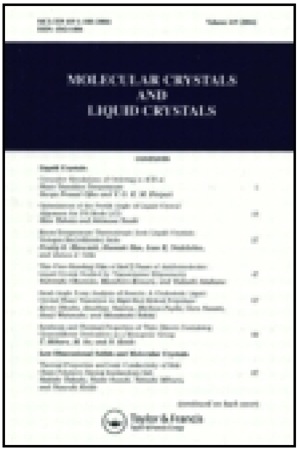

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THE INVESTIGATION OF LC CELL TEMPERATURE FIELD INFLUENCED BY LASER BEAM

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Abstract This paper deals with the problem of laser beam thermal action on the LC cell. Theoretical investigations of temperature field appearing in the LC cell under the influence of continuously moving laser beam have been carried out. By varying the thermo-optical recording parameters we can control the surface of temperature field isotherms. This surface determines the resolution of the LC cell.

INTRODUCTION

For the first time, the information concerning the thermo-optical effect in LC appeared in mid 70's.[1] After that a number of attempts were made to create the projecting displays of high resolution.[2] The LC cell was filled with low-molecular LC. But still these investigations didn't receive further development since the cell with low-molecular LC has low contrast and the recorded information can be stored during limited period of time. A new impulse to the development of projecting displays on LC was given by the appearance of LC polymers.[3,4] The information recorded by means of laser beam, when cooling of LC cell to the temperature below the glass temperature, is recorded in glass form state. This feature of LC polymers provides the long term storage of recorded information. This is explained by high viscosity of LC polymers. From this point of view LC polymers have considerable advantages over low-molecular LC.

But the thermo-optical effect in LC didn't receive wide application in creation of projecting displays. The authors think, that the reason is not sufficient theoretical investigations and experimental efforts aimed at studying of this phenomenon. In its turn, low level of investigations hinders the synthesis of new LC materials. It is noted that if the power of laser beam is changed, the thickness of recorded line on LC cell also changes.[1,3] The given papers also discuss the possible reasons of this phenomenon. But for the time being the detailed investigations aimed at studying the reasons of image characteristics changes on LC cell were not conducted. That is why, the aim of the given article is the theoretical investigation of image characteristics dependency on LC cell (particularly, resolution) on the conditions of thermo-optical effect.

THEORY

Due to the fact that the process of information recording on LC cell results from thermal action of laser beam, we will consider the process of heat propagation in LC thin layer. It is convenient to analyze the process of heat propagation by means of temperature field, which is the set of temperature values at a given moment of time in all the points of the space. The temperature field is described by equations regarded as the systems of space coordinates $T = T(X, Y, Z)$. The temperature field of an object is characterized by isotherms. The isothermal surface is considered as geometric location of object's points possessing the same temperature. Heat propagation process is a set of momentous temperature fields for all the moments of time during a certain definite period and is described by an equation $T = T(X, Y, Z, t)$, expressing the temperature dependency in different points of an object on space coordinates and time.

Mathematic model of heat propagation process is represented by a system of equations describing the processes being investigated, and by equations describing the boundary conditions. Let us consider the equation of thermal conductivity[5]

$$div(\lambda \nabla T) - \frac{\partial}{\partial T}(c\rho T) + q_v = 0, \quad (1)$$

where λ - thermal conductivity factor, T - temperature, t - time, $c\rho$ - heat capacity per unit volume, $\dot{q}_v$ - power of internal sources of heat.

The Equation (1) is the most generalized mathematic recording of thermal conductivity equation. Let us decode it depending on conditions of our task. Since the process of heat propagation from the LC layer, heated by the laser beam, reaching the limit "substrate - medium" attenuates, i.e. the temperature difference equals zero, we will replace the system "medium - substrate - LC layer - substrate - medium" by the system "substrate - LC layer - substrate".

The LC layer thickness ($\approx 10\ \mu$m) is approximately two orders less than the thickness of glass substrates (≈ 1.5 mm). That is why we will consider the temperature field as a part of flat coordinates systems, and we will accept that the temperature is distributed equally along the thickness of LC layer and does not depend on coordinate Z, i.e. the derivative of the temperature on the coordinate Z equals zero $\left(\frac{\partial T}{\partial z} = 0\right)$.

