

Figure 6. Smectic film containing inclusions of nematic droplets with a single point defect (S = -1) (a) and two topological defects (S = -1/2) (b) at the inclusion surface. Horizontal size of the photos is 680 µm. The orientation of the **c**-director far from the inclusions (in the vertical direction) is uniform. At the droplet boundaries, the **c**-director is oriented parallel to them.

imposes constraints on the deformation of the molecular ordering field in the film. The placement of a particle in the film or its birth in the film (for example, as a liquid drop during film heating) gives rise, close to it or on its surface, to a topological defect or defects with the total topological charge S = -1 [22]. The particle and the associated topological defect (defects) make up a topological dipole (quadrupole).

Figure 6 presents a photograph of particles in the film of Sm C liquid crystal with the planarly oriented **c**-director at the particle boundaries. Particle 'a' has one point topological defect with the strength S = -1 on the left-hand side of the film-particle interface. Particle 'b' has two point topological defects of the strength S = -1/2 at its upper and lower boundaries. The total topological charge of each particle equals zero. Particle 'a' constitutes a topological dipole, particle 'b' makes up a topological quadrupole. The configuration of the molecular ordering field near the particles and interparticle interactions may be described using an electromagnetic analogy [22]. The orientation of a c-director in a film, described by the solution of the Laplace equation $\Delta \varphi = 0$, may be represented in the form of summarized deformations φ_i created by real (physical) and virtual topological defects. Attraction between dipole-type particles (a) leads to the formation of linear chains from particles with the dipole moment parallel to the chain [23, 24]. More complicated structures are formed from particles 'b' with quadrupole-quadrupole interactions. The particles are arranged so as to minimize the elastic strain energy of the cdirector field. For particles with quadrupole symmetry, four directions (light zones in Fig. 6b) correspond to the energy minimum. Formation of branched chains, clusters or translationally ordered structures was found in experiment [25, 26]. The actual task is to employ self-organization for obtaining structures of various types from micro- and nanoparticles, as well as their rearrangement with the use of external electric and magnetic fields or light-induced effects.

On-going studies of thin smectic films cover a broad spectrum of problems pertaining to different areas of condensed state physics (physics of thin films, surface, lowdimensional 2D and 1D systems, etc.). Further still many studies are currently practicable only on smectic films because ultrathin inorganic films of comparable quality are unavailable. As far as liquid crystals are concerned, studies of thin films have become an important area of investigation into new liquid crystalline materials. Moreover, the structures of many materials were only elucidated in the studies of freely suspended thin films.

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Electrooptics and photonics of liquid crystals

S P Palto

1. Introduction

This report is designed to briefly discuss some promising areas of research concerned with the electrooptics and photonics of nematic liquid crystals with special reference to the effects of bistable switching and lasing effect in chiral nematics.

The physics of liquid crystals (LCs) has been intensively developed in the last half century to provide a basis for their extensive practical application in a variety of electrooptical devices and high-tech products, such as information display systems and flat TV screens. It is worthwhile to note that the progress in LC science has been supported by major achievements in other areas of research. Most noteworthy are the development of mathematical models of the liquid-crystal state (first and foremost, the Frank–Oseen theory of elasticity [1, 2] and Leslie's nematic phase hydrodynamics [3]), the description of the structure and properties of various liquid-crystal phases based on symmetry considerations [4], and the synthesis of a huge number of new chemical compounds existing in the liquid-crystal state (Merck in Germany, Roche in Switzerland, BDH in UK, NIOPiK in Russia, along with many other companies world-wide). These achievements have been used by experimental physics to discover and explain a host of new physical effects.

The present report does not pretend to comprehensively review recent progress in liquid crystal optics and electrooptics, for which the reader is referred to monographs [5, 6]. It is confined to the discussion of selected research in electrooptics and photonics of nematic liquid crystals that comprise but a small number of on-going studies believed to be especially successful and that arouse the greatest interest. This communication presents a brief review of results reported by different research groups, including those obtained at the Laboratory of Liquid Crystals, Institute of Crystallography, RAS (Moscow) with which I am affiliated. To begin with, it is worth mentioning a variety of recently found and investigated modes of bistable switching in dual-frequency nematic liquid crystals [7]. Such switching exhibits a very beautiful electrooptical effect. The multistable and bistable states that can be switched over by short electrical pulses are interesting not only from the physical point of view but also due to the possibility of their application for the creation of new types of displays with the properties of 'electronic paper' [8]. Such devices have an advantage of markedly reduced energy consumption that is needed only for switching between different states and is not required to maintain one state or another. Moreover, the threshold nature of the switching removes constraints on the number of addressed elements in matrix displays, which do not have active elements (thinfilm transistors).

