Properties of nematic LC planar and smoothly-irregular waveguide structures: research in the experiment and using computer modeling

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Abstract

Nematic liquid crystal planar and smoothly-irregular waveguide structures were studied experimentally and by the computer modeling. Two types of optical smoothly-irregular waveguide structures promising for application in telecommunications and control systems are studied by numerical simulation: liquid crystal waveguides and thin film solid generalized waveguide Luneburg lens. Study of the behavior of these waveguide structures where liquid crystal layer can be used to control the properties of the entire device, of course, promising, especially since such devices are also able to perform various sensory functions when changing some external parameters, accompanied by a change in a number of their properties. It can be of interest to researchers not only in the field of the integrated optics but also in some others areas: nano-photonics, optofluidics, telecommunications, and control systems. The dependences of the attenuation coefficient (optical losses) of waveguide modes and the effective sizes (correlation radii) of quasi-stationary irregularities of the liquid-crystal layers on the linear laser radiation polarization and on the presence of pulse-periodic electric field were experimentally observed. An estimate was made of the correlation radii of liquid-crystal waveguide quasi-stationary irregularities. The obtained results are undoubtedly important for further research of waveguide liquid crystal layers, both from the theoretical point of view, and practical – in the organization and carrying out new experimental researches, for example, when developing promising integrated-optical LC sensors.

Keywords: waveguide, planar lens, smoothly-irregular, liquid crystal, laser, director, irregularities, optofluidics, sensor, numerical simulation.

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Introduction

In this paper we presented the results of studying the integrated optical waveguides and thin-layer waveguide lenses based on the *nematic liquid crystal* (NLC) [1, 2], in particular, their behavior under the high-power pulsed-periodic electric field [3–8]. The study of the behavior of such combined structures when changing some external parameters, accompanied by a change in a number of their properties, is undoubtedly of interest to researchers not only from this subject area, since the appearance of new properties and characteristics may be of practical interest as in the integrated optics and also in other areas, e.g. in optofluidics, nano-photonics, telecommunications, monitoring systems of environmental state parameters, etc (see e.g. [1–13]).

Liquid crystals (LC) structure is a viscous fluid consisting of molecules of elongated or disk-like shape, definitely arranged in the entire volume of this liquid [1, 2]. The most characteristic property of liquid crystals is their ability to change the orientation of molecules under the influence of electric or magnetic fields, which opens up wide opportunities for their use in various fields of science, technology and industry, including integrated optics and integrated optoelectronics (see, e.g. [1–13]).

The progress of technology stimulates further interest to the development and improvement of integrated optical and fiber optical sensors and integrated processors, intended for the use in different fields of science, engineering, and industry, particularly, in promising telecommunication technologies and in different control systems (see, e.g. [5, 12–14]).

The basis of most of the electro- and magneto-optical effects specific for LC is the director's (the axis of the predominant direction of molecules of a macroscopic volume of matter) reorientation under the action of a field or a fluid flow. The result of reorientation is the change in the optical properties of the medium. This process of reorienting the director (local or taking place throughout the sample as a whole) can be traced in all electro- and magneto-optical effects. The NLC does not have a layered structure in the initial state; their molecules glide continuously in the direction of their long axes, rotating around them, but retain a long-range orientation order: the long axes are directed along one preferred direction.

One of the major stages of developing an optical integrated system is the analysis and synthesis of the optical components, necessary for its normal functioning, by means of computer modeling and computer-aided design with the usage of modern numerical methods (see, e.g. [15–27]).

1. Experimental setup. Waveguiding NLC structures

The objects of the study are the integrated optical waveguide (Fig. 1, 2) formed from NLC 4-Cyano-4'-

pentylbiphenyl (4-Cyano-4'-pentylbiphenyl or 5CB), well known from publications in the scientific and technical literature, as well as planar waveguide NLC lenses (Fig. 2).

In Fig. 1 is depicted: 1 is the laser polarized focused beam, 2 is LC layer, 3 is the LC cell, 4 is the metal (copper) electrodes, 5 is the LC cell retainer, 6 is the glass plate on which LC cell is fixed. Scattering in NLC waveguide radiation is registered in the camera situated above LC cell, and then the signal enters in the computer.

