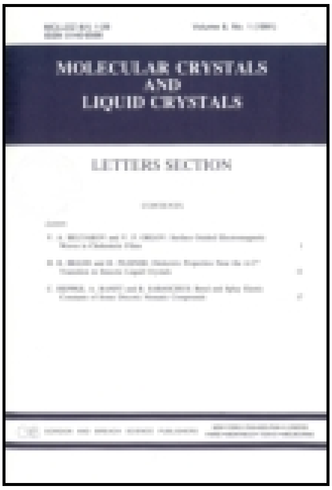

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Diffractive Liquid Crystal Pressure Detector

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In this work we present the study of reconfigurable by an applied electric field and sensitive to mechanical deformations bubble domain (BD) texture of cholesteric liquid crystal confined into a cell with homeotropic alignment conditions. We discuss the phenomenon of metastability of the BD texture, optimal conditions for obtaining and reconfiguring of the BD texture with applied electric field and pressure. We present and analyze time response curves to an applied electric field with the threshold pressure and suggest the application of the BD texture as a pressure detector.

Keywords Cholesteric liquid crystal; bubble domain texture; fingerprint texture

1. Introduction

Cholesteric liquid crystals (CLC) in a ground state have twisted director field with a periodicity characterized by the cholesteric pitch p. When confined in a cell with homeotropic surface alignment and the cell gap smaller than the pitch ($d < p$) the anchoring force unwinds cholesteric helix and liquid crystal (LC) has a uniform defect free homeotropic texture. When the cell gap is larger than the pitch ($d > p$) the LC director is twisted in the bulk of the cell and meets homeotropic boundary alignment conditions near the surface of substrates [1]. This LC texture is known as cholesteric fingerprint (FP) texture. The cell gap at which the LC director becomes unwind into the homeotropic nematic phase is called the unwinding critical thickness d_c [2]. Typically the d_c corresponds to confinement ratio of cell thickness over cholesteric pitch in the range of $0.5<d/p<1$.

For CLC in a cell with the confinement ratio near d_c a bubble domain (BD) texture can be obtained. The BD texture was also reported as a spherulite or cholesteric bubbles [3, 6]. Depending on the confinement ratio the BD texture can be not stable or metastable. In the case when the confinement ratio is too small or too big the DB texture will be replaced with homeotropic or FP textures, respectively.

The BD texture can be formed during a rapid phase transition from isotropic to liquid crystal phase or by applying electric field to the CLC sample with negative dielectric anisotropy. A transition from a homeotropic or FP texture to a BD texture can be initiated by applying of a low-frequency electric field. Depending on the confinement ratio, the metastable BD texture can be switched back to homeotropic or FP textures by applying a high-frequency electric field [3, 4, 5, 6]. It is also possible to generate single bubbles and control their position optically with a laser beam focused on the LC cell [8].

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The BD texture consists of a single layer of densely packed ‘bubbles’ with a uniform size which are embedded in a homeotropic matrix. It was shown that each bubble is formed by a distortion of the LC director field around two defects of opposite charges which are separated from each other in the bulk of LC layer along the normal to the cell and are to embed into a uniform homeotropic field [5, 7]. The metastability of bubbles can be explained by the energy barrier for nucleation of separated defects which is much larger than the thermal energy. However, it is possible to overcome the energy barrier for nucleation of defects inside of each bubble with a distortion of liquid crystal director caused by an applied pressure or a mechanical deformation of the cell. If the deformation is strong enough, all of the defects in BD texture will nucleate and the sample will return back to an original homeotropic or FP texture. In this work we suggest the application of the sensitive to mechanical deformation and reconfigurable by electric field BD texture for detection of pressure.

2. Experimental

For this study we prepared an induced CLC mixture using the nematic host with negative $\Delta\varepsilon$. The constituents of the CLC mixture are: 98.46% wt. ZLI-4788 ($\Delta\varepsilon = -5.7$) (Merck) and 1.54% wt. CB15 (HTP $= 6.3\ \mu\text{m}^{-1}$ in ZLI-4788) (Merck). The calculated value of the cholesteric pitch is $p = 10.3\ \mu$m.