Unfortunately, some interesting data on photooriented space-periodic liquid-crystal structures [9] have to be omitted in this brief report. The diffraction of light on such spatially periodic structures proves to be very sensitive to its polarization state and may be governed by an external electric field. Such structures are promising for the construction of polarization devices and for studying new laser effects in liquid crystals.

Effects discussed in this report are illustrated by the results of numerical simulation. I have obtained them with the aid of specially developed computer software. The reliability of such simulation was confirmed in our laboratory and by a number of research groups abroad. For example, the effect of bistable dual-frequency switching to be considered below had been computed (predicted) before it was exposed in experiment. Its subsequent thorough examination confirmed the results of simulation.

In what follows, only nematic liquid crystals are considered. The optics and electrooptics of ferroelectric liquid crystals is beyond the scope of this communication, although interesting results have been obtained in these fields, too [10-12].

2. Certain important definitions

and properties of nematic liquid crystals

Here are some of the main definitions necessary to make the problems under discussion more understandable to researchers working in fields other than that bound up with LC. Molecules that form liquid crystal phases in a certain temperature range (thermotropic liquid crystals) have a disk-like or, as a rule, rod-like shape responsible for the anisotropy of their physical properties. The nematic phase is only characterized by the molecular orientation ordering (Fig. 1a). Nematics are devoid of the translational periodicity intrinsic in solid crystals. A separate group of nematics is constituted by chiral nematics (cholesteric liquid crystals or nematics doped with chiral additives). Nematics and cholesteric liquid crystals are not different in terms of local molecular ordering. However, chiral nematics may have a distinguished direction along which the helicoidal distribu-



Figure 1. Example of the molecular formula for a classical liquid crystal (MMBA). Schematics of the molecular distribution in the nematic phase (a), helicoidal distribution of the director field in cholesterics (b), and three types of deformation of the director field [(c) splay, (d) bend, and (e) twist]. The local preferred direction of molecular orientation is characterized by the director \mathbf{n} depicted as a cylinder.

tion of molecules forms with a spatial period P_0 called the 'natural pitch of helix' (Fig. 1b).

The local orientational state of molecules in nematics is described by a single unit vector **n** called the 'director'. The director given at a certain point in space not only determines the preferred direction of molecular axes orientation in the vicinity of this point but also defines its own local frame of reference in which the permittivity tensor has the simplest diagonal form. Nematics are optically uniaxial media characterized by two principal values of the permittivity tensor, corresponding to the permittivity parallel (ε_{\parallel}) and normal (ε_{\perp}) to the director. Naturally, the components of the permittivity tensor depend on the field frequency. In the optical frequency range, their values are determined by electron transitions and the corresponding polarizabilities. In the case of rod-shaped molecules, permittivity as a rule takes its highest values along the director. In the lowfrequency region, where the contribution of other relaxation modes acquires importance, permittivity along the director may be lower than in perpendicular directions. In the latter case, liquid crystals are said to have negative dielectric anisotropy. There is a class of liquid-crystal materials for which the sign of dielectric anisotropy in the acoustic frequency range is inverted owing to specific frequency dispersion. Such liquid crystals are referred to as dualfrequency crystals, and frequency f_i at which dielectric anisotropy is absent is called the frequency of anisotropy sign inversion. Dielectric anisotropy is positive ($\Delta \varepsilon =$ $\varepsilon_{\parallel} - \varepsilon_{\perp} > 0$, $f < f_i$) below this frequency, and negative above it. It is bistable electrooptical effects in a dualfrequency LC that will be considered at length below.

