Electronic Supplementary Material (ESI) for Polymer Chemistry.

Supplementary Information for:

Helicity control of π-conjugated foldamers containing D-glucose-based single enantiomeric units as a chiral source

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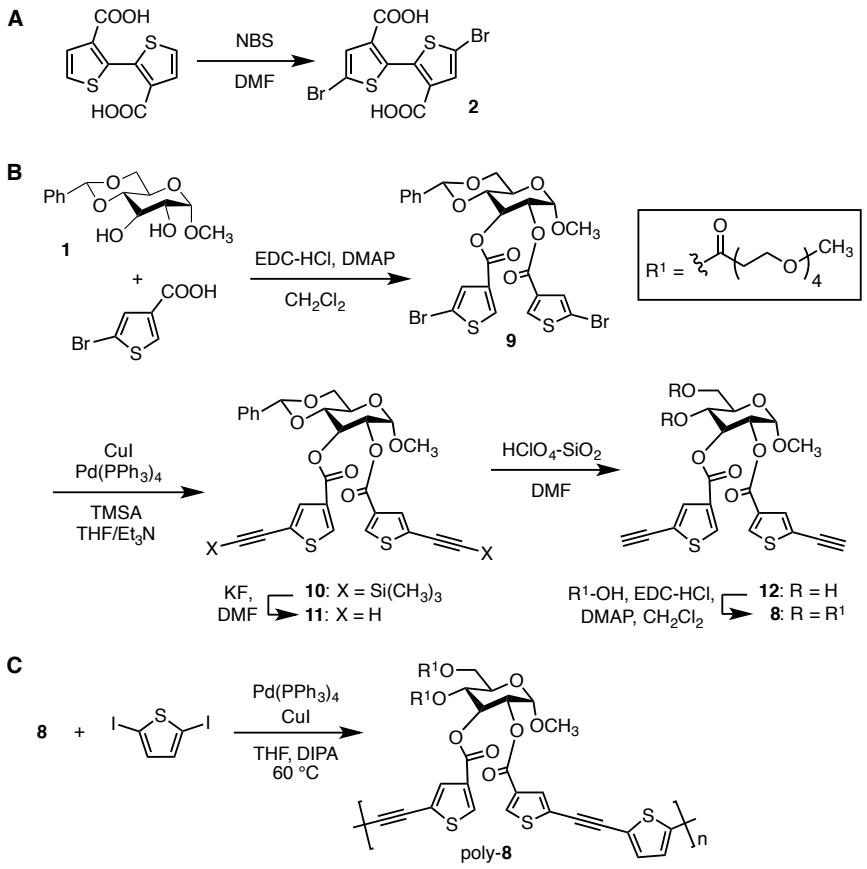
Table of content:

1. Synthesis

2,2′-Bithiophene-5,5′-dibromo-3,3′-dicarboxylic acid (**2**), an optically active diethynyl compound (**8**) and a model polymer (poly-**8**) were synthesized according to Scheme S1.



Scheme S1 Synthesis of **2** (A), **8** (B) and poly-**8** (C).

2. To a solution of 2,2′-bithiophene-3,3′-dicarboxylic acid (0.80 g, 3.1 mmol) in DMF (32 mL) was added NBS (3.36 g, 18.9 mmol) at 0 °C under nitrogen atmosphere. After stirring at room temperature for 72 h, The reaction system was diluted with ethyl acetate, and the solution was washed with saturated sodium sulfite aqueous solution, 1 N HCl aqueous solution and water, dried over Na_2SO_4 and concentrated. The target compound (1.24 g, 97%) was obtained as a pale yellow solid and was used for the next step without further purification. ^{1}H NMR (500 MHz, DMSO-d_6, rt): δ 7.51 (s, 2H, ArH).

9. To a solution of **1** (0.63 g, 2.2 mmol), 5-bromothiophene-3-carboxylic acid (0.95 g, 4.6 mmol) and DMAP (0.82 g, 6.7 mmol) in dichloromethane (100 mL) was added EDC-HCl (1.28 g, 6.7 mmol) at 0 °C under nitrogen atmosphere. After stirring at room temperature for 12 h, the reaction system was diluted with dichloromethane and the solution was washed with 1 N HCl aqueous solution and water, and then dried over Na_2SO_4. After filtration, the solvent was removed by evaporation and the crude product was purified by silica gel chromatography using dichloromethane as the eluent to give the desired compoud as a white solid (1.40 g, 95% yield). ^{1}H NMR (500 MHz, $CDCl_3$, rt): δ 8.00 (s, 1H, ArH), 7.96 (s, 1H, ArH), 7.40-7.46 (m, 4H, ArH), 7.32-7.35 (m, 3H, ArH), 5.87 (t, J = 9.2 Hz, 1H, CH), 5.55 (s, 1H, CH), 5.07-5.11 (m, 2H, CH), 4.36 (dd, J = 10.0, 5.5 Hz, 1H), 4.03 (td, J = 10.0, 4.8 Hz, 1H, CH), 3.80-3.87 (m, 2H, CH_2), 3.44 (s, 3H, OCH_3).

10. The title compound was prepared from **9** in the same way as (a*R*)-**4** and obtained in 82% yield as a white solid. ^{1}H NMR (500 MHz, $CDCl_3$, rt): δ 7.98 (s, 1H, ArH), 7.94 (s, 1H, ArH), 7.55 (d, J = 6.9 Hz, 2H, ArH), 7.40-7.46 (m, 2H, ArH), 7.31-7.36 (m, 3H, ArH), 5.89 (t, J = 11.5 Hz, 1H, CH), 5.54 (s, 1H, CH), 5.07-5.12 (m, 2H, CH), 4.36 (dd, J = 10.6, 3.7 Hz, 1H, CH), 4.00-4.06 (m, 1H, CH), 3.83 (q, J = 10.5 Hz, 2H, CH_2), 3.43 (s, 3H, OCH_3), 0.24 (s, 9H, TMS), 0.23 (s, 9H, TMS).

11. The title compound was prepared from **10** in the same way as (a*R*)-**5** and obtained in 71% yield as a white solid. ^{1}H NMR (500 MHz, $CDCl_3$, rt): δ 8.01 (s, 1H, ArH), 7.97 (s, 1H, ArH), 7.58-7.61 (m, 2H, ArH), 7.40-7.46 (m, 2H, ArH), 7.32-7.36 (m, 3H, ArH), 5.89 (t, J = 9.7 Hz, 1H, CH), 5.55 (s, 1H, CH), 5.09-5.11 (m, 2H, CH), 4.36 (dd, J = 10.9, 4.0 Hz, 1H, CH), 4.00-4.06 (m, 1H, CH), 3.81-3.87 (m, 2H, CH_2), 3.44 (s, 3H, OCH_3), 3.35 (s, 1H, C≡CH), 3.32 (s, 1H, C≡CH).

12. The title compound was prepared from **11** in the same way as (a*R*)-**6** and obtained in 95% yield as a white solid. ^{1}H NMR (500 MHz, $CDCl_3$, rt): δ 8.00 (d, J = 4.0 Hz, 2H, ArH), 7.59 (s, 2H, ArH), 5.59 (t, J = 9.5 Hz, 1H, CH), 5.09 (dd, J = 10.3, 3.4 Hz, 1H, CH), 5.06 (d, J = 4.0 Hz, 1H, CH), 3.89-3.97 (m, 3H, CH, CH_2), 3.80-3.85 (m, 1H, CH), 3.43 (s, 3H, OCH_3), 3.35 (s, 2H, C≡CH), 2.87 (d, J = 5.2 Hz, 1H, OH), 1.98 (t, J = 6.6 Hz, 1H, OH).

8. The title compound was prepared from **12** in the same way as (a*R*)-**7** and obtained in 53% yield as a white viscose oil. $[\alpha]^{25}_D$ +141.0 (*c* 0.2, $CHCl_3$). ^{1}H NMR (500 MHz, $CDCl_3$, rt): δ 7.99 (s, 1H, ArH), 7.95 (s, 1H, ArH), 7.58 (s, 1H, ArH), 7.56 (s, 1H, ArH), 5.77 (t, J = 10.0 Hz, 1H, CH), 5.29 (t, J = 10.0 Hz, 1H, CH), 5.12 (d, J = 3.4 Hz, 1H, CH), 5.05 (dd, J = 10.3, 3.4 Hz, 1H, CH), 4.30 (q, J = 5.7 Hz, 1H,

CH), 4.21 (dd, J = 12.3, 2.0 Hz, 1H, CH), 4.06-4.12 (m, 1H, CH), 3.76-3.80 (m, 2H, CH_2), 3.54-3.66 (m, 22H, CH_2), 3.44-3.49 (m, 4H, CH_2), 3.43 (s, 3H, OCH_3), 3.38_2 (s, 3H, OCH_3), 3.37_7 (s, 3H, OCH_3), 3.35 (s, 1H, C≡CH), 3.34 (s, 1H, C≡CH), 2.68 (t, J = 6.6 Hz, 2H, CH_2), 2.45-2.56 (m, 2H, CH_2). ^{13}C NMR (126 MHz, $CDCl_3$, rt): δ 171.26, 170.34, 160.97, 160.91, 135.43, 135.10, 133.35, 133.33, 132.08, 131.94, 123.39, 123.37, 96.95, 82.58, 82.50, 75.80, 75.76, 72.06, 71.96, 70.72, 70.65, 70.63, 70.52, 70.47, 70.37, 68.14, 67.46, 66.51, 66.41, 62.11, 59.17, 55.73, 35.08, 34.91. IR (KBr, cm^{-1}): 2106 (C≡C), 1732 (C=O). HRMS (FAB): m/z calcd for $C_{41}H_{55}O_{18}S_2$ ($M+H^+$), 899.2824; found 899.2841.

Poly-8. Copolymerization of **8** with 2,5-diiodothiophene by Sonogashira–Hagihara cross-coupling was carried out using $Pd(PPh_3)_4$ as a catalyst in a dry Schlenk flask under nitrogen atmosphere in a similar way as reported previously[S1,S2] and the target poly-**8** was obtained in 44% yield as a yellow solid. ^{1}H NMR (500 MHz, $CDCl_3$, 55 °C): δ 8.03 (s, 1H, ArH), 8.00 (s, 1H, ArH), 7.59 (s, 1H, ArH), 7.57 (s, 1H, ArH), 7.14 (s, 2H, ArH), 5.78 (t, J = 9.5 Hz, 1H, CH), 5.27 (t, J = 9.7 Hz, 1H, CH), 5.07-5.11 (m, 2H, CH), 4.22-4.30 (m, 2H, CH_2), 4.10 (d, J = 8.0 Hz, 1H, CH), 3.77 (t, J = 6.3 Hz, 2H, CH_2), 3.51-3.66 (m, 22H, CH_2), 3.44-3.49 (m, 7H, CH_2, OCH_3), 3.37 (s, 3H, OCH_3), 3.35 (s, 3H, OCH_3), 2.66 (t, J = 6.3 Hz, 2H, CH_2), 2.45-2.52 (m, 2H, CH_2). IR (KBr, cm^{-1}): 2196 (C≡C), 1732 (C=O).

