Cyclobutene Based Macrocycles

Pan Wang[‡a,b], Ruqiang Lu[‡a], Arthur France-Lanord[c], Yanming Wang[c], Jingjing Zhou[b], Jeffrey C. Grossman[c*] and Timothy M. Swager[a*]

[a]Department of Chemistry, Massachusetts Institute of Technology, Massachusetts 02139, United States.
Email: tswager@mit.edu
[b]School of Science, Westlake University, Hangzhou 310024, Zhejiang Province, China.
[c]Department of Materials Science and Engineering, Massachusetts Institute of Technology, Massachusetts 02139, United States.
Email: jcg@mit.edu

Supporting Information

Contents

1. General information

Unless stated otherwise, all reactions were carried out under an atmosphere of nitrogen using standard Schlenk techniques. All solvents and reagents were obtained from commercial sources and were purified according to standard procedures before use.

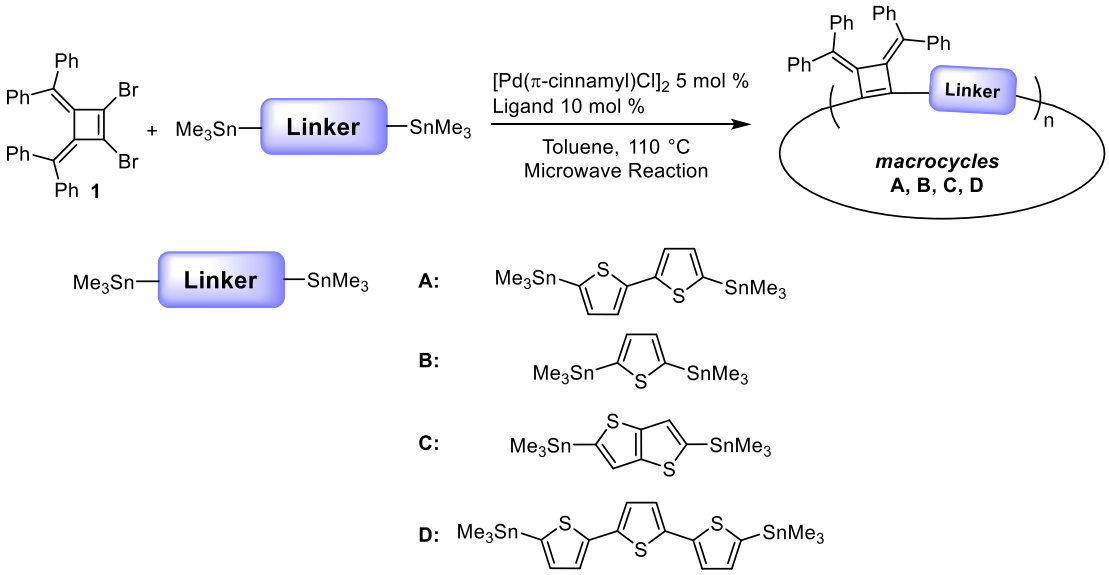
^{1}H NMR spectra were recorded on a Bruker Avance 400 MHz or 500 MHz spectrometer. All signals were reported in ppm with the internal TMS signal at 0.0 ppm or $CHCl_3$ at 7.26 ppm, or THF at 3.58 ppm as a standard. Data for ^{1}H NMR were recorded as follows: chemical shift (δ, ppm), multiplicity (s = singlet, d = doublet, t = triplet, m = multiplet or unresolved, coupling constant(s) in Hz, integration). ^{13}C NMR spectra were recorded on a Bruker Avance 101 MHz or 126 MHz spectrometer. All signals are reported in ppm with the internal $CDCl_3$ signal at 77.0 ppm or THF-d_8 at 67.21 ppm as a standard. Infrared spectra were recorded on a Thermo Scientific Nicolet 6700 Fourier Transform Infrared Spectrometer (FT-IR) using the attenuated total reflectance (ATR) technique on a Ge crystal; frequencies are given in reciprocal centimeters (cm^{-1}) and only selected absorbances are reported. High resolution mass spectra (HRMS) were obtained at the MIT DCIF (Department of Chemistry Instrumentation Facility) using electrospray ionization (ESI).

Microwave reactions were carried out on a microwave reactor (CEM, OU3154). MALDI-TOF analysis were obtained from a high-resolution Bruker Autoflex LRF Speed mass spectrometer. Electron paramagnetic resonance (EPR) measurement were carried out on a Bruker EMX-Plus spectrometer with an ER4119HS high sensitivity X-band resonator.

Scanning electron microscopy (SEM) images were obtained from a JEOL 6010LA. UV-vis spectra were recorded on Agilent Cary 60 spectrometer at room temperature. Fluorescence measurements were performed at room temperature with a Horiba Jobin Yvon SPEX Fluorolog-τ3 fluorimeter (model FL-321, 450 W Xenon lamp) using right-angle with solution samples and front-face with thin film samples.

2. General Procedure for the Synthesis of Macrocycles

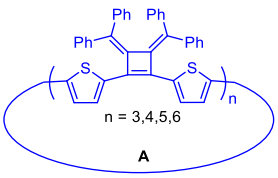
Scheme S1.

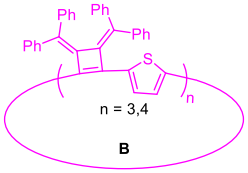
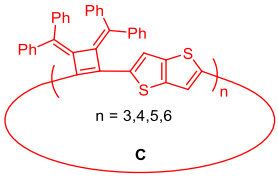
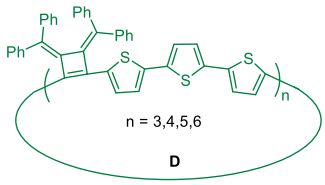


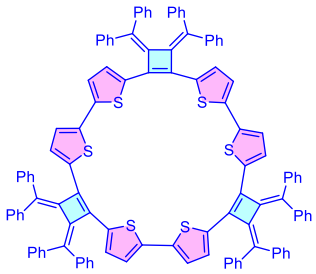
General Procedure for Macrocycles:

To a flame-dried microwave tube was added [Pd(π-cinnamyl)Cl]$_2$ (4.0 mg, 0.05 equiv, 7.5 μmol), ligand (7.4 mg, 0.1 equiv, 15 μmol), toluene (1.5 mL) under nitrogen atmosphere, stirred at room temperature for 15 min. 1,2-dibromo-3,4-bis(diphenylmethylene)cyclobutene **1** (81.0 mg, 0.15 mmol) and distannyl compound (1 equiv, 0.15 mmol) were dissolved in toluene (1.5 mL) and were added to the catalyst solution under nitrogen atmosphere. The microwave tube was loaded to the microwave reactor, heated to 110 °C for 4 h. The reaction was then cooled to room temperature, KF (2.2 equiv) was added to the solution for 10 min to remove tin reagents. The whole mixture was diluted with dichloromethane (DCM), passed through a pad of celite, washed with DCM. The organic solvent was removed by rotary evaporation, the remaining materials were re-dissolved in small amount of DCM, precipitated from MeOH. The resulting solids were filtered, red solids were obtained and dried in vacuum oven at 50 °C for 12 h.

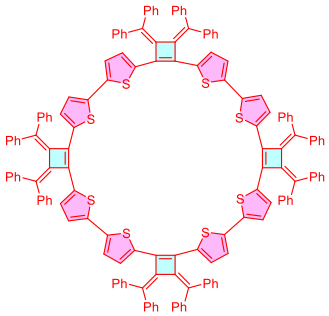
Table S1.

Macrocycles	Result	Yield (%)	Note
	0.15 mmol scale 68.0 mg	83	Red solids

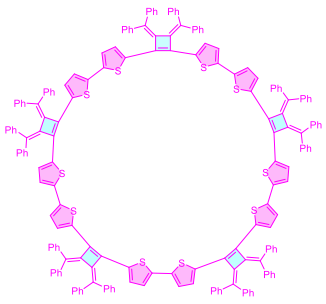
	0.15 mmol scale 52.8 mg	76	Red solids
	0.15 mmol scale 71.7 mg	92	Red solids
	0.15 mmol scale 93.8 mg	99	Red solids



A1 (n = 3), red solid. ^{1}H NMR (500 MHz, THF-d_8): One repeating unit, δ 7.12–7.10 (m, 2H), 7.07–6.95 (m, 8H), 6.83–6.80 (m, 4H), 6.69–6.66 (m, 2H), 6.64–6.61 (m, 4H), 6.43 (d, J = 3.9 Hz, 2H), 5.52 (d, J = 3.9 Hz, 2H). ^{13}C NMR (126 MHz, THF-d_8): δ 146.96, 141.54, 141.16, 139.14, 138.14, 131.72, 131.49, 131.04, 130.70, 129.12, 127.34, 127.23, 126.89, 126.75, 123.34. HRMS-Q-TOF: Exact mass calcd. for $C_{114}H_{73}S_6^+$ $[M+H]^+$: 1633.4031; Found: 1633.4068.

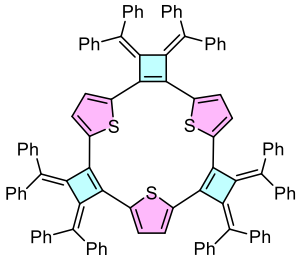


A2 (n = 4), red solid. ^{1}H NMR (400 MHz, THF-d_8): One repeating unit, δ 7.13–7.07 (m, 2H), 7.05–6.98(m, 6H), 6.83–6.81 (m, 4H), 6.68–6.66 (m, 2H), 6.64–6.61 (m, 6H), 6.37 (d, J = 3.9 Hz, 2H), 5.85 (d, J = 3.9 Hz, 2H). ^{13}C NMR (126 MHz, THF-d_8) δ 151.70, 146.68, 141.57, 141.24, 139.19, 138.60, 137.20, 132.26, 131.60, 131.11, 130.78, 128.89, 127.86, 127.44, 127.39, 126.91, 126.75, 124.92, 123.04. Exact mass calcd. for $C_{152}H_{96}S_8^+$ $[M]^+$: 2176.5272; MALDI-TOF Found: 2176.635.

