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# Impedance Spectroscopy Investigation of Electrophysical Characteristics of the Electrode–Liquid Crystal Interface

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Received July 10, 2014

**Abstract**—The behavior of frequency dependences of the impedance of a capacitive measuring cell with a liquid crystal has been investigated in the frequency range from  $10^{-1}$  to  $10^5$  Hz. A method for determining electrophysical characteristics of the liquid crystal in the bulk and at the liquid crystal–metal electrode interface has been proposed and tested for liquid crystals of the alkyl cyanobiphenyl series, which are doped with ionic surfactants. The method is based on the use of an equivalent electrical circuit, which makes it possible to approximate the impedance spectra with the required accuracy, and also on the determination of the frequency at the singular point in the impedance spectra, at which the reactive component of the electric current flowing through the liquid-crystal cell is negligible compared to the active component.

DOI: 10.1134/S1063783415010060

## 1. INTRODUCTION

Liquid crystals are weak electrolytes due to the formation of ions during the dissociation of molecules and the adsorbed water. Consequently, owing to the displacement of positive and negative ions toward the corresponding electrodes in response to an electric field applied to the measuring cell with a liquid crystal, there is an inhomogeneous distribution of the concentration of ions between the electrodes, which is particularly pronounced near the electrodes. The structure of near-electrode regions (the liquid-crystal interface in the vicinity of the electrode) depends on many factors, such as the shape and structure of liquid-crystal molecules, electrode material, surface roughness of the electrodes, particles adsorbed on the electrode surface, diffusion of ions and possible electrochemical reactions involving the electrode materials, strength of the applied electric field, and frequency of the applied electric field in the case where it is an alternating-current (ac) field. All these factors determine the dynamics of passage of the electric current through liquid-crystal cells and should be taken into account in the design and fabrication of various devices used in information displays, optoelectronics, and microwave technology, for example, controlled liquid-crystal microwave phase shifters [1].

Ions and ionic complexes in liquid crystals are formed as a result of the modification of the surface of the electrodes with different surfactants, which make it possible to obtain the initial normal or homeotropic

orientation of liquid-crystal molecules. Ions of dissociated surfactant molecules are partially adsorbed on the electrode surface and, simultaneously, exist in the bulk of the liquid crystal as oppositely charged mobile ions. In this case, the electric field can initiate the accumulation or removal of surfactant molecules from the surface of the electrodes, which affects not only the passage of the electric current but also the orientation of liquid-crystal molecules in the measuring cell [2].

There are many electrochemical methods for investigating the near-electrode effects in electrolytes. However, their application to liquid crystals is complicated because of small sizes of measuring cells and, accordingly, the limited volume of the liquid crystal. Apparently, one of the available and informative tools for studying the surface ionic phenomena in liquid crystals is the method of measuring frequency dependences of the complex resistance (impedance) [3, 4].

At present, the processes of space charge transfer and accumulation at the interface between a liquid crystal and a metal electrode have been investigated in many works, for example, [3, 5–7], devoted to the analytical treatment of specific features in the formation of an electric double layer and a diffusion region. The results of theoretical investigations allow one to approximate the experimentally observed frequency dependences of electrical conductivity, dielectric permittivity, and, in some cases, impedance of liquid-crystal cells, as well as to describe the dynamics of the

behavior of the current flowing through the cells [8, 9]. However, the use of the results of these investigations for analysis of the measured impedance spectra is complicated because of the necessity to fulfill certain conditions, which are not always implemented in a real experiment. Therefore, for the interpretation of the observed impedance spectra of liquid-crystal cells, researchers have often used the method of constructing equivalent electrical circuits [10, 11], for which the frequency dependences of the impedance coincide, with the required accuracy, with the measured impedance spectra. Moreover, some capacitive elements of the equivalent circuit are brought into correspondence with the capacitance of the electric double layer and adsorption capacity, whereas other elements make it possible to simulate processes of diffusion and electrochemical reactions. It should be noted that the main problems associated with the use of this method lie not only in the adequate choice of the equivalent circuit corresponding to the experiment but also in the realization of the correct correspondence between individual circuit elements and physical processes occurring in the measuring cell with a sample.

