Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

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Online publication date: 06 July 2010

To cite this Article Fedoryako, Alexander P. , Kutulya, Lidia A. , Popova, Ekaterina V. and Vashchenko, Valery(2008) 'Non-linear electromechanical transformations and amplification acoustical signal in ferroelectric liquid crystals', Liquid Crystals, 35: 12, 1367 — 1372

To link to this Article: DOI: 10.1080/02678290802617708

URL: http://dx.doi.org/10.1080/02678290802617708

Liquid Crystals,
Vol. 35, No. 12, December 2008, 1367–1372

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(Received 25 March 2008; final form 12 November 2008)

Resonance systems with ferroelectric liquid crystal have been investigated, and the parametrisation of an oscillation system with resonance properties depending on ferroelectric liquid crystal properties has been investigated. The parametric amplifier of mechanical oscillations has been obtained for the first time. The results have been analysed using different existing theories of SmC* liquid crystal dynamics.

Keywords: electromechanical effect; parametric amplification; parametric conversion; ferroelectric liquid crystals

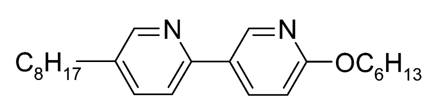
1. Introduction

The electromechanical effect in ferroelectric liquid crystal (FLC) was discovered by Pieranski et al. (*1*). This effect was explained by induced polarisation due to a shear flow in FLC. Later, the investigation of FLC behaviour in electrical fields also revealed a mechanical response (*2*). Thus, forward and reverse electromechanical effects exist in FLC systems. Brand and Pleiner have proposed a theoretical basis for the electromechanical effect (*3, 4*). The large-scale helix deformation and local deformation of smectic layers were considered as the electromechanical effect driving force. According to the Brand and Pleiner theory, the electromechanical effect is accompanied by a shift of the sample plates along the helix axis and perpendicular to FLC layers. Further, in the theoretical model by Eber et al. the dependence of mechanical strain versus electric field strength is assumed to be linear (*5*). However, experimental data have shown that this is true only for materials with a relatively small spontaneous polarisation (*6*). There are several similar phenomenological models of non-linear dynamics in FLC (*7–11*), which differ from each other only in the number of elasticity and viscosity constants used. The electromechanical effect and non-linear properties of FLC materials (*12*) can expand the range of their applications, particularly in parametric conversions of acoustic signals, including amplification. In spite of the use of similar effects in a wide range of applications in the field of solid materials (*13*), no examples are known regarding the use of FLC as a working medium.

2. Experiment

Experiments were carried out with three mixtures.

Mixture I.



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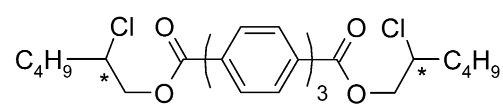


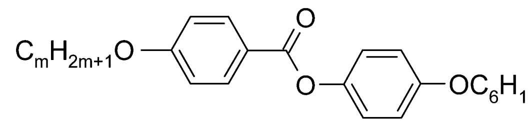
Chiral Guest – 24.8 wt.%

The phase sequence and transition temperatures are as follows:

$$I \rightarrow 80.5 \rightarrow \text{two-phase range I, SmA}^* \rightarrow$$
$$77.5 \rightarrow \text{SmA}^* \rightarrow 54 \rightarrow \text{SmC}^* \rightarrow \text{Cr},$$

where I is the isotropic phase; SmA* is the chiral smectic A phase; SmC* is chiral smectic C phase; Cr is the crystal. The main ferroelectric parameters of mixture I, such as spontaneous polarisation (P_S)= $-27.6\,\mathrm{nC\,cm^{-2}}$, smectic tilt angle ($\theta$)=21°, rotational viscosity (γ_φ)=0.3 Poise, were obtained at ΔT=20°C, where ΔT is the difference between SmA*→SmC* phase transition and the measurement temperatures.

Mixture II.



