

QUANTUM ELECTRONIC DEVICES

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Tunable liquid-crystal focusing device. 1. Theory

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Abstract. **A theoretical model for a modal liquid-crystal focusing device is developed. The solutions to the system of equations are investigated in the approximation of a small modal parameter. The necessary relations between the control harmonic potentials for implementing a phase delay profile in the form of a circular truncated cone with a controlled position of the base centre and in the form of an elliptical truncated cone with a controlled centre position and fixed directions of the major axes of the ellipse (which are parallel to the aperture edges) are found.**

Keywords: *liquid crystals, spatial light modulators.*

1. Introduction

The studies devoted to the formation of light fields with different spatial structures in the focal region, which became especially urgent after the invention of lasers, have been intensively carried out during several decades. The interest in these fields is primarily determined by such laser applications as marking, welding, and material processing. The methods for the laser manipulation of microscopic objects, which have been actively developed in recent years, require both light fields with a complex structure and fields acting as point traps. To apply laser control in practice, it is necessary to implement dynamic control of traps. Light fields with an enlarged depth of focus are of interest for laser measurement systems, as well as for trapping microscopic particles. As previously, an important problem is to control the focal length of imaging systems, for example, in coherent optical tomographers [1].

We believe the methods using diffractive optical elements [2] to be most appropriate for implementing various spatial distributions. The development of multielement phase liquid-crystal (LC) spatial light modulators [3, 4] made it possible to control the real-time spatial characteristics of light fields with a maximum intensity up to several W cm^{-2}. However, they are complicated in production and control, and therefore, have a high cost. In addition, some applications do not need such complex devices.

LC lenses with a tunable focal length can be applied in systems that require automatic focusing. They can be implemented in different ways, for example, using a natural distribution of the electric field induced in the LC layer by an electrode of special shape [5 – 10]. This approach allows one to form spherical lenses with a small aperture (less than 1 mm in diameter). Several versions of lenses (with modified and additional conducting layers) have been proposed to increase the aperture and expand functionality. As a result, spherical lenses with a possibility of controlling the focal spot both in the screen plane and in three dimensions have been developed [8, 9]. However, the design of these lenses is complicated, and they are difficult to fabricate (due to the presence of thin optical-quality glass layers). The control voltages across these layers are close to 100 V, which is unacceptable for some practical applications.

Another way to design tunable lenses, which is based on the so-called modal technique for controlling LC spatial light modulators, was proposed in [11, 12]. Its distinctive feature is the use of a high-resistivity transparent coating in the modulator, due to which a parabolic-like distribution of the voltage applied to the LC layer is formed in the LC-cell aperture. This technique made it possible to develop cylindrical and spherical LC lenses with aperture sizes more than 1 mm and control voltages not higher than 10 V [11, 12]. This approach was further developed in [13], where the focal length of the lenses was decreased by applying a new resistive coating and changing the geometry. The use of a modal lens in combination with a 2D LC deflector (prism) made it possible to displace the spot in the focal plane when manipulating microscopic objects [14]. The change in the control regimes expanded the functional possibilities of the LC deflector and made it possible to implement several optical elements with a complex profile of phase delay [15]. However, no detailed theoretical description of the control regimes was performed.

It is well known that two crossed cylindrical lenses with equal focal lengths in the overlap region form a spherical lens. It is of interest to consider an LC device based on crossed substrates of cylindrical modal LC lenses, designed as a whole. This device (which will be referred to as a focusing device) will have four control contact electrodes and new focusing properties. In this paper, we report the results of theoretical study of the functional possibilities of this LC focusing device.

