

# Synthesis and Properties of Amino Acid-derived Optically Active Photo-responsive Polymers

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## Summary

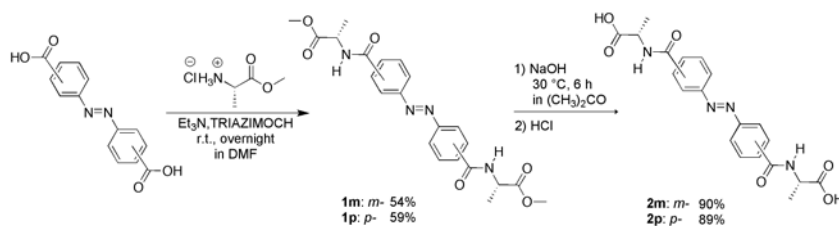
Optically active azobenzenedicarboxylic acids were synthesized from L-alanine, and the polycondensation of the diacids with *o*-, *m*-, *p*-xylylenediols, 5-norbornene-2,3-*endo,endo*- and *exo,exo*-dimethanols, *m*-, *p*-xylylenediamines, and *trans*-1,4-cyclohexanediamine was carried in *N,N*-dimethylformamide. Polymers with weight-average molecular weights of 3,300–33,700 were obtained in 63%–quantitative yields. All the polymers reversibly isomerized the azobenzene units from *trans* to *cis* and vice versa upon UV- and visible-light irradiations. The polymers exhibited no evidence for the formation of a chiral secondary structure.

## Introduction

Polymers that transform the structures by external stimuli such as temperature [1], pH [2], and light [3,4] gather much interest. Especially, photo-responsive polymers enable the design of highly sensitive photo-functional materials because of easy control over the irradiation wavelength, time, and intensity. Conformational changes of polymers induced by the isomerization of photochromic groups lead to the changes of physical and chemical properties including viscosity, conductivity, solubility, wettability, morphology, and so on [3–8].

Many attempts have been made to synthesize well-defined photo-responsive polymers, where azobenzene [9–12], spiropyran [13–15], and diarylethene [16–19] are commonly introduced as a photo-responsive chromophore at the main chain or side chain. For example, *trans*-azobenzene absorbs light around 320 nm based on the  $\pi$ – $\pi^*$  transition to transform into *cis*-azobenzene, and the *cis*-isomer absorbs light based on the  $n$ – $\pi^*$  transition around 430 nm to transform into *trans*-one reversibly, accompanying large changes of conformation and dipole moment. The *cis*-form also isomerizes into *trans*-one upon heating due to the low activation energy from *cis* to *trans*. We have previously synthesized conjugated polymers bearing azobenzene moieties in the main chain [20–23], some of which reversibly undergo *cis-trans* isomerization in spite of the rigid structures. We have also synthesized polyacetylenes substituted with azobenzene at the side chains [24–27]. Among them, chiral polymers form a helical structure with predominantly one-handed screw sense, and the photo-isomerization of the azobenzene moieties triggers the transformation of the secondary

structure to alternate the chiroptical properties. Amino acids are the useful biological chiral resources. Polymers containing amino acids attract attention due to their optical and biological activities [28–33]. In the course of our study on azobenzene-containing conjugated polymers, we have designed novel optically active amino acid-based polymers containing azobenzene moieties in the main chain, expecting the changes of chiroptical properties upon photo-irradiation. This article deals with the polycondensation of optically active azobenzenedicarboxylic acids with diols and diamines, and the photo-isomerization behavior of the obtained polymers (Scheme 1).



**Scheme 1.** Synthesis of monomers

## Experimental

### Measurements

$^1\text{H}$  (400 MHz) and  $^{13}\text{C}$  (100 MHz) NMR spectra were recorded on a JEOL EX-400 spectrometer. IR spectra were measured on a JASCO FT/IR-4100 spectrophotometer. Melting points (mp) were measured on a Yanaco micro melting point apparatus. Specific rotations ( $[\alpha]_D$ ) were measured on a JASCO DIP-100 digital polarimeter with a sodium lamp as a light source. Elemental analysis was done at the Microanalytical Center of Kyoto University. Number- and weight-average molecular weights ( $M_n$  and  $M_w$ ) of polymers were determined by gel permeation chromatography (GPC) on TSK gel  $\alpha$ -3000, using a solution of LiBr (10 mM) in *N,N*-dimethylformamide (DMF) as an eluent at a flow rate of 1.0 mL/min, calibrated by polystyrene standards at 40 °C. UV–vis absorption spectra were recorded on a JASCO J-820 spectropolarimeter.

### Materials

All the reagents and solvents were used as purchased without purification.