Host: m=8 — 50%; m=10 — 50%

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ISSN 0267-8292 print/ISSN 1366-5855 online

DOI: 10.1080/02678290802617708
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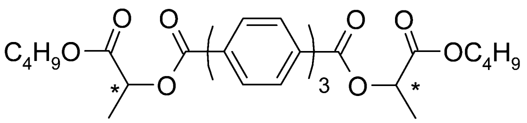


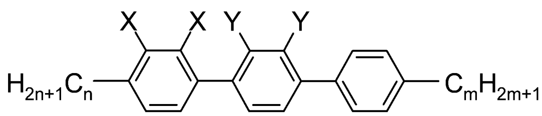
Chiral Guest – 14 wt.%

The phase sequence and transition temperatures are as follows:

$$I \rightarrow 87 \rightarrow BP \rightarrow 86.4 \rightarrow N^* \rightarrow 74 \rightarrow SmC^* \rightarrow Cr.$$

The main FLC parameters of mixture II at ΔT=20°C are P_S=−50 nC cm^{-2}, θ=28°, γ_φ=0.51 Poise.

Mixture III.



n=5, *m*=7, *X*=F, *Y*=H — 25 %
n=5, *m*=7, *X*=H, *Y*=F — 50 %
n=7, *m*=5, *X*=F, *Y*=H — 25 %

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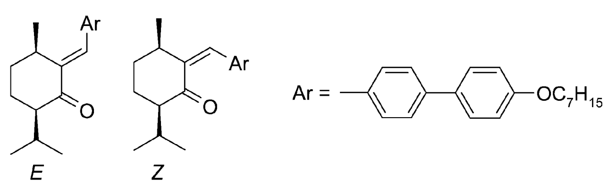

~1:9

Chiral Guest – 15.5 wt.%

CG is the photostationary mixture of *E*- and *Z*-isomers that was obtained from pure *E*-form through 1 hour of irradiation with non-filtered light from a mercury lamp DRSh-120 (*14*). The phase sequence and transition temperatures of III are

$$I \rightarrow 106 \rightarrow N^* \rightarrow 66 \rightarrow SmA^* \rightarrow 59 \rightarrow SmC^* \rightarrow Cr.$$

The main ferroelectric parameters of the mixture at ΔT=20 C are P_S=28 nC cm^{-2}, θ=29.8°, γ_φ=0.48 Poise.

The investigations were carried out on planar aligned samples (the smectic layers were perpendicular to the substrate plate). A FLC was placed in a cell consisting of two plane parallel glasses coated with transparent ITO electrodes. The area of the cell plates was not less than 5 cm^2. The cell thickness was set in the range from 24 to 33 μm by using spacers. Special boundary conditions were chosen to obtain the planar alignment of the FLC sample. The cell construction gave small shifts of the upper plate.

We studied FLC as an active medium in the double-frequency and three-frequency parametric amplifications scheme (Figure 1(a) and 1(b)). The first scheme is a single-resonance oscillation system. The resonance properties depend on both membrane properties and FLC properties in that scheme. The information signal is tuned in the resonance frequency (ω_0) of the oscillation system. The pumping signal can have a value $\omega p = n\omega_0$, where *n*=2, 3, 4, etc. The sample was excited electrically by harmonic voltages supplied by an internal oscillator of the lock-in and then amplified. The vibrating loudspeaker, which was connected via a rod to the upper bounding plate, was used as a pumping acoustic oscillator. The plate was glued to the rod. The information signal was applied by means of a piezoceramic vibrating membrane, which was glued to the upper bounding plate. We investigated the electrical response of the sample, which was detected by the PC sound board and analysed by PC.