2. All-atom molecular dynamics simulation

An all-atom molecular dynamics (MD) simulation was carried out using the Forcite module of the BIOVIA Materials Studio 2018 (Dassault Systèmes BIOVIA, San Diego, CA, USA) on the supercomputer system (PRIMERGY CX2570 M4, Fujitsu, Tokyo, Japan). The MD cell was built by means of usual procedure of the Amorphous Cell module. The MD cell length and angle were (a = 50 Å, b = 50 Å, c = 50 Å) and (α = 90º, β = 90º, γ = 90º), respectively. Here, a single model of (a*R*)-**7** was put in the center of the cell, and the solvent molecules of chloroform were packed in the cell at density of 1.492 g cm^{-3}. Sequentially, the geometry of the MD cell was optimized. Simulation in the NVT ensemble (constant number of atoms, volume and temperature) was conducted at 298 K for 20 ps (time step of 0.2-fs, 100,000 steps) and the NPT ensemble (constant number of atoms, pressure and temperature) was conducted at pressure of 1.013×10^{-4} GPa and at 298 K for 3,000 ps (time step of

1.0-fs, 3,000,000 steps) to equilibrate the MD cell. The Nose thermostat was used to control the temperature. The Berendsen barostat was used to control the pressure. After the equilibration at 298 K, simulation in the NVE ensemble (constant number of atoms, volume and energy) was conducted for 2,000 ps (time step of 1.0-fs, 1,000,000 steps) as the production run. The Universal forcefield was used, and the charges were assigned by the Gasteiger.

3. Molecular mechanics simulation

A molecular mechanics (MM) calculations of a polymer was carried out using the Forcite module of the BIOVIA Materials Studio 2018 on a Windows 10 PC. The model polymer containing acetyl groups at the 4- and 6-positions of glucose units was used for the computational study as a simplified model (see Fig. S8A). The most low-energy conformation was searched by changing a torsion angle between glucose- and thiophen-based monomeric units every 0.5 degree in the range from −179.5 to 180 degree. Before MM simulation using the cvff forcefield, the initial structures of a polymer chain model were generated in the manner of a head-to-tail orientation and a degree of polymerization of 20.

Supporting data

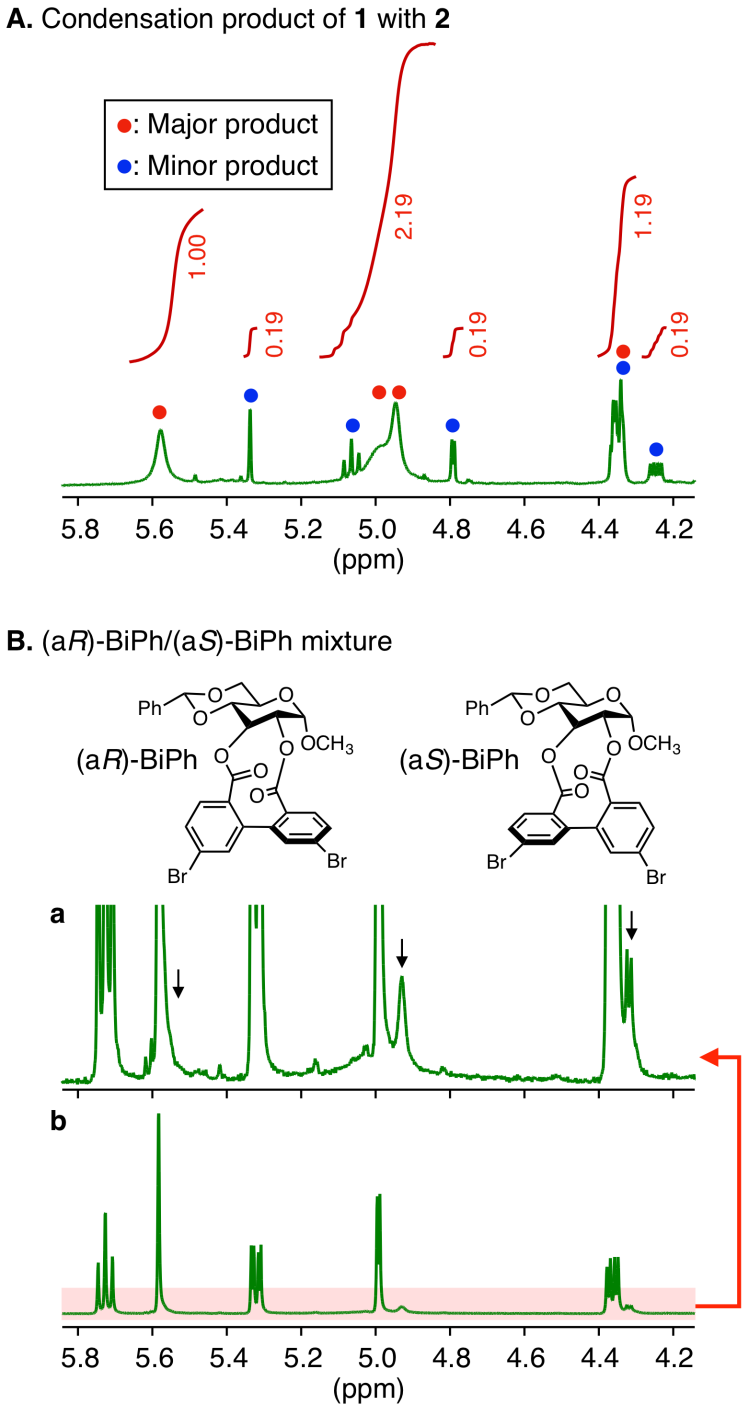


Fig. S1 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectra of the condensation products of **1** with **2** (A) and the previously reported (a*R*)-BiPh/(a*S*)-BiPh mixture (B) in the region of glucose protons.[S1] The enlarged spectrum (a) corresponds to the areas indicated by the red square (b). The peaks indicated by arrows in (a) are derived from the glucose protons of the (a*R*)-BiPh.

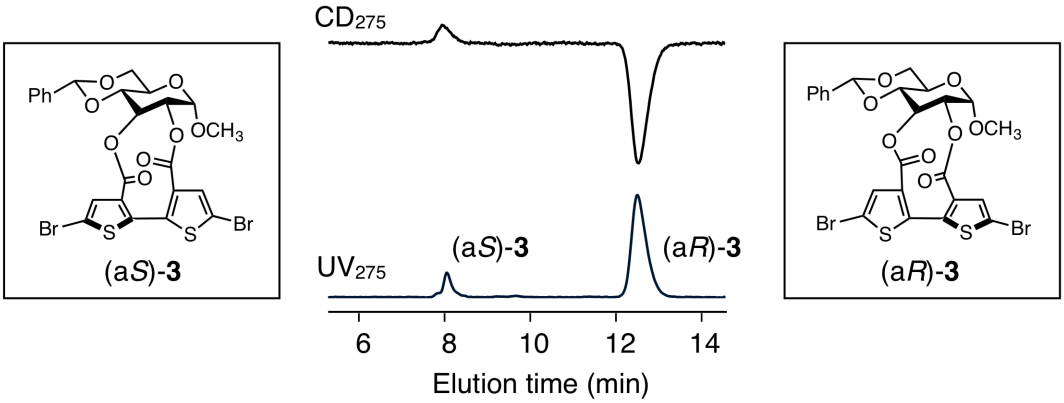


Fig. S2 Chromatograms for the diastereomer separation of **3** on a Chiralpak IA column (25 cm × 0.46 cm (i.d.); eluent, hexane/dichloromethane/ethanol (70/30/1, v/v/v); flow rate, 0.5 mL min^{-1}).

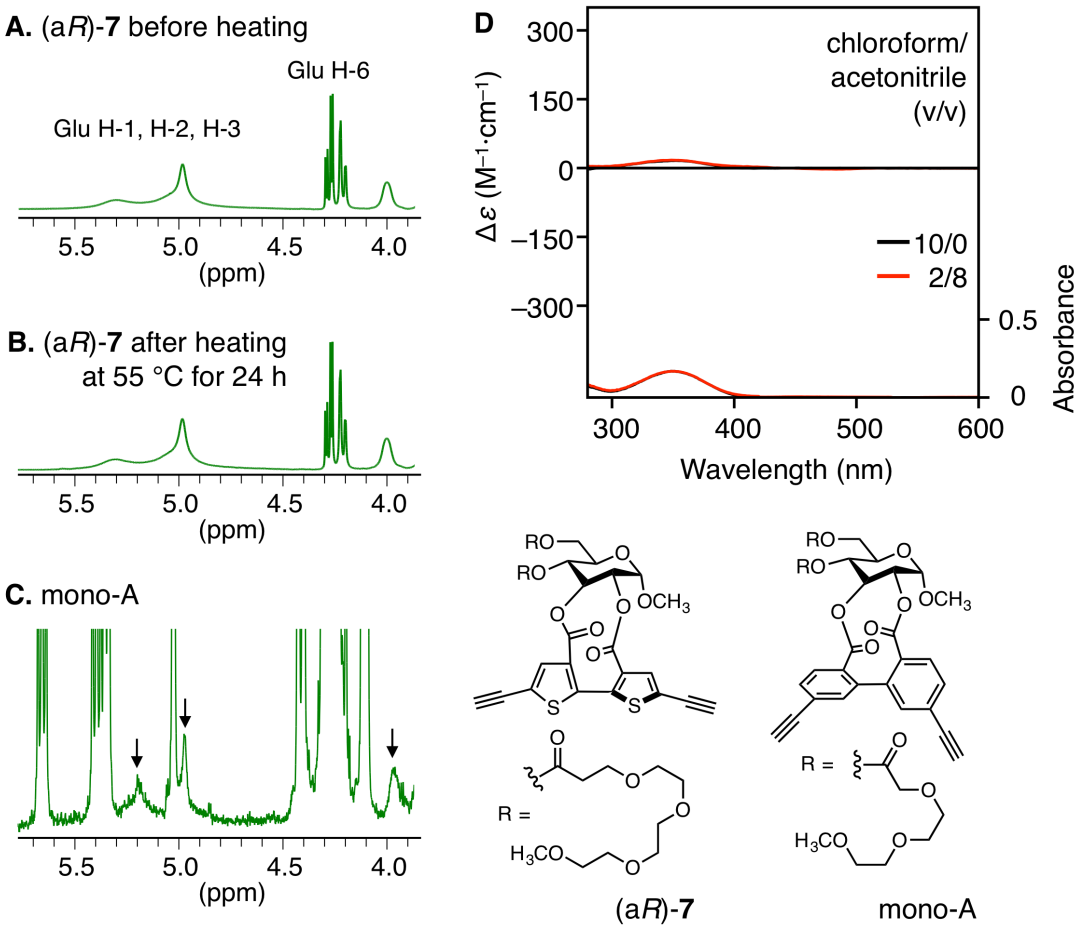


Fig. S3 ^{1}H NMR spectra ($CDCl_3$, 500 MHz, rt) of (a*R*)-**7** in the region of glucose protons before (A) and after (B) thermal treatment at 55 ºC for 24 h. (C) ^{1}H NMR spectrum ($CDCl_3$, 500 MHz, rt) of the previously reported mono-A in the region of glucose protons. The peaks indicated by arrows are derived from the glucose protons of the (a*R*)-isomer. (D) Absorption and CD spectra of (a*R*)-**7** in chloroform and chloroform/acetonitrile (2/8, v/v) at 25 °C. [Glucose unit] = 1.0 × 10^{-4} M.