### Synthesis of **1m**

3,3'-Azobenzenedicarboxylic acid (1.08 g, 4.00 mmol) was dissolved in DMF (12 mL), and triethylamine (1.23 mL, 8.80 mmol) was added to the solution at room temperature. L-Alanine methyl ester hydrochloride (1.23 g, 8.80 mmol) and 4-[4,6-dimethoxy-1,3,5-triazin-2-yl]-4-methylmorpholinium chloride (TRIAZIMOCH, Tokuyama Co., 2.86 g, 8.80 mmol) were added to the mixture, and the resulting mixture was stirred at room temperature overnight. DMF was then distilled off using a rotary evaporator, and the residue was dissolved in  $\text{CH}_2\text{Cl}_2$ . The solution was washed with 0.5 M HCl, saturated  $\text{NaHCO}_3$  aq., saturated NaCl aq., and then dried over anhydrous  $\text{MgSO}_4$ . The residue was purified by recrystallization with methanol/ethyl

acetate to obtain **1m** as orange solid in 54%. Mp 192–194 °C.  $[\alpha]_D^{+40}$  ( $c = 0.100$  g/dL in DMF at room temperature).  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  1.57 (s, 6H,  $-\text{CHCH}_3-$ ), 3.82 (s, 6H,  $-\text{OCH}_3$ ), 4.80–4.87 (m, 2H,  $-\text{CHCH}_3-$ ), 6.83 (d, 2H,  $-\text{CHNH}-$ ), 7.95–8.01 (m, 8H, Ar).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  18.7 ( $-\text{CHCH}_3-$ ), 48.6 ( $-\text{CHCH}_3-$ ), 123.2, 128.1, 136.1, 154.2 (Ar), 166.0 ( $-\text{NHCO}-$ ), 173.6 ( $-\text{COOCH}_3$ ). Anal. Calcd for  $\text{C}_{22}\text{H}_{24}\text{N}_4\text{O}_6$ : C, 59.99; H, 5.49; N, 12.72. Found: C, 59.71; H, 5.41; N, 12.76.

#### Synthesis of **2m**

0.5 M NaOH aq. (8.00 mL, 4.00 mmol) was added to a suspension of **1m** (0.805 g, 1.81 mmol) in acetone (40 mL), and the mixture was stirred at 30 °C for 6 h. 0.5 M HCl aq. (8.00 mL, 4.00 mmol) was added to the resultant mixture, and it was concentrated on a rotary evaporator. The residual solid was washed with ethyl acetate to obtain **2m** as orange solid in 86% yield. Mp 256–257 °C.  $[\alpha]_D^{+80}$  ( $c = 0.100$  g/dL in DMF at room temperature).  $^1\text{H}$  NMR (400 MHz,  $\text{DMSO}-d_6$ ):  $\delta$  1.42 (d,  $J = 7.4$  Hz, 6H,  $-\text{CHCH}_3-$ ), 4.42–4.49 (m, 2H,  $-\text{CHCH}_3-$ ), 7.73 (t,  $J = 7.8$  Hz, 2H, Ar), 8.09 (d,  $J = 7.6$  Hz, 4H, Ar), 8.44 (s, 2H, Ar), 8.94 (d,  $J = 7.1$  Hz, 2H,  $-\text{CHCH}_3\text{NH}-$ ), 12.5 (s, 2H,  $-\text{COOH}$ ).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  16.9 ( $-\text{CHCH}_3-$ ), 48.3 ( $-\text{CHCH}_3-$ ), 121.4, 125.4, 129.7, 130.6, 135.3, 151.7 (Ar), 165.3 ( $-\text{NHCO}-$ ), 174.1 ( $-\text{COOH}$ ). Anal. Calcd for  $\text{C}_{20}\text{H}_{20}\text{N}_4\text{O}_6$ : C, 58.25; H, 4.89; N, 13.59. Found: C, 57.96; H, 4.91; N, 13.48.

#### Synthesis of **1p**

The title compound was synthesized from 4,4'-azobenzenedicarboxylic acid and L-alanine methyl ester hydrochloride in a manner similar to **1m**. Yield 49%. Mp 231–233 °C.  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ ):  $\delta$  1.57 (s, 6H,  $-\text{CHCH}_3-$ ), 3.82 (s, 6H,  $-\text{OCH}_3$ ), 4.80–4.87 (m, 2H,  $-\text{CHCH}_3-$ ), 6.83 (d, 2H,  $-\text{CHNH}-$ ), 7.95–8.01 (m, 8H, Ar).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  18.7 ( $-\text{CHCH}_3-$ ), 48.6 ( $-\text{CHCH}_3-$ ), 123.2, 128.1, 136.1, 154.2 (Ar), 166.0 ( $-\text{NHCO}-$ ), 173.6 ( $-\text{COOCH}_3$ ).