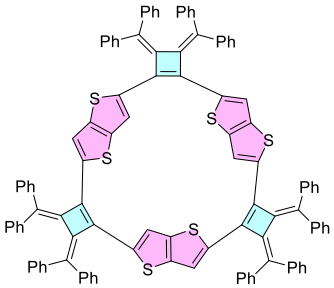


A3 (n = 5), red solid. ^{1}H NMR (400 MHz, THF-d_8): One repeating unit, ^{1}H NMR (500 MHz, THF-d_8) δ 7.217.17 (m, 2H), 7.14 – 7.08 (m, 8H), 6.92 (d, J = 7.1 Hz, 4H), 6.79–6.71 (m, 6H), 6.50 (d, J = 3.9 Hz, 2H), 5.93–5.90 (d, J = 3.9 Hz, 2H). ^{13}C NMR (126 MHz, THF-d_8) δ 151.69, 146.67, 141.56, 141.23, 139.17, 138.59, 137.19, 132.25, 131.59, 131.10, 130.77, 128.88, 127.85, 127.39, 126.90,

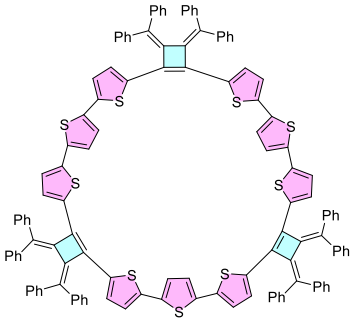
126.74, 124.91, 123.03. Exact mass calcd. for $C_{190}H_{120}S_{10}^{+}$ $[M]^{+}$: 2720.6592; MALDI-TOF Found: 2720.638.



B1 (n = 3), red solid.^{1}H NMR (400 MHz, THF-d_8): δ 7.34–7.30 (m, 2H), 7.21–7.18 (m, 4H), 7.09–7.06 (m, 4H), 6.86–6.84 (m, 4H), 6.79–6.73 (m, 6H), 5.25 (s, 2H). Exact mass calcd. for $C_{102}H_{66}S_{3}^{+}$ $[M]^{+}$: 1386.4327; MALDI-TOF Found:1386.6201.



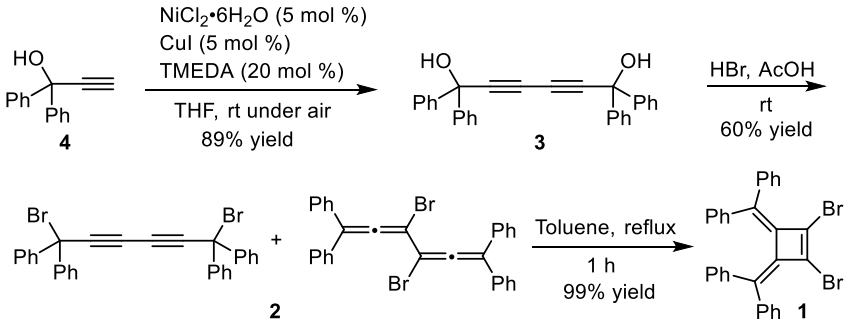
C1 (n = 3), red solid. ^{1}H NMR (400 MHz, CD_2Cl_2): One repeating unit, δ 7.28–7.25 (m, 2H), 7.20–7.13 (m, 8H), 6.99–6.98 (m, 4H), 6.83–6.80 (m, 2H), 6.76–6.73 (m, 4H), 5.98 (s, 2H). Exact mass calcd. for $C_{108}H_{66}S_{6}^{+}$ $[M]^{+}$: 1554.3489; MALDI-TOF Found:1554.3508.



D1 (n = 3), red solid. ^{1}H NMR (500 MHz, CD_2Cl_2): One repeating unit, δ 7.22–7.18 (m, 2H), 7.15–7.11 (m, 8H), 6.96–6.93 (m, 4H), 6.83–6.81 (m, 4H), 6.77–6.74 (m, 4H), 6.62 (d, J = 3.9 Hz, 2H), 5.70 (d, J = 3.9 Hz, 2H). Exact mass calcd. for $C_{126}H_{78}S_{9}^{+}$ $[M]^{+}$: 1878.3590; MALDI-TOF Found: 1878.2930.

3. Synthesis of the Cyclobutene monomer

Scheme S2.



The monomer 1,2-dibromo-3,4-bis(diphenylmethylene)cyclobutene **1** was synthesized with slightly modification according to a route described by Toda and co-workers.[1]

Synthesis of 3:

To a round flask was added compound **4** (6.3 g, 30 mmol) , $NiCl_2•6H_2O$ (0.36 g, 0.05 equiv., 1.5 mmol), CuI (0.29 g, 0.05 equiv., 1.5 mmol) and anhydrous THF (40 mL), *N*,*N*,*N*',*N*'-tetramethylethylenediamine (TMEDA) (0.9 mL, 0.2 equiv., 6 mmol) was added at last. The reaction mixture was stirred at room temperature under air for 12 h. After the completion of the reaction as indicated by TLC analysis, THF was removed under reduced pressure. The reaction was then diluted with EtOAc, filtered through a pad of celite. The organic phase was washed with 1 M HCl, sat. NaCl (aq) and dried over anhydrous Na_2SO_4. The solvent was removed under reduced pressure. The residue was isolated by flash chromatography to give the product **3** in 89% yield (5.6 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.58–7.55 (m, 8H), 7.37–7.27 (m, 12H), 2.81 (s, 2H).

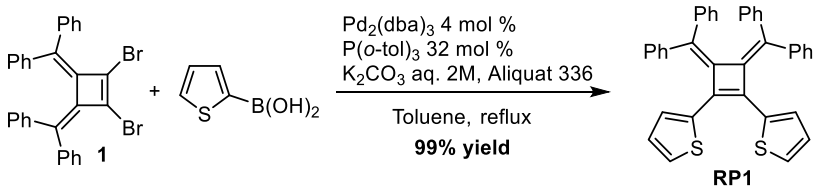
Synthesis of 2:

To a round flask was added compound **3** (2.7 g, 6.5 mmol) and HOAc (20 mL), stirred at room temperature. HBr (3 mL) was added dropwise and stirred at room temperature for 15 min, yellow precipitates formed. The solids were filtered, washed with H_2O, hexane and then EtOAc. Yellow solids were obtained to give the product **2** in 66% yield (2.3 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40–7.38 (m, 8H), 7.35–7.29 (m, 12H).

Synthesis of 1:

To a round flask was added compound **2** (2.3 g, 4.2 mmol) and toluene (10 mL), heated to reflux for 1 h. The solvent was removed under reduced pressure, and the resulting residual was washed with cold hexane to give pure 1,2-dibromo-3,4-bis(diphenylmethylene)cyclobutene **1** in 99% yield (2.3 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.27–7.26 (m, 6H), 7.18–7.15 (m, 4H), 6.78 (d, J = 7.7 Hz, 4H), 6.72 (t, J = 7.3 Hz, 2H), 6.62 (t, J = 7.5 Hz, 4H).

Scheme S3.



Synthesis of RP1:

To a flame-dried Schlenck tube was added 1,2-dibromo-3,4-bis(diphenylmethylene)cyclobutene **1** (108.1 mg, 0.2 mmol), 2-thienylboronic acid (51.2 mg, 2 equiv., 0.4 mmol), $Pd_2(dba)_3$ (97% purity, 7.3 mg, 0.04 equiv, 8 μmol), P(*o*-tol)$_3$ (97% purity,19.5 mg, 0.32 equiv, 64 μmol) and toluene (4 mL). 2 mL 2 M aq. K_2CO_3 was added to the above solution, 1 drop of Aliquat 336 was added subsequently. The whole solution was heated to 105 °C for 12 h. After the completion of the reaction as indicated by TLC analysis, the mixture was cooled to room temperature and passed through a pad of silica and washed with DCM. The solvent was removed under reduced pressure and the residue was isolated by flash chromatography to give the product **RP1** in 99% yield (116 mg). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.15–7.13 (m, 2H), 7.10–7.05 (m, 10H), 6.96–6.94 (m, 4H), 6.81 (t, J = 7.3 Hz, 2H), 6.74 (t, J = 7.5 Hz, 4H), 6.61 (dd, J = 5.0, 3.7 Hz, 2H), 6.02 (d, J = 3.6 Hz, 2H).

4. 2D NMR Analysis of Macrocycle A1, A2 and A3

(1) 2D NMR of Macrocycle A1

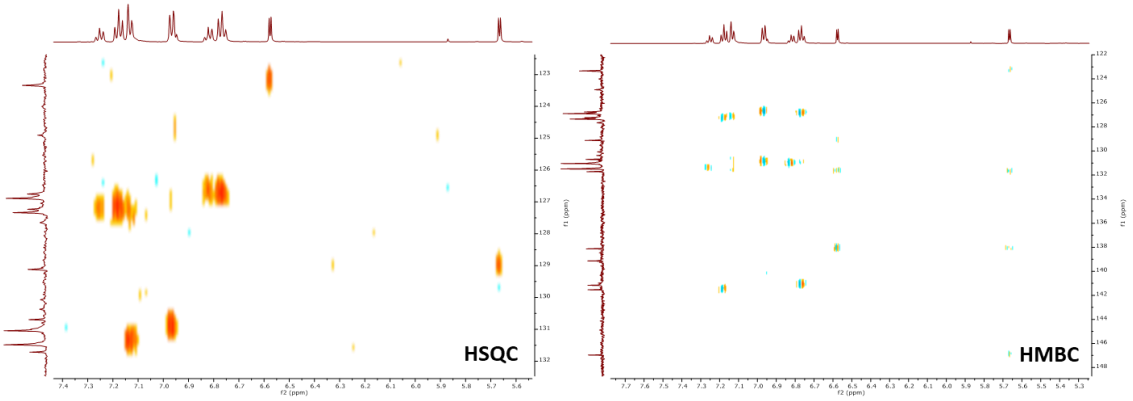


Figure S1.

