

Ultimate diastereoselectivity in the ring closure of photochromic diarylethene possessing facial chirality

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ESI-1. Experimental details of the synthesis of diarylethene 10

General. Chemical reactions were carried out under a dry nitrogen atmosphere. Dry tetrahydrofuran (THF) was purchased and used as received. All other solvents were also used as received. Flash column chromatography was carried out on 230-400 mesh silica gel using ethyl acetate and hexane as the eluant. Analytical thin-layer chromatography was performed on the pre-coated 0.25-mm thick silica gel TLC plates.

¹H NMR Spectra were recorded in deuteriochloroform (CDCl₃) with a 270 MHz, 400 MHz NMR or 500 MHz spectrometer. The J values are expressed in Hz and quoted chemical shifts are in ppm. The splitting patterns are indicated as s, singlet; d, doublet; t, triplet; m, multiplet. Infrared spectra (IR) were recorded on a FT-IR spectrometer. Low- and high-resolution mass spectra were measured by the electron impact mass spectrometry using a Mass spectrometer. Ultraviolet and visible spectra were recorded on a UV/Vis spectrophotometer. Optical rotation measurements were carried out using a polarimeter. The melting points were measured using a hot stage microscope and these values were uncorrected.

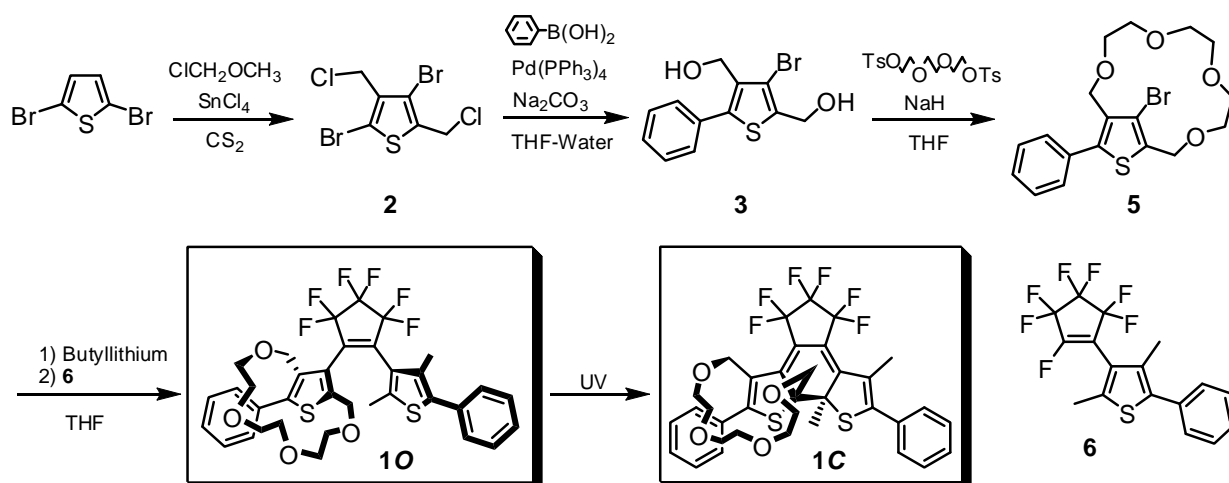
Photochemical reactions at 313 nm in *n*-hexane (3.04 x 10⁻⁵ M) were carried out in a 10 mm path length quartz cell using a 500 W high-pressure mercury lamp which was separated by filters (a 5 cm water filter, a UV-D35 glass filter, a 5 cm aqueous NiSO₄ 6H₂O solution, a 1 cm aqueous K₂CrO₄ solution, and a 1 cm aqueous potassium diphthalate solution) and those at 515 nm were carried out using a 500 W xenon lamp which was separated by filters (a 5 cm water filter, a Pyrex glass filter, a IRA-25S glass filter, a Y-47 glass filter, and a KL-50 interference glass filter). During the photoreactions, the solutions in the cell were stirred continuously.

High-performance liquid chromatography (HPLC) equipped with a UV/Vis detector and a column (Wakosil 5SIL, 4.6 mm diameter x 150 mm) was used to follow the photochromic reactions during photoirradiation.

In order to check the diastereoselectivity in hexane, toluene, and ethyl acetate, an HPLC apparatus equipped with different columns and different solvent systems were used. Details are shown in ESI-4.

Synthesis of diarylethene.

Synthesis of **10** was carried out according to the following procedures:



2,4-Dibromo-3,5-bis(chloromethyl)thiophene (**2**)¹

To a stirred solution of 2,5-dibromothiophene (20.0 g, 82.7 mmol, 1.0 eq) and chloromethyl methyl ether (34.0 ml, 448 mmol, 5.4 eq) in 100 ml of CS₂ at 0 °C was added dropwise a mixture of SnCl₄ (20.0 ml, 171 mmol, 2.1 eq) in 10 ml of CS₂. The mixture was then stirred for 1 h at 0 °C and 1 h at room temperature. The reaction was quenched by adding water, and the resultant mixture was extracted with CS₂ two times. The combined organic layer was dried over anhydrous sodium sulfate, filtered, and the solvent evaporated. The residue was purified by column chromatography on silica gel using hexane as the eluant to give 13.8 g (40.7 mmol) of compound **2** as a white solid in 49 % yield.

Mp. 83.2-85.1 °C (lit.¹ mp. 86.0-88.0 °C). ¹H NMR (400 MHz, CDCl₃, TMS) δ/ppm 4.57 (s, 2H), 4.70 (s, 2H). IR (ATR, neat) ν/cm⁻¹ 2968, 1531, 1432, 12258, 1037, 901, 725, 637. LRMS (EI, 70 eV) m/z (relative intensity), 344 (1.4), 342 (8.1), 340 (21.6), 338 (24.3), 336 (9.0, M⁺), 305 (74.8), 303 (100), 259 (29.1).

3-Bromo-2,4-bis(hydroxymethyl)-5-phenylthiophene (**3**)

To a stirred solution of **2** (6.01 g, 17.7 mmol, 1.0 eq), phenyl boronic acid (2.25 g, 18.5 mmol, 1.0 eq) and tetrakis(triphenylphosphine)Palladium(0) (1.81 g, 1.56 mmol, 0.09 eq) in 100 ml of THF was added 60 ml of aq. sat. sodium carbonate (2.83 mol dm⁻³, 170 mmol, 9.6 eq). The mixture was then refluxed for 9 h. The reaction was quenched by adding 0.5 mol dm⁻³ HCl aq. and the resultant mixture was extracted with ethyl acetate three times. The combined organic layer was dried over anhydrous sodium sulfate, filtered, and the solvent evaporated. The residue was purified by column chromatography on silica gel using AcOEt/hexane = 1/2 as the eluant to give 3.02 g (10.1 mmol) of compound **3** as a white solid in 57 % yield.

Mp. 123.5-130.4 °C. ¹H NMR (400 MHz, CDCl₃, TMS) δ/ppm 1.90 (t, J/Hz = 6.1, 1H), 1.96 (t, J/Hz = 6.3, 1H), 4.62 (d, J/Hz = 6.3, 2H), 4.86 (d, J/Hz = 5.9, 2H), 7.40-7.49 (m, 3H), 7.52-7.56 (m, 2H). IR (ATR, neat) ν/cm⁻¹ 3302, 2868, 1441, 1344, 1050, 694. LRMS (EI, 70 eV) m/z (relative intensity), 300 (91.8), 298 (93.6, M⁺), 281 (27.3), 201 (62.7), 173 (100). Found: m/z 297.96633.

Calcd for C₁₂H₁₁BrO₂S: M, 297.96631.

NOE experiment of **30**

NOE experiments of **30** were carried out in CDCl₃ (Fig. S11, p. S13). Upon irradiation of the methylene protons at δ 4.62 (methylene A), the phenyl protons at δ 7.53 showed an NOE signal. On the other hand, when the methylene protons at δ 4.86 (methylene B) were irradiated, none of the phenyl protons showed NOE signals. This means that methylene A is close to the phenyl group, while methylene B is remote from the phenyl group. Only the structure of **30** can fulfill these requirements.

