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Solvophobically driven self-association of a butadiyne-bridged pyridine macrocycle

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This work is dedicated to Professor Reginald H. Mitchell on the occasion of his 65th birthday.

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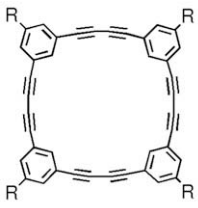
ABSTRACT

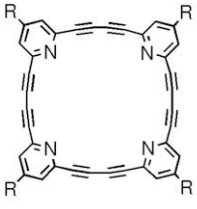
A butadiyne-bridged square-shaped pyridinophane **2b** having ester groups derived from triethylene glycol monomethyl ether was prepared and its self-assembling properties were investigated to assess the repulsive dipole–dipole interaction in less polar solvent and solvophobic driving force in polar solvents. Concentration-dependent ^{1}H NMR spectra showed that whereas **2b** did not self-assemble in chloroform-*d*, it did in polar solvents consisting of chloroform-*d* and methanol-d_4 (4:6 to 6:4) with increasing association constants with the increasing methanol-d_4 composition. Comparison of the free energies of association with those of the previously reported benzene macrocycle **1b** indicates that solvophobically induced self-association of **2b** is more promoted than **1b**. The reasons for this difference are discussed from both enthalpy and entropy points of view.

1. Introduction

Macrocyclic metaphenylene–ethynylene, metaphenylene–butadiynylene, and their hybrid oligomers constitute a central class of shape-persistent molecules,[1] which have been attracting much interest because of their self-assembling properties in solution,[2] solid,[3] and liquid crystalline phases,[4] as well as at interfaces or on surfaces.[2g,3d,4d,5] In solution aggregation is driven by π–π stacking interaction, mainly in less polar solvents such as chloroform, and/or solvophobic interaction in polar solvents. Self-assembly due to stacking of macrocycles containing pyridine rings in solution,[3c,d,6] however, was not reported except for the following examples because of electrostatic repulsion owing to dipole–dipole interaction of the pyridine rings. Association was observed only when other driving force was provided as in the size-selective heteroassociation of pyridinylene–butadiynylene macrocycles with the corresponding benzene macrocycles due to electrostatic interaction,[6a] solvophobically driven aggregation of a macrocycle containing pyridine substituents by a *nonpolar* solvent (cyclohexane),[6b] dimerization of a macrocycle possessing positively charged interior pyridinium ion moieties,[6b] and the formation of a dimeric metal complex of a macrocycle having exterior nitrogen atoms for coordination.[6e] By contrast, Abe and Inouye reported that acyclic pyridinylene–enthynylene oligomers and polymers having polar oligoethylene glycol side chains adopt in polar solvents a helical conformation.[7] It should be pointed out that the polymers adopt the stacking geometry even though they possess substituents of electron-donating nature, which generally inhibit aromatic stacking even in polar media.[2c,8] The thus formed one-dimensional cavity was used to bind saccharide derivatives by hydrogen bonding interaction. It is, therefore, expected that, for a pyridine-containing macrocycle, solvophobic interaction would overcome the repulsive dipole–dipole interaction to promote self-association in polar solvents if it is soluble in such media. To provide an answer to this question and to obtain a rough estimate of the relative energies of the attractive and repulsive interactions, we investigated self-association behavior of square-shaped pyridinylene–butadiynylene macrocycle **2b** in polar solvents.



1a R=$CO_2C_8H_{17}$
1b R=$CO_2(CH_2CH_2O)_3CH_3$



2a R=$CO_2C_8H_{17}$
2b R=$CO_2(CH_2CH_2O)_3CH_3$

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Previously, we synthesized and investigated self-association of octyl ester-substituted square macrocycle **1a** in chloroform. Since **1a** was not soluble in polar solvents consisting of chloroform and methanol, we prepared the corresponding ester **1b** of triethylene glycol monomethyl ether (TEG). Extrapolation of the free energies of association of **1b** in chloroform/methanol (8:2 to 3:7) mixtures to pure chloroform and methanol, assuming infinite association with equal association constants, yielded a rough estimate of ΔG of -7.2 and -31.2 kJ mol^{-1}, respectively.[2f] These results suggest that if the contributing driving forces of self-association can be divided into aromatic π–π stacking interaction of dispersive and electrostatic natures[9] and solvophobic intereaction,[1d,8,10] though they are generally collective and difficult to separate, it may be possible to estimate the relative magnitude in polar and less polar solvents. Assuming that, for example, the magnitude of π–π stacking interaction is constant in chloroform and methanol[11] and that the solvophobic interaction is absent in pure chloroform,[12] we can assess the solvophobic contribution to ΔG of -24.2 kJ mol^{-1} in methanol, which is significantly larger compared to π–π stacking force in chloroform. In contrast to **1a**, the corresponding pyridine analog **2a** did not self-assemble in chloroform presumably owing to the dipole–dipole repulsion.[6a] While **2a** was not soluble in polar solvents, its TEG ester derivative **2b** would be soluble in polar solvents and thus would provide an estimate of dipole–dipole repulsion on the basis of the above assumptions. In this connection, we prepared **2b** and examined its self-association behavior in polar solvents.

