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Excitation of convective motions and surface hydrodynamic soliton-type waves in liquid crystals by a Gaussian laser beam

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***Abstract*. The possibility of exciting convective motions with a toroidal symmetry in a disordered liquid-crystal cell with an open surface, which is locally heated by a Gaussian laser beam, is demonstrated experimentally. A perturbation of the free surface of the liquid crystal and a convective hydrodynamic motion are determined by temperature gradients. It is shown that a radial distribution of the director of a nematic liquid crystal appears in the convection region. Under certain experimental conditions, soliton-type hydrodynamic orientation waves are observed at the free surface of a nematic liquid crystal. It is found experimentally that the velocity of these waves is determined solely by the liquid-crystal parameters and is independent of the incident laser-radiation power.**

Keywords: *laser action, convection, instability, liquid crystals.*

1. Introduction

Processes of the development of stream instabilities in liquids, which appear under heating by a laser beam, currently attract great attention. In particular, an absorbing liquid was placed in a flat vessel and heated with focused argon-laser radiation directed from the bottom upwards [1, 2]. The appearance of cellular structures was explained by an instability of capillary waves in a liquid film heated nonuniformly over depth.

In the classical work by Benard [3] on the convective instability, a constant temperature was maintained at the lower plane of the sample, while the upper surface was in free contact with the ambient air. Benard found that the surface level lowered in the heated region near the points of the ascending liquid flow. However, other authors [4] observed an opposite structure (i.e., a rise of the heated region), when the sample material was changed under the same experimental conditions. In Ref. [5], a concave profile of the surface is explained by a competition between the streams determined by the surface tension and buoyant force. The prevalence of this or that mechanism may be critically related to the vessel depth.

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The most typical manifestations of the action of high-power laser radiation on a substance are a surface perturbation and the formation of a relief. An increased attention to them is determined by the technological prospects of their applications. Reliefs are excited on various materials exposed to radiations with different frequencies and durations. Structures are formed due to the development of instabilities of capillary or gravity waves in a nonuniform radiation interference field. The presence of a strong correlation of the parameters of these structures with the characteristics of laser radiation allows us to regard them as laser-induced gravity – capillary waves.

Experimental data on the generation of cellular and filamentary structures are presented in Refs [6 – 8]. Large areas of small-scale structures are formed at the periphery of cellular structures. It is assumed on this basis that various hydrodynamic instabilities developing in a melted silicon film, which is exposed to a laser pulse, may play a significant role in the formation of surface structures. Paper [9] reports on a new class of electromagnetically controlled instabilities in the interface between two liquids. The surface perturbation is caused by the radiation pressure produced by a cw laser.

There are a great number of works devoted to studies of convection in a liquid layer heated from below (see, for example, monographs [10 – 12] and papers [13 – 15]). Applying laser radiation makes it possible not only to produce a volumetric heat release with an almost arbitrary desirable spatial distribution but also to easily control the parameters of this distribution. The first experimental data showing the possibility of thermocapillary excitation of hydrodynamic motions by a laser beam were obtained in Refs [1, 16, 17]. Long before this, it was predicted that regular convective motions might be excited in a nematic liquid crystal (NLC) due to the absorption of laser radiation with a spatially periodic intensity distribution [18]. It was also shown that hydrodynamic motions lead to a reorientation of the director and, thus, to a modulation of the NLC permittivity.

A rigorous theory of a strong orientation – thermoconvective nonlinearity predicted in Ref. [18] was developed in Ref. [19]. The influence of the contribution of this optical-nonlinearity mechanism to the self-focusing of light in a NLC was observed for the first time in Ref. [20], where a NLC cell closed from both sides was used. Under such conditions, convection is determined only by the gravitational mechanism. Paper [21] considers theoretically a problem of exciting regular convective motions in an isotropic liquid with a single open surface, when it absorbed light with a spatially periodic structure of the intensity distribution on the layer plane. A convection appeared due to a temperature dependence of the surface-tension coefficient of the liquid (the Marangoni thermocapillary mechanism).

A forced convection and light-hydrodynamic reorientation of molecules in an NLC with a single free surface was studied theoretically in Ref. [22]. The competition between the gravitational and thermocapillary mechanisms was considered and the conditions were ascertained under which one or the other mechanism made a significant contribution to the initiation of convective motions. Gravitational and thermocapillary mechanisms responsible for exciting hydrodynamic convections, which are determined by the absorption of light with a spatially periodic structure of the intensity distribution, in isotropic and anisotropic liquids were observed experimentally and analysed theoretically in Ref. [23]. When a travelling periodic intensity-distribution structure was formed, surface hydrodynamic waves were observed that propagated at a velocity coinciding with the motion velocity of this structure. The stability of convective cells and surface hydrodynamic waves were studied.