An interesting approach to the study of liquid-crystal interfaces was proposed by Serghei et al. [12], who, instead of the conventional approximation of experimental spectra of the dielectric permittivity and electrical conductivity, used special (singular) points observed in the frequency dependences of the imaginary components of the dielectric permittivity and electrical conductivity, which correspond to the extrema at the frequencies  $f_{\text{on}}$  and  $f_{\text{max}}$ . These frequencies are associated with the “onset” and “completion” of the electrode polarization and depend on the length of the measuring cell and on the size of the diffusion region. This approach to the analysis of the behavior of both the conductivity spectra and the dielectric spectra is a very promising tool for studying the charge transfer and accumulation processes in the interfacial region due to its simplicity and efficiency. A similar approach using the recording of the frequency at the maximum ( $f_{\text{peak}}$ ) in the frequency dependence of the imaginary component of the complex effective capacitance of the measuring cell with a liquid crystal was proposed by Cho and Granick [13]. These authors obtained a simple expression for determining the mobility of ions of a 5-cyanobiphenyl (5CB) liquid crystal at the frequency  $f_{\text{peak}}$ , which is a singular point of the spectrum, and estimated sizes of the diffusion region. A method for determining the main characteristics of the interfaces of liquid substances from the measured frequencies at the singularities observed in the complex dielectric permittivity spectra was also described by Klein et al. [14], who investigated polymer electrolytes.

In this work, using the measured impedance spectra, we have demonstrated the possibility of determining electrophysical characteristics of a liquid crystal in

the bulk and at the electrode–liquid crystal interface in the measuring cell. In particular, these characteristics have been determined using the frequency at a singular point in the frequency dependence of the phase angle between the electric current and the voltage. We have also used the specially developed equivalent electrical circuit, which makes it possible to simulate and calculate the characteristics of the electrochemical processes occurring in the measuring cell with a liquid crystal.

## 2. SAMPLE PREPARATION AND EXPERIMENTAL TECHNIQUE

For our investigations, we chose an 8-cyanobiphenyl (8CB) liquid crystal, which, depending on the temperature, can be in the smectic, nematic, or isotropic phase (the temperature of the transition to the isotropic state is 40.5°C). The liquid crystal was doped with an ionic surfactant, namely, cetyltrimethylammonium bromide (CTAB). The 8CB + CTAB sample was prepared by a simple mixing of the 8CB and CTAB components in a weight ratio of 1 : 0.01 at a temperature  $T = 50^\circ\text{C}$ . The surfactant dissolved in the liquid crystal and dissociated into  $\text{Br}^-$  ions and  $\text{CTA}^+$  complexes. The  $\text{CTA}^+$  complexes were adsorbed on the walls of the measuring cell with the formation of a monomolecular  $\text{CTA}^+$  layer. This layer provided a homeotropic orientation of the “director” in the liquid-crystal cell. In the bulk of the liquid crystal, the unadsorbed  $\text{CTA}^+$  complexes and  $\text{Br}^-$  ions participated in the processes of ionic conduction [15]. In order to compare the behavior of the frequency dependences of the impedance of the 8CB + CTAB liquid crystal containing  $\text{Br}^-$  ions and  $\text{CTA}^+$  complexes with the behavior of the impedance spectrum of the liquid crystal preliminarily purified from foreign impurities, we used a multicomponent nematic mixture MB-1 with a weak conductivity and a temperature of the transition from the nematic to isotropic state  $T > 110^\circ\text{C}$ .