Due to the fact that the substrates exert retaining action on phase transition energy in LC, i.e. they execute immediate heat removal from LC region, where phase transition occurs, we may consider that $q_v = 0$

LC thermal conductivity anisotropy can be observed when director is is parallel or perpendicular to the wall. Before the beginning of information recording process the molecules of LC have an homeotropic orientation. Since the process of heat propagation moves in the directions X and Y, and the director is placed perpendicularly relatively these axes, in this case the thermal conductivity anisotropy in given conditions can not be observed. Our system can be considered to be isotropic and the Equation (1) after the transformation will take the following form

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right), \tag{2}$$

where $a = \frac{\lambda}{c\rho}$ is temperature conductivity factor.

To solve the Equation (2) let us define the boundary conditions, i.e. initial temperature distribution (initial conditions) and heat exchange condition on the boundaries of a body (limiting conditions). The initial distribution of the temperature is given in all the volume of the layer at a given moment of time t = 0, which is taken a beginning of time counting. The further process of heat propagation is added to this initial temperature state. During the process of thermo-optical information, recording the LC cell heating takes place in thermo-chamber to the temperature below the phase transition temperature in isotropic state. In this case the initial condition has the following form

$$T_0 = T_m, \tag{3}$$

where T_m is the medium temperature in the thermo-chamber.

The limiting conditions express the thermal interaction of LC surface layer with the medium (glass substrate). The most suitable for our case are the limiting conditions of the third type, which determine the heat exchange on the limiting line between the body and medium with a preset temperature. This condition is expressed by Newton's rule

$$q_{2s} = \alpha(T - T_m), \tag{4}$$

where α is heat irradiation factor, q_{2s} is a specific heat flux through boundary surface, T is a temperature of points on layer's surface.

Heat irradiation with a factor α takes place from the surface of LC layer of thickness δ into the substrate. Then every elementary volume of the layer $\delta dx\,dy$, heated to the temperature $(T - T_m)$ releases during the time dt in the surrounding atmosphere from both surfaces of the layer the quantity of heat $dQ = 2\alpha(T - T_m)dx\,dy\,dt$. Referring this quantity of heat to the unit of volume, to the unit of time t, and to the unit of heat capacity per unit volume, we obtain the instantaneous velocity of temperature change, which is due to surface heat irradiation

$$\frac{\partial T}{\partial t} = -\frac{2\alpha(T - T_m)dx\,dy\,dt}{c\rho\delta dx\,dy\,dt} = -\frac{2\alpha T}{c\rho\delta}. \tag{5}$$

In order to obtain the differential equation of heat conduction for LC layer with heat irradiation, to the velocity of temperature change, defined by Equation (2), let us add (algebraically) the velocity of temperature change, which is due to heat irradiation and defined by Equation (5). Then we obtain

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) - b\,(T - T_m), \tag{6}$$

where $b = \dfrac{2\alpha}{c\rho\delta}$ is a temperature irradiation factor.

Let us assume that thermo-physical properties factors - heat conductivity λ; heat capacity per unit volume $c\rho$; heat irradiation α - are independent an the temperature. It means that differential Equation (6) and boundary conditions are linear.

Since the thickness of LC layer (≈ 10 μm) is approximately tree orders less than the length (≈ 15 mm) and width (≈ 15 mm), let us consider LC layer to be unlimited. We take laser beam as the linear concentrated source of heat.

Solving the Equation (6) by the sources method, we obtain the equation of laser beam heat Q propagation process

$$T(R,t) = T_m + \frac{Q}{c\rho 4\pi a t\,\delta} exp\left[-\frac{R^2}{4at} - b(T - T_m)\right], \tag{7}$$

where $R^2 = X^2 + Y^2$ is the square of distance from heat source to the LC layer point, having the coordinates X, Y.

In accordance with the principle of overlapping we may determine the process of heat propagation from continuously functioning source. In this case the continuously functioning source is represented as a set of instantaneous sources, describe by Equation (7) and distributed in accordance with the time interval of the source action. Having added the increments in temperature dT from all instantaneous sources, we will obtain the equation of heat propagation process of continuously functioning linear source

$$T(R,t)=\int_0^t \frac{P(t)dt}{c\rho 4\pi a t}\,exp\left[-\frac{R^2}{4at}-b(T-T_m)\right], \tag{8}$$

where $P(t)$ is heat source power, absorbed by LC layer.

