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Electrically switchable bistable dual frequency liquid crystal light shutter with hyper-reflection in near infrared

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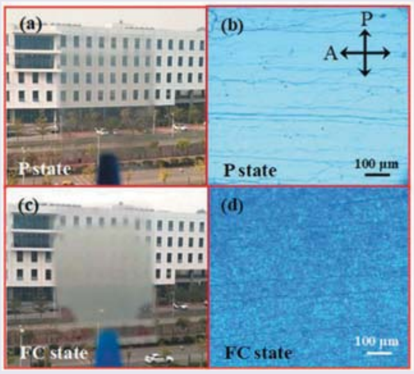
ABSTRACT
Bistable light shutter based on dual frequency cholesteric liquid crystals (LCs) have attracted intensive interests due to low energy consumption. Herein, we demonstrated an electrically switchable bistable dual frequency LC light shutter with a hybrid structure of cholesteric LC and chiral polymer film. The fabricated device can be switched between planar state which is transparent and focal conic state which is opaque in visible light through voltage pulse while keeping hyper-reflection in near infrared light in both states. The increase of reflection in near infrared light dramatically reduces the interior heat from solar energy, thus making it quite useful in temperature control. In addition, the reflection of near infrared light can be further improved by using cholesteric LC with larger birefringence. The proposed device is useful in smart windows of automobiles, energy-saving buildings and other photonic applications.



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Introduction

Liquid crystal (LC)-based light shutters have been demonstrated for decades with different methods such as polymer dispersed liquid crystals (PDLCs), polymer-stabilised cholesteric texture (PSCT), polymer network liquid crystal (PNLC) and so on [1–3]. The LC-based light shutters have attracted significant attention for its great potential in buildings, cars, photovoltaic devices and light emitting diodes [4–7]. Windows that can control the light and heat, where the visible light is used for maintaining interior illumination level and the infrared (IR) solar energy which is corresponding to the indoor temperature, are highly desirable especially in energy-saving buildings [8]. One of the major energy consumptions and expenses in building, cars, green house and indoor spaces come from the cooling devices used for temperature control. It is reported that more than 75% of the energy of IR light is attributed for near IR light lies between 700 and 1400 nm [9]. Therefore, the reflection ability of near IR light while keeping highly transparency in visible light is preferable in light shutter applications. The visible light provides the illuminance indoor thus reducing the energy consumption of artificial lights, and the reduction of IR light leads to less cooling power consumption indoor. Several IR reflectors based on LC or LC polymer have been demonstrated [10–12].

Bistable light shutters based on cholesteric LCs have attracted intensive interests due to low energy consumption. Many emerged methods have broken the reflectance limit of 50%, such as superimposing left- and right-handed cholesteric liquid crystal (CLC)s, making use of memory effects of polymer network

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[13,14]. Another significant design uses the structure of polymer film with another material refilling into it [15–18]. Yang et al. reported a bistable polymer stabilised cholesteric texture light shutter, where the light shutter was switched thermal effect and voltage pulses [19,20]. Besides, some light shutters by using dual frequency LC or silica-dispersed LCs were reported to achieve a reverse mode [21–25]. The pace of research has not stopped here, there are many optimisations after it. A faster response time, longer term stability, higher reliability, lower driving voltage and more energy saving can be achieved with different derivative designs [26–28]. Furthermore, the PDLC films will not be limited to specific conditions, the plastic substrates con be another choice [29]. Yoon et al. demonstrated a cholesteric LC device with a three-terminal electrode structure that can be operated in both dynamic and bistable modes [30]. Khandelwal et al. proposed the bandwidth of a CLC device can be wider with a higher applied voltage per micron thickness of the cell [31]. However, the current reported CLC light shutters do not possess strong IR reflection and large bandwidth.

