **7**: ^{1}H NMR (500 MHz, $CDCl_3$) 7.65 (t, J = 1.5 Hz, 1H),

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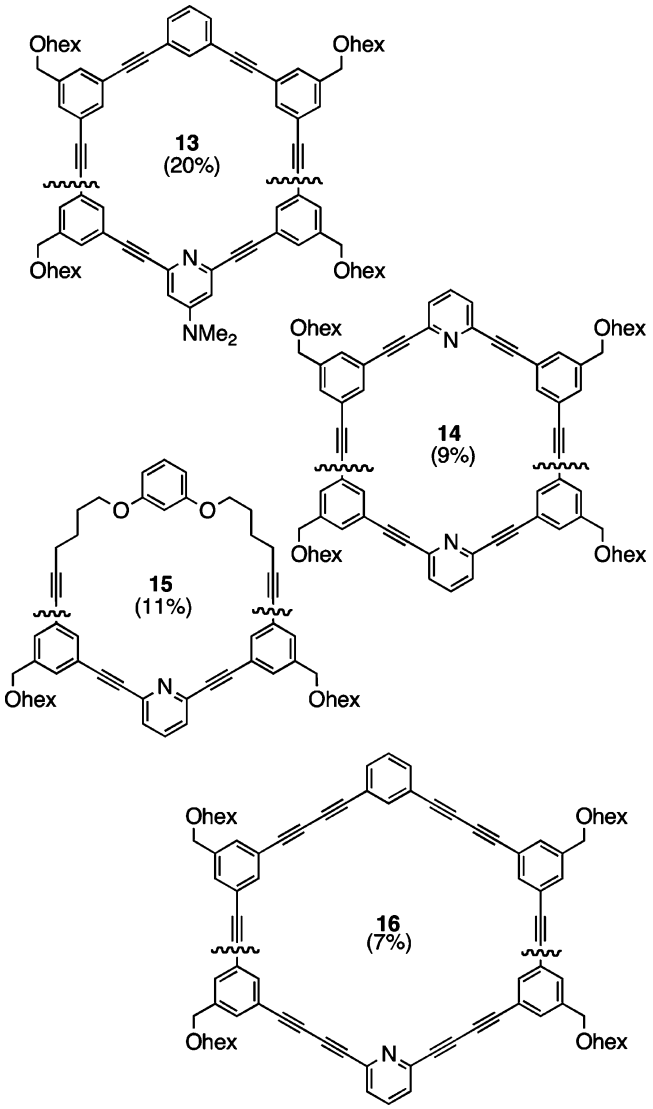

Figure 1. Prepared SPMs and related compounds.

7.55 (t, J = 1.5 Hz, 2H), 7.46−7.44 (m, 4H), 7.39 (d, J = 1.5 Hz, 2H), 7.30 (t, J = 7.5 Hz, 1H), 4.44 (s, 4H), 3.45 (t, J = 6.8 Hz, 4H), 1.46−1.58 (m, 4H), 1.56−1.26 (m, 12H), 0.88 (t, J = 7.0 Hz, 6H), 0.22 (s, 18H); ^{13}C NMR (125 MHz, $CDCl_3$) 139.8, 135.1, 134.5, 131.9, 131.3, 131.0, 129.0, 124.0, 123.9, 123.7, 104.5, 95.5, 89.6, 89.4, 72.4, 71.3, 32.1, 30.1, 26.3, 23.1, 14.5, 0.4; IR (KBr) 2957, 2931, 2857, 2157, 1596, 1479, 1443, 1359, 1249, 1106, 958, 843, 792, 759, 732, 685, 532, 411 cm^{-1}. Anal. Calcd for $C_{46}H_{58}O_2Si_2$; C, 79.03; H, 8.36. Found: C, 79.10; H, 8.08.

Preparation of Diyne 8. To a solution of **7** (2.96 g, 4.23 mmol) in THF (84.6 mL) was added dropwise 12.7 mL of TBAF solution (1.0 M in THF). After being stirred at room temperature for 3 h, the mixture was diluted with water and extracted with $CHCl_3$. The extract was washed with brine and dried over $MgSO_4$. After removal of the solvent in vacuo, the residue was purified by silica gel column chromatography (hexane/AcOEt 10:1) to provide **8** as a pale yellow solid (1.64 g, 70%). **8**: mp 48.2 °C; ^{1}H NMR (300 MHz, $CDCl_3$) 7.67 (s, 1H), 7.56 (s, 2H), 7.47−7.45 (m, 4H), 7.42 (s, 2H), 7.29 (t, J = 7.5 Hz, 1H), 4.45 (s, 4H), 3.46 (t, J = 6.6 Hz, 4H), 3.08 (s, 2H), 1.66−1.57 (m, 4H), 1.41−1.28 (m, 12H), 0.88 (t, J = 6.6 Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) 139.8, 134.8, 134.3, 131.7, 131.2, 131.1, 128.7, 123.6, 123.6, 122.8, 89.3, 89.2, 82.9, 78.0, 72.0, 71.1, 31.9, 29.9, 26.1, 22.8, 14.3; IR (KBr) 3283, 2936, 2854, 1594, 1476, 1361, 1151, 1120, 1025, 983, 889, 863, 782, 683, 627, 531 cm^{-1}. Anal. Calcd for $C_{40}H_{42}O_2$: C, 86.60; H, 7.63. Found: C, 86.41; H, 7.64.

