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Modal liquid-crystal wavefront corrector on a ceramic substrate: the single-contact approximation

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Abstract. **The possibility of manufacturing a multichannel modal liquid-crystal corrector of a new type based on a ceramic substrate with a high permittivity is confirmed theoretically and experimentally. A mathematical model of the single-electrode corrector is proposed and used to study the dependences of the voltage and phase profiles on the properties of the corrector design. The technology of manufacturing a ceramic substrate with built-in electrodes is developed.**

Keywords: *liquid crystals, spatial light modulators, adaptive optics.*

1. Introduction

Liquid-crystal (LC) optical adaptive devices are characterised by low control voltages, they are technologically effective and comparatively low-cost, and are of considerable interest for applications in low-cost adaptive optics systems used in astronomy, medicine, and industry. There exist two types of LC wavefront correctors: modal and zonal modulators.

Electrodes in typical electrically controlled zonal multielement LC modulators are in direct contact with a LC layer [1 – 3]. As a result, if the electrode size is greater than the LC layer thickness, the electric potential in the contact region is constant. However, the potential gradient between contact electrodes is high, which adversely affects the phase response of the corrector, resulting in diffraction losses in regions between contacts and formation of a step profile of the phase delay.

Modal LC correctors produce smooth phase profiles and require a smaller number of contact electrodes to compensate for low-order aberrations. We have developed correctors of this type [4 – 6]. However, they also have small regions where electrodes contact with a LC layer, which deteriorates the quality of wavefronts being formed.

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In this paper, we propose an alternative approach to the development of modal LC correctors. The approach is based on the use of fields produced by electrodes not contacting directly with a LC layer. This allows one to obtain smooth phase surfaces without inhomogeneities. We studied the possibility of manufacturing a modal LC corrector based on a thick dielectric layer for producing the modal response from an individual electrode. Ceramics with a high permittivity ($\sim$ 10000) was used as a dielectric. The first results of the verification of this approach are presented in [7, 8]. In this paper, we propose the designs of correctors based on this principle and the method for manufacturing a ceramic substrate with built-in cylindrical electrodes. The mathematical model of the corrector in the single-contact approximation is developed. We simulated numerically the distribution of the voltage applied to the LC layer and the phase profile of the reflected wave depending on the geometrical parameters of the corrector model. The optical response function of the corrector is studied experimentally.

2. Scheme of the LC corrector on a ceramic substrate and its operation principle

Figure 1a shows the principal scheme of the LC corrector based on a ceramic substrate. The corrector represents a multilayer structure. Liquid-crystal layer (*7*) is located between two cylindrical substrates, one of them made of glass and the other – of ceramics. On the upper substrate a mirror is located, and the lower substrate is covered with a transparent conducting layer. This layer is low-resistance, so that the potential in all its points is the same. Metal electrodes in the form of cylindrical rods are located in the upper substrate.

The operation of such a phase corrector is based on the electrooptical orientation S effect in nematic liquid crystals (NLCs). The principle of this effect is as follows. The electric voltage applied to a NLC layer causes the spatial reorientation of molecules, resulting in a change in the refractive index. By controlling the strength and spatial distribution of the electric field in the LC layer (Fig. 1), we can control the phase profile of the reflected wave.

We propose to use in the corrector the inhomogeneous spatial field distribution produced by each electrode located inside the ceramic substrate. Due to the high permittivity ($\sim 10^4$) of the ceramic substrate, the field strength (or the potential gradient) in it is small. As a result, the applied voltage drops mainly in the LC layer (high transfer coefficient), and the potential distribution along the substrate – LC layer interface is smooth and its width greatly exceeds the contact electrode diameter.