In this letter, we demonstrate an electrically switchable bistable dual frequency LC light shutter with a hybrid structure of cholesteric LC and chiral polymer film. The fabricated device can be switched between planar state that is transparent and focal conic state that is opaque in visible light through voltage pulse while keeping hyper-reflection in near IR light in both states. The handedness of the chiral photonic crystal structure and its reflected light's circular polarisation are the same, so that the left-/right-handed photonic crystal structure can reflect no more than 50% of unpolarised incident light. The polymer film layer maintains the feature of right handedness, even after soaking out the original CLC and refilling a new CLC with a different handedness. This layer is responsible for the left-handed polarised light. The second layer is full of the refilling CLC, which is in charge of the right-handed polarised light. The two parts work together and achieve a higher reflection. At the original state, the LCs form a right-handed helical structure under the effect of chiral dopants, and the direction of the spiral axis is perpendicular to the substrates. In the case of a current (AC) electric field at low frequency, the dielectric anisotropy of LC becomes positive. LCs tend to align along the direction of the electric field, and the distribution of spiral axis is disorganised. The device presents a scattering state. In contrast, when the frequency of this electric field increases, the dielectric anisotropy of LC becomes negative. LCs tend to be parallel to the substrates, and the spiral axis is vertical to the substrates. The device presents a transparent state [32–35]. The increase of reflection in near IR light dramatically reduces the interior heat from solar energy, which is quite useful in temperature control. In addition, the reflection of near IR light can be further improved by using cholesteric LC with larger birefringence. What is more, the temperature dependence of dual-frequency LC (DFLC) is the key property for devices' application. For this reason, compounds with a higher birefringence are a good choice for reflecting the specified light stably at room temperature [34–36]. The proposed device is useful in smart windows of automobiles and energy-saving building and other photonic applications.

Experimental details

The proposed light shutter device consisted of two parts including polymer film and cholesteric LC with opposite handedness. The light shutter was made of LC cell that was assembled by two indium tin oxide (ITO) coated glass substrates. The gap of cell was 20 μm. The inner surfaces of LC cell were coated with 6.0 wt.% polyimide (PI) alignment solution (ZKPI-410), resulting in anti-parallel rubbing alignment. The cholesteric LCs were mixed by nematic LC E7 (n_e= 1.741 and n_o = 1.517, from Jiangsu Hecheng□ HCCH) and chiral dopant R5011 or S5011 (from HCCH). The helical twisting power (*HTP*) of R5011 and S5011 are both 94 μm^{-1} for E7 in reactive mesogens (RMs). The RMs were the mixture of RM257, RM021, RM006, RM82 and RM010 with a weight ratio of 30: 15: 20: 20: 15 [37,38]. Darocur1173 was used as the photo-initiator. Table 1 shows the compositions of samples used in our experiments.

Figure 1 demonstrates the schematic of fabrication process of proposed light shutter. Firstly, the mixture of E7, R5011, RMs and darocur1173 was filled into the LC cell, where the samples were mixed by the heating magnetic stirrer (Thermo Scientific Cimarec). A planar state was formed due to the anti-parallel alignment of glass substrates, as shown in Figure 1(a). The RMs will orient with the CLC molecules in the LC cell. Then, an ultraviolet (UV) light (365 nm) was used to expose the sample to

Table 1. The compositions of samples.

	Film				
	E7	R5011	RMs	Darocur1173	
A1	72.72 wt.%	1.27 wt.%	25 wt.%	1 wt.%	
A2	72.83 wt.%	1.17 wt.%	25 wt.%	1 wt.%	
	Refilled CLC		Device		
	DFLC	S5011		Film	Refilled CLC
B1	98.19 wt.%	1.81 wt.%	S1	A1	B1
B2	98.40 wt.%	1.60 wt.%	S2	A2	B2
	B-03–3	S5011	S3	A1	B3
B3	98.48 wt.%	1.52 wt.%			

