Sequence-controlled supramolecular copolymer constructed by self-sorting assembly of multiple noncovalent interactions

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Supporting information

1. Self-sorting binding investigation on model compounds 1-6

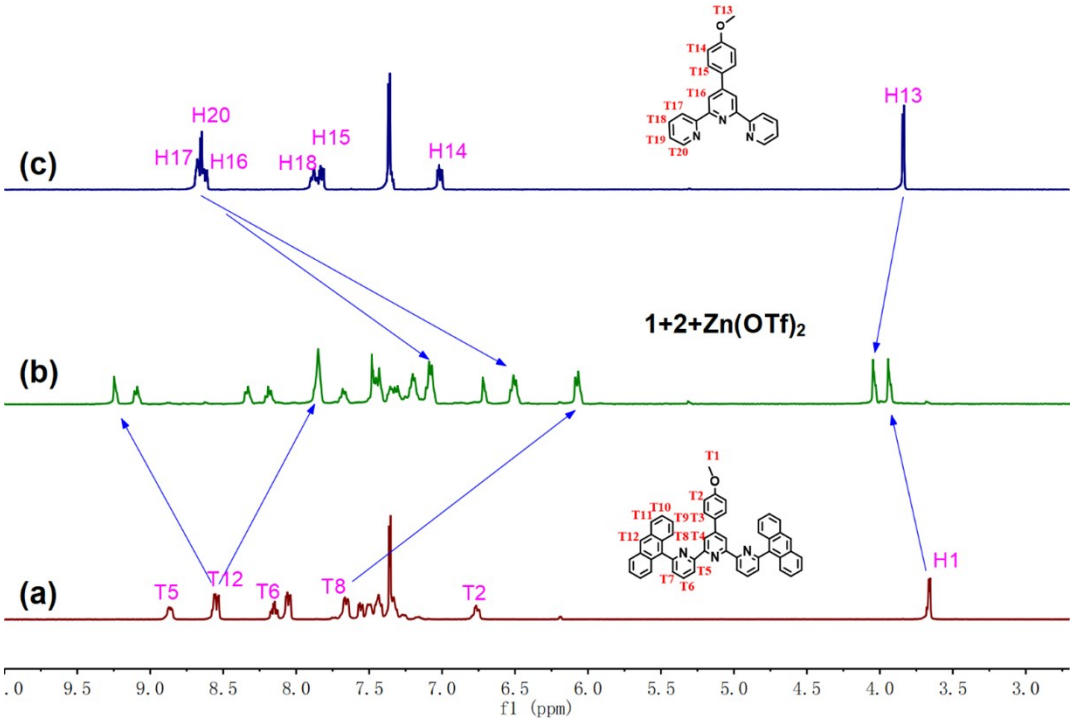


Fig. S1 ^{1}H NMR spectra (400 MHz, chloroform-d_3/acetone-d_6(3/1, *v*/*v*), 293 K) of (a) **1**, (b) an equimolar solution of **1**+**2**+**Zn(OTf)$_2$**, (c) **2**

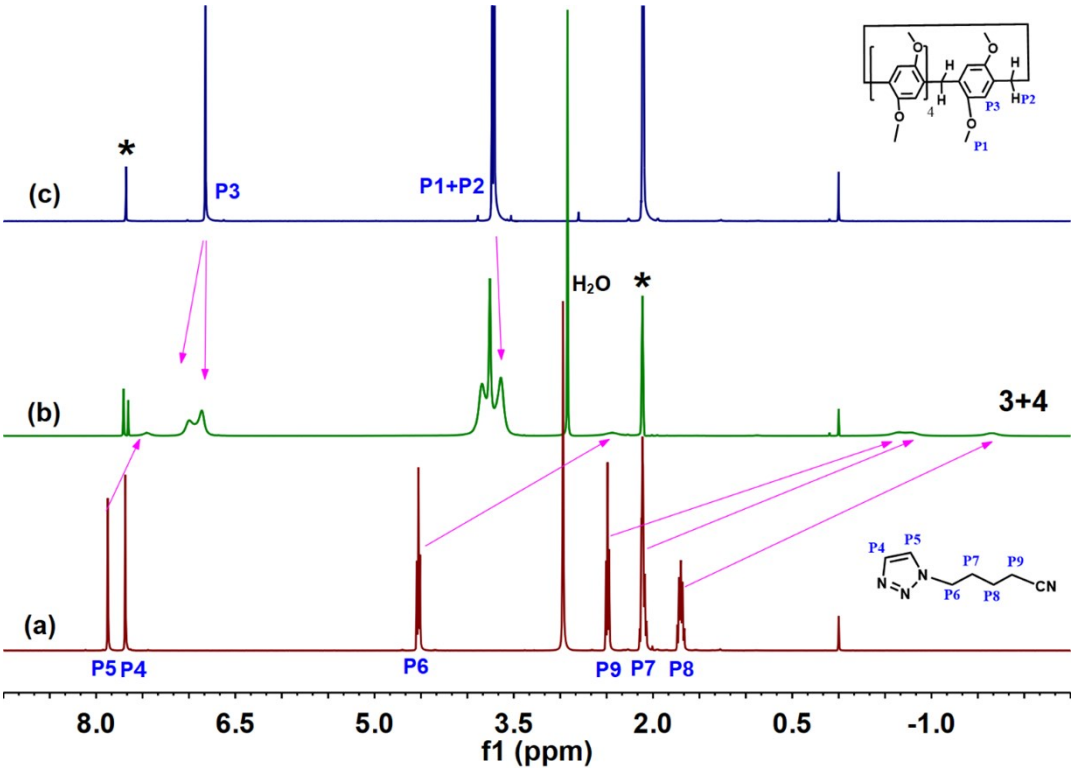


Fig. S2 ^{1}H NMR spectra (400 MHz, chloroform-d_3/acetone-d_6(3/1, *v*/*v*), 293 K) of (a) **4**, (b) an equimolar solution of **3** and **4**, (c) **3**.

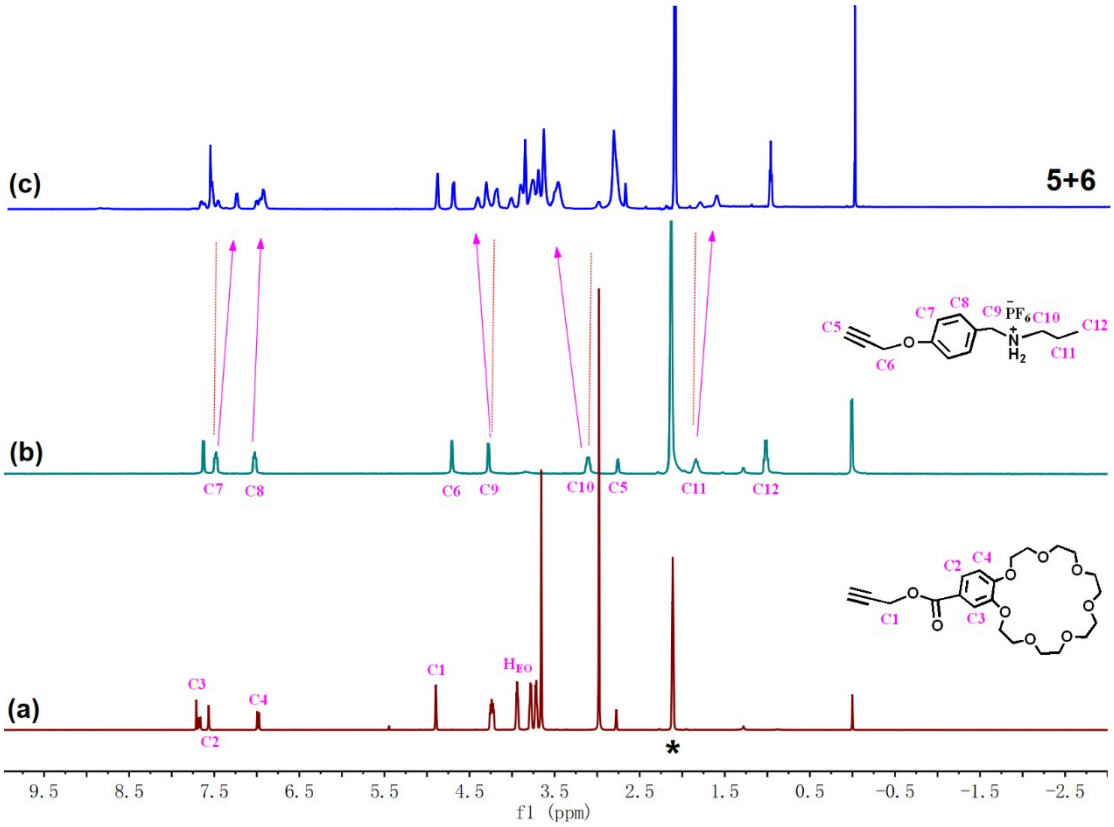


Fig. S3 ^{1}H NMR spectra (400 MHz, chloroform-d_3/acetone-d_6(3/1, *v*/*v*), 293 K) of (a) **5**, (b) **6**, (c) an equimolar solution of **5** and **6**.

