x.x: Dual Frequency Switchable Flexoelectric Cholesteric Devices

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Abstract

We demonstrate an electro-optical device based on the flexoelectric effect of a short-pitched cholesteric liquid crystal. By using a dual-frequency switchable nematic, a small amount of chiral dopant and a small amount of phase-separated polymer localized on the surface, we were able to create a device that operates in amplitude (flexoelectric) and phase (dielectric) modes. At high frequency the dual frequency liquid crystal suppresses the phase mode at higher voltage, which improves the switching speed, and thereby preserving the in-plane-switching mode.

1. Introduction

The evolution for next generation liquid crystal display (LCD) will require LCDs with motion picture quality, ultra high contrast, brightness and wide viewing characteristics. Currently, there are two major display technologies currently competing for the domination in LCD market; namely, in-plane-switching (IPS) [1] and vertical aligned (VA) nematic modes [2]. The IPS technology leads in better color uniformity and viewing angle, while the VA has the edge of high brightness, high contrast, slightly fast in response time and relative easy in large size panel production because of no rubbing process. The view angle issue for both technologies has been dramatically improved by using multiple domains, fringe field and lateral field [3-5] and the combination of appropriate polymer retarders [6] to tame the gray level and color shift at wide viewing angle.

While the challenge for these tow technologies resides in response time for perfect motion picture. The switching speed of nematic LCDs the rising time is related to the magnitude of applied voltage and the falling time is related to the viscosity of LC. The issue of response time has been approached by using thinner cell gap and higher switching voltage. However, thinner cell gap increases the difficulty in process while the higher switching voltage increases the power consumption. Other high speed LC technology such as optical compensated bend (OCB) mode, although possessing wide viewing angle distinctiveness, requires hundreds of millisecond to change the LC orientation from splay to bend [7]. Recently, the polymer stabilized bend mode nematic display that enables the stabilization of the twist or bend mode at zero voltage and continuous director rotation in response to the applied electric field [8]. The type of device does not require a threshold or warm-up voltage to maintain the bend state. Instead, it used polymer network for volume stabilization the LC orientation.

A short-pitch cholesteric material with its helical axis originally oriented perpendicular to the substrates can be re-oriented to parallel to the substrate by using a small bias voltage [9]. The uniform cholesteric film behaves as a switchable birefringent filter. An in-plane rotation of the optical axis can be achieved by applying an electric field across the cholesteric film, which was reported by Meyer as the flexoelectric effect [10]. An out-of-plane switching is possible if the applied voltage exceeds the critical field of unwinding the cholesteric LC with a positive dielectric anisotropy. The helix unwinding that takes place because of dielectric coupling is a polar and linear effect.

Recently, we have developed another type of electro-optical device based on the flexoelectro-optic effect in short pitch cholesteric using surface-stabilized cholesteric uniform lying helical texture [11]. We found that in order to create uniform lying helical texture and high optical contrast of flexoelectric ChLCDs using polymer stabilization and minimizing light scattering, one must use surface-localized and periodically-structured polymer network. The method of polymerization in liquid crystal to form inhomogeneous distribution of polymer network was employed to control the polymer morphology and localization of polymer network. During polymerization induced phase separation, we chose to use the gradient of light intensity to create the inhomogeneous polymer distribution and mostly localized at the substrate surfaces. Initially, the homogeneous single phase consists with uniformity distribution of prepolymer in uniformly lying helix induced by a small bias field. Liquid crystals are excluded from the surface as the polymeric network grew near the surfaces. The device enables tow modes of switching, but has limited rotation angle of optic axis. Therefore, further optimization of material and electro-optical parameters is necessary to achieve the maximum optical contract from the in-plane switching mode.

Dual frequency nematics have been known for their fast switching characteristics for a few decades but are usually avoided in the LCD industry because of their electro-optical parameters strongly depend on temperature [12-13]. The purpose of this work is to search for a solution for a fast in-plane switching flexoelectric cholesteric device by using a dual frequency switchable cholesteric LC mixture. In this case the in-plane cholesteric helix rotation can be maintained by using a high frequency voltage to suppress the dielectric coupling of cholesteric LC at high voltage. A homogeneous in-plane rotation of all the molecules produces a short wavelength periodic splay-bend structure with a small intrinsic relaxation time.

In this paper, we report the materials preparation, cell fabrication, and electro-optical properties, as well as the surface morphology of a fast switching flexoelectric cholesteric device.