Preparation of 10. To a mixture of **3** (0.172 g, 1.35 mmol) and diiodide **9** (6 g, 13.5 mmol) were added Et_3N (77.6 mL) and dry toluene (77.6 mL), and then Ar was bubbled for 30 min at room temperature. CuI (15 mg, 0.081 mmol) and $Pd(PPh_3)_4$ (94 mg, 0.081 mmol) were added, and the reaction mixture was stirred overnight. The mixture was evaporated, filtered through a pad of Celite, diluted with CH_2Cl_2, and washed with brine. The organic layer was dried over $MgSO_4$ and evaporated. The crude product was purified by silica gel column chromatography (hexane/AcOEt 10:1) to give **10** (898 mg, quant) as a pale yellow solid. **10**: mp 59.2 °C; ^{1}H NMR (300 MHz, $CDCl_3$) 7.83 (s, 2H), 7.70−7.64 (m, 3H), 7.51 (s, 2H), 7.45 (d, J = 4.8 Hz, 2H), 4.41 (s, 4H), 3.45 (t, J = 6.6 Hz, 4H), 1.65−1.51 (m, 4H), 1.40−1.28 (m, 12H), 0.88 (t, J = 6.6 Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) 143.7, 141.4, 139.7, 137.2, 136.7, 130.4, 126.7, 124.1, 93.8, 89.3, 88.0, 71.6, 71.1, 31.8, 29.8, 26.0, 22.8, 14.2; IR (KBr) 2933, 2854, 2218, 1591, 1556, 1455, 1359, 1237, 1201, 1159, 1118, 983, 861, 804, 768, 728, 678, 552 cm^{-1}. Anal. Calcd for $C_{35}H_{39}I_2NO_2$: C, 55.35; H, 5.18; N, 1.84. Found: C, 55.29; H, 4.95; N, 1.74.

Preparation of 12. To a mixture of CuI (10.5 mg, 0.055 mmol), $Pd(PPh_3)_2Cl_2$ (19.3 mg, 0.0275 mmol), and **10** (0.611 g, 0.918 mmol) were added Et_3N (1.5 mL) and dry THF (1.5 mL). The mixture was stirred for 10 min at room temperature under Ar. Trimethylsilylacetylene (0.28 mL, 2.0 mmol) was added, and the reaction mixture was stirred for 1 h. The mixture was evaporated, filtered through a pad of Celite, and diluted with CH_2Cl_2. The organic layer was washed with brine, dried over $MgSO_4$, and evaporated. The crude product was purified by silica gel column chromatography (hexane/AcOEt 20:1) to give **11** (411 mg, 90%) as yellow oil. **11**: ^{1}H NMR (500 MHz, $CDCl_3$) 7.64 (t, J = 7.5 Hz, 1H), 7.58 (s, 2H), 7.50 (s, 2H), 7.43−7.41 (m, 4H), 4.43 (s, 4H), 3.43 (t, J = 6.8 Hz, 4H), 1.62−1.57 (m, 4H), 1.38−1.26 (m, 12H), 0.87 (t, J = 7.0 Hz, 6H), 0.23 (s, 18H); ^{13}C NMR (125 MHz, $CDCl_3$) 143.8, 139.7, 136.7, 134.6, 131.6, 131.1, 126.6, 123.8, 122.6, 104.1, 95.4, 88.9, 88.8, 72.0, 71.0, 31.9, 29.9, 26.0, 22.8, 14.2, 0.07; IR (KBr) 2931, 2857, 2219, 2157, 1590, 1557, 1454, 1359, 1249, 1159, 1108, 958, 844, 807, 759, 729, 685 cm^{-1}. Anal. Calcd for $C_{45}H_{57}NO_2Si_2$: C, 77.20; H, 8.21; N, 2.00. Found: C, 77.13; H, 8.22; N, 1.92. To a solution of **11** (0.581 g, 0.83 mmol) in MeOH (2 mL) and CH_2Cl_2 (0.5 mL) was added K_2CO_3 (0.286 g, 2.07 mmol) and the reaction mixture was stirred overnight at the room temperature. The mixture was evaporated. To the residue was added water, and the mixture was extracted with CH_2Cl_2. The organic layer was washed with brine, and dried over $MgSO_4$ and evaporated under vacuo. The crude product was purified by silica gel column chromatography (hexane/AcOEt 10: 1) to afford **12** (0.300 g, 65%). **12** (65%, colorless solid): mp 35 °C; ^{1}H NMR (500 MHz, $CDCl_3$) 7.66 (t, J = 7.5 Hz, 1H), 7.60 (s, 2H), 7.53 (s, 2H), 7.45−7.43 (m, 4H), 4.44 (s, 4H), 3.44 (t, J = 6.7 Hz, 4H), 3.07 (s, 2H), 1.63−1.57 (m, 4H), 1.38−1.26 (m, 12H), 0.87 (t, J = 6.9 Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) 143.8, 139.8, 136.7, 134.7, 131.8, 131.5, 126.7, 122.8, 122.7, 88.9, 88.8, 82.8, 78.1, 71.9, 71.1, 31.9, 29.9, 26.0, 22.8, 14.3; IR (KBr) 3293, 2931, 2861, 2221, 1781, 1589, 1558, 1450, 1357, 1241, 1157, 1110, 995, 871, 809, 732, 686, 655, 624, 547 cm^{-1}. Anal. Calcd for $C_{39}H_{41}NO_2$: C, 84.29; H, 7.44; N, 2.52. Found: C, 84.15; H, 7.38; N, 2.40.