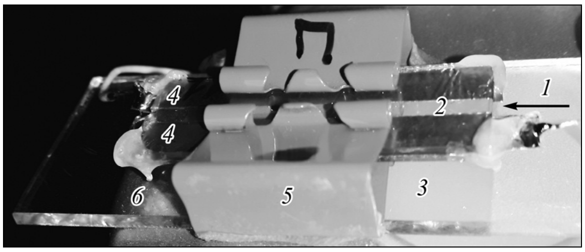

Fig. 1. Schematic representation of the experimental cell

(a)

(b)

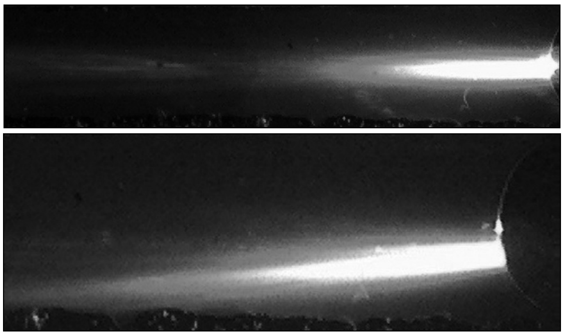

Fig. 2. Photograph of tracks of waveguide modes: (a) left and center of the photo – in the integrated optical NLC waveguide; at the right – planar NLC lens; (b) the focusing effect of a planar NLC lens when the incident beam is shifted to the left of the center. Dimensions on the areas shown in the photo in width are about 3 mm, and in length do not exceed 9–15 mm

In Fig. 2 on the right at the edge of the photograph is the planar NLC lens formed at the end of the waveguide. This lens performs the role both a matching and a focusing element. Immediately behind the NLC lens, one can clearly see the characteristic beam of radiation focused on it and the tracks of the modes. Lens dimensions: radius is 1.5 mm, thickness in the center was determined by the thickness of NLC waveguides (see below). As can be seen from the photos, the wide laser beam falling on the right is focused on a diffraction limited spot in the NLC waveguide layer.

2. Results of the study of NLC structures

In the experiments multimode NLC waveguides, formed by two glass plates and LC layer between them (Fig. 1), were studied. NLC had a homogeneous planar orientation with an optical axis along the direction of the director (coincides with the axis z).

Waveguides with different thicknesses (25, 75, and 125 μm) were studied in experiments, but the main part of the results is given only for NLC waveguides with $h = 25$ and 75 μm. Distance between copper electrodes was 0.2 cm. A high-voltage pulse (repetition frequency of 10 Hz) was applied to them. The NLC layer had refractive indices: ordinary ≈ 1.53 and extraordinary ≈ 1.70 (for the wavelength of laser radiation $\lambda \approx 0.64$ μm and temperature ≈ 25 °C). The glass plates had refractive indices: $n_1 = n_3 \approx 1.52$. Thus, in experiments and numerical calculations, three-layer symmetric waveguides with the following refractive indices were studied: $n_1 = n_3 \approx 1.52$, $n_2 \approx 1.53$. The input efficiency of the laser radiation into NLC waveguides did not exceed 35%.

The 3D "color" (grey scale) map surface of the dependence of the scattered laser radiation $I(z,y)$ for TE- and TM-polarization right after the NLC lens were also registered. The field E were switched off and then switched on. We plan to present these pictures after processing and analysis in one of our next work.

We considered the propagating and scattering of the guided modes on an extended bulk 3D NLC inhomogeneity (insert type) of the nonabsorbing or absorbing waveguide layer. The research three-layer waveguide was formed e.g. by two glass plates and the nematic liquid crystal layer between them (symmetric multimode NLC waveguide), or three-layer waveguide was formed by thin layer of the liquid crystal deposited on the glass substrate (asymmetric multimode NLC waveguide), i.e. in this case the LC waveguide lens was made before the planar waveguide face (see Fig. 1).

In order to quantify the optical losses in the waveguide, computer photometry of photographs of the corresponding mode tracks was carried out. To determine the optical losses α, we used the well-known expression:

$$I(z) = I_0 \exp(-\alpha z), \quad (1)$$

where $I(z)$ is the intensity of radiation (per unit area) at any point along the length of the waveguide, I_0 is the intensity at the distance $z = 0$ along the modes tracks, α was defined in cm^{-1}. Then optical losses were determined according to formula:

$$\alpha = \frac{1}{z} \ln\left(\frac{I_0}{I(z)}\right), \quad (2)$$

where $z \approx 0.3 \div 0.5$ cm.