2. Results and discussion

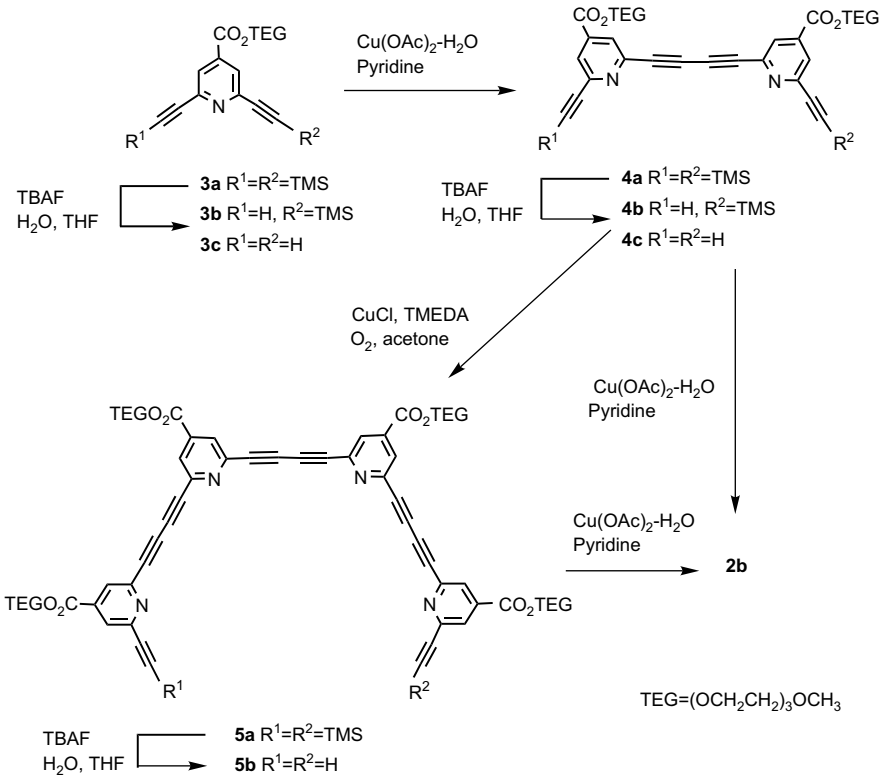
The synthesis of **2b** was carried out by oxidative dimerization of the dimer unit **4c** or intramolecular cyclization of linear tetramer **5b** as shown in Scheme 1. The unsymmetrically protected monomer unit **3b** was obtained by partial deprotection of **3a**, which was obtained from dichloropyridinecarboxylic acid by esterification with TEG followed by palladium-catalyzed cross coupling with (trimethylsilyl)acetylene. Oxidative coupling of **3a** gave dimer **4a**, the protecting groups of which were exhaustively removed to give **4c**. Oxidative coupling of **4c** under the usual Eglington coupling conditions gave the desired cyclic tetramer in a poor yield of 4%. Alternatively, partial deprotection of **4a** gave monoprotected dimer **4b**, the oxidative coupling of which gave linear tetramer **5a**. After deprotection of **5a**, intramolecular coupling of **5b** under high dilution conditions afforded **2b** in 24% yield (overall 5% from **4a**).

Self-association of **2b** was investigated on the basis of concentration-dependent ^{1}H NMR chemical shifts in chloroform-*d*/methanol-d_4 mixtures (4:6 to 6:4). The upfield shift (0.1–0.3 ppm) of the pyridine ring proton of **2b** was observed as its concentration increased, indicating solvophobically induced aggregation. However, because of the limited solubility of **2b** in methanol-enriched solvents and the small chemical shift change in chloroform-enriched solvents, the dilution experiments were carried out within a relatively narrow range of solvent composition. The chemical shift change was analyzed with the infinite association model of equal association constants (K_E),[2b,c,f,13] because oligomeric aggregation of shape-persistent macrocycles is most likely to occur in polar media.[2] Table 1 shows K_E and the corresponding free energies of

Table 1
Association constants and the corresponding free energies for self-aggregation of square-shaped pyridine macrocycle **2b** in polar solvents at 303 K[a]

Solvent	K_E (M^{-1})	ΔG (kJ mol^{-1})
$CDCl_3/CD_3OD$=6:4	15±1	−6.8±0.2
$CDCl_3/CD_3OD$=5:5	85±9	−11.2±0.3
$CDCl_3/CD_3OD$=4:6	327±64	−14.6±0.6

[a] Determined on the basis of the infinite association model of equal association constants.



