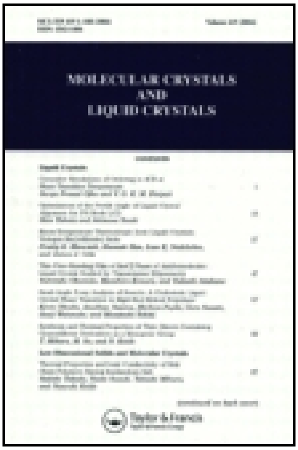

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W. Piecek [a] , Z. Raszewski [a] , P. Perkowski [a] , P. Morawiak [a] , G. Pajchrowski [b] & W. Ying [b]

[a] Military University of Technology, Warszawa, Poland

[b] Nanyang Technological University, EEE School, Singapore

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Transient Light Scattering Mode of an Orthoconic Antiferroelectric Liquid Crystal

W. Piecek[1], Z. Raszewski[1], P. Perkowski[1], P. Morawiak[1], G. Pajchrowski[2], and W. Ying[2]
[1]Military University of Technology, Warszawa, Poland
[2]Nanyang Technological University, EEE School, Singapore

Antiferroelectric Liquid Crystals (AFLC) have been extensively studied due to their physical properties offering unique electrooptical properties. Here an electrooptical effect which does not need polarizers – so called Transient Scattering Mode (TSM), observed previously for FLCs, and AFLC's was studied with using of the antiferroelectric liquid crystal with the saturated tilt angle $\theta = 45^\circ$ (Orthoconic Antiferroelectric Liquid Crystal - OAFLC). The working mixture with a short helical pitch λ at room temperature was used to induce a Bragg scattering. The electrooptical performance of two operation regimes of an unordered surface stabilised structure is presented and discussed.

Keywords: Bragg scattering; high tilted smectic liquid crystals; light scattering; orthoconic antiferroelectric smectic liquid crystals

INTRODUCTION

Antiferroelectric Liquid Crystals (AFLC) have been extensively studied due to their physical properties offering unique electrooptical properties [1]. Classical electrooptical effects [1,2] with AFLC slab as a wave plate utilize polarizers needed for preparing birefractive set-up.

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Address correspondence to W. Piecek, Eng. Adiunkt, Institute of Applied Physics, Department of New Technologies and Chemistry, Military University of Technology, Kaliskiego 2 St., 00-908, Warszawa, Poland. E-mail: wpiecek@wat.edu.pl

At proper circumstances a surface stabilised structure of an orthoconic antiferroelectric smectic liquid crystal (SSOAFLC) forms an optically uniaxial and optically negative medium with the optical axis normal to the surrounding glass plates [3–5]. When such a sample is placed between polarizers it provides perfect dark state for the normally incident light beam regardless the structure defects involving local disorientation of the smectic layer normal within OAFLC bookshelf structure [4]. Due to this properties OAFLCs in bookshelf structure provide a extremely high contrast and switching with a hemispheric viewing angle [6].

Here an electrooptical effect which need neither sophisticated cell preparation procedure nor polarizers, is presented. This is electrooptical effect recognised as Transient Scattering Mode (TSM) and which was observed previously for FLC's [7] , and AFLC's [8–13].

