Photo-switchable bistable twisted nematic liquid crystal optical switch

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Abstract: This work demonstrates a photo-switchable bistable optical switch that is based on an azo-chiral doped liquid crystal (ACDLC). The photo-induced isomerization of the azo-chiral dopant can change the chirality of twisted nematic liquid crystal and the gap/pitch ratio of an ACDLC device, enabling switching between 0° and 180° twist states in a homogeneous aligned cell. The bistable 180° and 0° twist states of the azo-chiral doped liquid crystal between crossed polarizers correspond to the ON and OFF states of a light shutter, respectively, and they can be maintained stably for tens of hours. Rapid switching between 180° and 0° twist states can be carried out using 408 and 532nm addressing light. Such a photo-controllable optical switch requires no specific asymmetric alignment layer or precise control of the cell gap/pitch ratio, so it is easily fabricated and has the potential for use in optical systems.

OCIS codes: (160.3710) Liquid crystals; (230.3720) Liquid-crystal devices; (230.1150) All-optical devices.

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1. Introduction

Bistable liquid crystal devices have attracted substantial interest for quite some time because they are bistable, enabling them to be used in highly multiplexed displays with passive matrices and to be operated with low power consumption [1–3]. Bistable LCDs may be in one of two stable states in the absence of any external field and thus they can retain an image even when the power is turned off. Various types of bistable LCDs, such as bistable twisted nematic (BTN) LCDs [4–6], zenithal bistable displays (ZBDs) [7], surface nematic liquid crystal displays [8], and cholesteric liquid crystal (CLC) displays [9, 10] have been proposed and commercialized for e-paper and other mobile applications. Each has its own operating principle and stable mechanisms that are associated with the particular liquid crystal, alignment condition, and elastic free energy density of the selected stable states. The BTN LCD has a good dark state and is therefore suitable for high-contrast bistable display applications.

Most BTN LCDs typically have two stable twisted states with a difference between twist angles of 2π, so they are commonly referred to as 2π-BTN. Typically, the twist angles of the two stable states are φ and φ + 2π, where φ represents the angle between the alignment directions on the bottom and top substrates of the cell. However, a major problem of the BTN LCD is that the φ and φ + 2π twist states are not stable states but they are meta-stable states. Therefore, long bistability between φ and φ + 2π twist states is difficult.

Dozov et al. proposed a π-BTN display, called BiNem, with 0° and 180° twist states [11]. Such a device utilizes two different anchoring conditions on two substrates to achieve bistability [12, 13]. One substrate is coated with a weak planar anchoring alignment layer, while the other is coated with a conventional polyimide, yielding a high tilted anchoring energy. An adequate chiral guest, which enables the pitch of the mixture to become four times the cell gap of the sample, is added to the nematic liquid crystals to equalize the elastic free energies of the two states. The device can be switched between the two states by breaking the anchoring of the liquid crystal at the alignment surface using different electric pulses. Compared with 2π-BTN display, the 0° and 180° twist states in the π-BTN display are truly stable and can be maintained stable for long time. However, the special alignment conditions and precise chiral dopant required for such a device complicate the fabrication process.

This work presents a photo-switchable BTN optical switch that is based on azo-chiral doped liquid crystal, which can be switched between 0° and 180° twist states by irradiation with 408nm and 532nm light. The switching mechanism is based on the fact that the photoisomerization of the azo-chiral Q1-3c-S can change the chirality of the mixture as well as the corresponding cell gap/pitch (d/p) ratio of the ACDLC cell, enabling switching between the 0° and 180° twist states [14–18].

2. Sample fabrication and measurement

The nematic LC and the azo-chiral dopant that were adopted in this experiment were 5CB (Merck) and Q1-3c-S (BEAM), respectively. The compound Q1-3c-S, whose helical direction
is left-handed, has a helical twisting power (HTP) of 30µm$^{-1}$. To form a 180° helical structure, which is chosen as one stable state in our proposed device, an appropriate amount of azo-chiral agent (Q1-3c-S) was dissolved in the 5CB, resulting in an initial d/p ratio between 0.25 and 0.75. Then the mixture, which was heated to the isotropic phase, was stirred for 4 hours to ensure that it had fully dissolved; it was then injected into an empty homogeneous aligned cell that was separated with a 7.5 µm thick spacer. Consequently, when the mixture was injected into the cell and cooled to room temperature, the 180° twist nematic state was established.

3. Result and discussion

Figure 1(a) presents the configuration of an optically switchable transmissive BTN LC device, including two linear polarizers and an ACDLC cell. Two polarizers are laminated on the top and bottom substrates of the ACDLC cell, respectively, and their corresponding transmission axes are parallel and perpendicular to the direction of rubbing of the PI film. When the ACDLC cell is in the 180° twist state, the liquid crystal molecules rotate by 180° along the helical axis from the top to bottom substrates, enabling the proposed device to transmit light under crossed-polarizers because of the existence of birefringence. When the ACDLC cell is in the 0° twist state in which the liquid crystal molecules are aligned along the direction of rubbing of the PI film, the liquid crystal molecules do not provide any phase retardation for incident light so all incident light is blocked by the crossed-polarizers. The ACDLC can also be applied in reflective mode, as shown in Fig. 1(b), in which a quarter-wave plate (QWP) and a reflective mirror are laminated on the back side of the ACDLC cell, unlike in transmissive mode. The optical axis of the QWP makes an angle of 45° from the alignment direction of the liquid crystal; therefore, the incoming linearly polarized light in the 0° twist state becomes circularly polarized light. Reflection of the outgoing beams from the mirror and their passing through the QWP produces a total phase difference of π. Therefore, the light is crossed by the top polarizer, so the ACDLC cell is in the OFF state. In the 180° twist state, the incoming light passes twice through the 180° STN producing sufficient phase retardation to enable it to pass through the top polarizer, so this state is regarded as ON state. The ON and OFF states of the transmissive/reflective BTN optical switch can be achieved using 180° and 0° twist states of LC, which are stable over long periods and can be easily switched between by irradiation with light of different wavelengths.