Scheme 1. Synthesis of macrocycle **2b**.

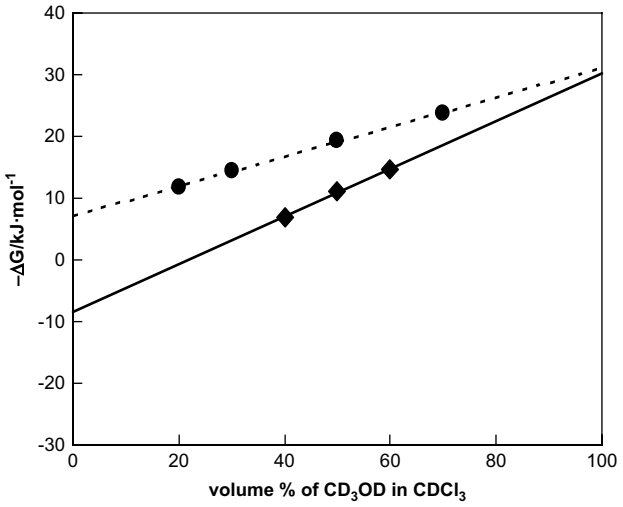


Figure 1. Relationship between $-\Delta G$ of aggregation of macrocycles **1b** and **2b** and the composition of CD_3OD in $CDCl_3$; solid circle: **1b** (Ref. 2f), solid square: **2b**.

association. The free energies ($-\Delta G$) were plotted against the solvent composition as shown in Figure 1, from which we estimate that the association in pure chloroform is endoergonic by 8.52 kJ mol^{-1}, being consistent with the absence of aggregation in this solvent. Figure 1 also indicates that the free energy of association in pure methanol would be -30.22 kJ mol^{-1}; the difference between the ΔGs in two solvents of **2b** (ca. 39.2 kJ mol^{-1}) is significantly larger than that of **1b** (24.2 kJ mol^{-1}). In other words, the aggregation of **2b** is more sensitive to the solvent polarity than that of **1b**, indicating that there must be additional stabilizing forces for aggregation of **2b** in polar solvents in addition to the solvophobic force. From the enthalpy aspect, because the pyridine unit of **2b** would be better solvated than the benzene unit of **1b** in polar solvents, the observed trend is contradictory to the expectation. However, the dipole–dipole repulsion must be reduced with increasing solvent polarity. Moreover, hydrogen bonding between the solvent and the nitrogen atom of the pyridine ring would promote self-association by electrostatic interaction. Indeed, as an extreme case, protonation of the pyridine rings of pyridinylene–ethynylene polymers with trifluoroacetic acid was shown to promote helix formation by favorable electrostatic interaction.[14] Hence, the difference between the response to the solvent polarity of **1b** and **2b** can be attributed to the reduction of repulsive dipole–dipole interaction and the increase of attractive electrostatic interaction between the pyridine rings of **2b** in polar solvents. On the other hand, from the viewpoint of entropy, the formation of hydrogen bonding network of the polar solvent (methanol) around the benzene moieties of **1b** would be entropically more unfavorable than that for the pyridine rings of **2b**. To minimize such network formation, aggregation of benzene macrocycle **1b** should be more strongly promoted than that of pyridine macrocycle **1b**, contrary to the observed tendency. Accordingly, the enhanced self-association tendency of **2b** in polar solvents is mostly likely of enthalpic origin.

In conclusion, we prepared butadiyne-bridged square-shaped pyridinophane **2b** having ester groups derived from triethylene glycol monomethyl ether and investigated its self-assembling properties to assess the repulsive dipole–dipole interaction in less polar solvent (chloroform-*d*) and solvophobic driving force in polar solvent (methanol-d_4). Comparison of the free energies of association with those of the previously reported benzene macrocycle **1b** indicates that solvophobically induced self-association of **2b** is more promoted than **1b**. The increased self-association driving force of **2b** compared to **1b** can be ascribed to the reduction of repulsive dipole–dipole interaction between the pyridine rings and increased electrostatic interaction both through weak hydrogen bonding with the solvent. These results provide additional aspects in self-assembly of shape-persistent macrocycles particularly with those containing heterocyclic components.