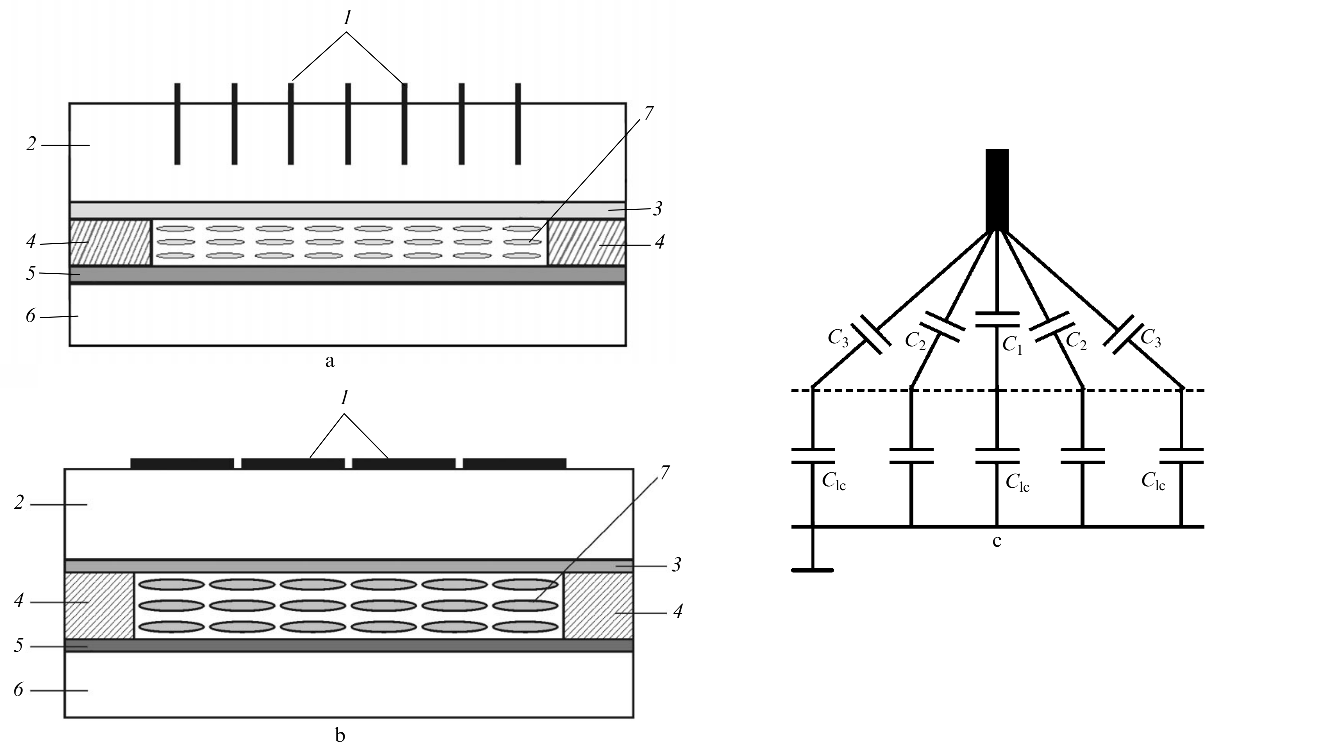

Figure 1. Schemes of the modal LC corrector based on a ceramic substrate with built-in electrodes (a) and electrodes located on the surface (b), and the equivalent electric circuit for one electrode (c): (*1*) metal electrodes; (*2*) ceramic substrate; (*3*) mirror; (*4*) spacers; (*5*) low-resistance electrode; (*6*) glass substrate; (*7*) NLC layer.

From the point of view of the circuit theory, this system represents a distributed capacitive voltage divider (Fig. 1c). The voltage applied between the contact and ground electrodes is divided between the capacities of the ceramic and LC layers. Note that the capacity of the ceramic layer decreases with distance from the contact electrode axis due to the increase in the distance between the electrode edge and LC layer boundary ($C_1 > C_2 > C_3 > ...$). The decrease in the capacity leads to the increase in the reactance of the layer, resulting in the decrease in the voltage drop across the LC layer. Thus, the potential distribution along the ceramic substrate – LC layer interface should have the downward going profile with a maximum at the contact axis. This variant of the corrector eliminates the step voltage distribution, which is observed for zonal correctors [1 – 3]. Note that, due to the absence of a direct contact between electrodes and the LC layer, the potential distribution should be smoother than that in modal multichannel LC correctors developed earlier [4 – 6].

Another variant of the corrector is presented in Fig. 1b, where electrodes are located not inside the ceramic substrate but are formed on its surface. The electrodes can be formed either by structuring the external metal layer of a printed-circuit board contacting with the ceramic substrate (as described in [7]) or by etching a conducting layer deposited on the substrate. Each of the schemes presented in Figs 1a, b has its own advantages.