The three-frequency scheme of parametric amplifier is a double-resonance oscillation system, where one resonance is at the information signal frequency and the other is at the pumping signal frequency. In this case a piezoceramic oscillator, which was glued to the lower bounding plate, was used as the pumping acoustic oscillator. The information signal was given as in the double-frequency scheme. We investigated the

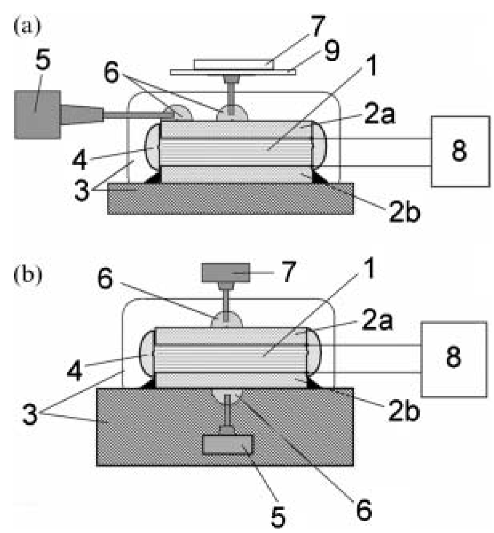

Figure 1. Block diagram of experimental setup for FLC studying as an active medium in a) double–frequency scheme and b) the multi–frequency scheme: 1, the ferroelectric liquid–crystalline material; 2, plates covered with conductive and orienting layer: (a), the movable plate, (b), the plate fixed on the thermostatic holder; 3, the hot stage; 4, the flexible hermetic seal for LC-cell (like sillicon resin); 5, the pumping acoustic oscillator; 6, the stiff glue (epoxide resin); 7, the acoustic signal wave source; 8, the personal computer, 9, the membrane.

electrical response of the sample, which was detected by the PC sound board and analysed by the PC.

3. Results and discussion

The different FLC textures were investigated in the double-frequency scheme (Figure 1(a)). The best results were obtained in the chevron and tilted layer structures. The pumping signal oscillations are the shearing oscillations along the normal to the smectic layers in both these structures. They parametrise the elasticity coefficient of the deformation of a layer structure, i.e. this coefficient becomes time dependent. The information signal was oscillations that changed the layer thickness of the FLC sample. Conditions of energy exchange between the pumping signal and the information signal appear due to the elasticity coefficient parameterisation in the oscillation system (Figure 2). When amplitudes of the information and pumping signals have values close to one another, the gain factor is not large. However, it increases when the amplitude of the information signal is substantially smaller than that of the pumping signal ($K\approx 2$, $A_P\approx 8$ a.u., $A_I\approx 0{,}1$ a.u.; $K\approx 8$, $A_P\approx 50$ a.u., $A_I\approx 0{,}1$ a.u.).

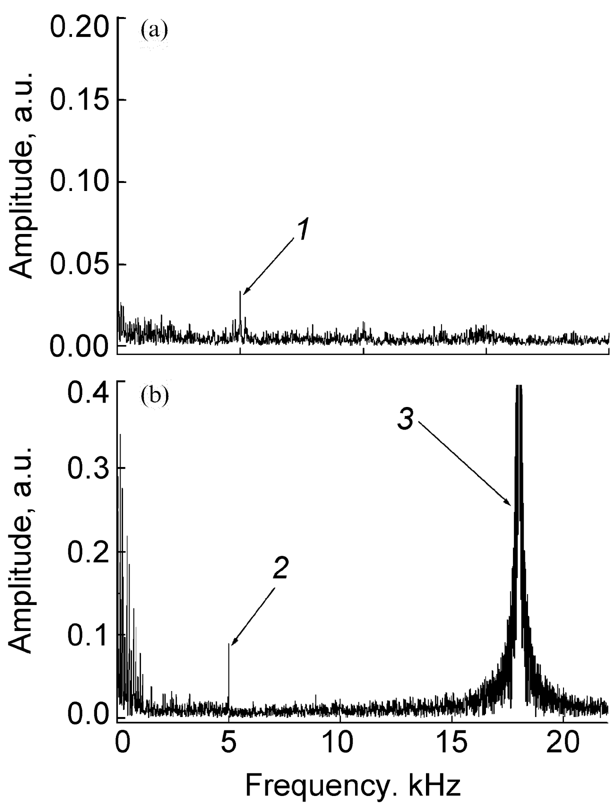

Figure 2. Output response spectra of the cell with the mixture III: a) the information signal only, (b) both me amplified information and pummping signals ($\Delta T=39°C$).