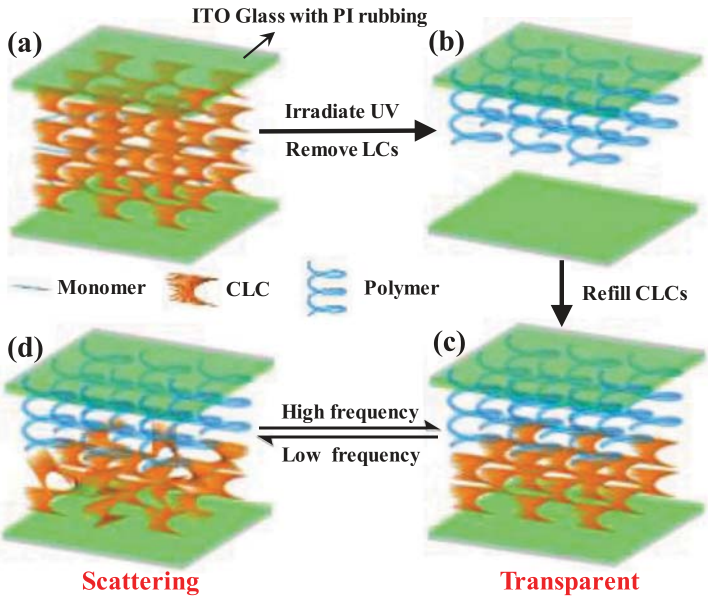

Figure 1. (Colour online) Schematic of fabrication process. (a) Original CLC sample; (b) Film; (c) Transparent state; (d) Scattering state.

polymerise the monomers, where the light intensity is 0.3 mW/cm^2 and the exposure time is 30 min. The UV light was provided by UV-LED point light source (LOTS UVEC-4II). By controlling the exposure time well, a polymer network with chiral structure was formed in the side near to the UV exposure direction while the polymer network was not completely in the side which is far from the UV exposure. After that, the LC cell was opened and the film with one substrate was immersed in toluene for 2 h to soak out the CLC and unpolymerised monomers. The thickness of resulting film was around 10 μm. Next, the polymer film on substrate was assembled with another ITO glass to form a new LC cell with a thickness of 20 μm, as shown in Figure 1(b). CLC with left-handedness chiral structure, which consisted of nematic LC DFLC HEF951800 (n_e= 1.714, n_o = 1.497, and Δn = 0.217) and chiral dopant S5011, was refilled to the new LC cell. The refilled new LC cell was used as our bistable light shutter device. For the polymer film part, due to the strong alignment effect of polymer film on LC molecules, the polymer film still exhibited right-handedness even though that CLC with left-handedness was refilled in. For the CLC part, it exhibited left-handedness. The careful adjustment of reflection spectra of those two parts will lead to a hyper-reflection in near IR range, which will significantly reduce the transmittance of IR and largely save energy in the room of building while the light shutter was applied in building glass. As a light shutter, the CLC part of the proposed device is switchable between transparent or planar state (P state, as shown in Figure 1(c)) and scattering or focal conic state (FC state, as shown in Figure 1(d)). The LCs exhibit dual-frequency under alternating current (AC) electric field with different frequency. When an electric field at low frequency (1 kHz) is applied, the LCs exhibit a positive dielectric anisotropy and the CLC molecules tend to align parallel to the applied field. The device will be switched from P texture to FC texture, which scatters incident light in random directions and leads to the scattering state. Conversely, once an electric field at high frequency (65 kHz) is applied, the LCs exhibit a negative dielectric anisotropy and CLC molecules tend to align perpendicular to the applied electric field. The device will be switched from FC texture to P texture, resulting in a transparent state. It is noticed that the scattering and transparent state are used to describe the light transmittance in visible light. For both P state and FC state of CLC, the transmittance in near IR range is kept relatively low.

