Structural chirality of cholesteric liquid crystal produces atropisomerism: chiroptical polyisocyanides from achiral monomer in cholesteric liquid crystal matrix

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ABSTRACT

1-Naphthyl isocyanide was polymerized with Ni(II) catalyst in a cholesteric matrix at the liquid crystal (LC) temperature range. The resultant polymers showed optical activity. In this reaction, the structural chirality of cholesteric LC effectively functions to impart one-handed helicity on the corresponding polymers as an optically active atropisomer.

Keywords: cholesteric liquid crystal, helical, isocyanide, optical activity

1. Introduction

Synthetic chiral polymers[1], such as polyaniline bearing camphor sulfonic acid [2], polysilanes [3], and polythiophene [4] with chiroptical activity, have been synthesized for the development of novel functions and biomimetic technology. Induction of optical activity for a polymer in solution by the external environment has been demonstrated, such as chirality transfer from a chiroptical solvent to poly(*n*-hexylisocyanate) of an optically inactive polymer [5].

Polyisocyanides have been investigated in the chiral polymer research; due to their unique main chain helical structure [6]. Polyisocyanides form a stable 4_1 helical conformation in solution, and the introduction of an appropriate chiral side chain maintains the one-handed helical structure. Atropisomerism in polymers has been demonstrated for polyisocyanides [7]. Chiroptically active polyisocyanides having a side chain, such as polyisocyanides with an alanine-based substituent [8], polyisocyanopeptides [9], and poly(zwitterionic isocyanides) with birefringence [10], and liquid crystalline polyisocianide [11], have been studied. Helical sense-selective polymerization initiated by aryl-rhodium complexes has been developed [12], and the synthesis and doping effect of tetrathiafulvalene-substituted polyisocyanide has been performed [13]. The helical structure has been directly observed using atomic force

microscopy (AFM) for polyisocyanides prepared by helical sense-selective living block copolymerization, which provided evidence that polyisocyanides clearly form a helical structure [14]. Polymerizations of chiral isocyanides as monomers in isotropic solvents were performed. This produces right- and left-handed helical polyisocyanides whose helical sense can be controlled by the polymerization solvents and temperature. The resultant polymers show lyotropic liquid crystallinity [15].

Liquid crystal (LC) science and technology have been developed for materials science such as synthesis of new functional LC materials [16], and preparation of uniaxial alignment of the nanotubes by using lyotropic LC [17]. Chiral LC, especially cholesteric LC shows characteristic properties. The individual molecules of cholesteric LCs aggregate in a three-dimensional (3-D) one-handed helical structure for the formation of structural chirality.

Cholesteric LCs can play a role of chiral matrix for chemical reactions under appropriate conditions. A cholesteric LC matrix was employed to obtain optically active polythiophene derivatives from optically inactive monomers [4]. The polythiophenes displayed chiroptical activity based on chiral aggregation derived from a cholesteric LC-like order. Furthermore, electrochemical driven control of chiroptical activity was

developed [18], and charge career (polarons) in helical form has been proposed for polymers prepared in cholesteric LC [19].

In this study, optically active poly(1-naphtyl isocyanide) is synthesised in a cholesteric LC matrix with the aid of a $NiCl_2$ catalyst. After removal of the cholesteric matrix, the resultant was dried in vacuum to give polymer in powder. The polymers thus obtained exhibit the Cotton effect in achiral solution at the corresponding wavelength of the π–π^* transition of the side chain and the n–π^* transition of the main chain, which indicates that both the side chain and the main chain form stable one-handed helical structures. Thus, synthesis of the one-handed helicoidal polymer as an optically active atropisomer was performed with 3-D structural chiral matrix of cholesteric liquid crystal. The helicity is maintained by inter-lock function between side chains through π-stacking.

The chiroptical activity of the polymers in this study may originate from atropisomerism for the polyisocyanides produced by the cholesteric matrix. This can be referred to as a chiral field effective reaction in a cholesteric matrix.

2. Experimental

2.1 Syntheis of cholesteric liquid crystal medium

Cholesteric (Ch*) LC compounds having a three ring system with terminal alkyl groups that have (*R*) and (*S*) configurations (4-ethoxy-benzoic acid 4'-[(*R*)-1-methyl-heptyloxy]biphenyl-4-yl ester and 4-ethoxy-benzoic acid 4'-[(*S*)-1-methyl-heptyloxy]biphenyl-4-yl ester), abbreviated as (*R*)-Ch*LC and (*S*)-Ch*LC, were prepared as cholesteric matrices using a previously reported method [20]