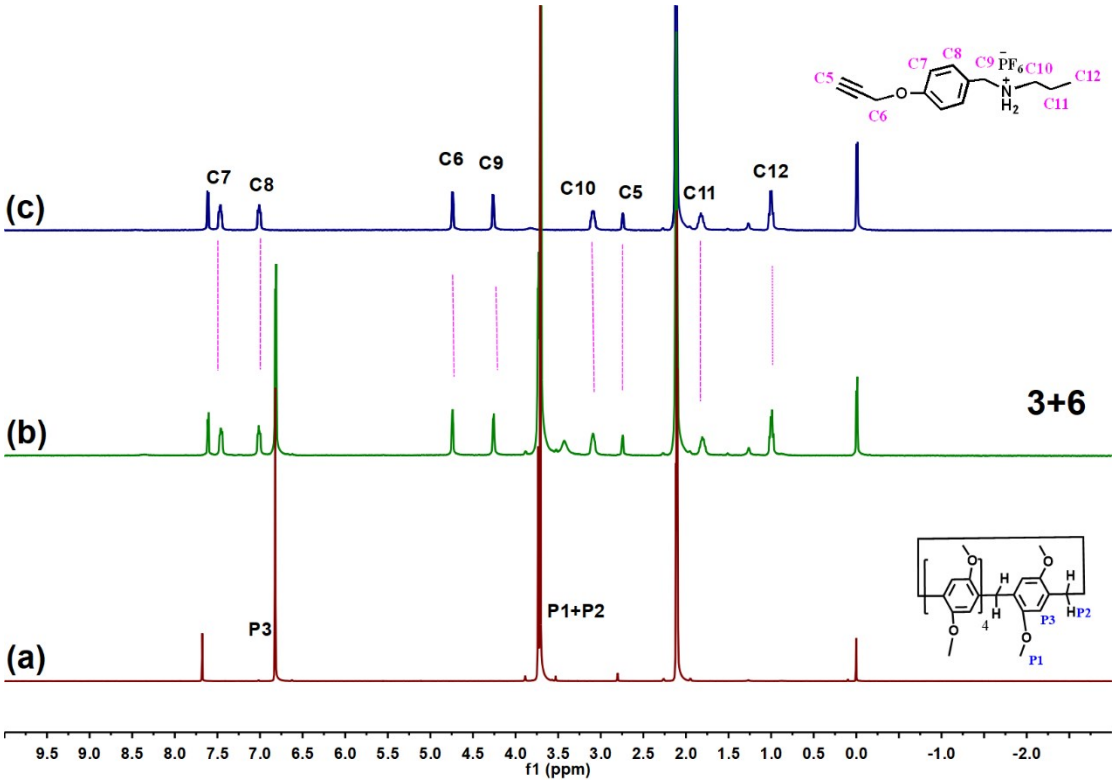


Fig. S4 ^{1}H NMR spectra (400 MHz, chloroform-d_3/acetone-d_6(3/1, *v*/*v*), 293 K) of (a) **3**, (b) an equimolar solution of **3** and **6**, (c) **6**.

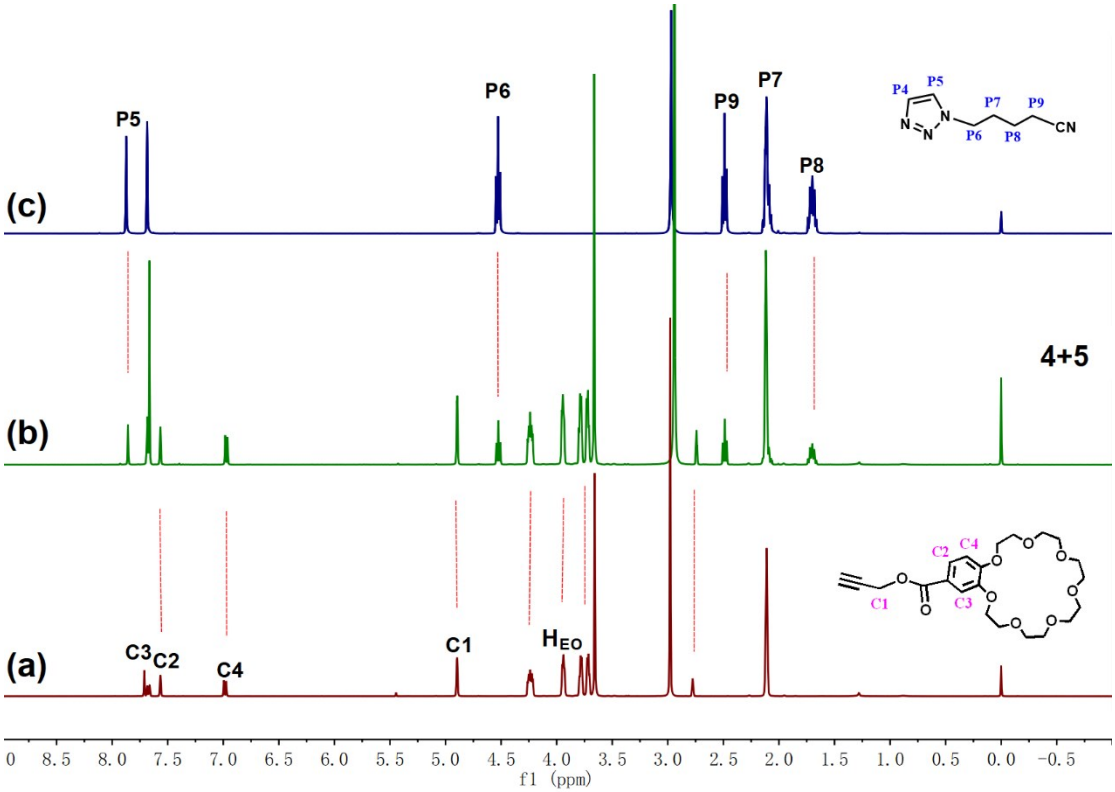


Fig. S5 ^{1}H NMR spectra (400 MHz, chloroform-d_3/acetone-d_6(3/1, *v*/*v*), 293 K) of (a) **5**, (b) an equimolar solution of **4** and **5**, (c) **4**.

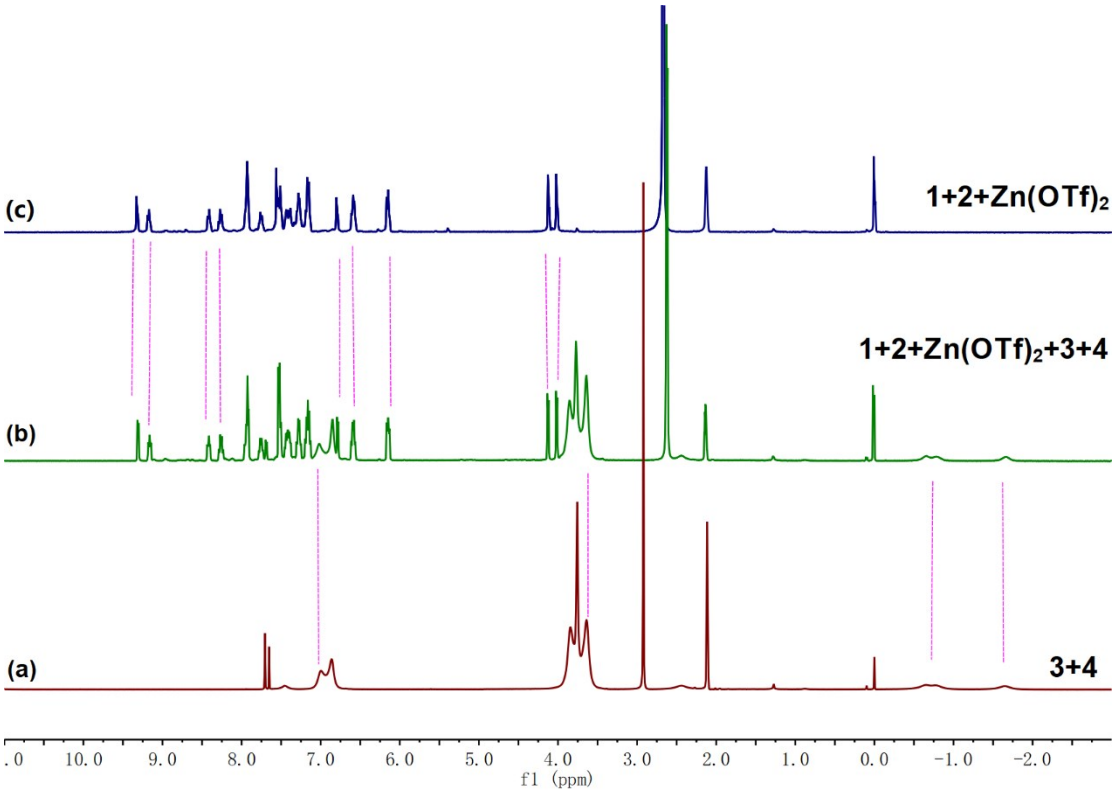


Fig. S6 ^{1}H NMR spectra (400 MHz, chloroform-d_3/acetone-d_6(3/1, *v*/*v*), 293 K) of (a) **3**+**4**, (b)**1**+**2**+**Zn(OTf)$_2$**+**3**+**4**, (c) **1**+**2**+**Zn(OTf)$_2$**.

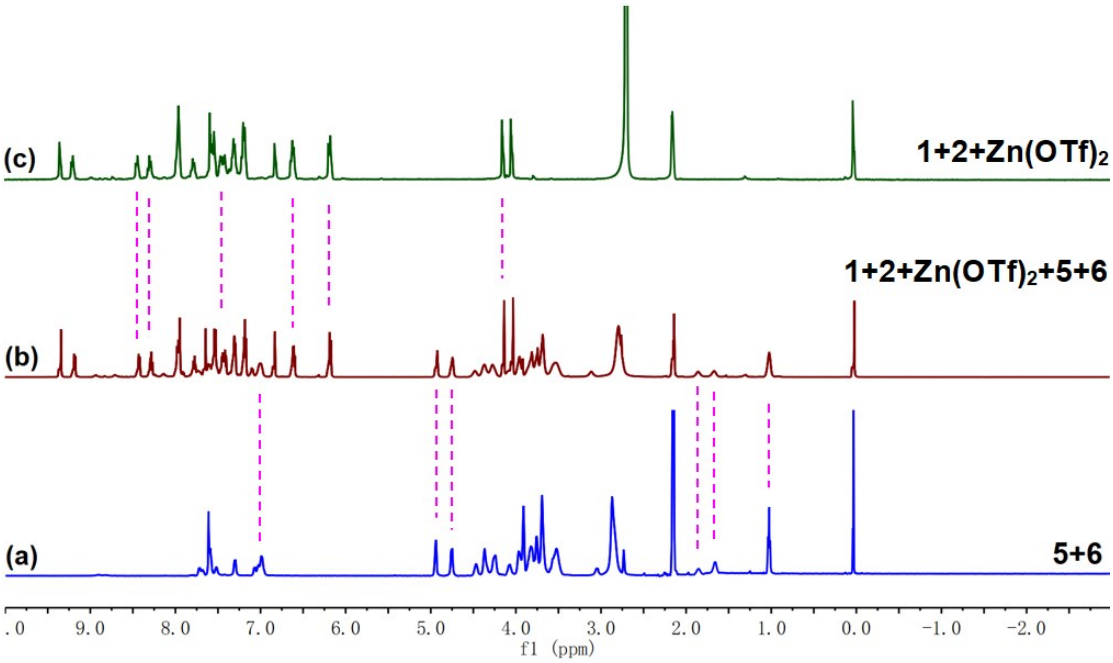


Fig. S7 ^{1}H NMR spectra (400 MHz, chloroform-d_3/acetone-d_6(3/1, *v*/*v*), 293 K) of (a) **5**+**6**, (b)**1**+**2**+**Zn(OTf)$_2$**+**5**+**6**, (c) **1**+**2**+**Zn(OTf)$_2$**.

