The dielectric properties of nematic LC-1289 in microwave range

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Abstract. The paper presents data on the anisotropic complex dielectric permeability of nematic LC-1289 in microwave range. The obtained data allow us to build a Cole-Cole diagram. It indicates the existence of two dispersion regions for transversal permittivity and one dispersion region for longitudinal permittivity and corresponding relaxation times.

1. Introduction
Dielectric properties underlie a lot of applications of liquid crystals. The studies of new mesogens with a diverse molecular structure, synthesized in order to improve their operational characteristics are of great importance.

Dielectric spectroscopy enables the investigation of the anisotropic relaxation processes in liquid crystals associated with molecular vibrations of dipoles. Using this method it is possible to obtain information about molecular parameters from the macroscopic properties of mesophases as well as ordinary isotropic dielectrics [1-16]. However, their study is mainly limited to frequencies up to several MHz. Static and optical properties are also well known. The least studied is the huge range from 10 MHz to 300 THz. There are few works in which an attempt is made to expand the studied frequency range to 10 GHz [4,9,10].

2. Object and Methods
Nematic liquid crystal LC-1289 consists of cyanobiphenyls and complex ethers of cyclohexane carbon acids. It was used in production of displays because of a wide range of nematic mesophase existence from melting temperature of –20 °C to the clearing one of 62 °C and due to high dielectric anisotropy.

For an alternating electric field with a cyclic frequency ω, the Debye theory [1] with one relaxation time τ gives expressions for frequency dependences of the real $\varepsilon'$ and imaginary $\varepsilon''$ parts

$$
\varepsilon' = \varepsilon_\infty + \frac{(\varepsilon - \varepsilon_\infty)}{1 + \omega^2 \tau^2},
\varepsilon'' = \frac{(\varepsilon - \varepsilon_\infty) \omega \tau}{1 + \omega^2 \tau^2}.
$$

where $\varepsilon$ and $\varepsilon_\infty$ are static and high-frequency permittivities.

Having eliminated $\omega \tau$ from equations (1), we can obtain the circle equation

$$
\varepsilon - \varepsilon_\infty = \frac{2}{1 + \omega^2 \tau^2}.
$$
\[
\left(\varepsilon' - \frac{\varepsilon + \varepsilon''}{2}\right)^2 + \varepsilon''^2 = \left(\frac{\varepsilon - \varepsilon''}{2}\right)^2
\]

and the graph of \(\varepsilon''\) versus \(\varepsilon'\) will be a semicircle - the Cole-Cole diagram. In the case of a liquid crystal, equations (1) and (2) for components \(\varepsilon_0\) and \(\varepsilon_\perp\) are used separately.

If there are two or several «relaxing subsystems», the permittivity dispersion \(\varepsilon(\omega)\) is described quite well by the sum of Debye equations that differ in relaxation times, and the contribution of each subsystem is taken into account with the corresponding weight coefficients. In the case of a large number of subsystems a continuous distribution function of relaxation times is introduced in the dispersion Debye equation.

To determine the dielectric constant and dielectric loss in the frequency range of \(10^3 - 10^7\) Hz we used the method of comparing the electric capacitance of the empty measuring capacitor and the one filled with the test substance. The real \(\varepsilon'\) and the imaginary \(\varepsilon''\) parts of permittivity were calculated using the formulae:

\[
\varepsilon' = \frac{C - C_p}{C_0 - C_p}
\]

\[
\varepsilon'' = \varepsilon' \tan \alpha
\]

where \(C_0\) and \(C\) are the capacitances of the empty measuring capacitor and the one filled with the test substance, \(C_p\) is the stray capacitance, \(\tan \alpha\) is the dielectric loss tangent. The electric capacitance and the dielectric loss tangent were measured using a WK 65120P precision analyzer. The voltage applied to the measuring capacitor was 0.5 V. This voltage value is less than the voltage affecting the orientation of the liquid crystal. The values of \(C_0\) and \(C_p\) were determined using reference liquids: benzene and toluene.

At a frequency of 39 GHz, the values of permittivity and dielectric loss were determined by the waveguide method of varying the thickness of a liquid dielectric [2]. This method is based on measuring changes in the reflection coefficient of an electromagnetic wave from the surface of a liquid with a change in its thickness. The liquid crystal was poured into the waveguide section, which was separated from the air part of the measuring setup by a thin mica plate. The thickness variation of the liquid crystal layer was carried out using a non-contact type piston moving directly in the liquid. The thickness of the liquid layer under the piston was measured with a micrometer. A continuous unmodulated high-frequency signal was supplied from the G3-30 generator through an attenuator and measuring line P1-12. The minima and maxima of the generated standing wave were recorded with a millivoltmeter.