3. Experimental section

3.1. Synthesis of 3a

To an ice-cooled solution of 2,6-dichloropyridine-4-carboxylic acid (989 mg, 5.15 mmol), 4-(dimethylamino)pyridine (105 mg, 0.859 mmol), triethylene glycol monomethyl ether (1.05 g, 6.37 mmol) in 45 mL of 1,2-dichloroethane was slowly added a suspension of 1-[(3-dimethylamino)propyl]-3-ethylcarbodiimide hydrochloride (1.22 g, 6.37 mmol) in 15 mL of 1,2-dichloroethane. The mixture was stirred at room temperature for 70 h. $CHCl_3$ and water were added to the mixture. The mixture was acidified with 0.5 N HCl, the organic layer was washed with saturated $NaHCO_3$ solution and saturated NaCl solution, and dried over $MgSO_4$. After removal of the solvent, the product was purified by chromatography on silica gel to give 1.50 g (86%) of TEG ester of 2,6-dichloropyridine-4-carboxylic acid as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) Δ 7.76 (s, 2H), 4.48–4.45 (m, 2H), 3.80–3.77 (m, 2H), 3.67–3.57 (m, 6H), 3.49–3.46 (m, 2H), 3.31 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 162.3, 151.0, 142.2, 122.4, 71.7, 70.5, 70.42, 70.39, 68.5, 65.3, 58.8; IR (neat) 3086, 2876, 2822, 1736, 1583, 1548, 1455, 1415, 1359, 1283, 1156, 1110, 1028, 893, 816, 765, 738 cm^{-1}; HRMS (FAB) found: 338.0566 (M^++1), Calcd for $C_{13}H_{18}NO_5Cl_2$: 338.0562.

A solution of the above ester (14.8 g, 43.9 mmol), PPh_3, (1.11 g, 4.23 mmol), (trimethylsilyl)acetylene (12.3 g, 125 mmol), CuI (193 mg, 1.01 mmol), and $Pd_2(dba)_3\cdot CHCl_3$ (298 mg, 0.351 mmol) in 200 mL of triethylamine was degassed by bubbling of Ar. The mixture was then heated at 74 °C for 46.5 h. After cooling, the mixture was filtered and the filtrate was washed with ether. The filtrate was concentrated and the residue was chromatographed on silica gel (hexane/AcOEt=9:1 to 0:1 as eluent) to give 16.8 g of **3a** (83%) as a yellow oil. ^{1}H NMR (270 MHz, $CDCl_3$) δ 7.91 (s, 2H), 4.53–4.49 (m, 2H), 3.86–3.82 (m, 2H), 3.73–3.63 (m, 6H), 3.55–3.52 (m, 2H), 3.37 (s, 3H), 0.27 (s, 18H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 163.3, 143.7, 137.7, 125.4, 102.2, 96.4, 71.6, 70.3, 70.2, 68.5, 64.7, 58.6, −0.6; IR (neat) 3075, 2959, 2898, 2819, 2162, 1735, 1590, 1549, 1454, 1397, 1330, 1251, 1224, 1190, 1110, 1030, 992, 847, 762 cm^{-1}; HRMS (EI) found: 461.2048, calcd for $C_{23}H_{35}NO_5Si_2$: 461.2054.

3.2. Synthesis of 3b

To a solution of **3a** (7.88 g, 17.1 mmol) in 100 mL of water and 300 mL of THF was added slowly over 30 min a solution of TBAF prepared by diluting a 13 mL of commercially available 1 M THF solution of TBAF with 87 mL of THF. After addition of 1 N HCl aq, the mixture was extracted with ether. The extract was washed with saturated NaCl solution and dried over $MgSO_4$. After evaporation of the solvents, the product was purified by chromatography on silica gel (hexane/AcOEt=19:1 to 1:3 as eluent) to give 1.76 g of **3b** (30%) as a yellow oil together with 1.93 g (25%) of unreacted **3a**. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.95 (d, J=1.4 Hz, 1H), 7.94 (d, J=1.4 Hz, 1H), 4.53–4.50 (m, 2H), 3.85–3.82 (m, 2H), 3.73–3.63 (m, 6H), 3.55–3.52 (m, 2H), 3.37 (s, 3H), 3.21(s, 1H), 0.28 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 163.7, 144.3, 143.3, 138.2, 126.2, 125.8, 102.3, 97.1, 81.7, 78.6, 71.9, 70.70, 70.66, 70.6, 68.9, 65.2, 59.0, −0.3; IR (neat) 3232, 3074, 2960, 2876, 2165, 2112, 1733, 1592, 1551, 1454, 1397, 1324, 1249, 1223, 1187, 1109, 1029, 987, 970, 904, 847, 767 cm^{-1}; HRMS (EI) found: 389.1661; calcd for $C_{20}H_{27}NO_5Si$: 389.1659.