Results

As far as we know, the solar radiation in the wavelength range is mainly between 200 and 3000 nm, which covers ultraviolet, visible light and IR light. For the area that we focus on, most of the radiation related to temperature is mainly in the near IR light range. More than 75% of the energy of IR light lies in the range of 700 and 1400 nm [9], where the longer the wavelength, the weaker the radiation. For photonic band of CLC, the central wavelength can be calculated by the equation of $\lambda = n \times p$, where n is the average refractive index, and p is the pitch of CLC chiral structure. The pitch is expressed by $p = [HTP \times x_c]^{-1}$, where HTP is helical twisting power, and x_c is concentration of chiral dopant. The linewidth $\Delta\lambda$ of photonic band is determined by $\Delta\lambda = p \times \Delta n$, where Δn is the birefringence and can be given by $\Delta n = n_e - n_o$ ($n_o$is ordinary refraction index and n_e is extraordinary refraction index of LCs) [39,40].

Figure 2(a,b) demonstrates the transmission spectra of sample A1, B1 and S1 with P and FC states. Because the LC cell is assembled by two ITO coated glass substrates, resulting in reduced transmittance in visible light. Considering the influence of collecting angle on the measured transmission spectrum, the micro-spectrophotometer with the collecting angle of 23° was used to test the performance of transmission. Figure 2(a) plots the transmission spectra of film sample A1, CLC sample B1 and device sample S1, respectively. For sample A1 and B1, the photonic bandgap is formed in the range of 800 ~990 nm and 760 ~910 nm, with central wavelength of 890 and 840 nm, and minimal transmittance of 32.80% and 35.13%, respectively. The sample S1 based on A1 and B1 demonstrates a photonic bandgap of 750–920 nm, with central wavelength of 830 nm and minimal transmittance of 1.04%. The broadened linewidth of 170 nm and lowered transmittance in near IR range are quite useful for energy-saving smart window application. Figure 2(b) plots the transmittance spectra of sample S1 at P state (black curve) and FC state (red curve). It can be seen that the total transmittance at FC state is lower than that of P state. A similar behaviour is observed in A2, B2 and S2 samples, as shown in Figure 2(c,d). For sample A2 and B2, the photonic bandgap is formed in the range of 930 ~1120 nm and 920 ~1110 nm, with central wavelength of 1050 and 1030 nm, and minimal transmittance of 23.44% and 30.56%, respectively. The sample S2 based on A2 and B2 demonstrates a photonic bandgap of 950–1120 nm (linewidth is 170 nm), with central wavelength of 1035 nm and minimal transmittance of 0.82%. Figure 2(d) plots the transmittance spectra of sample S2 at P state (black curve) and FC state (red curve). It is clear that the design of combing right-handed chiral film with left-handed chiral CLC can lead to a superposition of hyper-reflection thus keeping low transmittance in the desired IR range. In addition, when the device is switched from P state to FC state, the transmittance in visible range dramatically reduced while keeping the low transmittance in IR range. It is noted that the transmittance spectrum were measured at 0° incident angle.

The fabricated device can be used as a bistable light shutter, which is bi-directionally switchable between the P state and FC state through frequency-modulated voltage pulses. For example, the sample