Liquid crystal cells were fabricated from 1.15 mm thick glass substrates coated with ITO and alignment layer for homeotropic alignment. The alignment layer was made of polyimide SE1211 (Nissan Chemical) and cetyltrimethylammonium bromide (CTAB) (Sigma-Aldrich). No rubbing was applied to the alignment layer. The cell gap was maintained with particle spacers with a nominal thickness of 7 μm which were mixed with a UV curable optical adhesive OA65 (Norland) and dispensed on one of the substrates during the cell assembly process. Cells were capillary filled with a mixture of CLC in the isotropic phase and cooled down slowly to a room temperature.

Samples were tested observing the LC texture with a polarizing optical microscope (POM), observing laser diffraction patterns, and with an electro optical and dielectric studies. The experimental setup for electro optical measurements consisted of He:Ne laser (633 nm), polarizer, analyzer, and photodiode detector, all aligned along the optical axis. Transmission axes of polarizers were kept parallel in order to eliminate undesired noise coming from light scattering. The sample was placed in between of polarizer and analyzer in the way that detector was detecting the intensity of light at zero order diffraction maximum only. Dielectric study was performed by the capacitance measurements using a SI-1260 impedance/gain-phase analyzer (Schlumberger).

3. Results and Discussion

We started our study exploring the methods for obtaining of the BD texture. We have experimentally measured the unwinding critical thickness $d_c = 7.9\ \mu$m of our CLC mixtures in the cells with the alignment layer which we used. Measured d_c corresponds to the confinement ratio of 0.77. The metastable BD texture was observed in the range of confinement ratio of 0.5 to 0.9. For this reason the CLC confined in a cell with homeotropic anchoring conditions has a bistability between the BD and the homeotropic or the FP textures and can be switched between two states. The schematic diagram of existence of the metastable BD texture with no voltage applied is shown in Fig. 1.

Homeotropic, FP and BD textures can be easily distinguished by analyzing a far field laser diffraction pattern. The homeotropic texture doesn’t create any diffraction pattern,

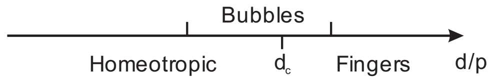

Figure 1. Diagram of existence of BD texture.

as show in Fig. 2d. A typical laser diffraction pattern form the FP texture is a diffraction line. If the laser beam is focused on the sample, the diffraction pattern form the FP texture will be in the form of a series of diffraction maxima aligned along the line, as show in Fig. 2f. The BD texture gives a very different diffraction pattern which consists of a series of concentric diffraction rings with the point of zero order diffraction maximum in the center, as shown in Fig. 2g. The diffraction pattern from a well ordered BD texture obtained with a laser beam focused on the sample will consist of multiple diffraction maxima with an arrangement that corresponds to the ordering of bubbles in the BD texture, as shown in