2,4-(2,5,8,11-Tetraoxa)dodecano-3-bromo-5-phenylthiophene (**5**)

To a stirred suspension of sodium hydride (60 % in oil, 422 mg, 10.5 mmol, 3.2 eq) in 350 ml of THF at reflux temperature was added dropwise a solution of **3** (1.00 g, 3.34 mmol, 1.0 eq) and triethylene glycol bis(*p*-toluenesulfonate) (1.54 g, 3.36 mmol, 1.0 eq) in 50 ml of THF. The mixture was then refluxed for 1 h and cooled to room temperature. The reaction was quenched by adding 0.5 mol dm⁻³ HCl aq. and THF was removed *in vacuo*. The resultant mixture was extracted with ethyl acetate three times. The combined organic layer was dried over anhydrous sodium sulfate, filtered, and the solvent evaporated. The residue was purified by column chromatography twice on silica gel using AcOEt/hexane (40 %) and AcOEt/hexane/pyridine = 6/9/1 as the eluant to give 44.8 mg (0.11 mmol) of compound **5** as a colorless oil in 3 % yield.

¹H NMR (270 MHz, CDCl₃, TMS) δ /ppm 3.34-3.87 (m, 12H), 4.47 (d, *J*/Hz = 12.9, 1H), 4.49 (d, *J*/Hz = 13.8, 1H), 4.73 (d, *J*/Hz = 12.9, 1H), 4.94 (d, *J*/Hz = 13.8, 1H), 7.37-7.48 (m, 5H). IR (ATR, neat) ν /cm⁻¹ 2860, 1443, 1355, 1087, 1007, 697. LRMS (EI, 70 eV) *m/z* (relative intensity), 414 (28.2), 412 (26.4, M⁺), 333 (91.8), 265 (60.9), 263 (58.2), 185 (100). Found: *m/z* 412.03445. Calcd for C₁₈H₂₁BrO₄S: M, 412.03439.

1-(2,4-Dimethyl-5-phenylthien-3-yl)heptafluorocyclopentene (**6**)²

To a stirred solution of 3-bromo-2,4-dimethyl-5-phenylthiophene (1.91 g, 7.14 mmol, 1.0 eq) in 50 ml of THF at -78 °C was added dropwise a hexane solution of *n*-BuLi (1.63 mol dm⁻³ in hexane, 5.0 ml, 8.2 mmol, 1.1 eq). The mixture was stirred for 30 min at -78 °C and then perfluorocyclopentene (6.0 ml, 45 mmol, 6.3 eq) was added in one portion. The mixture was stirred overnight and the reaction was quenched by adding water, and the resultant mixture was extracted with ethyl acetate three times. The combined organic layer was dried over anhydrous sodium sulfate, filtered, and the solvent evaporated. The residue was purified by column chromatography on silica gel using hexane as the eluant to give 2.48 g (6.58 mmol) of compound **6** as a white solid in 92 % yield.

Mp. 61.0-62.8 °C (lit.² mp. 63-64 °C). ¹H NMR (270 MHz, CDCl₃, TMS) δ /ppm 2.11 (s, 3H), 2.39 (s, 3H), 7.31-7.43 (m, 5H). IR (ATR, neat) ν /cm⁻¹ 2928, 1706, 1274, 1149, 968, 698. LRMS (EI, 70 eV) *m/z* (relative intensity), 380 (100, M⁺), 365 (19.1). Found: *m/z* 380.04807. Calcd for C₁₇H₁₁F₇S: M, 380.04695.

1-(2,4-Dimethyl-5-phenyl-3-thienyl)-2-[2,4-(2,5,8,11-tetraoxa)dodecano-5-phenylthien-3-yl]

hexafluorocyclopentene (**10**)

To a stirred solution of **5** (87.7 mg, 0.212 mmol, 1.0 eq) in 5 ml of THF at -78 °C was added dropwise *n*-BuLi (2.63 mol dm⁻³, 0.085 ml, 0.22 mmol, 1.1 eq). The mixture was stirred for 10 min at -78 °C and then was added dropwise a solution of **6** (82.0 mg, 0.218 mmol, 1.0 eq) in 1 ml of THF. The mixture was stirred overnight and the reaction was quenched by adding water, and the resultant mixture was extracted with ethyl acetate three times. The combined organic layer was dried over anhydrous sodium sulfate, filtered, and the solvent evaporated. The residue was purified by column chromatography on silica gel using AcOEt/hexane (20 %) as the eluant to give 64.1 mg (0.0923 mmol) of diarylethene **10** as an amorphous solid in 44 % yield.

In the following ¹H NMR data, Mj and Mn stand for the major and minor conformers, respectively. As the major singlet methyl group on C2 of thiophene group appears at δ 1.84 (anisotropic high-field shift), it belongs to the photo-cyclizable antiparallel conformer. The other is the parallel conformer without steric hindrance. The ratio of Mj/Mn is about 51/49.

¹H NMR (500 MHz, CDCl₃, TMS) δ/ppm 1.84 (s, 3H, Mj), 2.13 (s, 3H, Mn), 2.21 (d, *J*/Hz = 3.5, coupling with F (⁶*J*), 3H, Mj), 2.49 (d, *J*/Hz = 2.8, coupling with F (⁶*J*), 3H, Mn), 3.06-4.01 (m, 12H each), 4.08 (d, *J*/Hz = 21.1, 1H, Mn), 4.11 (d, *J*/Hz = 21.1, 1H, Mj), 4.21 (d, *J*/Hz = 20.5, 1H, Mj), 4.23 (d, *J*/Hz = 20.5, 1H, Mn), 4.74-4.84 (m, 4H each), 7.23-7.41 (m, 10H each, aromatic). IR (ATR, neat) ν/cm⁻¹ 2922, 1444, 1280, 1106, 697. LRMS (EI, 70 eV) *m/z* (relative intensity), 694 (15.5, M⁺), 544 (40.0), 532 (46.4), 517 (100). Found: *m/z* 694.16111. Calcd for C₃₅H₃₂F₆O₄S₂: M, 694.16461.

Diarylethene closed-form **1C**

A solution of **10** (20 mg) in hexane (80 ml) in a pyrex cylindrical cell was irradiated with 313 nm light for 8h. The solvent was then removed *in vacuo* and the residue was purified by column chromatography on silica gel using hexane as the eluant to give **1C** (12.3 mg) as an amorphous solid.

¹H NMR shows only one set of the peaks assignable to a diastereomer of **1C**.

¹H NMR (400 MHz, CDCl₃, TMS) δ/ppm 2.04 (d, *J*/Hz = 2.4, coupling with F (⁶*J*), 3H), 2.27 (s, 3H), 3.35-3.39 (m, 1H), 3.51-3.56 (m, 1H), 3.62-3.78 (m, 10H), 4.01 (d, *J*/Hz = 11.0, 1H), 4.30 (d, *J*/Hz = 11.2, 1H), 4.42 (d, *J*/Hz = 10.0, 1H), 4.76 (d, *J*/Hz = 10.3, 1H), 7.42-7.55 (m, 10H, aromatic). IR (ATR, neat) ν/cm⁻¹ 2925, 2861, 1486, 1335, 1121, 760, 696. LRMS (EI, 70 eV) *m/z* (relative intensity), 694 (6.3, M⁺), 532 (22.9), 518 (30.7), 517 (100), 502 (21.9).

References

- 1 M. Takeshita and M. Tashiro, *J. Org. Chem.*, 1992, **57**, 746 – 748.
- 2 S. Kobatake and M. Irie, *Tetrahedron*, 2003, **59**, 8359 – 8364.

