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# Approximation of electro-optical hysteresis characteristics of ChLC

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**Abstract.** In order to select proper cholesteric liquid crystal (ChLC) materials and drive schemes for cholesteric liquid crystal displays (ChLCD), it is necessary to make the protracted experimental analysis of electro-optical hysteresis properties of ChLCs. Method for approximation of electro-optical characteristics of ChLC offered in this article significantly decreases duration of experimental analysis above. Accuracy of this method is estimated by the comparison of volt-brightness and volt-contrast characteristics of ChLC obtained both by experimental measuring and proposed method of approximation.

**Keywords:** cholesteric liquid crystal, liquid crystal display.

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## 1. Introduction

Cholesteric materials have three main states: planar ( $P$ ), focal conic ( $FC$ ), and homeotropic ( $H$ ). The planar and focal conic states are stable in case of zero external electric and magnetic fields. In the planar state the helical axes are parallel to the display cell surface normal direction. The planar state of ChLC reflects light in accord with the Bragg rule. Therefore, display pixels with ChLC in the planar state look bright [1]. In the focal conic state, the helical axes are distributed almost chaotically. ChLC in this state becomes slightly diffusely scattered. The value of scattered light power in this case is much lower than the Bragg reflection of the planar state and that is why the ChLC cell with absorbed background seems dark when ChLC is in the focal conic state. Thus, the image on bistable ChLCD is formed by pixels with the planar and focal conic states of ChLC. Moreover, it is necessary to note that both the planar and focal conic domains can be contained in the same pixel simultaneously. The reflectance of such a pixel has an intermediate value. Gray scale operations for ChLCDs where such states are stable for a long time can be implemented [2–3]. In the homeotropic state, the helical structure in distribution of liquid crystal molecules is absent and all the molecules of ChLC are aligned along one direction. This direction (for ChLC with  $\Delta\varepsilon > 0$ ) coincides with the direction of the external electric field. The transition of ChLC to the

homeotropic state can be achieved by applying external electric field that exceeds the threshold value  $E_C$  [4].

In order to rewrite the information on ChLCDs, transitions between the planar and the focal conic states in pixels must be performed. A low voltage pulse can transform the planar state into the focal conic one. The value of electric field for this transition is always less than the threshold value  $E_C$ . The transition of ChLC from the focal conic state to the planar state is more complicated. Firstly, the transition to the homeotropic state must be performed. As the homeotropic state is unstable ChLC transforms into the planar state when external electric field is turned off quickly. It was studied that the transition of ChLC from the homeotropic state to the stable planar state occurs through the transient planar state ( $P^*$ ) [4]. The homeotropic-transient planar transition is very short. Investigation of this transition and its application in driving ideology for ChLCD allow creation of fast dynamic drive schemes with addressing speed of about milliseconds per row [5–8]. If the electric field is turned off slowly ChLC transforms from the homeotropic state into the stable focal conic one. Thus, from the homeotropic state ChLC can be addressed both in the planar and focal conic states.

Cholesteric material can be addressed in different stable states by the same voltage pulse depending on its initial state. For the fixed pulse duration there is a voltage range in which the field-induced homeotropic state is held and the planar, the focal conic and transient planar states

are addressed into the focal conic state by the same voltage pulse. Such behavior demonstrates hysteresis properties of ChLC that are widely used in addressing ChLCDs [8–9].

One of the problems that can be solved by the detailed experimental analysis of the electro-optical hysteresis characteristics of ChLC is the problem to select ChLC material and a drive scheme for ChLCDs. Unfortunately, direct measurements of all required hysteresis characteristics can take a lot of time. Therefore, the search of new ways to decrease the duration of such experimental analysis is actual and important problem. In our first work devoted to solving the problem mentioned above, the method for approximation of electro-optical characteristics of ChLC that describes a behavior of cholesteric material in transitions from the field-induced homeotropic state into the stable planar and focal conic states was examined [10]. This method allows to obtain the sufficient quantity of approximated characteristics of ChLC only due to measurements of four special electro-optical characteristics. In this article, we propose the possibility of adaptation of proposed earlier method for an approximation of electro-optical characteristics that describe electro-optical response of ChLC to voltage pulses from the initial stable planar state. Also, the comparison of volt-contrast characteristics of ChLC that were obtained both by experimental measurements and theoretical approximations are presented.