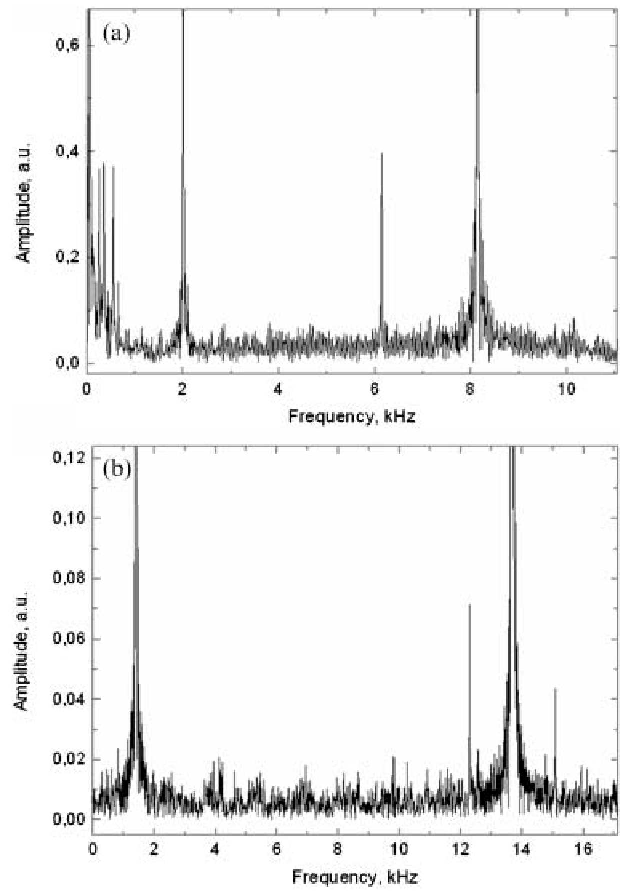

Figure 3. Output signal spectra including the lines of combination frequencies conforming to be frequencies difference (a) and to both combination frequencies (b) (mixture III, $\Delta T=39°C$).

The parametric conversion of signals with the formation of combination frequencies, which was necessary for the multi-frequency amplification scheme, was only obtained in the scheme shown in Figure 1(b). In our experimental setup, the output signal spectrum contains the lines of combination frequencies, which conform to the sum and the difference of the initial frequencies (Figure 3). This transformation is similar to an amplitude modulation. However, these phenomena have a different physical nature and differ in two attributes (*15*):

- the sideband spectrum frequencies at the modulation always are equal, while the combination frequencies at the parametric conversion usually have different amplitudes;
- the sideband spectrum frequencies' amplitude at modulation depend on the information signal amplitude, but the combination frequencies at the

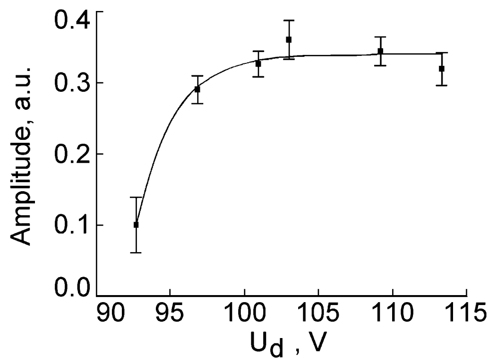

Figure 4. The dependence of the difference frequency amplitude on the pumping signal exciter voltage (mixture III, ΔT=39°C).

parametric conversion correspond to the energy sum of the pumping signal and the information signal.

Therefore, we carried out the investigations which confirmed a presence of the parametric conversion.

The difference combination frequency amplitudes (Figure 3(a)) support this conclusion because in the modulation case, they are always equal (*15*).