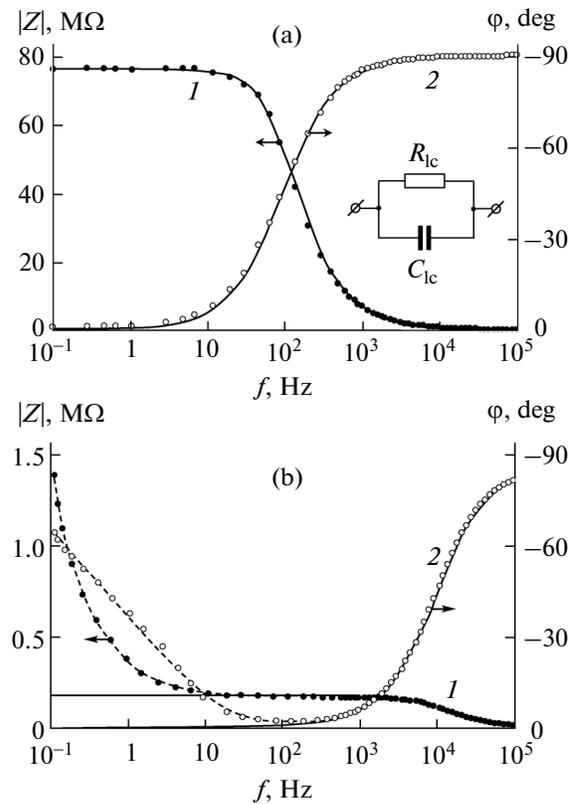
The impedance measurements in the frequency range from 0.1 Hz to 100 kHz were carried out using a standard cell consisting of two plane-parallel glass substrates with electrodes located on their inner sides and prepared from indium oxide with tin, which had the surface area  $S = 7.1 \times 10.0 \text{ mm}^2$  and the interelectrode gap  $d = 92 \text{ }\mu\text{m}$ . The capacitance of the empty cell was  $C_0 = 6.8 \text{ pF}$ . The prepared liquid-crystal sample was poured into the measuring cell at the temperature of the isotropic phase and was held for 2 h at room temperature. The cell in a special holder was placed in a thermostat with the controlled temperature in the range from 20 to 50°C and connected via the coaxial transmission lines with the impedance meter. The 8CB + CTAB sample was measured at three temperatures: 23°C (smectic phase), 35°C (nematic phase), and 45°C (isotropic state). The ac voltage applied to

the electrodes of the measuring cell varied in the range  $U = 0.2\text{--}0.5$  V. The measured values of the modulus of the impedance  $|Z|$  and the phase angle between the electric current and the voltage  $\varphi$  were transferred to a computer with the use of the LabView software package. Then, the real component  $Z' = |Z|\cos\varphi$  and the imaginary component  $Z'' = |Z|\sin\varphi$  of the complex impedance were calculated for each frequency. This made it possible to construct the corresponding frequency dependences.

### 3. EXPERIMENTAL RESULTS

Since liquid crystals, as a rule, are good insulators, the liquid-crystal cell with a sample can be simulated by a simple capacitor with capacitance  $C_{lc}$ , which has the impedance only with the imaginary component  $Z'' = 1/(-j\omega C_{lc})$ . Here,  $\omega = 2\pi f$  is the circular frequency. In this case, the electric current flowing in the external electrical circuit will be shifted in phase relative to the voltage by the angle  $\varphi = -90^\circ$ . Figure 1a shows the frequency dependences of the modulus of the impedance  $|Z|$  and the phase angle  $\varphi$  for the sample of the MB-1 liquid crystal. It can be seen from this figure that the phase angle  $\varphi$  is close to  $-90^\circ$  only at frequencies  $f > 10^4$  Hz. As the frequency decreases, the impedance of the measuring cell with the liquid crystal tends to the resistance  $R = 76$  M $\Omega$ , whereas the phase angle  $\varphi$  decreases to almost zero. This behavior of the impedance spectrum means that even the MB-1 liquid crystal specially purified from foreign impurities contains a noticeable amount of ions formed, as already noted, due to the dissociation of molecules of the liquid-crystal mixture and the adsorbed water [16]. The spectra of  $|Z|$  and  $\varphi$  shown in Fig. 1a are well approximated by the equivalent electrical circuit (see the inset in Fig. 1a) consisting of a capacitor with the capacitance  $C_{lc} = 87$  pF and a parallel-connected resistor with the resistance  $R_{lc} = 76$  M $\Omega$ , which simulates the ohmic resistance of the sample. For this scheme, the impedance is given by the formula  $Z = R_{lc} - 1/(j\omega C_{lc})$ . The results of the approximation are shown by solid lines in Fig. 1a.