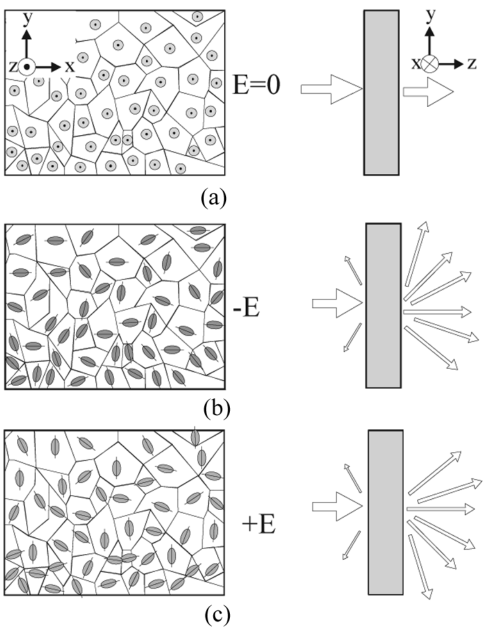


FIGURE 1 The domain dispersion (DS) operation mode in TSM of OAFLC. (a) The domain structure of OAFLC at zero field state. To the right hand site is the side view of the sample with the normally incident light beam (denoted as ⇨), and (b, c) The light scattering domains under opposite electric field, −E, +E action with a random planar orientation of its optical axes (denoted as ⃠) .

In this study a random bookshelf structure [14] of OAFLC is tested as a switchable scattering medium (see Fig. 1). The idea of the OAFLC TSM operation is as follows. Within the random bookshelf structure a bookshelf–like ordered domains exist (see Figs. 1 and 2). The in-plane orientation of the smectic layer normal within a single domain is randomly spread for all domains forming the structure. From this point of view a single domain is a medium with wound or unwound helical structure depending on the surface action, the used cell gap and external field action. The single domain exhibits well defined optical indicatrix (see i.e., Fig. 2). The optical axis of unwound structure of OAFLC is near parallel to the normally incident light beam. The optical axis of the wound state of OALFC is in-pane oriented however the anisotropy of the refractive index is very low [3] and the optical axes of domains are randomly spread. This would be a non-scattering regime.

At the saturated electric field the collection of domain with unwound synclinic FLC structure and higher optical anisotropy with randomly oriented in-plane optical axes forms a scattering medium for the same light beam at normal incidence (see Fig. 1). It will be called domain scattering (DS) mode. The additional Bragg scattering effects (BS) are expected during dynamic switching of the structure.

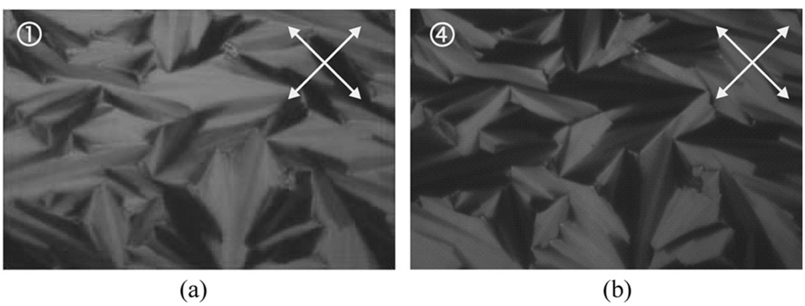


FIGURE 2 The microscope view of approximately $1.00 \times 0.66\,mm^2$ area of SCS observed in $20\,\mu m$ thick cell obtained at the cooling rate of 0.05 K/min. Number in pictures correspond with those in the Figures 4 and 6. The observation was done between crossed polarizers (which orientation is marked in the picture by arrows) to visualize a random orientation of the domains and the change of the refractive index anisotropy under electric field. The sample colour as well as the sample overall brightness does not change upon the cell rotation around the light beam direction. (1) The transparent state at zero electric field (wound OAFLC structure). (4) Opaque state at the voltage saturated voltage 94 V applied (unwound FLC structure).

As working OAFLC material the room temperature mixture W193B [5,15,16] with the right switching cone angle 2θ and a short helical pitch (helical pitch $\lambda = 0.3\,\mu m$ at the room temperature OAFLC phase) was used. The short pitch OAFLC mixture W193B seems to be attractive for presented experiment because, besides the orthoconic property it is capable to produce a strong Bragg scattering upon the helix winding/unwinding process [17,18].

The observations of the electrooptical performance of an unordered OAFLC structure operating at TSM is presented and discussed. The influence of the structural and optical properties of OAFLC on the electrooptical performance is considered.