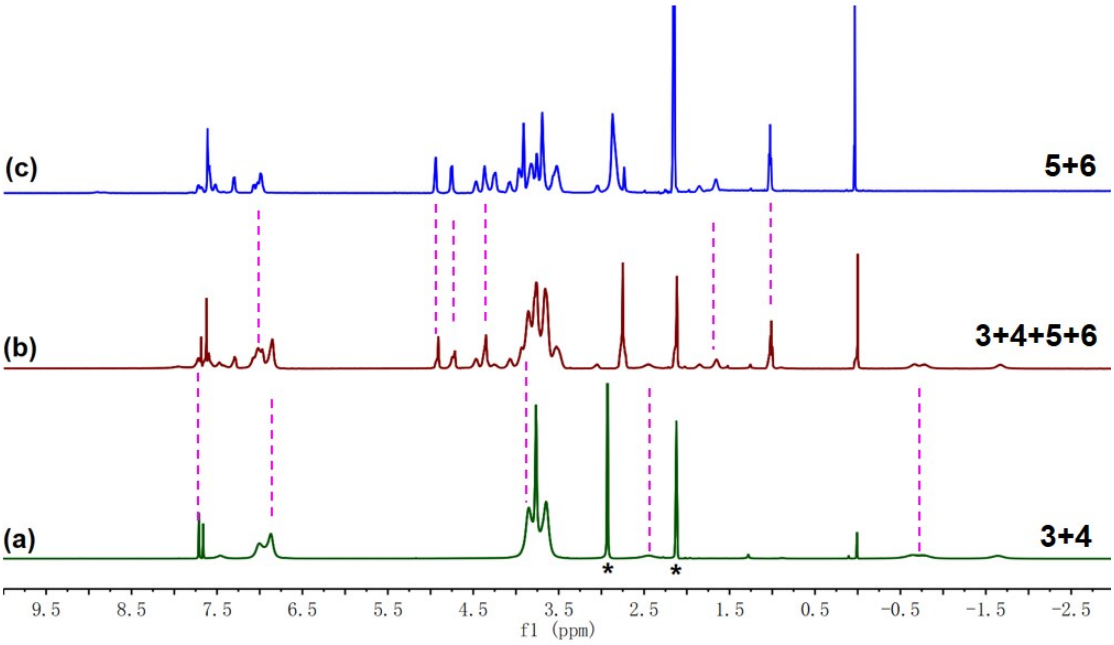


Fig. S8 ^{1}H NMR spectra (400 MHz, chloroform-d_3/acetone-d_6(3/1, *v*/*v*), 293 K) of (a) **3**+**4**, (b)**3**+**4**+**5**+**6**, (c) **5**+**6**.

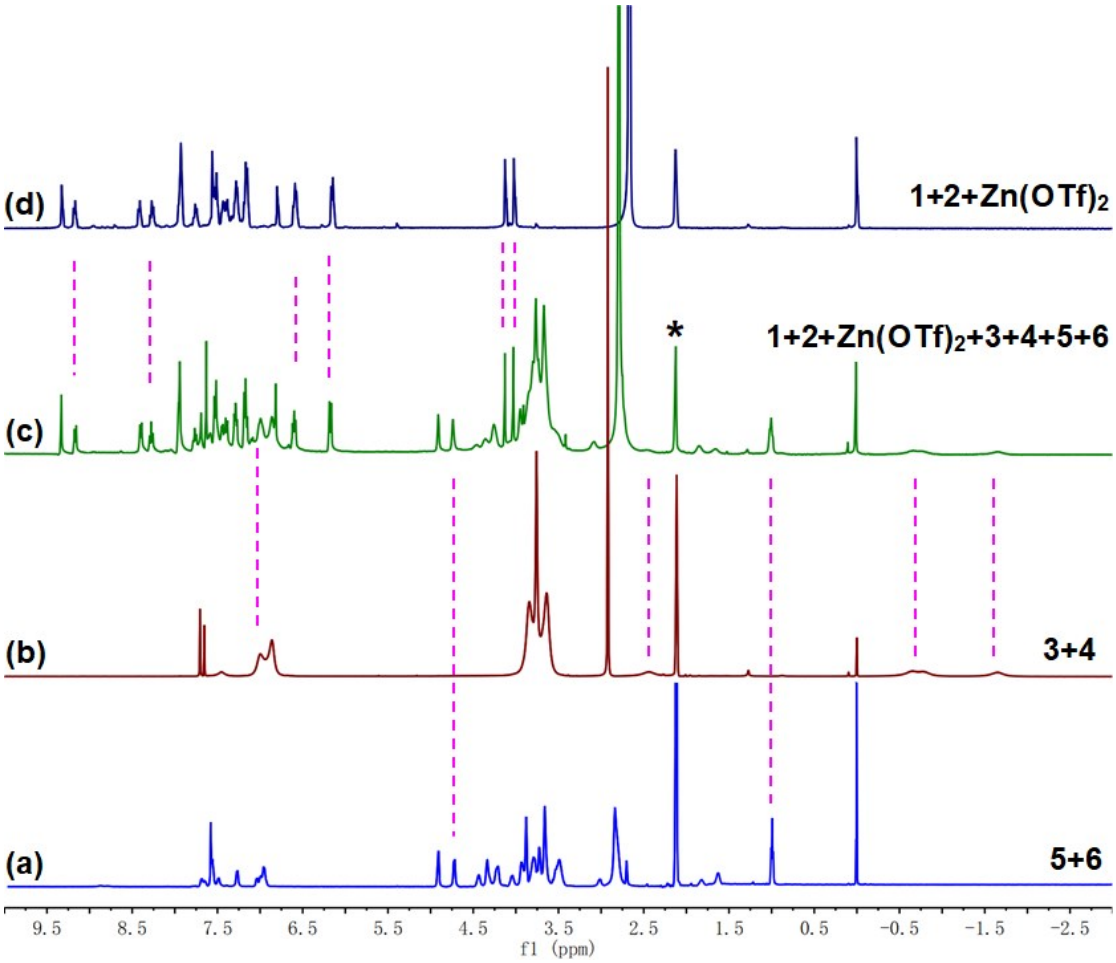


Fig. S9 ^{1}H NMR spectra (400 MHz, chloroform-d_3/acetone-d_6(3/1, *v*/*v*), 293 K) of (a) **5**+**6**, (b) **3**+**4**, (c) **1**+**2**+**3**+**4**+**5**+**6**+**Zn(OTf)$_2$**, (d) **1**+**2**+**Zn(OTf)$_2$**.

2. ^{1}H-^{1}H COSY NMR

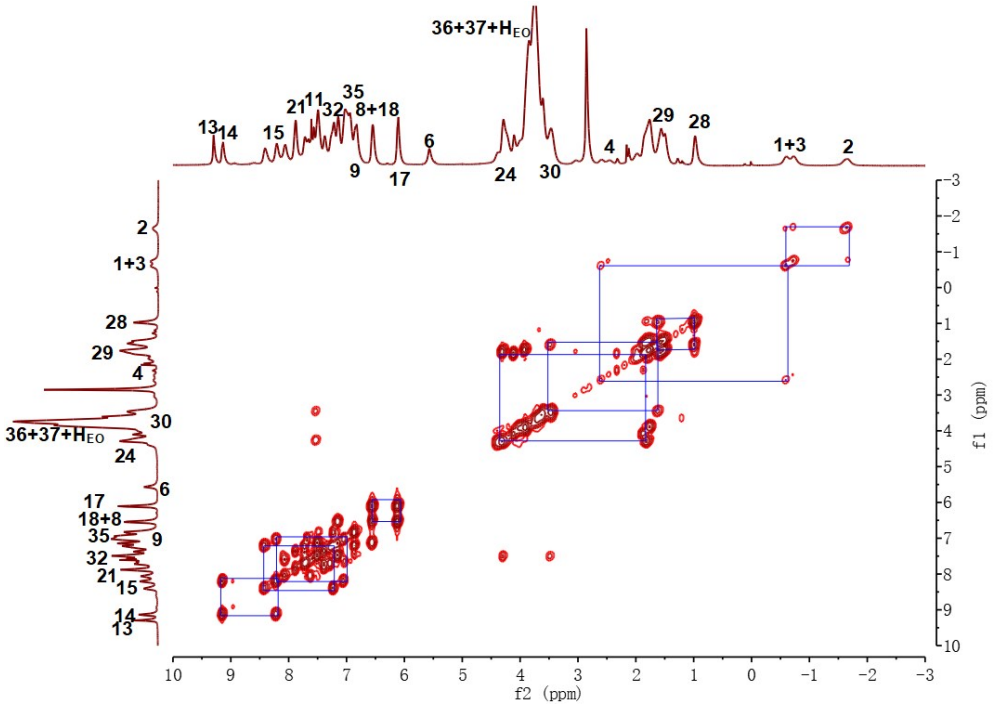


Fig. S10 ^{1}H-^{1}H COSY NMR spectrum (400 MHz, $CDCl_3$-CD_3COCD_3 = 3/1, v/v, 293 K, 30mM) of M1+M2+M3+M4+Zn(OTf)$_2$. The strong correlations between the protons H_1 and H_2 and between H_3 and H_4 on M1 were observed, the correlations between H_{28} and H_{29} and between H_{29} and H_{30} on M4 were also observed at the same time. By means of the ^{1}H–^{1}H COSY experiment, the complex ^{1}H NMR spectrum of M1+M2+M3+M4+Zn(OTf)$_2$ was identified.