Liquid crystal are also characterized by anisotropy of viscoelastic properties, besides that of permittivity. By now, convincing experimental data have been obtained in support of the Frank–Oseen model [1, 2] in which the elastic strain energy density of nematics is expressed in the form of three independent contributions:

$$F = \frac{1}{2} \left[K_1 (\nabla \cdot \mathbf{n})^2 + K_2 \left(\mathbf{n} \cdot \nabla \times \mathbf{n} + \frac{2\pi}{P_0} \right)^2 + K_3 (\mathbf{n} \times \nabla \times \mathbf{n})^2 \right]$$
(1)

The terms in Eqn (1) correspond to splay and bend, as well as to twist, with the respective elastic constants K_1 , K_3 , and K_2 (Fig. 1c-e). Moreover, F Leslie has demonstrated that the orientational dynamics and hydrodynamics of nematic LCs can be comprehensively described by five independent viscosity constants [3]. Equations of viscoelastic orientational dynamics, in conjunction with equations of hydrodynamics and Maxwell's electromagnetic theory for anisotropic and inhomogeneous media, provide the necessary basis (also used in this work) for the computer simulation of electrooptical and laser effects in liquid crystals.

In what follows, thin liquid-crystal layers (films) enclosed between two solid substrates will be considered. As a rule, substrates comprise glasses covered by transparent electrodes on which in its turn orienting polymer films that determine orientation conditions for the LC director at the boundaries are deposited. The spacing between the two substrates is normally set by special technological procedures (for example, using teflon gaskets ranging between a few microns and dozens of microns in thickness) and the gap is filled with LCs. Such a construction is called the liquid-crystal cell. A cell is usually placed between two light polarizers (e.g., in a polarization microscope), and the driving voltage of a certain waveform is applied to the electrodes.

3. Effects of bistable electrooptical switching

The interaction of LCs with orienting surfaces plays the key role in the physical mechanisms of bistable switching. Interactions between LCs and various surfaces are highlighted in numerous publications including books [13, 14]. Such interactions are usually described in terms of anchoring energy. Any surface is characterized by normal s. Moreover, a surface is said, with reference to LCs, to have an 'easy orientation axis' a parallel to which the molecules tend to orient themselves in the absence of the deformation of a director field. Thus, normal s and 'light' direction a make up one of the principal planes. If this plane is related to a local coordinate system x', y', z', so that x'-axis is perpendicular to this plane, and y'-axis is parallel to **a**, the anchoring energy Wmay be defined in terms of the physical work done in deflecting the director of the LC from the direction **a** in two orthogonal planes y'x' and y'z':

$$W = \frac{1}{2} W_a n_{x'}^2 + \frac{1}{2} W_z n_{z'}^2 \equiv \frac{1}{2} (\mathbf{M} \mathbf{n}) \cdot \mathbf{n} ,$$

$$\mathbf{M} = \begin{pmatrix} W_a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & W_z \end{pmatrix},$$
 (2)

where $n_{x'}$ and $n_{z'}$ are x'- and z'-components of the director, respectively. The physical work done in deflecting the director through one and the same angle in planes y'x' and y'z' may be different. Therefore, in the general case the coefficients W_a and W_z are also different and characterize the azimuthal and zenithal contributions to the anchoring energy, respectively. Expression (2) is written down in the local (intrinsic) frame of reference where it has clear physical meaning. This expression is convenient in that the transition to the energy representation in a laboratory coordinate system linked to the normal to the surface is easy to realize by applying to matrix **M** the similarity transformation for tensors:

$$W = \frac{1}{2} \left[(\mathbf{R}\mathbf{M}\mathbf{R}^{-1})\mathbf{n} \right] \cdot \mathbf{n} , \qquad (3)$$

1

where **R** is the rotation matrix. Representation (3) is the generalization of the known Rapini expression [15] and turns out to be convenient in general cases when the orienting surface has a complicated geometric form. The effect of zenithal bistability [16], realized in the case of LC orientation by relief surfaces, is only one example when representation (3) proves effective in the numerical simulation. Figure 2 illustrates the result of switching simulation in a cell where both surfaces contribute to the local homeotropic (with an easy axis coincident with the normal to the surface) orientation of the LC, but one of them has the relief of a sinusoidal shape; accordingly, the easy axis changes its local orientation relative to the fixed laboratory system of coordinates.

