

The Shackling Effect in Cyclic Azobenzene Liquid Crystal

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Electronic Supplementary Information

Abstract We demonstrate here a novel method for the design of liquid crystals (LCs) via the cyclization of mesogens by flexible chains. For two azobenzene-4,4'-dicarboxylate derivatives, the cyclic dimer, cyclic bis(tetraethylene glycol azobenzene-4,4'-dicarboxylate) (CBTAD), shows LC properties with smectic A phase, while its linear counterpart, bis(2-(2'-hydroxyethoxy)ethyl azobenzene-4,4'-dicarboxylate) (BHAD), has no LC phase. The difference is ascribed to the shackling effect from the cyclic topology, which leads to the much smaller entropy change during phase transitions and increases the isotropic temperature greatly for cyclics. In addition, the *trans*-to-*cis* isomerization of azobenzene groups under UV-light is also limited in CBTAD. With the reversible isomerization of azobenzene groups, CBTAD showed interesting isothermal phase transition behaviors, where the LC phase disappeared upon photoirradiation of 365 nm UV-light, and recovered when the UV-light was off. Combined with the smectic LC nature, a novel UV-light tuned visible light regulator was designed, by simply placing CBTAD in two glass plates. The scattered phase of smectic LC was utilized as the "OFF" state for light passage, while the UV-light induced isotropic phase was utilized as the "ON" state. The shackling effect outlined here should be applicable for the design of cyclic LC oligomers/polymers with special properties.

Keywords Azobenzene; Cyclic; Liquid crystals; Isothermal phase transition

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INTRODUCTION

The reversible photo-isomerization of azobenzene groups is attracting, where their isomers transform from a thermodynamically stable *trans*-configuration to a metastable *cis*-configuration under the irradiation of UV-light, and the bent *cis*-isomers gradually transforms into the rod-shaped *trans*-isomer accelerated by visible light or heating.^[1–10] This property affords azobenzene liquid crystals (LCs) the interesting photo-chemical phase transition behaviors,^[11–16] since the rod-shaped *trans*-configuration azobenzene units are typical mesogens,^[3,5,17–19] while the bent *cis*-isomers are usually non-mesogenic. Thus azobenzene LCs have broad application prospects in photo-controlled information storage, photo-electric sensors, and display devices.^[4,6,8,20–23]

Typically, the azobenzene mesogen is connected with at least one flexible electron-donating group (alkyl or alkoxy groups) to make the designed molecule easy to form LC phase.^[20,24] Their UV-Vis spectra are thus red-shifted with the

absorption peak around 365 nm, which is highly desirable for applications in photodeformable materials.^[15,17,18] However, due to the strong absorption of 365 nm UV-light, the photo-induced isothermal phase transitions can only be observed in very thin films of azobenzene LCs (~200 nm), as Ikeda *et al.* reported.^[5] This is much thinner than the thickness of a working LC device (typically a few to tens microns), and their application for the fabrication of light regulator has not been reported.

To weaken their absorbance at 365 nm UV-light, connection of azobenzene mesogen with electron-withdrawing groups is promising by blue-shifting the UV-Vis spectrum. However, reports about LC molecules with two electron-withdrawing groups connected mesogens are rare.^[25] The reason lies in the rigid shape of typical electron-withdrawing groups (cyano, nitro, carboxylic groups, etc.), which extends the mesogen length with enlarged aspect ratio. The crystal to LC transition temperature is thus raised, and when it is higher than the isotropic transition temperature (T_i), no LC phase can be observed.

Due to the endless topology, cyclic molecules typically show smaller hydrodynamic volume and melt viscosity, higher glass transition temperature and better thermal stability

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than their linear counterparts.^[26–38] The cyclics usually have higher phase transition temperatures than their linear counterparts, due to their compact molecular structure which reduces the entropy change (ΔS) during phase transitions.^[39–41] Inspired by this, we proposed a method to construct LCs by the cyclization of mesogens, which would reduce the entropy change during phase transitions and increase the isotropic temperature. Therefore, LC phases can be observed when it is higher than the crystal to LC transition temperature.

In this work, the carboxylic groups connected azobenzene units were used as mesogen to construct LC since flexible chains can be connected by ester bonds. The cyclic dimer, cyclic bis(tetraethylene glycol azobenzene-4,4'-dicarboxylate) (CBTAD), was synthesized according to Scheme 1. Bis(2-(2'-hydroxyethoxy)ethyl azobenzene-4,4'-dicarboxylate) (BHAD) was also synthesized as linear counterpart. Their property difference was investigated to reveal the topological effect. As predicted, BHAD does not show any LC phase, while CBTAD has. In addition, the photo-induced isothermal phase transition properties of CBTAD were studied, and a novel UV-light remote controlled optical regulator was constructed to illustrate the practical applications of azobenzene LCs.

