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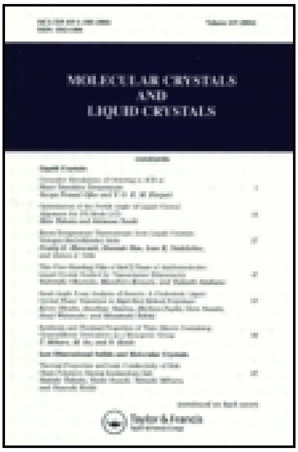

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

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I. Ilchishin [a], Eu. Tikhonov [a] & V. Belyakov [b]
[a] Institute of Physics, National Academy of Sciences, Kyiv, Ukraine
[b] L. D. Landau Institute for Theoretical Physics, Moscow, Russia

Version of record first published: 14 Jun 2011

To cite this article: I. Ilchishin, Eu. Tikhonov & V. Belyakov (2011): Effect of Optical Properties of Planar Texture on Some Lasing Characteristics Dye-Doped Cholesteric Liquid Crystals, Molecular Crystals and Liquid Crystals, 544:1, 178/[1166]-184/[1172]

To link to this article: http://dx.doi.org/10.1080/15421406.2011.569406

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Mol. Cryst. Liq. Cryst., Vol. 544: pp. 178/[1166]–184/[1172], 2011
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ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2011.569406

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Effect of Optical Properties of Planar Texture on Some Lasing Characteristics Dye-Doped Cholesteric Liquid Crystals

I. ILCHISHIN,[1] EU. TIKHONOV,[1] AND V. BELYAKOV[2]

[1]Institute of Physics, National Academy of Sciences, Kyiv, Ukraine
[2]L. D. Landau Institute for Theoretical Physics, Moscow, Russia

Effect of optical properties of a planar texture and its thickness on lasing spectrums and thresholds in dye-doped cholesteric liquid crystal (CLC) of steroid type is explored. Transition from the qualitative planar texture to the poor texture quality is accompanied by change of characteristic mode structures and by shift of barycentre in the long-wave side and the considerable growth of the lasing threshold. It is found that in the CLC texture created by substrates with perpendicular directions of orientation the stable single-mode lasing takes place. The obtained results show that in steroid CLC, unlike induced one, lasing spectrums could be described by the coupled wave model.

Keywords Cholesteric liquid crystal; distributed feedback laser; lasing spectra; lasing thresholds; phase defect; transmission

1. Introduction

In oscillation spectra of dye-doped CLC lasers the different values of an oscillation frequency relative to the selective reflection band (SRB) are experimentally registered. Even in the early work [1] it has been established that in CLC-materials with small birefringence what is the case as for the steroid CLC (cholesterol derivatives), the lasing spectrum is located close to the centre of the SRB and its characteristics can be explained within the limits of the coupled wave model for the medium with the refraction index space modulation [2]. The explanation of lasing spectra position in the case [1] is not correct in accordance with coupled wave model due to the extremely big coupling coefficient (big birefringence).

In this connection the authors of the publication [3] have advanced a hypothesis regarding the lasing spectrum location in the area of the CLC SRB edge by analogy with the predicted lasing spectrum location near the edge of the band gap for the photonic crystals [4]. Therefore the dye-doped CLC oscillation spectra and also their some other performances can be explained in terms of the photonic crystal model.

Address correspondence to I. Ilchishin, Institute of Physics, National Academy of Sciences, Nauky prosp. 46, 03028, Kyiv, Ukraine. Tel.: +38-044 5250929; Fax: +38-044 5251589; E-mail: lclas@iop.kiev.ua

According to this approach the location of the lasing spectrum close to the SRB center is connected with the photonic crystal defects and modes of the structured defects [5]. The analogous approach concerning the nature of the lasing spectrum determined by the defective structure modes is also used in the new theoretical model [6].

In connection with the our purpose the study was directed on revealing of the steroid type CLC optical quality on spectroscopic and threshold performances of lasing. Our purpose also included the determination of applicability of existing theoretical models to lasing behavior of CLC with small birefringence ($\Delta n \approx 0, 05$).