The arrangement of electrodes inside the substrate allows the use of thick substrates which have good strength and better flatness. In this case, the control voltage range is independent of the substrate thickness. An increase in the substrate thickness in correctors of the second type leads to a strong increase in the control voltage, which can achieve a few hundreds of volts. On the other hand, the formation of contacts on the surface reduces the capacitive influence of electrodes on each other and the density of their location can be increased without additional expenses. In addition, the use of transparent dielectric substrates and ITO (indium and tin oxides) electrodes is promising for the development of transparent modal wavefront correctors, which have no analogues.

3. The mathematical model

Figure 2 presents the model of a corrector based on a ceramic substrate.

We assume that ceramics and a NLC are dielectrics with the constant permittivity. Because NLC correctors are controlled by ac voltage, the spatial distribution of the potential in each medium is described by the wave equation

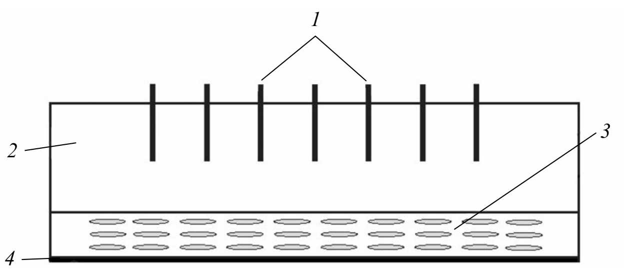

Figure 2. Model of the LC corrector based on a ceramic substrate: (*1*) electrodes; (*2*) ceramic substrate; (*3*) NLC layer; (4) low-resistance electrode.

$$\Delta\varphi - \frac{\mu\varepsilon}{c^2}\frac{\partial^2\varphi}{\partial t^2} = 0, \qquad (1)$$

where Δ is the Laplace operator; ε and μ are the permittivity and permeability of the medium; c is the speed of light in vacuum; and t is time.

However, for the operation voltage frequencies (1 – 100 kHz), the wavelength proved to be considerably larger than the characteristic size of the system under study. The permittivity of media in this frequency range is constant, and therefore we can use the quasi-stationary field approximation [9]. Then, the potential distribution is a frequency-independent function and is determined by the Laplace equation

$$\Delta\varphi = 0. \qquad (2)$$

To determine the properties of the voltage distribution in the LC layer, we consider the case when voltage is applied only to the central electrode in the ceramic substrate. We will select a coordinate system so that the z axis passes through the symmetry axis and the xy plane coincides with the plane of a low-resistance electrode. Then, due to the axial symmetry of the problem, Eqn (2) will have the form

$$\frac{\partial^2\varphi}{\partial r^2} + \frac{1}{r}\frac{\partial\varphi}{\partial r} + \frac{\partial^2\varphi}{\partial z^2} = 0 \qquad (3)$$

in the cylindrical coordinate system, where r and z are cylindrical coordinates.

This equation should be supplemented by the boundary conditions

$$\varphi|_{\Omega} = \varphi_0,$$

$$\varphi(r, z = 0) = 0, \qquad (4)$$

$$\frac{\partial\varphi(r = 0, z)}{\partial r} = 0.$$

Here, Ω is the contact electrode surface. On the medium interface the standard conditions of the continuity of the normal components of the electric field induction vector should be fulfilled. We assume that the potential vanishes at large distances from the corrector.

Of most interest for practical problems is the potential distribution at the ceramics – LC interface and its dependences on the corrector design properties such as the electrode diameter and its immersion depth. The results of simulation are presented in the next section.

4. Results of simulations

The system under study is a multilayer structure with a complex boundary. Because of this, Eqn (3) with the corresponding boundary conditions was solved numerically. Simulations were performed by using a LC corrector with the following geometrical and electrophysical parameters: the ceramic substrate thickness was 5 mm, the LC layer thickness was 12.5 μm, the ceramic substrate radius was 20 mm, the permittivity of the ceramics and LC layer was 10^4 and 13.5, respectively. We assumed in calculations that the permittivity of the LC layer is constant and equal to its mean value for the BL037 LC (Merk, Germany) used in the study. Figures 3 – 6 present the results of numerical simulations performed for the corrector on a ceramic substrate, which are compared with calculations performed for a similar corrector based on a glass substrate with a high-resistance layer [4].