The figure presents the calculated distributions of a director field in two states that undergo switching. This example is noteworthy in that the switching is realized by voltage pulses of opposite signs. The results of simulation confirm the inference of Wood et al. [16] concerning the flexoelectric nature of this effect. They also indicate that an important factor in the case under consideration is the magnitude of the anchoring energy because switching requires that anchoring on the relief surface be broken down



Figure 2. Results of modeling zenithal bistability (see the main text). The figure shows spatial distribution of the director field (*x*-component) in *xz*-plane in two states. Switching from state (a) to (b) and back is effected by 2-ms long unipolar voltage pulses +20 and -15 V, respectively. The main LC parameters are as follows: $K_1 = 5 \text{ pN}$, $K_2 = 3 \text{ pN}$, $K_3 = 10 \text{ pN}$, viscosity $\gamma = 0.1 \text{ Pa}$ s, dielectric anisotropy $\Delta \varepsilon = 10$, flexoelectric coefficients $e_1 = 20 \text{ pC m}^{-1}$, and $e_3 = 0$. Adhesion energy density at either surface is $W_a = W_z = 0.1 \text{ mJ m}^{-2}$.

and defects be created in the distribution of the LC director field in one of the states.

Multistable LC states are feasible at simpler boundary conditions, too. Let us consider, by way of example, a very important case of planar boundary conditions when easy axes at either orienting surface are parallel and lie in their planes. Let a nematic liquid crystal be doped with a chiral additive to ensure the natural pitch P_0 of helix. To begin with, we confine ourselves to a situation with no external field which, under the chosen boundary conditions, excludes splay and bend deformations of the director field. Integration of free energy density (1) over thickness *d* of the LC layer taking into account anchoring energy (3) leads to the following expression for the free energy per unit area:

$$\Phi = \frac{K_2 d}{2} (q_0 - q)^2 + W_{a1} \sin^2 \varphi_1 + W_{a2} \sin^2 \varphi_2.$$
 (4)

Here, $q_0 = 2\pi/P_0$, and *q* corresponds to the spatial frequency of the helicoidal director distribution:

$$n_x = \cos(qz + \varphi_1), \quad n_y = \sin(qz + \varphi_1), \quad n_z = 0$$
 (5)

in the presence of anchoring resulting in boundary conditions

$$\varphi_1 + qd = \varphi_2 + \pi k , \qquad -\pi < \varphi_{1,2} \leqslant \pi , \tag{6}$$

where $\varphi_{1,2}$ are the azimuthal angles of the director's deflection from the easy axes at the first and second surfaces, respectively, and k are the integers. By varying (4) over angles $\varphi_{1,2}$ it is easy to find conditions for the extreme values of the free energy that, at similar anchoring on either boundary, have the form

$$\varphi_1 = -\varphi_2, \quad q = q_0 + \frac{W_a}{2K_2} \sin(\pi k - qd).$$
(7)

An additional condition

$$K_2 + 2W_a d\cos\left(\pi k - qd\right) > 0 \tag{8}$$

ensures energy minima, i.e., equilibrium configurations of the director distribution (in the case being considered both states with a global energy minimum and metastable states are dealt with). It is straightforward to graphically present solutions (7) as points of intersection of two functions

$$f(q) = q - q_0$$
 and $g(q) = \frac{W_a}{2K_2} \sin(\pi k - qd)$.

Evidently, the higher the ratio of anchoring energy W_a to elastic modulus K_2 , the larger the number of metastable configurations for the director field distribution. These configurations are different in terms of the wave number q- that is, in the number of spiral turns on the layer thickness d. It should be emphasized that the function g(q) is the same for all even values of k but undergoes a phase shift by π for all odd values of k. Consequently, there exist two groups of solutions for even and odd values of k, respectively The existence of two groups of solutions reflects physical mechanisms underlying bistable switching. By way of example, different k values correspond to various twisted states of the director, differing in the number of spiral half-turns on the thickness d. If only states within a single group (e.g., even k) are considered, the orientation of the director in the center of the cell (z = d/2) remains unaltered. However, passage from the group of even k values to the 'odd' group requires that the director orientation in the cell center be swung through 90°; this is impossible under symmetric boundary conditions. In other words, transitions between states from different groups under uniform external influences (temperature variations, application of an electric field) are forbidden. At the same time, transitions are permitted within one group, for instance, due to the director 'slippage' at the boundaries [17]. Moreover, transitions between the states within one of the groups are possible even at an infinite anchoring energy on the surfaces, when slippage is impossible, by virtue of continuous deformation of the director field in the bulk. There is no such deformation for transitions between the states of different groups and hence they are forbidden. This means that the states within one of the groups are topologically equivalent and defectness switching between them is possible even with rigid anchoring.