Unlike an isotropic liquid, the NLC instability mechanism is determined mainly by the behaviour of the director that specifies the direction of the predominant molecular orientation. As a consequence, a stationary convection occurs in a homeotropically aligned NLC (its molecules are aligned perpendicular to the cell substrates) heated from above [24].

This work is devoted to an experimental study of the excitation of hydrodynamic convections in an disordered NLC layer with an open (being in contact with the air) surface that are induced by the absorption of laser radiation with a Gaussian intensity distribution. Thermal gradients produced due to a local heating lead to a surface perturbation and a toroidal convective motion, which in turn leads to a toroidal distribution of the NLC director. Under certain experimental conditions, soliton-type hydrodynamic orientation waves are observed at the free NLC surface.

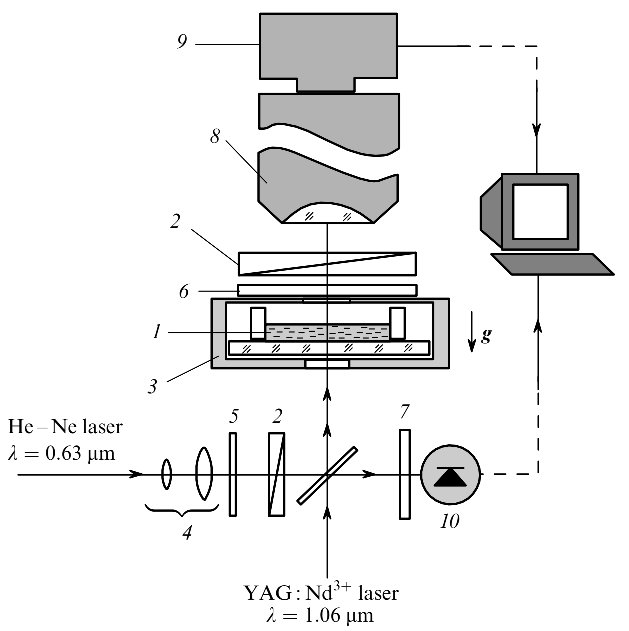

Figure 1. Scheme of the experimental setup: (*1*) cell with a liquid crystal; (*2*) polarisers; (*3*) thermostat; (*4*) telescopic expander of the laser beam; (*5*) quarter-wavelength plate; (*6*, *7*) light filters; (*8*) MBS-2 microscope; (*9*) CCD camera; and (*10*) photodetector.

2. Experimental results

Horizontally installed cells with the 5TsB NLC were used in the experiments (Fig. 1). The upper boundary of the cells was open being in contact with the air. The temperature of the cells was maintained at a constant level of 293 ± 0.3 K using a thermostat. The cells mounted between crossed polarisers were illuminated from below by a normally incident laser beam with a Gaussian intensity distribution. We used a 1.06-μm cw Nd^{3+} : YAG laser with a beam FWHM of 1.7 ± 0.1 mm at the entrance to the cell. The cells were also illuminated from below by a linearly polarised expanded beam of a low-power (~ 3 mW) 0.63-nm He – Ne laser.

Hydrodynamic motions of the NLC were observed on a PC display through an improved MBS-2 microscope equipped with a CCD camera. These motions were visualised by adding an Al powder (the size of particles was $\sim 2 - 3$ μm) with a weight concentration of $\sim 10^{-3}$ % to the NLC. The absorption coefficient of this complex at a wavelength of 1.06 μm was $\alpha \approx 10$ cm^{-1}. The velocity of the NLC hydrodynamic motions was determined as the velocity of powder particles.

When the sample was illuminated by laser radiation with a Gaussian intensity distribution, hydrodynamic motions were initiated and clearly observed on the PC display using the microscope. Under certain experimental conditions (depending on the incident-radiation intensity and NLC layer thickness), these motions formed a toroidal structure of convective motions. Toroidal convective motions resulted in a toroidal distribution of the NLC director, which was clearly seen in the polarisation microscope. The direction of the NLC director averaged over layer thickness and its distribution in the cell plane were determined qualitatively by the polarisation method using the probe radiation of the He – Ne laser.