2. Samples and Experimental Set-Up

As the matrix of the CLC 3-component mixture of oleate, pelargonate and cholesterol chloride with temperature alteration of spiral pitch $\approx$3 nm/C° was used. CLC was doped with the benzanthrone or phenolenone dyes at weight concentration of 0.2–0.3%. The maximum of the SRB was chosen to be superimposed with a fluorescence maximum in spectral region of about 600 nm. The planar texture was produced by the known method of LC orientation with surface rubbing substrates and their additional shift along director as it was described in [7].

Optical pumping of the doped CLC was carried out by the second harmonic ($\lambda = 530$ nm) of a Q-switched Nd^{3+} laser operating in a slow pulse repetition rate mode with the pulse duration $\cong$20 ns. The second harmonic radiation focused by a lens with focal distance of 21 sm on the sample of doped CLC in a spot with a diameter $\approx$1.0 mm. A maximal power density of the second harmonic radiation was $\sim$27 MWt/sm^2 and attenuated by neutral filters. The lasing spectra of the dyed CLC corresponding to each pumping pulse were optically imaged in a focal plane of a spectrograph with an inverse dispersion 0.6 nm/mm and then displayed by the web camera on a PC monitor.

3. Results and Discussion

The lasing spectra and thresholds of the laser oscillation were studied with various thicknesses of the doped CLC and different techniques of a planar texture making. It was established that for optical quality planar texture from the point of view of spectroscopic parameters (half width of SRB in the range of 20–22 nm for used CLC mixture, 50% reflection in maximum of SRB for linear polarization of light, level of scattering outside of SRB in less than 1%), the lasing spectrum consists of 3 narrow lines matching to the lowest longitudinal modes of the DFB- laser at rather low lasing threshold ($\sim$60 kW/sm^2). The transmission spectra of a planar texture of the steroid CLC doped with the phenolenone dye No. 490 ($\approx$0,3% on weight, absorption peak 540 nm) are presented in Figure 1. Presence of SnO_2 transparent electrodes led to the noticeable improvement of the planar texture: the SRB narrows more than 10% in comparison with an analogous SRB for a texture with an orienting layer of polyimide lacquer (see Fig. 1, curve 2). Besides, the intensity of the Bragg diffraction maximum (see Fig. 1 curve 1) in the region of 600 nm is increased on 5–6%). The position of the lasing spectra (shown by the arrows in Fig. 1) demonstrates that in the case of better planar texture, the lasing spectrum barycentre practically coincides (difference $<$1 nm,) with the centre of the SRB. The texture quality decline in the case of SnO_2 layer absence can be seen in Figure 1 (curve 2) as shift of the lasing spectrum towards a right edge (red spectral shift) of the SRB.

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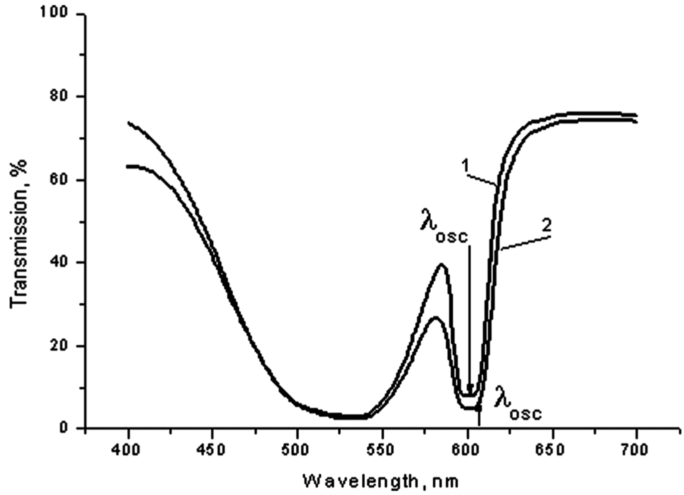

Figure 1. Transmission spectra of phenalenone dye in the mixture of CLC next composition: 40% cholesteryl oleate, 35% cholesteryl pelargonate and 25% cholesteryl chloride. 1 – glass substrates with SnO_2 and polyimide lacquer layers; 2 – glass substrates with polyimide lacquer layer. The layer thickness is 45 μm. Arrows positions of lasing spectra are indicated.