EXPERIMENTAL

Materials

Tetrahydrofuran (THF), dichloromethane (CH_2Cl_2), chloroform (CHCl_3) (all from Chinasun Specialty Products Co., Ltd., analytical reagent (AR)) and triethylamine (TEA, TCI (Shanghai) Development Co., Ltd., 99%) were refluxed over CaH_2 and then distilled. Glucose, *N,N*-dimethylformamide (DMF, AR), thionyl chloride (99%) and heptane (AR) were purchased from Chinasun Specialty Products Co., Ltd. 4-Nitrobenzoic acid (Aladdin Chemical Technology Co., Ltd., 99%), 1,4-diazabicyclo[2.2.2]octane (DABCO, 99%), tetraethylene glycol (TEG, 99%), diethylene glycol (DEG, 99%) were purchased from TCI (Shanghai) Development Co., Ltd. These materials were used as received.

Synthesis of Azobenzene-4,4'-dicarbonyl Chloride (AZO-COCl)

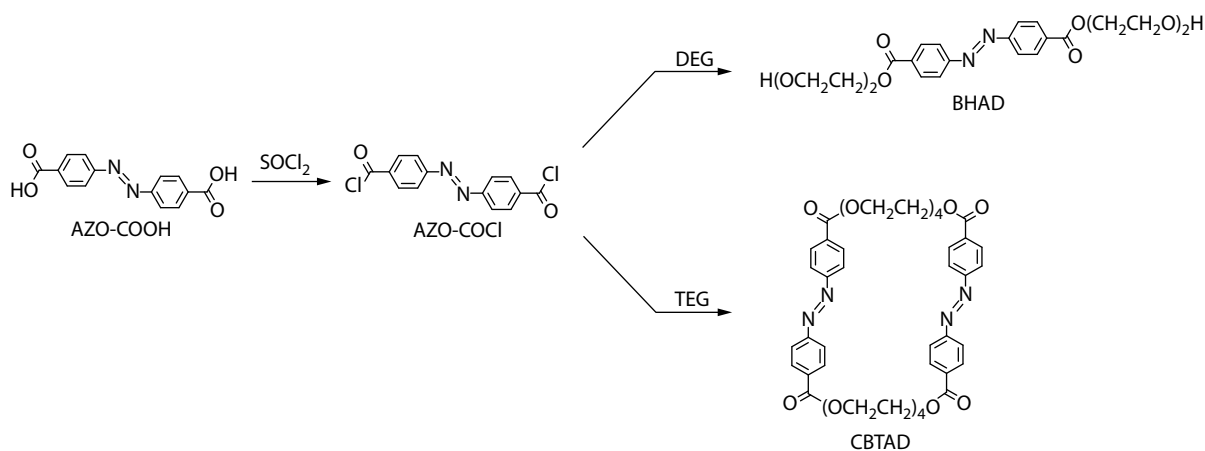
Azobenzene-4,4'-dicarboxylic acid was synthesized from 4-nitrobenzoic acid and glucose following reference.^[25] It was refluxed in thionyl chloride (15 g in 100 mL) for 8 h, and then excess thionyl chloride was removed by distillation to obtain crude product. After recrystallization in heptane, a red needle-like crystal was obtained. Yield: 80%. $^1\text{H-NMR}$ (400 MHz, CDCl_3 , δ , ppm): 8.07–8.06 (d, 4H), 8.33–8.31 (d, 4H).

Synthesis of Bis(2-(2'-hydroxyethoxy)ethyl) azobenzene-4,4'-dicarboxylate (BHAD)

To a solution of diethylene glycol (DEG) (13.88 g, 130.8 mmol) and triethylamine (TEA) (1.32 g, 13 mmol) in 100 mL of dichloromethane at 0 °C, a solution of AZO-COCl (2 g, 6.5 mmol) in THF (100 mL) was added dropwise. The mixture reacted further for 0.5 h after the completion of titration. After filtration, the organic layer was collected and washed for three times with deionized (DI) water, dried by Na_2SO_4 , and the solvent was removed by rotation evaporation. The crude product was purified by silica gel column chromatography (eluent: dichloromethane/acetone=3/1, V/V) to afford a reddish brown product. Yield: 64%. $^1\text{H-NMR}$ (400 MHz, CDCl_3 , δ , ppm): 8.24–8.22 (d, 4H), 8.00–7.98 (d, 4H), 4.60–4.48 (t, 4H), 3.92–3.84 (t, 4H), 3.82–3.74 (t, 4H), 3.72–3.64 (t, 4H). MS (m/z): Calcd. for $\text{C}_{22}\text{H}_{27}\text{N}_2\text{O}_8$ (M)⁺: 447.177; Found: 447.174.

Synthesis of Cyclic Bis(tetraethylene glycol azobenzene-4,4'-dicarboxylate) (CBTAD)

To a solution of triethylamine (TEA) (10 g, 0.1 mol) and 1,4-diazabicyclo[2.2.2]octane (DABCO) (0.6 g, 5 mmol) in 600 mL of dichloromethane at 0 °C, a solution of azobenzene-4,4'-dicarbonyl chloride (15.25 g, 50 mmol) and tetraethylene glycol (TEG) (10.19 g, 52.5 mmol) in THF (350 mL) was added dropwise under N_2 . The mixture reacted further for 0.5 h, then 20 mL of ammonia and 50 mL of DI water were added to stop the reaction. The organic phase was collected by filtration, washed with dilute hydrochloric acid and DI water for three times, respectively. The organic phase was dried by Na_2SO_4 , and the solvent was removed by rotation evaporation to obtain a crude product. After silica gel column chromatography (eluent:



Scheme 1 Synthetic routes and chemical structures of linear bis(2-(2'-hydroxyethoxy)ethyl) azobenzene-4,4'-dicarboxylate (BHAD) and cyclic bis(tetraethylene glycol azobenzene-4,4'-dicarboxylate) (CBTAD).

dichloromethane/acetone=5/1, V/V), a pink product was obtained. Yield: 15%. $^1\text{H-NMR}$ (400 MHz, CDCl_3 , δ , ppm): 8.17–8.11 (d, 8H), 7.91–7.81 (d, 8H), 4.50–4.40 (t, 8H), 4.50–4.40 (t, 8H), 3.90–3.80 (t, 8H), 3.75–3.66 (t, 16H). MALDI-TOF mass (m/z): Calcd. for $\text{C}_{44}\text{H}_{48}\text{N}_4\text{O}_{14}\text{Na}$ ($\text{M}+\text{Na}$) $^+$: 879.31; Found: 879.34.

RESULTS AND DISCUSSION

Detailed characterizations of the precursors and BHAD are provided in Figs. S1–S8 (in the electronic supplementary information, ESI). Differential scanning calorimetry (DSC), polarized optical microscopy (POM) and small angle X-ray scattering (SAXS) investigations revealed that BHAD had no LC phase (Fig. S6–S8 in ESI). The cyclic azobenzene molecule, CBTAD, was synthesized under pseudo high dilution conditions via a method developed by Brunelle *et al.*^[42] After column chromatography, neat CBTAD was obtained as a pink solid.

Fig. 1(a) shows the $^1\text{H-NMR}$ spectrum of CBTAD, where each peak and its integration value fit well with the structure illustrated. The structure was further confirmed by the MALDI-TOF mass spectrum as shown in Fig. 1(b). The peak observed matches well with the sodium ionized theoretical molecular weight ($\text{C}_{44}\text{H}_{48}\text{N}_4\text{O}_{14}\text{Na}^+$, theoretical $m/z=879.31$; found: 879.34), while no impurity peak was observed.

Fig. 2(a) shows the UV-Vis spectra of CBTAD in chloroform. With the two electron-withdrawing carboxylic groups con-

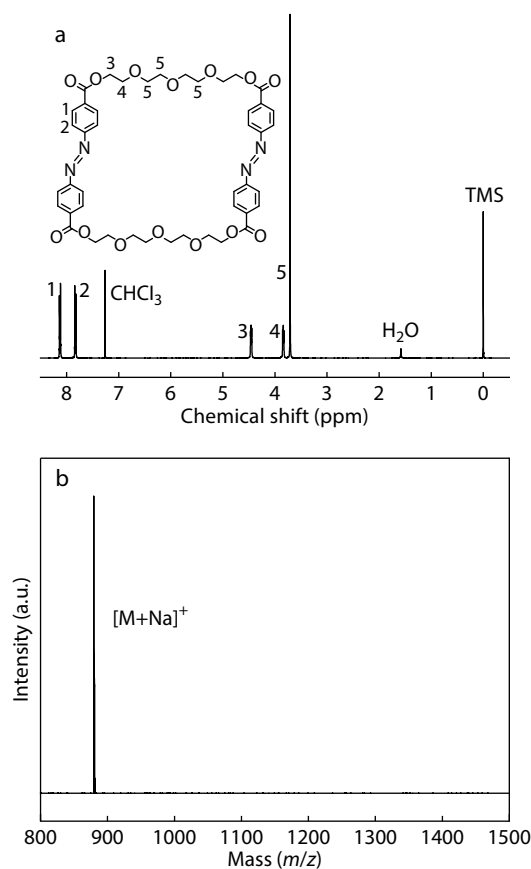


Fig. 1 $^1\text{H-NMR}$ spectrum (a) and MALDI-TOF mass spectrum (b) of CBTAD.

nected at azobenzene both sides, the absorption maxima are blue-shifted to 330 nm as predicted, which is ascribed to the $\pi-\pi^*$ transition of *trans*-azobenzene units, while the absorbance at 365 nm dropped significantly. The absorption coefficient is about $1.1 \times 10^4 \text{ L}\cdot\text{mol}^{-1}\cdot\text{cm}^{-1}$ at 365 nm, much smaller than that of typical azobenzene molecules with electron-donating groups ($\sim 2.6 \times 10^4 \text{ L}\cdot\text{mol}^{-1}\cdot\text{cm}^{-1}$).^[20] Thus the UV-light penetrates deeper in CBTAD. Irradiation with 365 nm UV-light induced the *trans*-to-*cis* isomerization of the azobenzene units, as the absorbance at 330 nm decreased abruptly, while that at 455 nm corresponding to the absorbance of *cis*-azobenzene groups increased slightly, as shown in Fig. 2(a). The system reached the photostationary state quickly in about 4 s. With the irradiation of 460 nm visible light, the absorbance at 330 nm gained quickly, as shown in Fig. 2(b). After 6 s of visible light irradiation, nearly 99% of azobenzene units retained the *trans*-configuration.