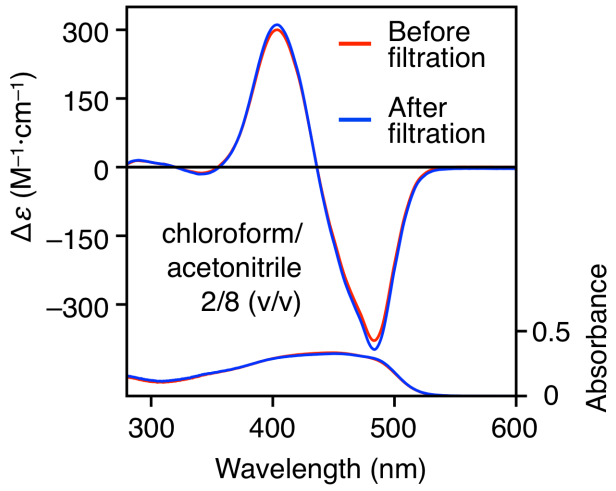


Fig. S4 Absorption and CD spectra of poly-**7** in chloroform/acetonitrile (2/8, v/v) at 25 °C before (red line) and after (blue line) filtration through a membrane filter with a pore size of 0.20 μm. [Glucose unit] = 1.0×10^{-4} M.

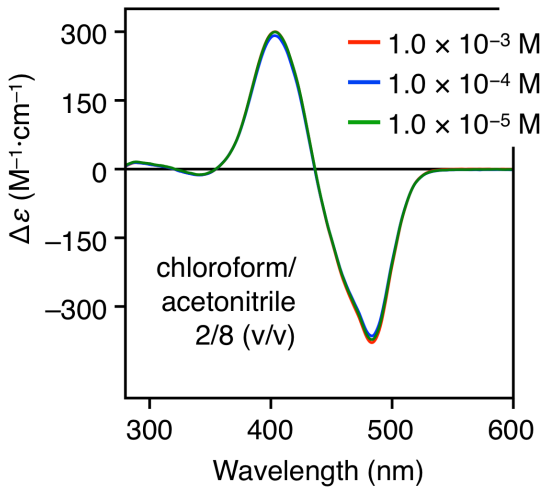


Fig. S5 CD spectra of poly-**7** in chloroform/acetonitrile (2/8, v/v) at 25 °C. The spectra indicated by green, blue and red lines were obtained from the solutions with poly-**7** concentrations of 1.0×10^{-5} M (cell length: 10 mm), 1.0×10^{-4} M (cell length: 1.0 mm) and 1.0×10^{-3} M (cell length: 0.10 mm), respectively.

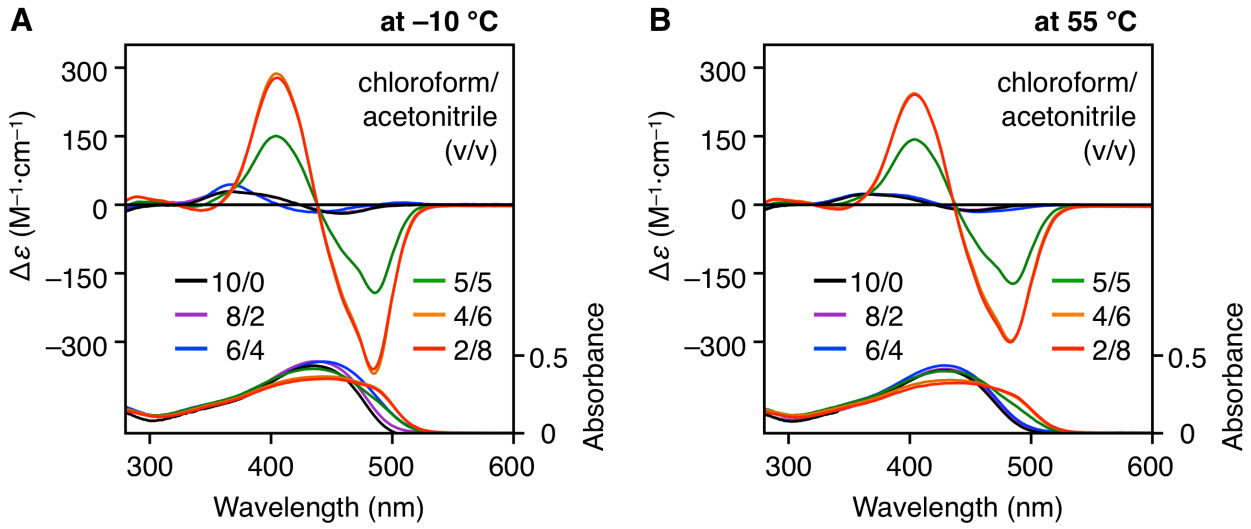


Fig. S6 Absorption and CD spectra of poly-**7** in chloroform/acetonitrile (10/0–2/8, v/v) at −10 °C (A) and 55 °C (B). [Glucose unit] = 1.0×10^{-4} M.

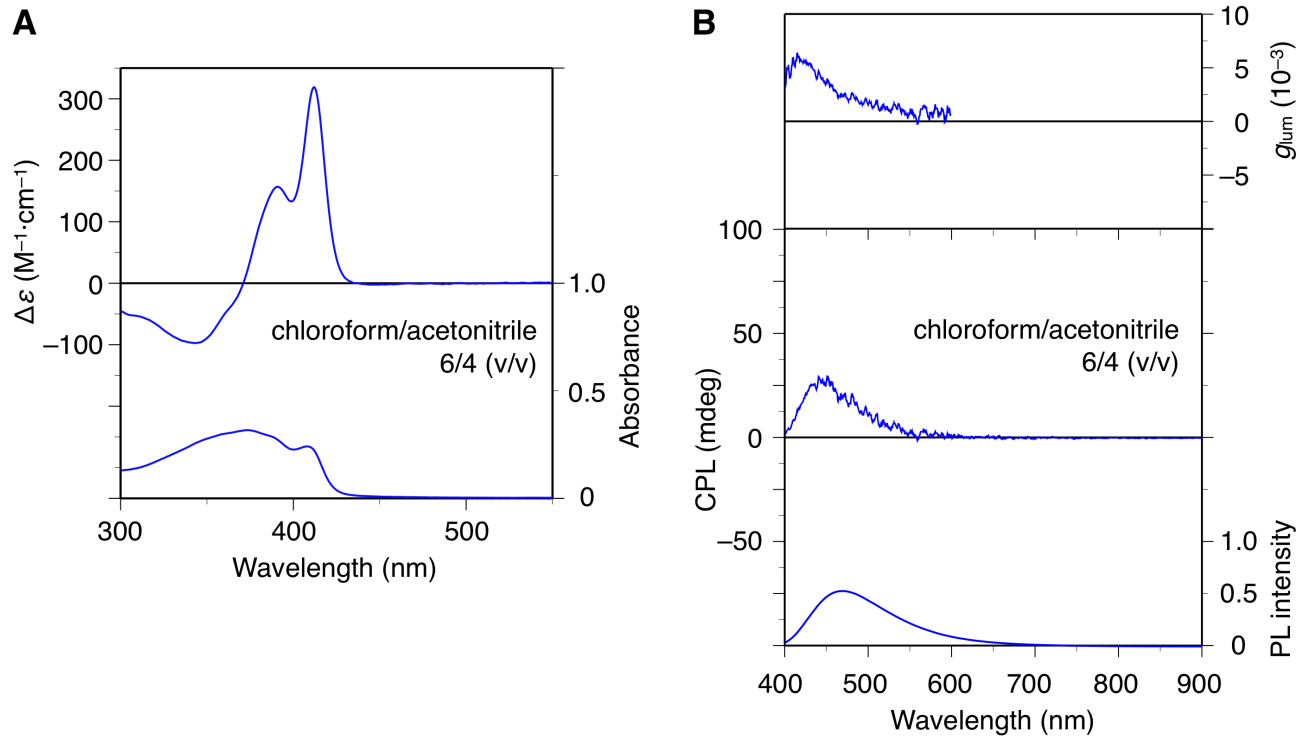


Fig. S7 (A) Absorption and CD spectra of poly-A in chloroform/acetonitrile (6/4, v/v) at 25 °C. [Glucose unit] = 1.0×10^{-4} M. (B) PL (bottom), CPL (middle) and g_{lum} (top) spectra of poly-A in chloroform/acetonitrile (6/4, v/v) at room temperature. λ_{ex} = 292 nm. [Glucose unit] = 1.0×10^{-4} M. (Reproduced with permission from ref S4. Copyright 2017 The Chemical Society of Japan.).