The lasing spectra of the dyed CLC sample which transmission spectrum is shown in Figure 1 (curve 1) as function of pumping power are presented in Figure 2. From the figure it is seen that for the more qualitative planar texture with a less halfwidth and greater diffraction reflection in its maximum the lasing spectrum is disposed in the centre of the SRB and characterized by the rather narrow lines (longitudinal modes). With the pumping power density increase the number of observable modes remains invariable up to region of sample destruction at pumping >430 $I_{thr.}$, where $I_{thr.}$ is a thresholds pumping power density at which lasing of doped

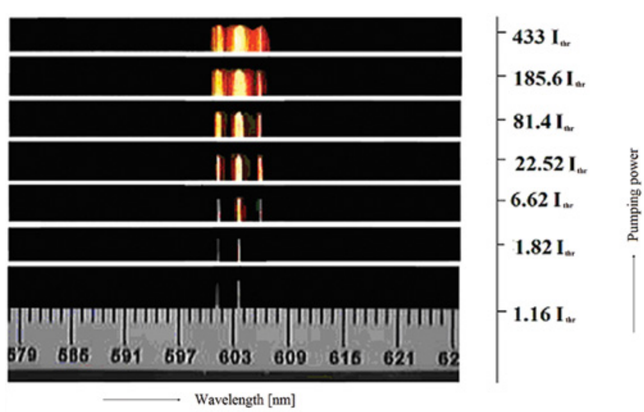

Figure 2. The lasing spectra as pumping intensity for a sample, that indicated on a Figure 1 with a layer SnO_2 on substrates (transmission spectrum 1). High mode selection is the number of longitudinal modes in a spectrum does not change with pumping increase. The layer thickness is 45 μm. (Figure appears in color online.)

CLC appears. Presence of only 3 modes in the lasing spectrum in a wide pumping range testifies the strong threshold mode selection and is agreed with the theory of the helical DFB- laser, developed in [8,9]. Meanwhile, lasing spectra of the CLC with strong birefringence are characterized by more than 3 modes as it was observed in [3].

The lasing spectrum for the sample which transmission is shown by curve 2 in Figure 1, is presented in Figure 3. Besides, the spectrum was shifted towards the long-wave side of the SRB; the deterioration of the planar texture has led to an essential broadening of a mode spectrum and the strong growth of the lasing threshold. Comparing the data presented in Figure 1, 2 and 3 we come to a conclusion that at almost equal absorption and the given pumping and thickness of the both samples (45 μm), the better optical quality planar texture with layer SnO_2 has the lasing threshold two orders of magnitude lower. Similar results are observed when the active film thickness changes within the limits (45–160) μm. For qualitative samples CLC with SnO_2 on substrates the thickness increasing leads to a gradual broadening of the lasing mode spectrum and moving the spectrum barycentre to the long-wave edge of its SRB.

Important results have been obtained in the case of textures CLC prepared by rubbing the orienting substrates in two crossly perpendicular directions (Fig. 4). In such textures, (it is seen in Fig. 5), there is a stronger threshold selection of modes so that the oscillation arises only due to the main mode excitation with the lowest threshold.

It is seen from Figure 5. that the pumping growth leads only to visible (hardware-based) broadening of this line, as well as in the case presented in Figure 2. The obtained data testifies an essential decrease (orders of magnitude) of the lasing linewidth in the case. More precise measurements as for the real line width using interferometer technique will be presented in a separate work elsewhere.

Possible explanation of above mentioned lasing behaviour is formation of a local "defect mode" due to a phase jump of the director orientation in a texture at the mismatched turn of oriented substrates. The following lasing behaviour based on the "defect mode" as a phase jump was described in [6] considered as a defect insertion of an isotropic layer into a perfect cholesteric structure. Main expressions of the work are directly applicable to our case of a phase jump of the cholesteric