ESI-2. UV-vis absorption spectral change by photoirradiation of **1O** in toluene and ethyl acetate

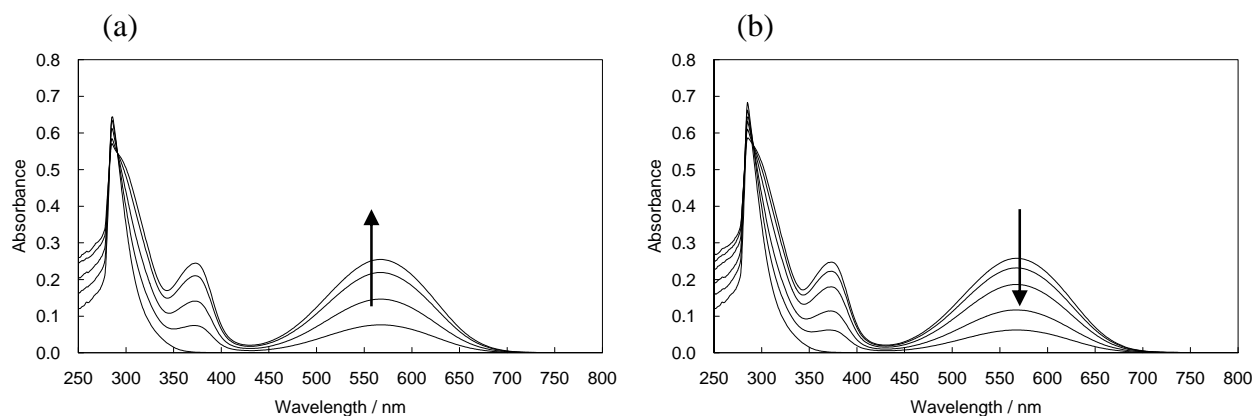


Figure S1. Absorption spectral changes in toluene

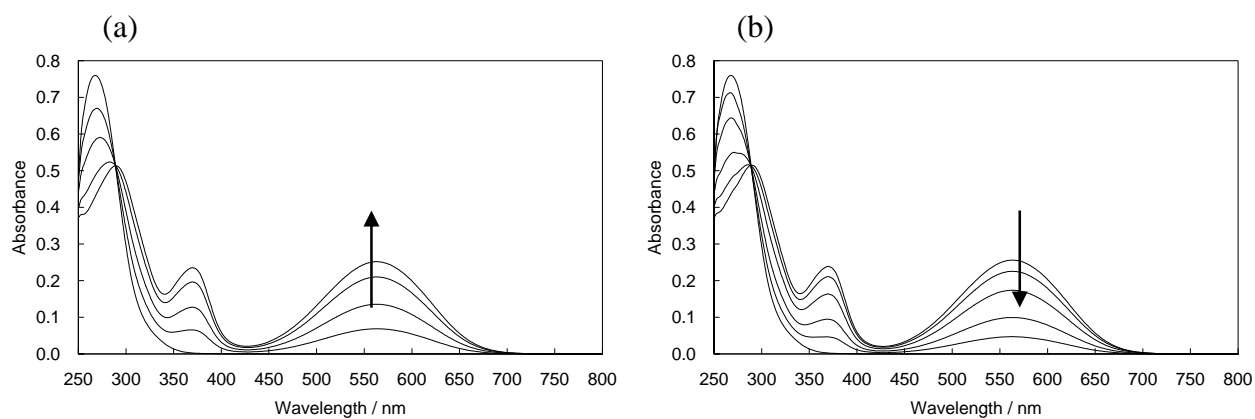


Figure S2. Absorption spectral changes in ethyl acetate

ESI-3. HPLC chromatograms of diarylethene **10** during photoirradiation

The photochromic reaction of **1** in hexane was followed by UV-vis spectral change as well as HPLC. First, **10** solution in hexane was measured (Fig. S3). Then, after 313-nm light irradiation was carried out until no change in the absorption spectra was observed (*i.e.* at the photostationary state: pss), the ratio of the components was determined by detection at the isosbestic point (Fig. S4). The new peak at *ca.* 13.5 min is assigned to the C-form. This pss solution was further checked at the absorption maximum wavelength of the C-form in the visible region (Fig. S5) where only C-forms can be detected. As shown in Fig. 3, only one peak was observed. However, this did not mean that the diastereoselectivity was 100%. Therefore, we carried out photoirradiation in hexane, toluene, and ethyl acetate, and their pss solutions were examined by HPLC equipped with different columns using different solvent systems as eluants. Details are described in ESI-4.

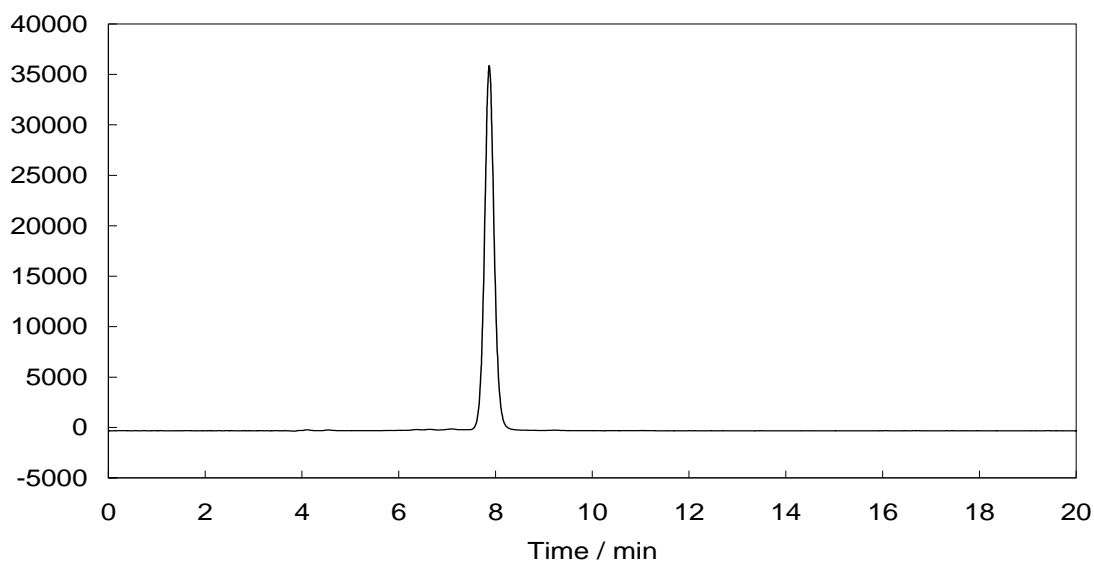


Figure S3. HPLC chromatogram of **10** before 313-nm light irradiation in hexane

Wakosil 5SIL, 33 v/v% AcOEt/hexane, 0.5 ml min⁻¹

Detection wavelength: 287 nm

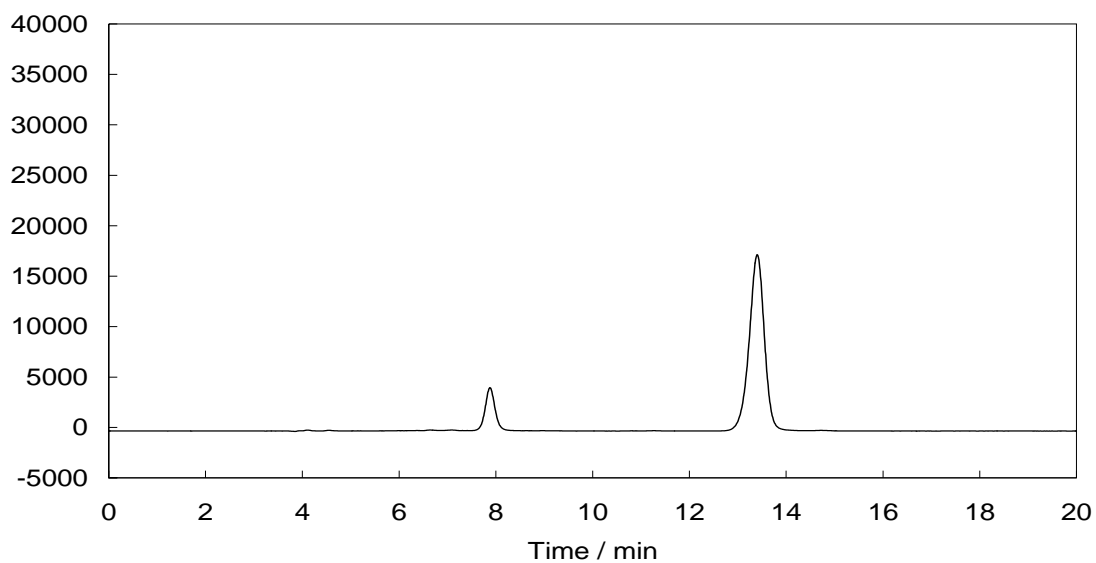


Figure S4. HPLC chromatogram of **1** at the photostationary state of 313-nm light in hexane
Wakosil 5SIL, 33 v/v% AcOEt/hexane, 0.5 ml min⁻¹
Detection wavelength: 287 nm

