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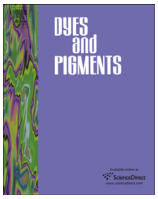

# Photo-controllable tristable optical switch based on dye-doped liquid crystal

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This work demonstrates an optically switchable tristable optical switch that is based on the light-matter interactions of dichroic dyes, azo-chiral and liquid crystal. The photo-induced isomerization of the azo-chiral dopant can alter the thickness/pitch ratio of liquid crystal film and enable the homeotropically aligned device to exhibit three stable – fingerprint, focal conic, and homeotropic textures. The dichroic dyes in the three textures have different absorptive properties. Tristable attenuation, scattering, and transparent states can be achieved using the dichroic dye doped fingerprint, focal conic, and homeotropic textures, respectively. All states can stably exist for several hours, and be switched from one state to another through light-induced isomerization effect of azo-chiral. Such a multi-stable optical switch exhibits easy switching, a desirable contrast ratio, and low power consumption. It therefore exhibits the potential to be utilized in practical portable information systems.

## 1. Introduction

Guest–host liquid crystal devices (GH-LCDs) have been developed and extensively used in various optical devices, including information displays [1–3], thin film polarizers [4], and color optical switches [5]. GH-LCDs are normally prepared by doping dichroic dyes into a liquid crystal (LC) host. The dichroic dyes are elongated and can dichroic absorb the incident light. The absorption of incident light that is polarized parallel and perpendicular to the principal axes of the dichroic dyes is maximal and minimal, respectively. When a small quantity of dye is dissolved into an LC host, the dye molecules are oriented parallel to the LC molecules. Accordingly, the orientation and absorption of dichroic dye-doped LC cells vary with their alignment, so the absorption is easily modulated by controlling the LC directors. A variety of GH-LCDs have already been realized using various kinds of liquid crystal, such as nematic [6,7], smectic [8], cholesteric liquid crystal (CLC) [9] and blue phase [10]. Each has its own operating principle that is associated with the alignment conditions and driving methods. However, these proposed GH-LCDs are mono-stable devices, so they depend on external power to maintain a constant state. The power consumption restricts their practical application in portable information systems.

The authors recently introduced dichroic dye into the electrically switchable multi-stable CLC that can adopt stable planar, focal conic, and uniformly-lying helical (ULH) states [11] and the optical properties of the dichroic dye in these three stable states were studied. The authors further proposed a bistable reflective electro-optical switch that used dichroic dye doped planar and ULH states [12]. However, although the proposed bistable electro-optical switch has the advantages of being polarizer-free and of consuming little power, its high switching voltage (>120 V) and low contrast ratios still make its practical application difficult.

This study develops a photo-controllable multi-stable optical switch that is based on dichroic dye and azo-chiral compound-doped LCs [13–19]. When an azo-chiral compound is dissolved into an LC system, the trans–cis photoisomerization of the azo-chiral dopant can change the chirality of the mixtures and enable structural transitions among the chiral and achiral systems [20–24]. The optical properties and driving method of the three stable textures – fingerprint, focal conic, and homeotropic textures – were examined herein.

## 2. Experimental

The subject system was prepared by adding a left-handed azo-chiral Q1-3c-S, also called ChAD-3C-S, (BEAM Co.) with a helical

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twisting power of 30 $\mu m^{-1}$ [25] and dichroic dyes (S-428, Mitsui Chemical Inc.) into nematic liquid crystal (5CB, Merck). The azo-chiral Q1-3c-S served to change the chirality of the chiral nematic liquid crystal, and the dichroic dyes were used for absorbing the incident light. The doping concentrations of both compounds are important. The optimal concentration of azo-chiral Q1-3c-S is in the range of 2–3 wt%. A lower concentration cannot induce the focal conic textures, while a higher concentration makes the fingerprint texture meta-stable rather than stable. A higher concentration of dichroic dyes helps the device to exhibit a better opaque state and a better contrast ratio, but at the cost of reduced transparency of the transparent state. In this experiment, 2 wt% azo-chiral Q1-3c-S and 7 wt% dichroic dyes were added to the mixture. Then, the mixture, which was heated to the isotropic phase, was stirred for four hours to ensure that it had fully dissolved; it was then injected into an empty homeotropically aligned cell that was separated by an 11 μm thick spacer. Finally, when the mixture was injected into the cell and cooled to room temperature, the focal conic texture was formed.