The first observations of bistable switching between topologically equivalent states (homogeneous and helicoidal, or 2π -twisted) were reported by Berreman and Heffner [18]. The authors demonstrated that at d/P_0 ratios within the range of $\sim 0.5 - 0.7$ (when the equilibrium ground state corresponded to the helicoidal distribution of the director with one half-turn on the layer thickness), the switching occurred between the metastable homogeneous state (unwound spiral) and the helicoidal 2π -state with a pitch P of helix equal to the thickness d. Such switching was possible owing to the specific interaction with hydrodynamic flows, depending on the shape of the switching voltage on the cell. A serious problem in the Berreman-Heffner effect is the presence of three states, one of which, being the ground state (thermodynamic equilibrium π -state), is topologically not equivalent to the two switchable states. Therefore, passage to the 'operating' conditions requires elimination of the state that is topologically not equivalent, which can be realized



Figure 3. Frequency dependences of permittivity components for a dualfrequency LC (liquid-crystal mixture TF140CH, M I Barnik, Institute of Crystallography, RAS, Moscow).

only through the formation of defects. We have recently shown [19] that the choice of an LC with the ratio $K_3/K_2 > 3$ allows a similar switching to be performed in the conditions when the ground state is the 2π -state, and the problem related to the presence of the topologically non-equivalent π -state becomes resolved.

We have described one more effective way to realize different modes of bistable switching [7] using dual-frequency LCs.

Figure 3 illustrates the frequency dependence of dielectric anisotropy for one such LC. It shows positive dielectric anisotropy in the low-frequency range ($\Delta \varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} > 0$, $f < f_i = 5 \text{ kHz}$), and negative dielectric anisotropy in the high-frequency range. Thus, the director tends to orient parallel to the low-frequency field, and normally to the highfrequency field. Results of computer simulation indicate that the use of a special driving voltage from low-frequency and high-frequency pulse packets makes it possible to realize different bistable switching regimes. Figure 4 demonstrates the results of numerical simulation and measurements of the electrooptical response in conditions of switching between the homogeneous state and the helicoidal 2π -state. In this case, the states being switched are topologically equivalent and the uniform director distribution corresponds to the ground state. Due to the dual-frequency control, bistable switching shows but weak dependence on the amount of chiral doping. In order to remove degeneracy between the twisted states of different signs $(2\pi \text{ and } -2\pi)$ and exclude the corresponding domains, only a small amount of chiral doping $(d/P_0 \sim 0.02)$ or only a minor (fractions of a degree) azimuthal displacement of the easy axis direction at one of the surfaces is needed. It is worthwhile mentioning that the time of switching to the 2π -state is practically determined by the parameters of the high-frequency voltage packet and may be as large as fractions of a millisecond. Reverse switching to the homogeneous state contains a large portion of the director free relaxation; therefore, its time is determined by the viscoelastic properties of the LC and the cell thickness d. The free relaxation part may manifest itself in the electrooptical response as a transmission 'bounce' following a pulse of the low-frequency field. Both numerical simulation and experiment demonstrate that the 'bounce' is suppressed as the doping of the LC with a chiral agent decreases. This means that the effective (electrooptical) switching time can also be



Figure 4. Electrooptical response (light transmission) to bistable dualfrequency switching between homogeneous and helicoidal (2π) states: (a) results of computer simulation; (b) experimental results, and (c) switching voltage pulses and their shapes. The LC cell is placed between the crossed polarizers, so that the axis of one of them coincides with the easy axes of LC orientation at the boundary surfaces. Parameters used in computer simulation were close to the measured ones in an experimental LC (refraction indices $n_{\perp} = 1.5$, $n_{\parallel} = 1.72$; rotational viscosity $\gamma = 0.5$ Pa s; Leslie viscosity coefficients $\alpha_4 = \alpha_5 = 0.25$ Pa s, and dielectric anisotropy is shown in Fig. 3).

diminished to the duration of a low-frequency pulse. We have also confirmed in experiment the possibility of other regimes of dual-frequency bistable switching between different topologically equivalent states: $-\pi/2 \leftrightarrow 3\pi/2$, $-\pi \leftrightarrow +\pi$, and some others.