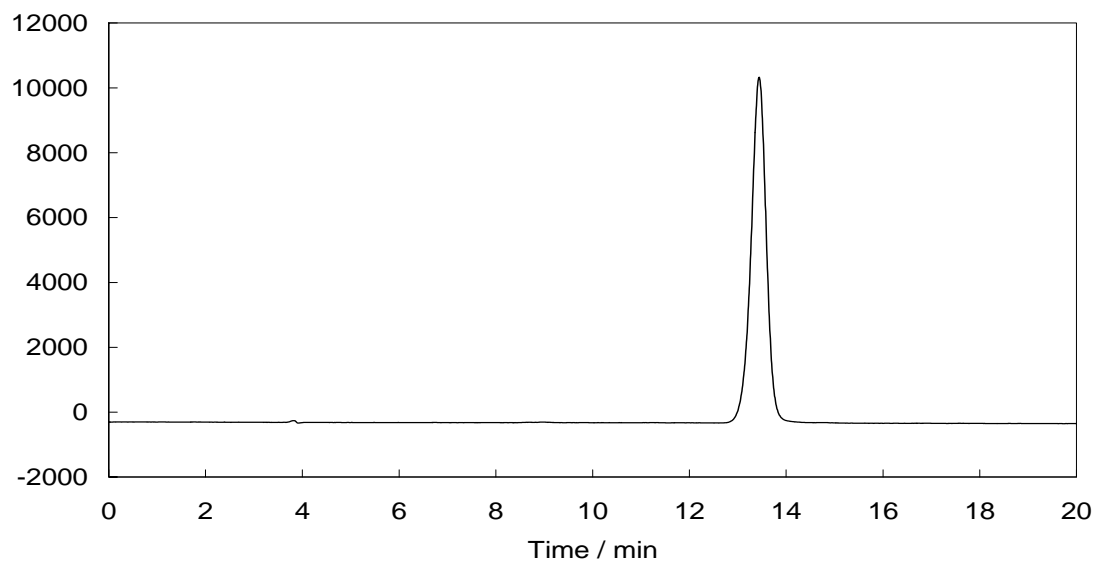


Figure S5. HPLC chromatogram of **1** at the photostationary state of 313-nm light in hexane
Wakosil 5SIL, 33 v/v% AcOEt/hexane, 0.5 ml min⁻¹
Detection wavelength: 559 nm

ESI-4. Diastereoselectivity examination with HPLC

In order to confirm that only one of two possible diastereomers of **1C** was formed upon 313-nm light irradiation to the solution of **1O**, solutions of hexane, toluene, and ethyl acetate of **1O** were irradiated and their pss solutions were examined by HPLC using three different columns with different solvent systems. Some of the results are shown as chromatograms. The rest of the results have been tabulated as follows: When columns with chiral adsorbents were used, the enantiomers (**1O_f** (faster-moving) and **1O_s** (slower-moving)) were resolved so that two pairs of peaks would be observed if two diastereomers were generated. However, none of them showed evidence of the generation of minor-colored forms. Together with the results of DFT calculations, we could conclude that the minor diastereomer was not produced by 313-nm light irradiation for all of these solvents.

Table S1. Detection of HPLC peaks

Solvent	Column	2-Propanol/Hexane	Ethyl acetate/Hexane	chloroform/Hexane
Hexane	Wakosil 5SIL	E, 1 peak (17%)	E, 1 peak (33%) Fig S6	-----
	Daicel Chiralpak IA	P, 2 peaks (5%)	G, 2 peaks (15%)	P, 2 peaks (10%)
	Daicel Chiralpak IB	G, 2 peaks (5%)	E, 2 peaks (15%)	P, 2 peaks (20%)
	Daicel Chiralcel OD-H	E, 2 peaks (5%)	-----	-----
Toluene	Wakosil 5SIL	E, 1 peak (17%)	E, 1 peak (33%)	-----
	Daicel Chiralpak IA	P, 2 peaks (5%)	G, 2 peaks (15%)	P, 2 peaks (10%)
	Daicel Chiralpak IB	G, 2 peaks (5%)	E, 2 peaks (15%) Fig. S7	P, 2 peaks (20%)
	Daicel Chiralcel OD-H	E, 2 peaks (5%)	-----	-----
Ethyl acetate	Wakosil 5SIL	E, 1 peak (17%)	E, 1 peak (33%)	-----
	Daicel Chiralpak IA	P, 2 peaks (5%)	G, 2 peaks (15%)	P, 2 peaks (10%)
	Daicel Chiralpak IB	G, 2 peaks (5%)	E, 2 peaks (15%)	P, 2 peaks (20%)
	Daicel Chiralcel OD-H	E, 2 peaks (5%) Fig. S8	-----	-----

Wakosil 5SIL: Non-chiral column. Enantiomers cannot be distinguished.

Daicel Chiralpak IA and IB: Chiral column. Distinguishes enantiomers. Ordinary solvents can be used.

Daicel Chiralcel OD-H: Chiral column. Distinguishes enantiomers. Column requires 2-propanol to be contained in the eluant.

E: Excellent resolution. G: Good resolution. P: Poor resolution.

Detection wavelength: 559 nm.

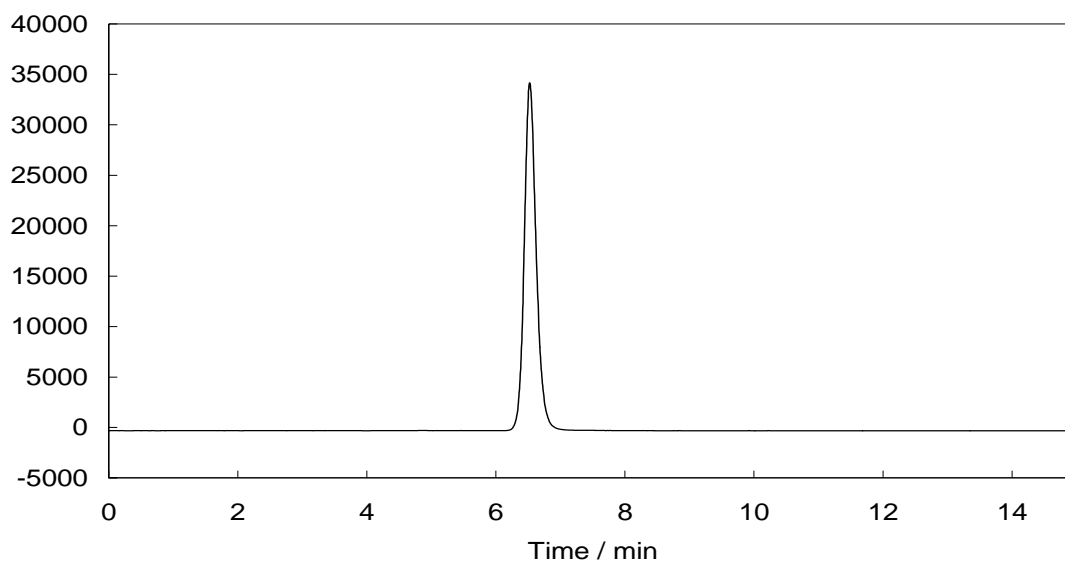


Figure S6. HPLC chromatogram of **1** at the photostationary state in hexane
Wakosil 5SIL, 17 v/v% 2-PrOH/hexane, 0.5 ml min⁻¹
Detection wavelength: 559 nm