Let's give an example of the results of computer processing of data for some of the researched multimode NLC waveguides both for TE and TM-polarization (see Fig. 3, Fig. 4, Fig. 5, and Fig. 7).

TE-polarization, $h = 75$ μm, without the external electric field E: $\bar{\alpha}_{TE} = 4.5$ cm^{-1}, $r_{TE} \approx 0.15 \div 0.6$ μm; with the field E: $\bar{\alpha}_{TE} = 3$ cm^{-1}, $r_{TE} \approx 0.1 \div 0.4$ μm.

TM-polarization (see Fig. 3), $h = 75$ μm, without the field E: $\bar{\alpha}_{TM} = 6$ cm^{-1}, $r_{TM} \approx 1.0 \div 1.8$ μm; with the field E: $\bar{\alpha}_{TM} = 5$ cm^{-1}, $r_{TM} \approx 0.5 \div 1.5$ μm. Here r_{TE} and r_{TM} are r_{ef} for each polarization (see formula (3)).

For NLC waveguide with $h = 25$ μm similar results were obtained, which allowed us to assume that the multimode NLC waveguides under study are of the same type and we can consider the results mainly for some of them, for example, for NLC waveguide with $h = 75$ μm. In cases where the need arises, we will specifically note these different types of multimode NLC waveguides.

The size of the NLC irregularities was estimated in accordance with the Rayleigh criterion. Having determined the losses α of the optical power in the NLC waveguide in accordance with formula (2), it is possible to estimate the effective size r_{ef} of the irregularities of the LC layer in accordance with the approximate formula [4]:

$$r_{ef} \approx \lambda\left(\alpha h_{ef}\right)^{1/2} C\left(\theta\right), \qquad (3)$$

where $C(\theta)$ is the dimensionless correction factor.

We used formula (3) to obtain estimates for a number of NLC waveguides in accordance with the Rayleigh criterion, showed that the dimensions of irregularities in the NLC layer vary in the range from about 0.08 to 2.00 μm, and the error in the determination does not exceed 15–20 %.

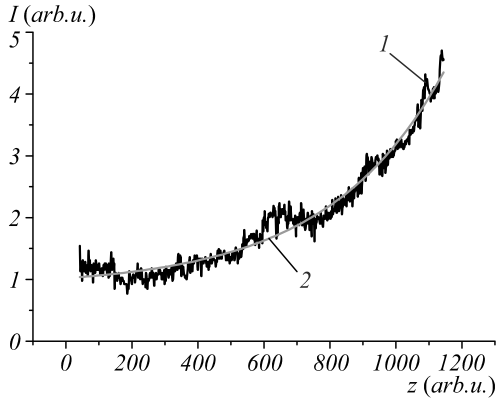

Fig. 3. Dependence of the intensity I of the scattered laser radiation on the coordinate z (1 arb.u.≈3.5 μm) with the field E switched on. TM-polarization. The numbers denote: 1 is the experimental curve, 2 is the fitting exponential curve

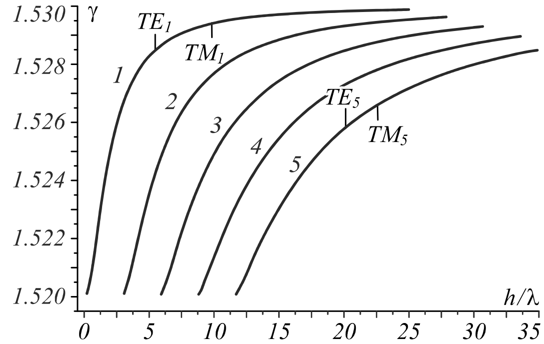

Fig. 4. Dispersion relations for the first five TE and TM modes of NLC waveguide; γ is the effective refractive index of nematic liquid crystal waveguide

It is important to note that the maximum values of the attenuation coefficient in some liquid-crystal waveguides reached values of about 10 cm^{-1} and more. The waveguide sections with such large losses were not studied in detail.