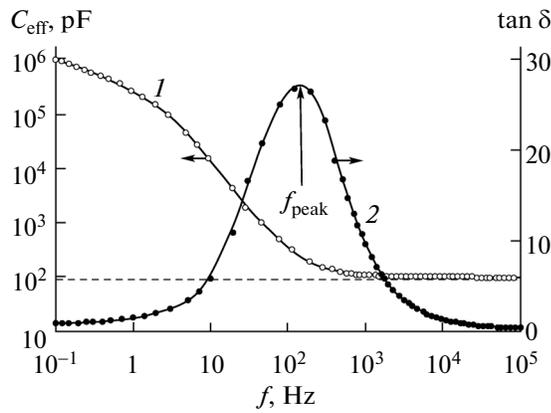
The frequency dependences of the modulus of the impedance  $|Z|$  and the phase angle  $\varphi$  measured for the ion-containing liquid crystal 8CB + CTAB are shown in Fig. 1b. It can be seen that these dependences differ significantly from the dependences shown in Fig. 1a by a strong increase in the impedance  $|Z|$  and the phase angle  $\varphi$  in the frequency range  $f \leq 100$  Hz. As in many electrolytes, such a sharp increase in the impedance at low frequencies is associated with the voltage drop across the thin electric double layer formed at the liquid crystal–metal electrode interface. With an increase in the frequency  $f \geq 100$  Hz, the dependences  $|Z|(f)$  and  $\varphi(f)$  exhibit the same behavior as the corresponding frequency dependences measured for the



**Fig. 1.** Frequency dependences of (1) the modulus of the impedance  $|Z|$  and (2) the phase angle  $\varphi$  for the liquid crystals (a) MB-1 and (b) 8CB + CTAB in the nematic phase. Solid and dashed lines represent the results of the approximation using the equivalent circuits shown in the inset to this figure and in Fig. 3, respectively.

MB-1 sample. Therefore, the experimental data in this frequency range can be approximated using the same equivalent circuit consisting of a parallel-connected capacitor and a resistor with the capacitance  $C_{lc} = 96.22$  pF and resistance  $R_{lc} = 172$  k $\Omega$ , respectively. The results of this approximation are shown by solid lines in Fig. 1b. As might be expected, these results are in good agreement with the experiment only in the “high-frequency” region of the spectrum.

It is important to note that, in the vicinity of the frequency  $f \approx 110$  Hz, the phase angle  $\varphi$  has a minimum value (see Fig. 1b). In this frequency range, the reactive component of the current flowing through the liquid-crystal cell is negligible compared to the active component. In this case, the dielectric loss tangent of the capacitive measuring cell with the sample  $\tan\delta = \frac{Z'}{Z''}$  reaches the maximum at the frequency  $f_{\text{peak}}$ . Figure 2 shows the frequency dependences of the dielectric loss tangent  $\tan\delta(f)$  and the effective capacitance  $C_{\text{eff}}$  of the liquid-crystal cell with the 8CB +



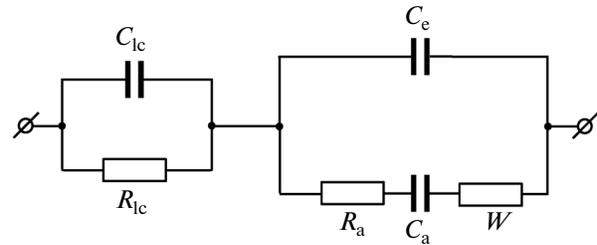
**Fig. 2.** Frequency dependences of (1) the effective capacitance and (2) the dielectric loss tangent for the 8CB + CTAB liquid crystal in the measuring cell.