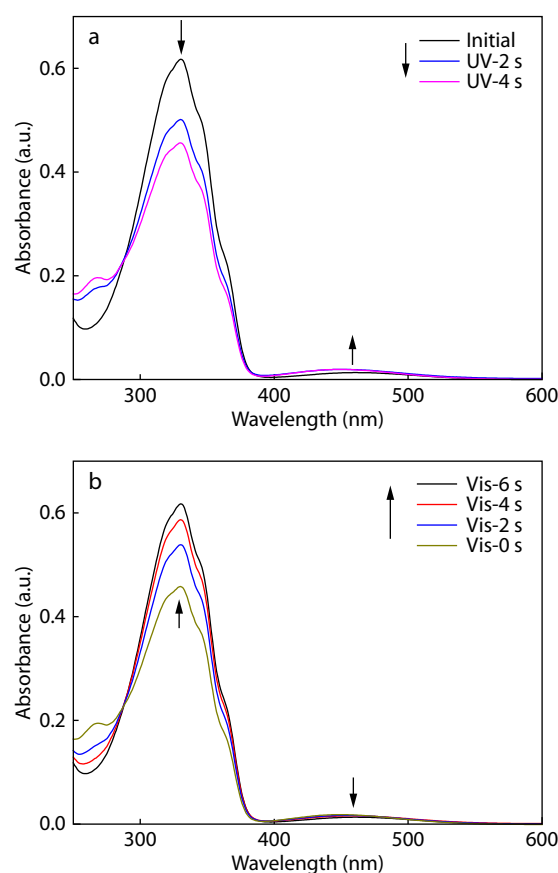


Fig. 2 UV-Vis spectra of CBTAD in chloroform, under the irradiation of 365 nm UV-light (a) and 460 nm visible light (b) with different time.

To study the cyclic topology effect on the isomerization process, the UV-Vis spectra of CBTAD and linear BHAD at initial state and photostationary state were plotted, as shown in Fig. 3. At photostationary state, the absorbance for CBTAD is about 74% of initial state, suggesting 26% of *trans*-isomers converted to *cis*-isomers when assuming the *cis*-isomer has little absorption at 330 nm. For BHAD, the absorbance at photostationary state is about 50% of initial state, indicating a 50% conversion of *trans*-to-*cis* isomerization. These results

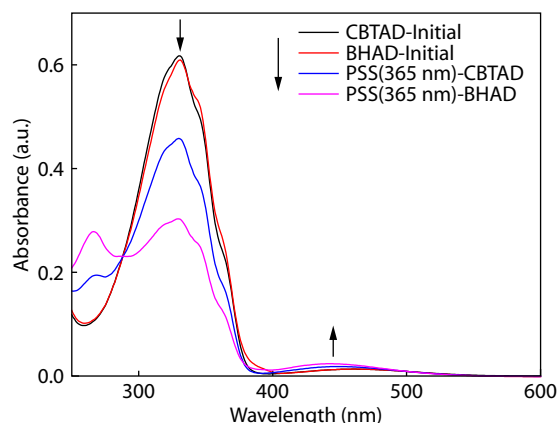


Fig. 3 UV-Vis spectra of CBTAD and BHAD in chloroform at initial state and photostationary state (PSS) under the irradiation of 365 nm UV-light.

suggest that the strained cyclic topology limits the *trans*-to-*cis* isomerization, a special shackling effect. As the conversion of isomerization for CBTAD is about half of that for BHAD, when one azobenzene unit undergoes the *trans*-to-*cis* isomerization in cyclic dimer, the other must remain the *trans*-configuration due to the ring strain.

The thermal stability of CBTAD was revealed by TGA, with the 5% weight decomposition temperature around 357 °C (Fig. S5 in ESI). DSC investigations indicate CBTAD has quite complicated phase transition behaviors, as shown in Fig. 4. There are three exothermic peaks observed during cooling at 173, 148 and 65 °C, which can be ascribed to the corresponding isotropic-to-LC, LC-to-crystal and crystal-to-crystal phase transitions, respectively, when combined the POM and wide angle X-ray diffraction (WAXD) results. During the 2nd heating, it revealed a few crystal-to-crystal phase transitions before 162 °C, the crystal to LC phase transition around 162 °C, and the LC to isotropic phase transition at 178 °C.

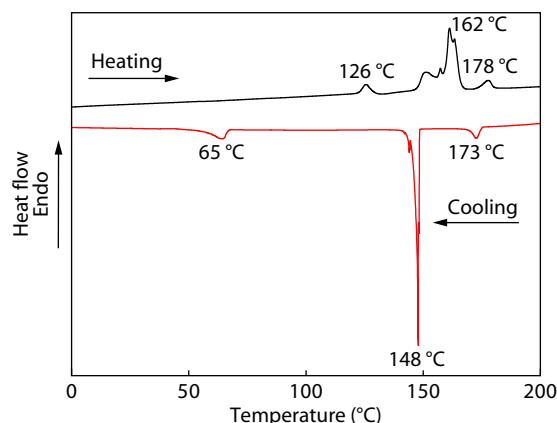


Fig. 4 DSC 1st cooling and 2nd heating curves of CBTAD. Scanning rate: 10 °C/min.