EXPERIMENT

Cell Preparation and Structures of OAFLC in this Cells

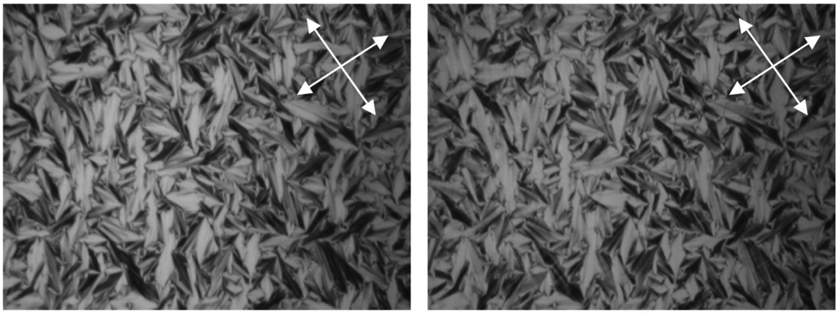
Custom made cells were prepared using the flat substrate glasses (Nippon Glass) with transparent ITO conductive electrodes. Both glasses used for the cell assembling were covered by commercial low density SE130 polyimide (Nissan Chemicals). Cells were assembled using 20 μm glass spacers (Nippon Glass) and stabilized by the UV curable seal from NOA65 adhesive (Norland Adhesives). The cell gap of empty cells was measured by spectroscopic method (Prema SPM 9001 spectrometer). Assembled cells were placed into the hot stage (Instec HCS402) mounted on the rotating table of the polarizing microscope (Biolar PI, PZO, Warszawa, Poland). The microscope used was equipped with the long distance objective of magnification 10 fixed at constant distance for all measurements. The sample illuminating halogen lamp was powered from stabilized DC power supply (HP E3631A). The modulation of the light transmitted through the cell was detected by the linear silicone photodiode (PIN20, FLC Electronics, Sweden) which, was integrating the light from the view filed of the microscope by using an special objective. The optical response was recorded by the digital oscilloscope (HP54601b). Snapshots of sample textures were registered by Canon D5 digital camera body mounted on the microscope at constant magnification of 10×4.5. Cells were driven by HP33120A Arbitrary/Function pulse generator equipped with the linear amplifier (F20AD, FLC Electronics, Sweden). The 100 kΩ resistor was applied in parallel to the cell to register a switching current peak while driving. The light detector, the camera, the oscilloscope as well as the pulse generator and the resistor were connected to the PC driving unit for synchronized operation and the data collection.

OAFLC Material and Surface Stabilized Structures

Prepared cells were filled with W193B OAFLC mixture at the isotropic state (the temperature was T = 125°C) by capillary action. As to obtain a desired OAFLC structure with the planar orientation of the director, cells were slowly cooled to the room temperature in the vicinity of the low frequency AC electric field (the electric field strength was E = 2 V/μm at the frequency f = 15 Hz, triangle pulse).

The sample cooling rate highly influenced the domain structure of the material, hence a different cooling rates were tested. The main difference obtained at various cooling rates was the average diameter of domains obtained. Nevertheless, all structures obtained after such a treatment, look transparent (i.e., see also Figs. 6a and 7) when they were observed at the right angle without polarizers. The slower cooling rate the bigger domain size was. The transparency of the cell at zero field was proportional to the average diameter of obtained domains also. In the Figures 2 and 3 structures obtained at the cooling rate of 0.05 K/min (so called Slow Cooling Structure – SCS), and at 5.0 K/min (so called Fast Cooling Structure – FCS) are shown. The size of domains obtained for SCS varied from tens to hundreds micrometers while for FCS they were smaller by one order approximately. SCS structure was characterized by perfect transmission of the unpolarized white light at the normal incidence at zero electric field applied while the FCS was a noticeably opaque.