2.2 Monomer synthesis

Basically synthesis of the monomer was performed according to the method reported in the literature [21]. A solution of *tert*-butanol 24 mL, $(CH_3)_3COK$ (1.8 g, 16 mmol) in three necked round bottom flask was stirred for 2 days at 45 ºC under argon flow. This solution was added to another solution of 1-naphthylformamide (1 g, 8.2 mmol) in *tert*-butanol (4 mL) very slowly. After 24h, $POCl_3$ (0.54 g, 35 mmol) was added to the mixture and stirred for 40 min at 10–20 ºC. Further, the reaction mixture was stirred for 1 h at room temperature. The mixture was poured into a large volume of aqueous $NaHCO_3$ (10 wt%, 50 mL) solution, the organic layer was extracted with ether. The ether solution was dried with $MgSO_4$. After filtration, the crude product was dissolved in *n*-hexane (20 mL) and cooled. The precipitation was removed by filtration. The

filtrate was purified by column chromatography (silica gel, CH_2Cl_2) followed by evaporation to afford desired monomer (pale yellow liquid, 0.42g, 2.7 mmol, Y = 33 %). All of the procedures were carried out in the hood except recrystallization (draft chamber). The unfavorable odor of the equipment used in this preparation due to the isocyanides can be suppressed by washing with 1–5 % methanolic sulfuric acid [21]. ^{1}H NMR and ^{13}C NMR measurements confirm the chemical structure of the monomer, as shown in Figure 1 (^{13}C NMR) and Figure 2 (^{1}H NMR).

2.3 Polymerization

Polymerization was performed in the cholesteric LC matrix (Scheme 1). The resultant polymers are abbreviated as PNI[(*R*)-Ch*LC] (prepared in (*R*)-Ch*LC) and PNI[(*S*)-Ch*LC] (prepared in (*S*)-Ch*LC). The spring form in Scheme 1 is an ideal architecture.

PNI[(*R*)-Ch*LC]. (*R*)-CLC (0.5 g, 1.00 mmol) was placed in ϕ = 1cm a small Schlenk flask with stirring bar. The flask was heated at 140 ˚C to show isotropic phase of the CLC solution. Then, the temperature was gradually decreased to 97 ºC and stirred at an exact speed of 75 rpm. Then, 1-naphthyl isocyanide (17.6 mg, 0.115 mmol) as a monomer was added to the cholesteric liquid crystal solvent. Visual inspection

confirmed the solution showed cholesteric phase with rainbow color. $NiCl_2$ (0.96 mg, 7.5×10^{-3} mmol) as a catalyst was added to the cholesteric liquid crystal mixture to initiate polymerization. The reaction mixture was stirred at a rate of 75 rpm at 97 ˚C. After 24h, a small amount of acetone (ca. 2 mL) was added to the mixture, and 60 mL of acetone was added to the solution and stirred for 4h. The supernatant solution was removed with pipette. And 70 mL of acetone was added to the solution and stirred. This procedure was repeated. The polymer was collected and dried under vacuum to yield 3.7 mg (2.4×10^{-2} mmol) of yellow powder. Y = 21 %.

PNI[(*S*)-Ch*LC]. PNI[(*S*)-CLC] was synthesized by the similar method to PNI[(*R*)-CLC]. Quantity used: (*S*)-CLC (0.5 g, 1.00 mmol), 2-naphthyl isocyanide (17.6 mg, 0.115 mmol). Y = 54 %, 9.5 mg (6.2×10^{-2} mmol), yellow powder. Note that the difference of polymerization yield between PNI[(*R*)-Ch*LC] and PNI[(*S*)-Ch*LC] is not derived from monomer reactivity in the LC solvents because the monomer can be polymerized in both (*R*)-Ch*LC and (*R*)-Ch*LC with the same condition except chirality. This micro-scale polymerization experiment may result in low polymerization yield for the polymer PNI[(*R*)-Ch*LC] with a technical reason in the practical experiment.

3. Measurements

Infrared (IR) spectra were obtained with a JASCO FT/IR 550 spectrometer. Number average molecular weight (M_n), weight average molecular weight (M_w), and molecular weight distribution (MWD) of the polymers were estimated with gel permeation chromatography (GPC) (PLgel 5 μm MIXED-D columns, Agilent technologies) eluted with tetrahydrofuran (THF) by polystyrene standard calibration. Circular dichroism (CD) spectra were recorded on a JASCO J-720 spectrometer. Ultra visible (UV-vis) spectra were recorded on a Jasco U-3500 spectrophotometer. CD and UV-vis spectra of the polymers were obtained at room temperature in chloroform solution calculated from molecular weight of monomer repeat unit, or cast film of the polymers from chloroform solution. Dynamic light scattering (DLS) measurements for the polymer was carried out with Otsuka electronics FDLS-3000 (λ = 532 nm).

4. Results and discussion

4.1 GPC

The number-average molecular weight (M_n) and weight-average molecular weight (M_w) were estimated using gel permeation chromatography (GPC).

The polymers are partially soluble in THF and chloroform. The insoluble fraction in THF is considered to consist of high molecular weight chains. Furthermore, thermal induced scission reaction of the main chain might occur at the high polymerization temperature range, yielding the low molecular weight fractions. However, the insolubility of the polymers in acetone indicates that the molecular weight values are satisfactory (the THF soluble fractions are insoluble in acetone). DLS measurements evaluated that the average aggregation size of PNI[(*R*)-CLC] is 406 nm in *N*-methylpyrrolidone (NMP) solution (the signal is a normal distribution). The molecular weight measurements can be performed for the aggregation particles less than 0.1 μm (fractions passed through 0.1 μm membrane filter).