One can see from Fig. 3a that the radial voltage distribution on the LC layer for the corrector on a ceramic substrate near the contact decreases slower than that for a similar modal corrector based on a glass substrate with built-in contacts. Therefore, the phase delay will change slower with distance from the contact (Fig. 3b). The corrector proposed here does not have the region of direct contact between the electrode and LC layer, and therefore regions with the constant voltage and phase are not observed. This in turn leads to the elimination of local jumps of the phase gradient near the contact, which are observed in modal correctors based on a glass substrate. The radius of the rod electrode in the corrector on a ceramic substrate used in calculations was set equal to 0.75 mm. The distance from the rod end to the LC layer was 1 mm. The geometrical parameters (distance between electrodes and

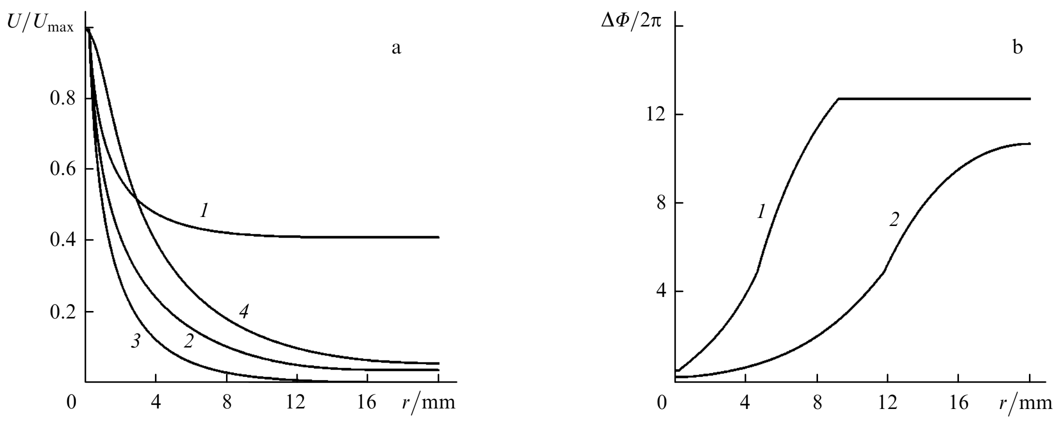

Figure 3. Radial voltage distributions normalised to the maximum for a corrector based on a glass substrate with built-in electrodes [curves (*1, 2, 3*) correspond to voltage frequencies 1, 10, and 50 kHz, respectively], for a corrector based on a ceramic substrate with built-in electrodes for the voltage frequency 10 kHz (*4*) (a), and the phase delay distributions for a modal corrector based on a glass substrate with built-in electrodes (*1*) and a corrector based on a ceramic substrate with built-in electrodes (*2*) with the voltage frequency 10 kHz (b).

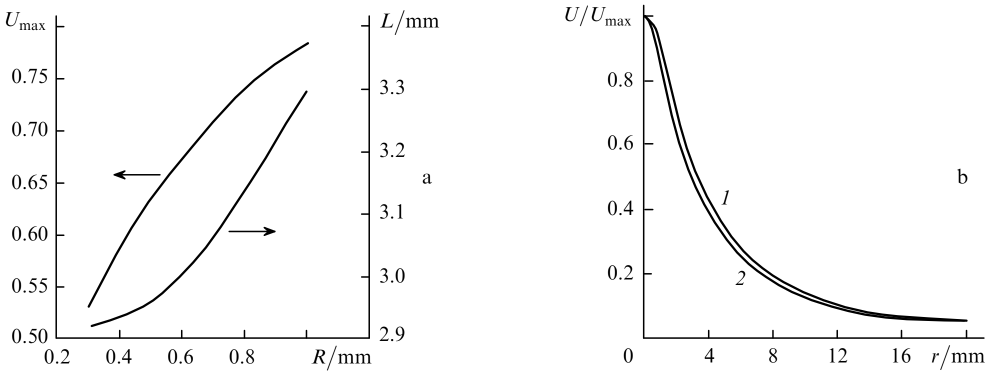

Figure 4. Dependences of the maximum voltage normalised to the electrode voltage on the electrode radius R and the voltage distribution half-width L (a), and radial voltage distributions for electrodes of diameters 1.0 (*1*) and 2 mm (*2*) (b). The distance from the electrode end to the LC layer is 1 mm.