The microscopic view at zero filed obtained in birefractive set-up exhibits the characteristic green colour proper to the obtained



(a) (b)

FIGURE 3 The microscope photography of approx. 1.00 × 0.66 mm area of FCS observed in 20 μm cell obtained at the cooling rate 5 K/min. Arrows indicate orientation of polarizers used. (a) Photogram taken at zero field and (b) Photogram taken at 25 V applied (triangle pulse, f = 100 mHz).

refractive index anisotropy Δn and the cell thickness d according to the maximum transmission regime in birefractive set-up:

$$d\Delta n = k\frac{\lambda}{2} \tag{1}$$

where λ stands for the light wave length (in vacuum) which affects a transmission through the birefractive set-up.

Bookshelf Random Structures of OAFLC in the Electric Field

The transmission of the light through the cell at normal incidence without polarisers was done. For the observation of the light transmission intensity the sample was placed in the birefractive set up also. This set-up was chosen to observe the movement of the optical axes directions within domains upon the helix unwinding process as well as changes of the effective refractive index anisotropy.

At the zero field the OAFLC SCS and FCS in birefractive set-up appeared as optically uniaxial in overall with the optical axis parallel to the incident light beam, as it was observed previously for unwound SSOAFLC structure in thin [4] and thick cells [19]. Upon electric field the majority of domains change the colour what was induced due to the change of the refractive index anisotropy of the medium. It is ascribed to the evolution of the OAFLC structure from the wound to unwound but still anticlinic structure (which are characterised by different refractive index anisotropies) and next, to the evolution from unwound anticlinic (OALFC) to unwound synclinic (OFLC) one, which obviously differ with refractive index anisotropy also [3].

Under the application of the triangle pulse of the electric field at frequencies f from 20 up to 100 Hz (triangle pulse) cell with SCS and FCS become gradually opaque. The cell with SCS was less opaque than this with FCS one. At this case the constant scattering of the transmitted and reflected light was observed, however the scattering at the saturated voltage was moderate for both SCS and FCS. In this case a v-shape like characteristic of the transmitted light vs. applied voltage (see Fig. 5). The v-shape characteristics was obtained with and without crossed polarizers used.

For the low frequency driving ($f < 1$ Hz) cells become opaque as well, but the dynamic and very intensive scattering pulses were additionally observed. This pulses were at a frequency four times bigger (see Fig. 4) in comparison to the driving voltage one. A optical characteristics of the electrooptical switching of cells operating under the microscope is presented below together with adjacent microphotograms (see Fig. 6).

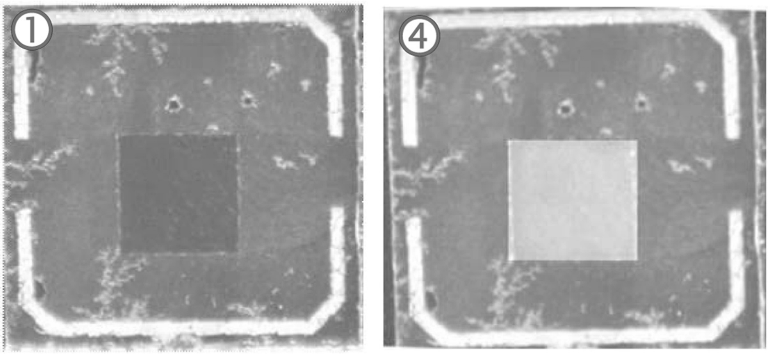


FIGURE 4 Snapshots of the 20 μm SCS cell without polarizers observed over an absorbing substrate at illumination from the spectator's side (reflective mode) at the low frequency switching regime. The square area in the middle of the cell is between ITO electrodes. (1) The transparent state (point ① in the Fig. 6a) at zero field (wound OAFLC state). (4) The maximum Bragg dispersion state (point ④ in the Fig. 6a) at the voltage of 64 V applied (triangle pulse f = 50 mHz).