The disparity of the combination frequency amplitudes and its dependence on the pumping vibration parameters was investigated. The output signals with combination frequencies containing the difference of the initial frequencies (Figure 3(a)), their sum or both combination frequencies simultaneously (Figure 3(b)) were obtained by modifying of the pumping vibration parameters. The relationship between the difference frequency amplitude and the pumping signal excitation voltage is presented in Figure 4.

No amplification of the combination frequencies was obtained in the multi-frequency scheme. We have investigated three mixtures, but parametric conversion and amplification were found only for mixture III. This system has the strongest non-linear properties, compared with mixtures I and II (*16*). We conclude therefore that non-linear properties are of great importance in the electromechanical transformations.

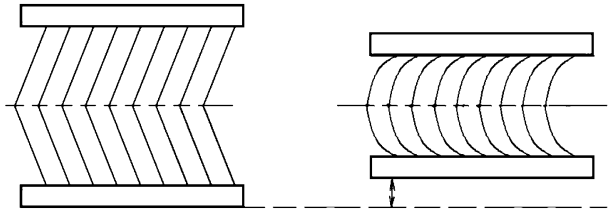

Figure 5. Variation of the change of the bend angle of smectic layers under the chevron structure deformation with the variation of sample thickness.

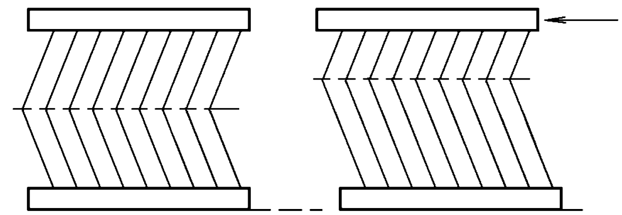

Figure 6. Change of chevron tip position under the shear deformation.

We then attempted to explain the obtained results using existing theories. In these theories deformation of the chevron structure (Figure 5) is usually described as a certain effective module, which depends on the module of helical structure deformation, the elasticity coefficient of the chevron tip and the elasticity coefficient of the director tilt in the smectic layers. The chevron tip position can be changed by the shear deformation (*17*) (Figure 6).

The chevron deformation energy changes with the sample thickness under such deformation. If the shear deformation acts on the sample periodically with the frequency ω_1, then the elasticity coefficient of chevron deformation is parametrised:

$$c(t) = c_0 \sin(\omega_1 t + \varphi_1), \qquad (1)$$

where $c(t)$ is the time-dependent elasticity coefficient of the chevron structure.

The scheme in Figure 1(a) can be considered as a parametric mixer where the shearing pumping oscillation and the thickness oscillation of the information signal are involved. This mixer exhibits a mechanical resonance depending on the elastic properties of the membrane and the elasticity coefficient of the chevron structure. As the latter is parametrised, then the motion equation of such a system is

$$\frac{d^2x}{dt^2} + 2\alpha\frac{dx}{dt} + \omega_0^2 x(1 + v\cdot\cos\omega_1 t) = 0, \qquad (2)$$

where ω_0 is the mechanical resonance frequency without parametrisation, v is the pumping signal amplitude and ω_1 is the pumping frequency. Let us consider this system in the conditions of free-damping oscillations as

$$x = ye^{-\alpha t}. \qquad (3)$$

Substituting this value in the (2) we get

$$\ddot{y} + y\left(\omega_0^2 - \alpha^2 + \omega_0^2 v\cos\omega_1 t\right) = 0. \qquad (4)$$

Let $\omega_f^2 = \omega_0^2 - \alpha^2$, where ω_f is the free-damping oscillations frequency and $\tau = \omega t/2$.

Let us substitute this into (4) to get

$$y''\frac{\omega^2}{u}+\left(\omega_f^2+\omega_0^2 v\cos 2\tau\right)y=0,$$
$$y''+\left(\frac{4\omega_f^2}{\omega_1^2}+\frac{4\omega_0^2}{\omega_1}v\cos 2\tau\right)y=0, \quad (5)$$
$$y''+(\delta+m\cos 2\tau)y=0,$$

where $\delta=4\omega_f^2/\omega_1^2$, m is the parametrisation coefficient and $m=4\omega_0^2/\omega_1^2\cdot v$.

