Light modulation features by cholesteric-nematic transition in nematic-cholesteric liquid crystal mixtures

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The studies of LCM (liquid crystal mixtures) as an optical active medium in display devices are presented. LCM properties and their application in low-frequency modulators, making use of the effect of cholesteric-nematic phase transition (CNPT) in visible and near infrared spectral regions are also reported. In this paper it is proved that the application of CNPT-effect gives a possibility to design effective low-frequency light modulators for laser systems and for medicine. As a result of these studies the requirements to the materials used as an active medium in different display devices can be determined.

1. Introduction

One of the important task at the present stage of display devices development is to make a number of spatial-time light modulators, deflectors, light modulators and other device of such a type. It is possible to solve this problem by using liquid crystal mixtures (LCM) as an optical active medium. The display devices on the base of liquid crystals are characterized by a low power consumption, simple technology, and relative cheapness. In this paper we report the studies of LCM properties and their application in low-frequency modulators, making use of the effect of cholesteric-nematic phase transition (CNPT) in visible and near infrared spectral regions. Such modulators can be effectively used in laser systems, systems of electronic slides [1] and in medicine [2].

The application of this effect gives a possibility to simplify the device construction while the LCM compositions optimization allows to achieve necessary operation parameters.

An electrical field applied to LCM with induced helix structure causes the CNPT effect that leads to mixture's transparency change. The change of an applied electrical field value corresponds to the light amplitude modulation.

The CNPT effect is one of the most complicated electrooptical effects in LC. In general case, the CNPT consists of two stages and each of them is accompanied by the optical activity of a pattern. The first stage consists in the LC-layer textural transition from a transparent Granjean texture to an opaque texture of "finger-prints". The second stage is the cholesteric-nematic phase transition from a "finger-prints" texture to a homeotropically aligned nematic. The presence of the textural transition is determined by an original alignment of the LC-layer. The CNPT will proceed without a textural transition if the original alignment is of a „finger-print"-type.

2. Experimental apparatus

The serial CZK-1 – material exhibiting the existence of mesophase in the temperature range 263-338 K and a dielectric anisotropy value +14 was used as a nematic matrix for our studies. The non-LC-substance WIHN-3 was used in order to reach an induced helix structure of the LC-layer. As a result a series of LCM had been synthesized with an optical active dopant (WIHN-3) content from 0,5 to 2 weight %, that corresponds to induced helix pitch values from 10,9 to 2,5 mm (T = 293 K), respectively.

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The studies of voltage-dependent contrast characteristics and time parameters of the mixtures were carried out in order to predict the modulation characteristics. All the experiments were carried out in a "sandwich"-type cell, the LC-layer thickness was equal to 25 mm. The distance between electrodes was supported by spacers from "Hostaphon".

The studies of the LCM-parameters were conducted by means of an experimental apparatus. The experimental apparatus (schematic diagram is presented in Figure 1) consists of three parts: an optical part, LCM-parameters registration part and temperature adjusting and control block.

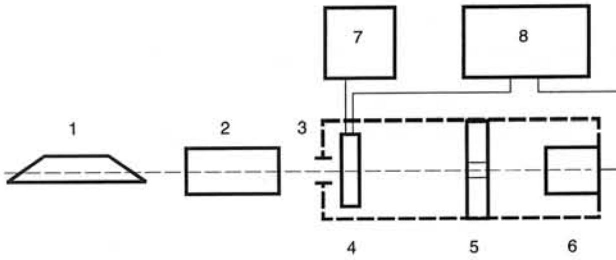

Fig.1. Schematic diagram of experimental apparatus: 1 – He-Ne laser; 2 – radiation power stabilization system; 3 – stable light-tight casing; 4 – LC-cell; 5 – diaphragm; 6 – photomultiplier; 7 – temperature adjusting and control block; 8 – LCM-parameters registration part.