3.3. Synthesis of 4a

A solution of **3b** (2.38 g, 6.12 mmol) in 50 mL of acetone was bubbled with O_2. To this solution was added a solution prepared by diluting a 4-mL solution of Hay catalyst, prepared from CuI (265 mg, 2.68 mmol) and TMEDA (114 mg, 0.981 mmol) in 20 mL of acetone, with 6 mL of acetone, and the mixture was bubbled with O_2. After stirring for 40 h, the mixture was diluted with 1 N HCl and ether. The organic layer was separated, washed with water and brine, and dried over $MgSO_4$. The solvent was removed in vacuo, and the residue was chromatographed on silica gel (hexane/AcOEt=9:1 to 1:9 as eluent) to afford 1.91 g (80%) of **4a** as a white solid together with unreacted **3b** (0.20 g, 8%). Mp 97–98 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.99 (d, J=1.4 Hz, 2H), 7.98 (d, J=1.4 Hz, 2H), 4.54–4.51 (m, 4H), 3.86–3.83 (m, 4H), 3.74–3.64 (m, 12H), 3.56–3.53 (m, 4H), 3.37 (s, 6H), 0.29 (s, 18H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 163.4, 144.5, 142.6, 138.2, 126.6, 102.0, 97.5, 80.4, 74.1, 71.9, 70.7, 70.61, 70.57, 68.8, 65.2, 59.0, −0.4; IR (KBr) 3070, 2969, 2933, 2875, 2824, 2155, 1733, 1590, 1547, 1452, 1396, 1323, 1245, 1225, 1190, 1101, 1023, 976, 950, 932, 904, 849, 767 cm^{-1}; HRMS (FAB) found: 777.3225; calcd for $C_{40}H_{53}N_2O_{10}Si_2$: 777.3239. Anal. Calcd for $C_{40}H_{53}N_2O_{10}Si_2$: C, 61.83; H, 6.75; N, 3.61. Found: C, 61.74; H, 6.73; N, 3.57.

3.4. Synthesis of 4b and 4c

Exhaustive deprotection of **4a** (1.91 g, 2.46 mmol) was done by carrying out the reaction as described for the preparation of **3b** for 12 h to give 1.58 g of **4c** as a brown solid, which was used without purification for the preparation of **2b**. Analytically pure sample of **4c** was obtained in a separate run to prepare **4b**.

When the deprotection was terminated after 1.5 h, mono protected **4b** (828 mg, 31%) was obtained as a white solid, together with **4c** (106 mg, 4%, white solid) and unreacted **4a** (1.01 g, 35%). Compound **4b**: mp 78–79 °C; ^{1}H NMR (270 MHz, $CDCl_3$) δ 8.04 (d, J=1.3 Hz, 1H), 8.01 (d, J=1.3 Hz, 1H), 8.00 (d, J=1.4 Hz, 1H), 7.98 (d, J=1.4 Hz, 1H), 4.55–4.51 (m, 4H), 3.87–3.83 (m, 4H), 3.74–3.64 (m, 12H), 3.56–3.53 (m, 4H), 3.37 (s, 6H), 3.26 (s, 1H), 0.29 (s, 9H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 163.3, 163.2, 144.5, 143.8, 142.7, 142.5, 138.3, 138.2, 127.0, 126.6, 126.5, 102.0, 97.5, 81.3, 80.4, 80.1, 79.1, 74.1, 73.9, 71.8, 70.61, 70.59, 70.54, 70.52, 68.72, 68.69, 65.23, 65.15, 58.9, −0.4; IR (KBr) 3231, 3075, 2955, 2877, 2820, 2152, 2111, 1732, 1590, 1548, 1453, 1396, 1322, 1224, 1189, 1113, 1029, 945, 848, 768 cm^{-1}; HRMS (FAB) found: 705.2857; calcd for $C_{37}H_{45}N_2O_{10}Si$: 705.2843; Anal. Calcd for $C_{37}H_{45}N_2O_{10}Si$: C, 63.05; H, 6.29; N, 3.97. Found: C, 62.89; H, 6.33; N, 3.93. Compound **4c**: mp 94–95 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (d, J=1.5 Hz, 2H), 8.01 (d, J=1.5 Hz, 2H), 4.54–4.52 (m, 4H), 3.86–3.84 (m, 4H), 3.73–3.65 (m, 12H), 3.56–3.54 (m, 4H), 3.38 (s, 6H), 3.26 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.4, 143.9, 142.8, 138.5, 127.1, 126.7, 81.4, 80.3, 79.2, 74.2, 71.9, 70.7, 70.65, 70.63, 68.8, 65.3, 59.0; IR (KBr) 3218, 3067, 2987, 2874, 2829, 2162, 2109, 1729, 1590, 1552, 1445, 1396, 1355, 1319, 1228, 1186, 1138, 1111, 1026, 953, 932, 904, 862, 829, 769, 730 cm^{-1}; HRMS (FAB) found: 633.2464; calcd for $C_{34}H_{37}N_2O_{10}$: 633.2448. Anal. Calcd for $C_{34}H_{37}N_2O_{10}$: C, 64.55; H, 5.74; N, 4.43. Found: C, 64.85; H, 5.83; N, 4.42.