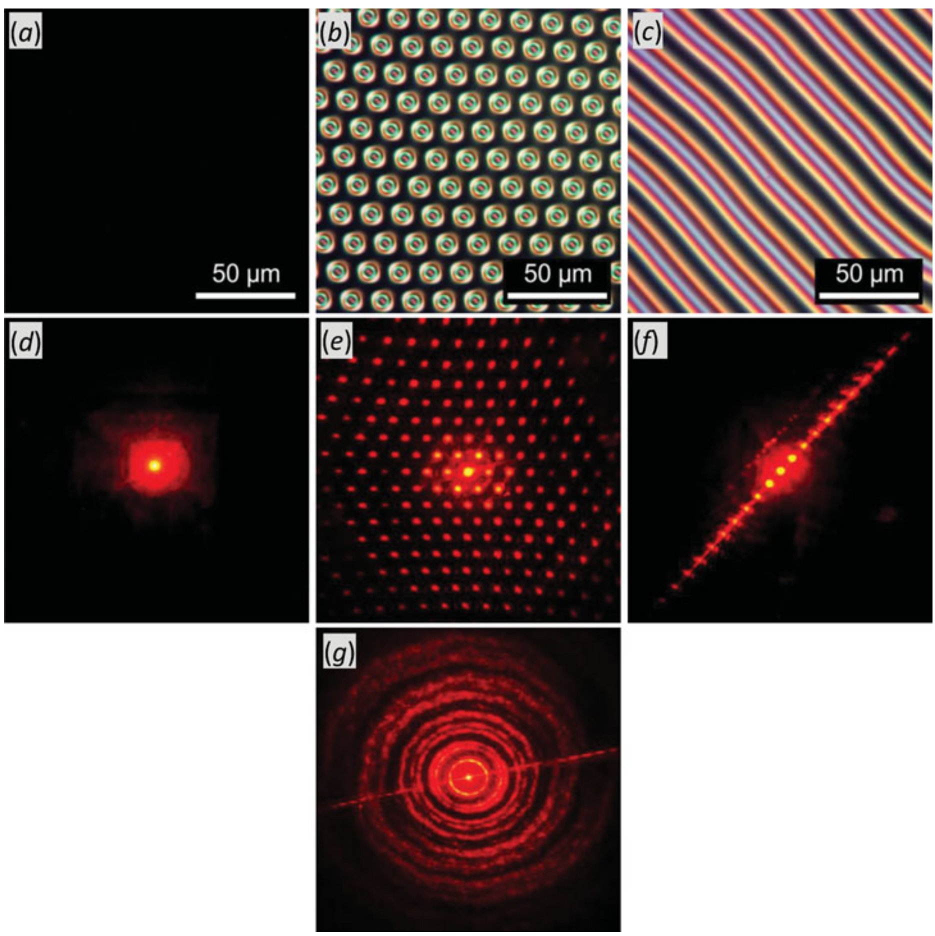

Figure 2. POM images and far field diffraction patterns from: a), d) the homeotropic texture; b), e), g) the BD texture; c), f) the FP texture.

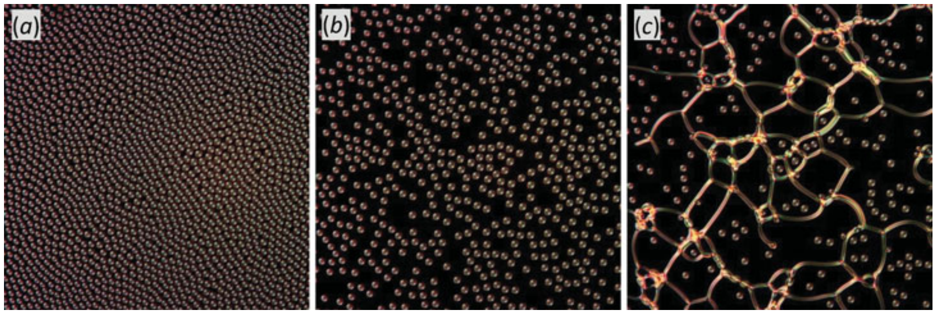

Figure 3. POM images of CLC textures in cell with homeotropic anchoring ($d < d_c$): a) densely packed BD texture; b) BD texture with small density of bubbles; c) single bubbles with defect lines.

Fig. 2e. In pictures in Fig. 2e and Fig. 2f the laser beam was focused on the sample with a lens to a beam waist less than 100 μm.

Results of our study showed that the BD texture can be generated by applying a low-frequency electric field with a square wave function, frequency of 100 Hz and magnitude of 15 Vpp. The BD texture can be erased by applying a high-frequency electric field with the same wave function, frequency of 5 kHz and magnitude of 15 Vpp.

For generating and reconfiguring of a densely packed BD texture it is important to choose the optimal frequency, amplitude and duration of switching voltage pulses. If the amplitude of the low-frequency voltage pulse is too small, the BD texture will be formed with a small density of bubbles, as shown in Fig. 3b. If the amplitude of the low-frequency voltage pulse is too big, the pattern of single bubbles with defect lines will be formed, as shown in Fig. 3c. The texture shown in Fig. 3c gives a weak diffraction pattern which is similar to the one shown in Fig. 2g, but has smaller contrast with the homeotropic texture and is more difficult to detect with a photodiode. In the case when the duration of applied voltage pulse is to short, the frequency of small, the transition between two bistable textures won't be completed or will take longer time.

For switching between the homeotropic and the BD textures a voltage pulse with steep slopes should be applied. In the case of slow decrease of the amplitude of low-frequency voltage the BD texture with small density of bubbles is formed, similar to texture shown in Fig. 3b. When the amplitude of high-frequency voltage is being slowly decreased at the point of switching voltage a not stable FP texture will be formed and slowly replaced with uniform homeotropic texture. It may take up to one minute for not stable FP defect lines to disappear.