The optical part is mounted on an optical bench and consists of a radiation source, laser radiation stabilizer, cuvette with an experimental cell and photo receiver. The cuvette, photo receiver and diaphragm of aperture (with angle of vision adjustment are located in a stable light-tight casing). It is necessary to measure correctly a contrast value, that depends on an aperture angle. We used the He-Ne laser with a radiation wavelength of 0,63 μm and P = 2 mW. The photomultiplier ΦEU-84/3 was used as a photoreceiver. The LCM -effect was studied in the temperature range from 293 to 338 K. The voltage-dependent contrast characteristics were obtained by means of a control signal with following parameters: alternating voltage frequency – 34 Hz; amplitude of signal - 0-40 V; voltage change velocity – 1,3 V/s. A relative value of CNPT field hysteresis was calculated by the formula [3]:

$$\delta U = \frac{U_{cn} - U_{nc}}{U_{cn}} \qquad (1)$$

3. Experimental studies of LCM parameters

3.1. Voltage-dependent contrast characteristics and time parameters of LCM

The results of measurements of voltage-dependent contrast characteristics are presented in Figures 2, and 3. Time parameters were obtained by means of rectangular-shaped pulses with amplitudes of 2 U_{cn}. Such a value of pulse amplitude was selected, according to [4], in order to avoid a strong time parameters dependence on a pulse amplitude. A control pulse duration was selected of such a value so as to obtain the "shelf" in the optical response with a duration of 30-40 % of the response pulse duration [5], and it was equal to 800 ms. The turn-on and switch-off time values were calculated by the method proposed in [6]. The time parameters of LCM dependences are shown in Figures 4 and 5. The analysis of obtained dependences leads to the following conclusions:

– the increase of an optical active dopant (OAD) concentration in LCM leads to the growth of threshold fields values of the direct cholesteric-nematic (U_{cn}) and inverse nematic- cholesteric (U_{nc}) transitions;

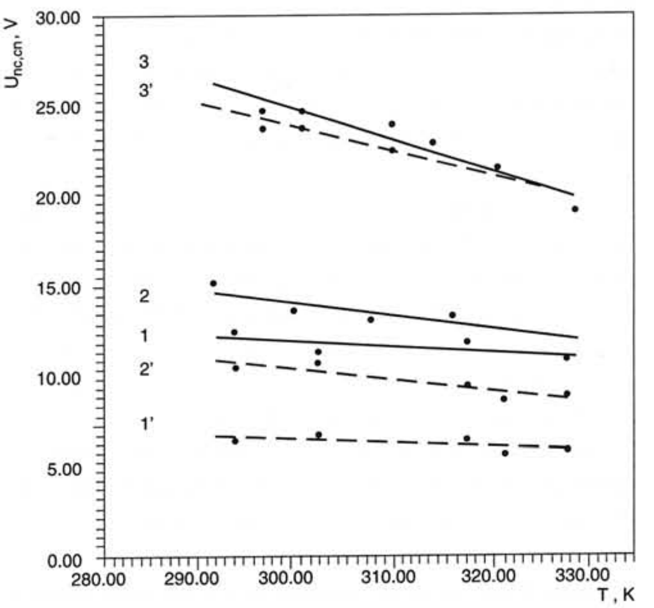

Fig.2. Dependence of CNPT threshold voltages U_{cn} and U_{nc} on temperature T for NCM with OAD concentrations:
0.5% (1 — U_{cn}, 1' — U_{nc});
1% (2 — U_{cn}, 2' — U_{nc});
2% (3 — U_{cn}, 3' — U_{nc}).