CTAB sample, which is calculated according to the standard formula

$$C_{\text{eff}} = \frac{\tan \delta}{2\pi f Z' [1 + (\tan \delta)^2]} \quad (1)$$

The dashed line in Fig. 2 indicates the capacitance  $C_{lc} = 96.22$  pF, which almost coincides with the dependence  $C_{\text{eff}}(f)$  in the frequency range from 1 to 100 kHz. It is obvious that this capacitance is determined by the static dielectric permittivity of the liquid-crystal sample  $\epsilon_{||}$  when liquid-crystal molecules are oriented parallel to the polarization of the high-frequency electric field. Taking into account that  $C_{lc} = \epsilon_{||} C_0$ , we can find  $\epsilon_{||} = 14.15$ . With a decrease in the frequency  $f < 1$  kHz, there is a gradual increase in the effective capacitance (open circles in Fig. 2) due to the screening of the internal electric field in the measuring cell, which is caused by the near-electrode polarization and the formation of an electric double layer. This effect is associated with the apparent increase in the dielectric permittivity of the liquid crystal. The frequency at the maximum of the dielectric loss tangent  $f_{\text{peak}} \approx 110$  Hz, which is well determined in the frequency dependence  $\tan \delta(f)$  (closed circles in Fig. 2) and below which the effective capacitance  $C_{\text{eff}}$  begins to increase almost linearly, can be considered as corresponding to the onset of the near-electrode polarization. At this frequency in the positive and negative half-cycles of the ac electric field  $E$ , the oppositely charged ions begin to overcome the distance  $d$  between the electrodes of the measuring cell and form a capacitor of the electric double layer with the capacitance  $C_e$ . The distance  $d$  is passed by ions for a transit time  $t_{\text{tr}}$ , which corresponds to the half-cycle of the field [17]

$$t_{\text{tr}} = \frac{d}{\mu E} = \frac{d^2}{\alpha V_0 \mu} \quad (2)$$



**Fig. 3.** Equivalent electrical circuit of the measuring cell with a liquid-crystal sample.

Here,  $V_0$  is the effective voltage across the electrodes of the cell,  $\mu$  is the mobility of the ions, and the coefficient  $\alpha = C_e/C_{lc}$  indicates the degree of attenuation of the voltage inside the cell. Taking into account formula (2), the frequency  $f_{\text{peak}}$  is defined as

$$f_{\text{peak}} = \frac{\alpha V_0 \mu}{2d^2} \quad (3)$$

This equation allows us to calculate important characteristics of the liquid crystal, such as the ion mobility  $\mu$ . Knowing the ion mobility, we can determine the diffusion coefficient of ions  $D$  for the known values of the capacitance  $C_e$ , which simulates the electric double layer, and the capacitance  $C_{lc}$  simulating the liquid-crystal volume. The diffusion coefficient of singly charged ions can be calculated according to the standard formula

$$D = \frac{\mu k_B T}{e} \quad (4)$$

Here,  $k_B$  is the Boltzmann constant,  $T$  is the absolute temperature, and  $e$  is the elementary charge.

In this work, for a more accurate estimation of the capacitances  $C_{lc}$  and  $C_e$  of the 8CB + CTAB liquid crystal, we used the method of approximating the impedance spectra with the use of the equivalent electrical circuit shown in Fig. 3. The left part of the equivalent circuit includes a capacitor with the capacitance  $C_{lc}$  and a resistor with the resistance  $R_{lc}$ , which simulate the volume characteristics of the liquid-crystal sample, whereas elements in the right part of the circuit simulate the characteristics of the liquid crystal–metal electrode interface. Here,  $C_e$  is the capacitance of the electric double layer, the elements  $R_a$  and  $C_a$  determine the resistance and capacitance of the adsorbed ions on the electrodes, and  $W$  is the electrochemical element simulating the diffusion of ions in the system (diffusion-controlled Warburg impedance) [11]. The real and imaginary components of the Warburg impedance depend on the frequency, whereas their moduli are equal to each other; i.e., they are phase-shifted by  $45^\circ$ . This element has been widely used in electrochemistry for the study of fundamental problems in the kinetics of ions in electrolytes near the