(2) 2D NMR of Macrocycle A2

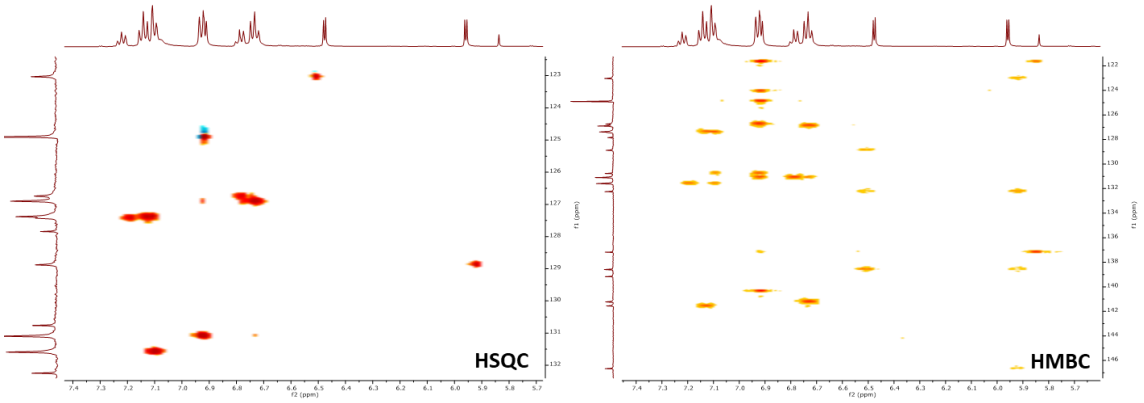


Figure S2.

(3) 2D NMR of Macrocycle A3

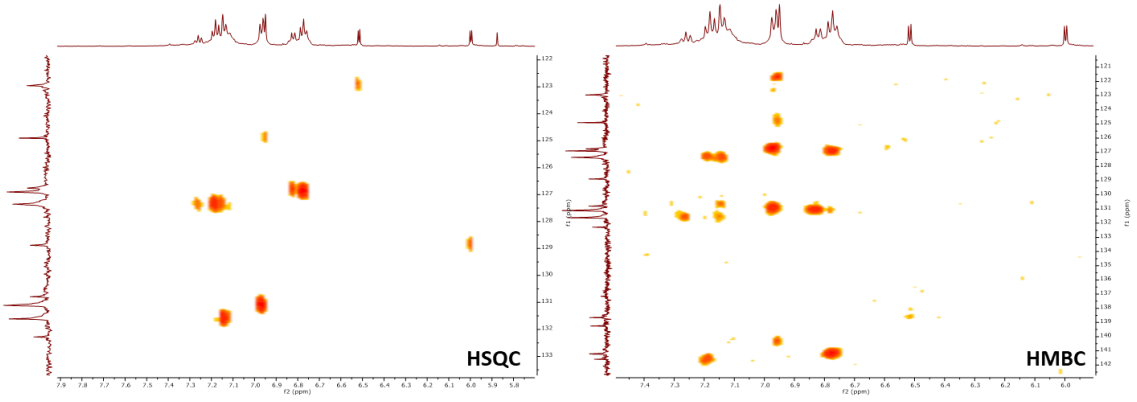


Figure S3.

5. Variable temperature (VT)-NMR Analysis of Macrocycle A1

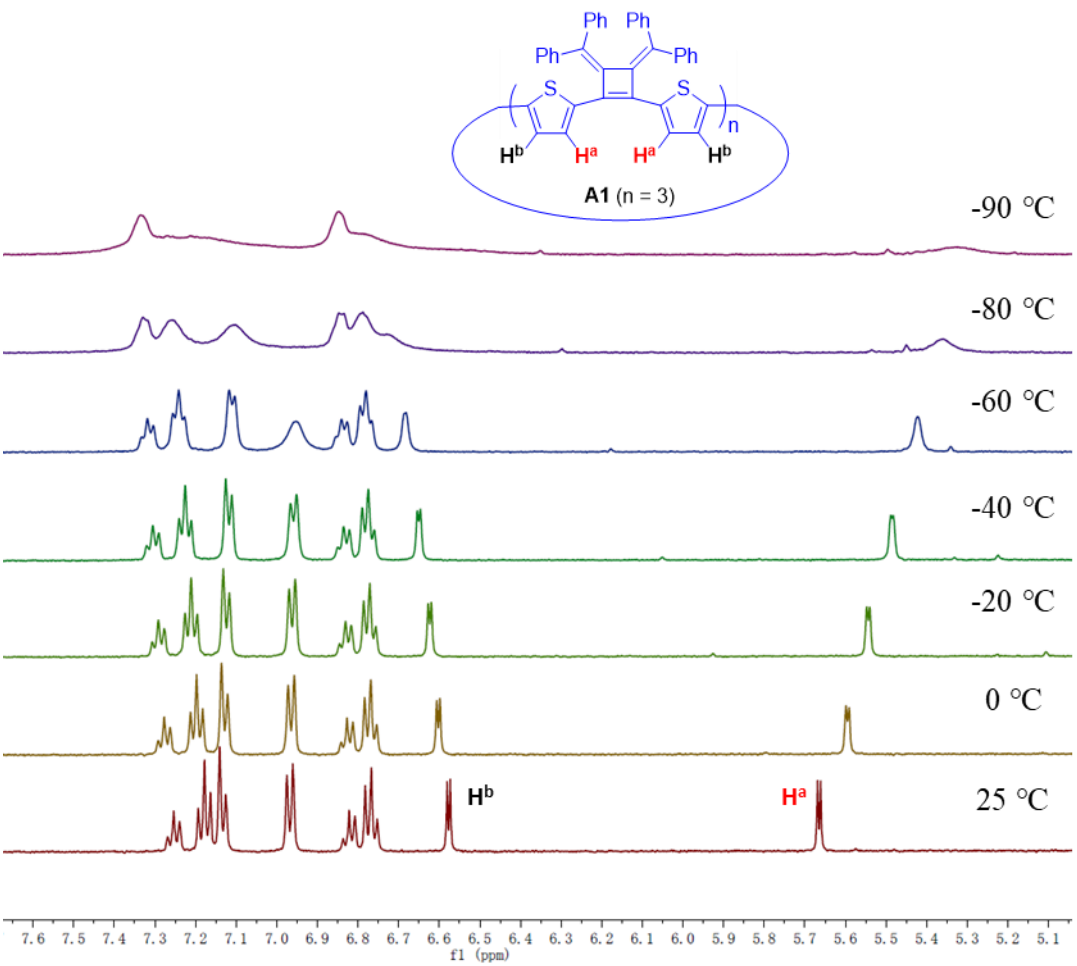


Figure S4. VT-NMR in THF-d_8, 500 MHz.
Aromatic region of ^{1}H NMR in THF-d_8 (500 MHz) from 25 °C to -90 °C.