Figure 2 shows the time evolution of the toroidal convection for a cell thickness $L \approx 1.15$ mm and an incident-radiation power $P \approx 2.31$ W. The photographs were taken with 2-s intervals after the exciting laser radiation was switched on. In this case, the following pattern of the developing convective NLC motions was observed: first, a thermocapillary surface wave was generated (Fig. 2a) and travelled over the NLC surface (this is discussed in Section 3), and a nucleus of a toroidal convective motion then appeared (Fig. 2b). Its dimensions increased with time to certain values depending on the NLC-layer thickness and the incident-radiation power (Figs 2c – 2f). A switching hydrodynamic wave (the black ring in Figs 2c – 2e) formed at the boundary between the region of the hydrodynamic motions and the rest of the NLC layer. Its velocity coincided with the rate of the increase in the radius of the toroidal-convection region.

Figure 3 shows the maximum radial velocity V_r^{max} of the toroidal switching wave as a function of the incident laser power at various NLC-layer thicknesses L. We see that V_r^{max} increases monotonically with the incident radiation power at comparatively large L (~ 1.3 mm). This monotonic behaviour is not observed at small L (< 1.1 mm), which is evidently caused by an abrupt decrease in the NLC-layer thickness at the centre of the incident laser beam due to a

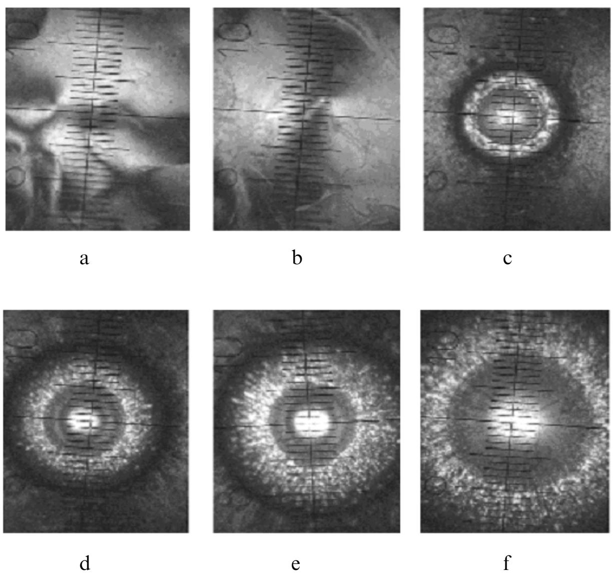

Figure 2. Time evolution of the toroidal convection for the NLC-layer thickness $L \approx 1.15$ mm and an incident-radiation power $P \approx 2.31$ W. Photographs are taken with 2-s intervals after switching the exciting laser radiation on.

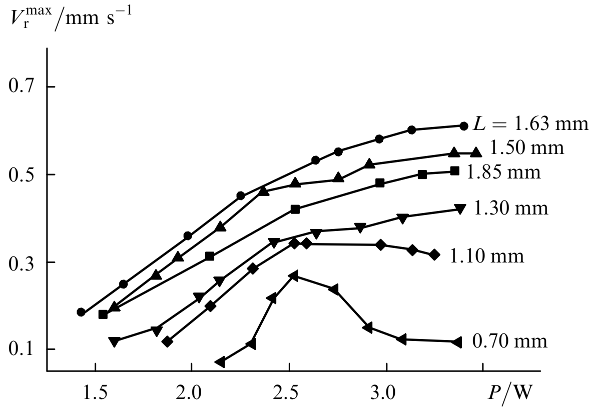

Figure 3. Radial velocity of the toroidal switching wave as a function of the incident laser-radiation power for various NLC-layer thicknesses.

temperature dependence of the surface-tension coefficient. Special test experiments have confirmed this assumption.

Some time ($\tau \sim 20 - 30$ s) after the incident laser beam is switched on, a steady-state regime of toroidal NLC convection establishes. The convective region has sharp regions determined by the given NLC-layer thickness and the incident laser power. Figures 4a and 4b show the diameter D of the steady-state convective toroid as a function of the incident laser power and the NLC-layer thickness.

The time-averaged maximum projection of the convective-motion velocity W_r^{max} on the horizontal plane was also measured in the experiment. Figure 5 shows W_r^{max} as a function of the incident laser power P at various NLC-layer thicknesses. At small L (< 0.7 mm), the monotony of these curves is disturbed, which, in view of the cause mentioned above, is evidently determined by a decrease in the NLC-layer thickness at $P \geqslant 2.8$ W. Here, the interaction of the NLC-surface molecules with the solid substrate may play a certain role. The cause of this behaviour of the function $W_r^{max}(L)$ at small L is not completely clear by now and requires additional experiments. In particular, a substantial progress in this direction may be achieved in experiments with various solid substrates.