We performed all our measurements on the display cell filled with the liquid crystal mixture BL126 (Merck), cell thickness  $d = 4.4 \mu\text{m}$  at the room temperature. Display Measuring System SV-200 was used to measure all the experimental characteristics.

## 2. Experiment

We performed experimental measurements of electro-optical characteristics that describe electro-optical response of the ChLC to voltage pulses from the initial stable planar state. We used the sequences of voltage pulses with the waveform that is demonstrated in Fig. 1. A high voltage  $U_{r1} = 50\text{V}$  is applied to the display cell during the time interval  $T_{r1} = 0.5\text{ s}$  in order to transform the ChLC into the homeotropic state. Then, during the time interval  $T_{r2} = 2\text{ s}$  ChLC transforms into the stable planar state. Thus, during the time interval  $T_{reset} = T_{r1} + T_{r2}$  ChLC is transformed into the stable planar state irrespectively to its initial state. Then, the bias voltage pulse ( $U_b, T_b$ ) is applied to analyze the response of cholesteric material. The final reflectance of ChLC is measured in two seconds ( $T_{wait} = 2\text{ s}$ ) after the bias pulse, when the external field is absent ( $U_{wait} = 0\text{ V}$ ) and when the reflectance does not change more in time. Ten dependencies of the stabilized reflectance of the cholesteric display cell vs. the amplitude of the bias voltage  $U_b$  for different values of the bias time  $T_b$  (0.05, 0.1, 0.2, 0.3, 0.5, 0.7, 1, 3, 5 and 10 s) were measured. In Fig. 2 five of them are presented. The way of analytical approximation of these dependencies will be presented below.

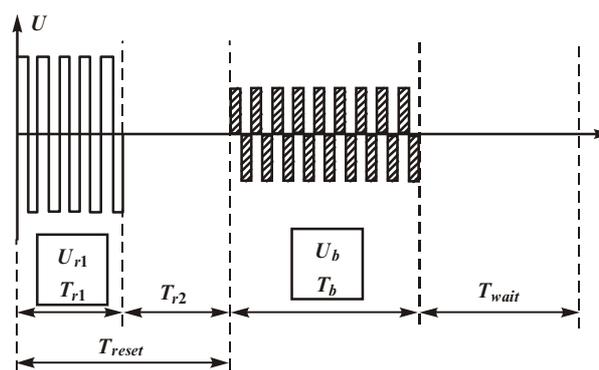


Fig. 1. The voltage waveform to measure the electro-optical response of the ChLC.

## 3. Method of approximation

The stable state of ChLC in a display cell is a complicated domain structure with a different preferred direction of the helical axis orientation in different domains. In our simple model of stable cholesteric state, we assume that this state consists of two type of domains: the “planar” domains in which helical axes are strongly parallel and the “focal conic” domains in which helical axes are strongly perpendicular to the display cell surface normal direction. It is possible to define the parameter  $v$  as a part of the “planar” domains in a stable state of ChLC ( $0 \leq v \leq 1$ ). So, the reflectivity ( $R$ ) of the stable state of ChLC is determined through the parameter  $v$  in accord to the following equation:

$$R(v) = R_{\min} + (R_{\max} - R_{\min}) \times v \quad (1)$$

where  $R_{\min}$  and  $R_{\max}$  are reflectivities of the focal conic state and the planar one, correspondingly. However, the approximation of electro-optical characteristics from Fig. 2 by formula (1) is very simplified. Therefore, we propose the following dependency  $R(v)$  that gives us good coincidence of experimental and theoretical curves:

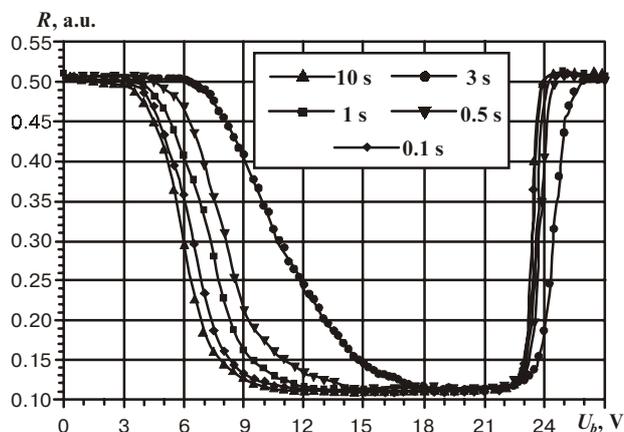


Fig. 2. Experimental dependencies  $R(U_b)$  at different values of the bias time  $T_b$ .

$$R(v) = R_{\min} + (R_{\max} - R_{\min}) \times \sin^2\left(\frac{\pi}{2} \times v\right) \quad (2)$$

Each experimental curve in Fig. 2 and our model distribution of the “planar” and “focal conic” domains can be presented as it is shown in Fig. 3. For each curve in Fig. 3, four threshold voltages can be determined:  $U_p^c$ ,  $U_{p-fc}^{\max}$ ,  $U_{p-fc}^{\min}$  and  $U_{p-p}$ . The voltage  $U_p^c$  is the threshold voltage that transforms ChLC into the homeotropic state during the bias time  $T_b$ . The voltages  $U_{p-fc}^{\max}$  and  $U_{p-fc}^{\min}$  are the maximal and the minimal voltages that address the cholesteric material from the stable planar state into the final stable focal conic state with the minimal reflectance. Finally, the voltage  $U_{p-p}$  is the maximal voltage that does not change reflectance from the stable planar state of ChLC during the bias time  $T_b$ .

As we can see from the formula (2), for the approximation of electro-optical characteristics of ChLC, it is necessary to set the value of the maximal reflectance  $R_{\max}$ , the minimal reflectance  $R_{\min}$  and the law of the parameter change. The values of  $R_{\max}$  and  $R_{\min}$  can be easily determined from the experimental data of Fig. 2:  $R_{\max} = 0.51$  and  $R_{\min} = 0.11$ . For each curve in Fig. 2 there are two ranges of voltage  $U_b$  changing for which reflectance differs from  $R_{\max}$  and  $R_{\min}$ : in the range  $\Delta_I(T_b) = U_p^c(T_b) - U_{p-fc}^{\max}(T_b)$  reflectance increases from  $R_{\min}$  to  $R_{\max}$  and in the range  $\Delta_{II}(T_b) = U_{p-fc}^{\min}(T_b) - U_{p-p}(T_b)$  reflectance decreases from  $R_{\max}$  to  $R_{\min}$  with an increase of the voltage  $U_b$ . In order to define the parameter  $v$  as a function  $v = F(U_b, T_b)$ , the following dependencies should be determined (see Fig. 3):  $U_p^c(T_b)$ ,  $U_{p-fc}^{\max}(T_b)$ ,  $U_{p-fc}^{\min}(T_b)$  and  $U_{p-p}(T_b)$ . Then, the function  $v = F(U_b, T_b)$  can be expressed in the following way:

$$v(U_b, T_b) = \begin{cases} 1, 0 \leq U_b \leq U_{p-p}(T_b) \\ \frac{U_{p-fc}^{\min}(T_b) - U_b}{\Delta_{II}(T_b)}, U_{p-p}(T_b) \leq U_b \leq U_{p-fc}^{\min}(T_b) \\ 0, U_{p-fc}^{\min}(T_b) \leq U_b \leq U_{p-fc}^{\max}(T_b) \\ \frac{U_b - U_{p-fc}^{\max}(T_b)}{\Delta_I(T_b)}, U_{p-fc}^{\max}(T_b) \leq U_b \leq U_p^c(T_b) \\ 1, U_b \geq U_p^c(T_b) \end{cases} \quad (3)$$