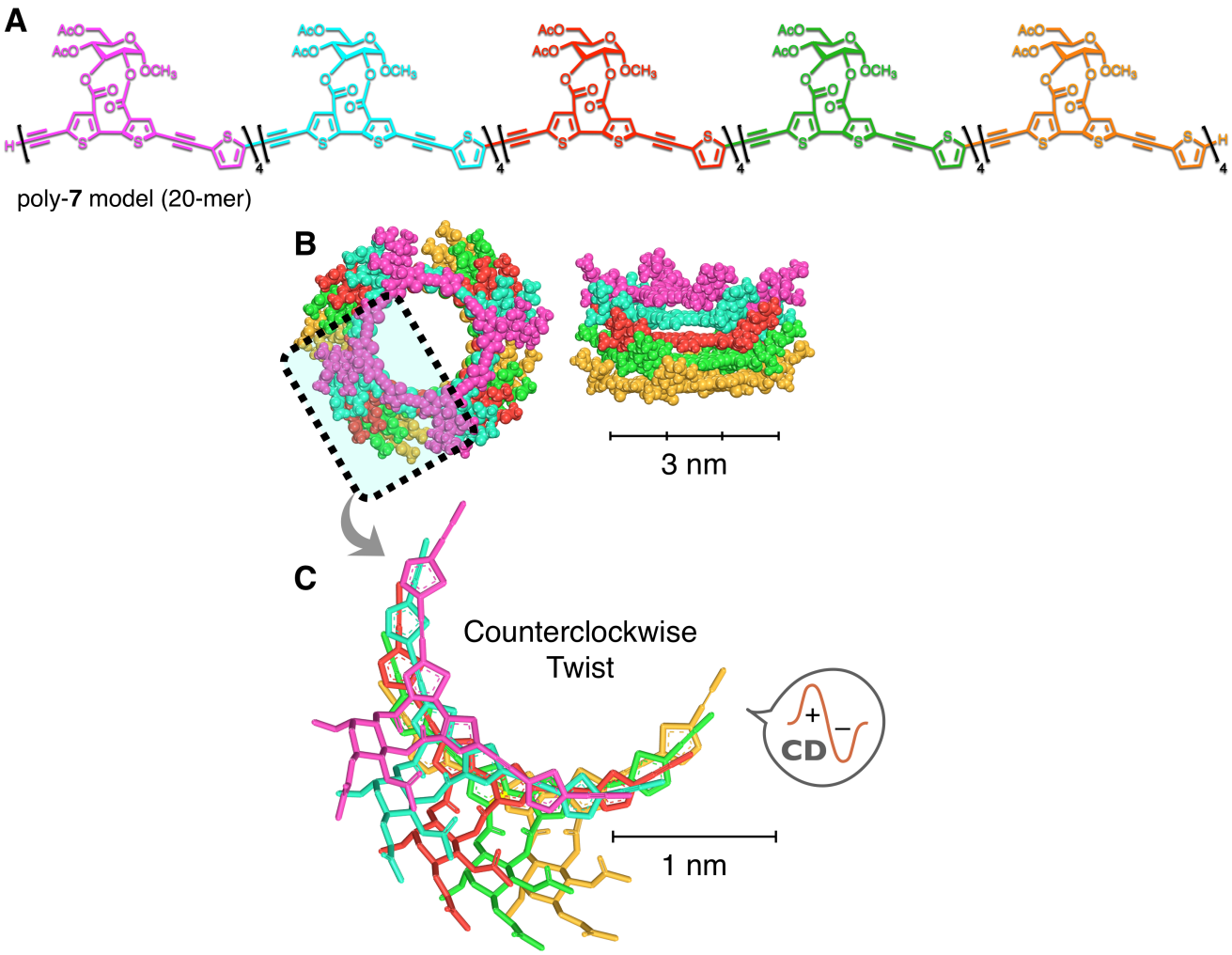


Fig. S8 (A) Structure of the 20-mer model of poly-**7**, which is color-coded for every four units. (B) Top view (left) and side view (right) of the possible right-handed helical structure of the 20-mer model of poly-**7**, which is color-coded according to (A). The structures are shown using the space-filling model. (C) Simplified molecular model displaying only the part of the structure inside the dashed rectangle in (B), where all of the units are arranged in a counterclockwise twisting manner. The structure is shown using the stick model and the hydrogen atoms have been omitted to simplify the view.

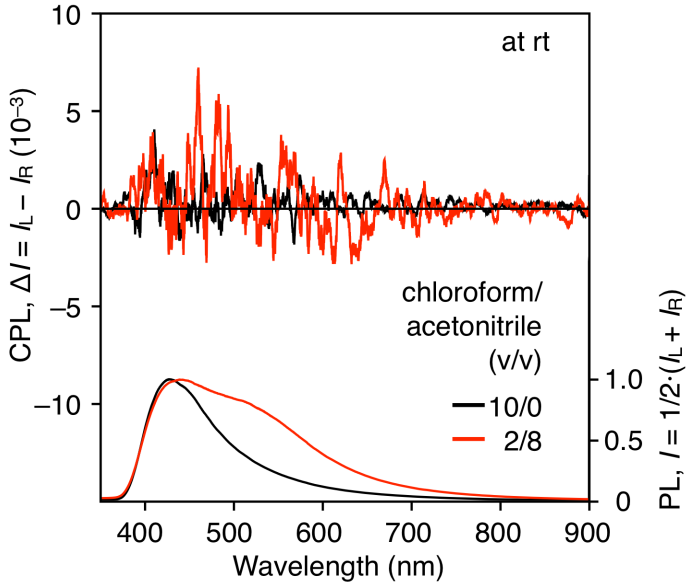


Fig. S9 PL and CPL spectra of poly-**8** in chloroform and chloroform/acetonitrile (2/8, v/v) at room temperature. λ_{ex} = 300 nm, [Glucose unit] = 1.0 × 10^{-4} M.

NMR spectral data

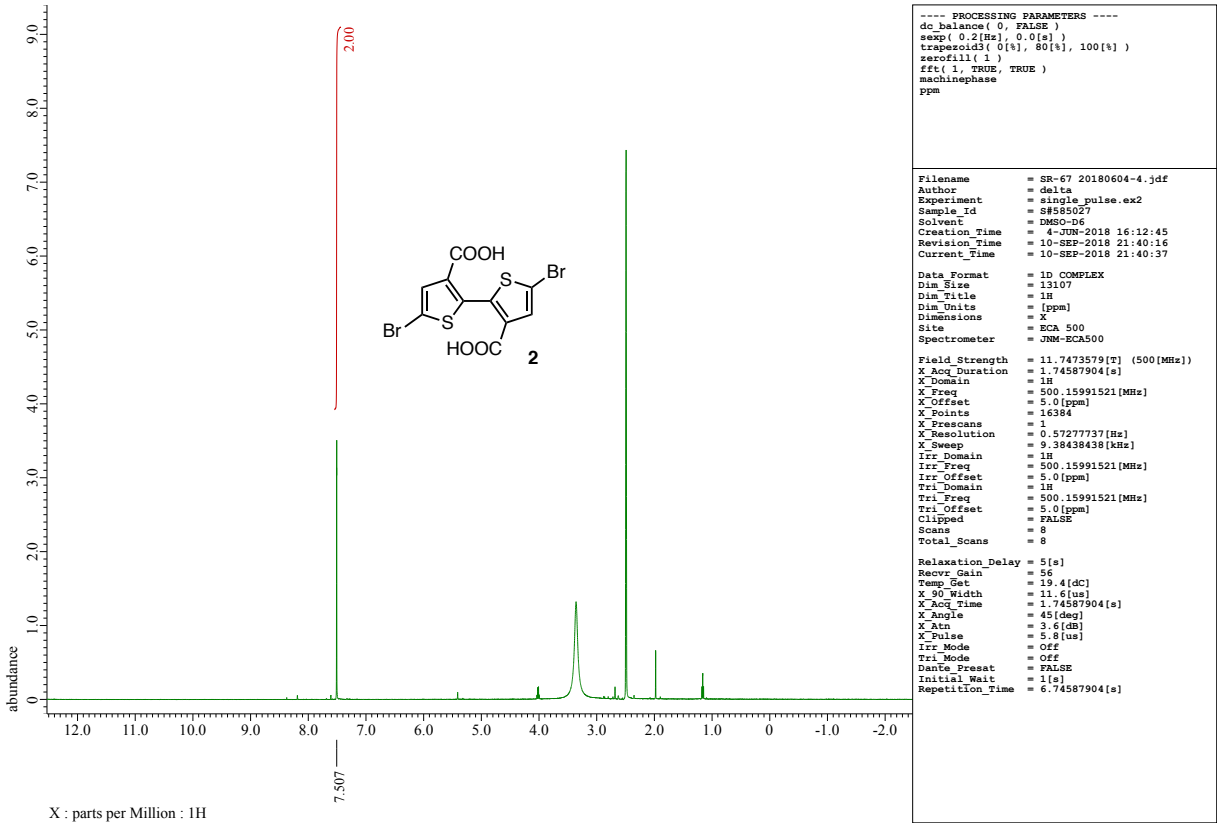


Fig. S10 ^{1}H NMR (DMSO-*d* , 500 MHz, rt) spectrum of **2**.

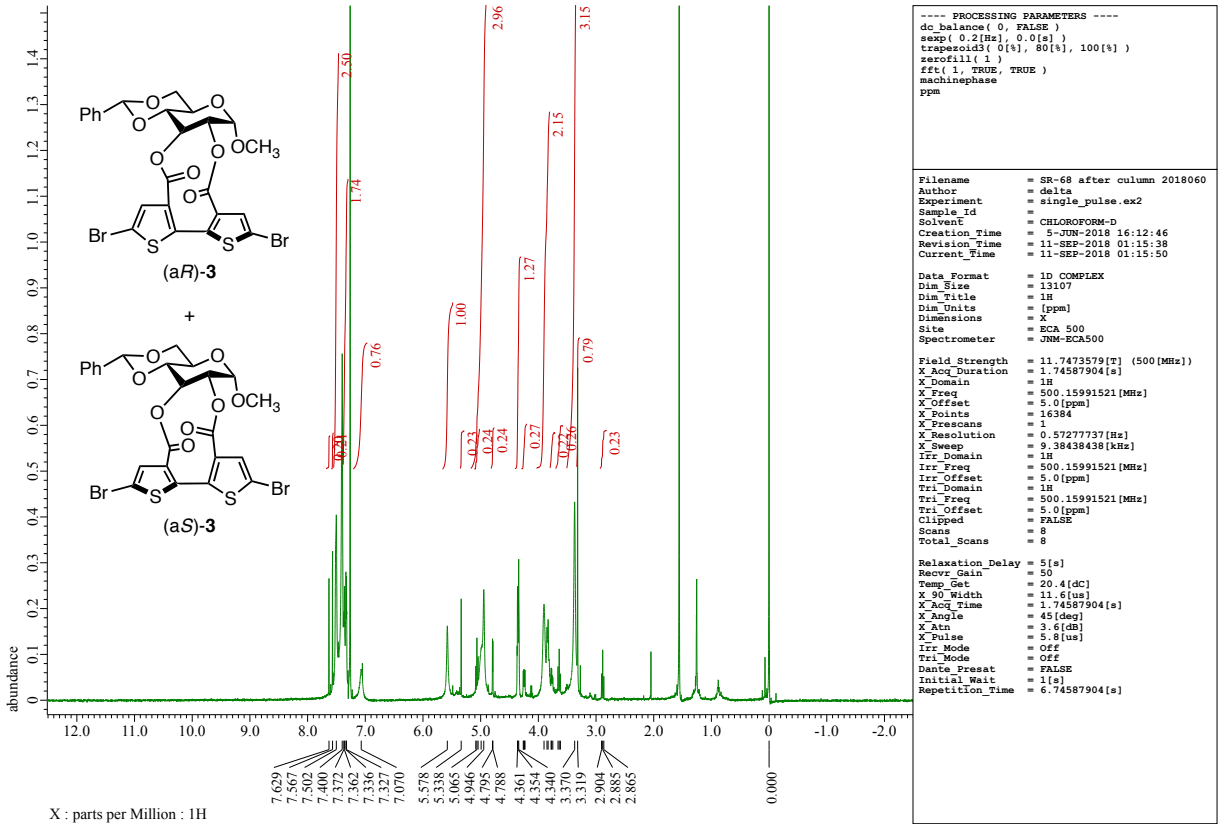


Fig. S11 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of the (a*R*)-**3**/(a*S*)-**3** mixture.