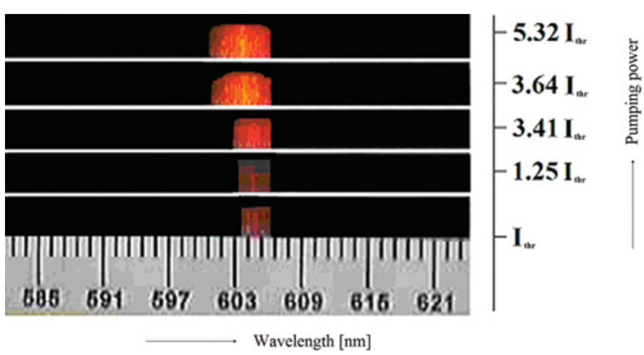

Figure 3. The lasing spectra as pumping intensity for sample, indicated on a Figure 1 without a layer SnO_2 on substrates (transmission spectrum 2 on Fig. 1). A mode structure disappears and lasing thresholds increases on two orders. The layer thickness is 45 μm. (Figure appears in color online.)

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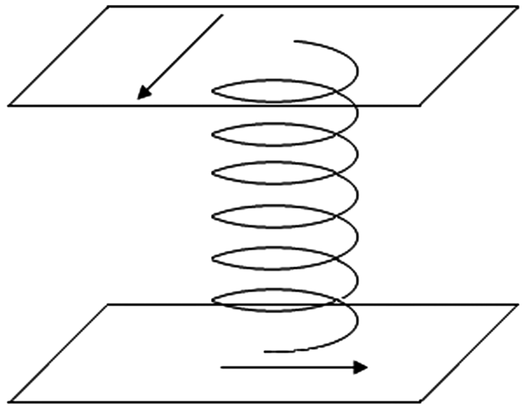

Figure 4. Scheme of CLC texture with crossed directions of rubbing on the different substrates. Arrows indicates directions of rubbing on substrates.

spiral if the factor "**kd**", where **k** is the wave vector and **d** is the inserted isotropic layer thickness, is substituted in the formulas given in [6] by $\Delta\boldsymbol{\varphi}$, as the phase jump of the director orientation of the cholesteric spiral.

The corresponding lasing threshold for the defect mode frequency at the centre of SRB reaches the lowest value for the phase jump angle $\Delta\boldsymbol{\varphi} = 90°$. To clarify the origin of the observed effect it is desirable to check some other theoretical predictions related to the defect modes, namely, the connection of the phase jump and position of the defect mode frequency inside the SRB. Rotation of the plate by an angle less than 90° in the experiment has to results in approaching the defect mode frequency (i.e., the lasing frequency) to the high frequency edge of SRB and, correspondently, the rotation of the plate by an angle larger than 90° results in approaching the defect mode frequency (i.e., the lasing frequency) to the low frequency edge of the SRB. In both cases (rotation angle <90° or >90°) the lasing threshold should be higher than for the rotation angle 90°. In the general case the value γ (lasing

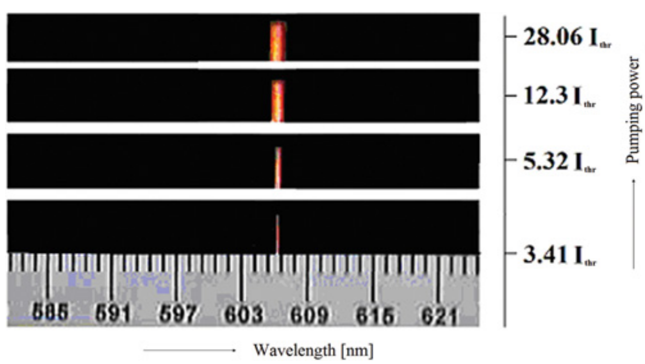

Figure 5. The lasing spectra as pumping intensity for a sample, indicated on a Figure 1 with turn on 90° one of orienting substrates. The layer thickness is 45 μm. The single mode lasing is saved up to the high levels of pumping, that results in destruction of sample. (Figure appears in color online.)