6. MALDI-TOF Analysis

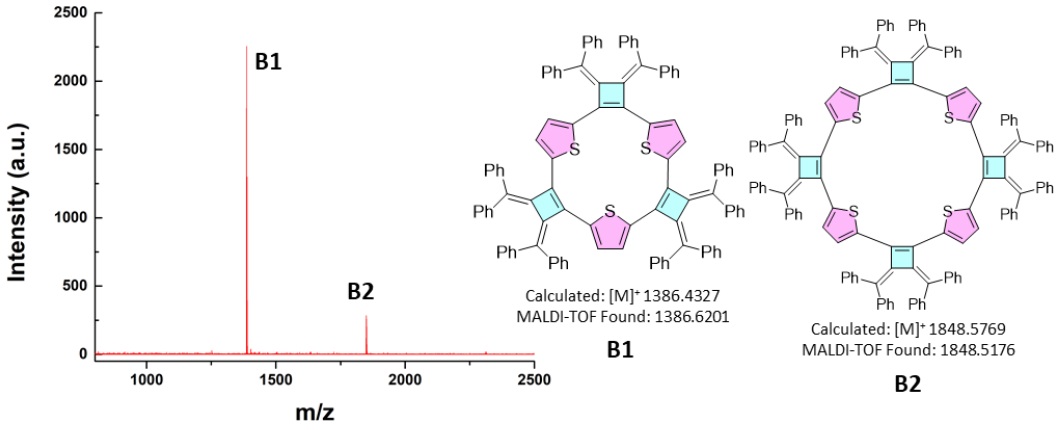


Figure S5. Macrocycles B

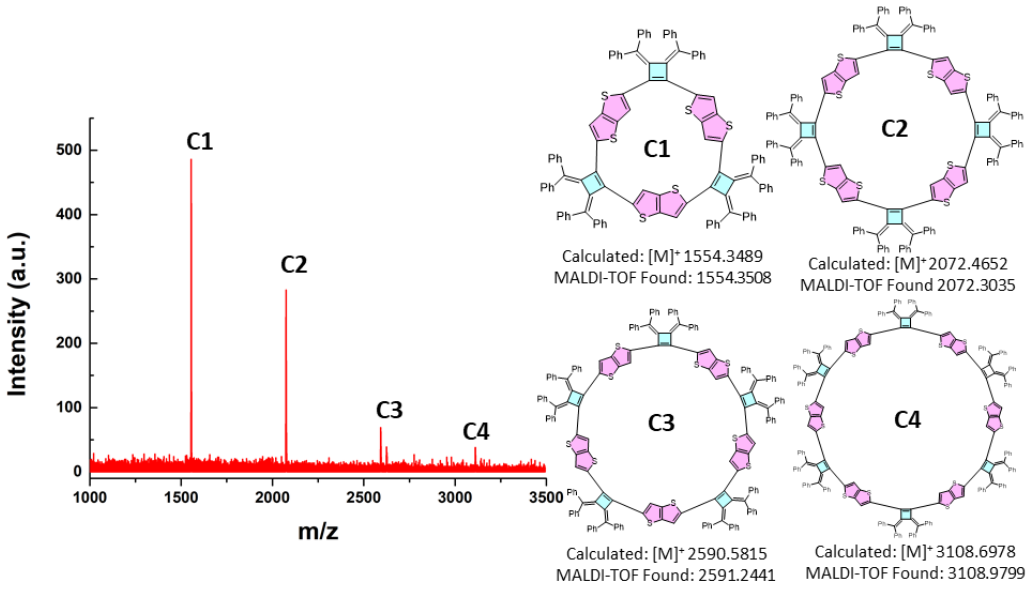


Figure S6. Macrocycles C

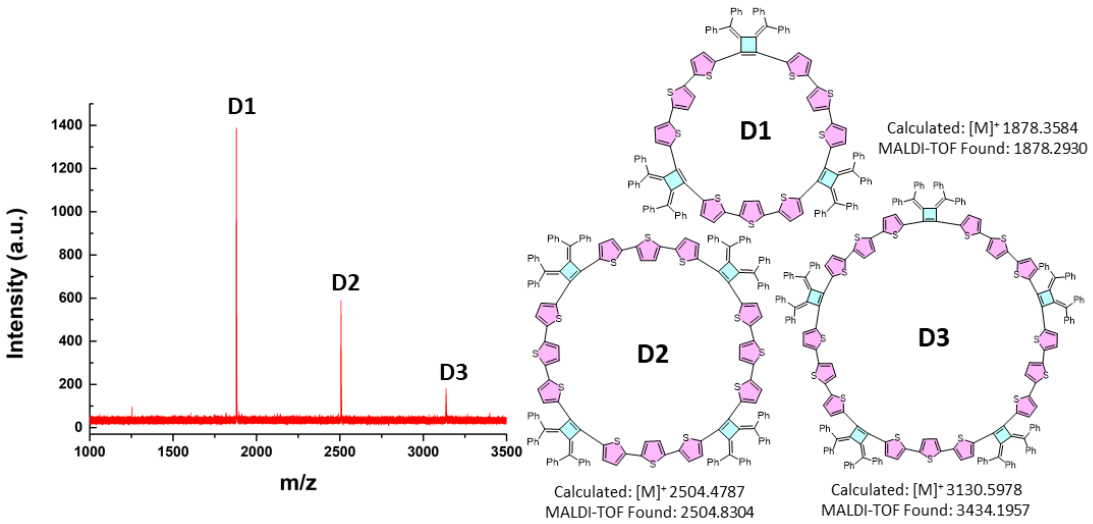


Figure S7. Macrocycles D

7. Photophysical Properties

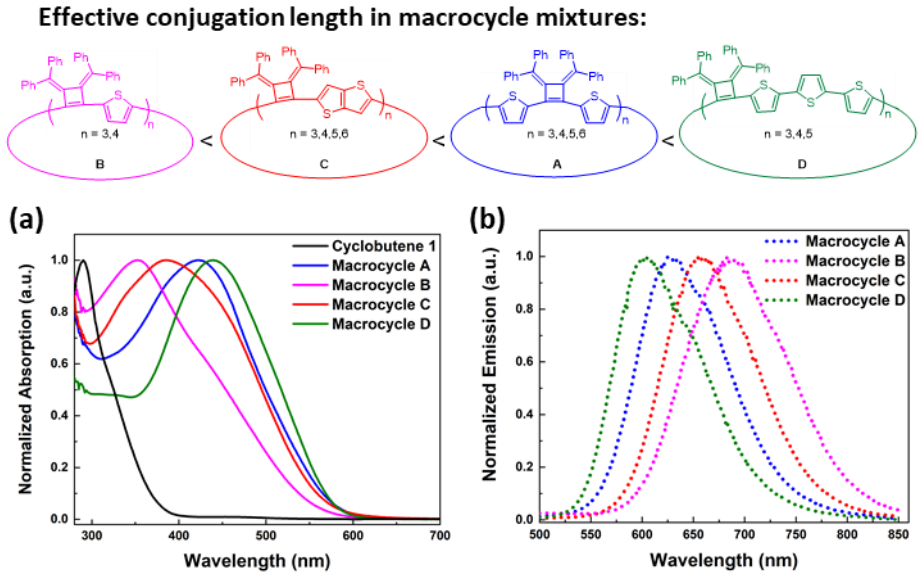


Figure S8. Normalized (a) UV-vis spectra and (b) emission spectra of macrocycle mixtures in THF solutions. The emission spectra were measured after excitation at the maximum of each absorption wavelength.

8. TGA Spectra of the Macrocycles

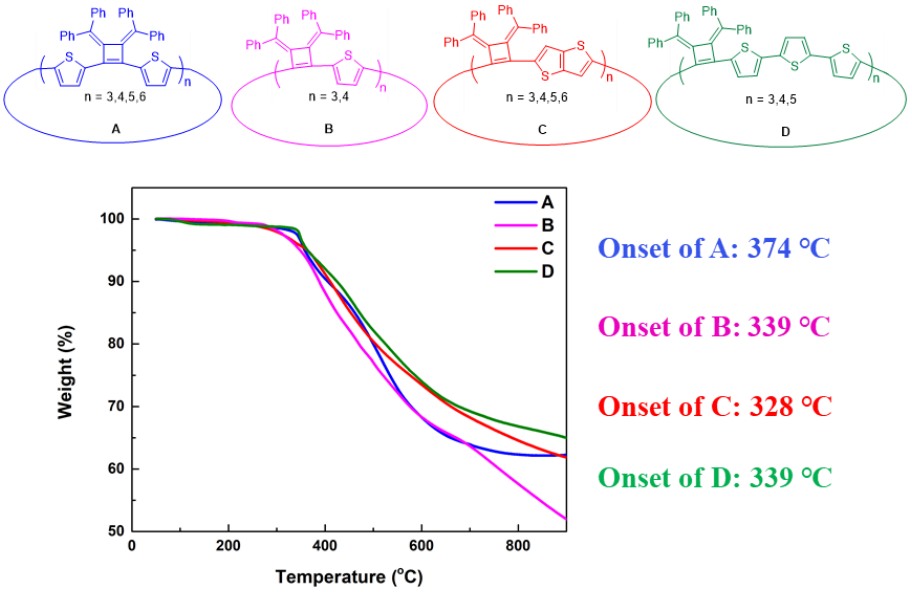


Figure S9. TGA traces of macrocycle families **A**, **B**, **C** and **D**. TGA analysis was conducted in N_2 atmosphere with a ramping rate 20 °C/min to 900 °C.

9. Cyclic Voltammetry of the Macrocycles

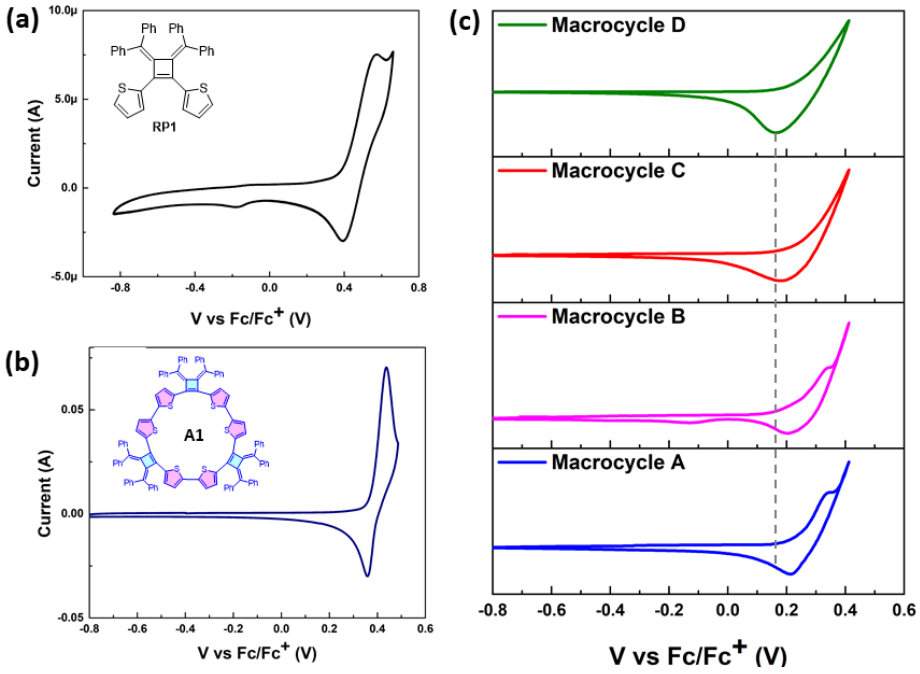


Figure S10. (a) Cyclic voltammetry with compound **RP1** dissolved in DCM, 0.1 M Bu_4NPF_6 in DCM was used as the electrolyte. Pt wire as the counter electrode, $Ag/AgNO_3$ as the reference electrode. Ferrocene was used as external standard. Cyclic voltammetry with (b) macrocycle **A1**, (c) macrocycle mixtures **B**, **C** and **D** spin-coated on ITO glasses which were used as the working electrodes. 0.1 M Bu_4NPF_6 in CH_3CN was used as the electrolyte, Pt wire as the counter electrode, $Ag/AgNO_3$ as the reference electrode. Ferrocene was used as external standard.