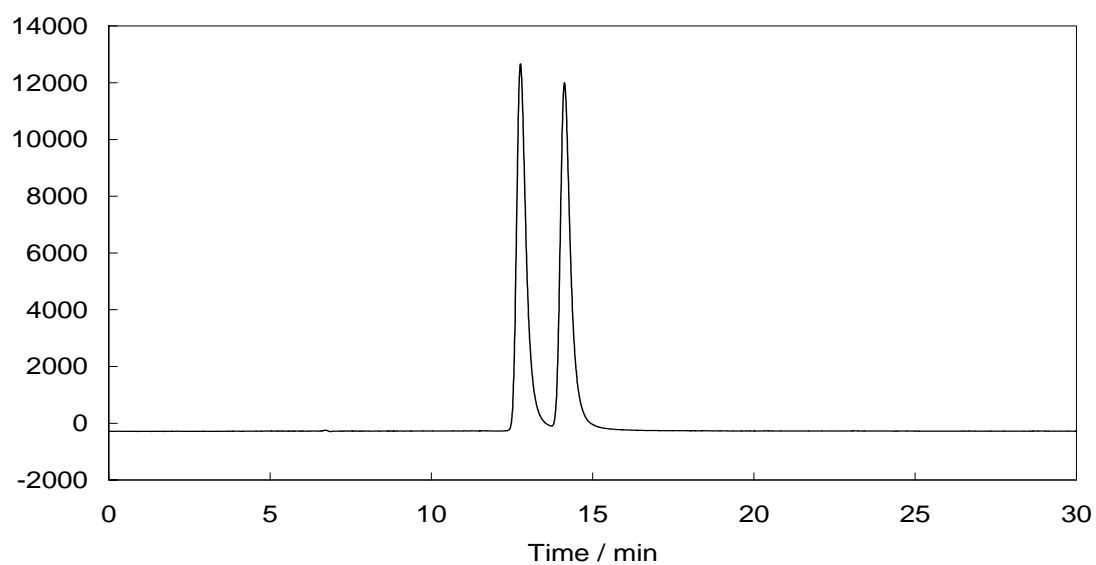


Figure S7. HPLC chromatogram of **1** at the photostationary state in toluene
Daicel Chiralpak IB, 15 v/v% AcOEt/hexane, 0.5 ml min⁻¹
Detection wavelength: 559 nm
The ratio of **10_f** and **10_s** is 50/50.

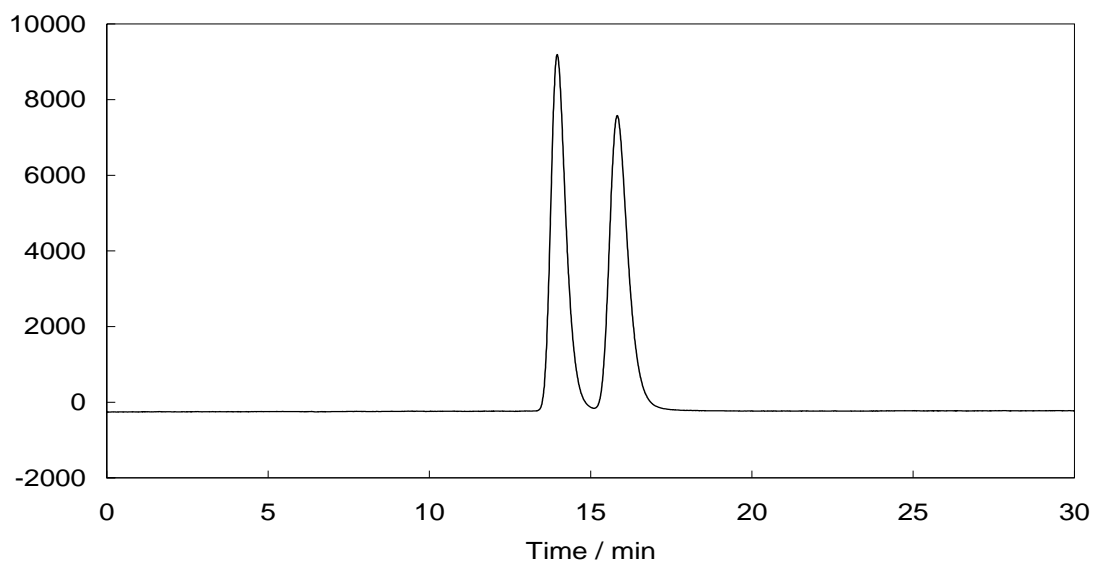


Figure S8. HPLC chromatogram of **1** at the photostationary state in ethyl acetate

Daicel Chiralcel OD-H, 5 v/v% 2-PrOH/hexane, 0.5 ml min⁻¹

Detection wavelength: 559 nm

The ratio of **1O_f** and **1O_s** is 50/50.

ESI-5. ¹H NMR spectra of compounds and diarylethene 10 in CDCl₃

DFILE: comp 4.als
 COMINT: comp 4
 DATIM: Tue Dec 01 10:43:58 2009
 OBNUC: 1H
 EXMOD: NON
 OBFRO: 399.65 MHz
 OBSET: 124.00 KHz
 OBFIN: 105000.00 Hz
 POINT: 32768
 FREQU: 7992.01 Hz
 SCANS: 16
 ACQTM: 4.1001 sec
 PD: 2.9000 sec
 PW1: 7.20 usec
 IRNUC: 1H
 CTEMP: 20.8 c
 SLVNT: CDCL3
 EXREF: 0.00 ppm
 BF: 0.12 Hz
 RGAIN: 24