2. Principle of operation

Let us consider the design of the modal LC focusing device (Fig. 1a). A nematic LC layer is placed between two glass substrates. Transparent high-resistivity coatings (with a surface resistance from 100 kΩ □$^{-1}$ to several MΩ □$^{-1}$) and low-resistivity opaque stripe contacts are deposited on the substrate surfaces that are adjacent to the LC layer. The substrates are oriented so as to make their contact electrodes orthogonal. As a result, we have a device with a rectangular aperture. The

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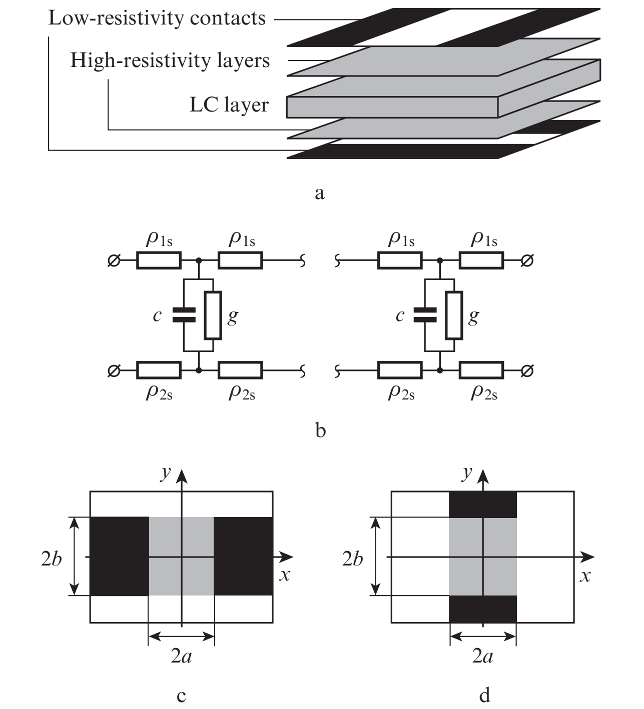

Figure 1. (a) Schematic diagram of the modal LC focusing device, (b) equivalent scheme of distributed voltage divider, and (c, d) geometry of contacts for the (c) top and (d) bottom substrates.

thickness of the LC layer is set by spacers and the initial planar orientation is provided by orienting the coatings deposited on the substrates (not shown in Fig. 1a).

This design provides a capacitive–resistive voltage divider in the aperture area (Fig. 1b). Here, the active elements are represented by specific (per unit area) surface resistances of the high-resistivity coatings, ρ_{1s} and ρ_{2s}, while the reactive component is determined by the LC-layer capacitance c. The LC layer has a specific conductivity g, which is generally low; however, the influence of the layer can be significant at low-frequency control voltages. When an ac sinusoidal voltage is applied to the contacts, the instantaneous voltage at the centre of the focusing device aperture lags behind the change in the control voltage across the contacts. As a result, the effective voltage smoothly decreases from the contacts to the centre of the aperture. A change in the frequency leads to a change in the reactive capacitive resistance of this divider. For example, if the frequency increases, the gradient of the effective voltage from the edge to the centre of the aperture and, correspondingly, the drop of the effective voltage increase along the high-resistivity electrodes. Thus, one can change the voltage distribution over the aperture by controlling the divider characteristics.

LC molecules become reoriented under the voltage applied (the so-called S effect) [16]. Therefore, the spatial distribution of the phase delay introduced by the LC layer into a transmitted light wave can be changed by controlling the behaviour of the voltage profile.

3. Mathematical model of focusing device

Let us analyse the focusing device operation within the theory of LC correctors with a modal principle of control [11]. The properties of the focusing device are determined by the potential distribution in the aperture area; therefore, to reveal the main aspects of operation of the focusing device, we will consider the design where the width of the contact electrodes on one of the substrates is equal to the intercontact distance on the other substrate, and the high-resistivity coating is only present on the contacts and in the aperture area. In this case, we will not consider the areas covered by metal contact electrodes, which are optically opaque and are not involved in focusing the light passing through the LC focusing device. The contacts and coordinate system are schematically shown in Figs 1c and 1d.

The system of equations describing the potential distribution on each substrate in the aperture area (on the surface of high-resistivity coating) can be derived in the same way as in [11]. It has the form

$$\nabla\left(\frac{1}{\rho_{1s}}\nabla\varphi_1\right) = c\frac{\partial U}{\partial t} + gU,$$
$$\nabla\left(\frac{1}{\rho_{2s}}\nabla\varphi_2\right) = -c\frac{\partial U}{\partial t} - gU. \qquad (1)$$

Here, φ_1 and φ_2 are the potentials of the high-resistivity electrodes and U is the difference in the potentials φ_1 and φ_2.