For the formation of the BD texture with an electric field a major role play free ions in the CLC mixture. The CLC with small amount of free ions upon increasing of applied voltage will go through the transition from completely unwound homeotropic or FP textures to the translationally invariant configuration (TIC) with uniform in-plane twist [1]. After the voltage pulse is removed the CLC returns to its original texture and no BD can be obtained regardless of the frequency of the applied voltage. The switching of the CLC with an applied voltage is changed with an introduction of free ions into a CLC mixture from the CTAB component of the alignment layer. When voltage is applied, the CLC with big amount of free ions will switch to the dynamic light scattering and after the voltage pulse is removed the BD texture will be formed. To our understanding, the fluctuation of the free ions in the bulk of the cell caused by a low-frequency electric field induces local distortions of LC director field which create defects stabilized in the form of cholesteric BD texture after the voltage is removed.

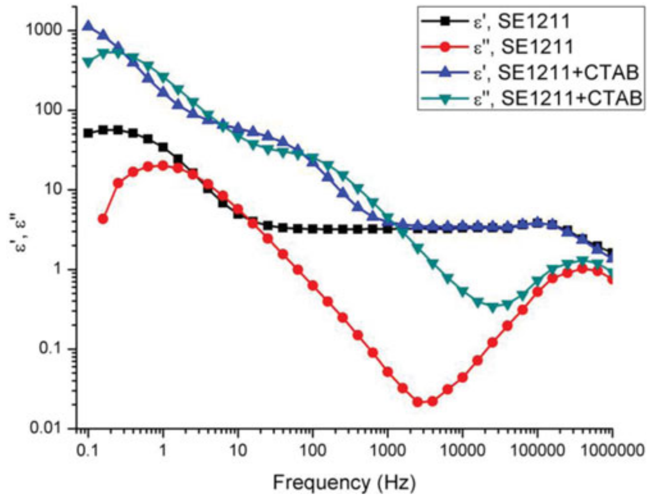

Figure 4. The complex dielectric permittivity parts of CLC mixture in the cell with and without CTAB as function of frequency.

The dielectric measurements show that the CLC mixture in the cell with CTAB as the alignment layers at low-frequencies has a significantly bigger complex dielectric permittivity than the CLC mixture in the cell without CTAB alignment layers, as shown in Fig. 4. High dielectric permittivity at low frequencies of the CTAB sample can be explained by the presence of a significant amount of free ions in the bulk of CLC.

The metastable BD texture is not sensitive to the temperature and is stable for a long time. We observed a stable BD texture for six months. The metastable BD texture can be erased by the pressure applied to the cell. The threshold pressure creates a distortion of the LC director which is sufficient for overcoming the energy barrier between distance separated point defects which form a cholesteric bubble. As result, the defects of opposite charges annihilate and CLC returns to its original texture.

We suggest using the phenomenon of voltage controlled bistability between the BD and the homeotropic or the FP textures and the sensitivity of the BD texture to the mechanical distortion of LC director field for detection of a pressure. The signal from such detector can be read by analyzing the intensity of light transmitted through a LC cell at the point of zero order diffraction maximum of a laser diffraction pattern. The homeotropic texture doesn't create any diffraction pattern and the maximum amount of light is transmitted through the cell. In the case of the BD texture some of light is consumed by diffraction maxima of other orders and the intensity of light transmitted through the cell to the point of zero order diffraction maximum is smaller than in the case of homeotropic texture.

After voltage pulse is applied the LC material switches with a characteristic response time. We define response time as a time which it takes for material to transform from an original equilibrium state to the state when detector voltage reaches saturated level, within 10% of either value. After the voltage pulse is removed the LC material returns back to an equilibrium state with a characteristic time called here an equilibrium time. We define the equilibrium time from the moment when the voltage pulse was removed and until the detected light intensity reaches the saturated level, within 10% of either value. For switching between two bistable textures the voltage pulse has to be applied for a time not shorter than

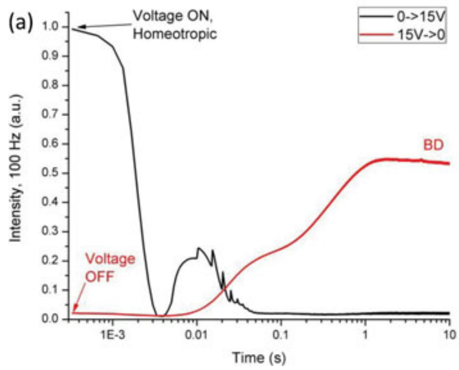

Figure 5. Time response of the sample to the applied electric field at: a) low frequency; and b) high frequency.

the response time. The switching will be completed over the total switching time which is a sum of response and equilibrium time.