When cooled slowly from isotropic phase (>180 °C), a typical fan-shaped smectic A LC texture emerged at around 176 °C during POM observation, as shown in Fig. 5. The LC phase turned into crystal phase when the temperature

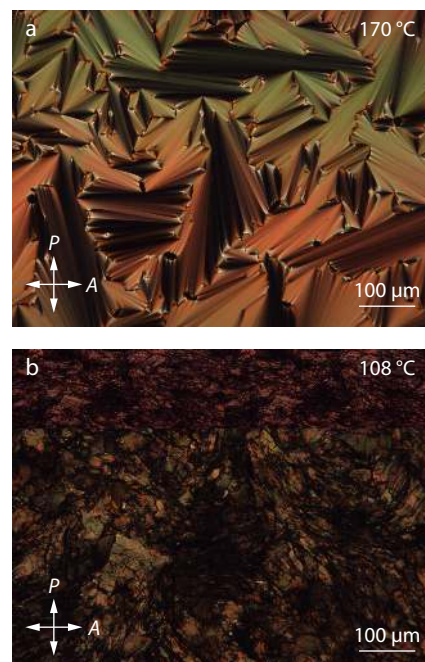


Fig. 5 POM images of CBTAD at (a) 170 °C (LC phase) and (b) 108 °C (crystal phase).

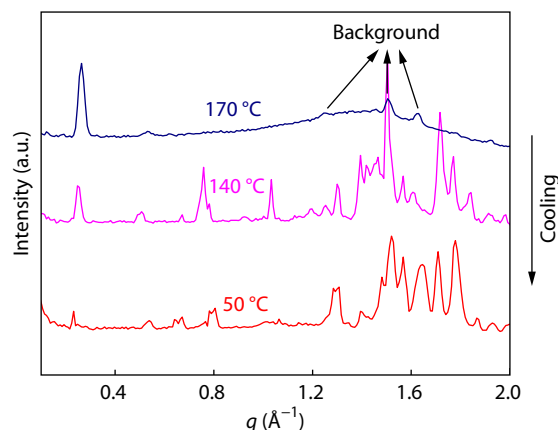


Fig. 6 WAXD patterns of CBTAD during cooling.

dropped below 155 °C since the system lost its fluidity and typical LC textures.

The phase transition process of CBTAD were further confirmed by WAXD experiments. Fig. 6 shows its WAXD patterns during cooling. At 170 °C, two Bragg peaks were observed at q value of 0.263 and 0.530 Å⁻¹, assigned to the (001) and (002) peaks of smectic phase. The deduced d -spacing between smectic layer is about 24 Å. The d -spacing does not change with temperature in LC phase, confirming it is a smectic A phase. As the length of azobenzene dicarboxylate mesogen length is around 15 Å at its *trans*-configuration, the detected d -spacing indicates that the smectic lamellar is formed by the single layer of CBTAD molecules, as shown in Fig. S9 (in ESI).

At 140 °C, the sample was crystallized and a variety of peaks emerged. The crystal changed to another form below 65 °C as the peak position and intensity observed at 50 °C are

quite different from those observed at 140 °C. Fully estimation of their crystal structure should be interesting, yet it is quite difficult and out of the scope of this work.

Compared to BHAD, which has no LC phase, the cyclic topology in CBTAD links two azobenzene mesogens together and helps them arrange orderly in the mesophase, another type of shackling-effect. Previously, we have reported the shackling effect from the cyclic topology in metallo-supramolecular polymers, which induced red-shift of absorption bands in the UV-Vis spectra due to interchain charge-transfer transitions.^[43] Here the shackling effect reported is from cyclic topology, which helps the ordered arrangement of mesogens to form LC phases, and limits the *trans*-to-*cis* isomerization as previously reported.

The shackling effect induced LC phase formation can be better explained by the free energy thermodynamic plots, as shown in Fig. 7. Typically, when the crossover point (*i.e.*, phase transition temperature) for crystal and isotropic curves is lower than that for crystal and liquid crystalline curves, no LC phase can be observed (Fig. 7, left), as in the case of linear BHAD. When the mesogens are cyclized by flexible spacers, their entropy is reduced due to the compact molecular morphology. With the definition of Gibbs free energy, $G = H - TS$, the isotropic curve moves upper, and the LC phase can be observed when the crossover point for crystal and LC curves is lower than that for crystal and isotropic curves (Fig. 7, right).

The above illustration is confirmed by the observation that the crystal to LC and LC to isotropic phase transition temperatures for CBTAD are much higher than the isotropic transition temperature for the linear BHAD. In addition, by measuring enthalpy change (ΔH) and temperatures at phase transition point ($\Delta G = 0$), the entropy change (ΔS) can be deduced. The entropy change for CBTAD at LC to isotropic phase transition point is $9.39 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$, much smaller than that for BHAD at crystal to isotropic phase transition point ($48.04 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$). These results support our assumption well.