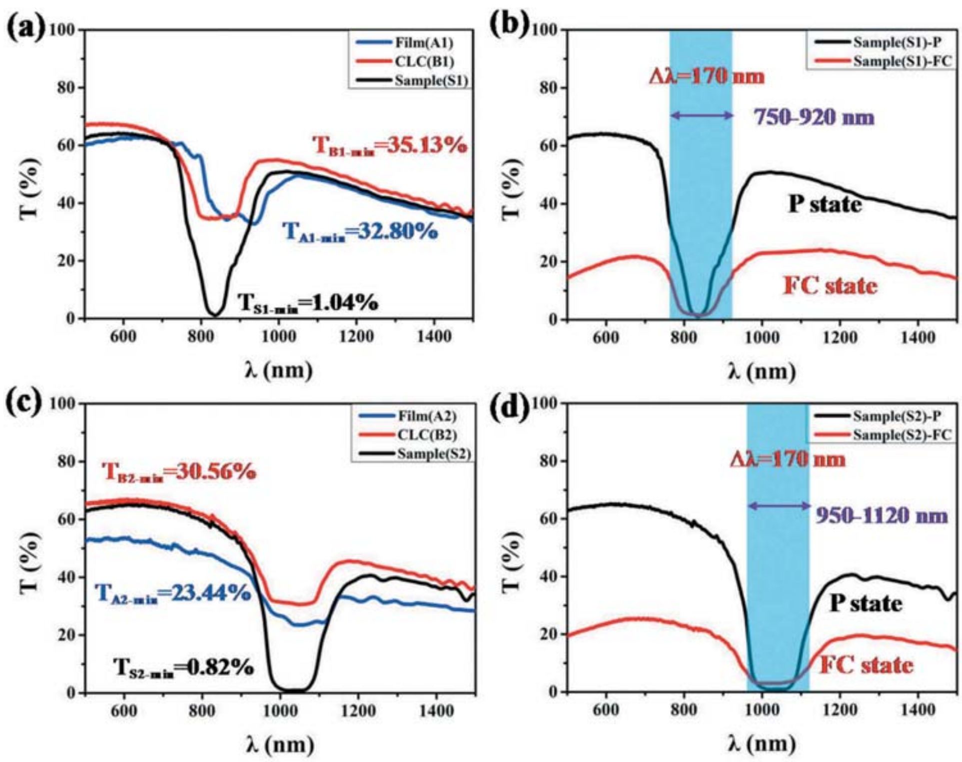

Figure 2. (Colour online) (a) Transmittance of A1, B1, and S1; (b) Transmittance of S1 at P state and FC state; (c) Transmittance of A2, B2, and S2; (d) Transmittance of S2 at P state and FC state.

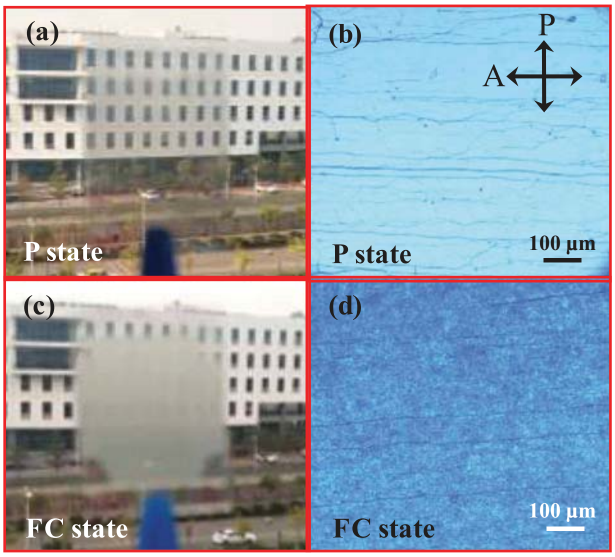

Figure 3. (Colour online) (a) Real photo of sample S1 at P state; (b) Image observed in POM of sample S1 at P state; (c) Real photo of sample S1 at FC state; (d) Image observed in POM of sample S1 at FC state. The scale bar is 100 μm.

can switch from P state to FC state quickly at AC square wave with the voltage of 250 V and frequency of 1 kHz, then switch back from FC state to P state at the voltage of 150 V and 65 kHz. Figure 3(a,b) demonstrate the real photo and image observed in polarising optical microscope (POM, Nikon Ci) of sample S1 at P state. The POM images of samples are obtained under the charge-coupled device (CCD) camera (Nikon, DSFi2), where the directions of polariser and analyser are represented by P and A, respectively. It can be seen that the device in P state is transparent in visible range, where the helical axis of CLC is normal to the cell substrate. Therefore, through the device, we can see the building behind it. In contrast, in FC state the device is scattering in visible range, where the LCs molecules are in randomly oriented poly-domains. Therefore, the image behind the device is blocked and we cannot see it. Figure 3(c,d) demonstrates the real photo and image observed at polarisation optical microscopy of sample S1 at FC state. The scale bar is 100 μm. It is noticed that the response time of fabricated device sample 1 is around 2.5 s for switching from P state to FC state and 1.5 s for switching from FC state to P state.