Figure 5 shows the intensity of transmitted light through the sample to the point of zero order diffraction maxima as a function of time after the switching voltage pulse of low or high frequencies was applied or removed. The response time to a low-frequency voltage when switched from the homeotropic texture to the dynamic light scattering is 0.020 s. The equilibrium time after the low-frequency voltage is removed and material switches to the BD texture is 0.665 s. When switching from the BD texture to the TIC with a high-frequency voltage, the response time is 0.045 s. The equilibrium time after the high-frequency voltage is removed and material returns form the TIC to the homeotropic texture is 2.100 s.

The change of light intensity at zero order diffraction maximum in response to applied critical pressure as a function of time is shown in Fig. 6. The data shown in Fig. 6 was

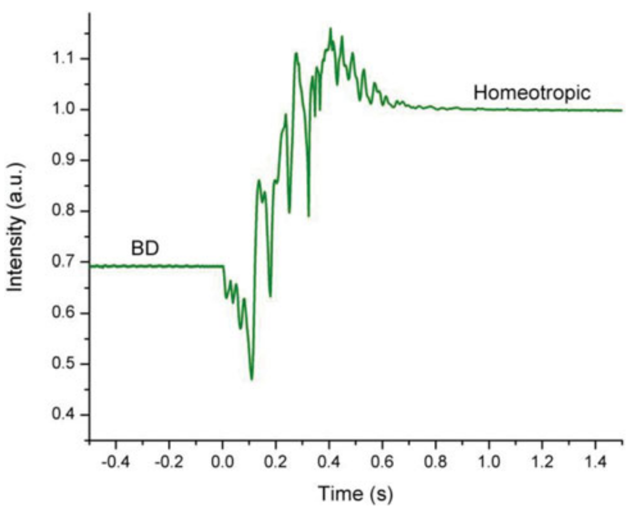

Figure 6. The light intensity detected at diffraction maxima of zero order during switching from BD to homeotropic texture caused by pressure of 2.1e+5 Pa.

obtained by monitoring the intensity of light while gradually increasing the load applied to the cell. The force from the load on the cell was transmitted through a small ring with a contact area of 1.4e-5 m^2. The ring with the load was placed in the middle of the cell and the laser beam for detection of a diffraction pattern was guided through the center of the ring. When the threshold pressure is applied the BD texture switches to homeotropic texture which corresponds to a change of intensity of light detected by a photodiode detector. In Fig. 6 the threshold pressure was applied at the zero moment of time and the BD texture is replaced with the homeotropic texture over the equilibrium time 0.450 s.

For tested samples, switching occurs when loading the cell with a mass of ~300 g, which corresponds to a pressure of 2.1e+8 Pa. It should be noted that test cells were made of rigid glass substrates. The sensitivity threshold will significantly depend on the design of LC cell and the way of delivery of the force to the cell. In particular, the sensitivity threshold is expected to be smaller in the cells made of thinner glass, plastic substrates, or substrates of a bigger size, etc.

4. Conclusion

We studied the sensitivity of the BD texture of cholesteric liquid crystal confined into a cell with homeotropic alignment conditions to mechanical deformations and conditions for reconfiguring of the BD texture with an applied electric field. We suggest the application of the phenomenon of bistability between the BD and the homeotropic or the FP textures for a detection of a pressure. The obtained time response curves to an applied voltage pulse demonstrate that for switching from the homeotropic to the BD texture the pulse of low frequency voltage has to be applied for 0.020 s and the switching time is 0.685 s. For switching from the BD to the homeotropic texture the pulse of high frequency voltage has to be applied for 0.045 s and the switching time is 2.145 s. The switching form the BD to the homeotropic texture caused by an applied critical pressure occurs over the equilibrium time of 0.450 s. The measured sensitivity threshold of tested samples is 300 g or 2.1e+5 Pa. Collected data proves the potential suitability of application of the BD texture for a detection of pressure.

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