As we can see from Figs 2 and 3, states of ChLC with any values of reflectance between  $R_{\min}$  and  $R_{\max}$  are both in the range  $\Delta_I$  and in the range  $\Delta_{II}$ . In our model, these states have the same domain distribution and differ only in a sequence of textural transitions of ChLC during application of the voltage waveform from Fig. 1. In the ranges  $\Delta_I$  and  $\Delta_{II}$ , the “focal conic” domains are formed by reorientation of the initial “planar” domains during the bias time by the voltage  $U_b$ . These ranges differ in the formation of the final “planar” domains. In the range  $\Delta_I$ , the planar state in the “planar” domains is formed from the homeotropic state of ChLC when the bias voltage is turned off. The “planar” domains in the range  $\Delta_{II}$  are the initial “planar” domains that do not reorient by the bias voltage.

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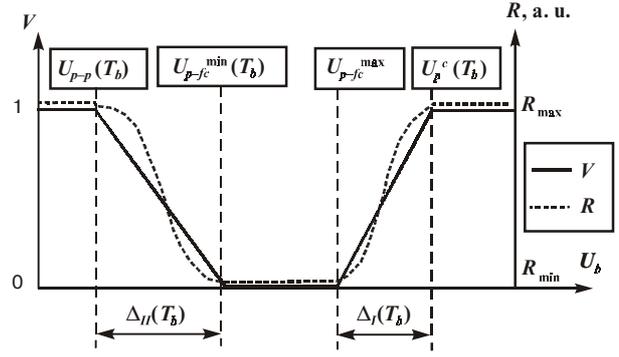


Fig. 3. Schematic form of experimental curves and model distribution of domains.

As we can see from the formula (3), in order to define the parameter  $v$  in the range  $\Delta_I$  it is necessary to be aware of the behavior of functions  $U_{p-fc}^{\max}(T_b)$  and  $U_p^c(T_b)$ . It is possible to suppose that  $U_{p-fc}^{\max}(T_b) = \text{const} = 22.8$  V (see Fig. 2). In Fig. 4 experimental and approximated dependencies  $U_p^c(T_b)$  are presented. We approximate the function  $U_p^c(T_b)$  as follows:

$$U_p^c(T_b) = U_p^{c(ST)} \times \left[ 1 + a_1 \times \left( \sqrt{1 + T^*/T_b} - 1 \right) \right], \quad (4)$$

where  $U_p^{c(ST)} = U_p^c(\infty)$ ,  $a_1$  is a coefficient and  $T^*$  is some characteristic time that we set to be equal to the characteristic time for this ChLC [10]:  $T^* = T_{FC} = 1$  s. The coefficient  $a_1$  can be determined directly from the formula (4) using experimental data from Fig. 4 (curve  $U_p^c$ ). From the experimental curve  $U_p^c$ , we can determine  $U_p^{c(ST)} = U_p^c(10\text{ s}) = 23.8$  V and  $U_p^c(1\text{ s}) = 24.15$  V. Substituting these data into the formula (4), we obtain the value of the coefficient  $a_1 = 0.035$ . In the range  $\Delta_{II}$ , in order to define the parameter  $v$  it is necessary to know behavior of functions  $U_{p-fc}^{\min}(T_b)$ ,  $U_{p-p}(T_b)$  and  $\Delta_{II}(T_b)$ .