3.5. Synthesis of 2b by oxidative dimerization of 4c

To a solution of $Cu(OAc)_2\cdot H_2O$ (308 mg, 1.70 mmol) in 100 mL of a mixture of pyridine and benzene (3:2=v/v) was added a solution of **4c** (95 mg, 0.15 mmol) in 100 mL of the same solvent mixture through a Hershberg dropping funnel over a 18 h period. The funnel was rinsed with 40 mL of the solvent mixture and the reaction mixture was further stirred for 4 h. After most of the solvent was removed in vacuo, the residue was passed through a short plug of silica gel column (elution with $CHCl_3$) to remove inorganic salts. The product was purified by chromatography on silica gel followed by recycling GPC to afford 4 mg (4%) of **2b** as a yellow solid. Mp 167 °C (decomposed); ^{1}H NMR (400 MHz, $CDCl_3$, 30 °C) δ 7.95 (s, 8H), 4.54–4.52 (m, 8H), 3.86–3.84 (m, 8H), 3.74–3.65 (m, 24H), 3.57–3.54 (m, 8H), 3.39 (s,12H); ^{13}C NMR (68 MHz, $CDCl_3$, 30 °C) δ 163.3, 143.5, 138.9, 125.1, 82.3, 74.8, 72.0, 70.8, 70.72, 70.69, 68.9, 65.4, 59.0; IR (KBr) 3077, 2873, 2225, 2152, 1731, 1591, 1542, 1419, 1391, 1350, 1259, 1117, 1026, 945, 848, 767 cm^{-1}; HRMS (FAB) found: 1261.4498; calcd for $C_{68}H_{69}N_4O_{20}$: 1261.4505.

3.6. Synthesis of 5a

Hay coupling of **4b** (1.93 g, 2.74 mmol) was carried as described for the preparation of **4a** to give 1.58 g (82%) of **5a** as a white solid. Mp 100–101 °C; ^{1}H NMR (270 MHz, $CDCl_3$) δ 8.07 (d, J=1.3 Hz, 2H), 8.06 (d, J=1.3 Hz, 2H), 8.01 (d, J=1.5 Hz, 2H), 7.99 (d, J=1.5 Hz, 2H), 4.56–4.51 (m, 8H), 3.87–3.83 (m, 8H), 3.75–3.62 (m, 24H), 3.59–3.53 (m, 8H), 3.38 (s, 6H), 3. 37 (s, 6H), 0.29 (s, 18H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 163.3, 162.9, 144.5, 143.1, 142.9, 142.4, 138.4, 138.2, 127.44, 127.39, 126.6, 126.5, 101.9, 97.5, 80.6, 80.2, 79.9, 74.4, 74.2, 73.8, 71.8, 70.59, 70.56, 70.51, 70.48, 68.7, 68.6, 65.3, 65.1, 58.9, −0.4; IR (KBr) 3075, 2956, 2874, 2825, 2157, 1732, 1544, 1394, 1322, 1225, 1111, 854, 768 cm^{-1}; MS (FAB) m/z 1407.3 $(M+H)^+$. Anal. Calcd for $C_{74}H_{86}N_4O_{20}Si_2$: C, 63.14; H, 6.16; N, 3.98. Found: C, 63.07; H, 6.23; N, 3.88.

3.7. Synthesis of 5b

Deprotection of **5a** (206 mg, 0.146 mmol) was carried as described for the preparation of **4b** to give 162 mg (88%) of **5c** as a yellowish brown solid. Mp 119–120 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.07 (two d, J=1.5 Hz, 4H), 8.05 (d, J=1.2 Hz, 2H), 8.01 (d, J=1.2 Hz, 2H), 4.55–4.52 (m, 8H), 3.86–3.83 (m, 8H), 3.72–3.64 (m, 24H), 3.56–3.53 (m, 8H), 3.375 (s, 6H), 3.371 (s, 6H), 3.26 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.3, 163.2, 143.9, 143.2, 143.1, 142.7, 138.6, 138.5, 127.62, 127.60, 127.2, 126.8, 81.4, 80.5, 80.3, 80.1, 79.2, 74.5, 74.4, 74.1, 71.9, 70.73, 70.71, 70.66, 70.6, 68.80, 68.78, 65.4, 65.3, 59.1; IR (KBr) 3220, 3073, 2876, 2824, 2155, 2109, 1734, 1589, 1544, 1451, 1394, 1319, 1225, 1187, 1112, 1029, 948, 849, 768 cm^{-1}; HRMS (FAB) found: 1263.4691; calcd for $C_{68}H_{71}N_4O_{20}$: 1263.4662. Anal. Calcd for $C_{68}H_{70}N_4O_{20}\cdot H_2O$: C, 63.74; H, 5.66; N, 4.37. Found: C, 63.88; H, 5.82; N, 4.23.