It is essential that in the case of a finite but substantially different anchoring energy of a LC at the two orienting surfaces, the above forbidding of transitions between topologically nonequivalent states is lifted. For example, transitions between the homogeneous state and the π -state (half-turn of the helix on thickness d) are feasible when the electric field is strong enough to break anchoring at one of the boundaries. In this situation, 'chiral' doping ensures the equality of the free energies of the homogeneous and π states, so that they both may be regarded as ground states in the thermodynamic sense.

When the field is switched off, transitions between these states are very unlikely, even at a small difference between their energies, because they are topologically nonequivalent. In practice, states with a lifetime of more than hundreds of hours are realized. This approach was first demonstrated by the French company NEMOPTIC (BiNem technology) using special orienting covers that ensured a low anchoring energy at one of the surfaces [8]. The use of dual-frequency LCs



Figure 5. Results of computer simulation of the electrooptical response (coefficient of reflection) to bistable dual-frequency switching between homogeneous planar and topologically nonequivalent twisted (π) states (a) and the corresponding switching voltage pulses (b). The anchoring energy density at one of the orienting surfaces, $W_a = W_z = 0.02 \text{ mJ m}^{-2}$, is much smaller than at the other (0.1 mJ m⁻²). The LC cell is placed between the mirror and the polaroid (only one polaroid is used) with the axis at 45° to the easy axes of the orienting surfaces. The layer thickness *d* and optical anisotropy Δn of the LC correspond to the optical delay $\Delta nd = 0.16 \text{ µm}$.

opens up new possibilities. Figure 5 shows the results of numerical simulation under dual-frequency control.

It is noteworthy that in the BiNem technology utilizing single-frequency LCs, switching is strongly dependent on the d/P_0 ratio and the pretilt angle of the director at the boundaries of the LC layer; this may cause problems in real electrooptical devices. In our case, the dual-frequency switching is less sensitive to both the d/P_0 ratio and the director pretilt. It can be seen from Fig. 5 that this effect may be employed to construct electrooptical devices operating in a reflective mode and using a single polaroid; this approach is of importance for the development of new displays with high reflective power ('electronic paper' displays).

4. Optics and photonics

of spatially periodic liquid-crystal structures

Various types of spatial periodicity of the LC director fields (cholesteric LCs, periodicity of boundary conditions, fieldinduced periodic LC structures, etc.) are interesting from the standpoint of photonics and lasing effect [20-22]. The following discussion is confined to cholesteric LCs, with special reference to some of their new features revealed in numerical simulations.

By virtue of specific optical properties of cholesteric LCs, they are referred to as one-dimensional photonic crystals [22], the reason being the presence of a selective reflection band in the optical spectrum, corresponding to the forbidden zone for waves of a certain polarization. Figure 6a presents transmission and reflection spectra of a cholesteric LC layer with a pitch of helix $P = 0.4 \,\mu\text{m}$ at the normal incidence of a nonpolarized light beam. These spectra were computed based on the exact solution of the Maxwell equations by the 4×4 complex matrices method using the algorithm developed in Ref. [23]. In the example given, the 600–680-nm



Figure 6. Calculated transmission (*T*) and reflection (*R*) spectra (a), and emission spectrum *I* (b, c), demonstrating initiation of lasing effect in an LC cholesteric layer (pitch of helix $P = 0.4 \,\mu\text{m}$, refraction indices $n_{\perp} = 1.5$, $n_{\parallel} = 1.7$). Amplification (inversion) of the LC medium was simulated by negative magnitudes of the principal absorption indices: (b) $k_{\perp} = 0$, $k_{\parallel} = -0.15$; (c) $k_{\perp} = -0.15$, $k_{\parallel} = 0$.