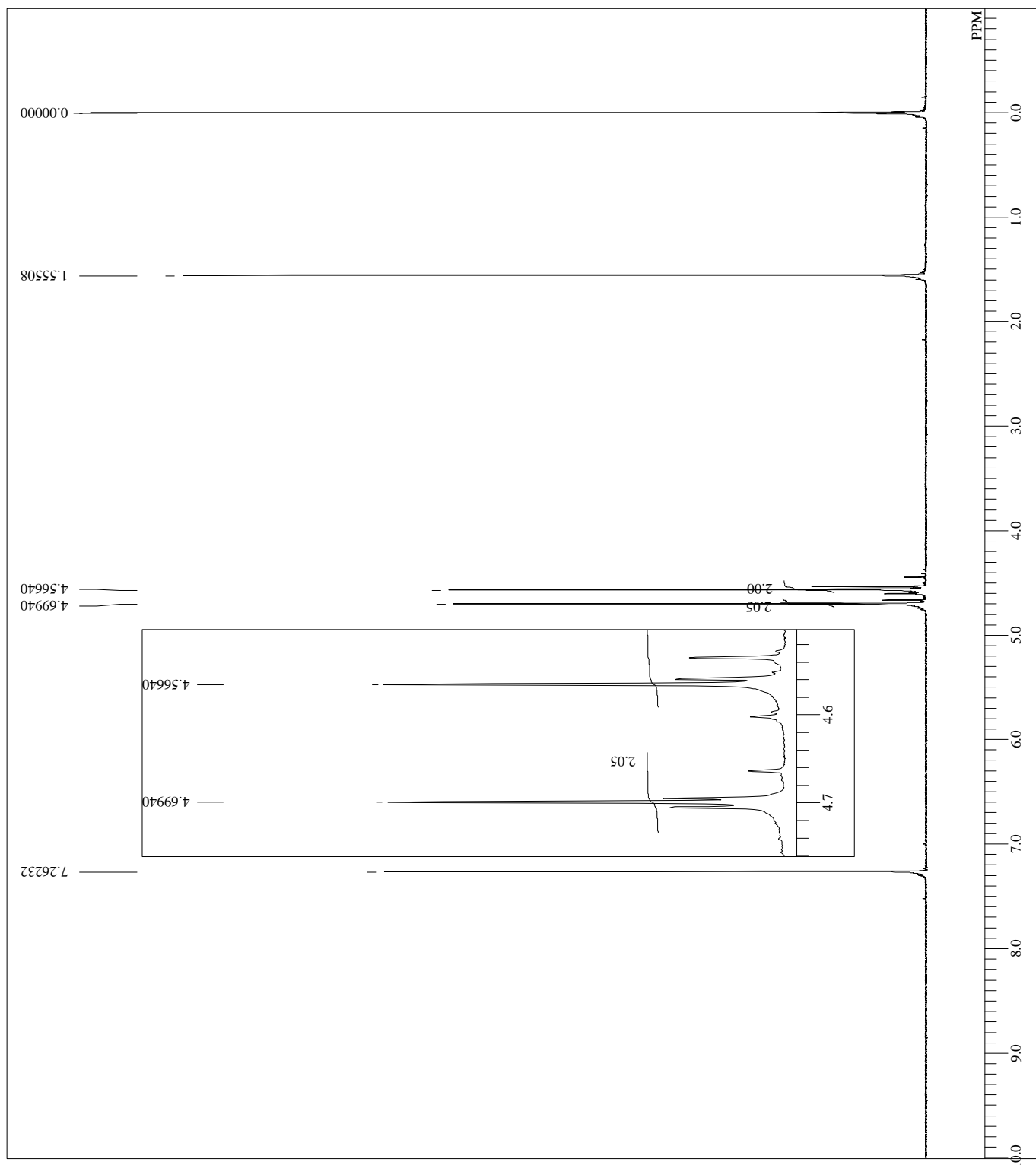
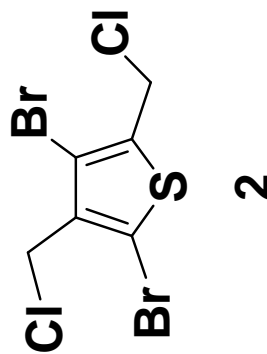


Fig. S9 ¹H NMR spectrum of compound **2** (400 MHz, TMS, CDCl₃)

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 EXMOD: NON
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 OBSET: 124.00 KHz
 OBFIN: 10500.00 Hz
 POINT: 32768
 FREQU: 7992.01 Hz
 SCANS: 16
 ACQTM: 4.1001 sec
 PD: 2.9000 sec
 PW1: 7.20 usec
 IRNUC: 1H
 CTEMP: 20.5 c
 SLVNT: CDCL3
 EXREF: 0.00 ppm
 BF: 0.12 Hz
 RGAIN: 22

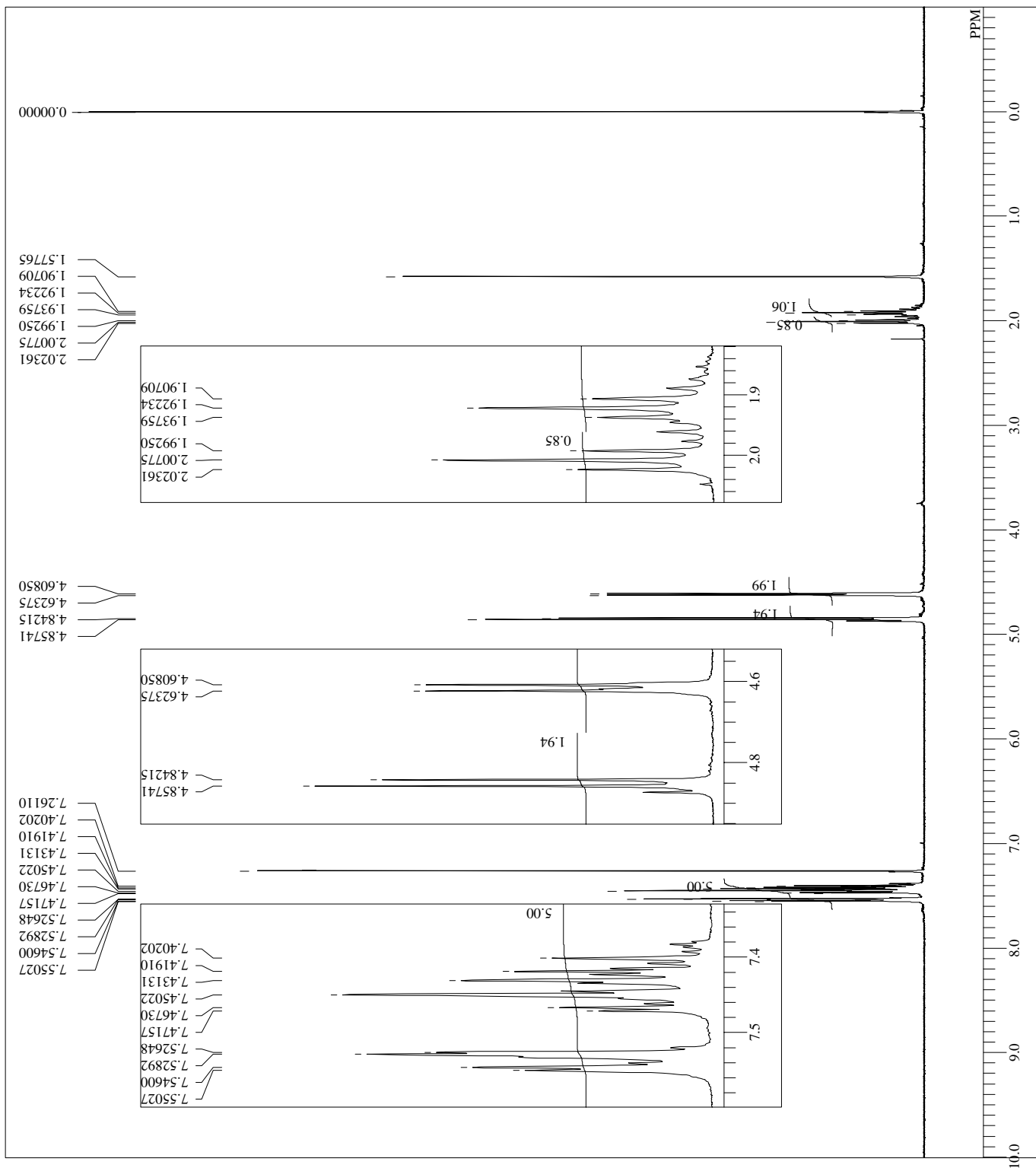
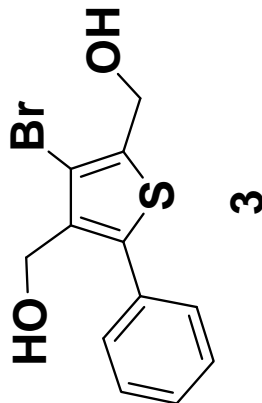


Fig. S10 ¹H NMR spectrum of compound **3** (400 MHz, TMS, CDCl₃)