Preparation of the Precursor (Dibromide) of 13 (Pre13-DiBr). The dibromide of the cyclization precursor was prepared by the coupling reaction of 2,5-diethynyl-4-dimethylaminnopyridine[21] and **4** based on the method used for synthesis of **5**. **Pre13-DiBr** (36%, colorless solid): mp 112−114 °C; ^{1}H NMR (300 MHz, $CDCl_3$) 7.62 (s, 2H), 7.47 (s, 4H), 6.71 (s, 2H), 4.43 (s, 4H), 3.44 (t, J = 6.6 Hz, 4H), 3.05 (s, 6H), 1.62−1.55 (m, 4H), 1.38−1.28 (m, 12H), 0.87 (t, J = 6.7 Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) 154.6, 143.4, 141.4, 133.8, 131.0, 129.7, 124.6, 122.4, 109.9, 90.5, 86.2, 71.8, 71.1, 39.5, 31.9, 29.9, 26.0, 22.8, 14.3; IR (KBr) 2930, 1590, 1524, 1427, 1384, 1216, 1169, 1099, 1025, 971, 856, 825, 808, 689 cm^{-1}. Anal. Calcd for $C_{37}H_{44}Br_2N_2O_2$: C, 62.72; H, 6.26; N, 3.95. Found: C, 62.57; H, 6.06; N, 3.78.

Preparation of the Precursor (Diyne) of 15 (Pre15-Diyne). A mixture of resorcinol (0.207 g, 1.88 mmol), 4-pentyn-1-*p*-toluenesulfonate[22] (0.95 g, 3.76 mmol), K_2CO_3 (1.43 g, 10.34 mmol), and LiBr (0.245 g, 2.82 mmol) in dry DMF (3.62 mL) was stirred at 80 °C for

13 h. The mixture was cooled to room temperature, filtered, and evaporated. The crude product was then purified by column chromatography (hexane/CH_2Cl_2 5:1) to give **Pre15-Diyne** (335 mg, 66%) as a colorless solid. **Pre15-Diyne**: mp 54−56 °C; ^{1}H NMR (500 MHz, $CDCl_3$) 7.14 (t, J = 8.3 Hz, 1H), 6.47−6.43 (m, 3H), 3.94 (t, J = 6.3 Hz, 4H), 2.25 (dt, J = 2.5 Hz, 7.0 Hz, 4H), 1.95 (t, J = 2.5 Hz, 2H), 1.91−1.85 (m, 4H), 1.73−1.67 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) 160.4, 130.1, 106.9, 101.6, 84.3, 68.8, 67.4, 28.5, 25.3, 18.3; IR (KBr) 2959, 2207, 2098, 1706, 1590, 1562, 1475, 1410, 1252, 1045, 847, 795, 761, 702, 682, 635, 507, 449 cm^{-1}. Anal. Calcd for $C_{18}H_{22}O_2$: C, 79.96; H, 8.20. Found: C, 79.87; H, 8.41.

Preparation of 1-[(Hexyloxyl)methyl]-3-iodo-5-[(2-trimethylsilyl)ethynyl]benzene (17). BuLi (1.6 M) in hexane (7.5 mL, 12 mmol) was added to a solution of 1-bromo-3-[(hexyloxyl)methyl]-5-[(2-trimethylsilyl)ethynyl]benzene[23] (2.2 g, 6 mmol) in anhydrous THF (16.5 mL) at −78 °C under nitrogen. After 1 h, a solution of 1,2-diiodoethane (3.4 g, 12 mmol) in THF (5 mL) was added. The mixture was allowed to warm slowly to room temperature (1 h), poured into $Na_2S_2O_3$ aq, and extracted with CH_2Cl_2. The organic layer was dried over $MgSO_4$, and the residue obtained after removal of solvents was subjected to column chromatography (hexane/CH_2Cl_2 5:1) to provide **17** (1.69 g, 71%) as a yellow oil. **17**: ^{1}H NMR (500 MHz, $CDCl_3$) 7.70 (d, J = 1.5 Hz, 1H), 7.61 (d, J = 1.5 Hz, 1H), 7.35 (s, 1H), 4.37 (s, 2H), 3.42 (t, J = 6.7 Hz, 2H), 1.60−1.56 (m, 2H), 1.34−1.26 (m, 6H), 0.87 (t, J = 7.0 Hz, 3H), 0.22 (s, 9H); ^{13}C NMR (125 MHz, $CDCl_3$) 141.1, 139.6, 136.6, 130.3, 125.2, 103.3, 96.0, 93.8, 71.6, 71.0, 31.9, 29.8, 26.0, 22.8, 14.3, 0.06; IR (KBr) 2954, 2931, 2861, 2159, 1589, 1558, 1457, 1434, 1357, 1249, 1157, 1103, 956, 848, 763, 686, 663 cm^{-1}. Anal. Calcd for $C_{18}H_{27}IOSi$: C, 52.17; H, 6.57. Found: C, 52.44; H, 6.63.

