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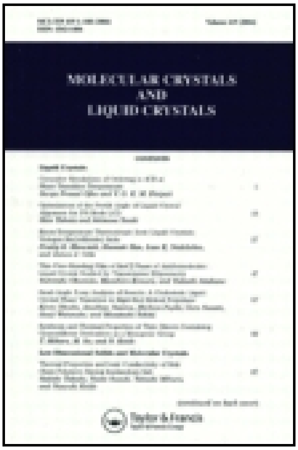

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
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Stimulation of Convective Motions and Hydrodynamic Orientational Surface Waves in Liquid Crystals by Laser Radiation with Gaussian Cross Distribution of Intensity

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Version of record first published: 18 Oct 2010

To cite this article: R. B. Alaverdyan, A. G. Arakelyan, R. S. Hakobyan, S. Ts. Nersisyan, K. M. Sarkisyan & Yu. S. Chilingaryan (2004): Stimulation of Convective Motions and Hydrodynamic Orientational Surface Waves in Liquid Crystals by Laser Radiation with Gaussian Cross Distribution of Intensity, Molecular Crystals and Liquid Crystals, 421:1, 261-269

To link to this article: http://dx.doi.org/10.1080/15421400490501888

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Mol. Cryst. Liq. Cryst., Vol. 421, pp. 261–269, 2004
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ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421400490501888

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STIMULATION OF CONVECTIVE MOTIONS AND HYDRODYNAMIC ORIENTATIONAL SURFACE WAVES IN LIQUID CRYSTALS BY LASER RADIATION WITH GAUSSIAN CROSS DISTRIBUTION OF INTENSITY

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It has been experimentally demonstrated the possibility of stimulation of convective motions with toroidal symmetry in the nonoriented nematic liquid crystal (NLC) cell with free surface. The cell is locally heated either from top or from bottom by gaussian laser radiation. Perturbation of free surface of NLC and hydrodynamic convective motion are conditioned mainly by horizontal thermal gradients. It has been demonstrated that in the zone of convection appears the radial distribution of NLC director orientation. At certain conditions of experiment, we have observed hydrodynamic orientational soliton like waves on the free surface of NLC.

Keywords: convection; laser influence; liquid crystals; orientational wave

1. INTRODUCTION

Processes of evolution of laser driven flow instabilities in liquids recently are on considerable attention. In particular, in references [1,2] absorbing liquid was in flat vessel, and heating was realized by focused argon laser beam, incident from bottom. Appearance of cellular structures is explained by instability of capillary waves into liquid layer, inhomogeneous heated by depth.

This research was made possible in part by the Award No AP2-2302-YE-02 of the U.S. Civilian Research & Development Foundation for the Independent States of the Former Soviet Union (CRDF).

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In classical Benard's studies of the convective instability [3] the bottom of the liquid sample was heated at a constant temperature, while the upper surface was in free contact with the ambient air. Benard found that the surface was depressed at the hotter areas, near the points of upwelling flow. However, other authors [4] later observed an opposite structure (that is, an elevation of the hotter regions) when the sample material was changed while keeping the same experimental setup. It was suggested [5], that the concavity of the surface may be determined by the competition between surface-tension and buoyancy-driven flows, and that the predominance of one or the other mechanism may be critically related to the depth of the vessel.

The perturbations of surface and relief formation are characteristic features of interaction between substance and powerful laser radiation; the high interest of these effects is conditioned by technological perspectives of their application. The use of laser radiation gives a possibility not only to achieve a heat absorbing with almost any desirable spatial distribution, but also to easily control the parameters of this distribution. For example, for the first time the possibility of termocapillary excitation of hydrodynamic motions by the laser beam was experimentally demonstrated in Refs [1,2,6], and the possibility of regular convective motion excitation in nematic liquid crystal (NLC) due to absorption of laser radiation with the spatially periodic intensity distribution was predicted earlier in [7]. It was also shown, that hydrodynamic flows cause reorientation of the director and, hence, modulation of the NLC permittivity. The exact theory describing the strong orientational-convectional-thermal nonlinearity predicted in [7] was given in [8]. The contribution of the above mentioned mechanism of optical nonlinearity in light self-focusing phenomena in NLC was observed for the first time in [9]. There the NLC cell was closed on both sides, so that convection was conditioned only by gravitational mechanism. In the paper [10] it was theoretically analyzed possibility of excitation of regular convective motions in isotropic liquid with the single free surface for the case when the liquid absorbs light with the spatially periodic structure of intensity distribution. Convection was conditioned by temperature dependence of the liquid surface tension (thermocapillary mechanism of Marangoni). Forced convection and light induced hydrodynamical reorientation of NLC molecules is investigated theoretically in [11]. In the same paper, the competition between the gravitational and thermocapillary mechanisms was discussed, and there were determined conditions, under which one of these mechanisms makes the main contribution to the convective motions. Experimental observation and theoretical investigation of gravitational and thermocapillary mechanisms of excitation of hydrodynamic convection in isotropic and anisotropic liquids, caused by absorption of light with the spatially periodic structure of intensity distribution are given in Ref. [12].

