Nonlinear dynamics of liquid crystal: ultrasonic light modulator

O A Denisova
Department of Physics, Ufa State Petroleum Technological University, Ufa, Russia

Abstract. The article discusses the influence on the physical properties of a planar-oriented cholesteric liquid crystal (chlesterlypelargonate) with a thickness of 10-15 microns, the propagation of elastic waves in the ultrasonic range (exposure frequency 600 kHz). Changing the pitch of the crystal spiral leads to changes in its optical properties, which is shown in the modulation spectrum of light reflection from the cholesteric layer in the selective scattering region. It was found that a positive peak is observed at a light wavelength of 436 nm, and a negative peak at 427 nm. A technique of experimental measurements is proposed, which uses the principles of modulation spectroscopy, which makes it possible to record with a high degree of accuracy even insignificant changes in optical spectra, which are not possible to register with conventional optical spectrometers. By analyzing the reconstructed reflection spectrum, it can be concluded how the swirling of a liquid crystal affects the processes that occur in it during the propagation of ultrasonic waves. The considered nonlinear processes are interesting for creating ultrasonic light modulators based on liquid crystals.

1. Introduction
Interest in issues related to the influence of external factors on liquid crystals (LC) continues unabated. This is evidenced by the works of recent years, published by researchers from different countries [1-14]. The various properties of liquid crystals, which are very interesting for practical application, depend on the equilibrium in the distribution of molecules. Orientational rearrangement of molecules caused by the action of ultrasound, heating, electric and magnetic fields, the effect on the chemical composition of the liquid crystal, by doping, lead to significant changes in their physical properties. For example, the authors of [3], using the effect of ultrasound on the liquid crystal layer, propose a lens with variable focus. Thanks to the use of LC, the design has a small size. In [4], a new generation device for displaying information on a cholesteric liquid crystal (CLC) containing a chiral additive is considered. It reacts to a redox reaction, which improves the speed of the device and reduces its power consumption. The influence of sound waves on biological systems is still relevant for medical research. Cholesteric liquid crystals are used as models of living cells. And we can continue to give similar examples.

Below are the results of studying the optical properties of cholesteric liquid crystals under the action of ultrasound on them. To describe the propagation of an ultrasonic wave in a CLC, in addition to the functions of the density of sound energy, medium, angular momentum, a variable is introduced associated with the pitch and angle of inclination of the spiral. In the first case, the internal structure of a nematic liquid crystal has no significant effect on the propagation of an ultrasonic wave, and the speed of sound actually coincides with the speed of sound of the isotropic phase. In the second case, a sound appears for which the velocity is determined by the wave vector of the spiral of the twist structure of the NLC, and \( c = 0 \). Since in this situation the
parameters of the spiral change, the optical properties of the NLC should change with the propagation of the ultrasonic wave.

2. Research objects and experimental technique
Let us consider an experimental situation in which the transverse wavelength is greater than the pitch of the spiral. An experimental study of the propagation of an ultrasonic wave in swirling liquid crystals is difficult due to a number of side factors associated with a change in the pitch of the CLC-coil. These factors include crystal heating, as well as significant orientation effects. In this regard, experimental studies of the propagation of an ultrasonic wave should be carried out at sufficiently low intensities of ultrasound acting on the CLC and with continuous heat removal. Taking this circumstance into account, a special registration technique was developed, which is based on the principles of modulation spectroscopy. This technique allows accurate measurements of subtle changes in spectra that are not recorded by conventional optical spectrometers.

The essence of the method is as follows: the action of an ultrasonic wave periodically changes the pitch of the CLC-coil and, accordingly, with selective scattering of light, the wavelength changes, and with monochromatic radiation, the intensity of the scattered light flux. These changes are recorded by the photodetector, separated from the noise and converted to a form convenient for measurements by the phase-sensitive detection system, and then are presented, for example, in the form of the ratio of the variable \( I \) and constant \( I \) of the signal components.

The \( \frac{I}{I} \) ratio can be measured in various ways. The simplest is to register only \( I \) at constant \( I \) in the entire spectral range. To determine \( \frac{I}{I} \) in this case, it is necessary to introduce a correction factor into the final result, which is determined by the value of \( I \). This problem was solved by maintaining a constant signal level at the output of the photoelectric multiplier by changing the voltage across the diodes using a phase-sensitive amplifier, which through the feedback circuit in the source high voltage was controlled by a computer. After preliminary amplification, the alternating signal was fed to a selective amplifier, then to a voltage converter. A reference voltage with a frequency of 79 Hz was supplied to the voltage converter from a low-frequency generator, which was also used to modulate the high-frequency signal of the generator, which was carried out for the convenience of recording and isolating the useful signal against the background of noise.