Preparation of the Precursor of 16 (Pre16-Diyne). To a mixture of CuI (0.011 g, 0.06 mmol), $Pd(PPh_3)_2Cl_2$ (0.021 g, 0.03 mmol), and 1,3-diiodobenzene (0.33 g, 1 mmol) was added Et_3N (10 mL), and then the mixture was stirred for 10 min at 0 °C under Ar. 1-Trimethylsilylbutadiyne[24] (0.367 g, 3 mmol) was added, and the reaction mixture was stirred 5.5 h. The mixture was evaporated, filtered through a pad of Celite (washed with CH_2Cl_2), diluted with CH_2Cl_2, and washed with brine. The organic layer was dried over $MgSO_4$ and evaporated. The crude product was purified by silica gel column chromatography to give bis-1,3-[(4-trimethylsilyl)-1,3-butadiyn-1-yl]-benzene (quant, yellow solid): mp 106−108 °C; ^{1}H NMR (300 MHz, $CDCl_3$) 7.55 (t, J = 1.5 Hz, 1H), 7.43 (dd, J = 7.8 Hz, 1.6 Hz, 2H), 7.25 (t, J = 7.8 Hz, 1H), 0.22 (s, 18H); ^{13}C NMR (75 MHz, $CDCl_3$) 136.6, 133.5, 128.9, 122.2, 91.7, 87.7, 75.4, 75.2, −0.2; IR (KBr) 2959, 2207, 2098, 1706, 1590, 1562, 1475, 1410, 1252, 1045, 847, 795, 507, 449 cm^{-1}. Anal. Calcd for $C_{20}H_{22}Si_2$: C, 75.41; H, 6.96. Found: C, 75.23; H, 6.94. To a solution of bis-1,3-[(4-trimethylsilyl)-1,3-butadiyn-1-yl]benzene (95 mg, 0.3 mmol) in MeOH (1.5 mL) was added K_2CO_3 (0.207 g, 1.5 mmol) and the reaction mixture was stirred for 1 h at room temperature. The mixture was diluted with HCl aq and extracted with pentane. The organic layer was dried over $MgSO_4$ and slowly evaporated. The product (terminal alkyne) was obtained as a colorless oil, which was used without further purification. To a mixture of CuI (4.5 mg, 0.024 mmol), $Pd(PPh_3)_4$ (14 mg, 0.012 mmol), and **17** (0.274 g, 0.66 mmol) were added Et_3N (0.47 mL) and dry THF (0.47 mL). Then crude bis-1,3-[1,3-butadiyn-1-yl]benzene was added and the reaction mixture was stirred for 1 h. The mixture was evaporated, and filtered through a pad of Celite (eluent: CH_2Cl_2). The filterate was washed with brine, dried over $MgSO_4$, and evaporated. The crude product was purified by silica gel column chromatography (hexane/AcOEt 20:3) to give 1,3-bis[4-(3-henyloxylmethyl-5-(2-trimethylsilyl)ethynylbenzene)-1,3-butadiyn-1-yl]-benzene (143 mg, 64%, glutinous brown oil): ^{1}H NMR (300 MHz, $CDCl_3$) 7.65 (s, 1H), 7.52−7.48 (m, 4H), 7.43−7.41 (m, 4H), 7.30 (t, J = 7.7 Hz, 1H), 4.42 (s, 4H), 3.43 (t, J = 6.6 Hz, 4H), 1.62−1.50 (m, 4H), 1.37−1.27 (m, 12H), 0.87 (t, J = 7.0 Hz, 6H), 0.23 (s, 18H); ^{13}C NMR (125 MHz, $CDCl_3$) 139.8, 136.3, 134.9, 133.3, 131.8, 131.4, 128.9, 123.9, 122.5, 122.0; 103.9, 95.6, 81.3, 80.5, 74.9, 74.3, 71.9, 71.0, 31.9, 29.9, 26.0, 22.8, 14.3, 0.06; IR (KBr) 2956, 2159, 1725, 1587, 1444, 1407, 1363, 1249, 1156, 1110, 977, 927, 854, 792, 759, 682, 541, 464 cm^{-1}. Anal. Calcd for $C_{50}H_{58}O_2Si_2$: C, 80.38; H, 7.82. Found: C, 80.23; H, 7.76. To a solution of above compound (1 mmol) in MeOH (2 mL) and CH_2Cl_2 (0.5 mL) was added K_2CO_3 (0.345 g, 2.5 mmol) and the reaction mixture was stirred for 2 h at room temperature. The mixture was evaporated and the residue was diluted with water, and extracted with CH_2Cl_2. The organic layer was washed with brine, and dried over $MgSO_4$ and evaporated. The crude product was purified by silica gel column chromatography to give the desired product. **Pre16-Diyne** (55%, dark yellow oil): ^{1}H NMR (400 MHz, $CDCl_3$) 7.65 (t, J = 1.2 Hz, 1H), 7.54 (s, 2H), 7.50 (dd, J = 1.4 Hz, 7.6 Hz, 2H), 7.47 (s, 2H), 7.45 (s, 2H), 7.31 (t, J = 7.8 Hz, 1H), 4.44 (s, 4H), 3.45 (t, J = 6.6 Hz, 4H), 3.07 (s, 2H), 1.64−1.53 (m, 4H), 1.39−1.24 (m, 12H), 0.88 (t, J = 6.8 Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) 140.0, 136.3, 135.0, 133.3, 132.0, 131.7, 128.9, 122.9, 122.5, 122.2, 82.6, 81.2, 80.7, 78.4, 74.9, 74.5, 71.8, 71.1, 31.9, 29.9, 26.0, 22.8, 14.2; IR (KBr) 3297, 2930, 2857, 1587, 1444, 1362, 1247, 1107, 870, 793, 682, 463 cm^{-1}. Anal. Calcd for $C_{44}H_{42}O_2$: C, 87.67; H, 7.02. Found: C, 87.53; H, 7.16.