3. Concentration-dependent ^{1}H NMR spectra

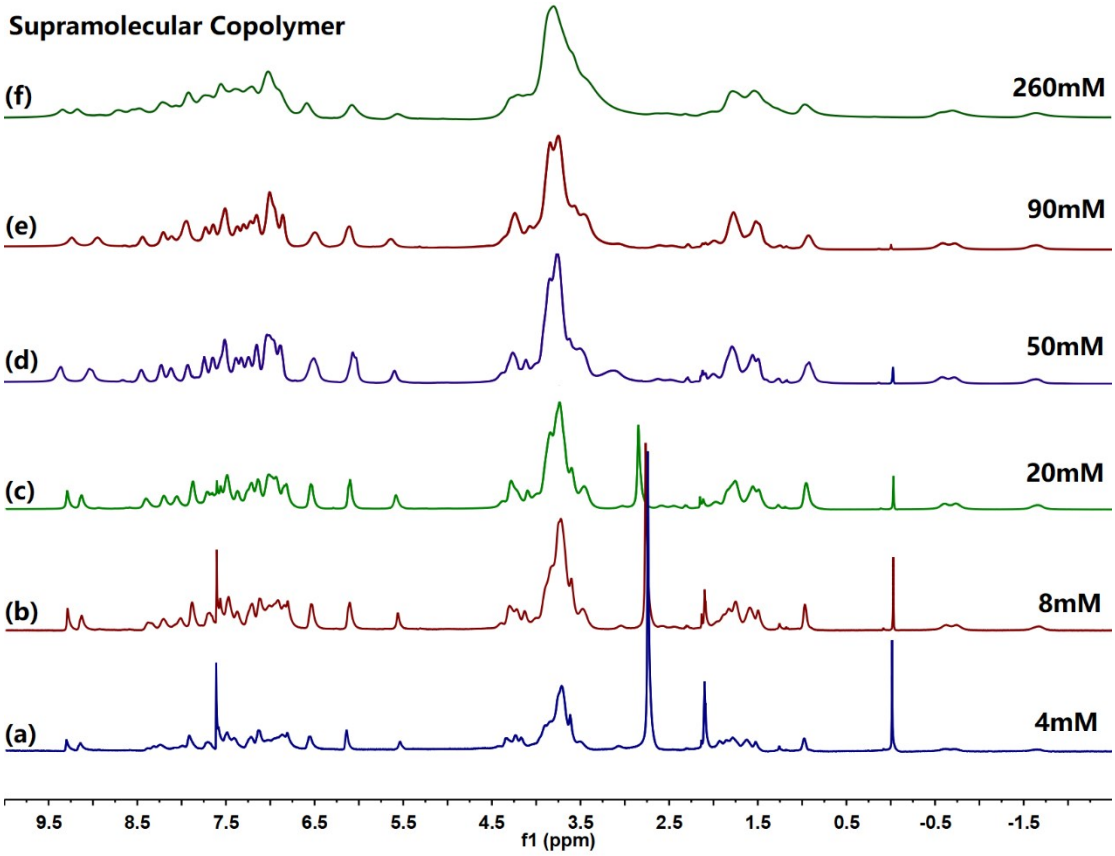


Fig. S11 ^{1}H NMR spectra (400 MHz, $CDCl_3$-CD_3COCD_3 = 3/1, v/v, 298 K) of M1+M2+M3+M4+$Zn(OTf)_2$ at different concentrations (a) 4 mM, (b) 8 mM, (c) 20 mM, (d) 50 mM, (e) 90 mM, (f) 260 mM.

4. 2D DOSY NMR spectrum

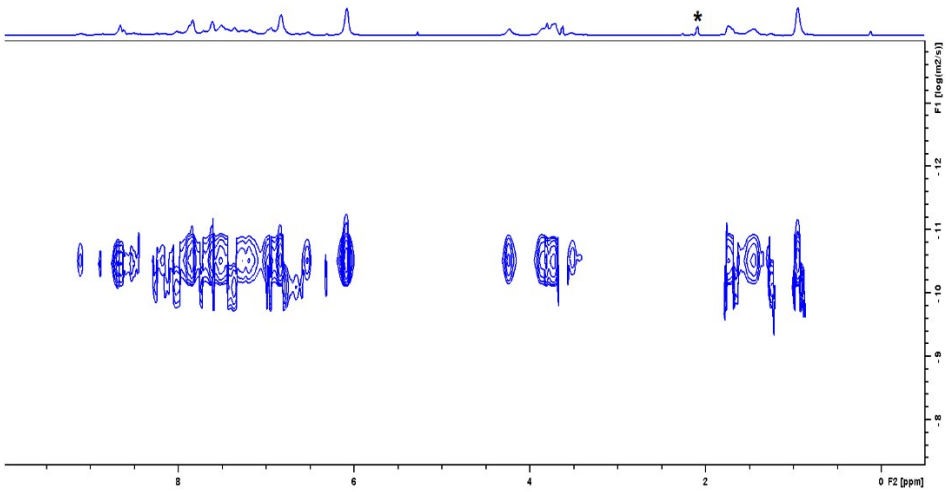


Fig. S12 Representative DOSY NMR spectrum (600 MHz, $CDCl_3$-CD_3COCD_3 = 3/1, v/v, 293 K) of M1+M2+M3+M4+$Zn(OTf)_2$, the concentration of M1 is 130 mM.

5. The discussion of binding constants

(1) tpy-Zn^{2+}-tay binding constant

To determine the association constant tpy-Zn^{2+}-tay, UV-vis titration experiment (Job plot method) was performed according to the reported method.[S1] Model compounds **1** and **2** were chosen as the ligands. The samples were prepared so that the total molar concentration of ligands ($\frac{[1]+[2]}{2}$) and zinc ion was 2×10^{-5}M in each sample: only the ratios of zinc ion to ligands were altered. The absorbance intensity at 410 nm was plotted (Fig. S13) against the mole fraction of Zn^{2+}. The Job plot indicates a 1:1:1 binding among Zn^{2+}, 1 and 2.

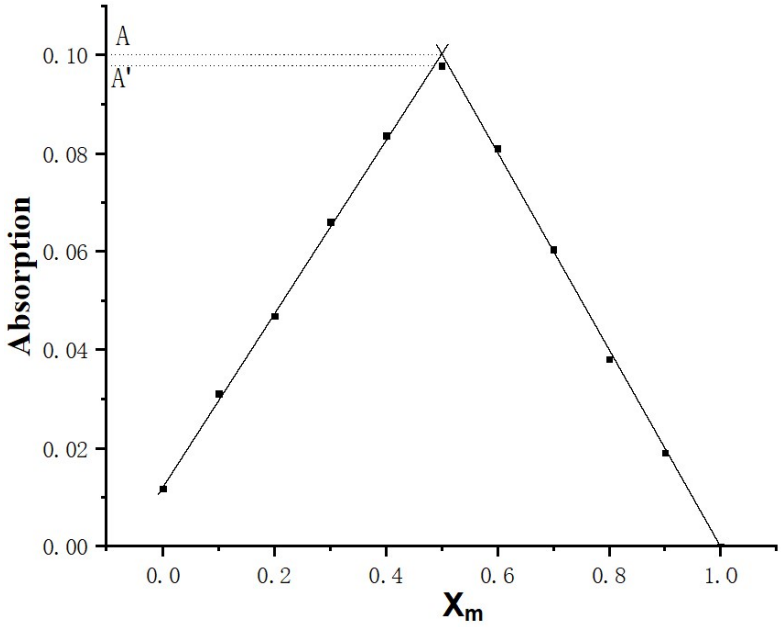


Fig. S13 Job plot of the complex formed among zinc ion, 1 (ligand) and 2 (ligand) showing a 1:1:1 stoichiometry by plotting the absorbance intensity at 410 nm against the mole fraction of zinc ion. Concentration: **[1]=[2]**, $\frac{[1]+[2]}{2}$ + $[Zn(OTf)_2]$ = 20μM.

Furthermore, the data of job plot were divided into two groups around X_m= 0.5. When $X_m \leq$ 0.5, the fitting equation is A = 0.1776X_m + 0.01311. When $X_m \geq$ 0.5, the fitting equation is A = -0.20397X_m + 0.20349. The intersection point of the two fitting curves is taken (X_m=0.4982, A=0.1023), and the experimental value is X_m=0.5, A'= 0.0999. The degree of dissociation of complex [Zn**12**](OTf)$_2$ was calculated from **Eq. 1**. According to the formula,[S5] the dissociation degree(α) of complex [Zn**12**](OTf)$_2$ was calculated to be 0.023.

$$\alpha = (A - A')/A, \textbf{ (Eq. 1)}$$

The binding constant *K* was then calculated to be 8.1×10^{14} M^{-1} based on **Eq. 2**.

$$[Zn\mathbf{12}](OTf)_2 \rightleftharpoons \mathbf{1} + \mathbf{2} + Zn(OTf)_2$$

total concentration	C	0	0	0	
equilibrium concentration	C(1-α)		Cα	Cα	Cα

$$\boldsymbol{K} = \frac{[Zn12](OTf)_2}{[1]\,[2]\,[Zn(OTf)_2]} = \frac{C(1-\alpha)}{[C\alpha]^3} \quad \textbf{(Eq.2)}$$

Where C is the total concentration of the complex [Zn**12**](OTf)$_2$ and α is the degree of dissociation of complex [Zn**12**](OTf)$_2$ when X_m value is 0.5, with the hypothesis that the ligands and zinc ion only form the complex [Zn**12**](OTf)$_2$. The C is 1×10^{-5} M and the α is 0.023 when X_m is 0.5.

(2) B21C7-SEA binding constant:

Because B21C7-SEA is a slow exchange interaction, we used model compounds 5 and 6 to determine the binding constant K_a of the B21C7-SEA according to ^{1}H NMR single point method.[S2] It could be calculated from integrations of complexed and uncomplexed peaks in ^{1}H NMR spectrum. The *K*a value was determined at 6.00 mM host and guest in $CDCl_3$-CD_3COCD_3(3/1, v/v) solution. Using the reference method,[S2] *K*a {[5•6]/[5][6] } = [(1.62/2.62) × 6 × 10^{-3}]/[(1-1.62/2.62) × 6 × 10^{-3}]^2 =706 ± 56 M^{-1} in chloroform/acetone solution(3/1, v/v).