The conditions at the aperture boundary near the edges of the contact electrodes on each substrate are as follows:

$$\varphi_1(-a; y; t) = \varphi_{11}(t),$$
$$\varphi_1(a; y; t) = \varphi_{12}(t),$$
$$\varphi_2(x; -b; t) = \varphi_{21}(t), \qquad (2)$$
$$\varphi_2(x; b; t) = \varphi_{22}(t).$$

The normal current components must be zero at the two other sides of the aperture on each substrate.

Since nematic LCs are controlled by an ac voltage, we will analyse single-frequency harmonic potentials. When studying the optical properties of this device, it is the stationary distributions of phase delay that are of primary interest; therefore, we will consider the frequency range where the electrical characteristics of the LC layer do not change in time at a constant potential vibration amplitude. The frequencies exceeding the inverse relaxation time of LC molecules satisfy these conditions. In this case, the spatial orientation of LC molecules and, therefore, all LC properties are determined by the mean squared voltage. Generally, when designing the modal wavefront correctors, the surface resistance of the high-resistivity coating is assumed to be constant. Then the boundary-value problem for the amplitude values of potentials can be written as

$$\nabla^2\varphi_1 = \chi_1^2\varphi_1 - \chi_1^2\varphi_2, \quad \nabla^2\varphi_2 = \chi_2^2\varphi_2 - \chi_2^2\varphi_1,$$
$$\varphi_1(-a; y) = \varphi_{11}, \quad \varphi_1(a; y) = \varphi_{12},$$
$$\varphi_2(x; -b) = \varphi_{21}, \quad \varphi_2(x; b) = \varphi_{22}, \qquad (3)$$
$$\left.\frac{\partial\varphi_1}{\partial y}\right|_{y=-b} = 0, \quad \left.\frac{\partial\varphi_1}{\partial y}\right|_{y=b} = 0,$$
$$\left.\frac{\partial\varphi_2}{\partial x}\right|_{x=-a} = 0, \quad \left.\frac{\partial\varphi_2}{\partial x}\right|_{x=a} = 0,$$

where

$$\chi_k^2 = \rho_{ks}(g - \mathrm{i}\omega c), \quad k = 1, 2; \tag{4}$$

χ_1 and χ_2 are the modal parameters for the first and second substrates. The physical meaning of these quantities is that the squares of modal parameters are the ratios of the resistance of high-resistivity layer to the impedance of the LC layer.

Thus, we have a system of equations, which can be used to determine the distribution of the voltage across the LC layer. With the known dependence of the phase delay on voltage, one can calculate the profile of the wavefront formed. Note that the electrical characteristics of the LC layer (c and g) are nonlinear functions of voltage; however, to understand the main possibilities of the device under study, it is sufficient to consider the solution in the approximation of constant impedance of the LC layer, where the specific capacitance and conductivity are assumed to be voltage-independent and equal to their means in the allowed ranges of variation [11]. For convenience we will assume the surface resistances of the high-resistivity layers to be equal: $\chi_1 = \chi_2 = \chi$. The character of voltage distribution over the aperture will depend on the modal parameter. As was shown in [11], the condition $|\chi l| \sim 1$ (l is the characteristic aperture size) is optimal for implementing the modal principle of controlling LC correctors. In our case the solution at $|\chi l| \ll 1$ is also of interest. Let us consider each of these cases separately.

4. Focusing device operation at the modal parameter $\sim 1/l$

To understand the operation of this device (as an LC corrector with the modal principle of controlling) in the optimal regime we will consider the case where potentials of the same amplitude are applied to the contacts of one of the substrates (for example, with index 1), while the contacts on the other substrate are grounded. This boundary-value problem was solved using the standard numerical methods from the Matlab package. The permittivity of the LC (13.5), which determines its specific capacitance, was chosen as an average for the real nematic crystal (BL037) the modal LC correctors were based on. On the assumption that the LC layer is a pure insulator, the conductivity in the frequency range of voltages under study can be neglected. The LC layer was 10 μm thick, the resistance of the high-resistivity layers was assumed to be 1 MΩ□$^{-1}$, and the aperture was shaped as a square with a side length $2a$ = 5 mm (the operation regime, as for the modal cylindrical LC lens, was estimated on the assumption that $l = a$). The change in the modal parameter was set by varying the frequency, which was the same for all applied potentials. The calculation results for this case are shown in Fig. 2. When calculating the phase delay profile, we used an experimental voltage–phase dependence for the LC used.