#### Synthesis of **2p**

The title compound was synthesized from **2p** in a manner similar to **2m**. Yield 98%. No mp was observed up to 281 °C (decomposition).  $[\alpha]_D^{+120}$  ( $c = 0.100$  g/dL in DMF at room temperature).  $^1\text{H}$  NMR (400 MHz,  $\text{DMSO}-d_6$ ):  $\delta$  1.42 (d,  $J = 7.7$  Hz, 6H,  $-\text{CHCH}_3-$ ), 4.39–4.48 (m, 2H,  $-\text{CHCH}_3-$ ), 8.00 (d,  $J = 8.3$  Hz, 4H, Ar), 8.11 (d,  $J = 8.3$  Hz, 4H, Ar), 8.88 (d,  $J = 7.1$  Hz, 2H,  $-\text{CHCH}_3\text{NH}-$ ), 12.6 (s, 2H,  $-\text{COOH}$ ).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ ):  $\delta$  16.8 ( $-\text{CHCH}_3-$ ), 48.3 ( $-\text{CHCH}_3-$ ), 122.6, 128.8, 136.5, 153.3 (Ar), 165.3 ( $-\text{NHCO}-$ ), 174.1 ( $-\text{COOH}$ ). Anal. Calcd for  $\text{C}_{20}\text{H}_{20}\text{N}_4\text{O}_6$ : C, 58.25; H, 4.89; N, 13.59. Found: C, 57.89; H, 4.86; N, 13.38.

#### Polycondensation: A typical procedure

A solution of **2m** (166 mg, 0.402 mmol), **3** (56 mg, 0.405 mmol), 1-[3-(dimethylamino)propyl]-3-ethylcarbodiimide hydrochloride (EDC•HCl, 162 mg, 0.845 mmol), and 4-(dimethylamino)pyridine (DMAP, 10 mg, 0.081 mmol) in DMF (0.8 mL) was stirred at 30 °C for 24 h. The resulting mixture was poured into a large amount of 0.5 M  $\text{NaHCO}_3$  aq. to precipitate a solid polymer. It was washed with 0.5 M  $\text{NaHCO}_3$  aq., separated by filtration with a membrane filter (pore size 0.2  $\mu\text{m}$ ), and dried *in vacuo*.

*Spectroscopic Data of the Polymers*

Poly(**2m-3**)  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta$  1.44 (br, 6H,  $-\text{CHCH}_3-$ ), 4.54 (br, 2H,  $-\text{CHCH}_3-$ ), 5.20 (br, 4H,  $-\text{CH}_2\text{O}-$ ), 7.23-7.40 (br, 4H, Ar), 7.72 (br, 2H, Ar), 8.09 (br, 4H, Ar), 8.42 (br, 2H, Ar), 9.09 (br, 2H,  $-\text{NHCO}-$ ). IR ( $\text{cm}^{-1}$ , KBr): 2877 (CH), 1744 (COO), 1647 (C=O), 1528 (NHCO), 1303, 1206, 1157, 758, 691.

Poly(**2m-4**)  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta$  1.44 (br, 6H,  $-\text{CHCH}_3-$ ), 4.54 (br, 2H,  $-\text{CHCH}_3-$ ), 5.16 (br, 4H,  $-\text{CH}_2\text{O}-$ ), 7.23-7.30 (br, 4H, Ar), 7.72 (br, 2H, Ar), 8.08 (br, 4H, Ar), 8.50 (br, 2H, Ar), 9.09 (br, 2H,  $-\text{NHCO}-$ ). IR ( $\text{cm}^{-1}$ , KBr): 2987 (CH), 1745 (COO), 1653 (C=O), 1527 (NHCO), 1304, 1205, 1157, 691.

Poly(**2m-5**)  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta$  1.44 (br, 6H,  $-\text{CHCH}_3-$ ), 4.54 (br, 2H,  $-\text{CHCH}_3-$ ), 5.13 (br, 4H,  $-\text{CH}_2\text{O}-$ ), 7.23-7.34 (br, 4H, Ar), 7.72 (br, 2H, Ar), 7.92-8.21 (br, 4H, Ar), 8.51 (br, 2H, Ar), 9.09 (br, 2H,  $-\text{NHCO}-$ ). IR ( $\text{cm}^{-1}$ , KBr): 2986 (CH), 1744 (COO), 1647 (C=O), 1527 (NHCO), 1306, 1209, 1157, 813.