PNI[(*R*)-Ch*LC]. M_n = 1,000; M_w = 2,100; MWD (molecular weight distribution, M_w/M_n) = 2.1 (THF soluble part).

PNI[(*S*)-Ch*LC].Samples for GPC were prepared by filtration in tetrahydrofuran (THF) solution using a 0.1 μm membrane filter to exclude insoluble material. GPC vs. polystyrene standard, M_n = 1,500; M_w = 2,600; MWD = 2.1 (THF soluble part).

4.2. IR

Figure 3 shows IR spectra of the cholesteric LC solvent ((*S*)-Ch*LC), the precursor of the monomer, the monomer, and the polymer (PNI[(*S*)-Ch*LC]). The vibration ascribed to CH out-of-plane stretching was observed in the high frequency region (~3000 cm^{-1}) for the cholesteric LC solvent. In the monomer spectrum, signals at 3224 cm^{-1} (ν_{N-H}) and 1655 cm^{-1} ($\nu_{C=O,\ amide}$), and 1550 cm^{-1} (δ_{N-H}) due to amide group and 1730 cm^{-1} ($\nu_{C=O,\ ester}$) are no observed [22]. The monomer had a sharp signal at 2120 cm^{-1} ascribed to C≡N stretching, while the corresponding polymer show no absorption band related with the C≡N stretching. This result indicated that opening of the isocyanide C≡N bond in the monomer was catalyzed by $NiCl_2$ to give a polymer with C=N bonds. The polymers display no C=O stretching vibration at 1730 cm^{-1} due to the cholesteric LC matrix. On the other hand, the IR spectra of the polymers show C-H out-of-plane vibration of naphthalene ring at 760 cm^{-1}. A set of these results indicates that the polymers were successfully synthesized in the cholesteric matrix.

4.3 Optical activity

Figure S1 (Supplementary content) displays optical absorption spectrum of the monomer in chloroform solution. An absorption band at 289 nm is observed due to π–π* transition of the naphthalene rings. The monomer shows no absorption in the

circular dichroism (CD). Figure 4 shows the CD and optical absorption spectra of the polymers (PNI[(*S*)-Ch*LC] and PNI[(*R*)-Ch*LC) (c = 5 x 10^{-5} mol/L in chloroform solution, calculated by monomer repeat unit, molar extinction coefficient for the polymers was determined. Both polymers display an optical absorption signal at 440 nm due to the n–π* transition of the main chain. Although polyisocyanides are not universally helical [7b], in this case the CD results suggest helical form of the main chain. The polymers prepared in the cholesteric matrix with *S*-configuration and *R*-configuration display a complementary mirror image Cotton effect. The CD signal of the polymer (PNI[(*R*)-Ch*LC]) prepared in (*R*)-Ch*LC displays negative first and negative second Cotton effects. On the other hand, the polymer (PNI[(*S*)-Ch*LC]) prepared in (*S*)-Ch*LC exhibits an opposite change in the Cotton effect. The result further demonstrates that helical direction of the cholesteric medium can control helical direction and optical activity of the resultant polymer.

Note that CD signals at around 300 nm correspond to π–π* transition of the side chain naphthyl group. The CD results for the polymers suggest that the side chains form an inter-molecular chiral π-stacking and main chain helicoidal structure.

4.4 Plausible mechanism

From these results, the conformation of the polymers is concluded to be produced by the transcription of chirality from the cholesteric matrix during the polymerization reaction. The main chains are arranged in a predominantly one-handed helical manner, induced by the cholesteric matrix as a helical vector (directors) matrix. Subsequent inter-chain interaction in the π-electron system of the side chain locks the excess helical sense (π-stacking inter-lock function), thereby preserving the formation even after dissolution. The Cotton effect observed in the CD spectra is not due to the cholesteric matrix, because the optical absorption and CD signals of the cholesteric compounds are at short wavelengths [22].

In addition, reaction temperature dependence on optical activity of the resultant polymer can be expected because cholesteric pitch length depends on temperature. Therefore, precise control of the reaction temperature for the polymerization in LC could allow control of optical activity of the polymers.

Figure 5 shows a plausible polymerization mechanism for the isocyanide monomer in a cholesteric matrix. Polymerization gives rise to phase separation between the resultant polymer and the cholesteric matrix during the reaction. The cholesteric LC matrix acts as a “one-handed chiral organized matrix” consisting of chiral directors, which effectively imparts chiral conformation to the polymer during the polymerization

reaction. The main chain grows with a twist in one sense during the polymerization process for formation of a predominantly one-handed helical isocyanide. Simultaneously, π-stacking occurs between the pendant naphthalene groups. It should be noted that the polymerization mechanism in a cholesteric matrix differs from that for polymerization using a chiral catalyst, because the external asymmetric physical (mechanical) environment functions to impart a chiral conformation on the polymer. During the polymerization reaction, no chiral matrix molecules react chemically with the monomer, which indicates that the cholesteric solvent behaves as a matrix only.