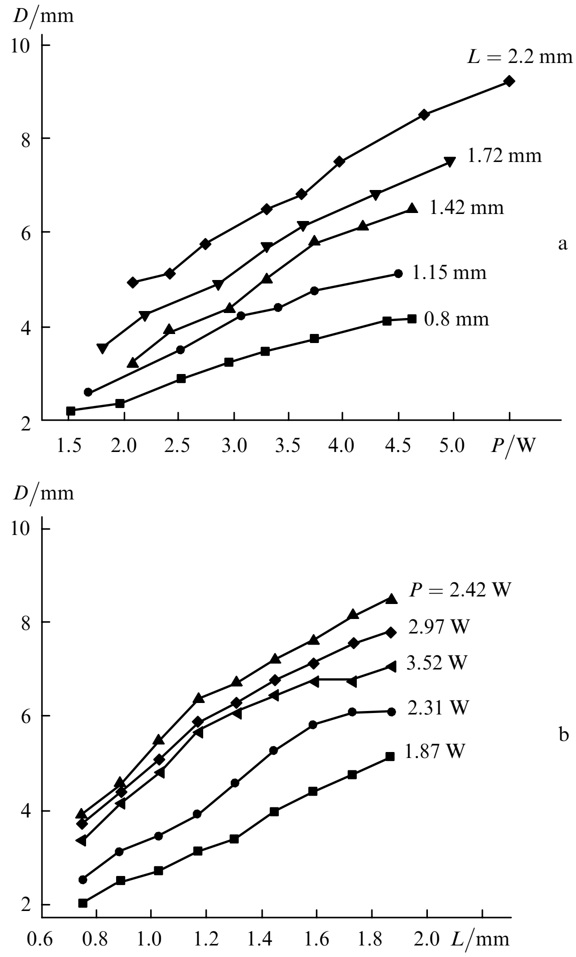

Figure 4. Diameter of a steady-state toroid as a function of (a) the incident-radiation power at various NLC-layer thicknesses and (b) the NLC-layer thickness at various incident-radiation powers.

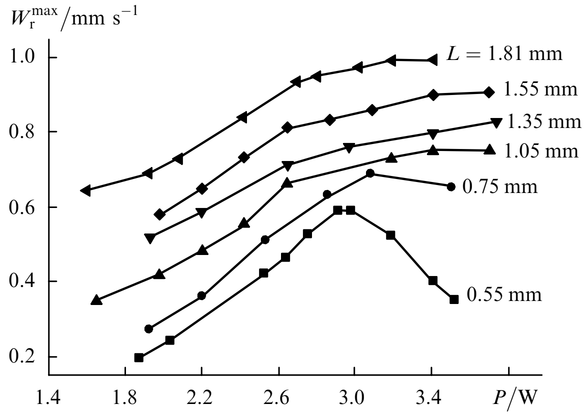

Figure 5. Time-averaged maximum projection of the velocity of convective motions as a function of the incident-radiation power at various NLC-layer thicknesses.

3. Observation of soliton-type surface hydrodynamic waves

In our experiment, the upper boundary of the NLC is open. Therefore, the NLC surface irradiated by an Nd^{3+} : YAG laser is deformed, first, due to the temperature dependence of the surface-tension coefficient and, second, due to the fact that the vertical velocity component at the free surface is nonzero for convective motions (see also Ref. [19]). To study experimentally the NLC-surface perturbation by a contactless method, a Fizeau-type laser interferometer was built. The measurement procedure is described in detail in Ref. [23].

When the sample was irradiated by a Gaussian beam from the Nd^{3+} : YAG laser, an interference pattern in the form of concentric rings of equal widths was observed in the field of view of the interferometer. Their centre coincided with the intensity maximum of the incident laser radiation. A complex deformation of the free NLC surface took place in the experiment. Immediately after the initiation of the exciting laser radiation, a depression corresponding to the intensity-distribution peak was formed within a time of $\sim 1-2$ s. However, a hill appeared at the centre of this depression, and the formation of a toroidal-convection nucleus was almost simultaneously observed. The maximum depression before the appearance of the nucleus was ~ 10 μm at an incident-laser power of ~ 3 W.