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When the travelling periodic structure of intensity distribution is produced, surface hydrodynamic waves are observed, which propagation velocity is equal to the travelling velocity of the periodic structure. The stability of convective cells and surface hydrodynamic waves are studied.

In this paper we have experimentally investigated the stimulation of hydrodynamic convections in nonoriented NLC layer with free (contacting with air) upper surface. They are caused by adsorption of laser radiation with Gaussian distribution of intensity. The thermal gradients created in cause of local heating generate perturbation of surface and toroidal convective motion, which causes the toroidal distribution of NLC director. At certain conditions of experiment, we have observed hydrodynamic orientational soliton like waves on the free surface of NLC. We have shown experimentally that the speed of wave propagation depends exceptionally on NLC parameters and is independent on power of laser radiation.

2. EXPERIMENTAL SETUP

In experiment, we used horizontally established cells of NLC 5CB (Fig. 1). The upper surface of cells was open and contacted with air. Temperature of air was 293 K. Temperature of the bottom of cell was kept constant (293 ÷ 0,3 K) using thermostat. Cells were established between crossed polarizers and illuminated either from bottom or from top by normally incident laser beam with Gaussian distribution of intensity. We used uninterrupted YAG:Nd^{3+} laser with wavelength $\lambda = 1.06\,\mu m$, width of 1.7 ± 0.1 mm on the half-height of intensity distribution. Cells were illuminated either from bottom or from top also with weak (~3 mWt), widened He–Ne laser radiation with linear polarization.

Hydrodynamic motions in NLC were observed on the display of personal computer by modernized microscope MBS-2, equipped by CCD camera. Visualization of hydrodynamic motions was performed by adding aluminum powder (size of particles $\sim 2 \div 3\,\mu m$) into NLC with concentration of $\sim 10^{-3}\%$ by weight. The optical absorption of this complex at wavelength $\lambda = 1.06\,\mu m$ was $\alpha \approx 10\,cm^{-1}$. The velocity of hydrodynamic motion of NLC was defined as velocity of the particles of powder.

3. EXPERIMENTAL RESULTS

In experiment, while the sample was illuminated from the top of the cell by laser radiation with Gaussian distribution of intensity, there were occurred hydrodynamic motions, which were observed on the display of personal computer. At certain conditions of experiment (depending on intensity of radiation and NLC layer thickness) these hydrodynamic motions formed

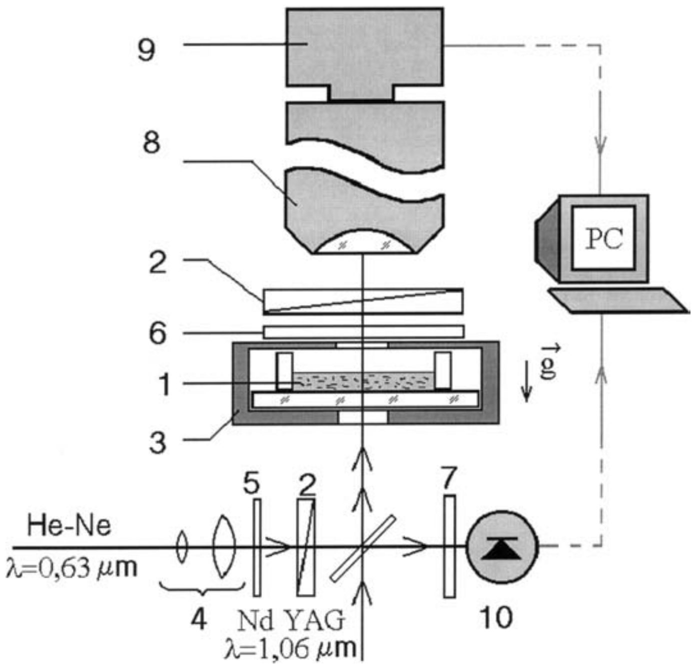

FIGURE 1 The experimental setup 1-a sell with liquid crystal; 2-polarizers; 3-thermostat; 4-telescopic expander of laser beam; 5-quarter-wave plate; 6,7-filters; 8-MBS type microscope; 9-CCD camera; 10-photodetector.

a toroidal structure of convection. The toroidal convective motions caused a toroidal distribution of NLC director, which we have seen in polarization microscope. The average by depth direction of NLC director was qualitatively determined by polarization method with help of probing beam of He–Ne laser.