2. Experimental

Our samples consist of a commercial, room-temperature nematic mixture MLC2048 (Merck), whose dielectric anisotropy changes sign at a specific inversion frequency. In this material, the parallel ($\varepsilon_{\parallel}$)and perpendicular ($\varepsilon_{\perp}$) dielectric permittivities are in the following relationship: $\varepsilon_{\parallel}(0) > \varepsilon_{\perp}(0) > \varepsilon_{\parallel}(\infty)$ and the crossover frequency f is ~10^4 Hz. A typical cholesteric material consists of 72.0% of a nematic or MLC2048, 25.0wt% chiral compounds mixture (CE1, CB15, R-1011, Merck), 2.85% reactive monomer (RM257, Merck) and 0.15% photoinitiator (Irgacure 651, Ciba). The intrinsic pitch of the cholesteric material is measured by using a spectrometer as 0.56 micron, which reflects a yellow green color on a microscopic cover slide. The monomer was added to the liquid crystal and these materials were vortex-mixed in a vial, heated to around 50 degree Celsius and cooled to room temperature. Electro-optical cells used in our experiments are made by EHC (Japan) with ITO electrodes (electrode area ~ 10 mm^2) and alignment layers deposited on the inner surface of the confining substrates used for achieving a planar alignment of the cholesteric liquid crystal. The cell gaps of the cells are 2 μm measured using a spectrometer. The cholesteric materials were filled into the cells by a capillary action. Depending on the pitch and cell gap ratio, as well as on the properties of the alignment layer, the helical axis may be oriented either along or perpendicular to the rubbing direction of the alignment layer. In our case, the cholesteric helix was reoriented parallel to the substrates by cooling the material from isotropic (at 106 degree of Celsius) to room temperature with or without a voltage of 2.5 V/μm @ 1 KHz. Once such a texture was obtained, the material was polymerized under an UV source at 0.08 mW/cm^2 intensity for 5 min at room temperature. The selected UV light provided formation of polymeric network localized at the both substrates' surfaces because of the high absorption of λ=322 nm by the liquid crystal mixture prevents photopolymerization of the photo reactive monomer far from the surfaces, thus leaving a substantial part of the volume free of the polymeric network. The scanning electron microscopic image was obtained by evacuating the liquid crystal using a 70/30 v/v mixture of hexane and dichloromethane, with the solvent refreshed several times over seven days. After solvent evaporation, the cell was carefully opened and the polymer network formed at the substrate surface was studied by SEM.

3. Results

Figure 1 shows the polarizing optical micrographs the textures of short-pitched cholesteric material at different temperatures. The cholesteric material is heated to the isotropic and then cooled slowly to the room temperature under an electric field. The uniform texture slowly to develop as the temperature is cooled to the room temperature. A small bias field is kept to prevent the uniform lying cholesteric helix being disturbed before fixing the polymer to the substrate surfaces. The uniform texture in Figure 1d is exposed to an UV illumination at room temperature.

(a) (b)

(c) (d)

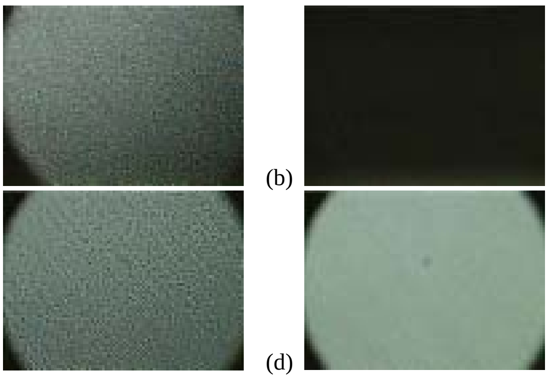

Figure 1. The polarizing optical microscopic texture of cholesteric as a function of temperature: (a) heating to an elevated temperature from room temperature, (b) at the isotropic temperature 106°C, (c) cooling from the isotropic temperature under an electric field of 5 V/μm, and (d) cooling to the room temperature with the electric field of 5 V/μm. The uniform optical texture was laying at a 45 degree with respect to the crossed polarizers.

Figure 2 shows the optical texture of the sample, whose optical axis is laid at 30 degree with respect to the crossed polarizers, at room temperature and without electric field. Notice that the strips of the cholesteric helix are relatively uniform after a 5-minutes UV exposure time, whereas some domain size distribution is observed because of the non-uniformity of cell gap of the commercial single pixel cell. From this, it can be inferred that once the film is polymerized, the alignment of the cholesteric helix is maintained.

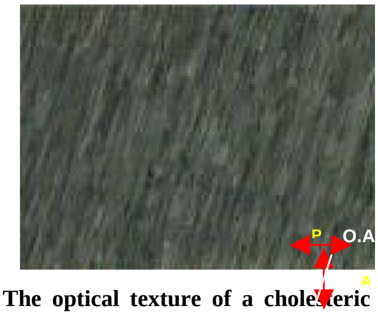

Figure 2. The optical texture of a cholesteric has polymer attached to the substrate surfaces. The photomicrograph was taken (500x) with the optical axis lying at 30 degree with respect to the crossed polarizers.