Preparation of the Precursor of 16 (Pre16-DiBr). Bis-2,6-[(4-trimethylsilyl)-1,3-butadiyn-1-yl]pyridine was prepared by the same method described for **Pre16-Diyne** using 1,3-diiodopydine was used instead of 1,3-diiodobenzene. The product was isolated as brown solid (78%): mp 170−172 °C; ^{1}H NMR (300 MHz, $CDCl_3$) 7.59 (t, J = 7.8 Hz, 1H), 7.40 (d, J = 7.8 Hz, 2H), 0.21 (s, 18H); ^{13}C NMR (75 MHz, $CDCl_3$) 142.8, 136.7, 128.1, 93.1, 87.3, 74.74, 74.65 −0.3; IR (KBr) 2959, 2207, 2098, 1590, 1475, 1410, 1252, 1045, 847, 795, 761, 702, 682, 635, 507, 449 cm^{-1}. Anal. Calcd for $C_{19}H_{21}NSi_2$: C, 71.41; H, 6.62.; N, 4.38. Found: C, 71.26; H, 6.72; N, 4.17. To a solution of bis-2,6-[(4-trimethylsilyl)-1,3-butadiyn-1-yl]pyridine (319 mg, 1 mmol) in MeOH (0.83 mL) and THF (4.37 mL) was added K_2CO_3 (0.415 g, 3 mmol) and the mixture was stirred for 1 h at room temperature and then Ar was bubbled through the mixture for 30 min. The mixture was added to a suspension of CuI (19 mg, 0.10 mmol), $Pd(PPh_3)_4$ (58 mg, 0.05 mmol), **4** (0.873 g, 2.2 mmol), and i-Pr_2NH (40 mL) in dry THF (40 mL), and the reaction mixture was stirred overnight. The mixture was evaporated the residue was filtered through a pad of Celite (eluent CH_2Cl_2). The filterate was washed with brine, dried over $MgSO_4$ and evaporated. The crude product was purified by silica gel column chromatography (hexane/AcOEt 20:3) to give **Pre16-DiBr** (599 mg, 84%) as glutinous brown oil. **Pre16-DiBr**: ^{1}H NMR (500 MHz, $CDCl_3$) 7.62 (t, J = 8.5 Hz, 1H), 7.50 (s, 2H), 7.46−7.42 (m, 4H), 7.36 (s, 2H), 4.39 (s, 4H), 3.42 (t, J = 6.7 Hz, 4H), 1.60−1.55 (m, 4H), 1.35−1.21 (m, 12H), 0.85 (t, J = 7.0 Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) 142.7, 141.6, 136.7, 134.2, 131.8, 130.1, 128.0, 123.1, 122.4, 81.3, 80.2, 74.6, 74.2, 71.4, 71.1, 31.8, 29.8, 25.9, 22.7, 14.2; IR (KBr) 2929, 2857, 2224, 1556, 1434, 1355, 1242, 1165, 1116, 859, 835, 806, 785, 728, 677,476 cm^{-1}; HRMS-FAB (m/z) $[M + H]^+$ Calcd. for $C_{39}H_{40}Br_2NO_2$ 712.1420, found 712.1425.

General Procedure for the Macrocyclization. A two-necked flask was evacuated and backfilled with argon (the cycle was performed twice) and then charged under a positive pressure of argon with Pd $(CH_3CN)_2Cl_2$ (1.4 mg, 0.0054 mmol), XPhos (7.7 mg, 0.0162 mmol), Cs_2CO_3 (106 mg, 0.324 mmol), 1,4-dioxane (4.86 mL, freeze-degassed three times), and the aryl bromide (0.054 mmol). The slightly yellow suspension was stirred for 5 min at 60 °C. Then the alkyne (0.054 mmol) in 1,4-dioxane (0.54 mL, freeze-degassed three times) was added dropwise via syringe pump for 5 h. The flask was covered with aluminum foil, and the reaction mixture was stirred for the indicated period of time at the same temperature. The resulting brown suspension was allowed to reach room temperature and evaporated. To the residue was added water, and the mixture was extracted with CH_2Cl_2. The combined organic layer was dried over $MgSO_4$, concentrated, and the residue was purified by silica gel chromatography. The purity of the product was confirmed by GPC analysis using $CHCl_3$ as eluent.