wavelength region corresponds to the forbidden zone. In this wavelength range, when the inequality

$$n_{\perp}P < \lambda < n_{\parallel}P \tag{9}$$

is fulfilled (where n_{\perp} , n_{\parallel} are the indices of refraction orthogonal and parallel to the LC director), photons with circular polarization [coincident in terms of direction (sign) with the sense of rotation of the cholesteric helix director] pass freely and undergo only Fresnel reflection from the boundaries of the LC layer. Indeed, the field vector of a wave with the wavelength falling in the range (9) rotates synchronously with the LC director. For this reason, photons 'see' (across the entire thickness of the LC layer) one and the same effective value of the refractive index lying in the range $(n_{\perp}, n_{\parallel})$ and depending on instantaneous orientation of the electric field vector of the wave as it enters the LC layer. In other words, for photons with the circular polarization sign coincident with the sign of the director field helix, a cholesteric LC film 'looks' like an isotropic one. Conversely, photons with opposite (orthogonal) circular polarization 'see' only the periodic structure; for them, the Bragg reflection conditions are satisfied. Thus, a cholesteric LC layer splits a nonpolarized wave into two circularly polarized ones, namely, transmitted and reflected. It should be emphasized that in the present work I proceed from the consensus among modern physicists on the sign of circular light polarization. It means that a wave has right-hand circular polarization if the angular momentum for its photons coincides with the direction of their motion. This 'modern' definition is consistent with the corresponding definition of the chirality sign of the LC cholesteric helix and helps us to better understand the nature of selective reflection. It should be borne in mind that in many books the 'classical' definition of circular polarization is used, where its sign is determined from the sense of the field vector rotation for an observer toward whom the photon moves.

The presence of a selective reflection band makes possible lasing effect in LCs using no outside mirrors. Lasers of this type are referred to as distributed feedback lasers. Figure 6 presents calculated spectra for an inverse cholesteric medium. Optical inversion of the medium, with the majority of the molecules residing in the excited state, was given by spectrally independent negative values of absorption coefficients (k < 0), which corresponded to the light amplification in the medium. As evident from the figure, lasing effect can be realized, depending on the absorption (amplification) anisotropy, either at the long-wave ($k_{\perp} = 0, k_{\parallel} < 0$, Fig. 6b) or the short-wave $(k_{\perp} < 0, k_{\parallel} = 0, \text{ Fig. 6c})$ edge of the forbidden zone. In experiment, this or that sign of the amplification coefficient anisotropy (in the case of inversion created by optical pumping or by a different method) can be realized by doping a cholesteric liquid crystal with various dichroic luminescent dyes, the molecules of which get built-in to the LC matrix in a different way, being oriented by the corresponding oscillators either parallel or perpendicular to the director. Laser generation in cholesteric LCs was first observed in Ref. [20]. However, the authors had expected to see the onset of generation at the center of the selective reflection band and therefore could not properly interpret the results of their experiment. Actually, realization of positive feedback necessary for lasing effect to appear is feasible only at the edges of the zone where the propagation of waves of one of the polarizations is not completely forbidden. The above-demonstrated role of absorption (amplification) anisotropy also has a fairly good qualitative interpretation. Indeed, a photon on the long-wave edge of the zone must interplay with the largest of the possible values of the refractive index (n_{\parallel}) if the rotation of the wave field vector is to be synchronous with the detector rotation. In other words, the field vector of propagating photons at the longwave edge of the zone is parallel to the LC director. Correspondingly, this makes it possible for them to optimally interact only with those molecular oscillators that are also parallel to the director. This accounts for the most favorable conditions for lasing effect at the long-wave wing in the presence of absorption anisotropy, when $|k_{\parallel}| > |k_{\perp}|$. Similarly, the opposite sign of absorption anisotropy ensures more favorable conditions for the generation at the shortwave edge of the zone. It is also worth noting that the ban on generation inside the forbidden zone may be lifted by introducing defects into an ideal cholesteric helix. In this sense, the situation is analogous to the band description of semiconductors [22].

Concluding, it seems appropriate to note that lasing effect in LCs has only recently become a subject of extensive studies, despite the fact that the first observations of this phenomenon were reported fairly long ago. The situation changed with the understanding that LCs constitute actually a specific type of photonic media.

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