Cholesteric liquid crystal (cholesteryl pelargonate) was placed in a flat capillary, where it formed a planar texture, and its state was monitored by a microscope. The thickness of the capillary was set by mica gaskets and was 10 - 15 μm. A longitudinal ultrasonic wave was excited using a shear transducer made of a bismuth selenite crystal with a resonance frequency of 600 kHz. Its acoustic contact with the cell was carried out by gluing it with a Canadian balsam. The experimental cell with a piezoelectric transducer was placed in a thermostated chamber, the temperature of which was set with an accuracy of 0.1° C and controlled using a chromel-alumel thermocouple. Data on temperature and \( \frac{I}{I} \) value were output through two channels to a computer.

3. Research results and their discussion
The measurements performed made it possible to reveal modulation features in the reflection spectrum of CLC in the region of selective light reflection for this type of crystal. As an example, Figure 1 shows the differential spectrum of cholesteryl pelargonate.
Figure 1. Modulation spectrum of light reflection from the CLC layer in the selective scattering region \((T = 345 \text{ K})\)

A positive peak is observed at 436 nm and a negative peak at 427 nm. According to the experimental conditions, this is the differential spectrum of the first derivative of \(I\), since the amplitude of the modulating field was small (pressure \(P \approx 10^3 \text{ dyn/cm}^2\) and the value of \(\Delta I/I\) remained small. By restoring the original shape of the selective reflection line from this differential spectrum, one can determine the coefficient of the photoelastic effect. The reconstructed reflection spectrum showed complete coincidence with the shape of the selective scattering line, the form of which is shown in Figure 2.

Figure 2. The reconstructed shape of the selective scattering line

To assess the photoelastic effect, it is first necessary to estimate the differential of the reflection coefficient of light from a CLC at angles of incidence close to normal [11]:

\[
\frac{\Delta I}{I} = 10^3
\]
\[ I \approx \frac{\sin^2(2\pi \delta q_o)}{\beta^2 + \sin^2(2\pi \beta \delta h \alpha)}, \quad \text{r.d.e} \quad \beta = \left[ \left( \frac{k_o^2 - q_o^2}{\beta^2} \right)^2 - 1 \right]^{1/2}, \]  

(1)

here \( \alpha \) is the angle of light scattering, \( \delta = (\varepsilon_1 - \varepsilon_2)/(\varepsilon_1 + \varepsilon_2) \), \( L \) is the crystal thickness, \( q_o \) is the wave vector of CLC structures, \( k_o \) is the wave vector of the incident light, \( \varepsilon_1 \) and \( \varepsilon_2 \) are dielectric permeability in the direction of the long and short axis of the molecules.

From (1) we have (for \( k_o \approx q_o \))

\[ \frac{\Delta I}{I} \approx \frac{\text{ctg}(2\pi \beta \delta q_o) \partial q_o}{\beta q_o} \]  

(2)

which qualitatively characterizes the changes in the differential spectrum. In addition, expression (2) predicts, under the condition \( 2\pi \beta \delta q_o \approx 2m\pi \) the appearance of a number of additional features that appear in the experimentally recorded spectra (Figure 2). It should also be taken into account that formula (2) is applicable only in the ideal case; therefore, the finiteness of the \( \Delta I/I \) value is explained by the imperfection of the real image representing the polycrystal.

4. Conclusion

In conclusion, it should be noted that using the described nonlinear processes observed in a cholesteric liquid crystal, increasing the number of reflections of a light wave from the surface of the LC layer, it is possible to create light modulators and deflectors with a sufficiently large modulation depth and a large deflection angle.

References

[1] Kapustina O 2015 Akusticheskiy Zhurnal 61 49
[2] Kapustina O 2004 Crystallography 49(4) 759
[3] Shimizu Y, Koyama D 2018 Appl. Phys. Lett. 112, 161104
[4] Tokunaga S, Zeng M 2019 JoVE Journal doi:10.3791/59244
[5] Buka A, Eber N 2012 Theory, Experiments and Applications 300
[6] Sun J, Srivastava A, Zhang W, Wang L, Chigrinov V, Kwok H 2014 Optics Letters 39(21) 6209
[7] Elaamans N, Hegde G, Komitov L 2016 Japanese Journal of Applied Physics 55(7) 115
[8] Kwon S, Huang W, Zhang S, Yuan F, Jiang X 2013 Smart Materials and Structures 22(11) 115017
[9] Huang S, Huang W, Shu L 2018 Journal of Advanced Dielectrics 8(2) 1830002-1
[10] Bahadur B 2014 Handbook of liquid crystals. Liquid crystals: Applications and Uses 1 500
[11] Blinov L 2011 Structure and properties of liquid crystals (Springer) p 433
[12] Sokolova A, Pavlova E, Bagrov D, Klinov D, Shaitan K 2019 Molecular Crystals and Liquid Crystals 669(1) 126
[13] Gahwiller C 2002 Phys. Rev. Lett. 28(24) 1554
[14] Budagovsky I, Ochkin V, Shvetsov S, Bobrovsky A, Boiko N, Shibaev V 2017 Molecular Crystals and Liquid Crystals 647 100