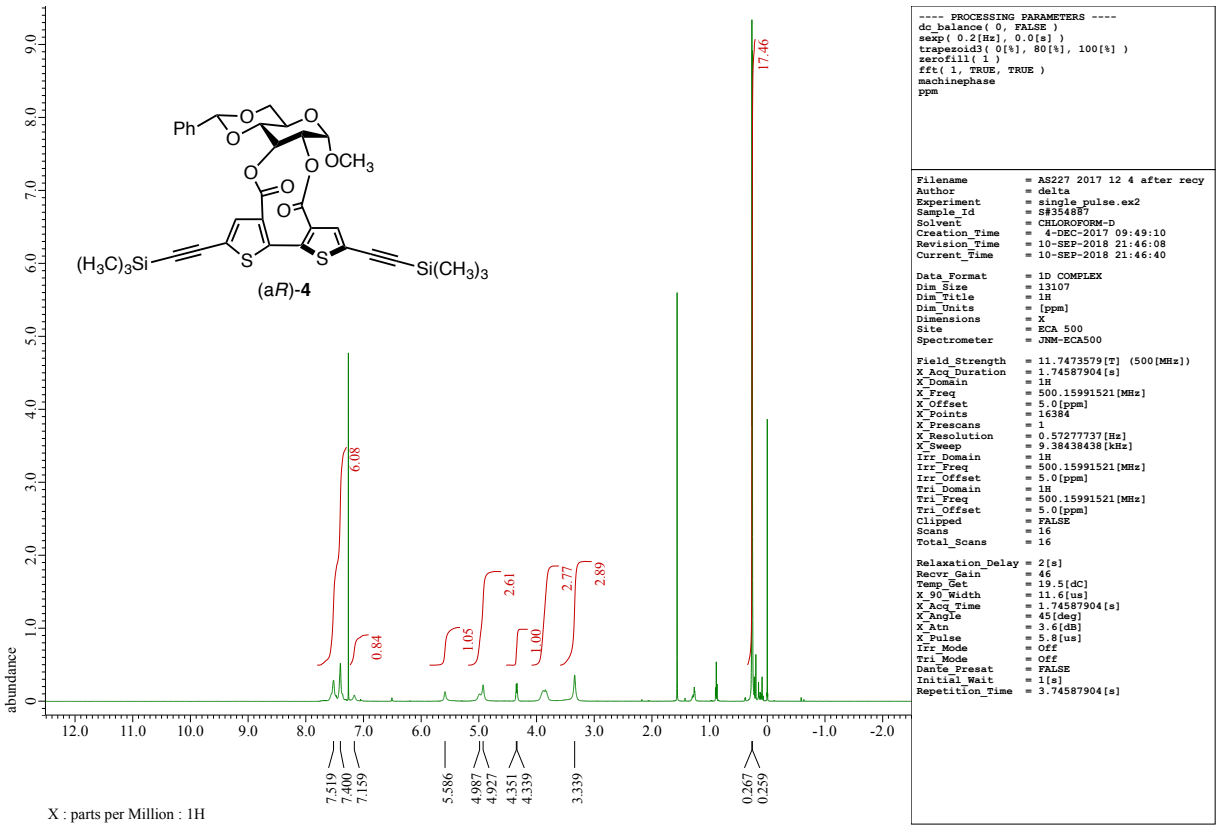


Fig. S12 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of (a*R*)-**4**.

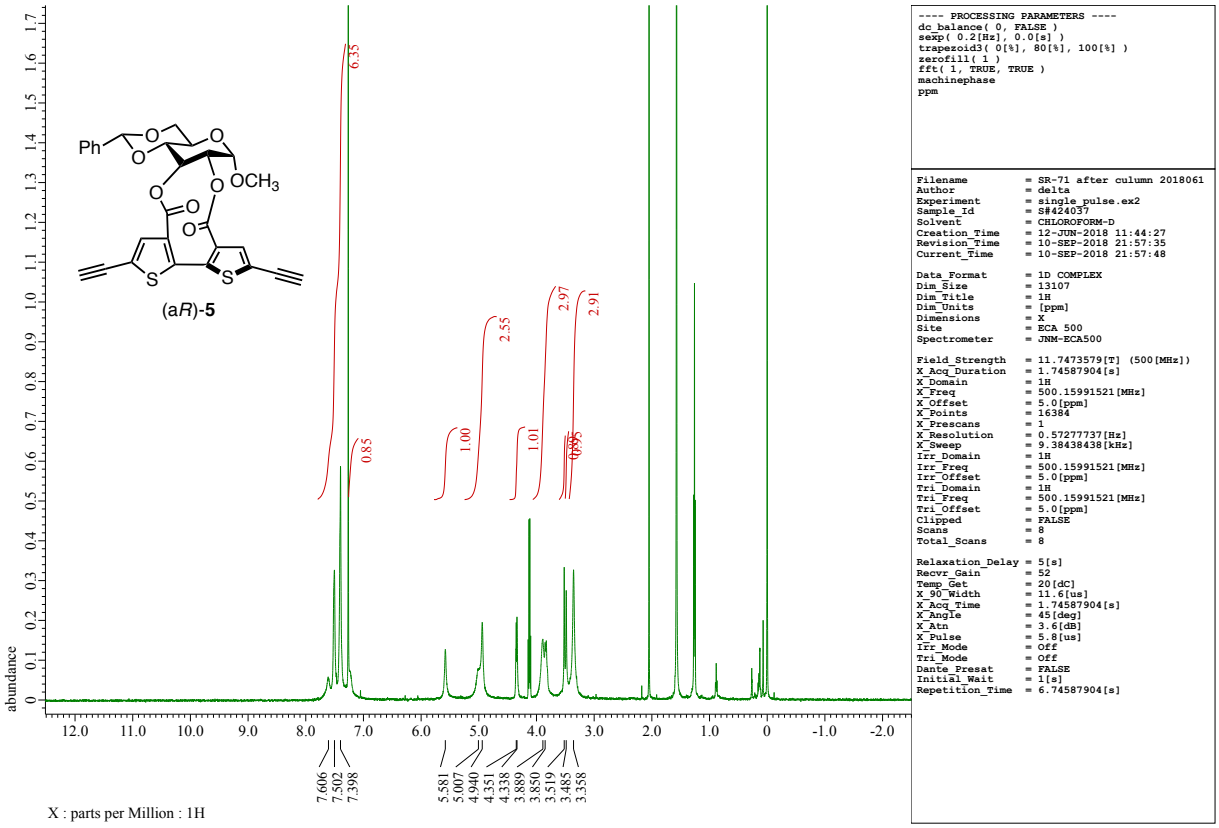


Fig. S13 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of (a*R*)-**5**.

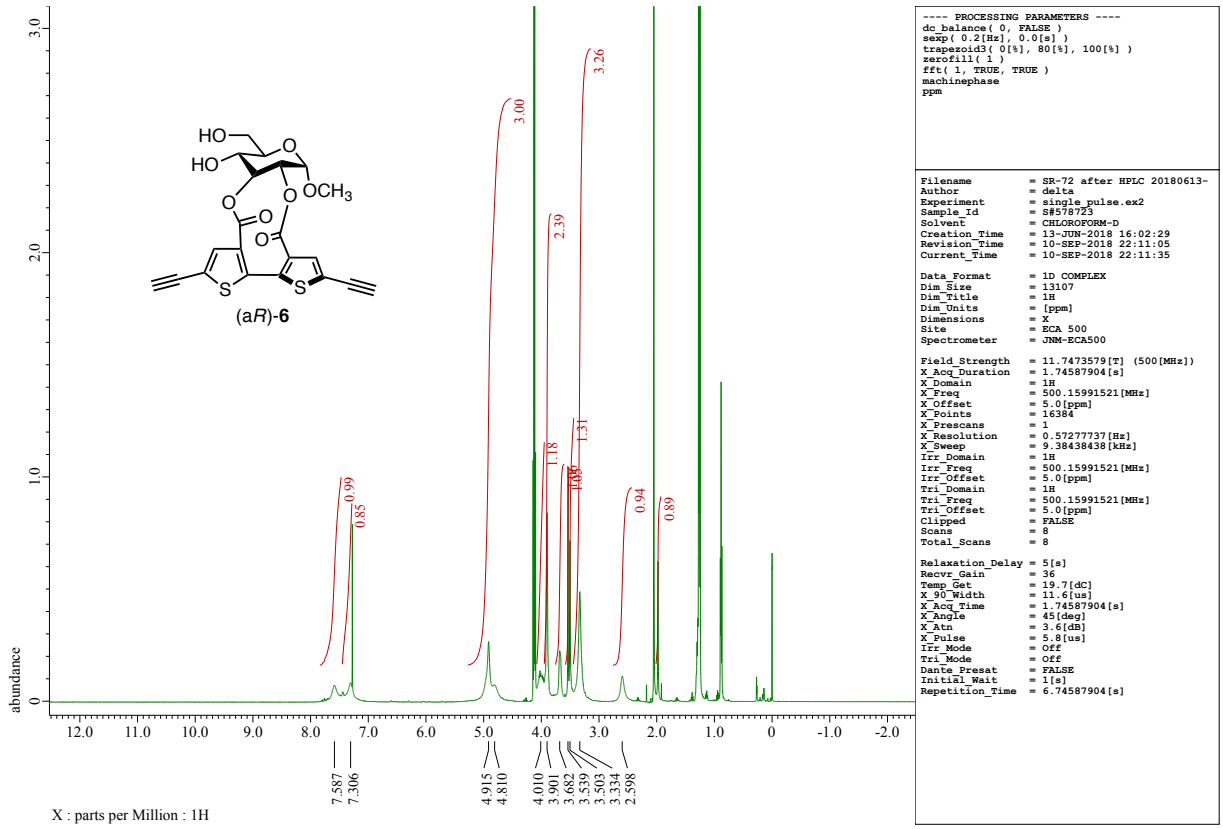


Fig. S14 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of (a*R*)-**6**.