We observed dependence that is typical of LC correctors based on the modal control principle: the deflection depth of the voltage and phase delay distributions increases with an increase in the frequency of the potential. It can be seen that, because of the strong effect of aperture edges, the phase profile has a shape of a smoothed tetragonal pyramid. This is related to the fundamental features of the formation of voltage distribution over the aperture for the correctors of this type. Note also that in this operation regime the voltage rapidly decreases near the corners, which leads to a significant drop of the phase delay; therefore, the control in the central (working) region is performed only in some part of the entire possible range of phase modulation for the LC layer. This regime is of no interest because it cannot provide a sufficient light focusing in the presence of distortions. Let us now consider the case of a small modal parameter. Note that the results obtained for small χ will also be valid for the above-considered focusing device operation regime, with allowance for the edge-induced features.

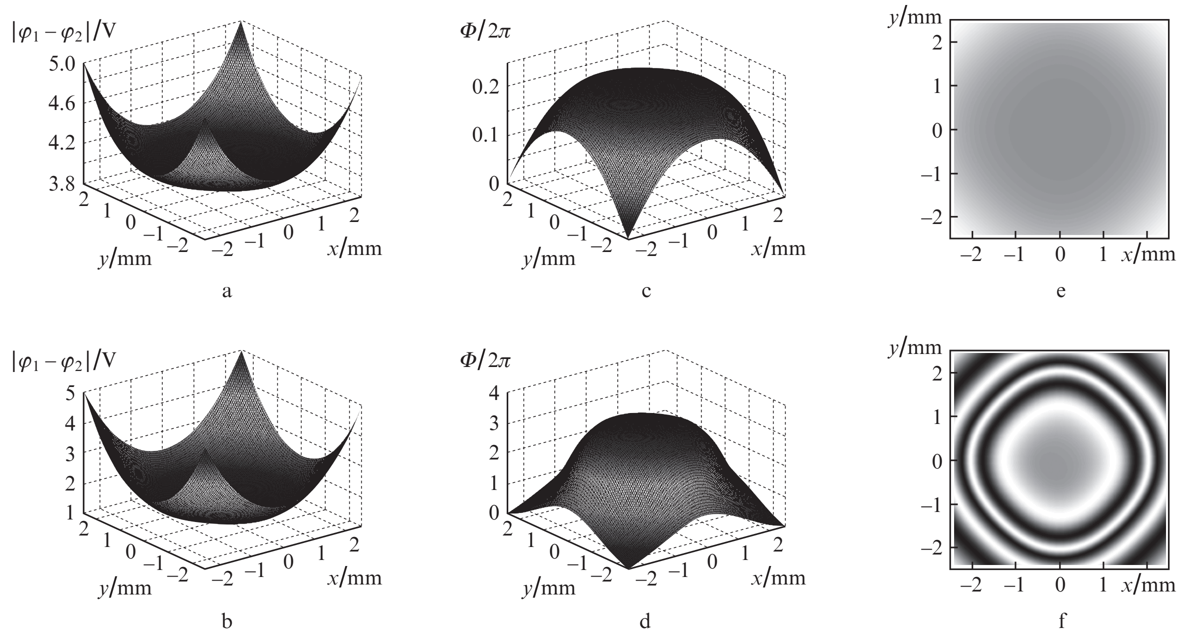

Figure 2. Distributions of (a, b) voltage and (c, d) phase delay and (e, f) the polarisation interference patterns at voltage frequencies of (a, c, e) 2.1 and (b, d, f) 8.4 kHz, corresponding to $|\chi l|$ = 1 and 2, and U = 5 V.