interface. Taking into account that, in this study, we used the liquid-crystal cell with a small interelectrode gap, the measured impedance spectra can be approximated using a finite diffusion Warburg element [18] with the impedance given by the formula

$$Z_{W_s}(\omega) = \frac{W_{sr}}{\sqrt{\omega}}(1-j)\tanh(W_{sc}\sqrt{j\omega}). \quad (5)$$

This element is characterized by two parameters defined by the expressions

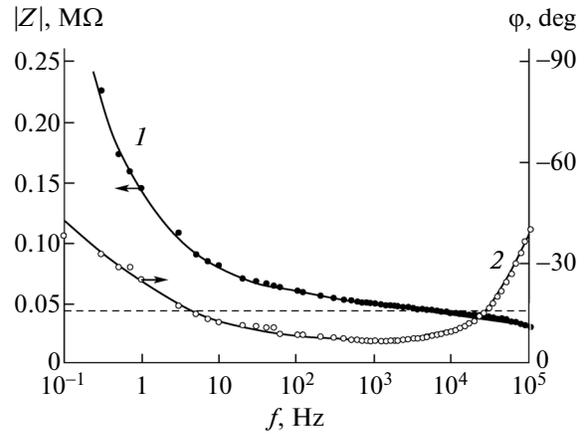
$$W_{sr} = \frac{RTN_A}{F^2 S n_s \sqrt{2D}}, \quad (6)$$

$$W_{sc} = \frac{\delta_N}{\sqrt{D}}, \quad (7)$$

where  $R$  is the gas constant,  $N_A$  is the Avogadro's number,  $T$  is the absolute temperature,  $F$  is the Faraday constant,  $S$  is the surface area of the plates of the measuring cell,  $n_s$  is the surface concentration of electrically active (mobile) ions,  $D = (D_+ D_-)/(D_+ + D_-)$  is the effective diffusion coefficient of cations with the concentration  $D_+$  and anions with the concentration  $D_-$ , and  $\delta_N$  is the thickness of the Nernst diffusion layer.

The measured impedance spectra were approximated by using the equivalent circuit (Fig. 3) with a special program for analysis and simulation of impedance spectra (EIS spectrum analyzer), as well as by calculating the impedance of the Warburg element and minimizing the corresponding functional by the complex nonlinear least-squares method [19]. It should be noted that the resistance of ions adsorbed on the electrodes  $R_a$  can be eliminated from the equivalent circuit (Fig. 2). In this case, the processes of charging and discharging of the capacitor with the capacitance  $C_a$ , which simulates the layer of adsorbed ions, will be determined only by the Warburg impedance.

The results of the approximation of the experimental spectra of the 8CB + CTAB liquid crystal in the nematic phase ( $T = 35^\circ\text{C}$ ) are represented by dashed lines in Fig. 1b. It can be seen that these data demonstrate a good agreement with the results of measurements. The frequency dependences of the impedance of the studied liquid-crystal sample in the smectic phase ( $T = 23^\circ\text{C}$ ) are not very different from the spectra shown in Fig. 1b for the nematic phase. However,



**Fig. 4.** Frequency dependences of (1) the modulus of the impedance and (2) the phase angle for the 8CB + CTAB liquid crystal in the isotropic phase. Solid lines show the results of the approximation using the equivalent circuit (Fig. 3).