To explain the established patterns of light scattering in the NLC waveguides, fluctuations in the local orientation of LC molecules were considered [1–4]. Fluctuations of the director are accompanied by elastic deformation of the medium, which leads to local random changes in the optical properties of the medium, which cause the scattering of light. In this case, the correlation radius for the director fluctuations depends inversely on the magnitude of the applied field [1].

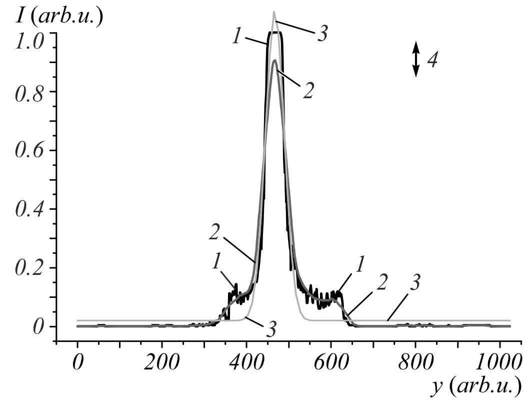

Fig. 5. The intensity profile of laser radiation behind the planar NLC lens. $\Delta I_{0.7} \le 50\lambda$

The known laws governing the scattering of light in a non-waveguide case are explained on the basis of the consideration of fluctuations in the local orientation of the molecules, i.e. director of NLC. As a result, the *radius of correlations* ξ of the director fluctuations can be calculated, which shows the distance at which the order given by the wall (the waveguide substrate) is stored, for example, when the field E is applied (the bigger the field, the order is preserved at a smaller distance from the wall) (see e.g. [3, 4]). It can be put in correspondence with the found correlation radius of the irregularities of the NLC waveguide.

Let us compare the regularity of the change in the radius of correlations of the director fluctuations $\xi \propto E^{-1}$ with the results obtained by us for changing the correlation radius of the irregularities of the NLC waveguide without the field and with the field: the correlation radius when the external field is switched on decreases for both types of modes.

This indicates a good agreement between our results and the classical theory of director fluctuations in LC [1, 3, 4]. Thus, the obtained estimate confirms the correctness of the experimental dependences found by us. Since

$$I\left(z\right) \propto \exp\left(-\alpha z\right) \propto \exp\left(-r_{ef} z\right),$$

then, as the correlation radius decreases, increases I and the damping coefficient α decrease, which was discovered in the experiments.

The use of the phenomenon of waveguide scattering made it possible to substantially increase the resolution by the correlation radii in comparison with the classical methods such as the optical microscopy. In addition, the waveguide method made it possible to obtain statistical information on waveguide irregularities in one measurement with a sufficiently large volume of the waveguide layer.

The advantage of this method is also the possibility of investigating waveguide irregularities in a wide range of changes in their lateral dimensions, including the size of the order of the wavelength of the probing radiation, as in the Mie's scattering theory (see e.g. [14–23]).

In the further research we plan to use in the numeric analysis the analytic solutions of the problem of waveguide propagation, transforming and scattering of electromagnetic monochromatic radiation in an irregular 3D integrated-optical waveguide that we obtained previously (see e.g. [17–27]).

Fig. 5 shows one of the radiation intensity profiles measured near the back focal plane of one of the studied planar NLC lenses (curve 1). In Fig. 5 are also indicated: 2 is the curve obtained by smoothing the original distribution 1; 3 is the fitting Gaussian curve; 4 is the error (less than 7 %).

The half-width of the distributions of type 1 in the vicinity of the focal plane, measured at the 0.5 level of its maximum (i.e. $\Delta I_{0.5}$), reached (10–45) λ, which is apparently caused by aperture restriction (small numeric aperture NA of the researched LC lenses) and also due to the fact that multimode (14 or more modes, see Fig. 4) LC waveguides were investigated [3–5].

We have compared also our measured half-width $\Delta I_{0.5}(y)$ with the half-width intensity profile at the focal distance, including the theoretical diffraction limited spot, given in the paper [9], which has a certain meaning in our case.

We can draw a conclusion, that, on the one hand, these sizes $\Delta I_{0.5}$ are close enough, and on the other hand, both of them in several times (> 3–6) more than the theoretical diffraction limited spot δ [28–30]:

$$\delta = 0.61\frac{\lambda}{NA}, \quad (4)$$

where numeric aperture $NA < 1$.