The gradient of UV light intensity, because of the absorption of short wavelength of UV light by liquid crystal, across the cell thickness direction during the polymerization resulted in the inhomogeneous distribution of the polymer network. As seen in Figure 3 the SEM morphology of polymer network formed on the substrate surface shows a regular periodicity of 0.3μm corresponding to half of the helical pitch of the cholesteric material. The direction of arrow represents the rubbing direction of the surface alignment layer. Furthermore, the surface localized polymer exhibits a sinusoidal pattern with a periodicity around 5 microns. This is due to the applied voltage of 2.5 V/μm @ 1 KHz which resulted in the rotation of the cholesteric helix in the plane of substrate upon the polymerization. By minimizing the amount of polymer using in modifying the surface and stabilize the cholesteric helix in plane, we can minimize the residual birefringence and light scattering because of the mismatching of refractive indices between the polymer and liquid crystal.

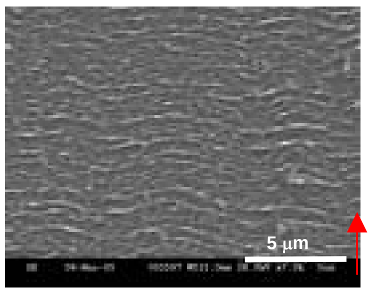

Figure 3. The SEM image of polymer network formed on a substrate surface having a regular periodicity of 3 micron, which corresponds to the half pitch of the cholesteric material.

The switching of a cell containing a short-pitched cholesteric material is investigated by using the experimental set-up consisting of functional generator, power amplifier, digital oscilloscope, a photodiode detector and optical polarizing microscope equipped with a digital camera. The short pitch cholesteric electro-optical device with the helical structure stabilized in the plane the surface-localized polymer acts as a birefringent plate. The field-induced in-plane rotation of optic axis, the flexoelectric effect, depends on the strength of applied electric field for a cholesteric material with positive dielectric anisotropic. The transmitted light intensity through the cell as a function of applied electric field is governed by the following equation:

$$I = I_o \sin^2[2(\theta + \varphi(E))]\sin^2(\pi d \Delta n(E)/\lambda)$$

where θ is the angle between the optical axis and the polarizer at zero field, d is the cell gap, Δn is the effective sample birefringence, E is the magnitude of electric field, $\phi(E)$ is the field-induced in-plane deviation of the optical axis and λ is the wavelength of light. Therefore, the linear modulation of the transmitted light incurred by the flexoelectric effect will be the major contribution at the low fields. At this high voltage condition, the device will operate in phase modulation (out-of-plane switching) mode that is a modulation of the transmitted light intensity because of the unwinding of cholesteric helical structure.

Figure 4 shows the electro-optical response of a cell driven in flexoelectric (in-plane switching mode) by different voltages and frequencies with a triangular-wave form. At an applied field of 4.0 V for a 2-μm cell, the cell shows a linear electro-optical response. The higher the applied voltage yields a larger angle deviation of optical axis in the plane parallel to the substrate which converts into the higher optical contrast between the field-ON and field-OFF states. As the applied electric field reaches 7V, the cell starts to exhibit not only the linear in-plane rotation of optical axis but also the non-linear response, relating to the dielectric coupling of liquid crystal molecules. The quadratic response becomes more intense when further increases the field to 10V as a sign of unwinding the helix. The complete unwinding of the cholesteric helix will take place when the field exceeds the critical field of a cholesteric material.

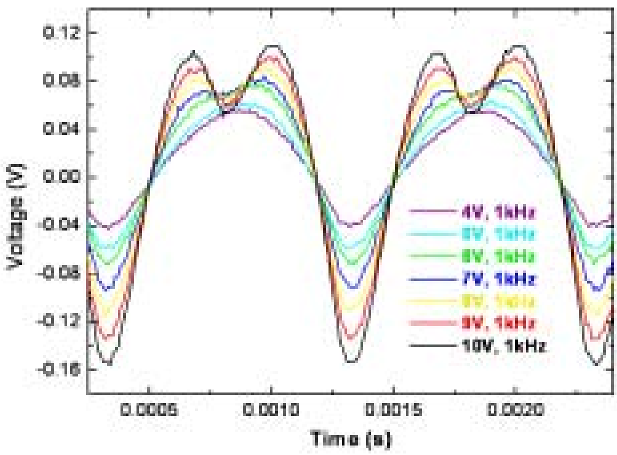

Figure 4. The electro-optical response switched from linear to non-linear for various voltages on application of a triangle wave with frequency of 1 KHz.