Poly(**2m-6**)  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta$  1.30-1.72 (br, 8H,  $-\text{CHCH}_3-$  bridge position), 2.20 (br, 2H, norbornene CH), 2.82-3.35 (br, 6H, norbornene CH,  $-\text{CH}_2\text{O}-$ ), 4.46 (br, 2H,  $-\text{CHCH}_3-$ ), 6.06 (br, 2H,  $-\text{CH}=\text{CH}-$ ), 7.70 (br, 2H, Ar), 8.09-8.21 (br, 4H, Ar), 8.42 (br, 2H, Ar), 9.09 (br, 2H,  $-\text{NHCO}-$ ). IR ( $\text{cm}^{-1}$ , KBr): 2979 (CH), 1746 (COO), 1606 (C=O), 1524 (NHCO), 1302, 1210, 1156, 997.

Poly(**2m-7**)  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta$  1.39-1.71 (br, 8H,  $-\text{CHCH}_3-$  bridge position), 2.16 (br, 2H, norbornene CH), 2.82-3.35 (br, 6H, norbornene CH,  $-\text{CH}_2\text{O}-$ ), 4.42 (br, 2H,  $-\text{CHCH}_3-$ ), 6.09 (br, 2H,  $-\text{CH}=\text{CH}-$ ), 7.72 (br, 2H, Ar), 8.09-8.21 (br, 4H, Ar), 8.42 (br, 2H, Ar), 9.08 (br, 2H,  $-\text{NHCO}-$ ). IR ( $\text{cm}^{-1}$ , KBr): 2980 (CH), 1746 (COO), 1647 (C=O), 1536 (NHCO), 1306, 1209, 1157, 813.

Poly(**2m-8**)  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta$  1.41 (br, 6H,  $-\text{CHCH}_3-$ ), 4.02 (br, 4H,  $-\text{CH}_2\text{NH}-$ ), 4.55 (br, 2H,  $-\text{CHCH}_3-$ ), 7.14-7.37 (br, 4H, Ar), 7.72 (br, 2H, Ar), 8.08 (br, 4H, Ar), 8.52 (br, 2H, Ar), 8.58 (br, 2H,  $-\text{CH}_2\text{NH}-$ ), 8.94 (br, 2H,  $-\text{NHCO}-$ ). IR ( $\text{cm}^{-1}$ , KBr): 2988 (CH), 1640 (C=O), 1536 (NHCO), 1326, 1218, 692.

Poly(**2m-9**)  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta$  1.39 (br, 6H,  $-\text{CHCH}_3-$ ), 4.11 (br, 4H,  $-\text{CH}_2\text{NH}-$ ), 5.04 (br, 2H,  $-\text{CHCH}_3-$ ), 7.14 (br, 4H, Ar), 7.71 (br, 2H, Ar), 8.11 (br, 4H, Ar), 8.46 (br, 4H, Ar), 8.81 (br, 2H,  $-\text{NHCO}-$ ), 9.93 (br, 2H,  $-\text{CH}_2\text{NH}-$ ). IR ( $\text{cm}^{-1}$ , KBr): 2940 (CH), 1651 (C=O), 1526 (NHCO), 1306, 758, 691.

Poly(**2m-10**)  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta$  1.06-1.18 (br, 8H,  $-\text{C}_6\text{H}_8\text{H}_2-$ ), 1.41 (br, 6H,  $-\text{CHCH}_3-$ ), 1.72 (br, 2H,  $-\text{C}_6\text{H}_8\text{H}_2-$ ), 4.45 (br, 2H,  $-\text{CHCH}_3-$ ), 7.73 (br, 2H, Ar), 8.09 (br, 4H, Ar), 8.43 (br, 4H, Ar), 8.71 (br, 2H,  $-\text{CH}_2\text{NH}-$ ), 9.09 (br, 2H,  $-\text{NHCO}-$ ). IR ( $\text{cm}^{-1}$ , KBr): 2938 (CH), 1647 (C=O), 1523 (NHCO), 1304, 1210, 1157.

Poly(**2p-3**)  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta$  1.44 (br, 6H,  $-\text{CHCH}_3-$ ), 4.54 (br, 2H,  $-\text{CHCH}_3-$ ), 5.17 (br, 4H,  $-\text{CH}_2\text{O}-$ ), 6.67 (br, 2H,  $-\text{NHCO}-$ ), 7.22-7.41 (br, 4H, Ar), 7.94 (br, 4H, Ar), 8.09 (br, 4H, Ar). IR ( $\text{cm}^{-1}$ , KBr): 2960 (CH), 1818 (COO), 1647 (C=O), 1604, 1515 (NHCO), 1250, 1172, 1087, 1021.

Poly(**2p-4**)  $^1\text{H}$  NMR (400 MHz, DMSO- $d_6$ ):  $\delta$  1.44 (br, 6H,  $-\text{CHCH}_3-$ ), 4.54 (br, 2H,  $-\text{CHCH}_3-$ ), 5.17 (br, 4H,  $-\text{CH}_2\text{O}-$ ), 6.67 (br, 2H,  $-\text{NHCO}-$ ), 7.22-7.41 (br, 4H, Ar), 7.94 (br, 4H, Ar), 8.09 (br, 4H, Ar). IR ( $\text{cm}^{-1}$ , KBr): 2959 (CH), 1818 (COO), 1647 (C=O), 1604, 1516 (NHCO), 1317.