The estimation of the focal length of the studied liquid-crystal lenses has shown that it is approximately in the range from $2R$ to $8R$, where R is the radius of the studied planar and smoothly-irregular LC lens. The results of the preliminary study did not allow making unambiguous conclusions about the effect of the linear polarization of laser radiation and the external pulse-periodic electric field on the parameters of the planar and smoothly-irregular NLC lenses under investigation. At the same time, it was unequivocally concluded that this influence is obvious and further research is needed in this direction.

In [27] one can see the plots of three-dimensional synthesized thickness profile $h(y,z)$ of the Luneburg thin-layer waveguide solid lens.

The studied Luneburg lens has the following structure: it is fabricated on a silicon substrate (SiO_2), coated with the first (regular) waveguide layer (the Corning 7059 glass), over which the second waveguide layer (Ta_2O_5) having the variable thickness $h(y,z)$ was applied. The covering layer was air. At this stage of the research, we have not numerically studied such Luneburg NLC lens, since it is very difficult to made it experimentally. Therefore, we have mentioned this profile to show how a profile similar to it will look like in the case of the smoothly-irregular LC lenses.

We should note that this solid Luneburg lens with the profile depicted e.g. in [27] (focal length $F = 7.5$ mm and $R = 5$ mm) executes the necessary amplitude-phase transformation with superresolution, exceeding the classical diffraction limit δ defined in the formula (4) (see e.g. [20, 26, 27]), because

$$\Delta I_{0.5} = \left|\mathrm{Re}\left(\mathbf{E}\right)\right|^2 < 0.5\lambda .$$

The thin-film waveguide generalized Luneberg lens is a three-layer regular waveguide on which an additional (fourth) waveguide layer (with refractive index n_4) of varying thickness $h(r)$ is applied, cylindrically distributed in a circle of radius R ($r \in [0, R]$). At the same time, an additional waveguide layer ensures the distribution of the effective refractive index of waveguide $\gamma(r)$, which is satisfies outside the radius R the next equation [20, 26, 27]:

$$\gamma(r)/\gamma = \exp\left[\omega(\rho, F)\right], \quad (5)$$

where

$$\rho = r\frac{\gamma(r)}{\gamma},\ \omega(\rho, F) = \frac{1}{\pi}\int_{\rho}^{1}\frac{\arcsin\left(x/F\right)}{\left(x^2-\rho^2\right)^{1/2}}\mathrm{d}x .$$

Thus, the focusing effect of the generalized Luneberg lens (5) is not achieved due to the gradient of the refractive index of the lens material, as in conventional volumetric Luneberg lenses, but by changing the thickness $h(r)$, which is accompanied by a corresponding change in the effective refractive index $\gamma(r)$, while $n_4 = \text{const}$. That is why waveguide generalized Luneberg lens was chosen as the object of comparison with NLC lenses.

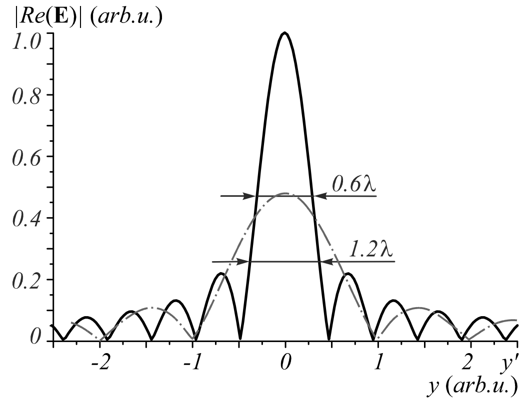

Fig. 6. Distribution of the electric field in the focal plane of the Luneburg waveguide lens presented on the Fig. 7. The solid line corresponds to accounting for 99% of the lens aperture, and the dot-dash line corresponds to 60% of the lens aperture; y′=y/λ

We have numerically simulated propagation of eigenmodes through a Luneburg waveguide lens within the previously obtained analytical solution of the vector electrodynamic problem for a smoothly irregular four-layer 3D integrated-optical waveguide. The programmes for numerical solution were developed in Maple and Delphi [3–5, 19, 20, 25–27]. The corresponding dispersion relation has been calculated, in particular, taking into account the shift of the propagation constants of hybrid modes. The vertical distribution of the electromagnetic field of a smoothly deformed mode in a Luneburg waveguide lens has been constructed.