in the isotropic state of the 8CB + CTAB liquid crystal ( $T = 45^\circ\text{C}$ ), the spectra  $|Z|(f)$  and  $\phi(f)$  change significantly (Fig. 4). Moreover, for the approximation of the spectra in the isotropic state, the capacitance  $C_a$  is eliminated from the equivalent circuit shown in Fig. 3, and a good approximation of the spectra is achieved by using the conventional Warburg diffusion impedance ( $W \equiv W_{sr}$ ), whereas the parameter  $W_{sc}$  is absent. The nominal parameters of the equivalent circuit elements for the 8CB + CTAB liquid crystal in the smectic, nematic, and isotropic phases are presented in Table 1. It should be noted that the relative error in the determination of the nominal parameters of the equivalent circuit elements and the coefficient  $\alpha = C_e/C_{lc}$  obtained from the results of the approximation of the experimental impedance spectra does not exceed 10%.

Using the obtained values of capacitance  $C_{lc}$  and taking into account that  $\varepsilon = C_{lc}/C_0$ , we can easily determine the dielectric permittivities of the liquid crystal in the smectic ( $\varepsilon_s = 13$ ), nematic ( $\varepsilon_n = 12.8$ ), and isotropic ( $\varepsilon_{is} = 7.9$ ) phases. In the smectic and nematic phases, the dielectric permittivities correspond to a homeotropic ordering of liquid-crystal molecules in the measuring cell, most likely, because of the presence of adsorbed surfactant molecules on the surface of the electrodes. In the ordered and iso-

**Table 1.** Nominal parameters of the equivalent circuit elements (Fig. 3) simulating the measuring cell with the 8CB + CTAB liquid crystal in the smectic ( $T = 23^\circ\text{C}$ ), nematic ( $T = 35^\circ\text{C}$ ), and isotropic ( $T = 45^\circ\text{C}$ ) phases

$T, ^\circ\text{C}$	$C_{lc}, \text{pF}$	$R_{lc}, \text{M}\Omega$	$C_e, \mu\text{F}$	$C_a, \mu\text{F}$	$W_{sr}, \text{M}\Omega \text{ s}^{-0.5}$	$W_{sc}, \Omega \text{ s}^{-0.5}$
23	89	0.24	0.8	1.5	0.6	9.8
35	87	0.17	0.25	1.2	0.4	1.35
45	54	0.45	0.017	—	0.2	—

**Table 2.** Electrophysical characteristics of the 8CB + CTAB liquid crystal in the smectic ( $T = 23^\circ\text{C}$ ), nematic ( $T = 35^\circ\text{C}$ ), and isotropic ( $T = 45^\circ\text{C}$ ) phases

$T, ^\circ\text{C}$	$\mu \times 10^{-9}, \text{m}^2 \text{V}^{-1} \text{s}^{-1}$	$d \times 10^{-10}, \text{m}^2 \text{s}^{-1}$	$n_s \times 10^{22}, \text{m}^{-3}$	$n_v \times 10^{22}, \text{m}^{-3}$	$\delta_N, \mu\text{m}$
23	0.024	0.06	7.3	6.8	7.6
35	1.4	0.37	1.6	7.3	8
45	4.4	1.2	6.2	13	—

tropic phases, the dielectric permittivity of the 8CB + CTAB liquid crystal agrees well with the values presented in other papers, for example, in [20].

In order to determine the electrophysical characteristics of the 8CB + CTAB liquid crystal under investigation, we use formulas (3) and (4), from which it is easy to calculate the ion mobility  $\mu$  and the diffusion coefficient  $D$ . The surface concentration of charge carriers  $n_s$  and the thickness of the Nernst diffusion layer  $\delta_N$  can be calculated from the Warburg impedance components  $W_{sr}$  and  $W_{sc}$  according to expressions (6) and (7). The volume concentration of ions  $n_v$  can be estimated from the electrical conductivity of the liquid crystal in the frequency range  $f \sim 10^2$ – $10^3$  Hz, where the reactive component of the current flowing through the liquid-crystal cell is negligible compared to the active component. In this case, the calculated mobility of ions near the interface is assumed to be the same as that in the bulk. This can be verified by calculating the bulk mobilities of ions according to the standard relationship between the mobilities of cations  $\mu_+$  and anions  $\mu_-$  in the bulk of the liquid crystal and the viscosity of the solution  $\eta$ , which in the case of liquid dielectrics has the form [21]