## 3. Results and discussion

Fig. 1(a) schematically depicts the operating principles and driving method of the tristable optical switch that exploits the focal conic, fingerprint, and homeotropic states of LC that is doped with a dichroic dye and an azo-chiral compound. The switching mechanism is based on the photoisomerization effect of the azo-chiral Q1-3c-S, which changes the chirality of the mixture and the corresponding thickness/pitch ratio (d/p), also called the confinement ratio, of the cell. This ratio dominates the arrangement of LCs. The compound Q1-3c-S has azo linkages, which has two distinct molecular configurations – the rod-like trans form and the bent cis form, as shown in Fig. 1(b). After the sample is fabricated, the LC cell is initially in the focal conic state. When the LC cell is irradiated using 408 nm light with an intensity of 10 mW/cm$^2$, the helical twisting power of the azo-chiral compound begins to decrease. If the reduced d/p of the homeotropically aligned CLC film is approximately in the range between one and four [26], a fingerprint state appears and can exist stably in the absence of the 408 nm irradiation. If the sample continues to be irradiated by 408 nm light, the reduced helical twisting power will enlarge the pitch of the chiral nematic LC. When the pitch exceeds the threshold pitch, $p_{th} = 2d(K_{22}/K_{33})$, where d is the thickness of the cell, and $K_{22}$ and $K_{33}$ are the elastic constants of twist and bend deformations [27], the helical torque becomes weak and the liquid crystal molecules becomes unable to twist in the cell. Therefore, the homeotropic anchoring dominates the orientation of the molecule, forming the homeotropic texture. When the 408 nm light has been turned off, the homeotropic texture is retained for a few hours and the sample slowly relaxes back to the high-chirality state via the cis-trans back-isomerization process. The dye-doped LC cell can be irradiated by 532 nm light to induce the fast back-isomerization of azo-chiral compound. If the intensity of the light is sufficiently high (>200 mW/cm$^2$), the homeotropic texture will relax back to focal conic directly. However, if the intensity of illumination is weak, the cell is switched to the fingerprint texture because the 2 wt% azo-chiral Q1-3c-S dopant makes the free energies of the both focal conic and fingerprint textures closer to each other. Rapid switching between the fingerprint and focal conic textures can be achieved by controlling the intensity of the addressing light, and both states are real-stable.

As presented in Fig. 1(a), when an LC cell is in the focal conic state, incident light cannot pass through it because it is absorbed by dichroic dye molecules and scattered by randomly oriented liquid crystal molecules. When an LC cell is in the fingerprint state, the liquid crystal and dye molecules twist along the helical axis, which is parallel to the glass substrate. Accordingly, dye molecules absorb arbitrarily polarized light without scattering. The CLC and dye molecules in the homeotropic state orient in the same direction perpendicular to the substrate of the cell, allowing all incident light to pass through the cell.

Fig. 2(a) and (b) displays the textures of the fingerprint, focal conic, and homeotropic states in a zero field, observed under a polarization optical microscope in transmission mode (T-POM) under crossed and parallel polarizers, respectively. The fingerprint texture involves randomly oriented liquid crystal molecules owing to the lack of a rubbing of the homeotropic alignment layers and the non-uniform distribution of color, which arises from the different color dispersion that is associated with the LC birefringence. The focal conic texture has a multi-domain structure in which the helical axes are randomly arranged throughout the cell. The homeotropic texture with liquid crystal molecules perpendicular to the substrate of the cell presents dark and bright states under crossed and parallel T-POM, respectively. The fingerprint state appears to

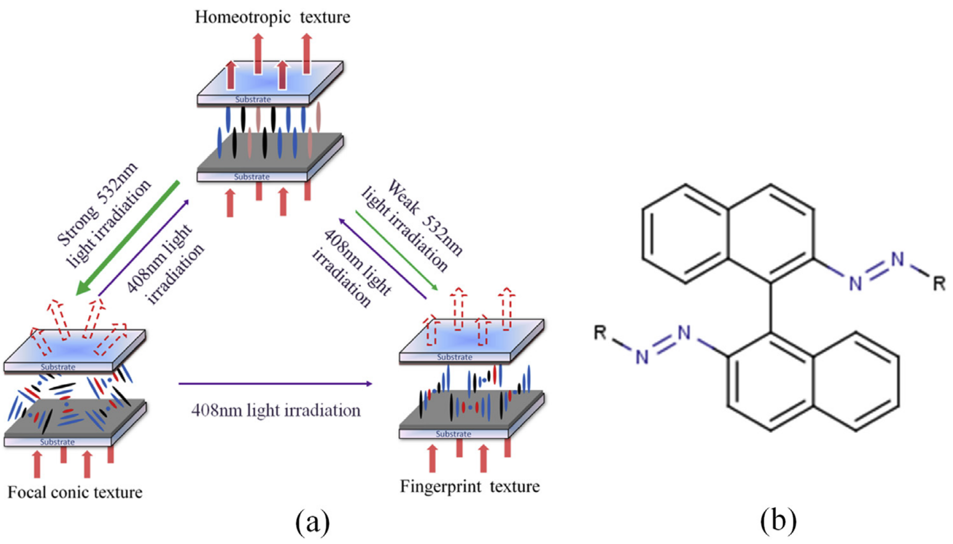

**Fig. 1.** (a) Operating mechanisms and driving scheme of proposed optical switch. (b) Chemical structure of azo-chiral dopant (Q1-3c-S).