A full-aperture Luneburg waveguide lens has been synthesized in the zero-order vector approximation. The methods considered here make it possible to perform (in the design stage) high-precision computer analysis of all features of operation of complex multilayer smoothly irregular integrated optical 3D elements of the Luneburg waveguide lens type that are most important for experimenters. An undoubted advantage of the theoretical description, methods, and algorithms is that they can be generalized to smoothly irregular integral 3D structures composed of layers of dielectric or magnetic materials, materials with nonlinear properties, or metamaterials (see e.g. [19, 20, 25–27, 35–37].

One and two-dimensional model of Frederiks effect were used for the investigation of the electric field effect on nematic liquid crystal director orientation (see Fig. 7) in the side-electrode cell that helped us to understand the behavior of NLC (see e.g. [4, 6–8, 31]). The solutions were obtained by the standard finite-difference methods. The programmes for numerical solution of two-dimensional parabolic partial differential equation were developed both in FORTRAN, and C/C++ [4–8].

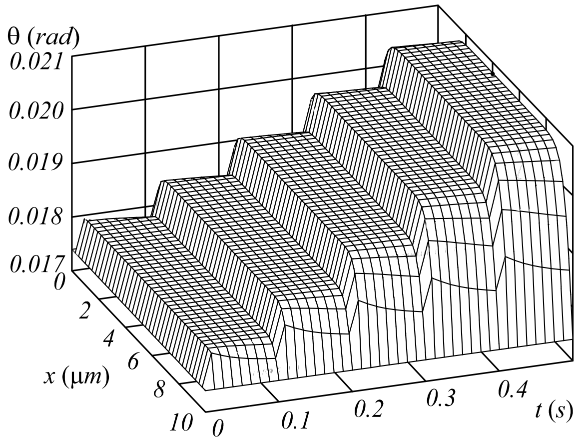

Fig. 7. 3D-dynamics of the profile Θ

As one example of the computer modeling one can see on the Fig. 7 3D-dynamics of the angle $\Theta(x;t)$ for the first 5 impulses of the external pulsed-periodic electric field $E(t)$ (pulse repetition period $T = 0.1$ s), where Θ is the deformation angle of the director (local molecular orientation) in the NLC waveguide sell (see e.g. [3–7]). While there is a characteristic “accumulation effect”:

$$\Theta_{t\to\infty} \to \Theta_{\max} < 86^\circ .$$

The results of the calculations were compared to the experiments and in most cases a good match was obtained (see e.g. [3–8, 31]). Details are beyond the scope of this work. Specific details of the results of the research of Frederiks phenomenon can be found in [1–8, 31].

Conclusion

Nematic liquid crystal waveguiding structures were researched by the numeric simulation and experimentally. The dependence of the attenuation coefficient of the waveguide modes and the sizes of the quasi-stationary irregularities of the liquid-crystal layer on the linear polarization of the incident laser radiation and the presence of a pulse-periodic electric field is experimentally observed. An estimate is made of the correlation radii of liquid-crystal waveguide irregularities. The observed decrease in the damping coefficient of the waveguide modes and the dimensions of irregularities in the liquid-crystal layer, when the external field is switched on, explained by the effect of a decrease in the fluctuations correlation radius of the local orientation of the molecules of the liquid crystal. We have also to emphasize that the non-stationary NLC waveguide structures under study exhibited occurrence of many mode tracks whose damping coefficient (and, correspondingly, track brightness) fluctuated with time, resulting in temporal variations in their parameters which creates certain difficulties in carrying out.

The significance of these studies is provided by the practical use and prospects of using liquid crystal materials in various modern integrated-optical devices, for example, in coupling elements, modulators, distributed Bragg reflectors, sensors, processors, etc (see e.g. [3–5, 10–13, 32–38]).

The results obtained are important for further investigation of dynamic processes inside non stationary waveguide liquid crystal layers, both from the theoretical point of view for understanding kinetic processes in the liquid crystals, and practical – in the organization and carrying out appropriate experimental and theoretical researches in the field of the optofluidics and waveguiding optics.

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