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Bistable salt doped cholesteric liquid crystals light shutter

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ABSTRACT

Liquid crystals have been used to make electrically switchable light shutters (windows), but most of them are monostable: opaque in the absence of applied voltage and transparent when a voltage is applied. Here we report a bistable switchable light shutter based on cholesteric liquid crystal doped with tetrabutylammonium bromide. The salt makes it possible for the liquid crystal to have different electro-optical responses to applied voltages with different frequencies. The shutter can be either transparent or opaque in the absence of applied voltage. It can be switched from the transparent state to the opaque state by applying a low frequency (60 Hz) voltage pulse and switched back to the transparent state by applying a high frequency (2 kHz) voltage pulse. Because of the bistability, it can be used for energy-saving switchable privacy control and architectural windows.

1. Introduction

Liquid Crystals have been used to make various light shutters and switchable windows [1–3]. Examples are polymer dispersed liquid crystals (PDLCs) and polymer stabilized cholesteric textures (PSCTs) [4–8]. They exhibit two optical states: transparent and opaque. They are usually in the opaque state in the absence of applied voltage and become transparent when a voltage is applied. They are monostable that a voltage must be applied to sustain one of the optical states. When they are used as large size architectural switchable windows, they consume a lot of energy when the voltage is applied in prolonged period. In order to save energy, bistable switchable windows are highly desirable, which can be either in the transparent or opaque state without applied voltages.

Polymer stabilized cholesteric (Ch) liquid crystals is one of the switchable window technologies. A Ch liquid crystal possesses a helical structure in which the elongated liquid crystal molecules twist spatially around an orthogonal axis-called the helical axis [2,9]. The distance over which for the molecules twist 360° is the helical pitch and denoted by P. The optical property of a Ch liquid crystal sandwiched between two parallel substrates depends on the direction of the helical axis with respect to the substrates. It exhibits three textures (states) with different optical properties due to different orientations of the helical axis. The first texture is the planar texture in which the helical axis is perpendicular to the substrates and the liquid crystal reflects light at the wavelength $\lambda = [(n_e + n_o)/2]P$ with the bandwidth $\Delta\lambda = (n_e - n_o)P$, where n_e and n_o are the extraordinary and ordinary refractive indices of the liquid crystal, respectively. The second state is the focal conic state in which the liquid crystal forms a poly-domain structure with the helical axis varies randomly from domain to domain and the liquid crystal is optically scattering. The third state is the homeotropic state in which the helical structure is unwound by externally applied voltages, with the liquid crystal molecules aligned perpendicular to the substrate, and the liquid crystal becomes transparent. Ch liquid crystals can be operated in various modes. One example is the polymer stabilized Ch texture (PSCT) normal mode light shutter which is in the opaque focal conic state without applied voltages and is switched to the transparent homeotropic state when a sufficiently high voltage is applied [7]. Another example is the polymer stabilized Ch texture (PSCT) reverse mode light shutter is in the transparent planar state (reflecting infrared light) without applied voltages and is switched to the opaque focal conic state when a voltage is applied [8,10]. The third example is the dual frequency polymer stabilized Ch texture bistable mode light shutter can be either in the opaque focal conic state or in the transparent homeotropic state in the absence of applied voltages [11]. When a low frequency voltage is applied, the liquid crystal exhibits positive dielectric anisotropy and is switched from the focal conic state to the homeotropic state. When a high frequency voltage is applied, the liquid crystal exhibits negative dielectric anisotropy and is switched from the homeotorpic state back to the focal conic state. The problem with the dual frequency liquid crystal is that the cross frequency (when the dielectric anisotropy changes from positive to negative) changes significantly with temperature and the high frequency is high

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(>10 kHz) such that the capacity effect of the liquid crystal film becomes so severe that large power suppliers are needed.

In this paper, we report a novel bistable mode Ch liquid crystal light shutter, which has some advantages over the bistable dual frequency Ch liquid crystal light shutter. This shutter is operated between the transparent planar state and scattering focal conic state. A low frequency (60 Hz) voltage pulse switches the shutter from the transparent state to the scattering state and a high frequency (2 KHz) voltage pulse switches it back to the transparent state.

2. Experiment

The Ch liquid crystal used in our experiment is a mixture of 95% nematic host HNG-7058 (HCCH, China) and 5% chiral dopant R811 (Merck). The mixture has a negative dielectric anisotropy. The pitch is 0.66 μm and thus reflects light at the wavelength around 1.1 μm. The Ch liquid crystal is then doped with salt tetrabutylammonium bromide [$(C_4H_9)_4N^+Br^-$] (TBAB, Sigma Aldrich), whose chemical structure is shown in Fig. 1. The mixture is filled into cells consisting of two parallel glass substrates with transparent Indium Tin Oxide (ITO) electrode. The inner surface of the substrates is coated with PI2555 (DuPont) and rubbed for homogeneous alignment of the liquid crystal. The cell thickness is controlled by 10 μm spacers.