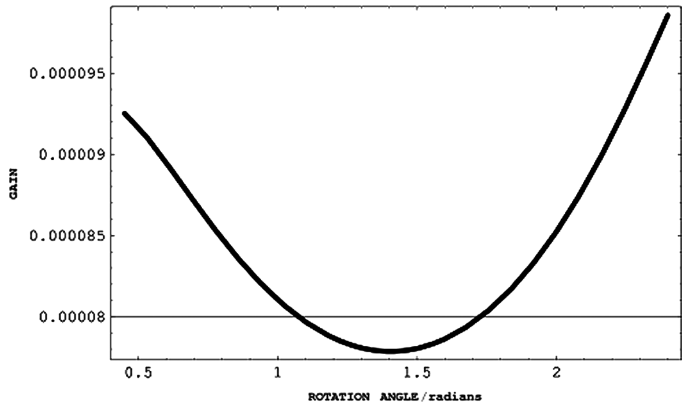

Figure 6. The dependence of lasing threshold γ on the plate rotation angle where the condition $|qL| \gg 1$ is fulfilled (calculation).

threshold value of the gain normalised by the light wave vector) has to be found by numerical approach. However for the case of thick cholesteric layers of thickness L (such that the condition $|qL| \gg 1$ is fullfieled, where $\mathbf{q} = \mathbf{k}\ \{1 + (\tau/2\kappa)^2 - [(\tau/\mathbf{k})^2 + \delta^2]^{1/2}\}^{1/2}$, $\boldsymbol{\delta}$ is the cholesteric dielectric anisotropy and $\boldsymbol{\tau} = \mathbf{4\pi/p}$, where $\mathbf{p}$ is the cholesteric pitch) an analytic expression for the dependence of γ on the plate rotation angle (the phase jump angle $\Delta\varphi$) may be found. The corresponding expression for the value of γ if $|qL| \gg 1$ at phase jump $\Delta\varphi = 90°$ is given by the following formula:

$$\gamma = -[\mathbf{4p}/(\mathbf{3\pi L})] \exp[-\mathbf{2\delta\pi\ L/p}] \tag{1}$$

The calculated dependence of lasing threshold γ on the plate rotation angle (the phase jump angle $\Delta\varphi$) in the angular range where the condition $|\mathbf{qL}| \gg 1$ is fulfilled is presented at Figure 6. The calculation results presented at the Figure 6 were obtained for the CLC layer thickness equal to 40 spiral half turns and $\boldsymbol{\delta} = 0.05$. We did not manage still to register an appropriate dip in SRB which existence is predicted by the theory [6] at generation with participation of the defective texture. Possible reason of failure – the typical method of sample transmission measuring which uses big squares of the sample while transmission dip can be connects with a small local region of sample.

4. Conclusions

1. In the lasing sample based on derivative cholesterol with small birefringence unlike induced CLC, the lasing spectrum is disposed nearby the centre of the SRB. The narrower the SRB (and than) the narrower the lasing lines, the nearer to the centre of the SRB the lasing lines are placed. It takes place at the use of substrates with SnO_2 layer. Use of substrates without SnO_2 layer results in broadening of SRB up to zero of diffraction reflection, disappearance of sharp linear mode structure in a lasing spectrum and its displacement to the right edge of the SRB.

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2. Similar displacement of lasing spectra from the centre of the SRB to its edge due to broadening of the SRB and decrease of diffraction reflection maximum is observed at the increase of sample thickness. It contradicts with possibility of explanation lasing on the centre of the SRB as lasing on "defect mode" and as unhinge-quality planar structure. At a such explanation lasing spectra with film thickness growth should be moved to the centre of the SRB.
3. Single mode lasing at the crossly oriented substrates can be related to the presence of phase jump in the spiral structure of CLC. Existing theoretical conception [6] allow to interpret the single mode lasing at the turn of orienting direction on one of substrates as display of imperfect mode lasing. A dip in the spectrum of selective reflection of CLC, which arises up concordantly [6] at presence of imperfect mode, by us while not discovered, possibly by reason of small area of sample ($3{,}5 \times 4\,\mathrm{mm}$) in which observed the single mode lasing of CLC and spectrum of SR it is needed to determine on the special equipment.
4. Descriptions of DFB-lasing in dye doped planar textures prepared on derivative cholesterol corresponds to theoretical models [2,8,9], and DFB-lasing – prepared on induced CLC has better correspondence with models [4,6].

Acknowledgment

This work was supported by the RFBR grant 11-02-90419-Ukr_f_a and by the SFFR grant F 40.2/066 (Ukr-Russ).

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