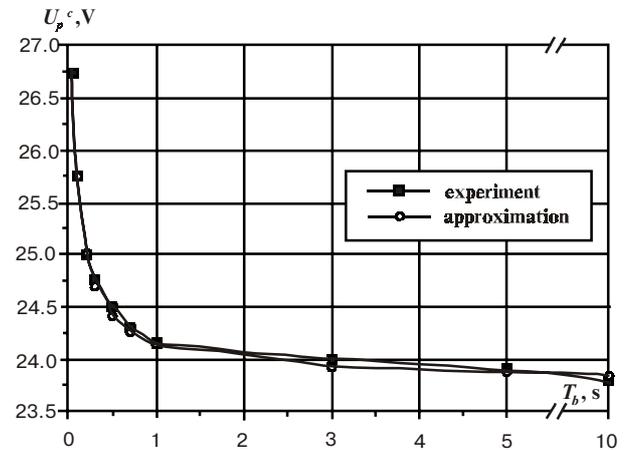


Fig. 4. Experimental and approximated dependencies of the voltage  $U_p^c$  vs. the bias time  $T_b$ .

In Fig. 5, experimental and approximated dependences  $U_{p-fc}^{\min}(T_b)$ ,  $U_{p-p}(T_b)$  and  $\Delta_{II}(T_b)$  are presented. We approximate functions  $U_{p-fc}^{\min}(T_b)$  and  $U_{p-p}(T_b)$  by expressions similar to presented earlier in the formula (4):

$$U_{p-fc}^{\min}(T_b) = U_{p-fc}^{\min(ST)} \times \left[ 1 + a_2 \times \left( \sqrt{1 + \frac{T_{FC}}{T_b}} - 1 \right) \right] \quad (5)$$

$$U_{p-p}(T_b) = U_{p-p}^{(ST)} \times \left[ 1 + a_3 \times \left( \sqrt{1 + \frac{T_{FC}}{T_b}} - 1 \right) \right] \quad (6)$$

where  $U_{p-fc}^{\min(ST)}$  is the minimal voltage that address cholesteric material from the stable planar state into the final stable focal conic state with the minimal reflectance during the bias time  $T_b = 10$  s,  $U_{p-p}^{(ST)}$  is the maximal voltage level that does not change reflectance of the stable planar state of ChLC during the bias time  $T_b = 10$  s,  $a_2$  and  $a_3$  – coefficients. The coefficients  $a_2$  and  $a_3$  can be determined directly from the formulae (5) and (6) using the experimental data from Fig. 5 (curves  $U_{p-fc}^{\min}$  and  $U_{p-p}$ ):  $a_2 = 0.244$  and  $a_3 = 0.403$ .

Substituting functions  $U_p^c(T_b)$ ,  $U_{p-fc}^{\min}(T_b)$ ,  $U_{p-p}(T_b)$  and  $U_{p-fc}^{\max}(T_b) = \text{const} = 22.8$  V in the formula (3), we can obtain the final expression for  $v = F(U_b, T_b)$ . Substituting this expression into the formula (2), we get the final expression for reflectance vs. the bias time:  $R(T_b)$ . Approximated dependencies  $R(U_b)$  at different values of the bias time  $T_b$  are presented in Fig. 6. In Figs 7 and 8, experimental and approximated volt-contrast characteristics of ChLC are presented. The comparison of these characteristics is carried out by calculations for each volt-contrast curve of the voltage range ( $\Delta U$ ) where contrast has a value not less than  $C_1 = 4.2:1$  and  $C_2 = 3.5:1$  (see Fig. 9). This comparison shows quite good coincidence of these voltage ranges both for experimental and approximated volt-contrast characteristics. It means that proposed simple method for the approximation of electro-optical characteristics of ChLC can be effectively used for the analysis of electro-optical hysteresis properties of ChLC.