The novelty of the bistable light shutter is the abnormal responses of the liquid crystal to applied voltages, depending on the frequency of the voltage. The applied voltage has two effects on the liquid crystal. First, the liquid crystal has a negative dielectric anisotropy. When a voltage is applied across the cell, independent of the frequency, it tends to align the liquid crystal perpendicular to the electric field, namely, parallel to the cell substrate. This is the dielectric interaction effect. Second, the liquid crystal has ions due to the doped salt. When a voltage is applied across the cell, it makes the ions to move along the electric field direction, namely, perpendicular to the cell substrate. The motion of the ions produces a turbulence and tends to align the liquid crystal along their moving direction [12–18]. Conversely, the voltage tends to align the liquid crystal perpendicular to the cell substrate. This is the turbulence effect. These two effects of the applied voltage complete against each other. The strength of the latter effect depends on the frequency of the applied voltage. At a low frequency, the ions fellow the electric field. The motion is sufficiently large and the aligning effect of the turbulence is dominant. The overall effect of the applied voltage is to align the liquid crystal perpendicular to the cell substrate. At a high frequency, the ions cannot fellow the electric field due to their limited mobility. The aligning effect of the dielectric interaction is dominant. The overall effect of the applied voltage is to align the liquid crystal parallel to the cell substrate.

The operation of the bistable light shutter is schematically shown in Fig. 2. The liquid crystal is initially in the planar state as shown in Fig. 2(a), where the liquid crystal is parallel to the cell substrate. Because the liquid crystal reflects infrared light, it is transparent in the visible light region. The polarizing optical microphotograph of the planar state is shown in Fig. 3(a). When a low frequency (60 Hz) voltage is applied across the cell, the turbulence effect dominates and tends to align the liquid crystal perpendicular to the cell substrate, while the liquid crystal tends to remain the helical structure due to the intermolecular interaction. The net result is that the liquid crystal is switched to the focal conic state as shown in Fig. 2(b), where the helical structure is retained and in some regions, the liquid crystal becomes perpendicular to the cell substrate. The focal conic state is a multi-domain structure and the liquid crystal becomes scattering. The polarizing optical microphotograph of the focal conic state under 40 V is shown in Fig. 3(b). When the low frequency voltage is removed, the liquid crystal remains in the focal conic state. Both the planar and focal conic states are stable at 0 V, because the helical structure is preserved in both the planar and focal conic state. Furthermore there is an energy barrier between these two states and the focal conic domains cannot rotate back to the planar state even though the surface alignment layer favors the planar state. The polarizing optical microphotograph of the focal conic state at 0 V is shown in Fig. 3(c). Nevertheless it is different from that under the applied voltage. The focal conic domain size at 0 V is bigger than that under the applied voltage. When a high frequency voltage is applied, the dielectric interaction effect dominates and tends to align the liquid crystal parallel to the cell substrate. Thus the liquid crystal is switched back to the planar state. When the applied voltage is removed, the liquid crystal remains in the planar state.

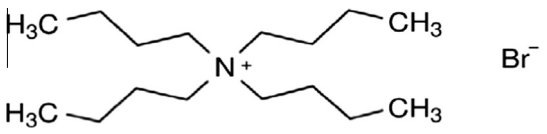

Fig. 1. Chemical structure of slat tetrabutylammonium bromide (TBAB).

When the salt TBAB is doped into the liquid crystal, it disassociates into positive and negatives ions and changes the electric resistivity of the liquid crystal. Using LCR meter *Hewlett Packard* 4284A, we measured the resistances of cells of 1 cm^2 area with various TBAB concentrations. The frequency and amplitude of the voltage used for the measurement were 60 Hz and 10 V, respectively. When the concentration of TBAB is 0%, the resistance of the cell at 60 Hz is 648 kΩ. When the concentration of TBAB is 3%, the resistance decreases to 55 kΩ.

We measured the electro-optical response of the bistable Ch liquid crystal light shutter. In the measurement a green He–Ne laser light at the wavelength 532 nm was used and a photodiode was used as the detector. In the measurement, a voltage pulse with the time interval of 2 s was applied, and the transmission was measured 1 min after the removal of the pulse. *Note the transmission was measured at 0 V.* Voltage pulses with the frequency of 60 Hz drove the liquid crystal from the transparent planar state to the opaque focal conic state. The transmittance of the material *after the removal of the applied voltage* vs. the amplitude of the applied voltage pulse is shown in Fig. 4. Initially the liquid crystal was in the planar state with high transmittance (~90%). The light lose was mainly due to the reflection at the glass–air interfaces. For the cell without salt, when the voltage was applied, there was no turbulence and the transmittance remained unchanged. For the cells with salt, turbulence was induced when a voltage was applied. When the amplitude of the applied voltage pulse was below 20 V, the induced turbulence was not big enough to change the state of the liquid crystal, and the transmittance remained high. When the voltage was increased above 20 V, liquid crystal was switched from the planar state to the focal conic state, and the transmittance decreased. Both the amount of the liquid crystal switched to the focal conic state and the domain size depended on the amplitude of the voltage pulse and the concentration of TBAB. As the voltage and the TBAB concentration were increased, the turbulence became more violent; more liquid crystal was switched to the focal conic state and the formed focal conic domain size decreased. Therefore, the transmittance decreased. Note that the scattering efficiency of the liquid crystal depended on the focal conic domain size. The material was most scattering when the domain size was slightly larger than the wavelength of the light. When the concentration of TBAB was