Poly(**2p-5**)  $^1\text{H}$  NMR (400 MHz,  $\text{DMSO-}d_6$ ):  $\delta$  1.45 (br, 6H,  $-\text{CHCH}_3-$ ), 4.46 (br, 2H,  $-\text{CHCH}_3-$ ), 5.14 (br, 4H,  $-\text{CH}_2\text{O}-$ ), 6.69 (br, 2H,  $-\text{NHCO}-$ ), 7.27-7.30 (br, 4H, Ar), 8.00 (br, 4H, Ar), 8.12 (br, 4H, Ar). IR ( $\text{cm}^{-1}$ , KBr): 2964 (CH), 1818 (COO), 1647 (C=O), 1604, 1514 (NHCO), 1317.

Poly(**2p-6**)  $^1\text{H}$  NMR (400 MHz,  $\text{DMSO-}d_6$ ):  $\delta$  1.27-1.78 (br, 8H,  $-\text{CHCH}_3-$  bridge position), 2.35 (br, 2H, norbornene CH), 2.71-3.35 (br, 6H, norbornene CH,  $-\text{CH}_2\text{O}-$ ), 4.45 (br, 2H,  $-\text{CHCH}_3-$ ), 6.06 (br, 2H,  $-\text{CH}=\text{CH}-$ ), 6.63 (br, 2H,  $-\text{NHCO}-$ ), 8.09 (br, 4H, Ar), 8.13 (br, 4H, Ar). IR ( $\text{cm}^{-1}$ , KBr): 2984 (CH), 1815 (COO), 1604, 1487 (NHCO), 1177, 1113.

Poly(**2p-7**)  $^1\text{H}$  NMR (400 MHz,  $\text{DMSO-}d_6$ ):  $\delta$  1.30-1.87 (br, 8H,  $-\text{CHCH}_3-$  bridge position), 2.35 (br, 2H, norbornene CH), 2.71-3.35 (br, 6H, norbornene CH,  $-\text{CH}_2\text{O}-$ ), 4.56 (br, 2H,  $-\text{CHCH}_3-$ ), 6.12 (br, 2H,  $-\text{CH}=\text{CH}-$ ), 6.57 (br, 2H,  $-\text{NHCO}-$ ), 8.08 (br, 4H, Ar), 8.12 (br, 4H, Ar). IR ( $\text{cm}^{-1}$ , KBr): 2964 (CH), 1821 (COO), 1647 (C=O), 1604, 1509 (NHCO), 1317, 1002.

Poly(**2p-8**)  $^1\text{H}$  NMR (400 MHz,  $\text{DMSO-}d_6$ ):  $\delta$  1.40 (br, 6H,  $-\text{CHCH}_3-$ ), 4.02 (br, 4H,  $-\text{CH}_2\text{NH}-$ ), 4.55 (br, 2H,  $-\text{CHCH}_3-$ ), 7.26-7.42 (br, 4H, Ar), 7.65 (br, 2H,  $-\text{NHCO}-$ ), 7.99 (br, 4H, Ar), 8.10 (br, 4H, Ar), 8.82 (br, 2H,  $-\text{CH}_2\text{NH}-$ ). IR ( $\text{cm}^{-1}$ , KBr): 2940 (CH), 1642 (C=O), 1530 (NHCO), 1297, 1159, 861.

Poly(**2p-9**)  $^1\text{H}$  NMR (400 MHz,  $\text{DMSO-}d_6$ ):  $\delta$  1.53 (br, 6H,  $-\text{CHCH}_3-$ ), 4.28 (br, 4H,  $-\text{CH}_2\text{NH}-$ ), 4.54 (br, 2H,  $-\text{CHCH}_3-$ ), 6.73 (br, 2H,  $-\text{NHCO}-$ ), 7.19-7.48 (br, 4H, Ar), 8.01 (br, 4H, Ar), 8.36 (br, 4H, Ar), 8.80 (br, 2H,  $-\text{CH}_2\text{NH}-$ ). IR ( $\text{cm}^{-1}$ , KBr): 2983 (CH), 1652 (C=O), 1604, 1527 (NHCO), 1304, 1177, 1003.