In order to express the equation of heat propagation process in case of moving continuously functioning source, we will apply the method of overlapping. For this aim the whole period of source functioning will be divided into infinitesimal elements, and we will consider the separate elementary actions of laser beam on LC layer. These elementary heat actions are applied to LC layer in successive moments of time in points, located along the axes of beam travel. The process of heat propagation from elementary actions of laser beam may be considered independently on each other. By adding these elementary process we obtain the equation of heat propagation process in case of continuous action of travelling laser beam

$$T(R,t)=T_m+\frac{P}{c\rho 4\pi a\delta}exp\left[-\frac{Vx}{2a}\right]\int_0^t \frac{dt}{t}exp\left[-\left(\frac{V^2}{4a}+b\right)t-\frac{R^2}{4at}\right] \tag{9}$$

Observing the moving temperature field, connected with concentrated heat source we may notice that the region of increased temperatures appearing at the initial stage of heating, in the course of time increases and reaches definite limiting sizes. The moving temperature field, saturated with the heat of laser beam travels with it.

That is why, the process of LC layer heating by laser beam of constant power is divided into two periods:

- thermal saturation when the size of heating zone increases;
- quasi stationary state of heat propagation process, when the temperature field remains constant.

The process of heat propagation tends to quasi stationary state in case of unlimited in duration of laser beam action on LC layer, i.e. $t \to \infty$. The equation of quasi stationary state of heat distribution process under heating of LC layer