In order to test the light scattering efficiency at high frequency regime of OAFLC TSM the cell with FCS was placed before the camera objective taking pictures of an example figure at constant fixed parameters. The cell was driven by increasing AC field (f = 50 Hz, square pulse). As it can be seen in the figure below, the transmitted light intensity drops with the driving voltage increasing what makes photograms more dark with the driving voltage increasing.

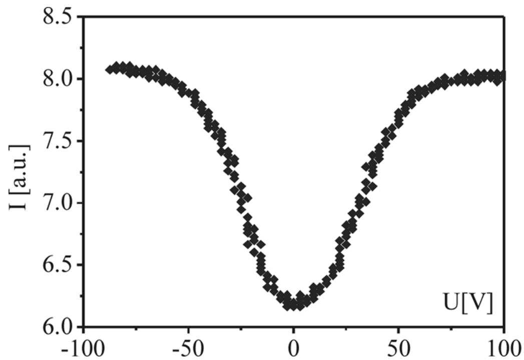


FIGURE 5 The intensity of the transmitted white light I vs. driving voltage U for the SCS sample in the birefractive set-up (triangle electric pulse, f = 25 Hz applied).

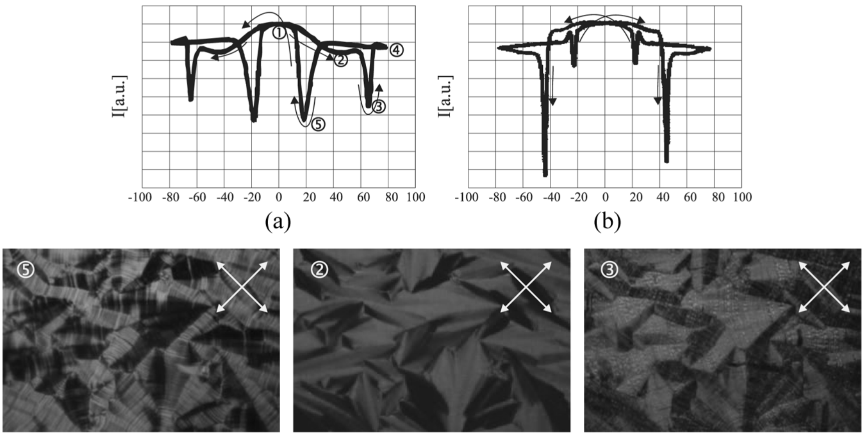


FIGURE 6 On the top – the light intensity I [a.u.] vs. AC voltage applied to the 20 μm cell (triangle pulse f = 100 mHz). (a) The oscillogram for the SCS cell in the birefractive set-up. The numbers indicate in the pictures presented below and in the Figure 2. (b) The oscillogram for the same cell in the measuring set-up without polarizers used at f = 50 mHz. Bottom, corresponding microphotograms (see also Fig. 2).

DISCUSSION AND CONCLUSIONS

The random bookshelf structures of OAFLC at zero field exhibit very good transparency nevertheless the helical structure is wound. Due to very short helical pitch (shorter than the visible light wavelength) the diffraction, hence scattering by the helical periodic structure seems not to exist here.

Moreover, let us consider, that the characteristic colour of the texture observed in our cells placed in birefractiv set-up at zero field is governed by the cell thickness d and efficient value of the optical refractive index anisotropy Δn. It was proved earlier [3,20] that the wound state of the OAFLC exhibits rather low value of Δn what promotes the high transparency of the random bookshelf structure at normal incidence.

As far as the electric field induces light scattering is concerned, let us recall that actually two switching regimes were observed: one is at high frequency and the other at low frequency driving. The main difference between them is that the first one has a v-shaped characteristics while the other has a more complicated nature.