Poly(**2p-10**)  $^1\text{H}$  NMR (400 MHz,  $\text{DMSO-}d_6$ ):  $\delta$  1.06-1.18 (br, 8H,  $-\text{C}_6\text{H}_8\text{H}_2-$ ), 1.42 (br, 6H,  $-\text{CHCH}_3-$ ), 1.72 (br, 2H,  $-\text{C}_6\text{H}_8\text{H}_2-$ ), 4.44 (br, 2H,  $-\text{CHCH}_3-$ ), 6.72 (br, 2H,  $-\text{NHCO}-$ ), 8.01 (br, 4H, Ar), 8.11 (br, 4H, Ar), 8.97 (br, 2H,  $-\text{CH}_2\text{NH}-$ ). IR ( $\text{cm}^{-1}$ , KBr): 2939 (CH), 1653 (C=O), 1604, 1522 (NHCO), 1487, 1299, 1007.

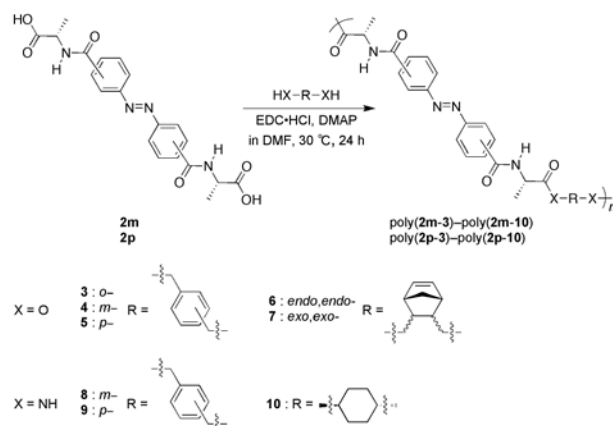
#### Photo-irradiation

Photo-irradiation was carried out with a 400 W high-pressure mercury lamp equipped with a power source (HB-400, Fuji Glass Work) at room temperature. The appropriate wavelengths were selected either with a Pyrex glass and a UV-D33S filter (Toshiba) for irradiation at  $300\text{ nm} < \lambda < 400\text{ nm}$  or with an L-42 filter (Toshiba) for irradiation at  $420\text{ nm} < \lambda$ . Sample solutions were fed in a quartz cell, and it was placed 20 cm apart from the lamp. The photo-isomerization was monitored by UV-vis absorption spectroscopy.

## Results and discussion

### Polycondensation

The polycondensation of **2m** and **2p** with diols **3–7** and diamines **8–10** was carried out using EDC•HCl as a condensation agent in the presence of DMAP in DMF at 30 °C for 24 h (Scheme 2). As summarized in Table 1, polymers with  $M_w$ 's of 3,300–33,700



**Scheme 1.** Polycondensation of **2m** and **2p** with diols **3–7** and diamines **8–10**

**Table 1.** Polymerization of **1** and **2**<sup>a</sup>

Monomer	Polymer			
	Yield (%)	$M_w^d$	$M_w/M_n^d$	$[\alpha]_D^f$ (deg)
<b>2m+3</b>	89 <sup>b</sup>	4,800	1.8	10
<b>2m+4</b>	86 <sup>b</sup>	7,500	1.7	6
<b>2m+5</b>	86 <sup>b</sup>	8,100	2.2	0
<b>2m+6</b>	80 <sup>b</sup>	6,600	1.8	2
<b>2m+7</b>	70 <sup>b</sup>	4,500	1.9	3
<b>2m+8</b>	65 <sup>c</sup>	3,300	1.4	4
<b>2m+9</b>	95 <sup>c</sup>	19,600	3.2	4
<b>2m+10</b>	63 <sup>c</sup>	7,600	1.5	8
<b>2p+3</b>	86 <sup>b</sup>	8,000	2.1	6
<b>2p+4</b>	99 <sup>b</sup>	20,400	4.5	−1 <sup>g</sup>
<b>2p+5</b>	99 <sup>b</sup>	13,100	2.6	33 <sup>g</sup>
<b>2p+6</b>	99 <sup>b</sup>	— <sup>e</sup>	— <sup>e</sup>	— <sup>e</sup>
<b>2p+7</b>	84 <sup>b</sup>	33,700	6.4	3 <sup>g</sup>
<b>2p+8</b>	75 <sup>c</sup>	3,500	1.5	55
<b>2p+9</b>	78 <sup>c</sup>	23,800	3.3	16
<b>2p+10</b>	85 <sup>c</sup>	8,200	2.5	15

<sup>a</sup>Conditions:  $[\mathbf{2m}]_0 = [\mathbf{2p}]_0 = [\mathbf{3-10}]_0 = 0.5$  M,  $[\text{EDC}\cdot\text{HCl}] = 1.1$  M,  $[\text{DMAP}] = 0.1$  M in DMF at 30 °C for 24 h. <sup>b</sup> $\text{NaHCO}_3$  aq.-insoluble part. <sup>c</sup>0.5 M HCl-insoluble part. <sup>d</sup>Estimated by GPC based on polystyrene standard; eluent, LiBr solution in DMF (10 mM). <sup>e</sup>Not determined. <sup>f</sup>Measured by polarimetry at room temperature,  $c = 0.10$  g/dL in DMF. <sup>g</sup>Measured in DMSO.  $[\alpha]_D$  of monomers, **2m**: +80 deg, **2p**: +120 deg.