10. FT-IR of the Macrocycles

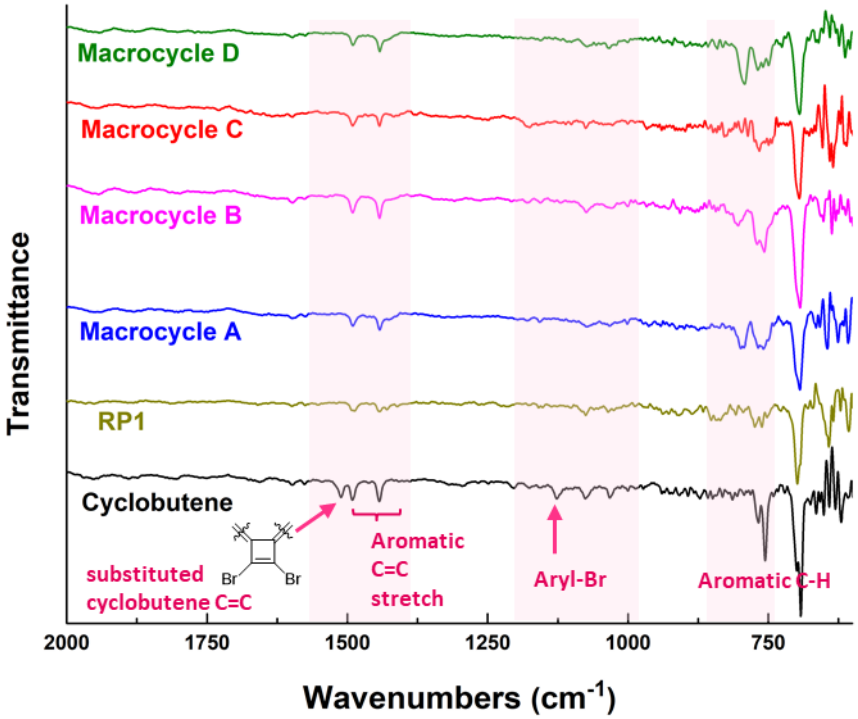


Figure S11. IR spectra.

11. Single X-ray Structure of Macrocycle A1

Single crystal diffraction was recorded on a Bruker D8 Venture Kappa DUO four-circle diffractometer and a Bruker Photon3 CPAD detector.

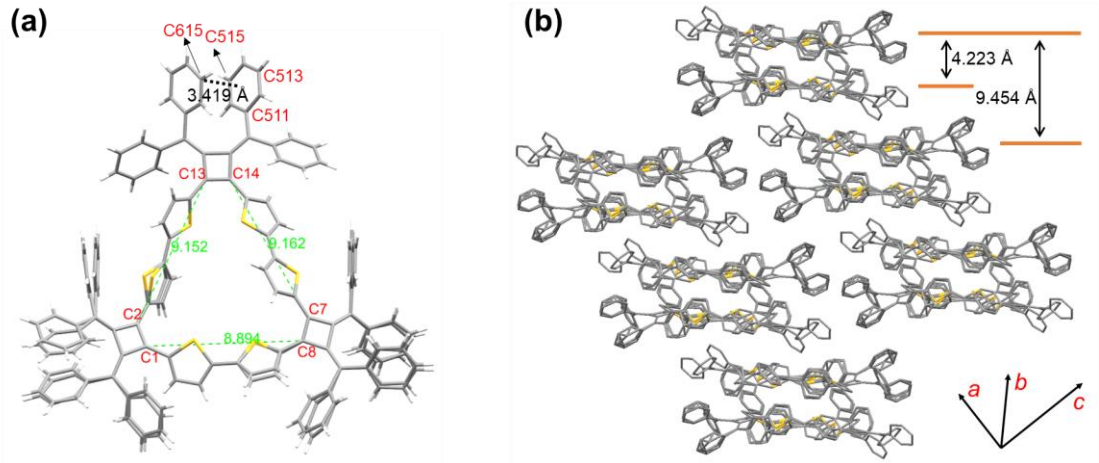


Figure S12. (a) Single crystal structure. The stacking distance of two inner phenyl rings of cyclobutene is the distance between C615 and the mean plane of C511, C513 and C515. (b) Molecular packing. The packing distance is the distance between the mean planes of C2, C8 and C14.

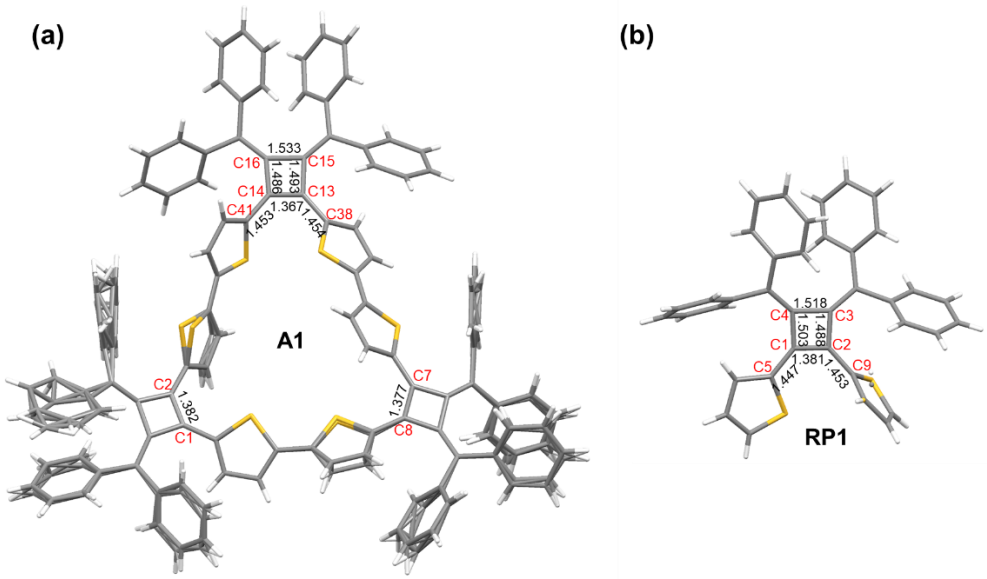


Figure S13. X-ray crystal structure of (a) **A1** and (b) **RP1**, showing the bond lengths in the molecules.

Table S2. Crystal data and structure refinement for **A1**.

CCDC	**2011836**
Empirical formula	$C_{114}H_{72}S_6$
Formula weight	1634.07
Temperature/K	100(2)
Crystal system	triclinic
Space group	P-1
a/Å	14.3999(4)
b/Å	18.2420(6)
c/Å	21.0069(6)
α/°	75.9362(19)
β/°	80.3480(17)
γ/°	78.2771(17)
Volume/Å^3	5200.3(3)
Z	2
ρ_{calc}g/cm^3	1.044
μ/mm^{-1}	1.543
F(000)	1704.0
Crystal size/mm^3	0.400 × 0.035 × 0.015
Radiation	CuKα (λ = 1.54178)
2Θ range for data collection/°	4.37 to 144.234
Index ranges	-17 ≤ h ≤ 16, -22 ≤ k ≤ 22, -25 ≤ l ≤ 25

Reflections collected	108676
Independent reflections	20143 [R_{int} = 0.0728, R_{sigma} = 0.0545]
Data/restraints/parameters	20143/8979/1571
Goodness-of-fit on F^2	1.094
Final R indexes [I >= 2σ (I)]	R_1 = 0.0514, wR_2 = 0.1427
Final R indexes [all data]	R_1 = 0.0603, wR_2 = 0.1495
Largest diff. peak/hole / e $Å^{-3}$	0.41/-0.52

12. Theoretical Studies of the Macrocycles

(1) Density Functional Theory (DFT) Calculations

All structural models were prepared using the MedeA® software [1].[2] For the geometry optimization step, the electronic structure was modeled using periodic plane-wave DFT at the Gamma-point with a kinetic energy cutoff of 400 eV, and the PBE functional.[3] The criteria on the energy and atomic forces convergence were respectively set to 10^{-5} eV and 0.02 eV/Å. For the determination of the frontier orbitals and HOMO-LUMO gap, we used def2-TZVP basis sets along with the PBE0 hybrid functional.[4]

(2) Molecular Dynamics (MD) Simulations

The molecular dynamics simulations were carried out using the Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS)[5] with the PCFF+ force field.[6] The PPPM method[7] was employed for computing long range Coulombic interactions with a tolerance level of 10^{-5}. For each simulation, the initial configuration, consisting of one macrocycle molecule with a vacuum space of 5 nm in *x*, *y*, and *z* three directions, was created using MedeA (a commercial simulation software). A conjugate-gradient (CG) minimization was performed to pre-relax the structure, followed by a MD run under the NVT ensemble at 300 K. Setting the time step of 1 fs, the simulation was run for a period of 100 ps, with a subsequent CG relaxation to obtain the final molecule geometry at a local energy minimum. For each type of molecule, the simulation was repeated three times, to explore different possible macrocycle conformations.