The photo-response performance is the most interesting

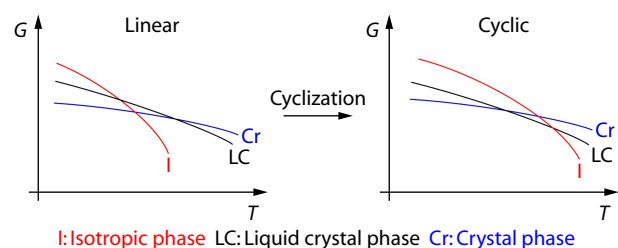


Fig. 7 Thermodynamic schematic illustration of the cyclization-induced LC phase by the shackling of mesogens. Left: for linear molecules; right: for cyclic molecules with similar structure.

properties for azobenzene materials. Fig. 8 represents the device for the observation of photo- and heat-induced isothermal phase transition behavior of CBTAD. For azobenzene molecules in LC state, under the irradiation of 365 nm (25 mW/cm²) UV-light, azobenzene groups undergo the *trans*-to-*cis* configuration transition. Since the curved *cis*-configuration could not form ordered LC phase, a photo-induced LC-to-isotropic phase transition occurs. As the *trans*-configuration is the thermodynamic stable state, when the UV-light is off, the azobenzene groups undergo a *cis*-to-*trans* configuration transition under heat or visible light, and the LC phase is reformed. The isothermal phase transition process can be observed easily through POM by the textures formed in LC state, while no birefringence in isotropic state.

For CBTAD at 175 °C with the LC layer thickness of 8 μm, the observed fan-shaped texture (Fig. 9a) was diminished quickly with irradiation of 365 nm UV-light. The texture started to change after irradiation time of 0.16 s, and totally disappeared after 1.76 s (Fig. 9b). It showed a typical LC-to-isotropic phase transition behavior due to the *trans*-to-*cis* configuration change of azobenzene units. After the removal of UV-light, the texture emerged after 2 s (Fig. 9c), and the fan-shaped texture was totally regained after 9.92 s (Fig. 9d). The heat-induced isotropic-to-LC phase transition is quite fast, probably due to the fast *cis*-to-*trans* configuration transition

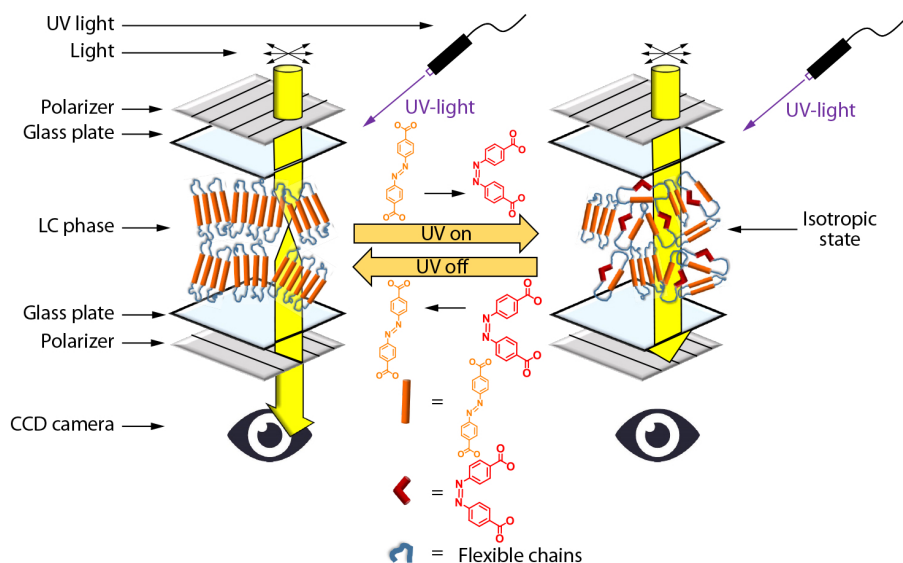


Fig. 8 Schematic illustration of the device for the photo-induced isothermal phase transition observation of CBTAD.

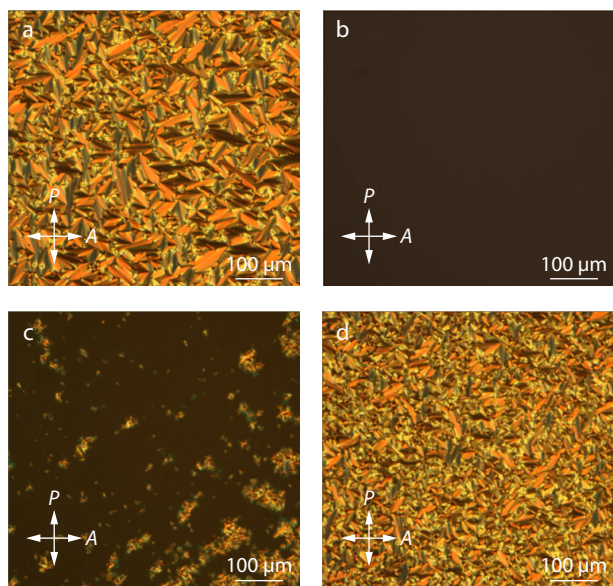


Fig. 9 POM images of reversible isothermal phase transitions of CBTAD at 175 °C. Photo-induced LC-to-isotropic phase transition under 365 nm UV-light (25 mW/cm²) irradiation: before irradiation (a); after irradiation of 1.76 s (b). The isotropic-to-LC phase transition after the removal of UV-light for 2 s (c) and 9.92 s (d). The LC layer thickness is controlled at 8 μm by spacer.

of azobenzene units and the low viscosity from the cyclic topology. The video for the isothermal phase transition process is provided in ESI (Video S1).