From the preceding results, it concludes that the in-plane switching of optical axis is limited by the dielectric coupling of the liquid crystal molecules that give a non-linear electro-optical response at high voltage. The solution of non-linear optical response at the high voltage is to use the dual frequency liquid crystal which enables the high frequency high voltage amplitude modulation. In order to produce such a material, our cholesteric sample consists of a dual-frequency nematic mixture MLC2048, chiral dopant and surface localized polymer. The material facilitates the electro-optical switching from non-linear to linear response on application of a triangular wave with voltage of 10 V. Increasing the frequency of applied electric field from 1 KHz to 4 KHz enables the suppression of non-linear electro-optical response at high applied electric field (see Figure 5). Note the time scale of each oscilloscope trace was not matched thus, their pattern were not matched precisely. Yet the results demonstrated that it is possible to maintain the linear optical response by using high frequency at high applied voltage.

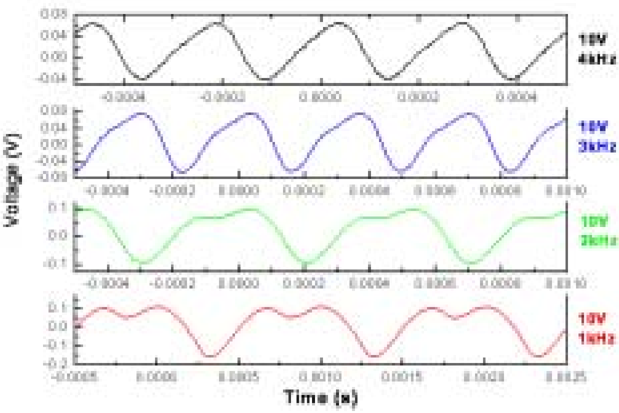

Figure 5. The electro-optical response switched from non-linear to linear for various frequencies on application of a triangle wave with voltage of 10V.

In Figure 6, we can see the electro-optic response switched from non-linear to linear response by changing the frequency from 500 Hz to 5 KHz. The cell is driven at the in-plane rotation of cholesteric helix at a voltage of 10 V using a triangular wave. If we look at the optical response curve, we can see that the non-linear response of the dielectric coupling takes place at this high voltage. This pattern reflects that the field is large enough to unwind the helix because of the positive dielectric anisotropic of the cholesteric material at low frequency of the field. By applying a high frequency field the liquid crystal molecules are switched back to the in-plane rotation only. The voltage parameter of the waveform also greatly influences the response time. In general, the response time for the flexoelectro-optical switching is around 200 microseconds.

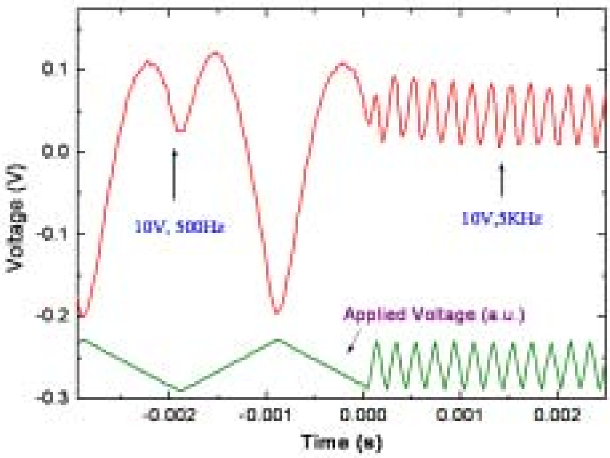

Figure 6. The electro-optical response switched from non-linear to linear by changing the frequencies from 500 Hz to 5 KHz on application of a triangle wave with voltage of 10V.

4. Conclusion

We demonstrated a short-pitch cholesteric device based on the flexoelectro-optical effect and dielectric switching. By choosing a dual-frequency switchable nematic to form the short-pitched cholesteric liquid crystal the non-linear in-plane electro-optical response can be further improved and become a linear optical response to the applied high voltage field. The two-mode switchable cholesteric devices, depending on the dielectric anisotropy of liquid crystal, the choice of volume or surface stabilization of the cholesteric helix, and the pitch of cholesteric, have a wide range of potential applications including amplitude modulators, light switches, phase-only spatial light modulators, beam deflectors and flat panel displays.

Therefore, optimization in material and electro-optical parameters for scaling the process and determining the manufacturing methods will enable these devices appropriate as key display technology.

5. References

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