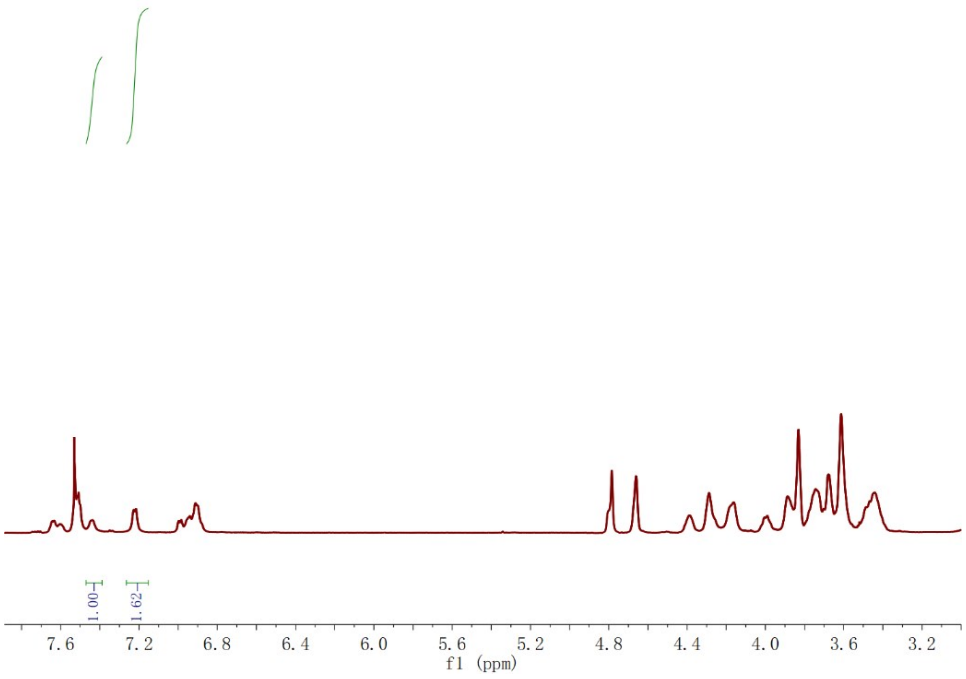


Fig. S14 Partial ^{1}H NMR spectrum (400 MHz, $CDCl_3/CD_3COCD_3$ = 3/1, v/v, 298 K) of 6.00 mM 5 and 6.

(3) P5-TPN binding constant

P5-TPN binding interaction is a slow exchange interaction, the binding constant was referred by literature value [S3]: K is equal to $(1.2 \pm 0.2) \times 10^4$ M^{-1} in $CDCl_3$-CD_3COCD_3.

6. Calculated value of maximum polymerization degree n_{max}.

For the M1+M2+M3+M4+$Zn(OTf)_2$ system, the maximum possible polymerization degree (n_{max}) could be estimated using a reported method by Gibson and coworkers.[S4a] Using the Carothers equation [S4b] and assuming that the same average association constant holds for each successive step (isodesmic), the maximum possible degree of polymerization(n_{max}) is related to the equilibrium constant K and the initial monomers concentration. It can be easily deduced as follows:

$$n_{max} = (2K\,[Host]_0)^{1/2},$$

where $[Host]_0 = [M2]$.[S4a]

The degree of polymerization (n_{max}) for M1+M2+M3+M4+$Zn(OTf)_2$ system at a concentration of 260 mM (260 mM M1 + 260 mM M2 + 130mM M3+ 130mM M4 +260mM $Zn(OTf)_2$) was calculated to be 19.2, with the hypothesis that the M2•Zn^{2+}•M1•M3 dissociation was negligible in the solution because the association constant of P5-TPN and tpy-Zn^{2+}-tay is much larger than that of B21C7-SEA. Thus, the repeat units of in the copolymer $[M4•M2•Zn^{2+}•M1•M3•M1•Zn^{2+}•M2]_n$ are about 19.2, and the molecular weight of supramolecular copolymer SCP is about 19.2*(6280 Da)=120.6 kDa.

7. Stimuli-responsiveness study by adding/removing K^+ or adding butanedinitrile

Because B21C7 can capture K^+,[S2] the adding-removing K^+ was expected to realize the reversible disassembly-reassembly of SCP, when adding 1 equiv. KPF_6 to the solution of SCP, the complicated ^1H NMR became relatively simpler (Fig. S15b), the sharp peaks corresponding to the uncomplexed protons H_{28}, H_{30}, and H_{EO} (denoted as H_{28uc}, H_{30uc}, and H_{EOuc}) were observed, indicating the disassembly of SCP. It should be noted that K^+ only destroyed the binding of B21C7-SEA, the host-guest interaction of P5-TPN and metal coordination tpy-Zn^{2+}-tay were not affected by the observation of ^1H NMR ($H_{1c\text{-}4c}$ and $H_{13c\text{-}14c}$ were still observed). After adding another smaller crown ether B18C6 to the solution, the ^1H NMR became complicated again as the B18C6 can capture K^+ tighter (Fig. S15c), suggesting the reformation of SCP. In addition, viscosity measurement also provided important evidence of disassembly-reassembly of SCP. When 1 equiv. KPF_6 was added into the solution of SCP, the specific viscosity of the solution of SCP decreased remarkably (Fig. S16), implying the disassembly of SCP. After adding 1.1 equiv. B18C6 into the solution, the specific viscosity of the solution almost recovered the original value, indicating the reformation of SCP.

On the other hand, the host-guest interaction P5-TPN may also be adjusted by adding a

competitive guest molecule. As shown in Fig. S17, when 1 equiv. butanedinitrile was added into the solution of M1+M2+M3+M4+$Zn(OTf)_2$, the complexed protons $H_{1\text{-}4}$ disappeared, new complexed proton H_{ac} was observed in the highfield region (-1.3 ppm), indicating TPN moiety inside the P5 cavity was replaced by the competitive butanedinitrile and the SCP disassembled into low molecular weight species. From the observation of ^1H NMR, the addition of butanedinitrile only destroyed the host-guest interaction of P5-TPN and did not affect the binding of B21C7-SEA and tpy-Zn^{2+}-tay.

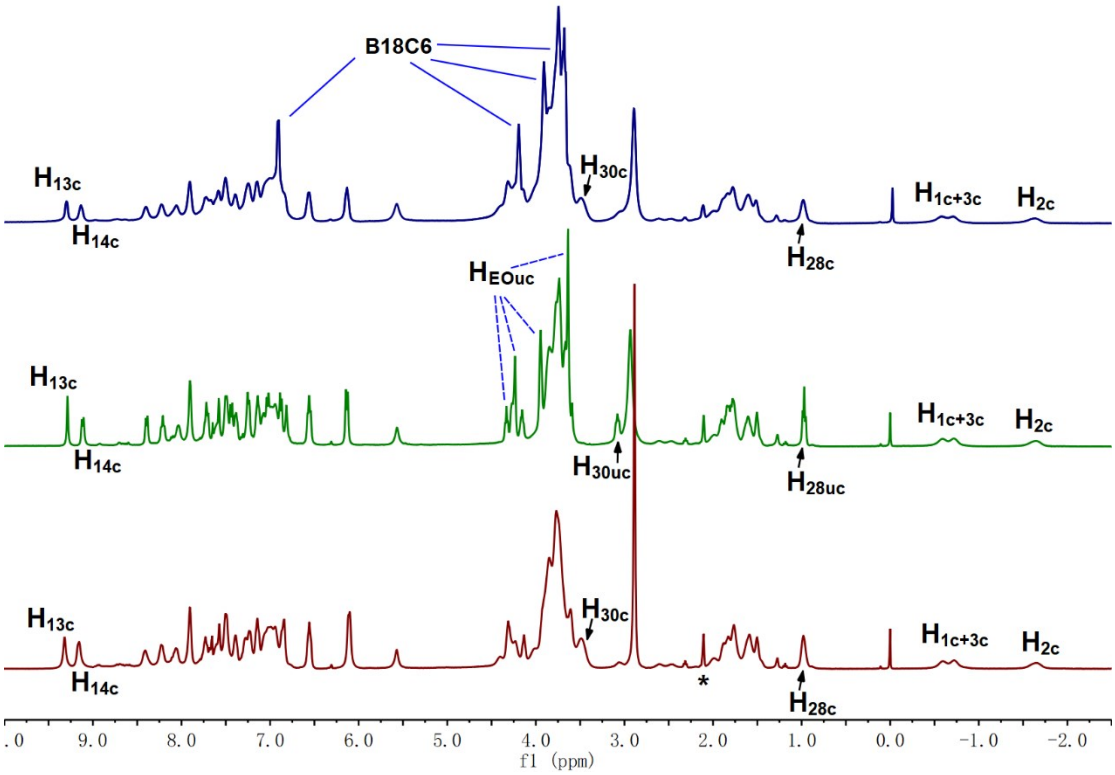


Fig. S15 ^1H NMR spectra (400 MHz, $CDCl_3$-CD_3COCD_3= 3/1, v/v, 298 K, 30 mM) of (a) M1+M2+M3+M4+$Zn(OTf)_2$, (b) after the addition of 1 equiv. KPF_6, and (c) after the addition of 1.1 equiv. B18C6. Peaks of complexed monomers and uncomplexed monomers were designated as c and uc, respectively.