Fig. 10 shows the recorded relative light intensity (brightness) change by CCD camera under crossed polarizer from the above CBTAD cells during the isothermal phase transition process. Details about the estimation of light intensity can be found in ESI. With the irradiation of UV-light, the intensity increased slightly (point a), as the camera can also response to UV-light. The intensity maintained for a short time (~0.16 s), then decreased quickly with time (after point b). After UV-light irradiation of about 1.7 s, all texture from LC state was diminished, and the intensity was constant (point c). The system was in the isotropic state. The relative intensity was high-

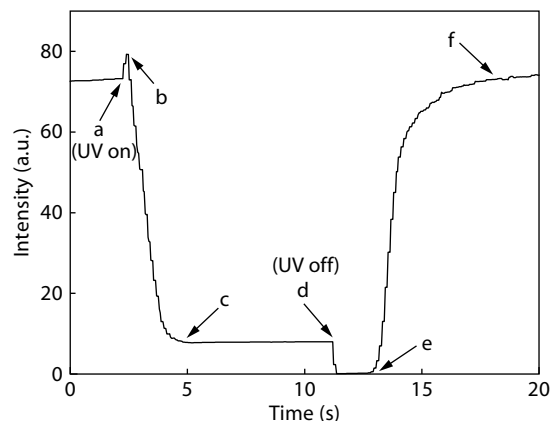


Fig. 10 The relative light intensity change during the isothermal phase transition process of CBTAD at 175 °C.

er than zero due to the scattered UV-light from the isotropic phase. When the UV-light was turned off, the intensity decreased to zero first (point d) since it was similar to background. It maintained a plateau for about 2 s, then the intensity increased quickly with time (after point e). This process is ascribed to the heat-induced *cis*-to-*trans* isomerization of azobenzene units, and the resultant isotropic-to-LC state transition. After 9.92 s of turning off the UV-light, the intensity was similar to that of initial intensity before UV-irradiation (point f), indicating the full reversibility of the UV-light and heat triggered isothermal phase transition process.

The effect of temperature and LC layer thickness on the isothermal phase transition performance of CBTAD was studied. The LC cell thickness was controlled by spacer (3 μm, 5 μm, 8 μm, or 10 μm). To facilitate statistical calculations, the photo-response time is set when the light intensity decreases to 90% of the original intensity for the LC-to-isotropic transition process, and the recovery time is when the intensity returns to 90% of the original intensity for the isotropic-to-LC transition process.

Fig. 11 shows the isothermal phase transition time revealed from POM related to thickness and temperature. Under the same temperature, the response time increases with

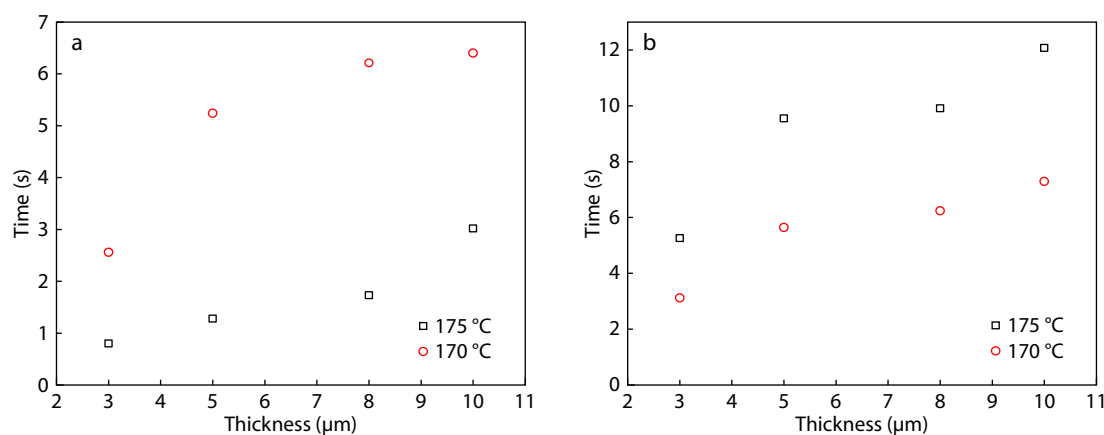


Fig. 11 Isothermal phase transition time of CBTAD revealed from POM related to thickness and temperature. (a) Response time and (b) recovery time.