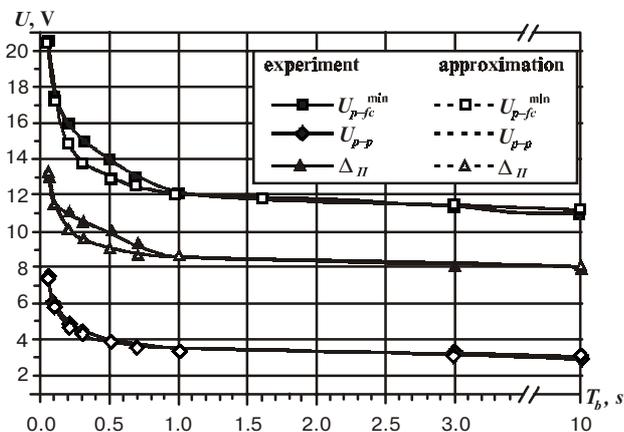


Fig. 5. Experimental and approximated dependencies of voltages  $U_{p-fc}^{\min}$ ,  $U_{p-p}$  and the voltage range  $\Delta_{II}$  vs. the bias time  $T_b$ .

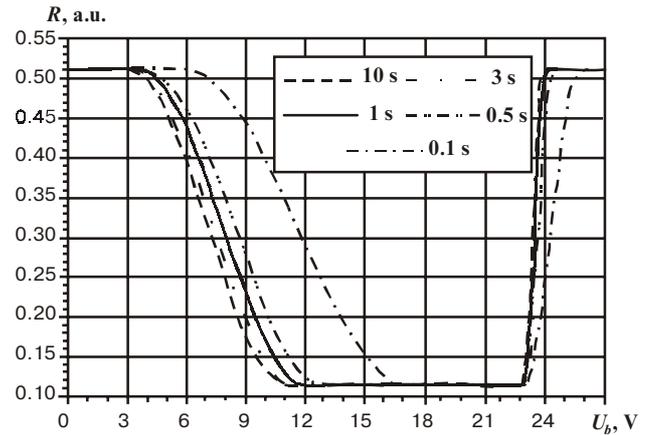


Fig. 6. Approximated dependencies  $R(U_b)$  at different values of the bias time  $T_b$ .

As a result for approximation of electro-optical volt-brightness and volt-contrast characteristics of ChLC, we need to measure six electro-optical characteristics of ChLC. Four electro-optical characteristics have been proposed earlier [10]:

1. Measurements of the quasi-static electro-optical response of ChLC from the initial field induced homeotropic state. In this case, the sequence of voltage pulses with the voltage waveform from Fig. 1 with  $T_{r2} = 0$  s and  $T_b > 10$  s should be used. From these curves, we determine several parameters of ChLC including the voltage level  $U_D$  as the minimal amplitude of a voltage pulse that can address ChLC from the homeotropic state to the stable focal conic state with the minimal reflectivity;
2. Measurements of the special dependency  $R_{\min}(T_b)$ . For this measuring, also the sequence of voltage pulses with the voltage waveform from Fig.1 with  $T_{r2} = 0$  s is used. But in this case, the bias voltage level is fixed ( $U_b = U_D$ ) and the bias time is changed. As a result, we obtain the experimental dependence  $R_{\min}(T_b)$ , and than from this curve we determine the value of the characteristic time  $T_{FC}$ ;

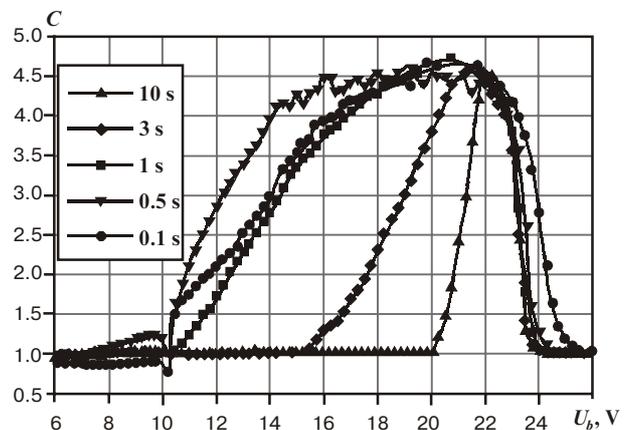


Fig. 7. Experimental volt-contrast characteristics of the ChLC.