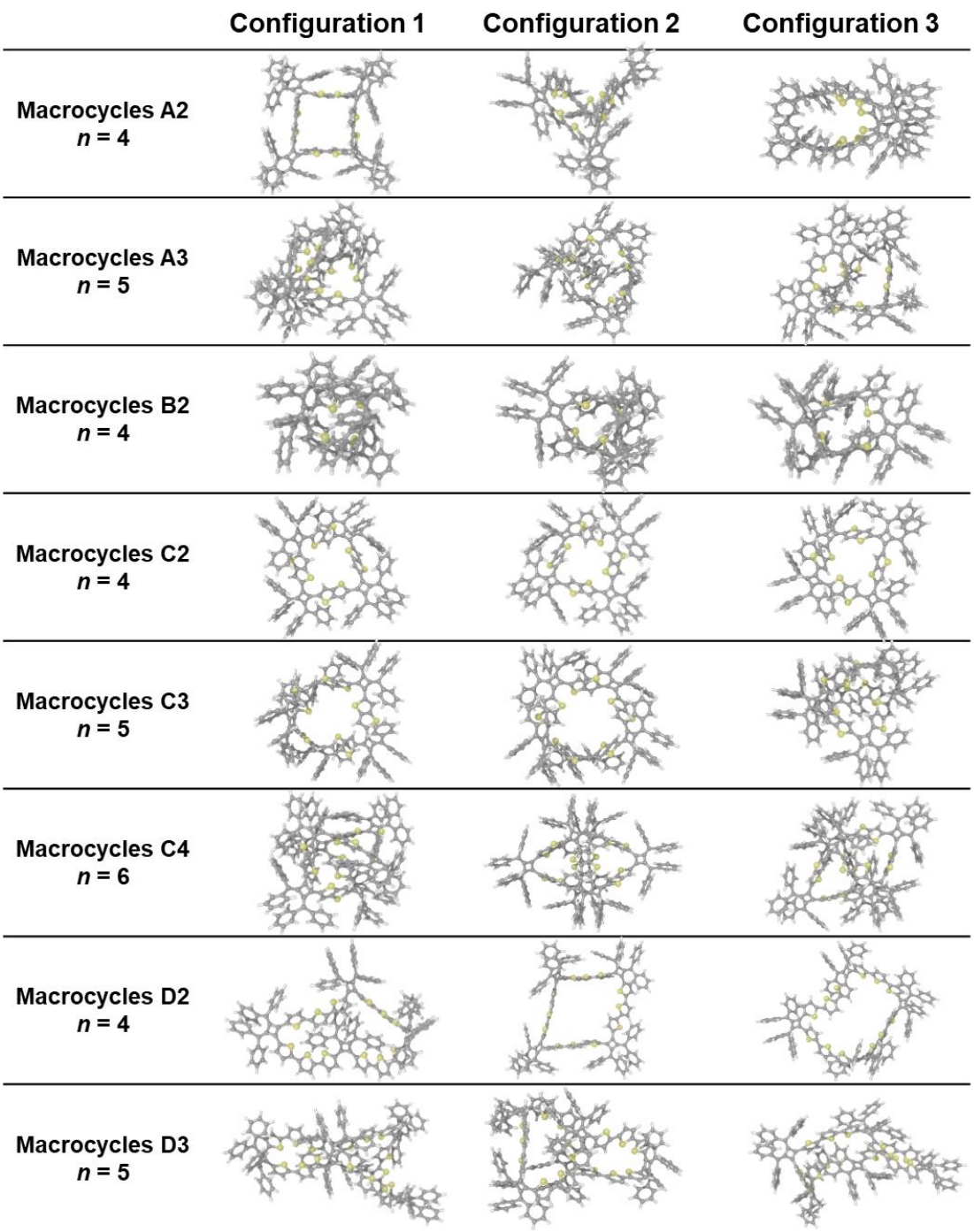
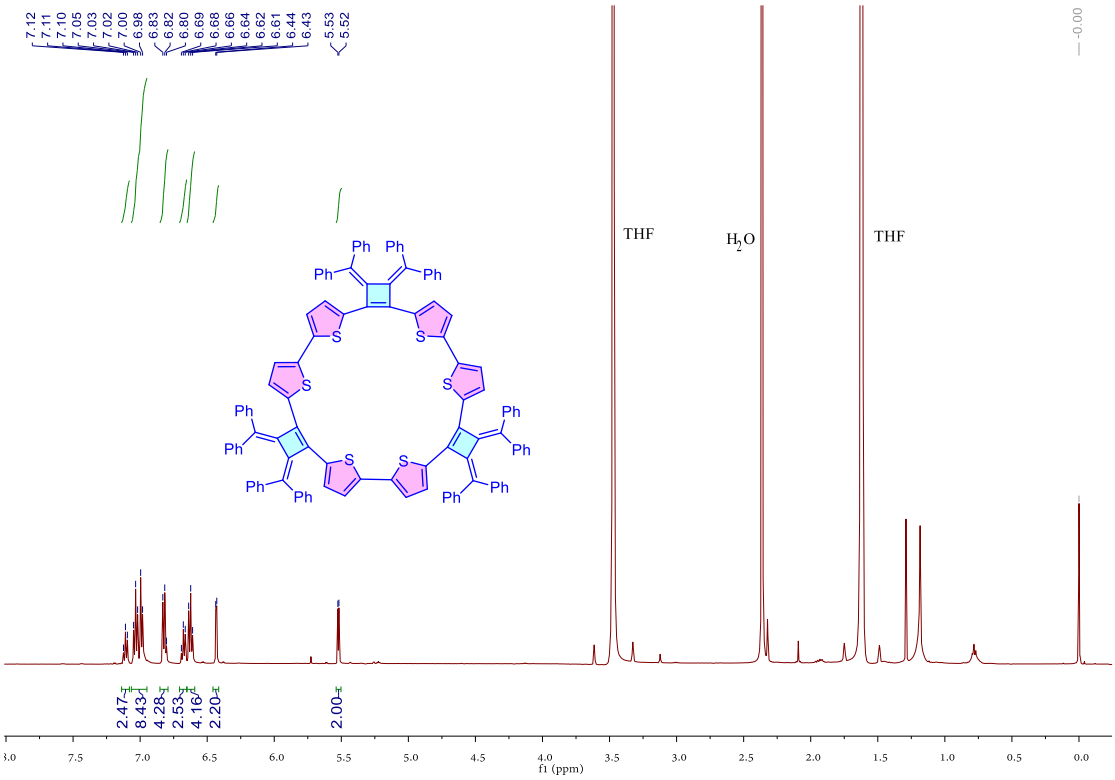
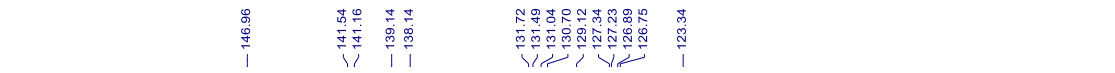


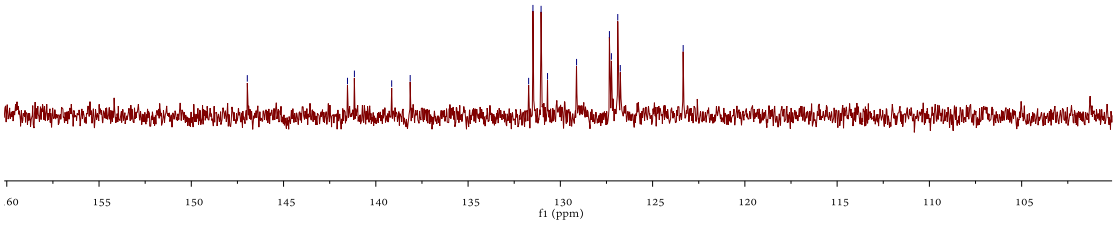
Figure S14. Relaxed geometries of a series of macrocycles predicted by a PCFF+ force field based atomistic model. Each configuration representing a possible local energy minimum of the macrocycle.

13. NMR Spectra

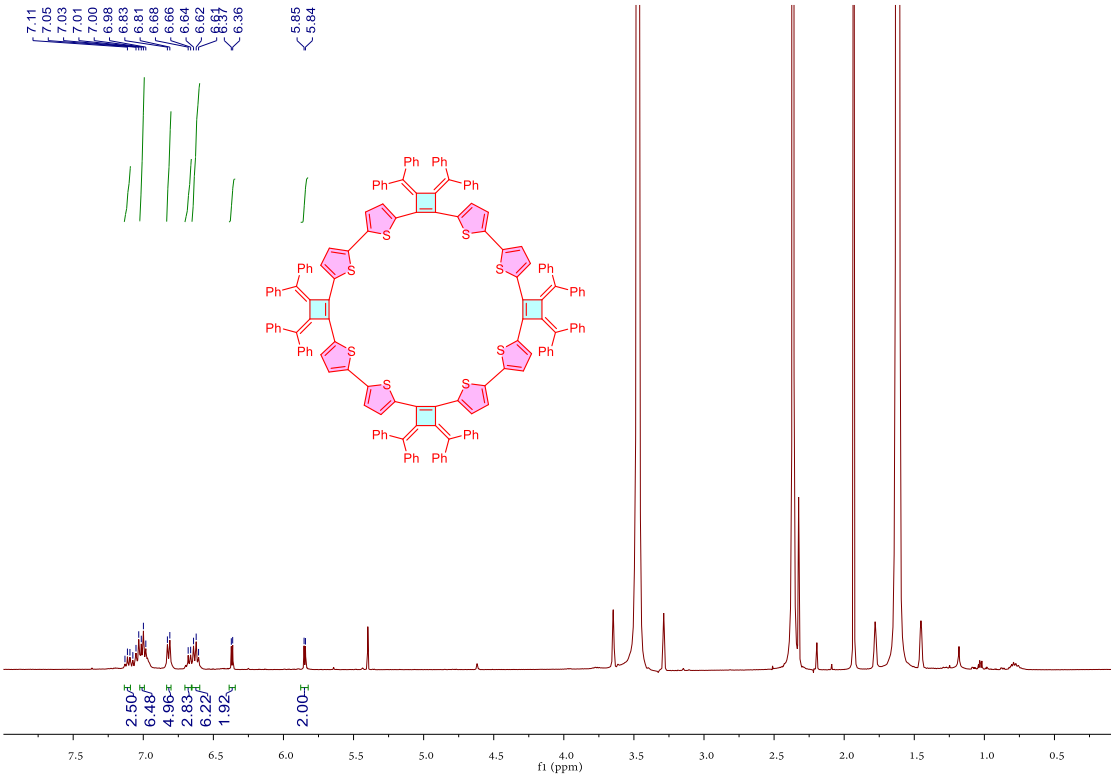
Macrocycle A1 (in THF-d_8)