Accordingly, the motion equation of our system is reduced to the Mathieu Equation (*18*), and its solution is well known:

$$y=Ae^{\mu\tau}\cdot MathieuC+Be^{\mu\tau}\cdot MathieuS, \quad (6)$$

where *MathieuC*, *MathieuS* are even and odd Mathieu functions, respectively, and

$$\mu^2=-(d+1)\pm\sqrt{4d+\left(m/2\right)^2}. \quad (7)$$

If the μ is real, the solution of the Mathieu equation is not stable: the parametric mixer can excite from noises and will work as a parametric generator of acoustic oscillations (the parametrisation coefficient is about 0.7 in such a case). This was also observed in our experiments. If μ is imaginary, the mixer can be used as the parametrical amplifier of an acoustic signal.

FLC can have non-linear dynamics for the realisation of the parametric conversion. Current theories used to describe electro-optical effects are based on several assumptions to simplify the FLC dynamics equations (*19–21*). Those assumptions are not always appropriate, especially for the quantitative description of the system and understanding of the subtle effects, which are of a fundamental importance in numerous cases. Several cases are discussed in this paper.

To obtain the parametric conversion in the FLC sample, input signals (pumping and information) interact with each other resulting in multiplication of these vibrations.

According to the Orsay Group theory, the free energy density of a deformation (*Fd*) has a form (*22*)

$$F_d=F_c+F_1+F_{c1}, \quad (8)$$

where F_c represents the distortion of the director field into fixed layers, F_l describes the layer distortion, and F_{cl} contains the cross summands describing both effects:

$$F_{c1}=C_1\frac{\partial\Omega_x}{\partial x}\times\frac{\partial\Omega_z}{\partial x}+C_2\frac{\partial\Omega_x}{\partial y}\times\frac{\partial\Omega_z}{\partial y}, \quad (9)$$

where variable $\vec{\Omega}$ defines the director rotation. The partial derivatives $\partial\Omega_z/\partial x$ and $\partial\Omega_z/\partial y$ represent the director field distortion while $\partial\Omega_x/\partial x$ and $\partial\Omega_y/\partial y$ describe the deformation of the layer structure. Obviously this may produce the parametric conversion appearance into FLC.

The parametric conversion is induced by the composite deformation and is presented in the Nakagawa theory (*8*). The free energy density is

$$2F_d=A\left(\frac{\partial a_i}{\partial x_i}\right)^2+B\frac{\partial c_i}{\partial x_j}+2C\frac{\partial a_i}{\partial x_i}\times\frac{\partial c_j}{\partial x_j}+\ldots, \quad (10)$$

where a is the wave vector of the layer structure and $|\vec{a}|=d_a/d_{(r,t)}$, d_a is the SmA* interlayer space, $d_{(r,t)}$ is the local interlayer space and $d_{(c)}$ is the interlayer space in SmC* phase. The term with the coefficient A describes the layer deformation, the term with coefficient B describes the director field deformation in the layer, and that with coefficient C describes the composite deformation of both the director field and the interlayer space deformation.

4. Conclusions

The parametric conversion and the parametric amplification of acoustic signals in a FLC sample with uniform planar orientation have been observed for the first time. The electric response parameters in the FLC sample depend on the deformation type. The asynchronous interaction of the acoustical signals takes place in parametric conversion and the parametric amplification. The dependence of the combination frequency amplitude on the pumping oscillation frequency is considered as the parametric conversion criterion. Parametrisation without combination frequencies takes place when the pumping signal and information signal are different deformation modes of FLC. For the parametric conversion, the pumping and information signals should be of same deformation mode.

The initial conditions of the parametric generation have been characterised. The observed parametric conversion occurs in working mixtures with a strong electromechanical effect.

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