were obtained in 63–99% yields. Except for poly(**2p-6**), the polymers were soluble in DMF and DMSO while insoluble in hexane and toluene (Table 2). Poly(**2p-6**) became insoluble in DMF after isolation even though it was soluble during the polycondensation. The *para*-azobenzene-derived polymers tended to be less soluble than the *meta*-counterparts, presumably due to the larger stiffness of the *para*-linked backbone [34].

**Table 2.** Solubility of the polymers<sup>a</sup>

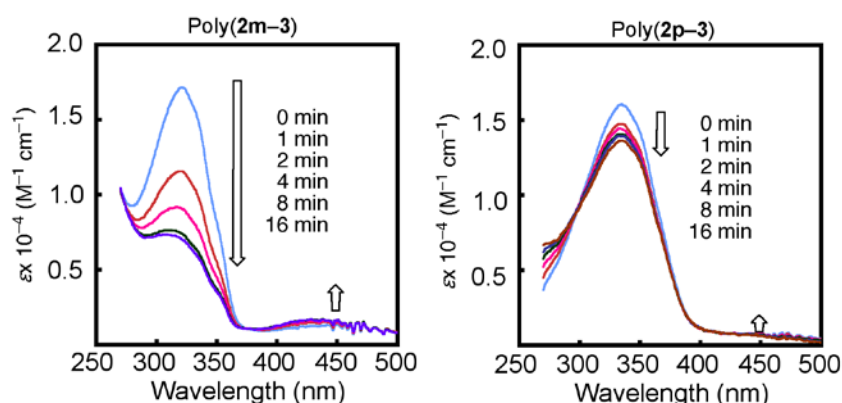
Polymer	Hexane	Toluene	CHCl <sub>3</sub>	CH <sub>2</sub> Cl <sub>2</sub>	THF	MeOH	DMF	DMSO
Poly( <b>2m-3</b> )	–	–	+	±	+	±	+	+
Poly( <b>2m-4</b> )	–	–	+	±	+	±	+	+
Poly( <b>2m-5</b> )	–	–	±	±	+	±	+	+
Poly( <b>2m-6</b> )	–	–	±	±	±	±	+	+
Poly( <b>2m-7</b> )	–	–	±	±	±	±	+	+
Poly( <b>2m-8</b> )	–	–	–	–	–	±	+	+
Poly( <b>2m-9</b> )	–	–	–	–	±	±	+	+
Poly( <b>2m-10</b> )	–	–	±	–	–	±	+	+
Poly( <b>2p-3</b> )	–	–	–	–	+	–	+	+
Poly( <b>2p-4</b> )	–	–	±	±	+	±	+	+
Poly( <b>2p-5</b> )	–	–	±	±	±	±	+	+
Poly( <b>2p-6</b> )	–	–	–	–	–	–	–	±
Poly( <b>2p-7</b> )	–	–	–	–	–	–	+	+
Poly( <b>2p-8</b> )	–	–	–	–	–	±	+	+
Poly( <b>2p-9</b> )	–	–	–	–	–	–	+	+
Poly( <b>2p-10</b> )	–	–	–	–	–	–	+	+

<sup>a</sup>Symbols: +, soluble; –, insoluble; ±, partly insoluble.

#### Photo-isomerization

Polymer solutions in DMF were irradiated with UV light at a wave length of 300 nm <  $\lambda$  < 400 nm at 20 °C. The isomerization of azobenzene unit was monitored by UV–vis absorption spectroscopy. As shown in Figure 1, poly(**2m-3**) strongly absorbed light at 320 nm, which is attributable to the  $\pi$ – $\pi^*$  transition band of *trans*-azobenzene units. This absorption remarkably decreased the intensity upon UV-light irradiation. Simultaneously, a weak absorption attributable to the n– $\pi^*$  transition band of *cis*-azobenzene units appeared around 440 nm, and increased the intensity. Poly(**2p-3**) also exhibited the photo-isomerization in a manner similar to poly(**2m-3**) as shown in Figure 1, but the degree of isomerization was much lower. It was estimated that the *trans/cis* contents of azobenzene units of poly(**2m-3**) and poly(**2p-3**) were 41/59 and 83/17, respectively, after UV-light irradiation in DMF for 32 min, based on the assumption that all azobenzene units existed in *trans* form at the initial state, and the

absorption around 320–340 nm was derived from *trans*-azobenzene units [35]. Also the monomer **2m** and **2p** had 23/77 and 40/60 of *trans/cis* contents, respectively, after 32 min UV-light irradiation in the same conditions. It is likely that *para*-linked azobenzene units are unfavorable to photo-isomerization compared with *meta*-linked ones, and seem to be amplified by becoming the polymer. This is because *para*-linked azobenzene units in the *trans*-form are more conjugated than *meta*-linked ones. In fact, the  $\lambda_{\text{max}}$  and band edge of the  $\pi$ - $\pi^*$  transition band of poly(**2p-3**) appeared at 340 nm, 20 nm longer than that of poly(**2m-3**). It presumed that this conjugation effects suppressed the photo-isomerization of *para*-linked polymer.