1 (16 mg (28% yield) from 0.054 mmol of the starting material, colorless solid): mp 164−165 °C; ^{1}H NMR (300 MHz, $CDCl_3$) 7.86 (s, 1H), 7.79−7.77 (m, 2H), 7.68−7.65 (m, 3H), 7.52−7.45 (m, 12H), 7.33 (t, J = 9.6 Hz, 1H), 4.49 (s, 8H), 3.51−3.46 (m, 8H), 1.68−1.59 (m, 8H), 1.43−1.19 (m, 24H), 0.91−0.84 (m, 12H); ^{13}C NMR (125 MHz, $CDCl_3$) 143.9, 139.8, 139.7, 136.7, 135.8, 135.0, 134.6, 131.3,

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131.2, 130.9, 130.5, 130.5, 128.7, 126.5, 123.9, 123.7, 123.7, 123.6, 122.8, 89.54, 89.52, 89.4, 89.2, 89.1, 88.9, 72.2, 72.1, 71.1, 71.0, 31.9*, 29.9*, 26.1*, 22.9*, 14.3* (*signals of the hexyl groups were appeared as a single set of peaks); IR (KBr) 2929, 2856, 2216, 1593, 1556, 1452, 1355, 1243, 1113, 983, 890, 863, 800, 728, 684, 537 cm^{-1}; HRMS-ESI (m/z) $[M + H]^+$ calcd for $C_{75}H_{80}NO_4$ 1058.6082, found 1058.6066.

13 (12 mg, (20% yield) from 0.054 mmol of the starting material, colorless solid): mp 242−243 °C; ^1H NMR (500 MHz, $CDCl_3$) 7.88 (s, 1H), 7.78 (s, 2H, br), 7.65 (s, 2H), 7.49−7.45 (m, 10H), 7.33 (t, J = 4.5 Hz, 1H), 6.72 (s, 2H, br), 4.48 (s, 4H), 4.47 (s, 4H, br), 3.49−3.45 (m, 8H), 3.05 (s, 6H, br), 1.64−1.60 (m, 8H), 1.60−1.28 (m, 24H), 0.88 (t, J = 4.2 Hz, 12H); ^{13}C NMR (150 MHz, $CDCl_3$) 143.5 (br), 139.7 (br), 139.6, 135.8, 134.9, 134.5, 131.2, 131.1 (br), 130.8, 130.5, 130.4, 128.6, 128.5, 123.7, 123.67, 123.65, 123.60, 123.0 (br), 109.7, 89.5, 89.4, 89.2, 72.1, 72.0, 71.0, 70.9, 39.6 (br), 31.9*, 29.9*, 26.0*, 22.8*, 14.3* (*signals of the hexyl groups were appeared as a single set of peaks. Three carbons of internal alkynes were not detected probably due to the overlap.); IR (KBr) 2931, 2861, 2221, 1589, 1527, 1450, 1427, 1357, 1272, 1118, 1018, 979, 887, 863, 825, 686, 539 cm^{-1}; HRMS-ESI (m/z) $[M + H]^+$ calcd for $C_{77}H_{85}N_2O_4$ 1101. 6504, found 1101.6504.

14 (10.6 mg (9% yield) from 0.108 mmol of starting material, colorless solid): mp 205 °C; ^1H NMR (500 MHz, $CDCl_3$) 7.81 (t, J = 1.5 Hz, 4H), 7.67 (t, J = 7.6 Hz, 2H), 7.51 (s, 4H), 7.49 (s, 4H), 7.46 (d, J = 7.6 Hz, 4H), 4.49 (s, 8H), 3.48 (t, J = 6.7 Hz, 8H), 1.66−1.56 (m, 8H), 1.39−1.27 (m, 24H), 0.88 (t, J = 7.0 Hz, 12H); ^{13}C NMR (125 MHz, $CDCl_3$) 143.9, 139.7, 136.7, 135.2, 131.2, 130.9, 126.4, 123.8, 122.8, 89.3, 89.1, 88.9, 72.1, 71.1, 31.9, 29.9, 26.1, 22.9, 14.3; IR (KBr) 3424, 2923, 2854, 2383, 2306, 2221, 1720, 1589, 1558, 1457, 1357, 1241, 1157, 1103, 995, 871, 809, 732, 686, 539, 416 cm^{-1}; HRMS-ESI (m/z) $[M + H]^+$ calcd for $C_{74}H_{79}N_2O_4$ 1059.6034, found 1059.6041.