5. Solution to the system of equations for the focusing device at a small modal parameter

To implement the regime of operation with a small modal parameter, it is necessary to reduce the frequency and/or resistance of high-resistivity coatings so as to satisfy the condition $|\chi l| \ll 1$. Physically, this means that the distributed capacitance system has enough time to recharge, and the potentials at the centre of the aperture have time to follow the changes occurring at the contact electrodes. In this case, the influence of frequency on the voltage distribution becomes negligible, and the voltage distribution is controlled via the potential amplitude and phase. These conditions satisfied, the terms on the right-hand side of Eqns (3) can be neglected, and these equations can be rewritten as

$$\nabla^2\varphi_1 = 0, \qquad \nabla^2\varphi_2 = 0. \tag{5}$$

The boundary conditions retain their form. Thus, we obtained a system of independent equations with the following solution:

$$\varphi_1 = \frac{\varphi_{12}-\varphi_{11}}{2a}x + \frac{\varphi_{12}+\varphi_{11}}{2}, \qquad \varphi_2 = \frac{\varphi_{22}-\varphi_{21}}{2b}y + \frac{\varphi_{22}+\varphi_{21}}{2}. \tag{6}$$

Then the voltage distribution over the aperture takes the form

$$U = \varphi_1 - \varphi_2 = \frac{\varphi_{12}-\varphi_{11}}{2a}x + \frac{\varphi_{12}+\varphi_{11}}{2} - \frac{\varphi_{22}-\varphi_{21}}{2b}y - \frac{\varphi_{22}+\varphi_{21}}{2}. \tag{7}$$

The phase delay profile formed by the LC layer depends on the distribution of squared voltage. For single-frequency harmonic potentials this is equivalent to the squared modulus of the complex voltage amplitude. Let us multiply the voltage by its complex conjugate and determine the form of equipotential lines (i.e., lines of constant voltage):

$$\begin{aligned} UU^* = {} & \frac{(\varphi_{12}-\varphi_{11})(\varphi_{12}-\varphi_{11})^*}{4a^2}x^2 - \frac{(\varphi_{12}-\varphi_{11})(\varphi_{22}-\varphi_{21})^*}{4ab}xy \\ & + \frac{(\varphi_{12}-\varphi_{11})(\varphi_{12}+\varphi_{11}-\varphi_{22}-\varphi_{21})^*}{4a}x \\ & - \frac{(\varphi_{22}-\varphi_{21})(\varphi_{12}-\varphi_{11})^*}{4ab}xy + \frac{(\varphi_{22}-\varphi_{21})(\varphi_{22}-\varphi_{21})^*}{4b^2}y^2 \\ & - \frac{(\varphi_{22}-\varphi_{21})(\varphi_{12}+\varphi_{11}-\varphi_{22}-\varphi_{21})^*}{4b}y \\ & + \frac{(\varphi_{12}+\varphi_{11}-\varphi_{22}-\varphi_{21})(\varphi_{12}-\varphi_{11})^*}{4a}x \\ & - \frac{(\varphi_{12}+\varphi_{11}-\varphi_{22}-\varphi_{21})(\varphi_{22}-\varphi_{21})^*}{4b}y \\ & + \frac{(\varphi_{12}+\varphi_{11}-\varphi_{22}-\varphi_{21})(\varphi_{12}+\varphi_{11}-\varphi_{22}-\varphi_{21})^*}{4}. \end{aligned} \tag{8}$$

Thus, we derived a second-order equation with respect to the coordinates:

$$Ax^2 + 2Bxy + Cy^2 + 2Dx + 2Ey + F = 0. \tag{9}$$

It can be shown that the equipotential lines for the potentials in the operating range of the device can be only elliptic and parabolic. Potential distributions in the form of ellipses, circles, and parallel straight lines are most interesting for practical purposes, because such distributions allow the device to focus light to a spot or a segment. Distributions with equipotential lines in the form of concentric circles are necessary to focus light to a round spot. Let us find the relations between the potentials applied to the contact electrodes that can form the aforementioned distributions.