Figure 1(c) displays in detail the mechanisms of the state transitions between the 0 and 180° twist structures of the ACDLC. The Q1-3c-S is an azobenzene derivative of binaphyl which has azo linkages with two distinct molecular configurations - the rod-like trans form and the bent cis form, as shown in Fig. 1(d). Thus, irradiation with 408nm light, within the absorption spectrum of compound Q1-3c-S, causes the photo-isomerization of azo configurations, transforming the azo configurations from trans isomers to cis isomers. The change of geometrical configuration from trans to cis reduces the chirality of the ACDLC and the corresponding d/p ratio of the sample [19–21]. The reduced chirality forces a state transition from the 180° twist state to the 0° twist state, which remains stable until the reverse process by a thermal or photochemical reaction. The initial d/p determined by the chiral concentration for the proposed device, is set between 0.25 and 0.75, so the ACDLC must initially be in the 180° twist state owing to the limitation imposed by the boundary condition. Upon irradiation with 408nm light, the trans-cis isomerization of the azo configurations reduces both the chirality of the ACDLC and the d/p of the sample. When the d/p is lower than 0.25, the state transitions from the 180° twist state to the 0° twist state. After the 408nm light is turned off, the low-chirality state naturally relaxes back to the high-chirality state via the cis-trans isomerization process. Although the 0° twist state in the ACDLC cell is just a meta-stable state owing to the unavoidable thermal relaxation of the azo-chiral Q1-3c-S, the stable period can be effectively extended by adopting another azo-chiral with high thermal stability [22]. On the other hand, the tolerated ranges of d/p in the two bistable states of the proposed device are large - 0.25<d/p<0.75 for the 180° twist state and d/p<0.25 for 0° twist state. Irradiation with light at 532nm can rapidly induce the back-isomerization of azo configurations.
configurations and can switch the chirality of the sample to its original value, enabling a reversible transition from the 0° twist state to the 180° twist states.

Figure 2(a) presents the photomicrographs of the 0° and 180° twist states of the ACDLC cell in a zero field, observed under a transmission-polarizing optical microscope. Before irradiation by 408nm light, the ACDLC cell is in the 180° twist state and exhibits ON state under crossed-polarizers. Notably, the ON state is green rather than white. Like the Super Twisted Nematic (STN) display, the ACDLC cell in the 180° twist state has large color dispersion. Figure 2(b) shows the measured transmission and reflection spectra of the BTN LC device in the 180° twist state, respectively. The transmittance and reflectance peaks are around 580nm and 550nm, respectively, which correspond to the present color in the ON state. A direct method to restrain the color dispersion is to reduce the thickness of the device [23]. However, the tradeoff is that the difficulty of fabrication is increased as a cleaner environment is needed to ensure a desirable yield. Irradiation by 408nm light transforms the 180° twist into the 0° twist state as a perfect OFF state. Figure 2(b) also displays the transmission and reflection spectra of the 0° twist state of the BTN LC device from 400 to 700nm. The 0° twist state is non-dispersive and exhibits excellent dark-state transmittance.
To examine the switching time of the BTN LC device, the erasing and writing times of the device with light of various intensities were measured. DPSS laser light at 408nm and 532nm was used in switching for erasing and writing, respectively, and an He-Ne laser provided the probe light. Figure 3(a) plots the dynamic erasing times of the BTN LC device with 408nm light of various intensities. The ACDLC cell was initially in the 180° twist state and optically switched to the 0° twist state through the photo-isomerization of the azo-chiral, reducing the transmittance. The stronger intensity of the 408nm light shortens the erasing time due to the increase in absorption rate of the azo-chiral. The shortest erasing time of 2s was obtained at an intensity of 30 W/cm². Figure 3(b) plots the variation in the writing time of the BTN LC device with the intensity of green light. Irradiation with green light transforms the 0° twist state into the 180° twist state by the back-isomerization of the azo-chiral and thereby increases transmittance. The switching time in the erasing process is shorter than that in the writing process for a given intensity of irradiation because the absorption of azo-chiral Q1-3c-S in the UV region is stronger than that in the green region.

Figure 4 displays the operation of the transmissive/reflective BTN LC devices in the 180° and 0° twist states, corresponding to ON and OFF states. The proposed device was mounted on a light box where a white light source was used for illumination. For operation in the ON
(180° twist) state, the device exhibits a green color since the large phase retardation leads to dispersion behavior. For operation in the OFF (0° twist) state, the device displays desirable dark state owing to the absorption by the crossed polarizers. If polarizers of higher quality are utilized in the device, then a darker OFF state is obtained and a higher contrast ratio is expected.

![Fig. 4. Images of the transmissive/reflective BTN LCD in OFF and ON states.](image)

### 4. Conclusion

In conclusion, this work proposed an optically switchable BTN LC devices, which could be operated in transmissive or reflective mode using an azo-chiral (Q1-3c-S)-doped liquid crystal. The ON and OFF states of the proposed device are implemented in the 180° and 0° twist states, respectively. Both 180° and 0° twist states are stable and each can be optically switched to the other by irradiation with 408nm or 532nm light. Such an optically switchable device does not require an asymmetric polar anchoring alignment layer or exact control of the d/p ratio, effectively mitigating the problem of the narrow processing window in the traditional BTN LCD, making the device highly promising for practical applications.

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