3.8. Synthesis of 2b by intramolecular oxidative coupling of 5b

Intramolecular Eglinton coupling of **5b** (189 mg, 0.15 mmol) was carried out as described for the oxidative dimerization of **4c**, except that pure pyridine was used as the solvent, to give 46 mg (24%) of **2b** as a yellow solid.

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References and notes

1. For reviews: (a) Moore, J. S. *Acc. Chem. Res.* **1997**, *30*, 402–413; (b) Höger, S. *J. Polym. Sci., Part A* **1999**, *37*, 2685–2698; (c) Grave, C.; Schlüter, A. D. *Eur. J. Org. Chem.* **2002**, 3075–3098; (d) Zhao, D.; Moore, J. S. *Chem. Commun.* **2003**, 807–818; (e) Höger, S. *Chem.—Eur. J.* **2004**, *10*, 1320–1329; (f) Höger, S. In *Acetylene Chemistry*; Diederich, F., Stang, P. J., Tykwinski, R. R., Eds.; Wiley-VCH: Weinheim, 2005; pp 427–452.

2. (a) Zhang, J.; Moore, J. S. *J. Am. Chem. Soc.* **1992**, *114*, 9701–9702; (b) Shetty, A. S.; Zhang, J.; Moore, J. S. *J. Am. Chem. Soc.* **1996**, *118*, 1019–1027; (c) Lahiri, S.; Thompson, J. L.; Moore, J. S. *J. Am. Chem. Soc.* **2000**, *122*, 11315–11319; (d) Tobe, Y.; Utsumi, N.; Kawabata, K.; Naemura, K. *Tetrahedron Lett.* **1996**, *37*, 9325–9328; (e) Tobe, Y.; Utsumi, N.; Nagano, A.; Naemura, K. *Angew. Chem., Int. Ed.* **1998**, *38*, 1285–1287; (f) Tobe, Y.; Utsumi, N.; Kawabata, K.; Nagano, A.; Adachi, K.; Araki, S.; Sonoda, M.; Hirose, K.; Naemura, K. *J. Am. Chem. Soc.* **2002**, *124*, 5350–5364; (g) Tobe, Y.; Nagai, T.; Araki, S.; Ichikawa, T.; Nomoto, A.; Sonoda, M.; Hirose, K. *Adv. Funct. Mater.* **2006**, *16*, 1549–1554; (h) Höger, S.; Bonrad, K.; Mourran, A.; Beginn, U.; Möller, M. *J. Am. Chem. Soc.* **2001**, *123*, 5651–5659; (i) Rosselli, S.; Ramminger, A.-D.; Wagner, T.; Silier, B.; Wiegand, S.; Häußler; Lieser, G.; Scheumann, V.; Höger, S. *Angew. Chem., Int. Ed.* **2001**, *40*, 3138–3141; (j) Rosselli, S.; Ramminger, A.-D.; Wagner, T.; Lieser, G.; Höger, S. *Chem.—Eur. J.* **2003**, *9*, 3481–3491; (k) Nakamura, K.; Okubo, H.; Yamaguchi, M. *Org. Lett.* **2001**, *3*, 1097–1099; (l) Saiki, Y.; Sugiura, H.; Nakamura, K.; Yamaguchi, M.; Hoshi, T.; Anzai, J. *J. Am. Chem. Soc.* **2003**, *125*, 9268–9269; (m) Saiki, Y.; Nakamura, K.; Nigorikawa, Y.; Yamaguchi, M. *Angew. Chem., Int. Ed.* **2003**, *42*, 5190–5192; (n) Lin, C.-H.; Tour, J. *J. Org. Chem.* **2002**, *67*, 7761–7768.
3. (a) Venkataraman, D.; Lee, S.; Zhang, J.; Moore, J. S. *Nature* **1994**, *371*, 591–593; (b) Höger, S.; Morrison, D. L.; Enkelmann, V. *J. Am. Chem. Soc.* **2002**, *124*, 6734–6736; (c) Henze, O.; Lentz, D.; Schäfer, A.; Franke, P.; Schlüter, A. D. *Chem.—Eur. J.* **2002**, *8*, 357–365; (d) Grave, C.; Lentz, D.; Schäfer, A.; Samori, P.; Rabe, J. P.; Franke, P.; Schlüter, A. D. *J. Am. Chem. Soc.* **2003**, *125*, 6907–6918.