When the laser radiation was turned on, we observed the following behavior of convective motion in NLC: at first a thermocapillary surface wave appeared, which propagated through surface of NLC (about this we shall mention in section 4). Then there was appeared an embryo of toroidal convective motion, which size increased to the value, which depends on thickness of NLC layer and power of incident radiation (see Fig. 2). Upon this, there was formed hydrodynamic wave of switching at the border separating hydrodynamic motions from the remaining part of NLC layer. The speed of switching wave was equal to the speed of increment of toroidal convection zone radius. The laser radiation power dependence of the maximal radial velocity of switching wave at several thicknesses of NLC layer is presented in Figure 3. As we can see in this figure, the maximal velocity of switching

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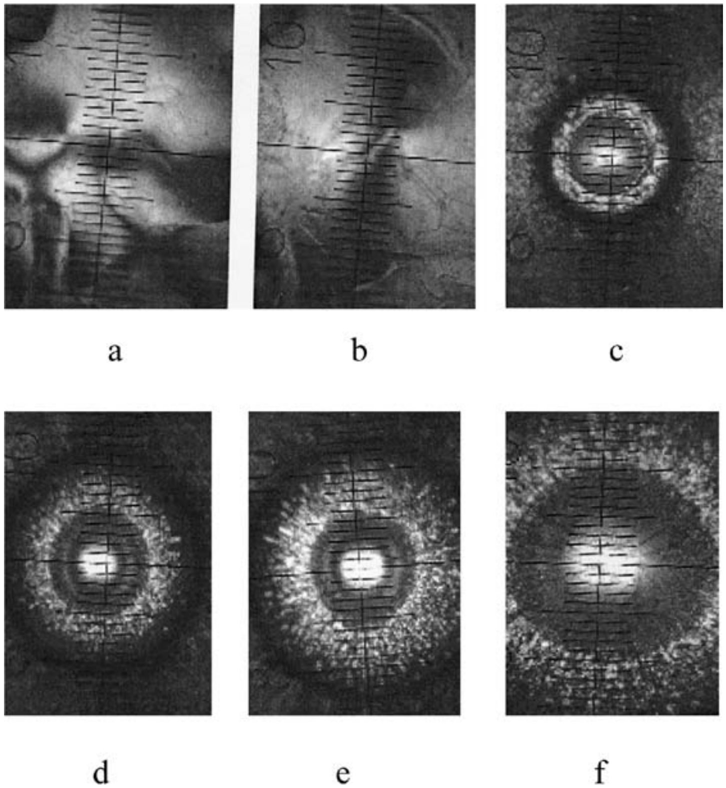

FIGURE 2 The temporal evolution of toroidal convection at NLC layer thickness L $\sim$ 1.15 mm and power of radiation P $\approx$ 2.31 Wt. The snapshots are written per every 2 s after turning on the laser radiation.

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wave increases monotonically with the power of radiation at relatively high values of NLC layer thickness (L $\sim$ 1.3 mm). This monotony is broken at low (L $\leq$ 1.1 mm) thickness of NLC layer, which, in our opinion, is conditioned by sharp decreasing of layer thickness at the center of incident beam in cause of temperature dependence of surface tension coefficient. Especially implemented testing experiments confirm this presumption.

After some time ($\tau \sim 20 \div 30$ s) from turning on the laser radiation, there is established stationary toroidal convection of NLC with sharp borders determined at given thickness of NLC layer and power of radiation. The laser radiation power and layer thickness dependence of established convective toroid diameter D are presented in Figure 4. At low values of laser radiation power (P $\sim$ 0.5 Wt) the diameter of convective toroid D $\sim$ 2L, which corresponds to the period of classical convection. When the power of laser

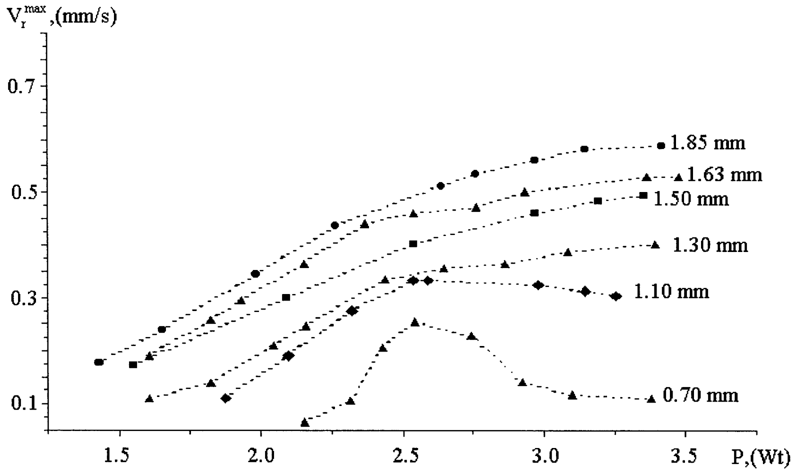

FIGURE 3 The laser radiation power dependence of the maximal radial velocity of switching wave at several thicknesses of NLC layer.