15 (4.5 mg (11% yield) from 0.037 mmol of the starting material, pale yellow solid): mp 65 °C; ^1H NMR (300 MHz, $CDCl_3$) 7.69−7.63 (m, 3H), 7.45−7.43 (m, 4H), 7.32 (s, 2H), 7.13 (t, J = 8.3 Hz, 1H), 6.58 (t, J = 2.8 Hz, 1H), 6.48 (dd, J = 2.8 Hz, 8.3 Hz, 2H), 4.44 (s, 4H), 4.04 (t, J = 6.0 Hz, 4H), 3.44 (t, J = 6.6 Hz, 4H), 2.48 (t, J = 6.6 Hz, 4H), 2.00−1.94 (m, 4H), 1.82−1.77 (m, 4H), 1.65−1.55 (m, 4H), 1.38−1.23 (m, 12H), 0.87 (t, J = 6.9 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) 160.6, 143.7, 139.5, 135.6, 130.8, 129.9, 126.4, 124.6, 122.4, 107.2, 100.5, 91.0, 80.6, 77.5, 77.4, 77.0, 72.1, 71.0, 70.9, 67.4, 31.9, 29.9, 28.4, 26.1, 25.5, 22.9, 19.2, 14.3; IR (KBr) 2927, 2856, 2218, 1717, 1590, 1557, 1492, 1455, 1285, 1183, 1155, 1104, 867, 806, 686, 453 cm^{-1}; HRMS-ESI (m/z) $[M + H]^+$ calcd for $C_{53}H_{60}NO_4$ 774.4517, found 774.4518.

16 (30 mg, (7% yield) from the 0.37 mmol of the starting material, colorless solid): mp 125 °C; ^1H NMR (300 MHz, $CDCl_3$) 7.73 (s, 1H), 7.67−7.57 (m, 5H), 7.49−7.43 (m, 12H), 7.30 (t, J = 7.8 Hz, 1H), 4.46 (s, 8H), 3.46 (t, J = 6.6 Hz, 8H), 1.66−1.57 (m, 8H), 1.41−1.20 (m, 24H), 0.88 (t, J = 6.9 Hz, 12H); ^{13}C NMR (125 MHz, $CDCl_3$) 143.1, 140.0, 140.0, 136.8, 135.5, 132.8, 131.6, 131.3, 131.1, 128.9, 127.7, 123.8, 123.7, 122.6, 122.4, 121.9, 120.4, 89.5, 89.2, 82.0, 81.2, 80.6, 79.8, 75.0, 74.54, 74.47, 74.2, 72.0, 71.9, 71.15, 71.13, 31.9*, 29.9*, 26.1*, 22.9*, 14.3* (*signals of the hexyl groups were appeared as a single set of peaks. Two carbons of internal alkynes were not detected probably due to the overlap); IR (KBr) 2923, 2854, 2221, 1720, 1589, 1450, 1357, 1257, 1157, 1110, 871, 802, 732, 686 cm^{-1}; HR-MS (FAB); HRMS-ESI (m/z) $[M + H]^+$ calcd for $C_{83}H_{80}NO_4$ 1154.6081, found 1154.6090.

■ ASSOCIATED CONTENT

Supporting Information

Schemes for the synthesis of compounds which appeared in the Experimental Section but were not mentioned in the main text; NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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■ REFERENCES

(1) For reviews, see: (a) *Modern Supramolecular Chemistry*; Diederich, F., Stang, P., Tykwinski, R. R., Eds.; Wiley-VCH: Weinheim, 2008. (b) Yamaguchi, Y.; Yoshida, Z. *Chem. −Eur. J.* **2003**, *9*, 5430. (c) Höger, S. *Chem.—Eur. J.* **2004**, *10*, 1320.

(2) Abe, H.; Chida, Y.; Kurokawa, H.; Inouye, M. *J. Org. Chem.* **2011**, *76*, 3366.

(3) (a) Campbell, K.; Kuehl, C. J.; Ferguson, M. J.; Stang, P. J.; Tykwinski, R. R. *J. Am. Chem. Soc.* **2002**, *124*, 7266. (b) Campbell, K.; McDonald, R.; Tykwinski, R. R. *J. Org. Chem.* **2002**, *67*, 1133. (c) Sun, S.-S.; Lees, A. J. *Organometallics* **2001**, *20*, 2353.

(4) Kobayashi, S.; Yamaguchi, Y.; Wakamiya, T.; Matsubara, Y.; Sugimoto, K.; Yoshida, Z. *Tetrahedron Lett.* **2003**, *44*, 1469.

(5) Yamaguchi, Y.; Kobayashi, S.; Miyamura, S.; Okamoto, Y.; Wakamiya, T.; Matsubara, Y.; Yoshida, Z. *Angew. Chem., Int. Ed.* **2004**, *43*, 366.

(6) (a) Zhao, D.; Moore, J. S. *Chem. Commun.* **2003**, 807. (b) Zang, L.; Che, Y.; Moore, J. S. *Acc. Chem. Res.* **2008**, *41*, 1596. (c) Sonoda, M.; Yamaguchi, Y.; Tahara, K.; Hirose, K.; Tobe, Y. *Tetrahedron* **2008**, *64*, 11490.

(7) For recent review, see: Tahara, K.; Lei, S.; Adisoejoso, J.; De Feyter, S.; Tobe, Y. *Chem. Commun.* **2010**, 8507.