6. Focusing device operation with equipotential lines in the form of ellipses and circles

According to the theory of second-order curves, the system of equations for the coefficients at which the lines are ellipses has the form

$$\begin{aligned} & x_0(AC - B^2) = BE - DC, \\ & y_0(AC - B^2) = BD - AE, \\ & (C - A)\sin 2\alpha + 2B\cos 2\alpha = 0, \\ & (A\gamma^2 - C)\sin^2\alpha - 2B(1+\gamma^2)\sin\alpha\cos\alpha + (C\gamma^2 - A)\cos^2\alpha = 0. \end{aligned} \tag{10}$$

Here, x_0 and y_0 are the coordinates of the circle centre; α is the angle of rotation of the principal axes with respect to the initial coordinate system; and γ is the ratio of the ellipse size along the principal axis Y to its size along the principal axis X.

Let us consider the practically important case where the principal axes are parallel to the aperture sides, i.e., $\alpha = 0$. Here, we have a system of four equations with eight unknowns. Let us write the potentials in the form

$$\varphi_{km} = R_{km} + \mathrm{i}I_{km}. \tag{11}$$

In this case, one can find a partial solution to the system of equations (10) by expressing the potentials of one of the substrates in terms of the real and imaginary parts of the potentials of the other substrate (with application of the Maxima software):

$$\begin{aligned} R_{21} = {} & [\gamma(aR_{11} - x_0R_{11} + aR_{12} + x_0R_{12}) \\ & + bI_{11} + y_0I_{11} - bI_{12} - y_0I_{12}]/2a\gamma, \\ I_{21} = {} & [-bR_{11} - y_0R_{11} + bR_{12} + y_0R_{12} \\ & + \gamma(aI_{11} - x_0I_{11} + aI_{12} + x_0I_{12})]/2a\gamma, \end{aligned} \tag{12}$$

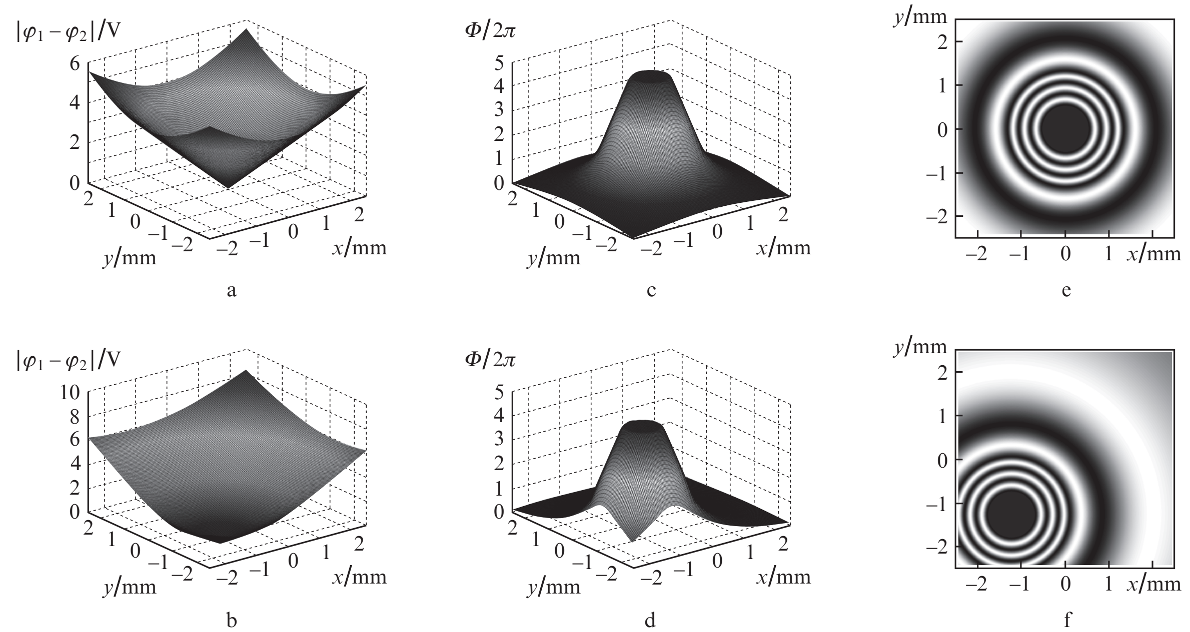

Figure 3. Distributions of (a, b) voltage and (c, d) phase delay and (e, f) the polarisation interference patterns at the centre coordinates $x_0/a = y_0/b$ = (a, c, e) 0 and (b, d, f) –0.5.