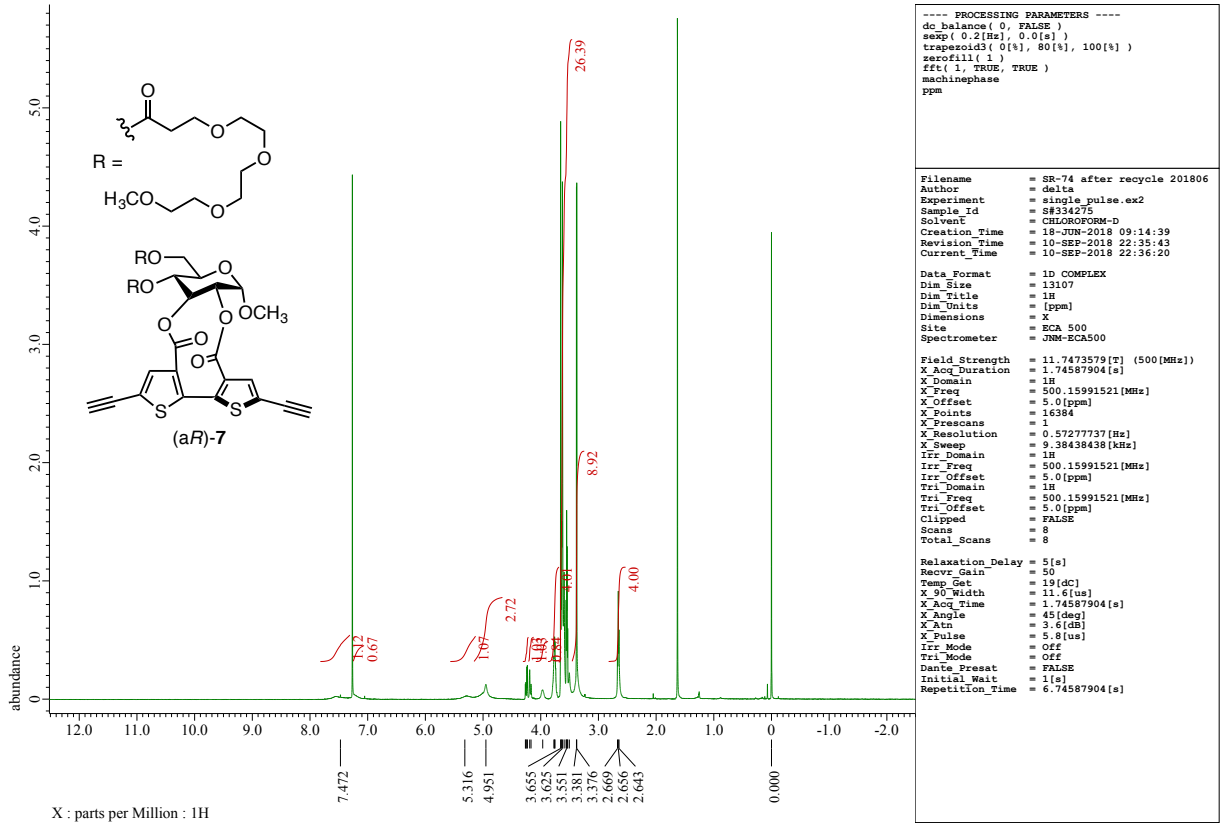


Fig. S15 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of (a*R*)-**7**.

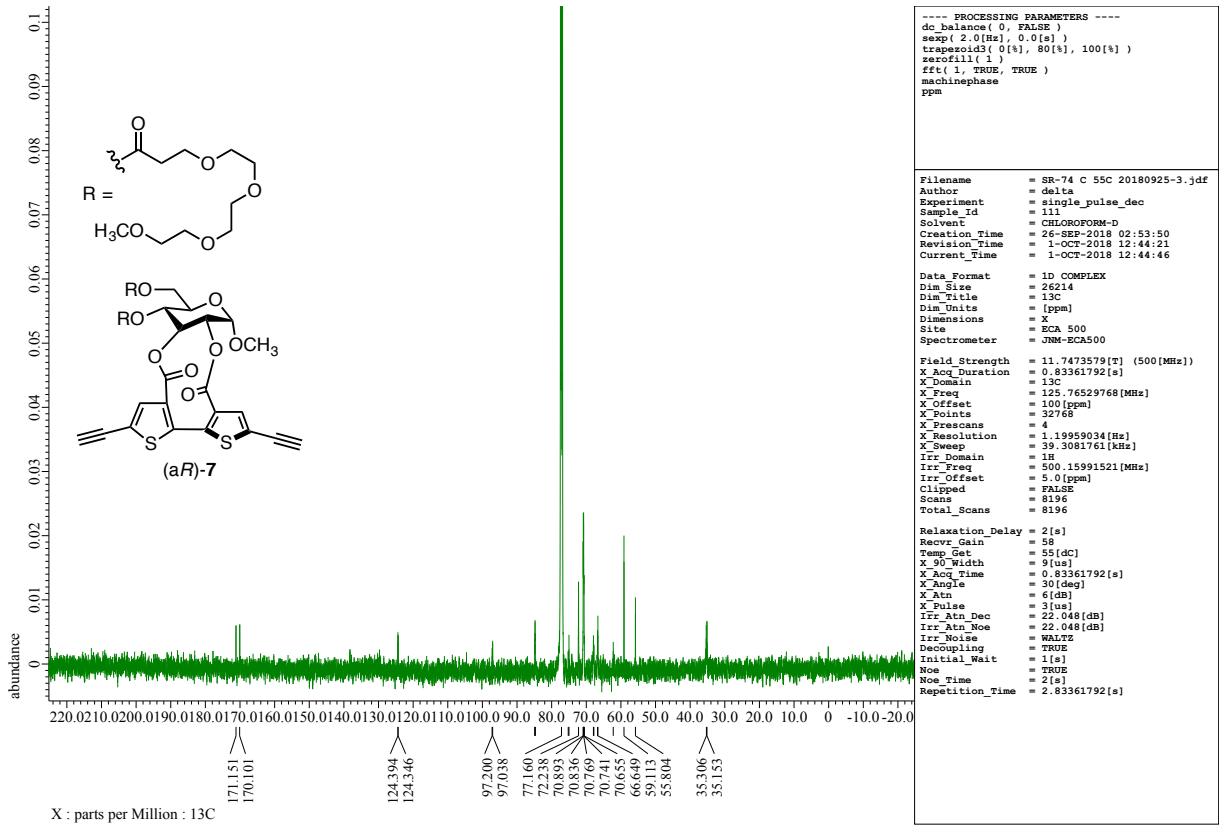


Fig. S16 ^{13}C NMR ($CDCl_3$, 126 MHz, rt) spectrum of (a*R*)-**7**.

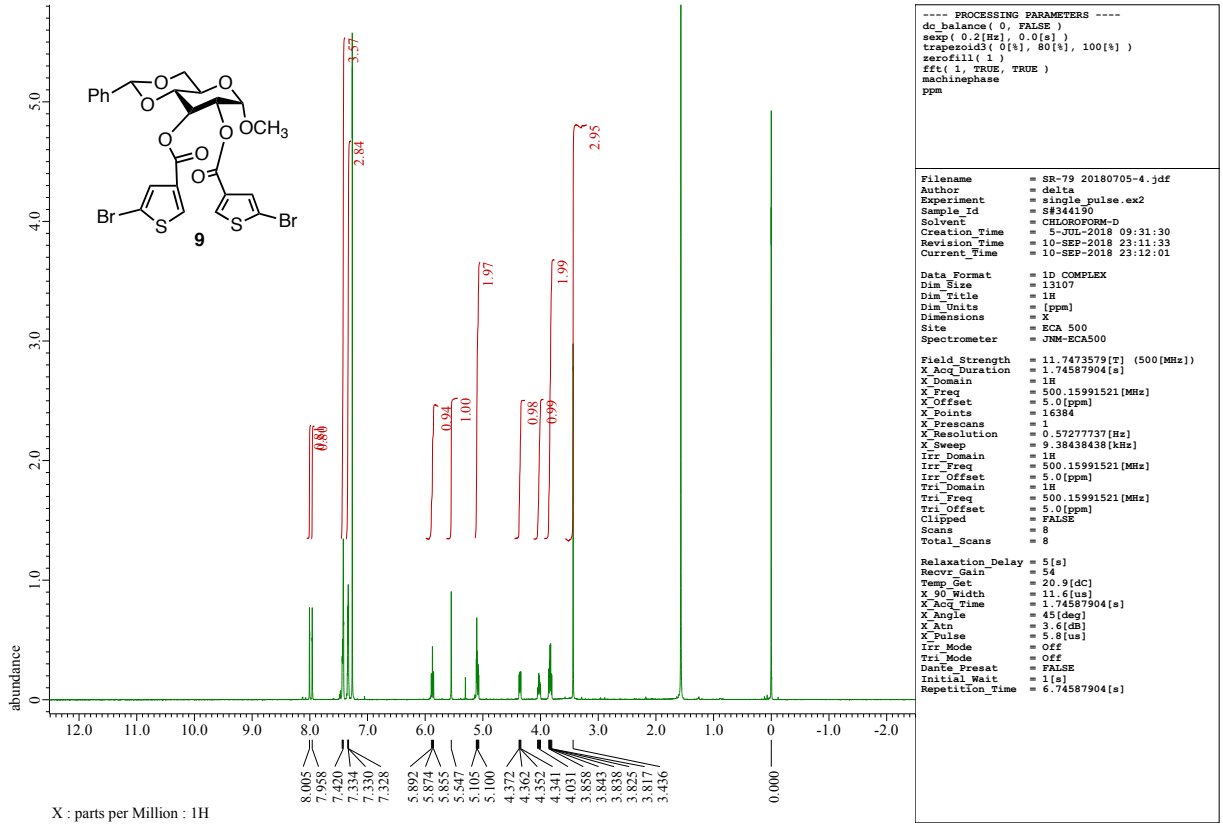


Fig. S17 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of **9**.

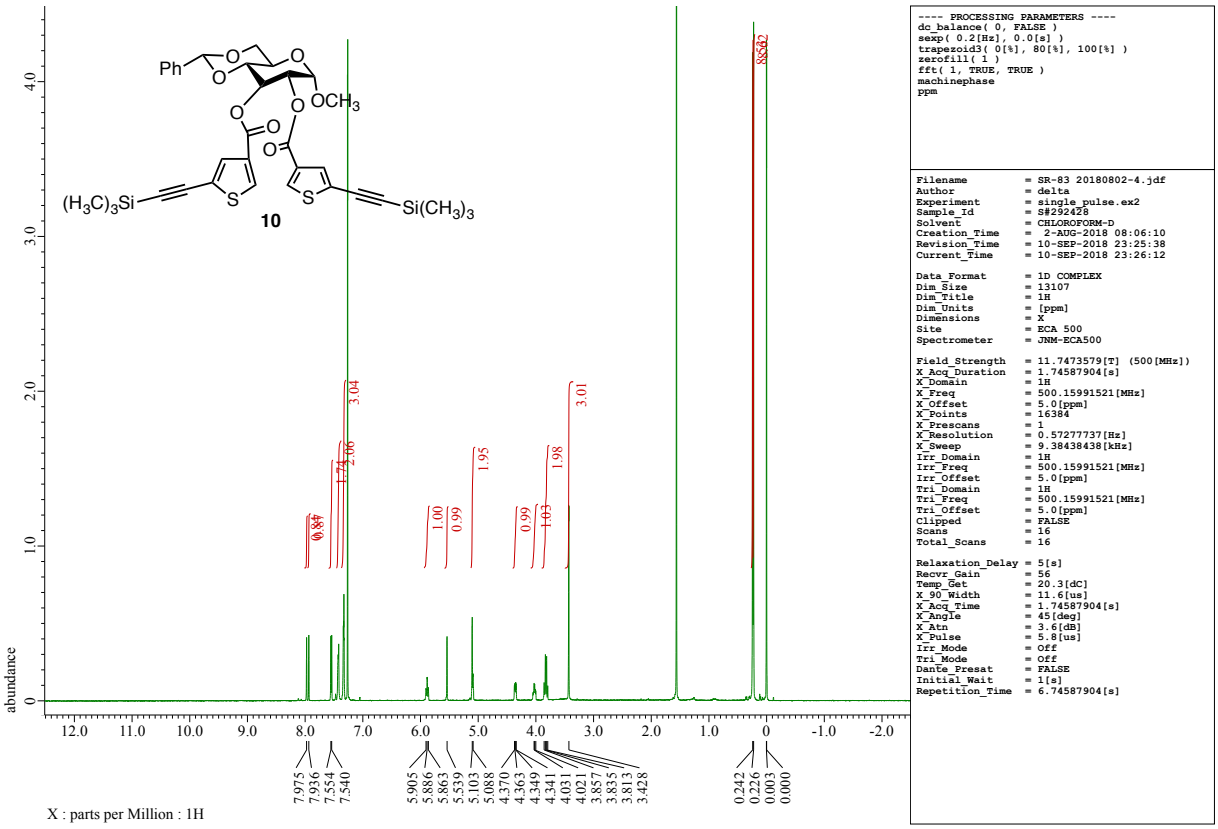


Fig. S18 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of **10**.