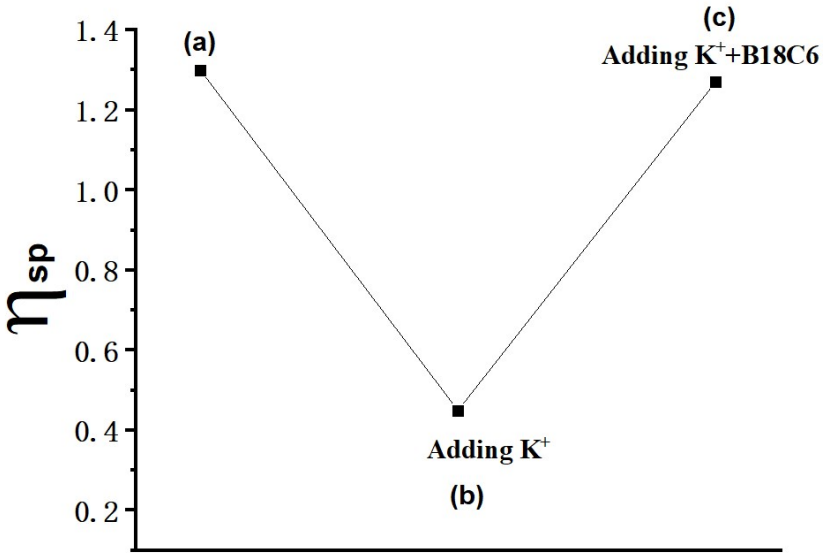


Fig. S16 The specific viscosity ($CHCl_3$-CH_3COCH_3= 3/1, v/v, 298 K, 30 mM) of (a) M1+M2+M3+M4+$Zn(OTf)_2$, (b) after the addition of 1 equiv. KPF_6, and (c) after the addition of 1.1 equiv. B18C6.

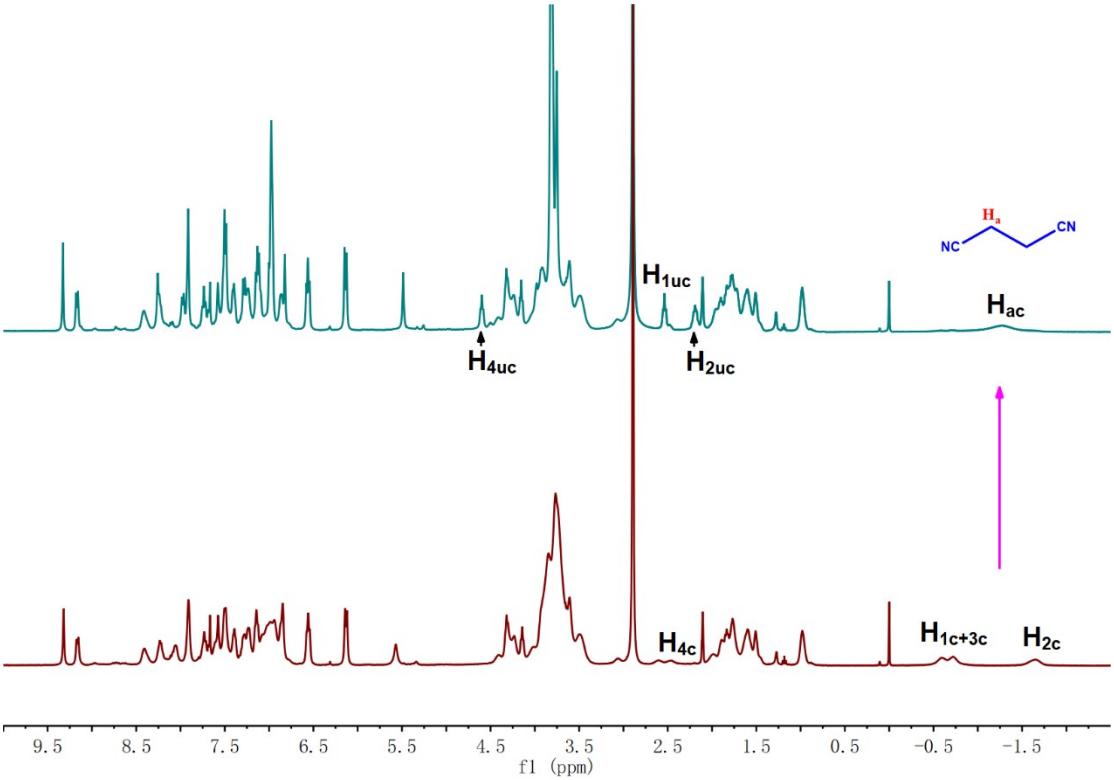


Fig. S17 ^1H NMR spectra (400 MHz, $CDCl_3$-CD_3COCD_3= 3/1, v/v, 298 K, 20 mM) of (a) M1+M2+M3+M4+$Zn(OTf)_2$, (b) after the addition of 1 equiv. butanedinitrile. Peaks of complexed monomers and uncomplexed monomers were designated as c and uc, respectively.

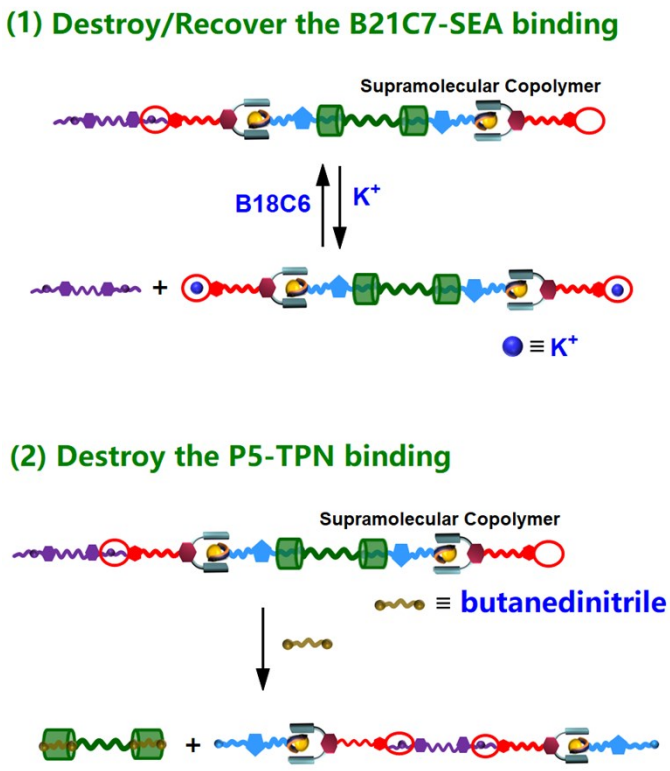


Fig. S18 Graphical representation of stimuli-responsiveness by adding/removing K^+ or adding butanedinitrile.

8. Fluorescence emission spectra

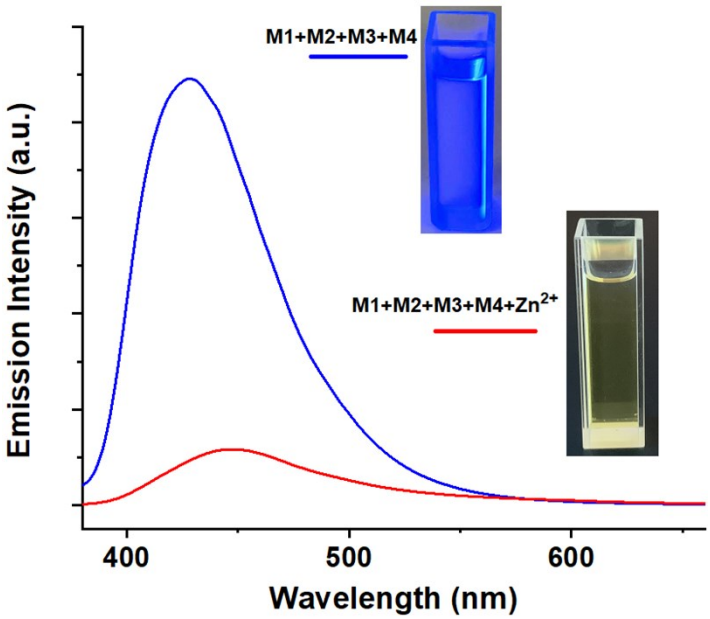
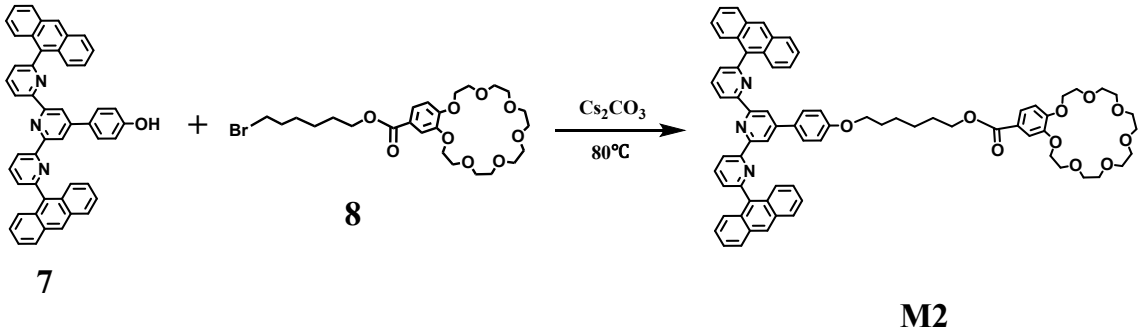


Fig. S19 Fluorescence emission spectra of the M1+M2+M3+M4 and M1+M2+M3+M4+$Zn(OTf)_2$ upon an excitation at 320 nm in $CHCl_3$-CH_3COCH_3 (v/v = 3/1, 0.1 mM). Inset: visual fluorescence emission images of M1+M2+M3+M4 and M1+M2+M3+M4+$Zn(OTf)_2$ using 365 nm UV lamp irradiation.

9. Synthesis of monomers

Synthesis of monomer M2



7 8 M2

Scheme S1. Synthesis of the monomer **M2**.