radiation is increased, the convection with "natural" diameter of toroid can't perform corresponding exchange of heating energy between heated and cool zones of NLC. As the result, the diameter of convective toroid increases, increasing the surface of heat exchanging.

In experiment, we have also measured the time-average maximum of convective motion velocity projection on horizontal plane W_r^{max}. The laser

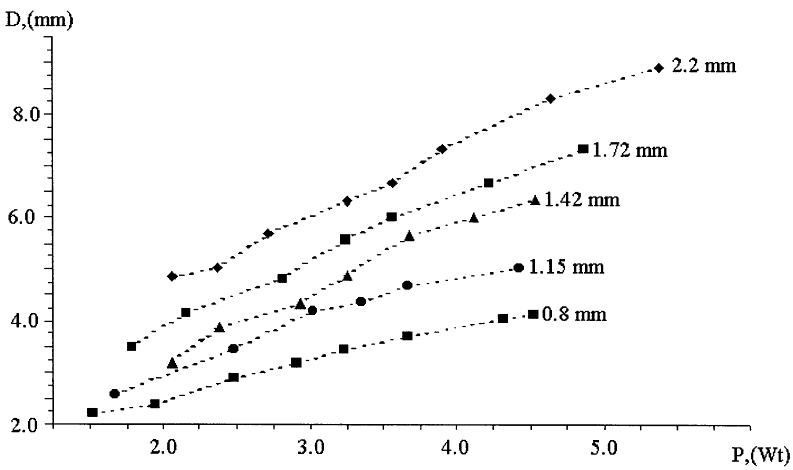

FIGURE 4 The dependence of established diameter of convective toroid, on the power of laser radiation at different values of cell thickness.

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radiation power dependence of W_r^{max} at several thicknesses of NLC layer is presented in Figure 5. At low ($L \leq 0{,}7\,mm$) thickness of NLC layer monotony of W_r^{max} dependence on radiation power is broken, which is, of the above mentioned reason, probably caused by decrement of layer at high power of radiation $P_{inc} \geq 2{,}8\,Wt$. There can have a certain role also the interaction between molecules of NLC bottom surface and hard substrate of cell. The mechanism of W_r^{max} (L) behavior at low L at present time completely is not known and needs more investigation. In particular, experiments with several substrates may give significant progress.

Qualitatively the same behavior of the convection parameters was observed when the sample was illuminated either from bottom or from top of the cell. That means convective motions are induced mainly by horizontal gradients of laser radiation and not by vertical temperature gradient (as in classical convection) due to the laser absorbance. Besides, laser absorbance was enough small to avoid of exceeding of vertical temperature gradient to its threshold value for classical convection.

4. OBSERVATION OF HYDRODYNAMIC ORIENTATIONAL SURFACE WAVES

In our experiment, the upper surface of NLC was open. So when the sample was illuminated by YAG:Nd^{3+} laser radiation, surface of NLC was deformed

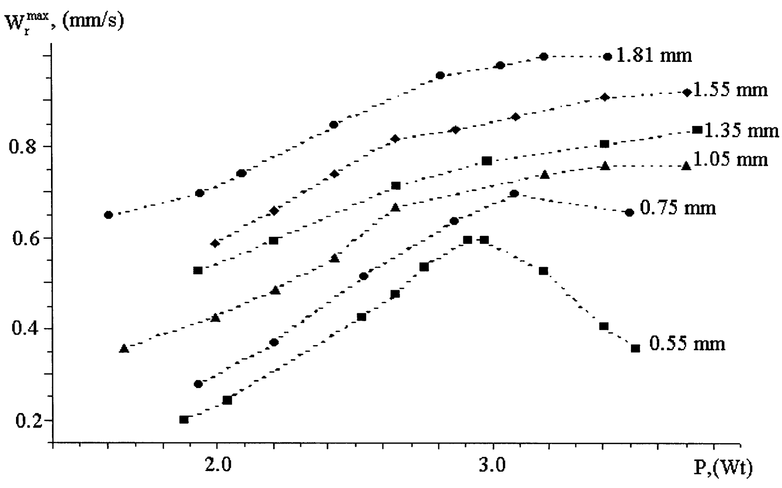

FIGURE 5 The laser radiation power dependence of the time-average maximum of convective motion velocity projection on horizontal plane at different values of NLC layer thickness.