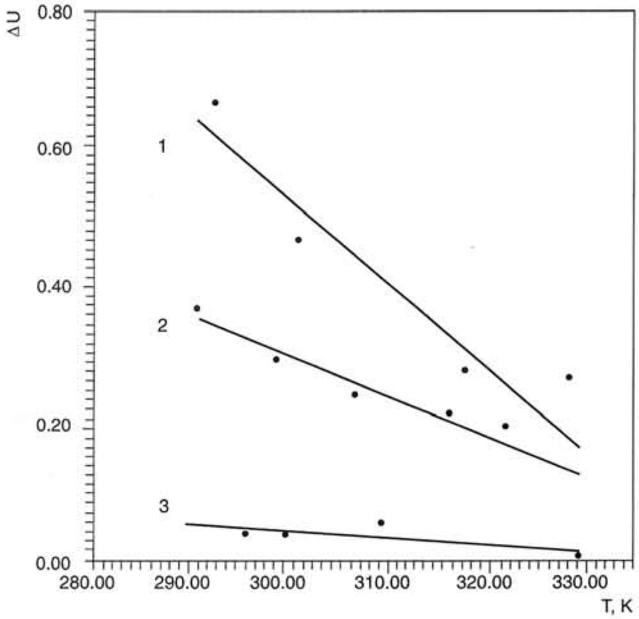

Fig.3. Relative value of field hysteresis dependence δU on temperature T for NCM with OAD concentrations: 1 — 0.5%; 2 — 1%; 3 — 2%.

– the increase of an OAD concentration in LCM leads to the decrease of a relative value of CNPT field hysteresis;

– the rise of LCM temperature leads to the decrease of threshold voltages, turn-on time and switch-off time of the mixture;

– the increase of an OAD concentration in LCM leads to the increase of a light diffusion on the focal-conic texture, that leads to the rise of contrast values.

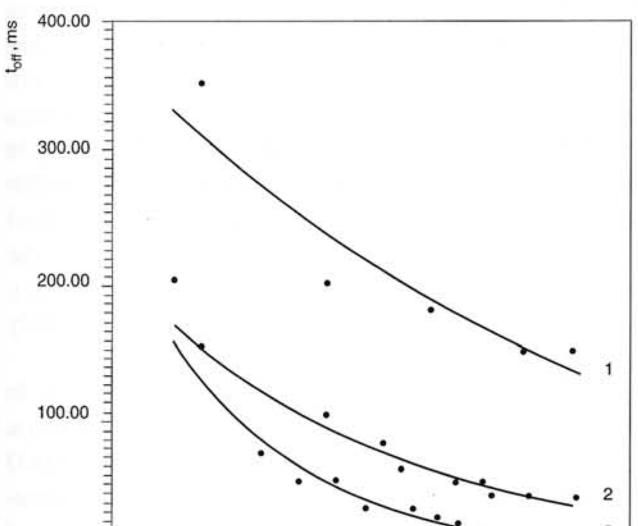

Fig.4. Dependences of CNPT turn-on times τ_{on} on temperature T for NCM with OAD concentrations: 1 — 0.5%; 2 — 1%; 3 — 2%.

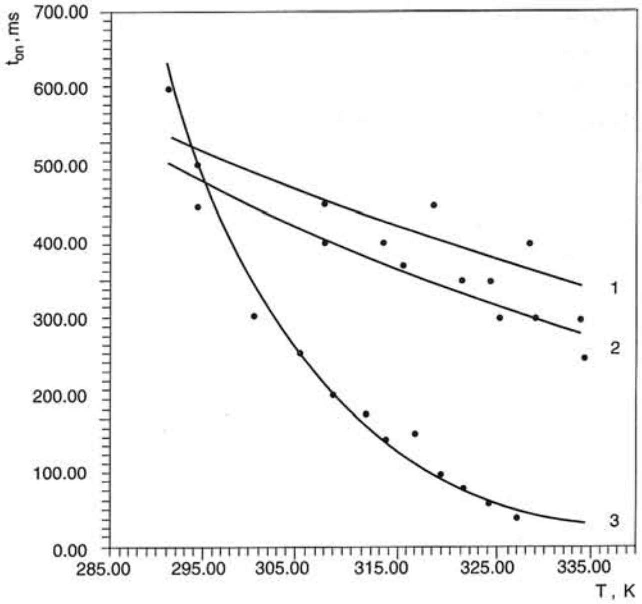

Fig.5. Dependences of CNPT switch-back times τ_{off} on temperature T for NCM with OAD concentrations: 1 — 0.5%; 2 — 1%; 3 — 2%.