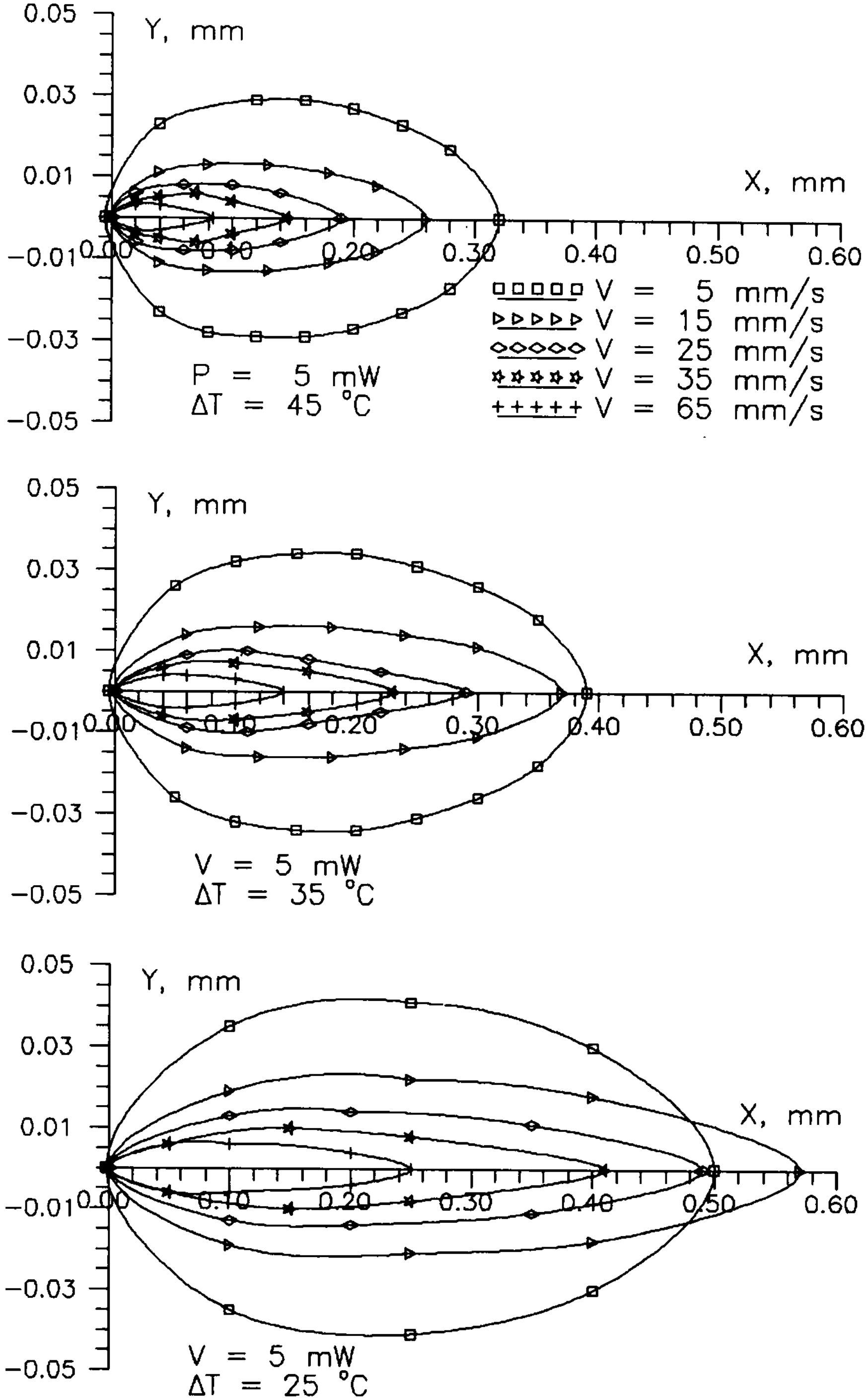

FIGURE 1 The family of isotherms at 115° C.