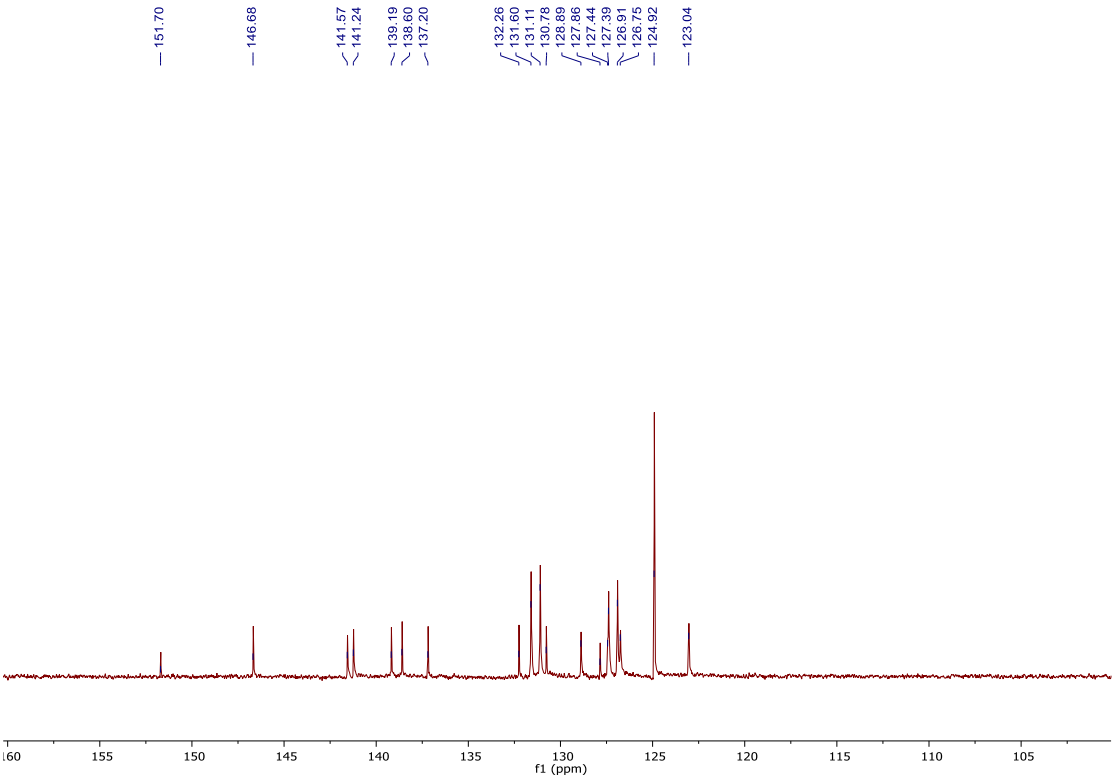




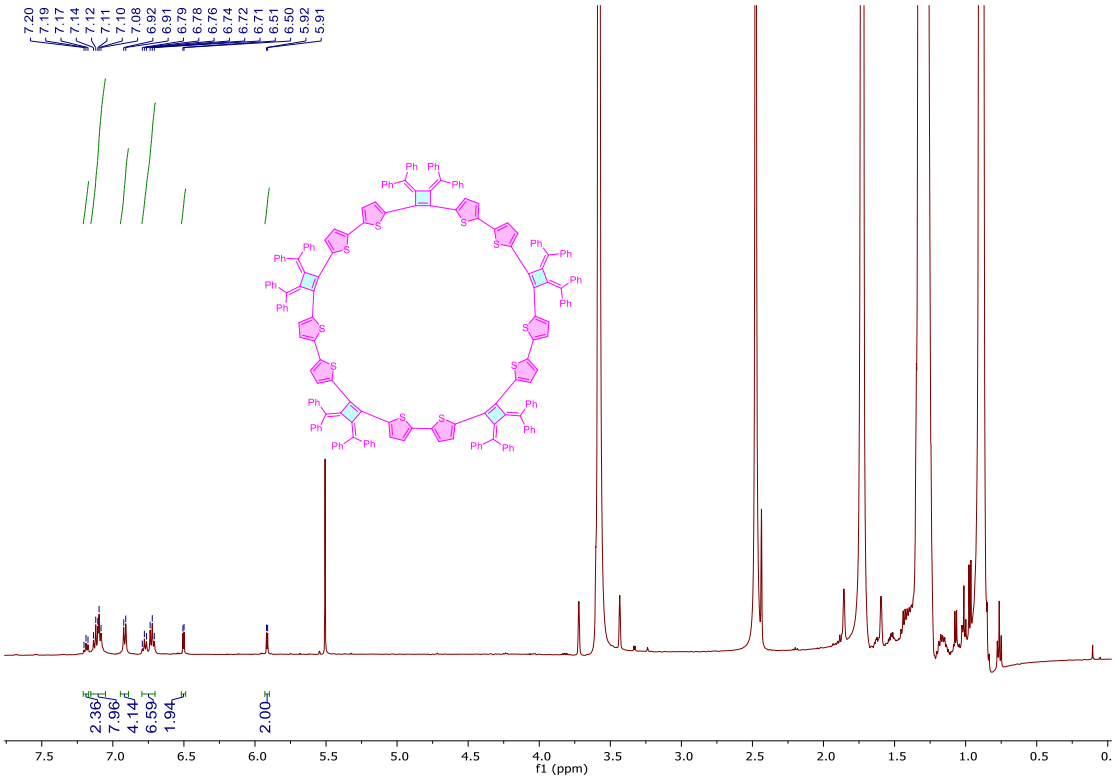


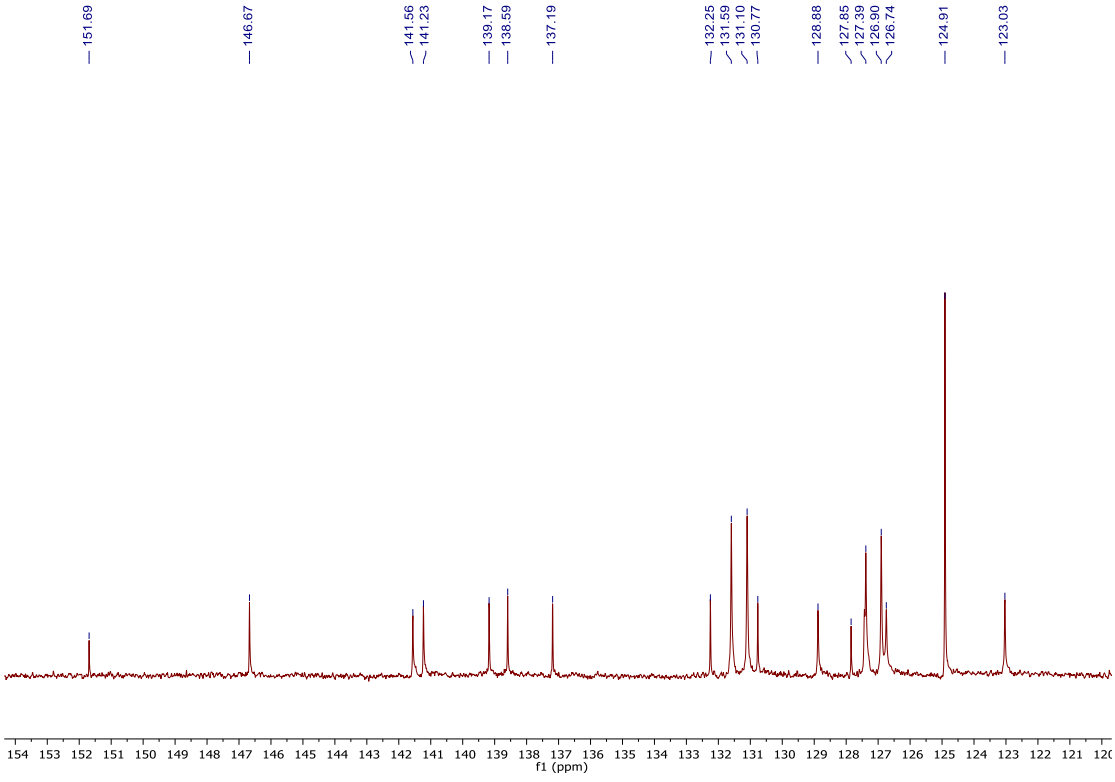
Macrocycle A2 (in THF-d_8)