$$\mu = \frac{e}{6\pi r\eta}, \quad (8)$$

where  $r$  is the ionic radius and  $e$  is the elementary charge. In the calculation of the ion mobility in the 8CB liquid crystal under the conditions where the ions in an electric field are displaced in the direction of the director, we used the viscosity  $\eta = 0.032$  Pa s measured at  $T = 34^\circ\text{C}$  [22], the radius of the  $\text{Br}^-$  ion  $r = 0.196$  nm, and the radius of the  $\text{CTA}^+$  ion  $r = 0.24$  nm. As a result, we obtained the mobilities  $\mu_{\text{Br}^-} = 1.35 \times 10^{-9} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$  and  $\mu_{\text{CTA}^+} = 1.1 \times 10^{-9} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$ . These mobilities are approximately equal to each other and close to the mobility of ions at the electrode–liquid crystal interface in the nematic state ( $T = 34^\circ\text{C}$ )  $\mu = 1.4 \times 10^{-9} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$ . The obtained values of the mobility  $\mu$ , the diffusion coefficient  $D$ , the surface ( $n_s$ ) and volume ( $n_v$ ) concentrations of ions, and the size of the Nernst diffusion layer are presented in Table 2.

As was already noted, the mobility of ions in the liquid crystal in the nematic phase at  $T = 35^\circ\text{C}$  (Table 2) almost coincides with the value obtained from formula (8). It is seen that the volume concentra-

tions of ions  $n_v$  in all the liquid-crystalline phases are approximately equal to each other, but the surface concentration of ions  $n_s$  has a minimum value for the nematic phase. Most likely, this is associated with the increased adsorption of STAB ions on the surface of the electrodes of the measuring cell due to the nematic ordering of the liquid crystal. As might be expected, the ion mobility in the isotropic phase is significantly higher than that in the nematic phase and is significantly lower than the mobility in the smectic phase. Obviously, this is associated with an increase in the viscosity of the liquid crystal with decreasing temperature.

#### 4. CONCLUSIONS

The behavior of frequency dependences of the impedance of a capacitive measuring cell with a liquid crystal was investigated in the frequency range from  $10^{-1}$  to  $10^5$  Hz. A method for determining electrophysical characteristics of the liquid crystal in the bulk and at the “liquid crystal–metal electrode” interface was proposed and tested for liquid crystals of the alkyl cyanobiphenyl series, which were doped with ionic surfactants. The results of measurements of the mobility, diffusion coefficient, and concentration of the ions, as well as the size of the Nernst diffusion layer, demonstrated a good agreement with the results obtained by the conventional methods.

The proposed method is based on the use of an equivalent electrical circuit with the elements simulating the physical processes occurring in the measuring cell with a liquid crystal. The appropriate choice of the nominal parameters of the equivalent circuit elements made it possible to approximate the measured impedance spectra with the required accuracy. The electrophysical characteristics of the liquid crystal were determined from the obtained nominal parameters of the equivalent circuit elements and from the frequency at the singular point existing in the impedance spectra. At this frequency, the reactive component of the current flowing through the liquid-crystal cell is negligible as compared to the active component. The advantage of the developed method is that it excludes the need to measure the viscosity of the liquid crystal, which is required for the estimation of the diffusion coefficient and mobility of the ions. This is especially important in the investigation of electrophysical characteristics

of new liquid-crystalline compounds, whose rheological properties are poorly understood.

#### ACKNOWLEDGMENTS

This study was supported by the Siberian Branch of the Russian Academy of Sciences (integration project no. 109).

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*Translated by O. Borovik-Romanova*