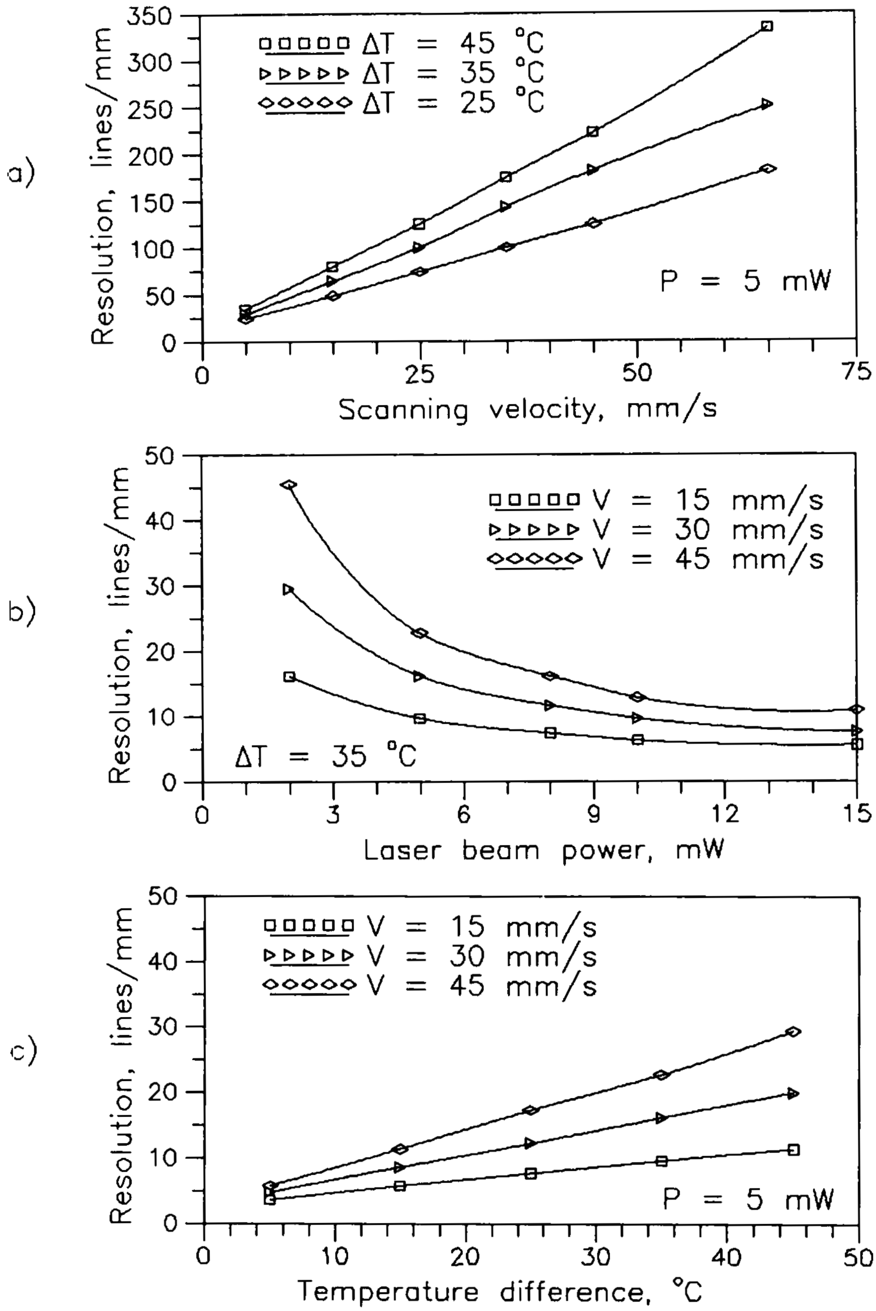

FIGURE 2 Theoretical dependencies of LC cell resolution on scanning velocity (a), laser beam power (b) and temperature difference (c).

by laser beam of P_0 power, travelling with a constant velocity V, we obtain from Equation (9), considering that $t = \infty$,

$$T(R,t) = T_m + \frac{P_0(1-k)}{c\rho 2\pi a\delta} exp\left[-\frac{Vx}{2a}\right] K_0\left[R\left(\frac{V^2}{4a^2}+\frac{b}{a}\right)^{\frac{1}{2}}\right], \tag{10}$$

where k is the LC layer transmission factor, K_0 is Bessel's function.

DISCUSSION AND CONCLUSION

The program of temperature field calculation is composed for the analysis of heat propagation process in thin LC layer under the action of laser beam. On the basis of temperature fields calculations the families of isotherms corresponding to phase transition temperature into isotropic state - 115 ^{0} C.

While heating the thin LC layer by linear sources the temperature along the thickness of the layer does not change. So, the isotherms in thin LC layer are the cylinder surfaces, built on the surfaces of isotherm curves, with generating lines, perpendicular to boundary surfaces of the LC cell.

From the Equation (10) it follows that the square of isothermal surface depends on energy parameters of information recording process, namely: on scanning velocity, laser beam power, medium temperature, where LC cell is placed. It follows that, the square of isothermal surface can be controlled by changing of information recording process parameters. Figure 1 represents the family of isotherms at 115 ^{0} C at different laser beam scanning velocities V = 5; 15; 25; 35; 65 mm/s for P = 5 mW and ΔT = 45; 35; 25 ^{0} C . These graphs show that temperature distribution in LC thin layer at moving laser beam is characterized by extending isotherms, shifted in the region rear of the source. The maximum linear size of isotherm surface along the coordinate Y perpendicular to the direction of laser beam movement determines the thickness of the line, recorded on LC cell. Since the resolution of LC cell is determined by the minimal line thickness the graphs of mutual LC cell resolution dependency on information thermo-optical recording process can be constructed. Similar temperature fields were built for different values of laser radiation power P and temperature difference ΔT (this is a difference between the medium temperature in thermo-chamber and the temperature of LC phase transition into isotropic liquid).

Figure 2(a) shows the graph of LC cell dependency on laser beam scanning velocity at different $\Delta T = 25; 35; 45\ ^0C$ for P = 5 mW. Figure 2(b) shows the graph of LC cell resolution dependency on laser beam power at V = 15; 30; 45 mm/s for $\Delta T = 35\ ^0C$. Figure 2(c) shows the graph of LC cell dependency on phase transition temperature and medium where LC cell is placed difference at V = 15; 30; 45 ^0C for P = 5 mW.

After the analysis of the graphs, shown in the Figure 2 it follows, that the thermo-optical recording parameters influence differently on LC cell resolution:

- V = var; velocity change in several times results in the change of the resolution approximately the same times, and this dependency is directly proportional, the resolution variation change is within the limits from 25 to 350 lines /mm, which is greater than at the change of two other parameters;
- P = var; the LC cell resolution dependency on laser beam power is inversely proportional, and the variation degree decreases from 1:1 at low powers (up to 5 mW) to 1: 0,25 at powers of 10 - 15 mW, resolution variation range is in the limits of 50 to 3 lines/mm;
- T = var; the increase of phase transition and medium temperature difference, i.e. the increase of gap between the medium temperature and LC phase transition temperature in isotropic melt leads to the increase of LC cell resolution, but the magnification degree is within the limits 3:1; the variation range is very low and is within the limits of 5 to 25 lines/mm.

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