3.2. Modulation characteristics

The studies of modulation characteristics were carried out by various-shaped control signals: rectangle, triangle and saw, with amplitudes of 2 Ucn in the frequency range from 1 to 100 Hz. The modulation depth was calculated by the formula [7]:

$$m = 1 - I_{min}/I_{max} \qquad (2)$$

were I_{min} , I_{max} – the intensities of light that passes through the cell with a scattering focal-conic cholesteric texture, and with a transparent nematic texture, respectively.

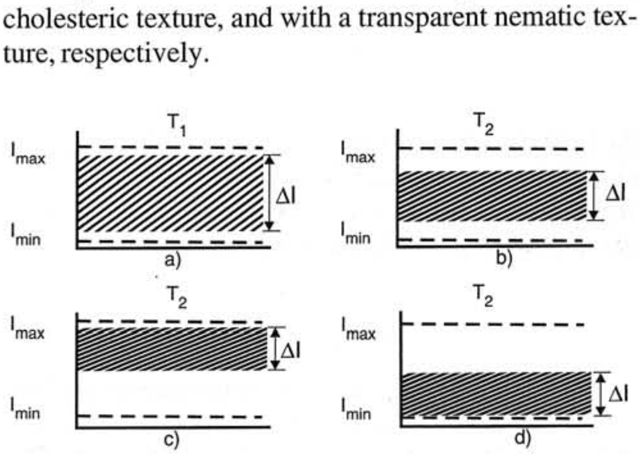

Fig.6. Versions of modulation zone filling.

Since the CNPT-effect is observed in LCM with a complex refraction index, an amplitude and phase modulation take place at the same time. The intensity of light that passes through the LC-layer [4]:

$$I(t) = Imax\ (1 + m \cos \Omega t) \qquad (3)$$

were: I_{max} – light amplitude;
Ω – modulation response frequency that in general case not coincides with forced frequency.

An amplitude modulation in the effect of CNPT is characterized by several features. Besides two extreme states of the LC-layer with light intensities of I_{min} and I_{max} there are many of intermediate states with light intensities I_i ($I_{min} < I_i < I_{max}$). The maximum modulation depth will be obtained only in the case when the control pulse parameters fulfil the following conditions:

$$\tau_i > \tau_{on}$$
$$T - \tau_i > \tau_{off}$$

τ_i – the control pulse duration;
T – the control pulse period;
τ_{on} – the LCM turn-on time;
τ_{off} – the LCM switch-off time.

Only in this case the modulated light intensity oscillations will be realized between two extreme values of I_{max} and I_{min}.

If the modulation will take place under the action of a control signal with the period of $T < \tau_{on} + \tau_{off}$, the oscillations of a modulated light intensity are realized between two intermediate points $I_{max1} < I_{max}$ and $I_{min1} > I_{min}$

To continue the discussion, it is necessary to introduce the term "modulation zone". It is the interval of modulated light intensity values limited by extreme values of I_{max} and I_{min}. Let us consider a possible versions of modulation zone filling subject to correlation between the τ_i and $T - \tau_i$ pulse parameters (Figure 6). It is evident that if the control pulse parameters fulfil the condition:

$$\frac{\tau_i}{T - \tau_i} = \frac{\tau_{on}}{\tau_{off}} \qquad (4)$$

the light modulation will be realized in the central part of modulation zone, and the value of $\Delta I = I_{max1} - I_{min1}$ will decrease with a control pulse period (T) decreasing (Figures 6 a, b). On condition that

$$\frac{\tau_i}{T - \tau_i} > \frac{\tau_{on}}{\tau_{off}} \qquad (4a)$$

the modulation takes place in the upper part of modulation zone, that corresponds to a version with incomplete "shutting" of the modulator (Figure 6c). While on condition that