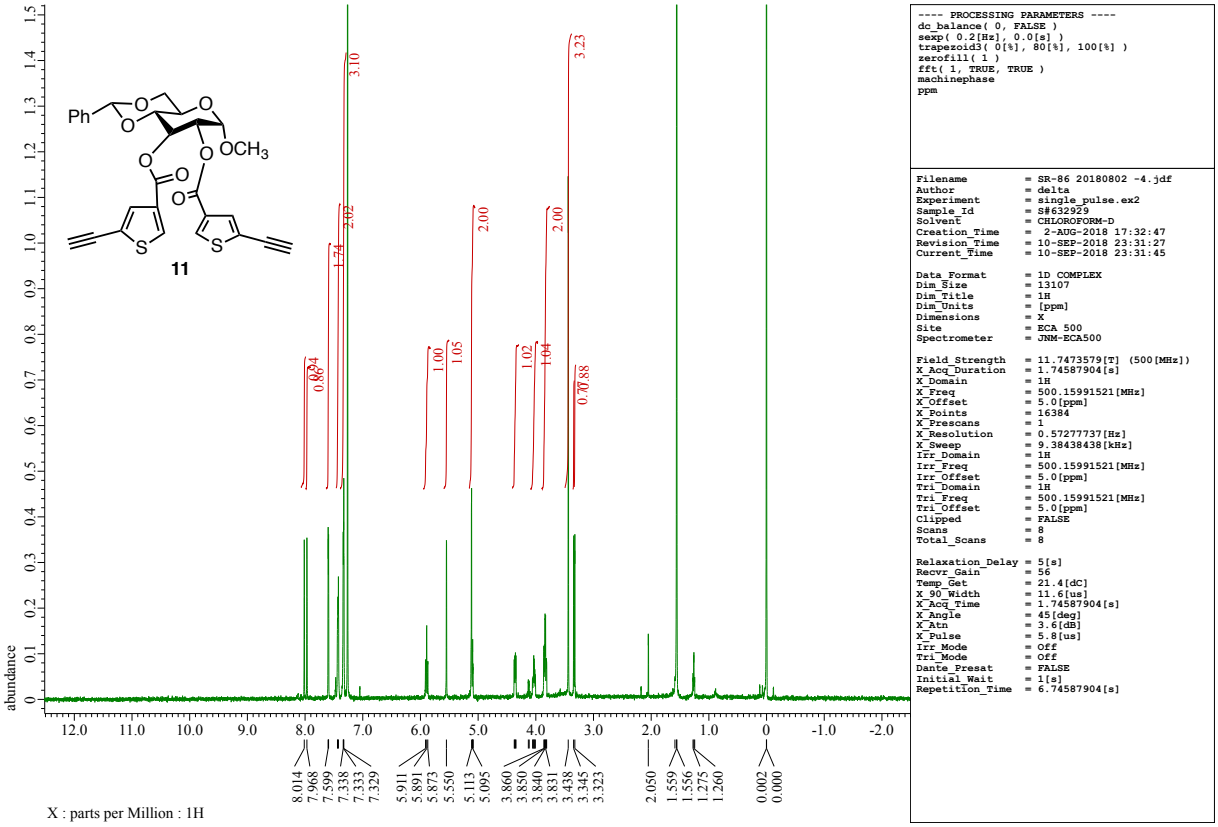


Fig. S19 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of **11**.

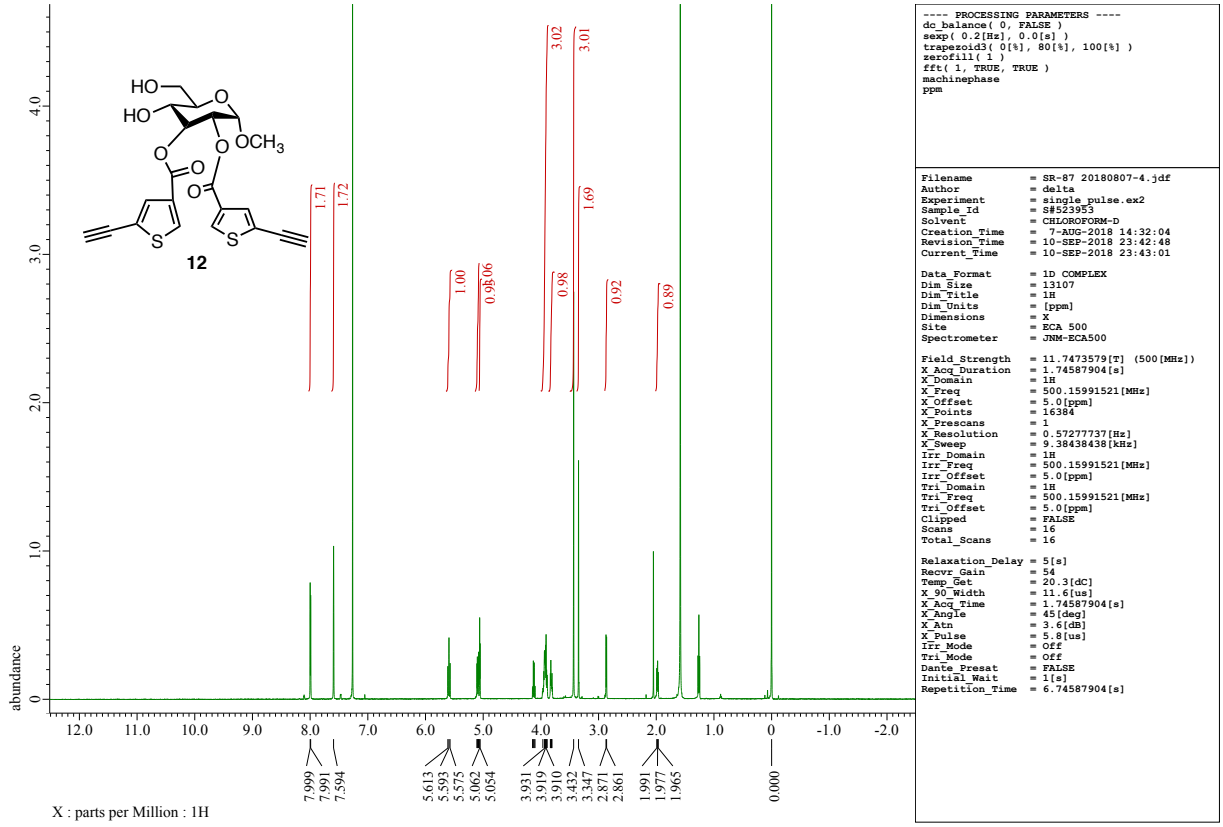


Fig. S20 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of **12**.

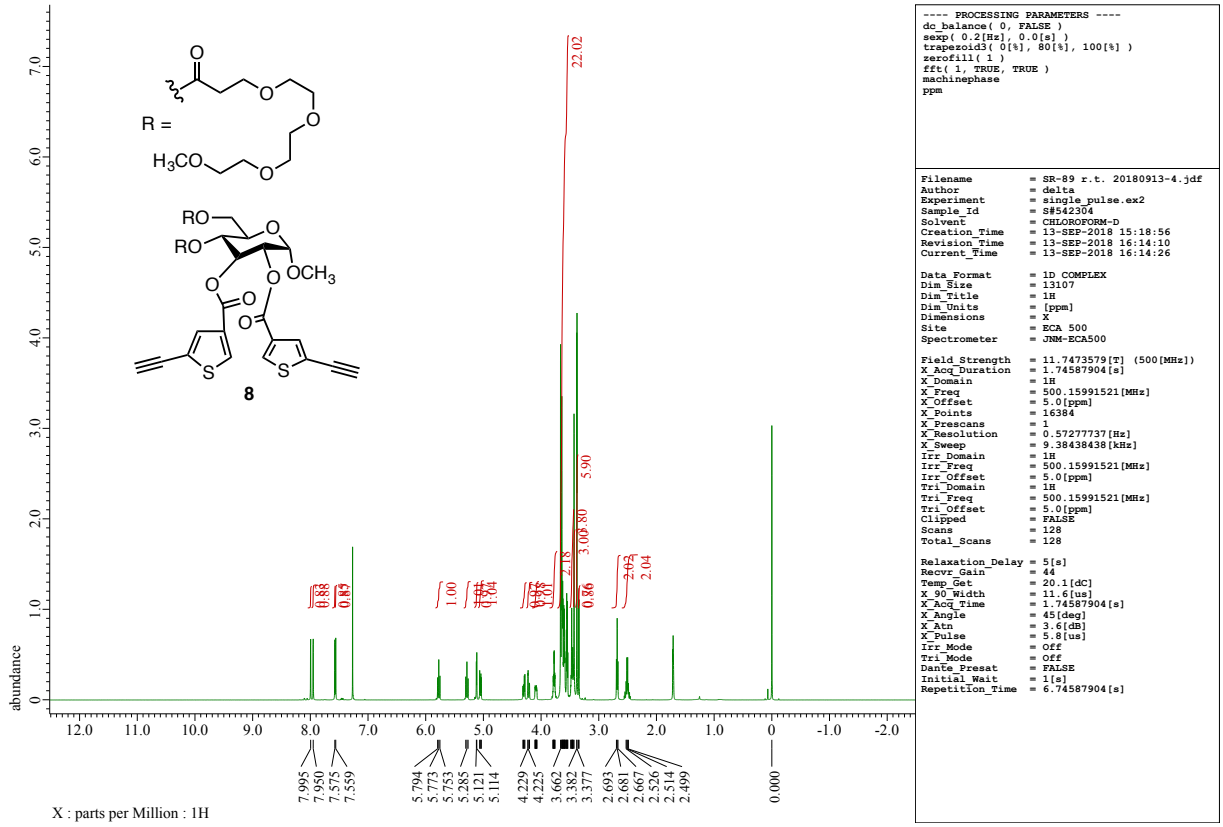


Fig. S21 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of **8**.