(8) (a) Zhang, W.; Moore, J. S. *Angew. Chem., Int. Ed.* **2006**, *45*, 4416. (b) Moore, J. S.; Zhang, J. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 922. (c) Zhang, J.; Pesak, D. J.; Ludwick., J. L.; Moore, J. S. *J. Am. Chem. Soc.* **1994**, *116*, 4227. (d) Zhang, W.; Moore, J. S. *J. Am. Chem. Soc.* **2004**, *126*, 12796.

(9) (a) Tobe, Y.; Nagano, A.; Kawabata, K.; Sonoda, M.; Maemura, K. *Org. Lett.* **2000**, *2*, 3265. (b) Tobe, Y.; Utsumi, N.; Nagano, A.; Sonoda, M.; Naemura, K. *Tetrahedron* **2001**, *57*, 8075. (c) Tobe, Y.; Utsumi, N.; Kawabata, K.; Nagano, A.; Adachi, K.; Araki, S.; Sonoda, M.; Hirose, K.; Naemura, K. *J. Am. Chem. Soc.* **2002**, *124*, 5350.

(10) (a) Abe, H.; Kurokawa, H.; Chida, Y.; Inouye, M. *J. Org. Chem.* **2011**, *76*, 309. (b) Collins, S. K.; Yap, G. P. A.; Fallis, A. G. *Org. Lett.* **2000**, *2*, 3189. (c) Shu, L.; Müri, M.; Krupke, R.; Mayor, M. *Org. Biomol. Chem.* **2009**, *7*, 1081. (d) Bell, M. L.; Chiechi, R. C.; Johnson, C. A.; Kimball, D. B.; Matzger, A. J.; Wan, W. B.; Weakley, T. J. R.; Haley, M. M. *Tetrahedron* **2001**, *57*, 3507. (e) Chem, T.; Pan, G.-B.; Wettach, H.; Fritzsche, M.; Höger, S.; Wan, L.-J.; Yang, H.-B.; Northrop, B. H.; Stang, P. J. *J. Am. Chem. Soc.* **2010**, *132*, 1328. (f) Opris, D. M.; Ossenbach, A.; Lentz, D.; Schlüter, A. D. *Org. Lett.* **2008**, *10*, 2091.

(11) (a) Miki, K.; Fujita, M.; Inoue, Y.; Senda, Y.; Kowada, T.; Ohe, K. *J. Org. Chem.* **2010**, *75*, 3537. (b) Marsella, M. J.; Wang, Z.-Q.; Reid, R. J.; Yoon, K. *Org. Lett.* **2001**, *3*, 885. (c) Grave, C.; Lentz, D.; Schäfer, A.; Samorì, P.; Rabe, J. P.; Franke, P.; Schlüter, A. D. *J. Am. Chem. Soc.* **2003**, *125*, 6907.

(12) (a) Buchwald, S. L.; Gelman, D. *Angew. Chem., Int. Ed.* **2003**, *42*, 5993. (b) Ngassa, F. N.; Gomez, J. M.; Haines, B. E.; Ostach, M. J.; Hextor, J. W.; Hoogenboom, L. J.; Page, C. E. *Tetrahedron* **2010**, *66*, 7919.

(13) For example, see: Finke, A. D.; Elleby, E. C.; Boyd, M. J.; Weissman, H.; Moore, J. S. *J. Org. Chem.* **2009**, *74*, 8897.

(14) Our attempts to obtain **11** from **6** by Sonogashira reaction under the conditions used for the synthesis of **5** failed.

(15) Huynh, C.; Linstrumelle, G. *Tetrahedron* **1988**, *44*, 6337.

(16) When the crude product was analyzed by GPC, a small amount of product(s) eluted faster than **1**, which would be a mixture of

oligomers. In addition, small amounts (ca. 15%) of the starting materials (**6** and **8**) were recovered.
(17) Grave, C.; Schlüter, A. D. *Eur. J. Org. Chem.* **2002**, 3075.
(18) Neeman, T. X.; Whitesides, G. M. *J. Org. Chem.* **1988**, *53*, 2489.
(19) Dana, B. H.; Robinson, B. H.; Simpson, J. *J. Organomet. Chem.* **2002**, *648*, 251.
(20) Lehmann, U.; Schlüter, A. D. *Eur. J. Org. Chem.* **2000**, 3483.
(21) Heemstra, J. M.; Moore, J. S. *J. Am. Chem. Soc.* **2000**, *122*, 11315.
(22) Deschanps, J.; Balog, M.; Boury, B.; Yahia, M. B.; Filhotl, J. S.; Lee, A.; Choueiry, A. A.; Barisien, T.; Legrand, L.; Schott, M.; Dutremez, S. G. *Chem. Mater.* **2010**, *22*, 3961.
(23) Grave, C.; Lentz, D.; Schfer, A.; Samor, P.; Rabe, J. P.; Franke, P.; Schlüter, A. D. *J. Am. Chem. Soc.* **2003**, *125*, 6907.
(24) Bruce, M. I.; Low, P. J.; Werth, A.; Skelton, B. W.; White, A. H. *J. Chem. Soc., Dalton Trans.* **1996**, 1551.