In a 250 mL round–bottom flask, compound 7 (4.00g, 5.9mmol), CS_2CO_3 (5.82 g, 18mmol), compound 8 (3.32 g, 5.9mmol), and DMF (150mL) were added. The reaction mixture was stirred at 80 ℃ for 14 hours. After the solid was filtered off, the solvent was removed under reduced pressure. The residue was dissolved in CH_2Cl_2 (150 mL) and washed twice with H_2O (200 mL). The organic phase was dried over anhydrous Na_2SO_4 and evaporated to afford the crude product, which was purified by flash column chromatography (dichloromethane/methanol=70:1). The fractions containing the product were combined and concentrated under vacuum to give M2 (4.10 g, 60 %) as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 8.95(d, J = 10.4 Hz, 2H), 8.68(s, 2H), 8.59 (s, 2H), 8.16 (t, J = 10.2 Hz, 2H), 8.09 (d, J = 11.2 Hz, 4H), 7.77 (d, J = 11.6 Hz, 4H), 7.58-7.64 (m, 5H), 7.47-7.53 (m, 5H), 7.36-7.43 (m, 4H), 6.84 (d, J = 11.2 Hz, 1H), 6.75 (d, J = 11.6Hz, 2H), 4.26 (t, J = 8.6 Hz, 2H), 4.16-4.21 (m, 4H), 3.89-3.97 (m, 4H), 3.85 (t, J = 8.8 Hz, 2H), 3.76-3.83 (m, 4H), 3.70-3.75 (m, 4H), 3.62-3.69 (m, 8H), 1.72-1.79 (m, 4H), 1.41-1.47 (m, 4H). ^{13}C NMR(100MHz, $CDCl_3$): δ (ppm) = 166.5, 159.9, 157.7, 156.6, 155.9, 152.9, 150.1, 148.4, 137.2, 135.6, 131.6, 130.3, 128.6, 127.6, 126.4, 125.9, 125.3, 123.9, 123.3, 120.2, 119.1, 114.7, 112.3, 71.4, 71.3, 71.1, 71.0, 70.7, 69.8, 69.6, 69.4, 69.2, 67.9, 64.9, 29.1, 28.8, 25.9, 25.8. High-resolution MALDI-TOF-MS ($C_{74}H_{69}N_3O_{10}$): m/z calcd for $[M]^+$ =1159.4983, found =1159.4958, error 2.1 ppm.

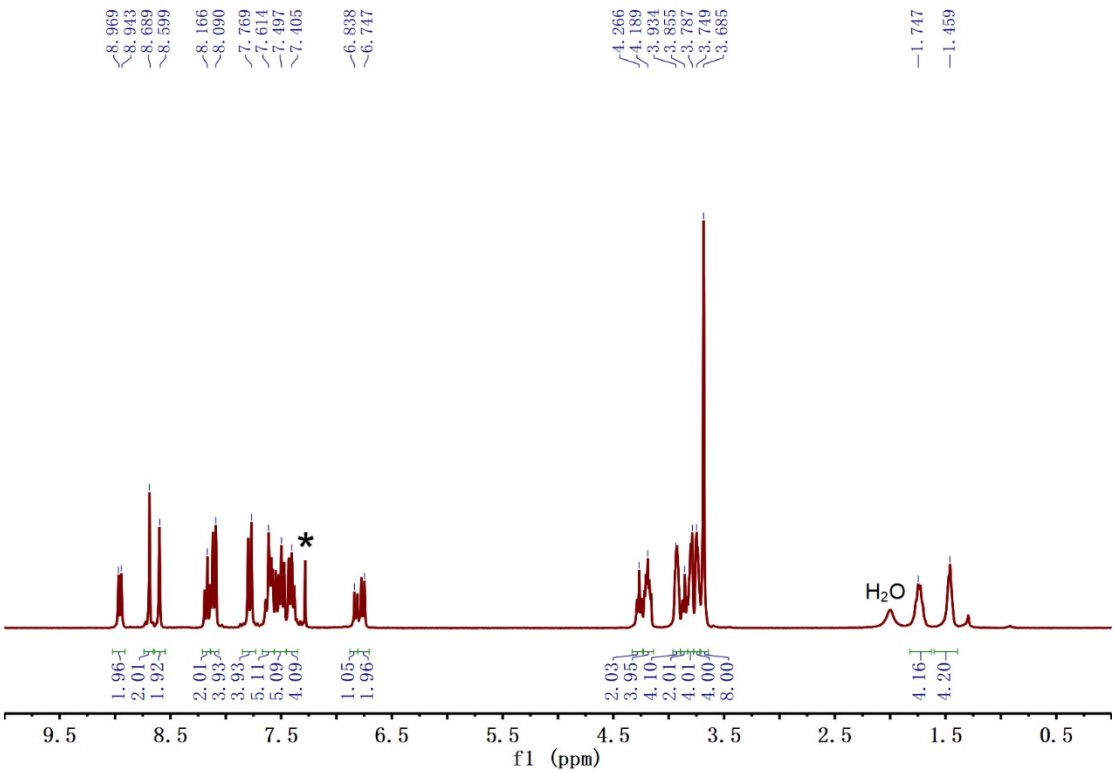


Fig. S20 ^{1}H NMR spectrum (400 MHz, $CDCl_3$, room temperature) of monomer **M2.**

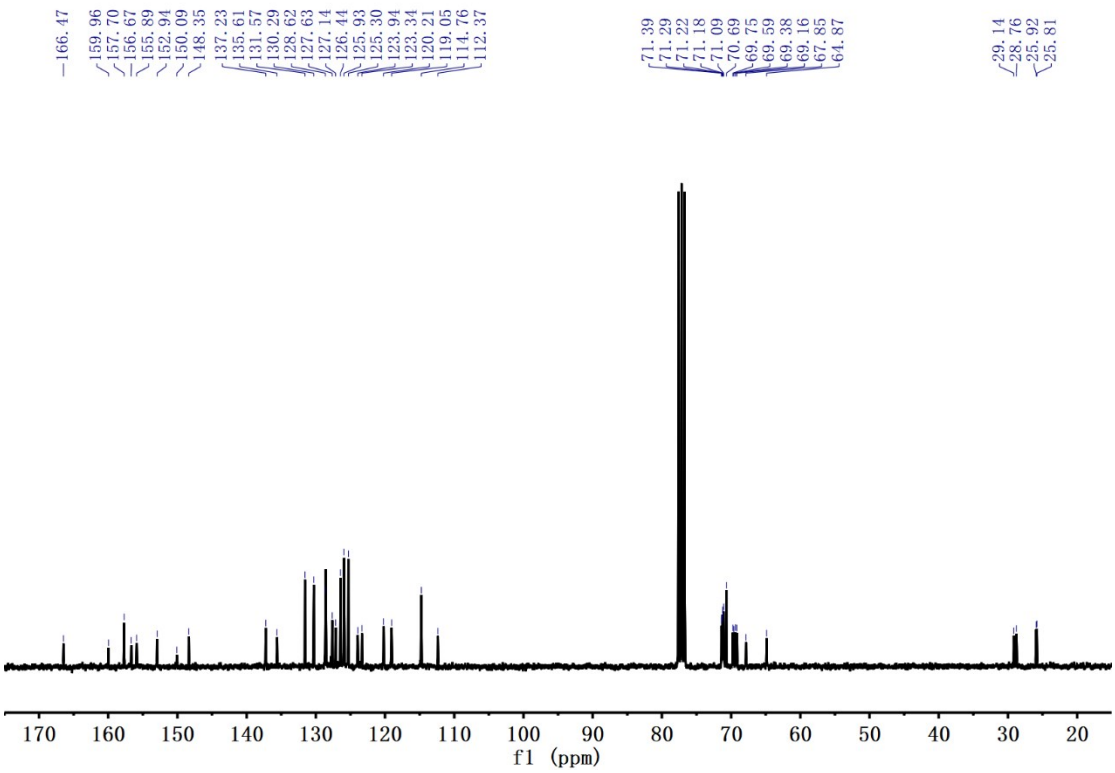


Fig. S21 ^{13}C NMR spectrum (100 MHz, $CDCl_3$, room temperature) of monomer **M2.**

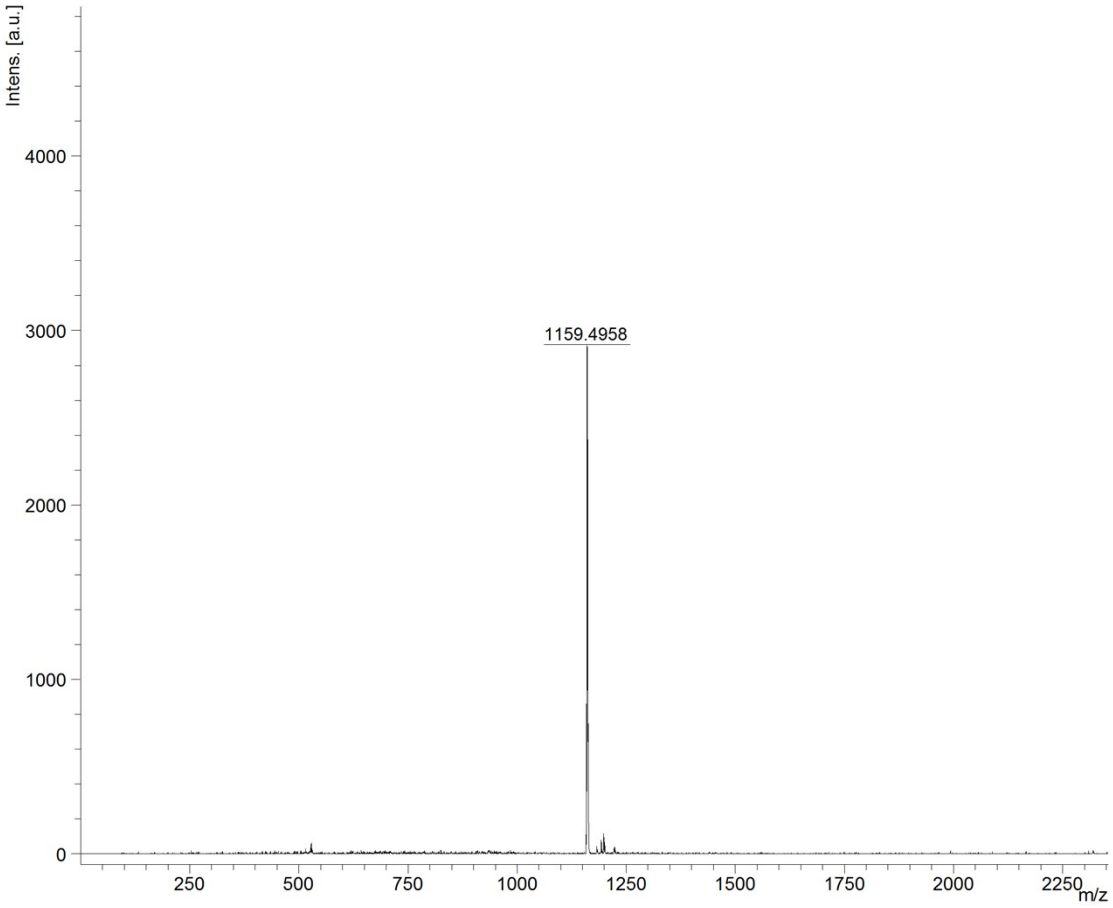
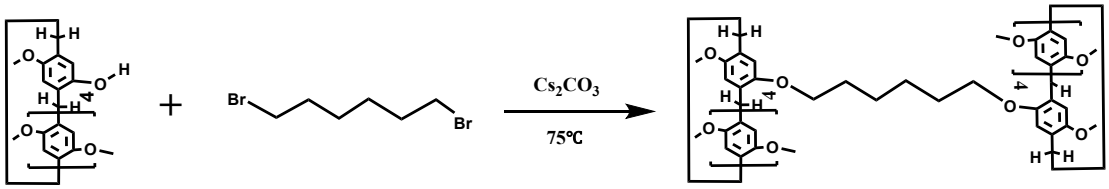


Fig. S22 High-resolution MALDI-TOF-MS of monomer **M2**.