4. (a) Zhang, J.; Moore, J. S. *J. Am. Chem. Soc.* **1994**, *116*, 2655–2656; (b) Mindyuk, O. Y.; Stetzer, M. R.; Heiney, P. A.; Nelson, J. C.; Moore, J. S. *Adv. Mater.* **1998**, *10*, 1363–1366; (c) Höger, S.; Enkelmann, F.; Bonrad, K.; Tschieske, C. *Angew. Chem., Int. Ed.* **2000**, *39*, 2268–2270; (d) Fischer, M.; Lieser, G.; Rapp, A.; Schnell, I.; Mamdouh, W.; De Feyter, S.; De Schryver, F. C.; Höger, S. *J. Am. Chem. Soc.* **2004**, *126*, 214–222.
5. (a) Shetty, A. S.; Fischer, P. R.; Stork, K. F.; Bohn, P. W.; Moore, J. S. *J. Am. Chem. Soc.* **1996**, *118*, 9409–9414; (b) Mindyuk, O. Y.; Stetzer, M. R.; Gidalevitz, D.; Heiney, P. A.; Nelson, J. C.; Moore, J. S. *Langmuir* **1999**, *15*, 6897–6900; (c) Tahara, K.; Lei, S.; Mamdouh, W.; Yamaguchi, Y.; Ichikawa, T.; Uji-i, H.; Sonoda, M.; Hirose, K.; De Schryver, F. C.; De Feyter, S.; Tobe, Y. *J. Am. Chem. Soc.* **2008**, *130*, 6666–6667; (d) Pan, G.-B.; Cheng, X.-H.; Höger, S.; Freyland, W. *J. Am. Chem. Soc.* **2006**, *128*, 4218–4219.
6. (a) Tobe, Y.; Nagano, A.; Kawabata, K.; Sonoda, M.; Naemura, K. *Org. Lett.* **2000**, *2*, 3265–3268; (b) Klyatskaya, S.; Dingenouts, N.; Rosenauer, C.; Müller, B.; Höger, S. *J. Am. Chem. Soc.* **2006**, *128*, 3150–3153; (c) Campbell, K.; McDonald, R.; Branda, N. R.; Tykwinski, R. R. *Org. Lett.* **2001**, *3*, 1045–1048; (d) Campbell, K.; McDonald, R.; Tykwinski, R. R. *J. Org. Chem.* **2002**, *67*, 1133–1140; (e) Campbell, K.; Kuehl, C. J.; Ferguson, M. J.; Stang, P. J.; Tykwinski, R. R. *J. Am. Chem. Soc.* **2002**, *124*, 7266–7267; (f) Sun, S.-S.; Lees, A. J. *Organometallics* **2001**, *20*, 2353–2358.
7. (a) Waki, M.; Abe, H.; Inouye, M. *Chem.—Eur. J.* **2006**, *12*, 7839–7847; (b) Waki, M.; Abe, H.; Inouye, M. *Angew. Chem., Int. Ed.* **2007**, *46*, 3059–3061.
8. Cubberley, M. S.; Iverson, B. L. *J. Am. Chem. Soc.* **2001**, *123*, 7560–7563.
9. (a) Hunter, C. A.; Sanders, J. K. M. *J. Am. Chem. Soc.* **1990**, *112*, 5525–5534; (b) Cozzi, F.; Siegel, J. S. *Pure Appl. Chem.* **1995**, *67*, 683–689; (c) Hunter, C. A.; Lawson, K. R.; Perkins, J.; Urch, C. J. *J. Chem. Soc., Perkin Trans. 2* **2001**, 651–669.
10. (a) Smithrud, D. B.; Diederich, F. *J. Am. Chem. Soc.* **1990**, *112*, 339–343; (b) Hill, D. J.; Mio, M. J.; Prince, R. B.; Hughes, T. S.; Moore, J. S. *Chem. Rev.* **2001**, *101*, 3893–4011.
11. We are not aware of reports regarding solvent effect on π–π stacking interaction of dispersive and electrostatic natures.
12. For shape-persistent macrocycles of phenylene–ethynylene and phenylene–butadiynylene types, chloroform is believed to best solvate the macrocyclic backbone. Both polar (such as methanol and acetonitrile) and apolar (cyclohexane) solvents are nonsolvents.[2]
13. Martin, B. B. *Chem. Rev.* **1996**, *96*, 3043–3064.
14. Abe, H.; Masuda, N.; Waki, M.; Inouye, M. *J. Am. Chem. Soc.* **2005**, *127*, 16189–16196.