Besides making the photonic band gap 'deepening' as mentioned above, the reflection of IR range can be further increased by making the photonic band gap 'broadening'. As we have observed, the linewidths of S1 and S2 are both around 170 nm. Herein, a sample S3 was fabricated by film A1 and refilled by CLC B3, which is a mixture of nematic LC B-03–3 (n_e= 1.88, n_o = 1.50, and Δn = 0.38, HCCH) and chiral dopant S5011 (*HTP*= 130 μm^{-1} for B-03–3). The larger birefringence of Δn =0.38 leads to a broaden linewidth according to the equation of $\Delta\lambda = p \times \Delta n$. Figure 4(a) plots the transmittance spectra of sample S3 at P state (black curve) and FC state (red curve). The FWHM is around 220 nm (from 720 to 940 nm) and the central wavelength of 830 nm. Figure 4(b) shows the photo of S3 at P state and FC state, where the logo of SUSTech can be seen or blocked.

To estimate the reflection effect on IR range, the total transmittance in the range from 700 to 1700 nm was integrated for film A1, CLC B1 and device S1-S3, respectively. The calculated total transmittance based on experimental data is T_{A1} =44%, T_{B1} = 45% and T_{S1} =33%. Compare with single film A1 and single CLC B1, the total transmittance of S1 reduces significantly for 10% and 13%, the corresponding improvement are 24% and 27%. The configuration of double-layer dramatically improves the 'block' effect of proposed device in IR range. The total transmittance in the range from 700 to 1500 nm can be further reduced by broadening the photonic band gap (S3). The calculated transmittance of S3: T_{S3} =23%, which is much lower than that of S1 with a reduction of 10% and an improvement of 30%. Therefore, both 'deepening' and 'broadening' photonic

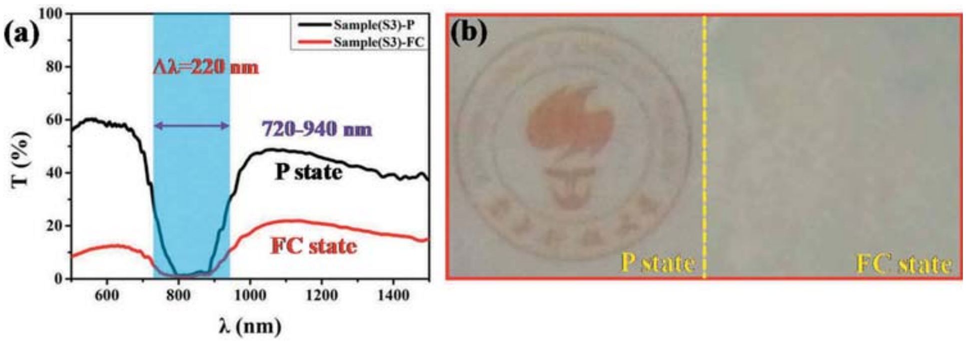

Figure 4. (Colour online) (a) Transmittance of S3; (b) Photographs of S3 at P and FC states.

band gap of light shutter will bring benefits on lowering the total transmittance in IR range, which is critical for energy-saving building and other photonic applications.

Conclusions

In conclusion, an electrically switchable bistable dual frequency LC light shutter is demonstrated based on a hybrid structure of cholesteric LC and chiral polymer film. The fabricated device can be switched between planar state which is transparent and focal conic state which is opaque in visible light through voltage pulse while keeping hyper-reflection in near IR light in both states. The transmittance in the centre of photonic band is reduced from around 30% to about 1% in designed IR range. In addition, the reflection of near IR light can be further improved by using cholesteric LC with larger birefringence. The total reflection in near IR range is improved by 10~12% compared with single CLC or film light shutter, and it can be further improved around 10% by using CLC with larger birefringence. The proposed device is useful in smart windows of automobiles and energy-saving building and other photonic applications.

Disclosure statement

No potential conflict of interest was reported by the authors.

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