Polymerization of *tert*-butyl isocyanide in cholesteric LC was also carried out as a comparative experiment, however no insoluble fractions in methanol were obtained. This result implies the π-stacking between monomer repeat units is an important factor for obtaining the chiral polymers in the cholesteric medium because the alkyl group (*tert*-butyl) of the side chain forms no π-stacking. The predominantly one-handed chiral π-stacking of the side chains and spring like helical structure of the main chain are locked during the polymerization. The insolubility of PNI[(*R*)-Ch*LC] and PNI[(*S*)-Ch*LC] in methanol can be derived from not only the production of the main chain but also the formation of the π-stacking between the monomer repeat units. Therefore, the helical sense selectivity for the PNI[(*R*)-Ch*LC] and PNI[(*S*)-Ch*LC] is

due to the cooperative function of the formation of helical structure of the main chain and the chiral π-stacking.

5. Conclusion

Chiroptically active poly(1-naphthyl isocyanide)s were prepared in a cholesteric matrix at the LC temperature range. The structural chirality of cholesteric LC effectively functions to impart predominantly one-handed helicity on the corresponding polymers. The chiroptical activity of the polymers originates from the structural chirality of cholesteric architecture. This is an example of atropisomer production via a physical chiral transfer reaction that employs the structural chirality of a cholesteric LC matrix.

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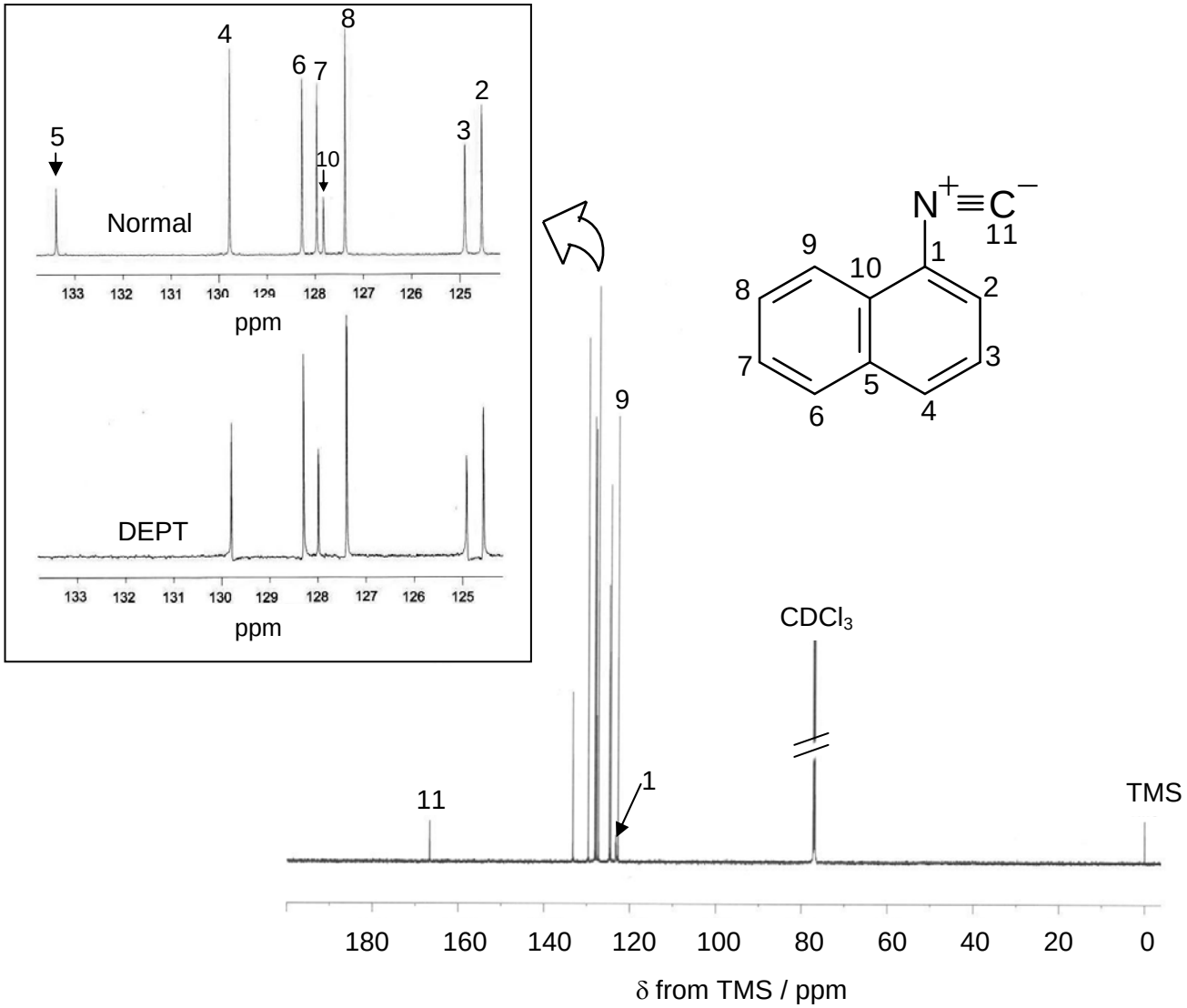


Figure 1. ^{13}C NMR of 1-naphtyl isocyanide. Inset shows high magnetic region of distortion enhance polarized transfer (DEPT) and normal ^{13}C NMR spectra. Arrows show signals of carbons having no protons revealed with DEPT.