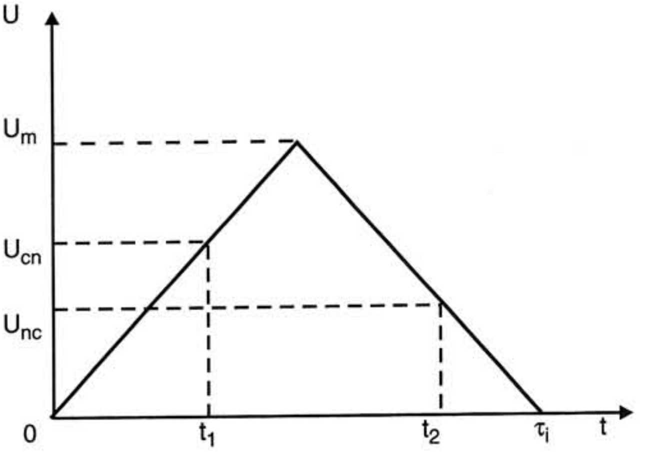

Fig.7. Schematic diagram of triangular shaped pulse.

$$\frac{\tau_i}{T - \tau_i} < \frac{\tau_{on}}{\tau_{off}} \qquad (4b)$$

the modulation occurs in the lower part of modulation zone that corresponds to a version with incomplete „opening" of the modulator (Figure 6d). It is interesting to note that provided ΔI values are identical, the modulation depth m will be larger in case (4b).

As the studies show, on condition that the modulation is realized by means of a non-rectangular pulse it is necessary to pay attention to the features connected by the control pulse amplitude change during the passing of this pulse through the cell. In order to achieve a correct interpretation of the experimental results the term of „effective pulse duration" (τ_e) has been introduced. Let us consider the triangular pulse, that is shown in Figure 7. The control voltage values that corresponds to time intervals of $0 - t_1$ and $t_2 - \tau_i$ are lower then threshold CNPT voltages U_{cn} and U_{nc}, respectively. Due to that, the voltages corresponding to this intervals cannot influence a modulated light intensity. The time interval from the moment when control pulse amplitude will increase to Ucn value (t_1), to the moment when it will have decreased to Unc value (t_2), is assumed to be the effective pulse duration, that really causes the modulated light intensity change.

Let us go on to the experimental results analysis. In Fig. 8 the experimental dependencies of modulation depth on control signal frequency for different OAD concentrations and control signal shapes are represented. As can be seen from the Figure 8, the value of m increases with a rise of OAD concentration for control pulses of all shapes in the frequency range from 1 to 10 Hz. Such a character of the dependence also occurs for frequencies up to 100 Hz for rectangular control pulse. It can be explained by two factors: that

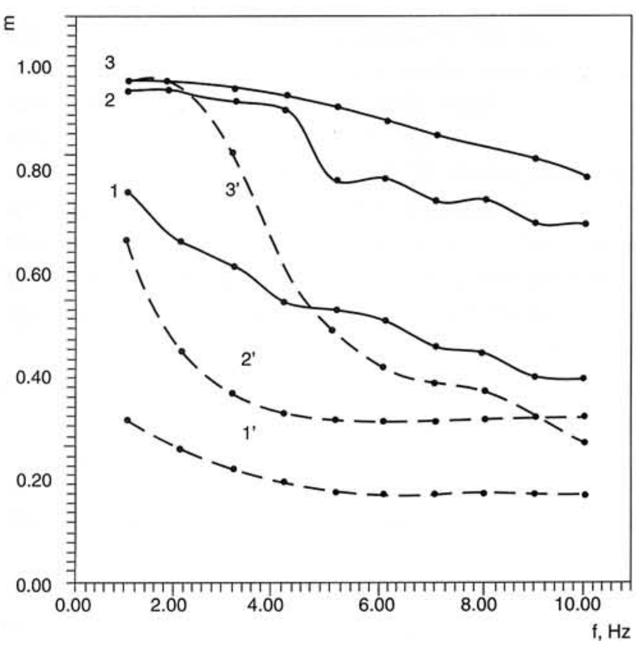

Fig.8. Dependence of modulation depth m on control pulse frequency f (T = 294K) for NCM with OAD concentrations:
0.5% — 1 (rectangle), 1' (triangle);
1% — 2 (rectangle), 2' (triangle);
2% — 3 (rectangle), 3' (triangle).