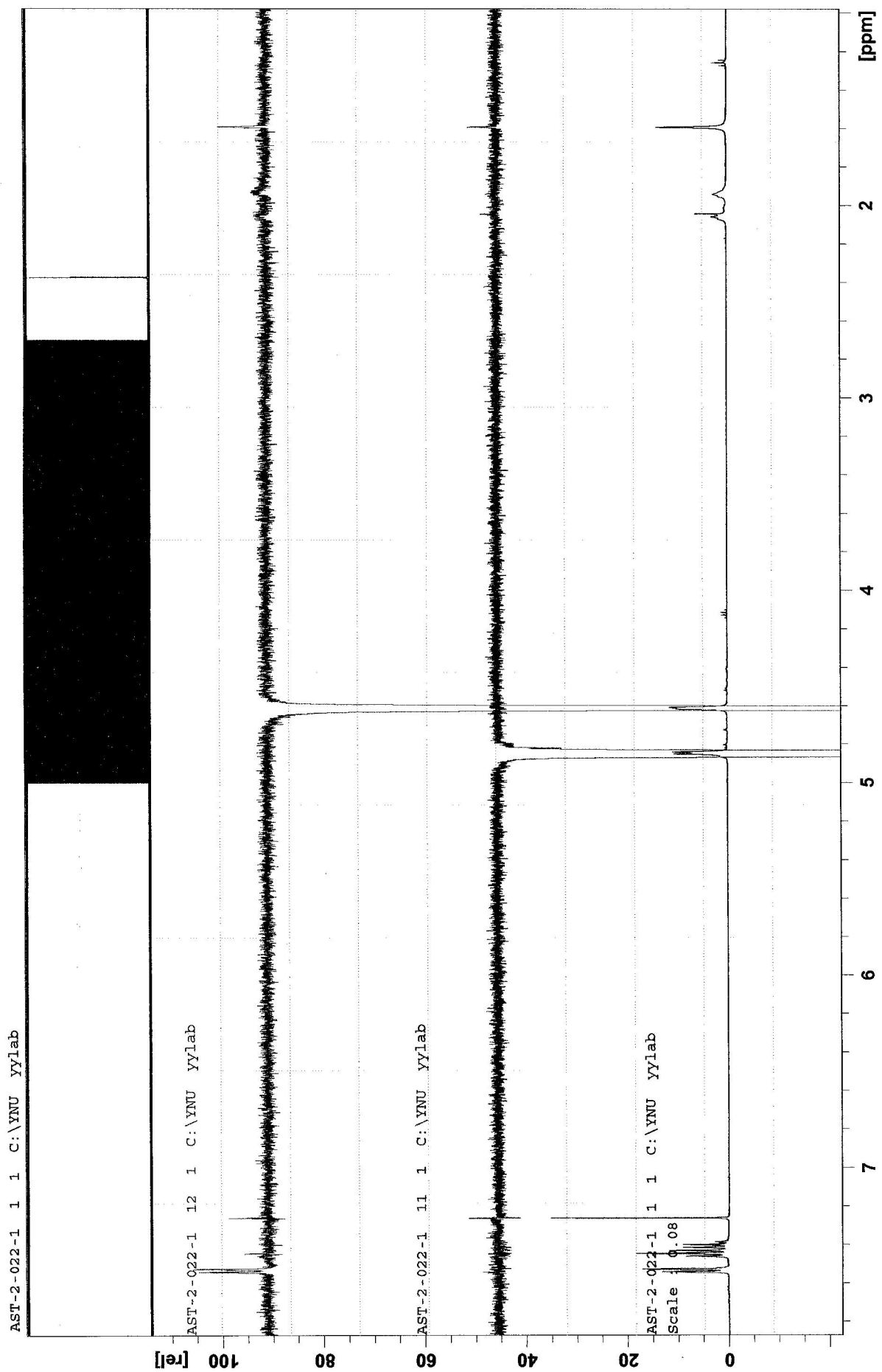


Fig. S11 NOE spectrum of compound **3** (500 MHz, TMS, C₂D₂Cl₄)

anyl-perfluorocyclopentene.als

COMT AST-2-094-1
DATIM Mon Jun 29 09:46:47 2009
OBNUC 1H
EXMOD NON
OBFRO 270.05 MHz
OBSET 112.00 KHz
OBFIN 5800.00 Hz
POINT 16384
FREQU 5405.40 Hz
SCANS 8
ACQTM 3.0310 sec
PD 3.9690 sec
PW1 4.90 usec
IRNUC 1H
CTEMP 23.4 c
SLVNT CDCL3
EXREF 0.00 ppm
BF 0.12 Hz
RGAIN 21

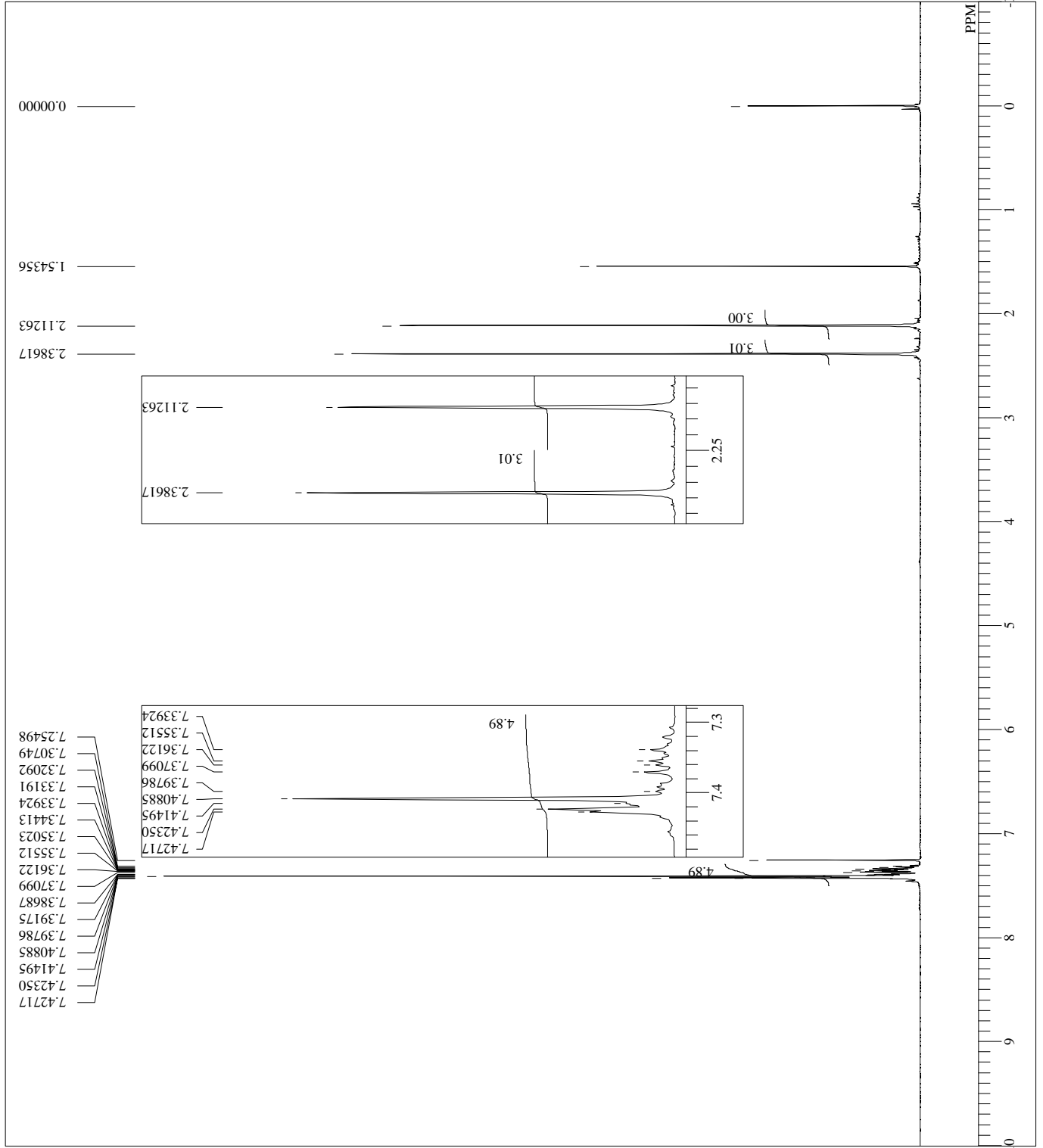
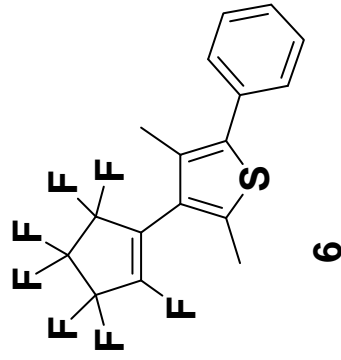