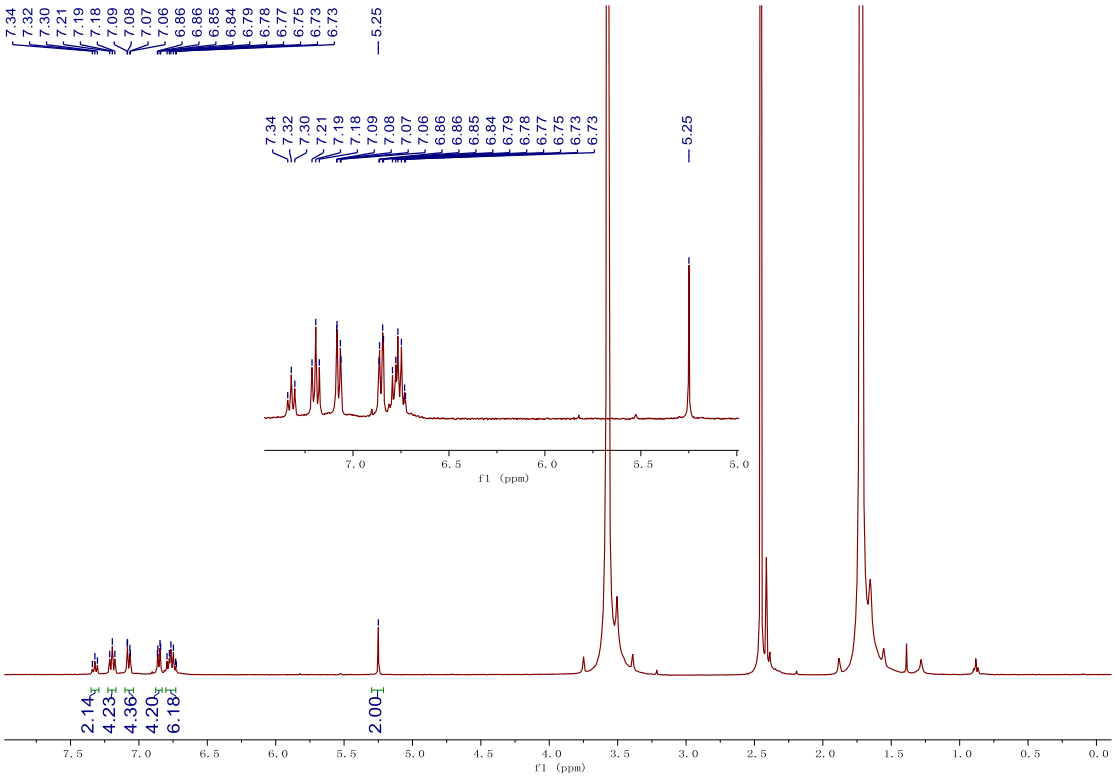


Macrocycle A3 (in THF-d_8)

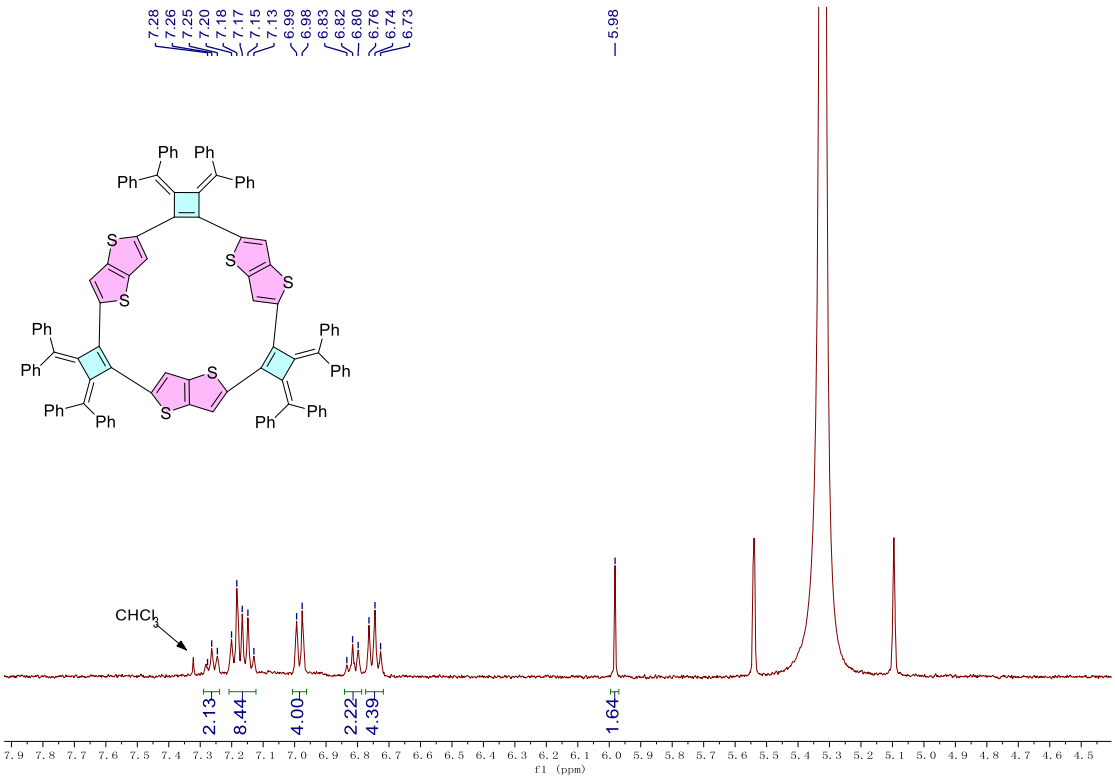




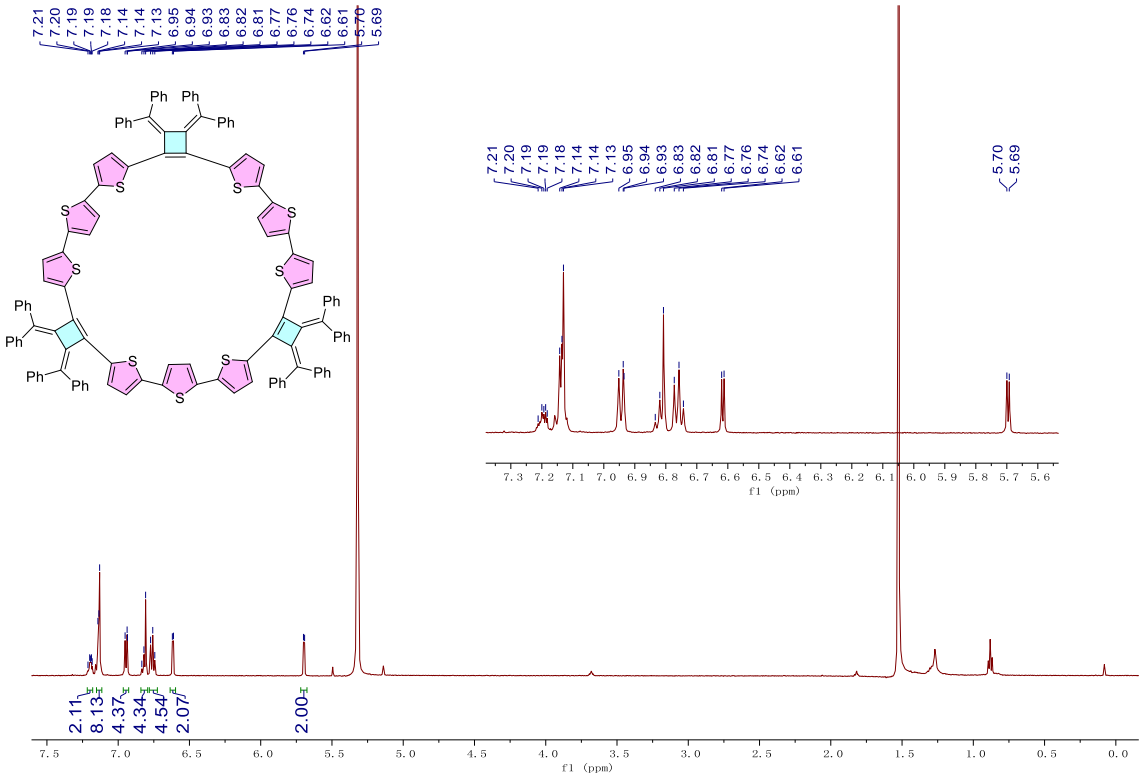
Macrocycle B1 (in THF-d_8)



Macrocycle C1 (in CD_2Cl_2)



Macrocycle D1 (in CD_2Cl_2)



14. References

1. F. Toda, K. Tanaka, T. Tamashima and M. Kato, Stereoselective Thermal Conversion of s-trans-Diallene into Dimethylenecyclobutene via s-cis-Diallene in the Crystalline State, *Angew. Chem. Int. Ed.*, 1998, **37**, 2724-2727.
2. MedeA-2.22, Materials Design, Inc, San Diego, CA USA. 2018.
3. J. P. Perdew, K. Burke and M. Ernzerhof, Generalized Gradient Approximation Made Simple, *Phys. Rev. Lett.*, 1996, **77**, 3865-3868.
4. C. Adamo and V. Barone, Toward reliable density functional methods without adjustable parameters: The PBE0 model, *J. Chem. Phys.*, 1999, **110**, 6158-6170.
5. S. Plimpton, *Fast parallel algorithms for short-range molecular dynamics*, Report SAND-91-1144; Other: ON: DE93018519; TRN: 93:002897 United States 10.2172/10176421 Other: ON: DE93018519; TRN: 93:002897 OSTI; NTIS; GPO Dep. SNL English, ; Sandia National Labs., Albuquerque, NM (United States), 1993.
6. H. Sun, COMPASS: An ab Initio Force-Field Optimized for Condensed-Phase ApplicationsOverview with Details on Alkane and Benzene Compounds, *J. Phys. Chem. B*, 1998, **102**, 7338-7364.
7. R. W. Hockney and J. W. Eastwood, *Computer simulation using particles*, crc Press, 1988.