$$R_{22} = [\gamma(aR_{11} - x_0R_{11} + aR_{12} + x_0R_{12}) - bI_{11} + y_0I_{11} + bI_{12} - y_0I_{12}]/2a\gamma,$$

$$I_{22} = [bR_{11} - y_0R_{11} - bR_{12} + y_0R_{12} + \gamma(aI_{11} - x_0I_{11} + aI_{12} + x_0I_{12})]/2a\gamma.$$

The second solution to the system is complex conjugate to the first solution, provided that the potentials φ_{11} and φ_{12} are also complex conjugate. Note that, according to the condition for the problem under consideration, the potentials on the first substrate must differ ($\varphi_{11} \neq \varphi_{12}$).

Thus, to provide distributions with equipotential lines in the form of concentric circles, one should assume that $\gamma = 1$, set the potentials φ_{11} and φ_{22} in the complex form (i.e., specify their real and imaginary parts), and define the coordinates of the circle centre (x_0, y_0). The complex amplitudes of the two other potentials, which must be applied to the other substrate, can be calculated using the above-mentioned relations. Some examples of the distributions obtained are shown in Fig. 3. The calculations were performed with φ_{11} = 4 V and φ_{22} = (–2.5–4.33i) V.

Let us consider another case of control (which is even more convenient for practical implementation and application), where the potentials have a constant phase on all contacts, and it is only their amplitudes that change. Let us fix the phase of all the potentials applied to the contacts as follows:

$$\begin{aligned}\varphi_{11} &= A_{11}e^0 = A_{11},\\ \varphi_{12} &= A_{12}\exp(i\pi) = -A_{12},\\ \varphi_{21} &= A_{21}\exp(i3\pi/2) = -iA_{21},\\ \varphi_{22} &= A_{22}\exp(i\pi/2) = iA_{22}.\end{aligned} \quad (13)$$

Here, A_{11}, A_{12}, A_{21}, and A_{22} are real values. After substitution of the potentials into the conditions of the problem, the solution takes the form

$$A_{12} = -A_{11}\frac{1-(x_0/a)}{1+(x_0/a)}, \quad A_{21} = \frac{A_{11}b}{\gamma a}\frac{1+(y_0/b)}{1+(x_0/a)},$$

$$A_{22} = \frac{A_{11}b}{\gamma a}\frac{1-(y_0/b)}{1+(x_0/a)}. \quad (14)$$

Then, we introduce another condition. Let the lengths of the ellipse semiaxes be preserved when the ellipse is displaced. Since the ratio of the semiaxis lengths is constant, it is sufficient to fix the length of only one semiaxis. We assume the voltage to be U_0 at a distance R from the ellipse centre along the X axis. In this case, the canonical equation of the ellipse has the form

$$A(x - x_0)^2 + C(y - y_0)^2 - Ax_0^2 - Cy_0^2 + F = 0. \quad (15)$$

In accordance with the conditions stated, (15) can be rewritten as

$$AR^2 - Ax_0^2 - Cy_0^2 + F = 0. \quad (16)$$

Using the coefficients in the explicit form and solution (14), we obtain the following expression for the amplitude:

$$A_{11} = \frac{a}{R}|U_0|\left(1 + \frac{x_0}{a}\right). \quad (17)$$

When an ellipse centred at the point (x_0', y_0') must be displaced to another position, with a centre at the point (x_0, y_0) but with its sizes preserved, the amplitude should change as follows:

$$A_{11} = A_{11}'\frac{1+(x_0/a)}{1+(x_0'/a)}. \quad (18)$$

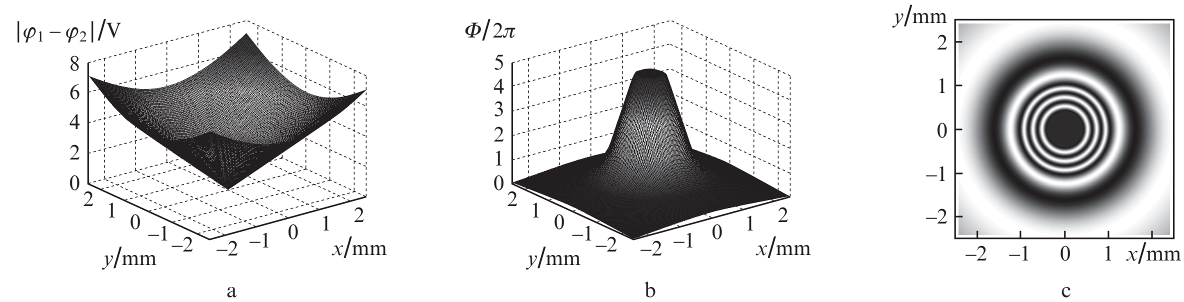

Figure 4. Distributions of the (a) voltage and (b) phase delay and (c) the polarisation interference pattern, obtained at A_{11} = 5 V, $x_0 = y_0 = 0$, and $a = b$ = 5 mm.

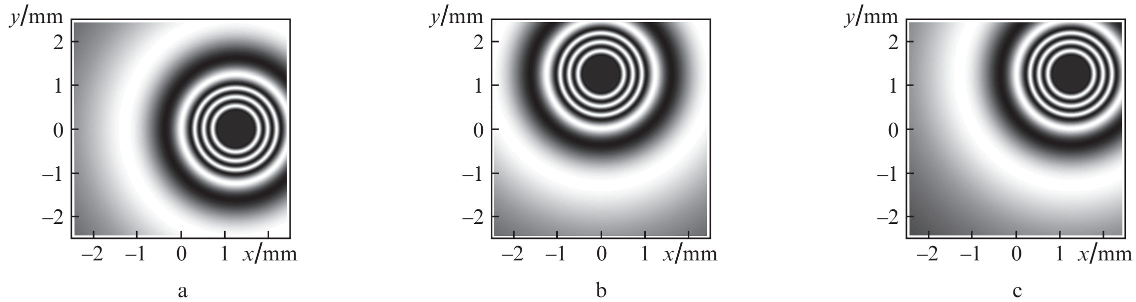

Figure 5. Polarisation interference patterns, calculated within the proposed model for a focusing device with an aperture of 5×5 mm, obtained at (a) x_0 = 1.25 mm, y_0 = 0, and A'_{11} = 5 V; (b) x_0 = 0, y_0 = 1.25 mm, and A'_{11} = 5 V; and (c) $x_0 = y_0$ = 1.25 mm and A'_{11} = 5 V.

In this control regime (with phases fixed) the independent parameters are the amplitude of the potential on one of the contacts (for example, A_{11}), the coordinates of the ellipse centre, the ratio of the ellipse axes, and one voltage value (U_0) with the corresponding value of the semiaxis R along the X direction. Applying potentials to the contacts in accordance with relations (14), we will form patterns of equipotential lines in the form of ellipses having the same center. If the voltage distribution must be displaced without changing its form, the amplitude must be varied according to formula (18).

To focus light to a round spot, one should form distributions with equipotential lines in the form of concentric circles. In this case, the relations for the potentials can easily be derived from the expressions found for the ellipse, with γ equated to unity. Examples of the distributions obtained are presented in Figs 4 and 5.

Note that the voltage at the centre of the circles decreases to zero. Since the voltage–phase dependence for the LC layer has a threshold character, the phase delay remains constant at voltages below the threshold. Due to this, the phase distribution profile in the focusing device has a shape of a truncated cone. This effect can be compensated for (as was proposed in [14]) by applying additional signals of another frequency to the contacts, so as to form a voltage above the threshold throughout the entire aperture. The frequencies of the signals applied must satisfy the condition of modal parameter smallness.

7. Conclusions

We considered the model of a tunable LC light focusing device and investigated its different working regimes within this model. Relations between the control parameters (potentials) were obtained for cases of practical importance in the approximation of a small modal parameter and harmonic voltages. The necessary relations for implementing the phase delay profile in the form of a circular truncated cone with a controlled position of centre and fixed directions of the major axes of the ellipse, which are parallel to the aperture edges, are presented. Phase elements with this profile make it possible to displace the focal spot along the aperture, providing an enlarged waist depth.

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