Synchronously with the NLC-surface deformation, a surface orientation wave was excited (a ring with an increasing radius and a radial distribution of the NLC director). This wave separated very soon (in $\sim 0.3-0.5$ s depending on the incident light power) from the region of the liquid heated nonuniformly by laser radiation. Figure 6a shows the time dependence of the surface-wave radius for an NLC-layer thickness $L \approx 1.5$ mm and various powers of the exciting laser radiation. The radius of the surface wave changes linearly with time at large radii, i.e., beyond the region of the nonuniformly heated NLC surface. This linearity is perturbed at small radii, i.e., in the initial period after the laser radiation is switched on. In our opinion, this is determined by the processes of the formation of a surface wave. Our studies show that, $\sim 0.5-1$ s later, the surface-wave velocity becomes virtually independent of both the time (the radius) and the power of the incident laser radiation and is determined exclusively by the NLC parameters. These facts indicate a soliton-like character of the surface orientation wave of the NLC director observed in our experiments.

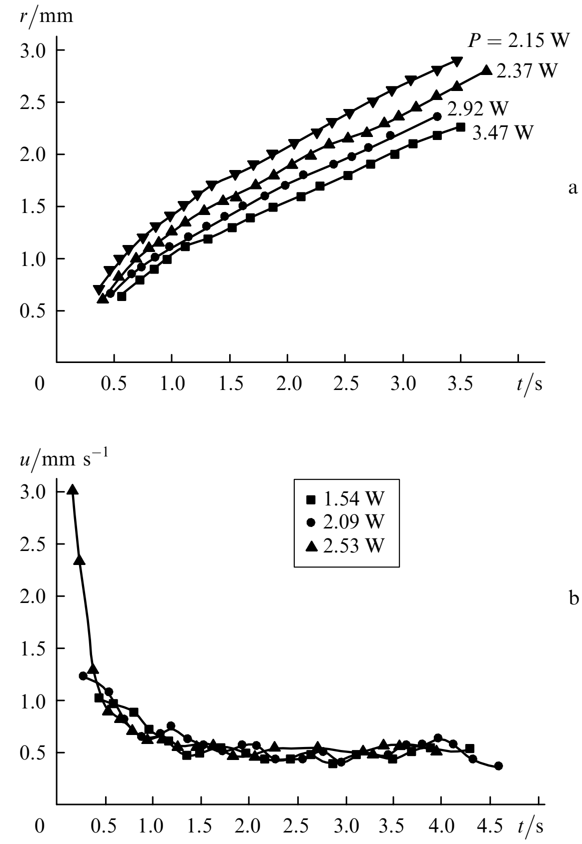

Figure 6. Time dependences of (a) the radius r and (b) velocity u of the surface wave at an NLC-layer thickness $L \approx 1.5$ mm.

4. Discussion and conclusions

In this study, the possibility of exciting toroidal convective motions and soliton-like surface orientation waves of the NLC director has been demonstrated. These effects are induced by a Gaussian laser beam. The physics of the phenomena observed is related to the appearance of a convective instability in a motionless liquid in which a temperature gradient is created. However, in contrast to the classical Rayleigh – Benard problem of the stability of a liquid layer of thickness L between two horizontal planes (the upper of them has a lower temperature than the bottom plane), our case has a number of peculiarities.

First, in addition to a vertical temperature change $(\partial T/\partial z)$ induced by the laser radiation transmitted through the medium $[I(z) = I(z=0)\exp(-\alpha z)]$, there is a horizontal change $(\partial T/\partial r)$ determined by the Gaussian beam profile $[I(r) = I(r=0)\exp(-r^2/a^2)]$.

Second, the establishment of the temperature regime in the system and, consequently, the parameters of transients are determined by a multiplex internal feedback. Apart from the standard mechanism related to the operating hydrodynamic streams, which execute an energy exchange between different layers of the medium, there are additional nonlinear mechanisms conditioned by interrelations between orientation – hydrodynamic and thermal effects induced by laser radiation. For example, this is an increase (decrease) in the heat release after reaching the instability threshold due to a positive (negative) absorption dichroism. Such effects evidently determine the complex character of the NLC-surface deformation.

It is also shown in this work that, when the NLC layer is irradiated by laser radiation with a Gaussian cross-sectional intensity distribution, a soliton-like director orientation wave is initiated on its free surface. Its velocity is determined solely by the NLC parameters. At thick NLC layers ($L \geqslant 0.5-0.6$ mm), the surface-wave velocity is independent of L. At thin NLC layers ($L \leqslant 0.5-0.4$ mm), the surface-wave velocity abruptly decreases with decreasing L. In our opinion, this effect is associated with the interaction of NLC surface molecules with the solid substrate.

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