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at first in cause of temperature dependence of surface tension coefficient, at second because the vertical component of convective motion's velocity wasn't equal to zero at the free surface (see also [12]).

For experimental investigation of NLC surface perturbation by noncontact method, we used the Fizo type laser interferometer. The technique of investigation is in detail described in our previous work [12]. Upon influence of radiation of YAG:Nd^{3+} laser with Gaussian distribution of intensity to the sample in the field of vision of interferometer appeared an interferention pattern like the concentric rings of equal thickness which center coincide with the center of laser beam. In experiment, a complex deformation of NLC free surface was observed. At initial moment after turning on laser radiation after $\sim 1 \div 2$ seconds there was formed a pit, corresponding to the maximum point of intensity distribution of laser radiation. However, at the center of this pit appeared an elevation and practically simultaneously a toroidal convection embryo forming was observed. Maximal depth of pit before appearing of the embryo was $\sim 10\,\mu\text{m}$ at power of radiation $\sim 3\,\text{Wt}$.

Simultaneously with deformation of NLC surface appears an orientational surface wave (a ring with increasing radius and radial distribution of NLC director), which is quickly (per $0.3 \div 0.5\,\text{s}$) separated from zone of liquid, inhomogeneous heated by laser radiation. The coordinate of surface wave depending on time changes linearly at high values of coordinate, i.e. out of zone of inhomogeneous heated surface of NLC. The linearity is breaking at low values of coordinate (i.e. at initial moment after turning on the laser radiation), which in our opinion is caused by processes of surface wave formation. As show our investigations (see Fig. 6) after the transient time (per $0.5 \div 1\,\text{s}$) the speed of surface wave is practically independent on time and power of incident laser radiation and is exceptionally determined by NLC parameters. This fact allows us to classify these waves as soliton like waves.

5. DISCUSSION AND CONCLUSIONS

So in the present paper experimentally have been demonstrated the possibility of excitation of toroidal convective motions and hydrodynamic orientational surface waves of NLC director. These effects are induced by laser radiation with Gaussian distribution of intensity. The mechanism of observed phenomena is related to occurrence of convective instability of steady liquid when into liquid a horizontal temperature gradient is created. In the present work, we have also shown, that in cause of influence of laser radiation with Gaussian distribution of intensity on the NLC surface appears a soliton like orientational wave of director, which speed of propagation depends exceptionally on NLC parameters and is independent on power of laser radiation. The speed of surface wave is also independent

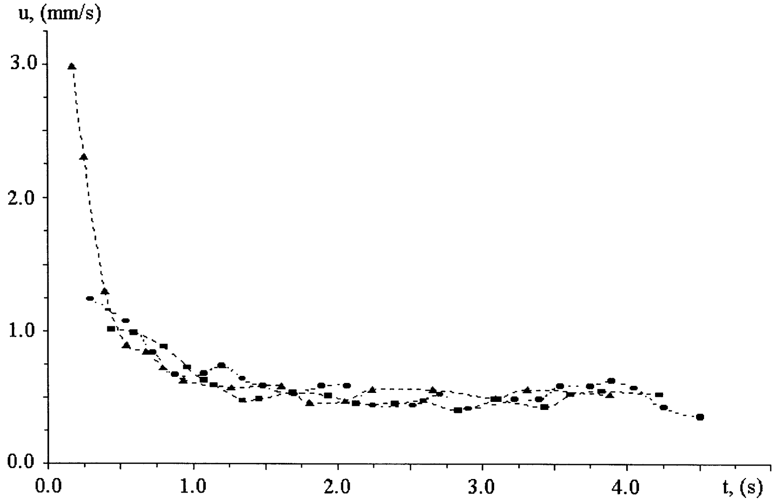

FIGURE 6 The dependence of velocity of surface wave on time at NLC layer thickness L ≈ 1.5 mm and power of laser radiation: ■-1.54 Wt, ●-2.09 Wt, ▲-2.53 Wt.

from thickness of layer at high thickness of layer (L≥0,5÷0,6 mm), and is sharply decreased at low thickness of layer of NLC (L≤0,5÷0,4 mm). Decreasing of speed at low L, in our opinion is caused by interaction between NLC molecules and the hard substrate of cell. These effects, seemingly, determine the complex character of NLC surface deformation.

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