**Figure 1.** UV-vis spectra of poly(**2m-3**) and poly(**2p-3**) with irradiation at  $300 < \lambda < 400$  nm measured in DMF ( $c = 0.05$  mM) at 20 °C.

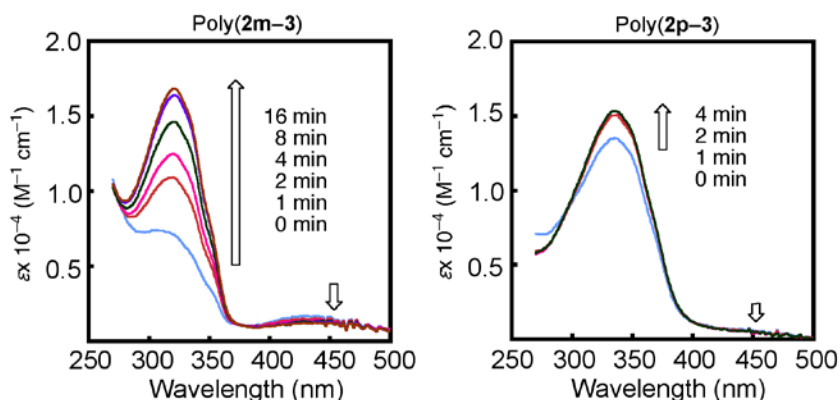
Poly(**2m-4**)–poly(**2m-10**) exhibited UV-vis spectroscopic changes in a manner similar to poly(**2m-3**), and poly(**2p-4**)–poly(**2p-10**) did similarly to poly(**2p-3**). The absorption around 320 nm decreased to 12–64% of the initial state to reach a constant value by UV-light irradiation for 32–48 min. These spectral changes clearly show that *trans*-to-*cis* photo-isomerization of azobenzene moieties took place at the polymer main chain.

Next, the UV-light irradiated samples were further irradiated with visible light to check the reversibility of photo-isomerization of the azobenzene units. As shown in Figure 2, poly(**2m-3**) and poly(**2p-3**) gradually increased the absorption around 320–340 nm and decreased that around 440 nm as visible-light irradiation. After 8–32 min, the polymers recovered the UV-vis absorption at the pre-irradiation state. These spectral changes indicate the proceeding of reversible *cis*-to-*trans* photo-isomerization of azobenzene moieties in the polymers without degradation. As described above, the *para*-linked polymers, poly(**2p-3**)–poly(**2p-10**), isomerized the azobenzene units from *trans* to *cis* (12–40%) less than the *meta*-linked counterparts, poly(**2m-3**)–poly(**2m-10**) (55–65%) upon UV-light irradiation.

The CD spectra of the polymers were measured in DMF ( $c = 0.05$  mM) at 20 °C with UV- and visible-light irradiations to obtain information on the chiroptical property. Unfortunately however, no CD signal was observed before and after the photo-irradiation, indicating that these polymers did not form a higher order structure.



The fluorescence spectra of the monomers and polymers were also measured in the same conditions, but no emission was observed before and after the photo-irradiation.



**Figure 2.** UV-vis spectra of poly(**2m-3**) and poly(**2p-3**) with irradiation at 420 nm <  $\lambda$ , after irradiation at 300 <  $\lambda$  < 400 nm for 32 min measured in DMF ( $c = 0.05$  mM) at 20 °C.

## Conclusion

In this article, we have demonstrated the polycondensation of optically active azobenzenedicarboxylic acids with various diols and diamines. The polymers obtained reversibly isomerized the azobenzene units from *trans* to *cis*, and *cis* to *trans* upon UV- and visible-light irradiations, which were confirmed by UV-vis absorption spectroscopy. CD spectroscopic study revealed that the polymers did not form a higher-order structure before and after the photo-irradiation. A stiffer main chain such as phenyleneethynylene seems to be necessary to accomplish the preparation of photo-responsive polymers with a regulated secondary structure [36]. Further study on molecular design of photo-responsive optically active polymers is now under progress.

## Acknowledgement

This research was partly supported by Iketani Science and Technology Foundation.

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