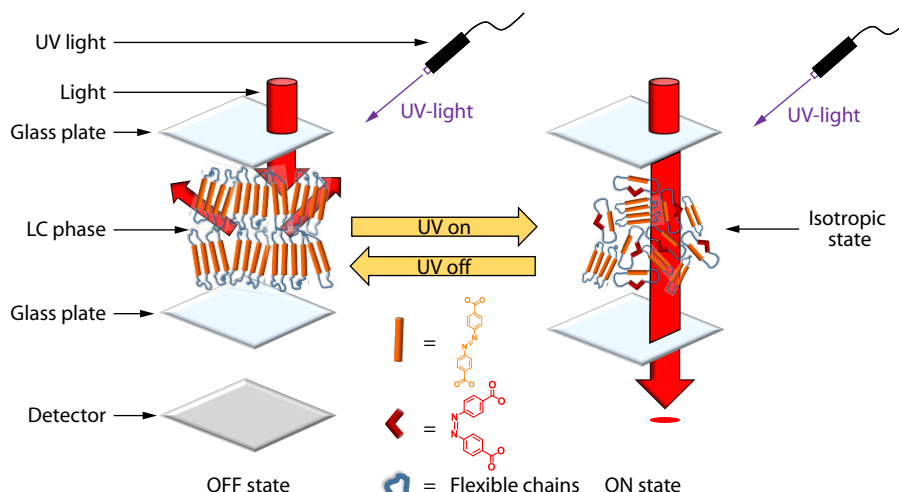


Fig. 12 A novel light regulator device based on the reversible isothermal phase transitions of CBTAD azobenzene molecules.

the increment of thickness, as shown in Fig. 11(a). It is reasonable as the UV-light intensity is reduced significantly for molecules at bottom layer due to the absorption from upper layer. When the thickness is the same, the response time decreases with the increment of temperature. For the recovery time, it increases with the increment of thickness, as shown in Fig. 11(b), similar to that of response time. Thus the thickness has reciprocal relationship with the isothermal phase transition time. On the other hand, the recovery time increases with the increment of temperature. This can be explained by the thermodynamic equilibrium between the *trans*- and *cis*- isomers. As the *trans*-isomer is more stable, the *cis*-isomer concentration increases with the increment of temperature based on Dainton's Equation.^[44–46] Thus the LC-to-isothermal transition is easier to proceed at higher temperatures, while the isotropic-to-LC transition is slower. The fastest estimated response time was about 0.80 s at 175 °C for 3- μm -thickness LC layer, while the recovery time was around 3.12 s (3 μm , 170 °C). These values are fast enough for device fabrications.

Ikeda *et al.* reported that the *trans*-to-*cis* configuration change is very fast (~ 200 μs) for azobenzene LC molecules.^[5] However, it only works on very thin films (200 nm) due to the short penetrating length of UV-light in their LC molecules with electron-donating groups. In our case, by connecting two electron-withdrawing groups at azobenzene both sides, their absorption at 365 nm is greatly reduced. Thus it can penetrate deeper, and the isothermal phase transitions can be clearly observed in the LC cells with several micron thickness, which is the typical thickness for LC display and for applications as light regulator.

The smectic LCs are famous for their unique bistable display properties.^[47,48] By specially tuning the domain orientation, they can be either in the stable scattered opaque state with focal conic/fan-shaped texture, or in the stable transparent state with homeotropic structure. The rapid reversible isothermal phase transitions of azobenzene molecules observed here provide another method for display/light regulator applications, by tuning the azobenzene molecules in LC (scattered state) or isotropic phase (transparent state). To

demonstrate this method, a simple device was constructed, as shown in Fig. 12. When the azobenzene molecules are in the smectic LC phase, the incident visible light is strongly scattered due to the different orientation of domains. The system is in the "OFF" state, as little light penetrates the device. By the irradiation of 365 nm UV-light, the LC-to-isotropic transition occurs due to the *trans*-to-*cis* configuration change of azobenzene units. The incident visible light can penetrate the LC cell and the system is in the "ON" state. When the UV-light is turned off, the isotropic-to-LC transition occurred and the LC phase is regained. The system turns back to the "OFF" state.

A simple working device based on the reversible isothermal phase transitions together with smectic LC nature was constructed, consisting of a red laser source, a 365 nm (25 mW/cm²) UV-light source, and a sample cell where CBTAD was sandwiched between two quartz glass sheets (5 μm), placing among a hot stage to control the temperature (175 °C), as shown in Fig. S10 (in ESI). The red laser could not pass through the sample cell when the UV-light was off, an "OFF" state. When the UV-light was turned on, the red laser beam passed through the sample layer and a red spot appeared. This is the "ON" state of the optical path (Fig. S10a in ESI). When the UV-light was turned off, the optical path was shuttled down about 4.20 s later, where the red spot on the detector disappeared (Fig. S10b in ESI). A video demonstrating the working process of our light-tuned-light regulator is provided in ESI (Video S2). The phenomena were well reproducible, indicating the good reliability and reproducibility of this display technique.

CONCLUSIONS

In summary, a shackling effect was revealed in cyclic azobenzene LCs, which enhances the formation of LC and limits the *trans*-to-*cis* isomerization of azobenzene units. The cyclic azobenzene LC showed interesting isothermal phase transition behaviors, and was utilized to construct a novel intelligent UV light-tuned optical regulator with potential applications in the field for remote control of optical signals. The cyclization-

induced LC formation method would enlarge the family of LCs for applications in opto-electronics.

NOTES

The authors declare no competing financial interest.

Electronic Supplementary Information

Electronic supplementary information (ESI) is available free of charge in the online version of this article at <http://doi.org/10.1007/s10118-022-2675-7>.

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