Fig. S13 ¹H NMR spectrum of compound 6 (270 MHz, TMS, CDCl₃)

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 OBNUC zg30
 EXMOD 500.13 MHz
 OBFRO 3.08 KHz
 OBSET 8.51 Hz
 OBFIN 32768
 POINT 10330.58 Hz
 FREQU 8
 SCANS 3.1720 sec
 ACQTM 3.8280 sec
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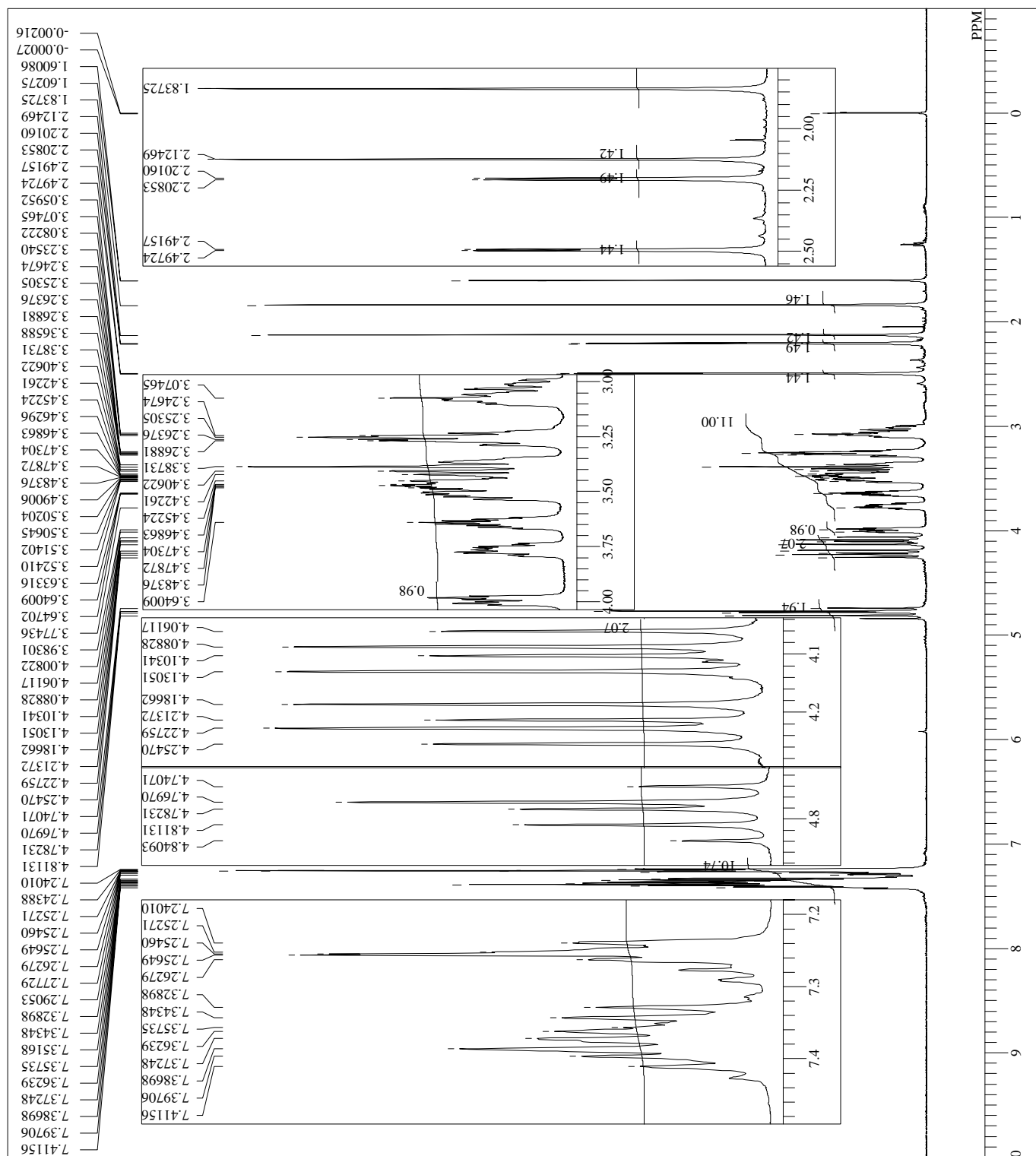


Fig. S14 ¹H NMR spectrum of diarylethene **10** (500 MHz, TMS, CDCl₃)

ESI-6. CD spectra of enantiomers of **1O** and their photostationary states

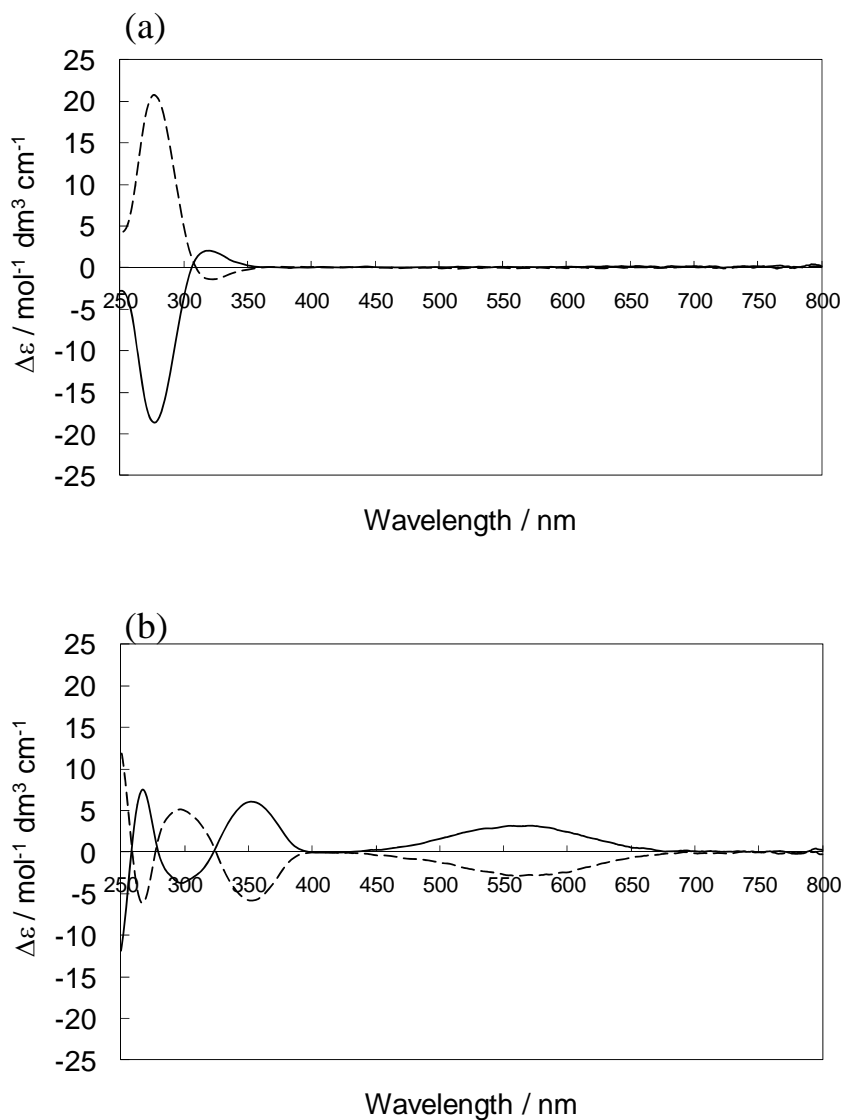


Figure S16. CD spectra of optically resolved enantiomers of **1O** and their pss of 313-nm irradiation in hexane. Optical resolution: Daicel Chiralpak IA with 4.5% CHCl_3 -hexane. Solid line: (a) **1O_f** (faster moving enantiomer) and (b) its pss. Broken line: (a) **1O_s** (slower moving enantiomer) and (b) its pss.