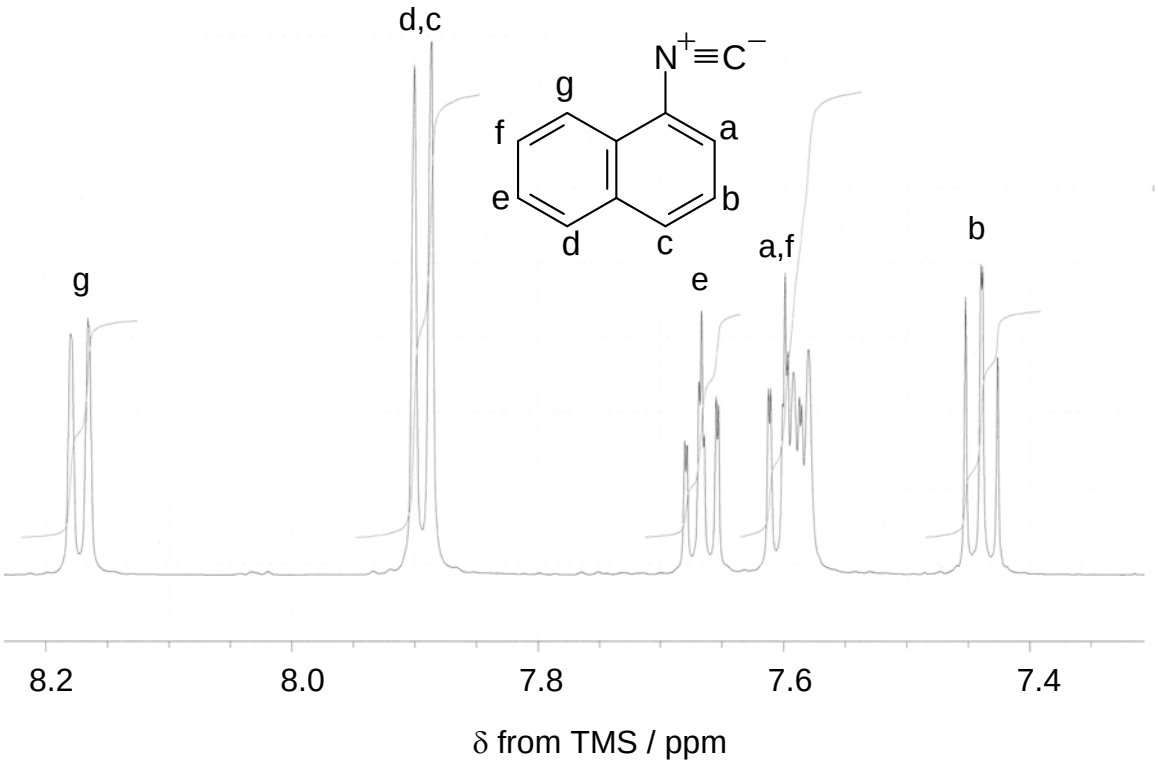


Figure 2. ^{1}H NMR of 1-naphtyl isocyanide.