Synthesis of monomer M3



9 **M3**

Scheme S2. Synthesis of the monomer **M3**.

A solution of compound 9 (2.00g, 2.7mmol), 1.6-dibromohexane (0.33g, 1.35mmol), Cs_2CO_3 (2.64g, 8.1mmol) in DMF (120 mL) was stirred for 14 h at 75 ℃. After the reaction mixture was cooled to ambient temperature, the solvent was evaporated under reduced pressure and the residue was partitioned between dichloromethane (70 mL) and water (70 mL). The aqueous layer was further washed with dichloromethane (2 × 30 mL). The organic phases were combined and dried over anhydrous Na_2SO_4. After the solvent was removed, the resulting residue was subjected to column chromatography (CH_2Cl_2 as eluent), to give M3 (1.25 g, 58 %) as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): ppm = 6.79-6.73 (m, 20H), 3.87 (t, *J* = 6.8 Hz, 4H), 3.72-3.79 (m, 20H), 3.61-3.69 (m, 54H), 1.82-1.87 (m, 4H), 1.60-1.66 (m, 4H). ^{13}C NMR (100MHz, $CDCl_3$): δ

(ppm) =150.9, 150.8, 128.3, 128.2, 115.1, 114.2, 114.1, 68.5, 55.9, 30.0, 29.4, 26.4. HR-ESI-MS ($C_{94}H_{106}O_{20}$): m/z calcd for $[M]^+$ =1555.7311, found =1555.7302, error 0.6 ppm.

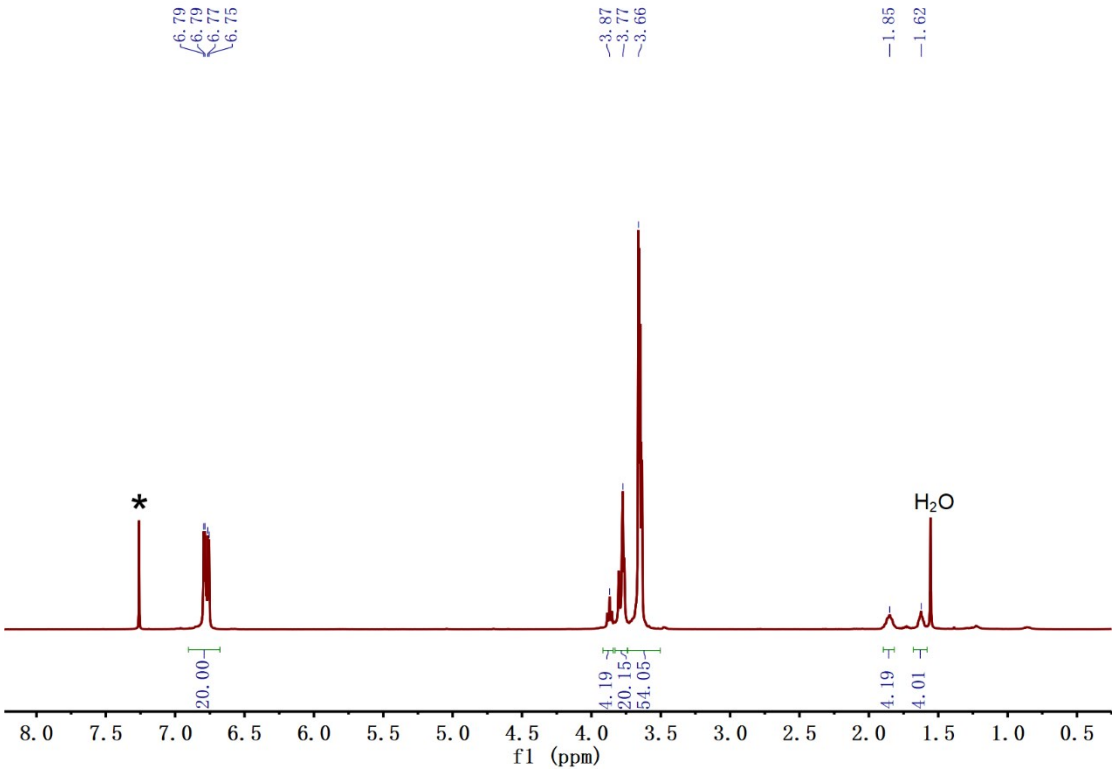


Fig. S23 ^{1}H NMR spectrum (400 MHz, $CDCl_3$, room temperature) of compound **M3**.

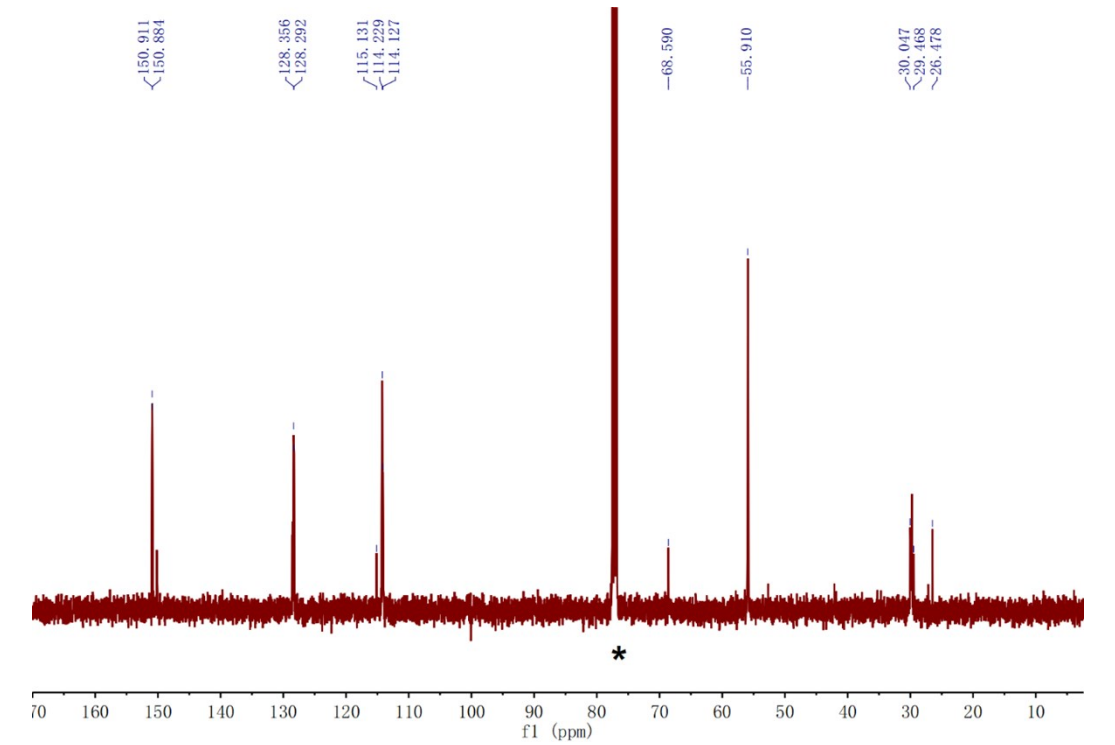


Fig. S24 ^{13}C NMR spectrum (100 MHz, $CDCl_3$, room temperature) of compound **M3.**

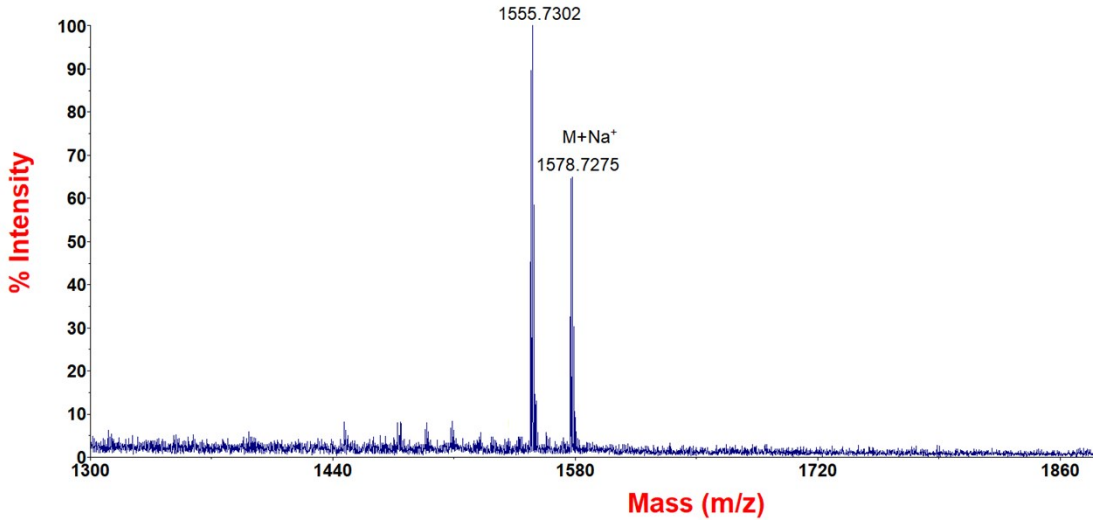


Fig. S25 High-resolution electrospray ionization mass spectrum of compound **M3**.

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