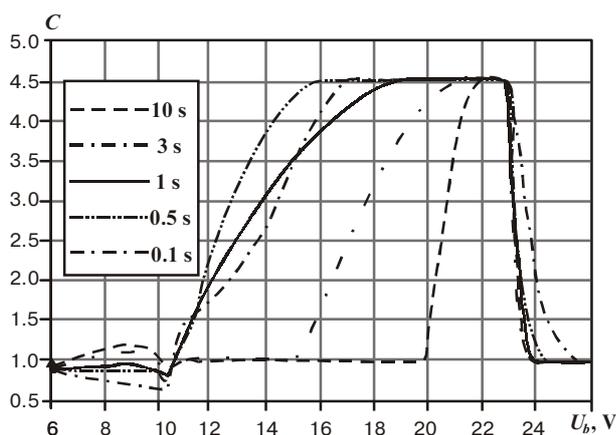


Fig. 8. Approximated volt-contrast characteristics of the ChLC.

3. Measurements of the electro-optical response of a cholesteric display cell as in the point 1 with  $T_b = T_{FC}$ ;
4. Measurements of the electro-optical response of a cholesteric display cell as in the point 1 with  $T_b > T_{FC}$ . And in this paper we offer two electro-optical characteristics more:
5. The measurement of the quasi-static electro-optical response of ChLC from the initial planar state. In this case, the sequence of voltage pulses with the voltage waveform from Fig. 1 and  $T_b > 10$  s must be used.
6. The measurement of the electro-optical response of a cholesteric display cell as in the point 5 at  $T_b = T_{FC}$ . The duration of experimental measurements of these six characteristics is about two hours that is significantly less than duration of experimental analysis necessary for investigation of electro-optical properties of ChLC using the standard way. Moreover, using the proposed method of approximation, it is possible to obtain approximated electro-optical characteristics of ChLC, similar to characteristics in a Figs 6 and 8, for any value of the parameter  $T_b$ .

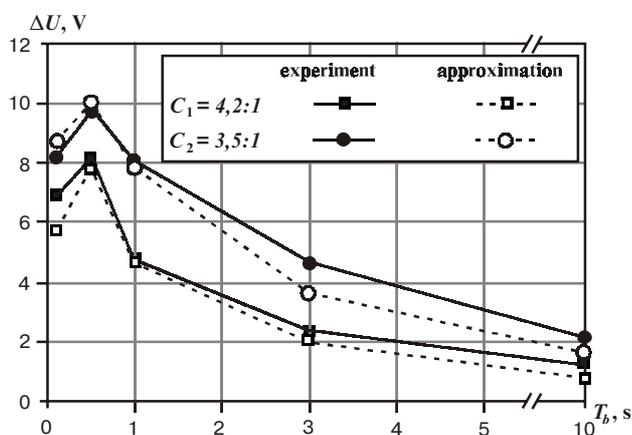


Fig. 9. The voltage range  $\Delta U$  vs. the bias time  $T_b$  for experimental and approximated volt-contrast characteristics.

## 4. Conclusions

In this article, the evolution of the proposed earlier method for an approximation of electro-optical characteristics of ChLC that describes a behavior of cholesteric material at transitions from the field induced homeotropic state to the stable planar and focal conic states was demonstrated. This method can also be implemented for an approximation of electro-optical characteristics that describe electro-optical response of ChLC on voltage pulses from the stable planar state. The volt-contrast characteristics can be obtained, too. As a result, this method allows to obtain approximated characteristics of ChLC only due to measurements of only six special electro-optical characteristics. It allows to essentially decrease the duration of experimental analysis of hysteresis properties of ChLC in comparison with the standard procedure of measuring electro-optical characteristics of ChLC.

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