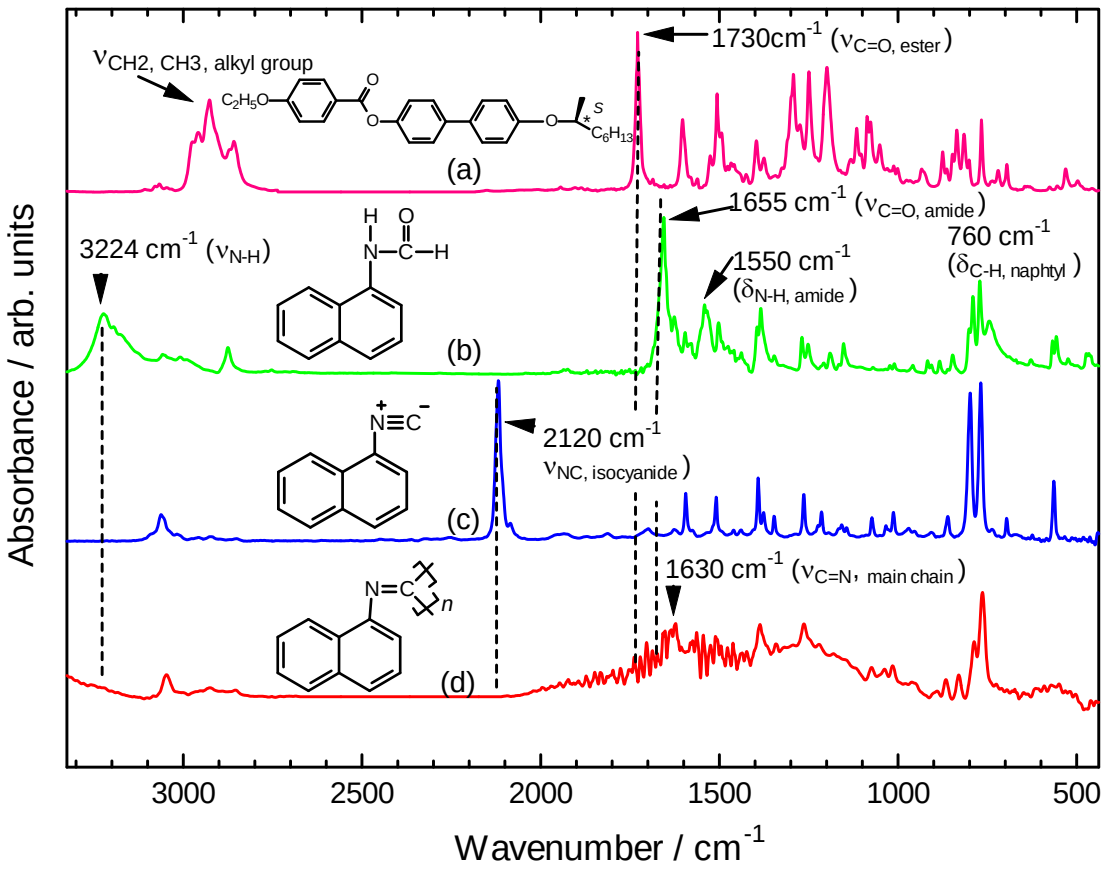


Figure 3. IR absorption spectra of (*S*)-Ch*LC (a), the precursor (b), monomer (c), and PNI[(*S*)-Ch*LC] (d).

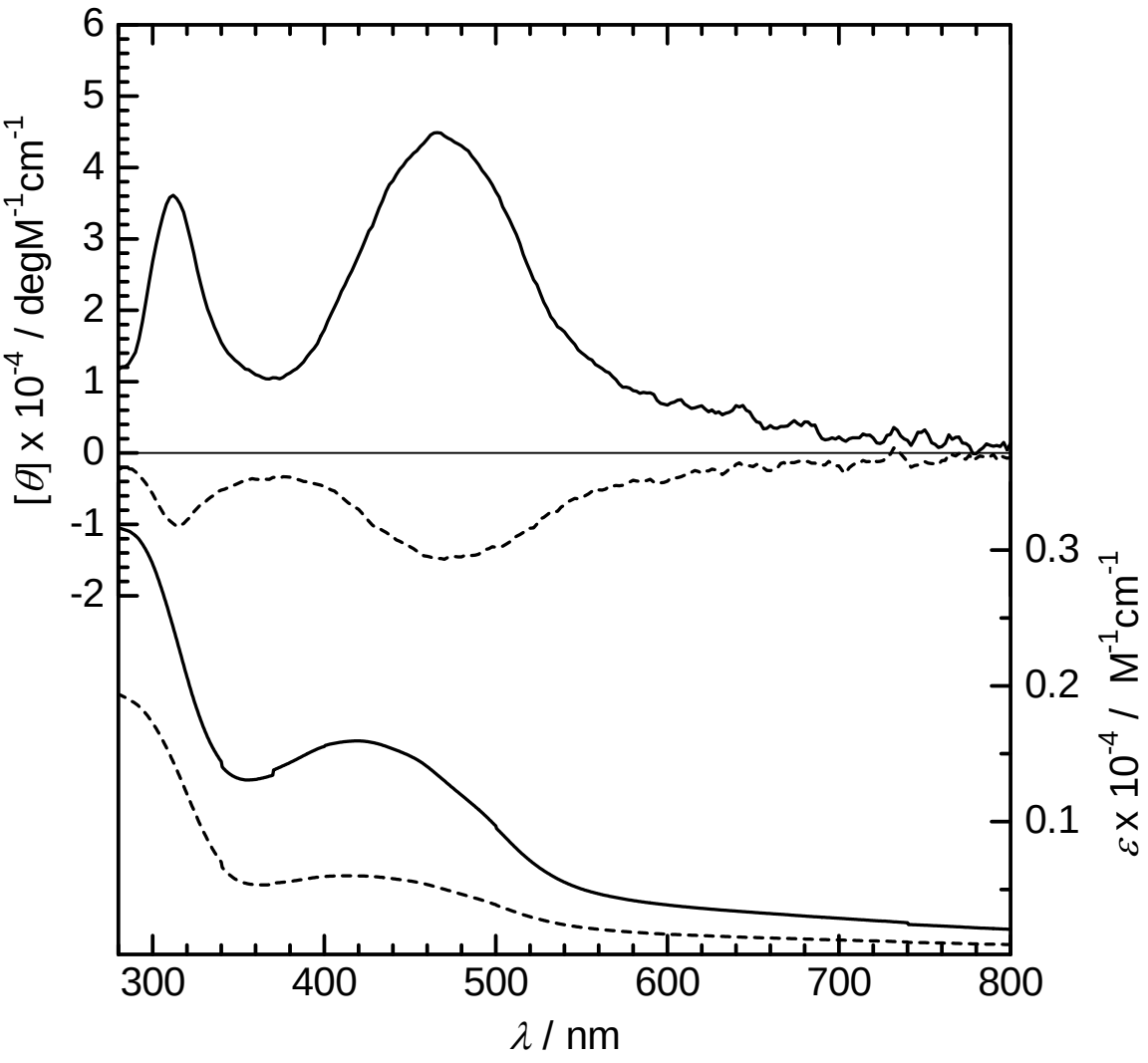


Figure 4. (a) CD and (b) optical absorption spectra of the PNI[(*S*)-Ch*LC] (solid lines) and PNI[(*R*)-Ch*LC] (dashed lines) polymers in chloroform solution.