For the first one, v-shaped characteristics, we suggest that the light scattering occurs mainly on the domain structure OAFLC with the defects between them and different orientation of optical axes within domains. The last one factor undergo the switching by the external electric field. Actually the electric field causes the reorientation of the optical axis as well as the change of the refractive index anisotropy Δn. Both factors affect the light scattering by the random bookshelf structure. From the experiment one can draw that the v-shaped light scattering efficiency depends apparently on the cell thickness and average OAFLC domain. The last observation can be drown from study of structures obtained with different cooling rates. The theory suggests, that the high value of the refractive index anisotropy Δn of the unwound state of random bookshelf structure of OAFLC would support the light scattering at this regime also [21].

The effective refractive index anisotropy Δn of the unordered SSOALFC apparently raises upon helix unwinding caused by increasing external electric field. This was manifested by the evolution of the texture colour from green to red one. This effects was described previously elsewhere [22]. Simultaneously the increasing of Δn was accompanied by the increase of the light scattering on the domain structure, as was expected. This can be directly seen in Figures 4, 5 and 7. Upon the fast switching the AFLC phase is suppressed by electric field alternating with the time constant smaller than the FLC-AFLC switching relaxation time and practically the switching occurs between two synclinic ferroelectric unwound states at saturated voltage and synclinic wound state at zero voltage applied [17]. This can be supported by single switching current peak observed at this regime. As one can see in the Figure 7, the application of this switching regime at TSM is possible light shutter which would be as fast as hundreds of microseconds.

The other, low frequency switching regime, presented in Figures 2, 4 and 6 involves even three mechanisms. Starting from a zero field

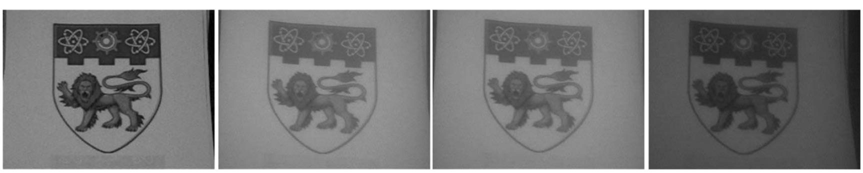


FIGURE 7 Snapshoths recorded at the constant illumination time and the diaphragm size taken through the unordered, 20 μm thick layer of OAFLC with FCS. To the left one can see a picture taken at the zero electric field. To the right hand side the picture taken at the saturated voltage of 94 V is presented. Pictures taken at 38 V and 76 V respectively, are presented in the middle.

state ① (see Fig. 6) the electric field driven helix unwinding of the anticlinic antiferroelectric phase occurs [22]. This phase process saturates at certain voltage giving antiferroelectric unwound state ②. As one can see the in the Figures 2① and 6② the orientation of the optical axes within domains remains constant what was expected. Upon further increasing of the electric field strength the structure rapidly switches from the anticlinic state to synclinic one. The switching occurs with the extraordinary scattering pulse (see Fig. 6a③) caused by randomly switched structure. The domain texture obtained at this moment can be seen in the Figure 6③. This domain texture is characterised by mixed areas with syn- and anticlinic orientation which differ with the orientation of the optical axis and the refractive index anisotropy. The scattering at this state is very efficient as it can be seen in the Figure 6a and 6b. The structure evolution upon increasing electric field saturates as the synclinic FLC structure presented in the Figure 2④. As one can see in the Figure 2① and 2④ the optical axes switch by the angle of 45° regarding to the zero field state.

Upon the electric field drop the structure relaxes directly from the synclinic ferroelectric state to the anticlinic wound state, what was reported earlier for analogue structures [17,22]. At this process the most intensive scattering of the white light occurred due to the periodical superposition of the antiferroelectric helical structure (green), and unwound synclinic area (orange) clearly seen in the Figure 6⑤. This areas significantly differ with the refractive indices and refractive indices anisotropy what promotes efficient light scattering. Unfortunately this is a dynamic process which can not be memorised according to our experiences.

Presented results clearly show that random bookshelf structure of OAFLC provides effective electrooptical effect based on the light scattering. The orthoconic property supports high transparency at the zero field while the relaxation from unwound ferro- to wound antiferroelectric structure provides extraordinary light scattering.

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