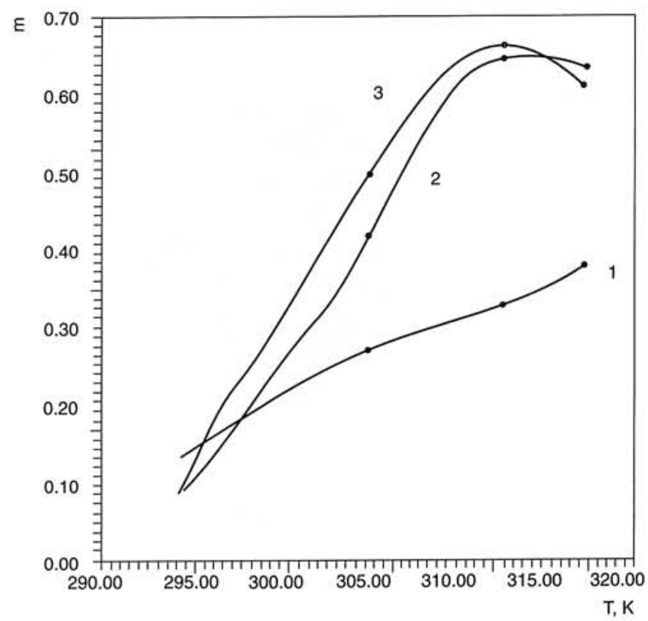

Fig. 9. Dependence of modulation depth m on temperature T (control pulse frequency f = 100 Hz) for NCM with OAD concentration c = 0.5%: 1 – rectangle; 2 – triangle; 3 – saw.

with a concentration rise the scattering ability of the focal-conic texture increases, on the one hand, and that with a concentration rise the values τ_{on}, τ_{off} decrease, on the other hand. The light scattering on a focal-conic texture is conditioned by two competitive factors : the scattering on quasi-domens of the structure and the selective light reflection [4]. The dopant concentration rise leads to strengthen both factors influence [8], that leads to increasing of the contrast value. The analysis of turn-on and switch-off times formulae, given in [9], gives a possibility to conclude that τ_{on} and τ_{off} decrease with the dopant concentration rise.

$$\tau_{on}\frac{\eta d^2}{C_1(Ed)^2 - C_2\left(\frac{d}{P_0}\right)} \qquad (5)$$

$$\tau_{on}\frac{\eta d^2}{C_2\left(\frac{d}{P_0}\right)} \qquad (6)$$

where

$$C_1 = \frac{\varepsilon_0 \Delta\varepsilon}{4\pi}$$

$$C_2 = V_6 \gamma K_{33} \pi^2$$

$$\gamma = \left(\frac{K_{22}}{K_{33}}\right)^{1/2}$$

η – viscosity of LC;
K_{22}, K_{33} – Frank elasticity constants;
d – thickness of LC-layer;
P_O – free pitch of LC-helix.

This is confirmed by the obtained experimental dependences (Figure 4). With increase of the control pulse frequency (up to 10 Hz) the modulation depth decreases for all shapes of control pulses. It is explained by the ΔI value decreasing with a frequency rise. Such a character of the dependency holds up to 100 Hz for rectangular pulses.

Considering the change of modulation depth with a temperature (Figure 9) it is necessary to note that the temperature rise causes the increase of the modulation depth for all shapes of control signals up to 10 Hz. It can be explained by the decreasing of τ_{on} and τ_{off} times with a temperature that leads to the rise of ΔI value. The modulation depth for non-rectangular signals increases most rapidly then for the rectangular signals. It is the result of CNPT threshold fields decreasing (that leads to the decreasing of τ_e). As a result the modulation by non-rectangular pulses in high temperatures is realized in the low part of modulation zone. Thus, owing to the displacement of modulation to the lower