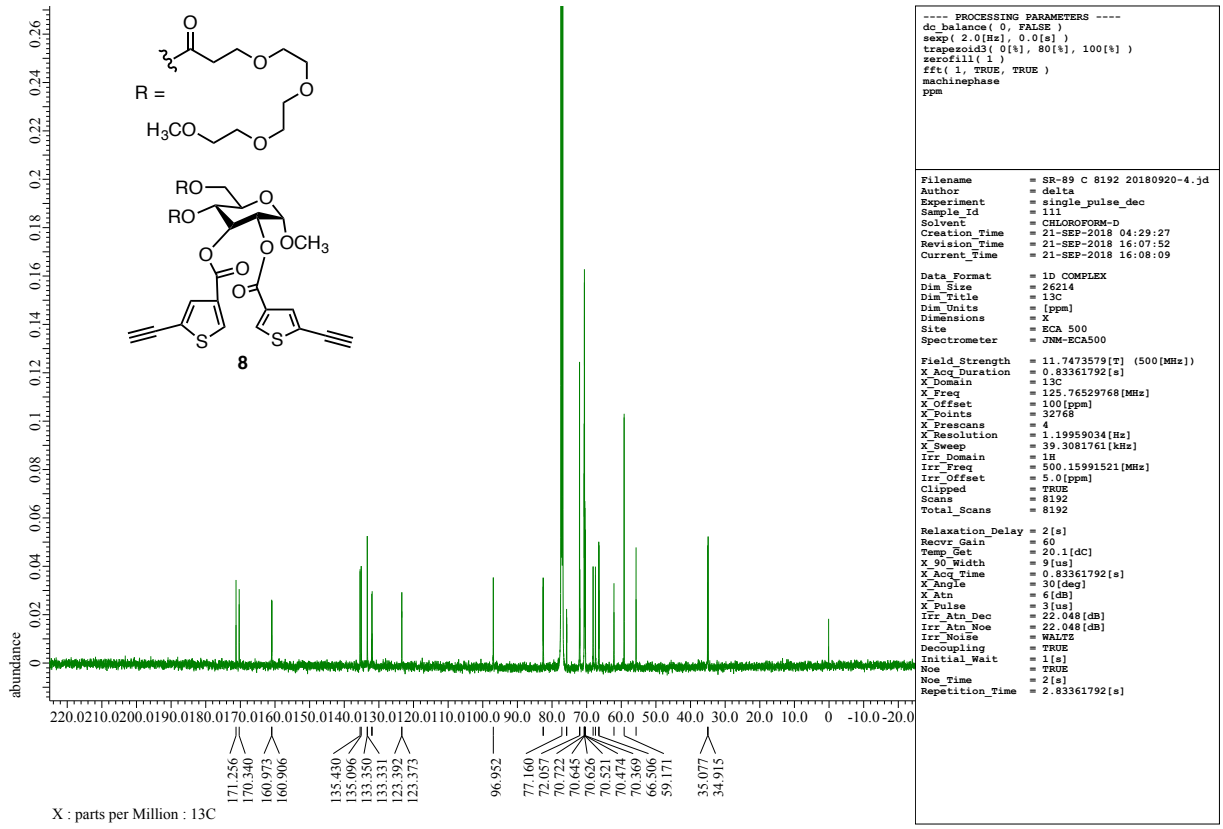


Fig. S22 ^{13}C NMR ($CDCl_3$, 126 MHz, rt) spectrum of **8**.

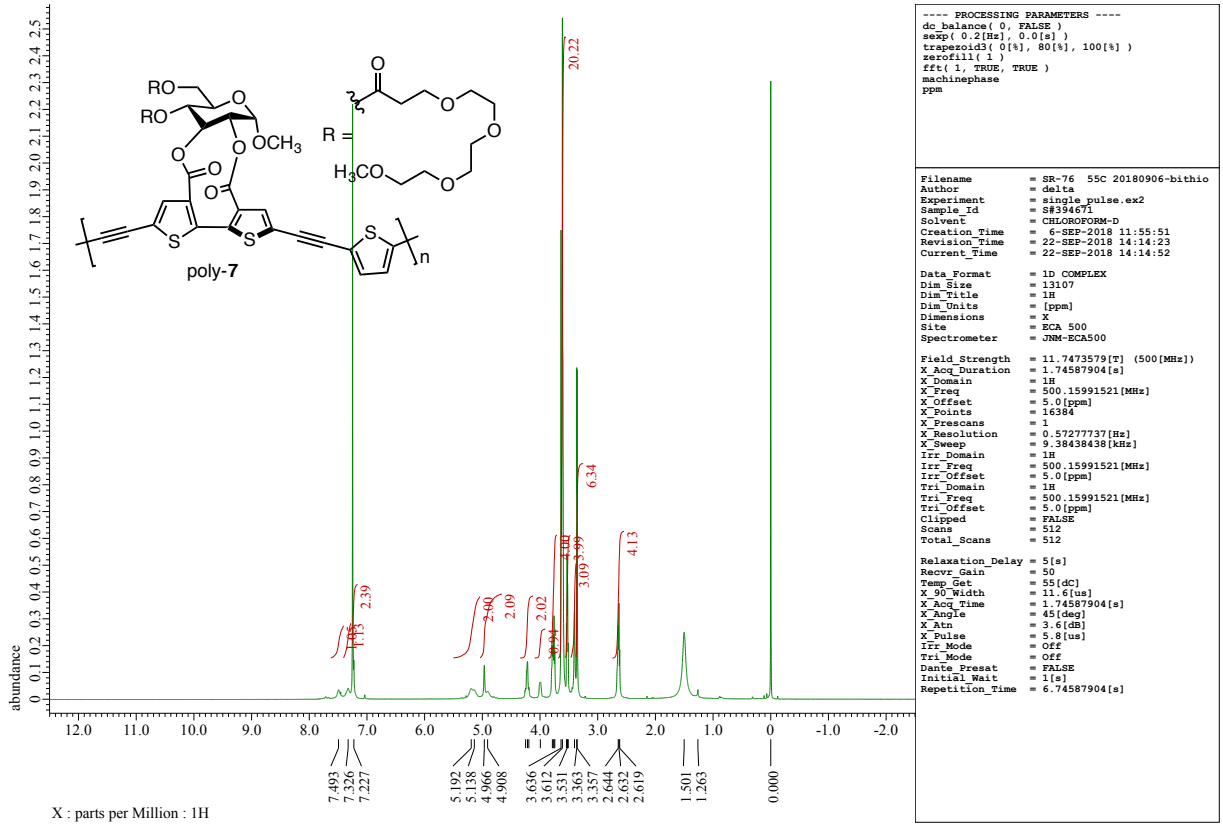


Fig. S23 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of poly-**7**.

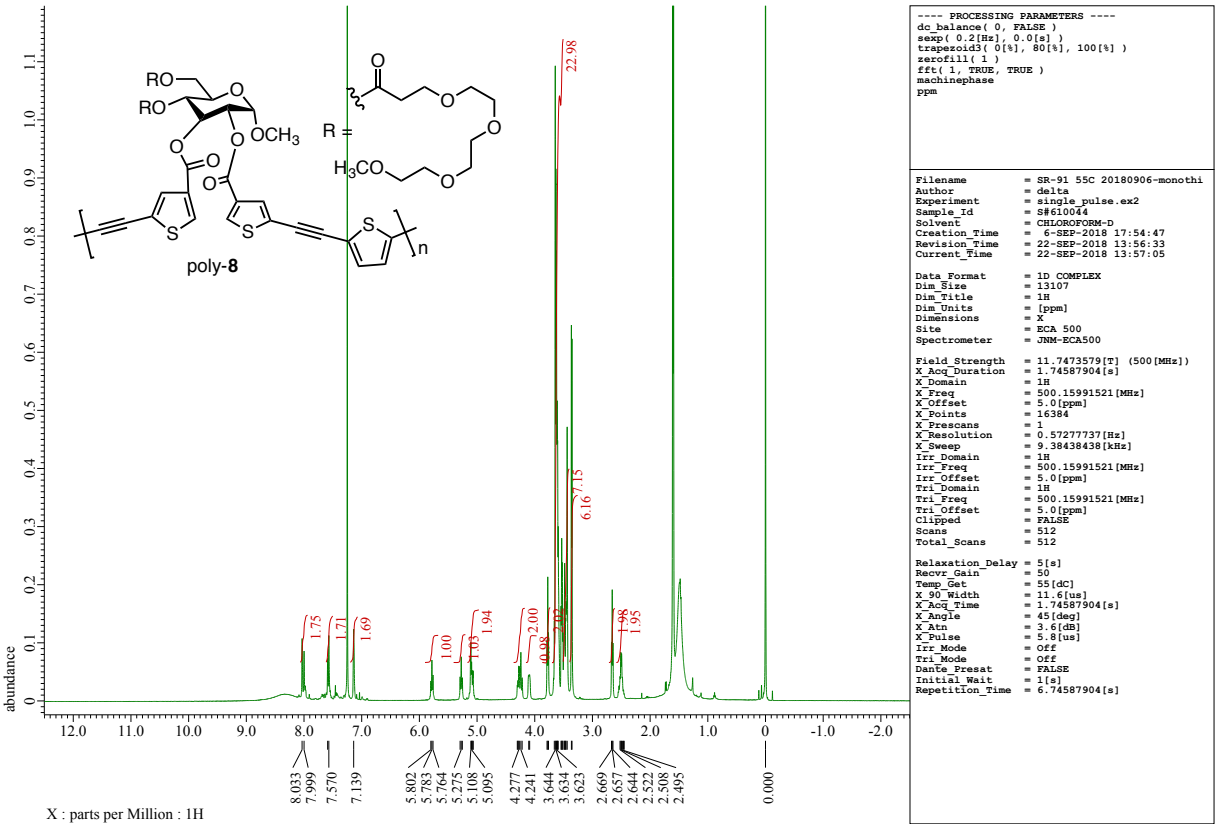


Fig. S24 ^{1}H NMR ($CDCl_3$, 500 MHz, rt) spectrum of poly-**8**.

Caption for supporting movie

Movie S1. Animation of all-atom MD simulation in the NVE ensemble after the equilibration at 298 K of the (a*R*)-**7** model (space-filling model) in chloroform (line model) at 0–2,000 ps as the production run. The hydrogen atoms of chloroform are omitted to simplify the view.

References

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