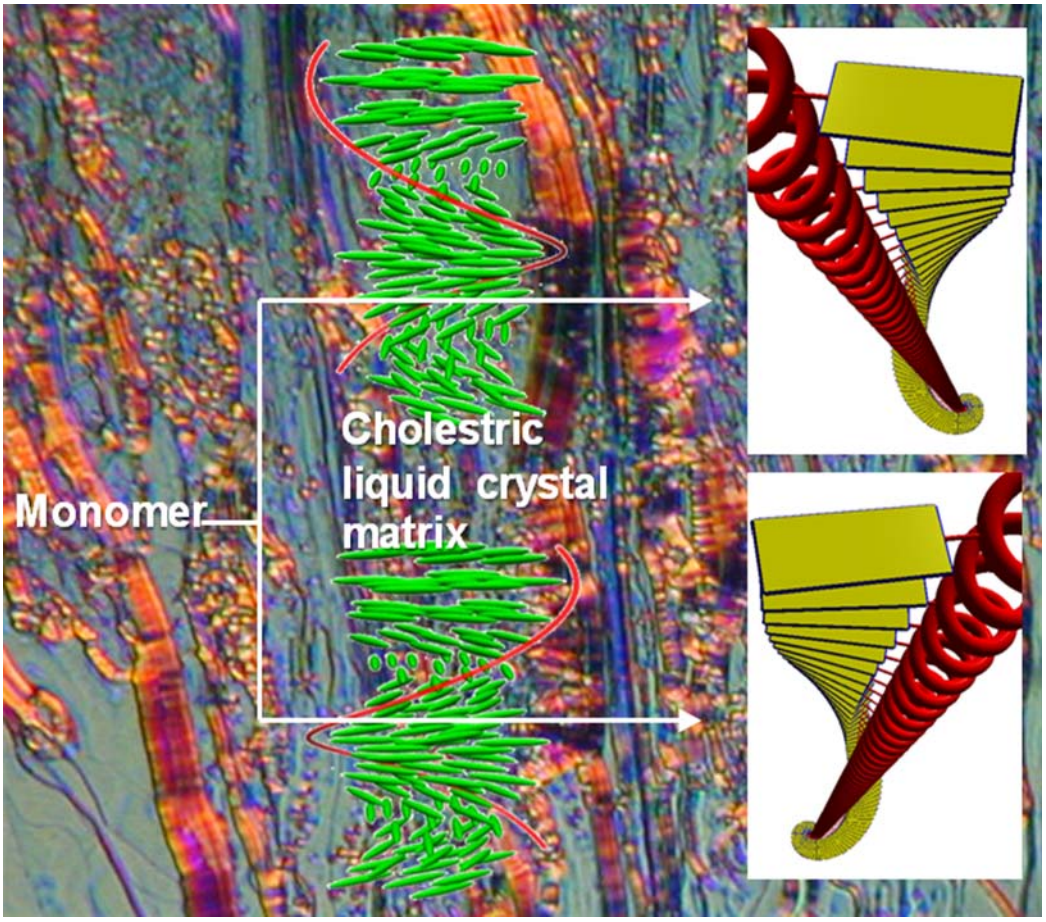
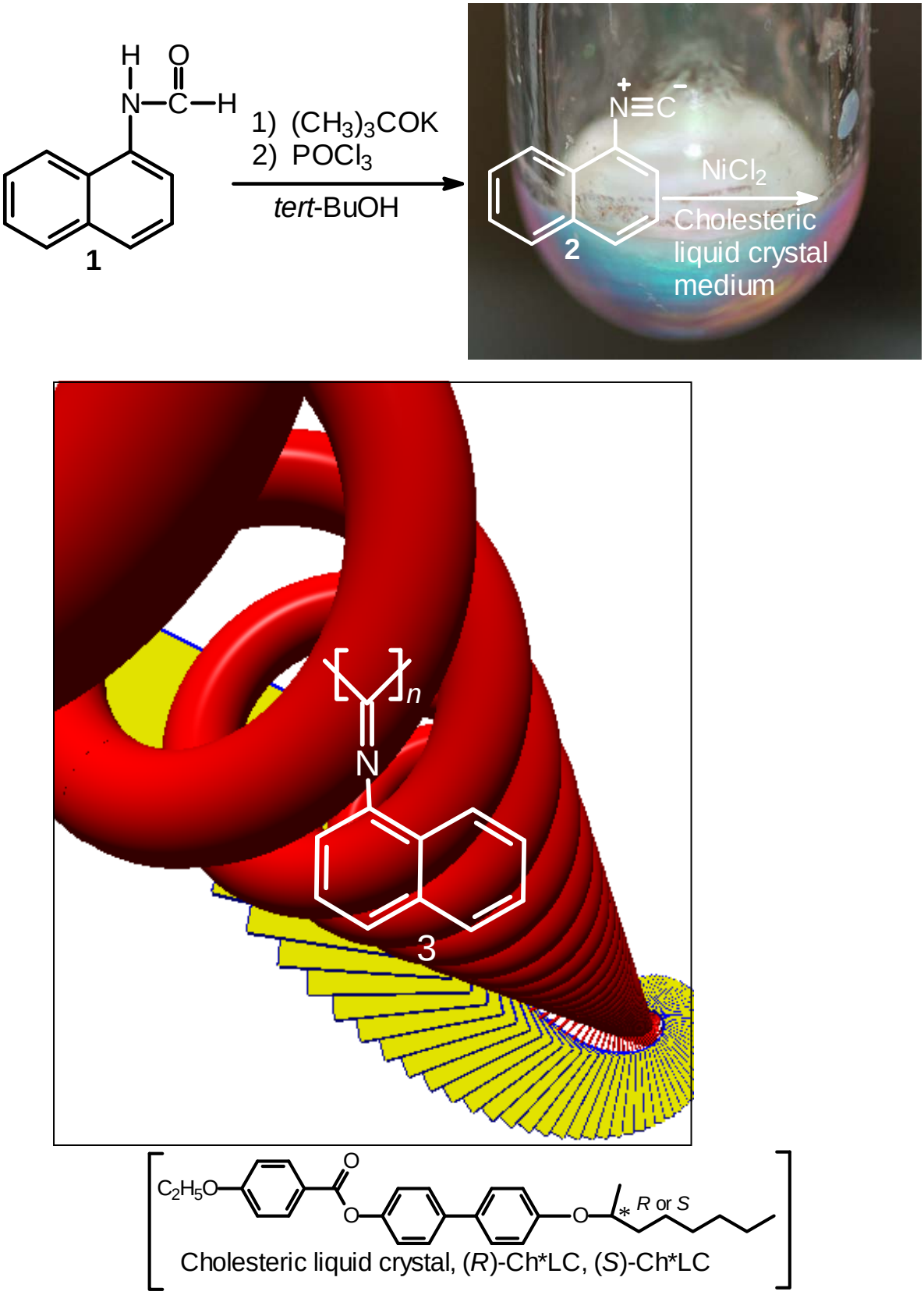