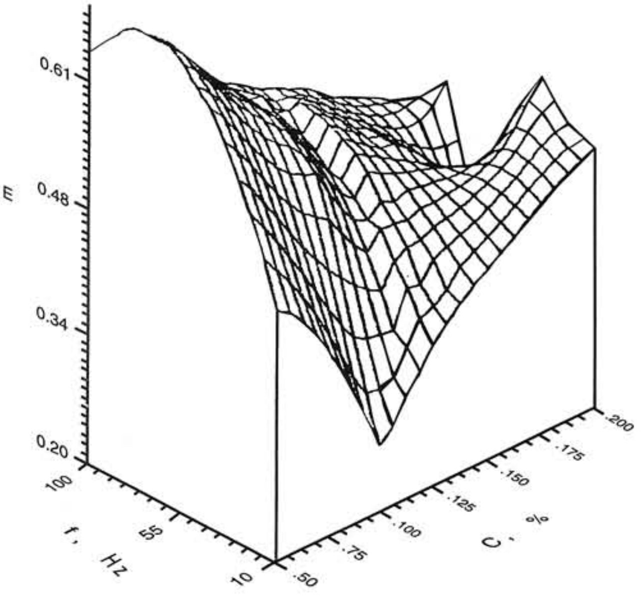

Fig.10. Dependence of modulation depth m on frequency f and OAD concentration c for triangular shaped signal (T = 313 K).

part of modulation zone it will be possible to obtain the larger modulation depth by non- rectangular pulses on condition that the ΔI values for rectangular and non-rectangular signals are approximately equal.

In Figure 10 the modulation depth dependence on frequency and temperature is represented for triangular- shaped signal in T = 313 K. In this diagram two intervals with a different character of modulation depth

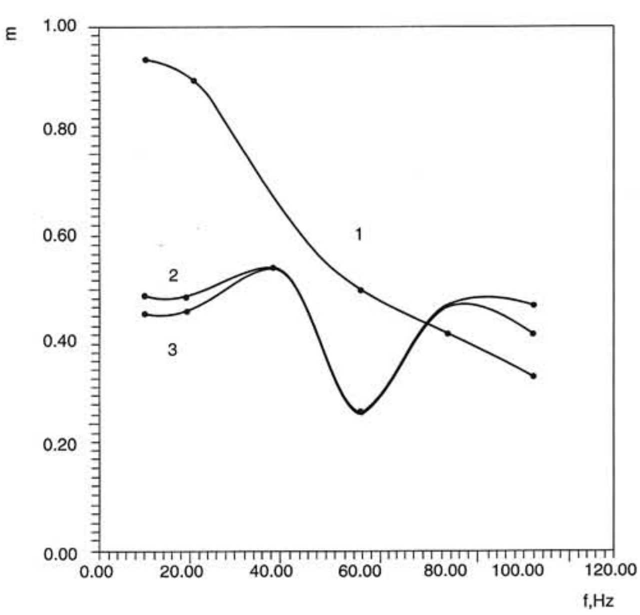

Fig.11. Dependence of modulation depth m on control pulse frequency f for NCM with OAD concentration c = 2% (T = 313 K): 1 – rectangle; 2 – triangle; 3 – saw.

behaviour can be marked. In the interval with OAD concentration values from 0.5 to 1% and control pulse frequencies from 10 to 100 Hz the increase of modulation depth is observed with the increase of control pulse frequency (if the requency increases the intensities of modulated light will be displaced into the lower part of modulation zone). In the interval with OAD concentration from 1 to 2% the high instability of a modulation depth is observed against rectangular signal (Figure 11).

4. Conclusions

1. The application of CNPT-effect gives a possibility to design an effective low-frequency light modulator for laser systems and medicine.

2. Our investigations lead to the following conclusions concerning the requirements to the materials to be used as an optical active medium:

– the materials with a high positive and low viscosity values must be used as nematic matrices for making a device with a low control voltages and satisfactory modulation depth;

– the substances with a high twisting ability must be used as optical active dopants that provides sufficiently low induced helix pitch values due to relatively low dopant concentrations. As a result it is possible to obtain the NCM with low relative hysteresis and high contrast;

– the rectangular pulses must be used as control signals to obtain the stable modulation;

– in the case of non-rectangular signals it is necessary to take into account that in the obtained dependences the intervals both with an anomalous high m values (by optimum correlation of pulse parameters) and with a low m values (by critical correlation) are observed with a a conservation of the general tendency to modulation depth increase.

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