The real and imaginary parts of the permittivity are determined from the relations:

\[
\varepsilon' = \left(\frac{\lambda_0}{\lambda_e}\right)^2 + \left(\frac{\lambda_0}{\lambda_0}\right)^2 + \left(\frac{\varepsilon''\lambda_e}{2\lambda_0}\right)^2
\]

\[
\varepsilon'' = \frac{\alpha\lambda_e}{\pi} \left(\frac{\lambda_0}{\lambda_e}\right)^2
\]

where \(\lambda_0\) is the wavelength in free space, \(\lambda_e\) is the wavelength in the liquid crystal located in the waveguide, \(\lambda_0\) is the boundary wavelength in the empty waveguide, \(\alpha\) is the damping constant. The attenuation constant was calculated by the formula:

\[
\alpha = \frac{1}{2(r_n - r_m)} \ln \frac{1 + \sqrt{\Psi}}{1 - \sqrt{\Psi}}
\]

where
\[
\Psi = \left( \frac{\sqrt{U_{\text{max} m}} - \sqrt{U_{\text{max} n}}}{\sqrt{U_{\text{max} m}} - \sqrt{U_{\text{min} m}}} \right) \left( \frac{\sqrt{U_{\text{max} n}} - \sqrt{U_{\text{min} n}}}{\sqrt{U_{\text{max} n}} - \sqrt{U_{\text{min} n}}} \right)
\]

(8)

\( U_{\text{max} m} \) and \( U_{\text{max} n} \) are the millivoltmeter readings at the maximum corresponding to the sample thickness \( r_m \) and \( r_n \), respectively, \( U_{\text{max} m} \) and \( U_{\text{max} n} \) are the extrapolated values corresponding to \( r_m \) and \( r_n \).

The director orientation of the nematic liquid crystal was set by a constant magnetic field with the induction of 0.5 T.

3. Experimental results and analysis

Figures 1, 2 show the frequency dependences of the dielectric constant along and across the director in liquid crystal LC-1289 at temperature \( T=273 \) K.

![Figure 1. Frequency dependances of a) longitudinal and b) transversal permittivities](image)

![Figure 2. Frequency dependances of permittivities](image)
The frequency dependence of the real part of the dielectric constant showed at least two sign changes. The first is about 750 kHz and the second is at the beginning of the gigahertz range. The refractive indices of a liquid crystal LC-1289 at a wavelength of 633 nm at room temperature are $n_o = 1.52$ for an ordinary wave and $n_e = 1.68$ for an extraordinary wave [17]. This corresponds to the values of $\varepsilon_r' = 2.82$ and $\varepsilon_r'' = 2.31$ at a frequency of 473.6 THz. Therefore, apparently in the terahertz range, the dielectric constant of LC-1289 changes slightly and retains the same sign of anisotropy. It should be noted that the imaginary part of permittivity also has a reversal of the sign of anisotropy at about 8.5 MHz.

The Cole–Cole diagrams shown in Figures 3 and 4 indicate the existence of two dispersion regions for transversal permittivity and one dispersion region for longitudinal permittivity and corresponding relaxation processes and times.

![Figure 3. Cole–Cole diagram for longitudinal permittivity](image3.png)

![Figure 4. Cole–Cole diagram for transversal permittivity](image4.png)
The obtained temperature dependences of the relaxation times for the longitudinal and transversal dielectric permittivity (Figure 5 a and b) allowed us to estimate the activation energies of these processes.

The activation energy $E_2 = 47.0$ kJ/mol of the first relaxation process for transversal permittivity is close to the value $E_1 = 48.8$ kJ/mol obtained for longitudinal dielectric constant.

A similar estimate of the second relaxation time for transversal permittivity gives a significantly lower activation energy $E_3 = 14.2$ kJ/mol.

**Conclusion**

Presented data on the anisotropic complex dielectric permeability of nematic LC-1289 in the microwave range and obtained Cole–Cole diagram indicate the existence of two dispersion regions for transversal permittivity and one dispersion region for longitudinal permittivity. Permittivity anisotropy shows two changes of sign on its frequency dependence.

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