Figure 5. Plausible structure of poly(1-naphtyl isocyanide). Background shows polarizing optical microscopic image of the cholesteric matrix, employed for the polymerization.



Scheme 1. Polymerization in cholesteric liquid crystal medium.

Supplementary content for:

Structural chirality of cholesteric liquid crystal produces atropisomerism: chiroptical polyisocyanides from achiral monomer in cholesteric liquid crystal matrix

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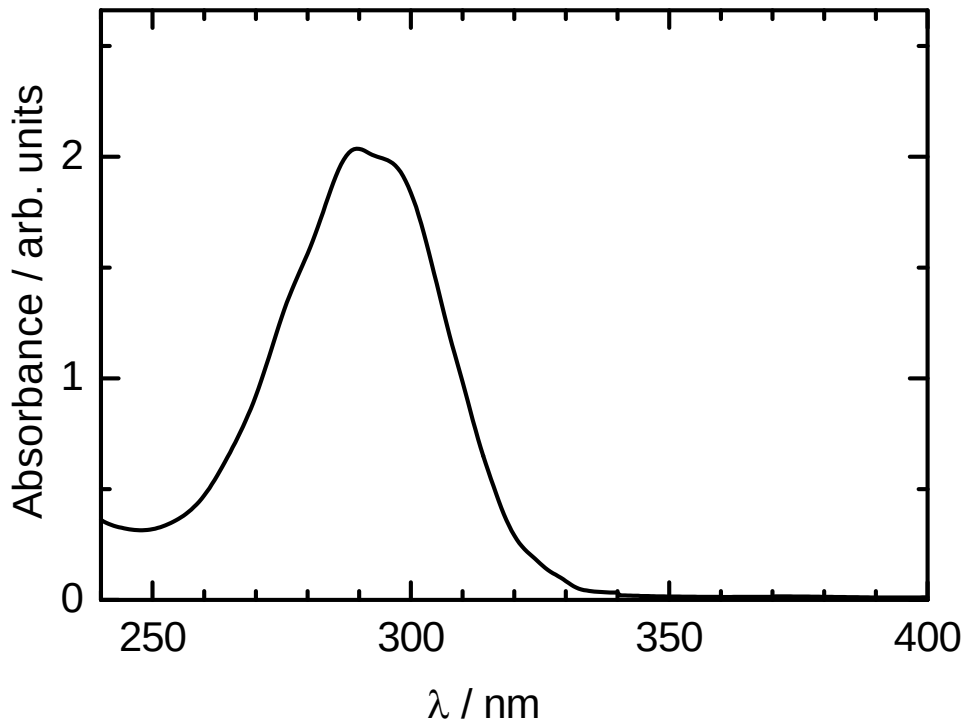

Figure S1. Optical absorption spectrum of 1-phenyl isocyanide (monomer) in chloroform solution.