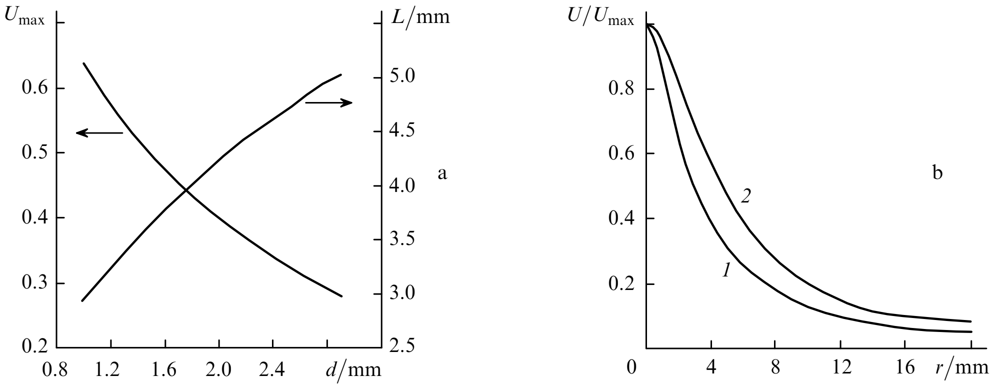

Figure 5. Dependences of the maximum voltage normalised to the electrode voltage on the distance d from the electrode to the LC layer and the voltage distribution half-widths L (a), and voltage distributions for $d = 1.0$ (*1*) and 2.5 mm (*2*); the electrode diameter is 1.0 mm.

their location, the layer thickness) of the modal corrector based on a glass substrate with a high-resistance layer and the electrophysical parameters of the LC layer are similar to those of the ceramic corrector. The electrode radius is 0.25 mm and corresponds to a real sample.

The voltage profile applied to the LC layer in the corrector under study can be controlled by different methods. The potential distribution should depend on the electrode radius and its immersion depth. As follows from simulations, the maximum value of the potential across the LC layer increases with increasing radius, which is caused by the increase in the area of the charge surface (Fig. 4a). Note that this is not accompanied by a noticeable change in the potential distribution itself (Fig. 4b). For example, its width L increases by no more than 15 %, whereas the maximum value virtually doubles.

Simulations of correctors with different electrode immersion depths revealed the following properties. As the distance d from the contact to the LC layer is increased, the potential maximum decreases by several times and the width of the voltage distribution considerably increases (Fig. 5). This is explained by the fact that the capacity of the ceramic layer (C_1, C_2, C_3, etc., Fig. 1c) decreases with this distance. As a result, the capacitive resistance of this layer increases and, therefore, the voltage drop across the LC layer decreases. The increase in the voltage distribution half-width is directly caused by the removal of the electrode from the LC layer.

Thus, the results of simulations show that the corrector of this type provides smooth voltage distributions of shape depending on the corrector design. The most important parameter is the distance d between the contact electrode and LC layer. As d is increased, the voltage drop across the LC layer decreases but the voltage distribution width increases. Variations in the electrode diameter mainly affect the maximum of the voltage distribution rather than its shape.

5. Experimental study of the LC corrector on a ceramic substrate

We fabricated a LC corrector by developing the technology of manufacturing ceramic substrates with built-in cylindrical electrodes. Holes of two diameters were drilled in a plate: holes of a small diameter – to a depth of smaller by 1 – 2 mm than the plate thickness, and coaxial holes of a large diameter – to a depth of smaller by 3 – 4 mm than the plate thickness. Such a configuration is determined by the necessity to minimise the mutual capacitive influence of electrodes and to fix electrodes in the plate. A small-diameter hole is filled with a readily deformable metal, for example, indium, and an electrode of the required length and diameter is inserted into it. After the assembling of electrodes, larger-diameter holes are filled with a polymerising composition, for example, an epoxy compound or acryl-based plastic. This allows us to fix reliably electrodes in the plate.

We fabricated a 5-mm-thick ceramic plate of diameter 40 mm polished to the flatness level $\lambda/4$ for $\lambda = 633$ nm. The BL037 NLC was used in the corrector. The thickness of

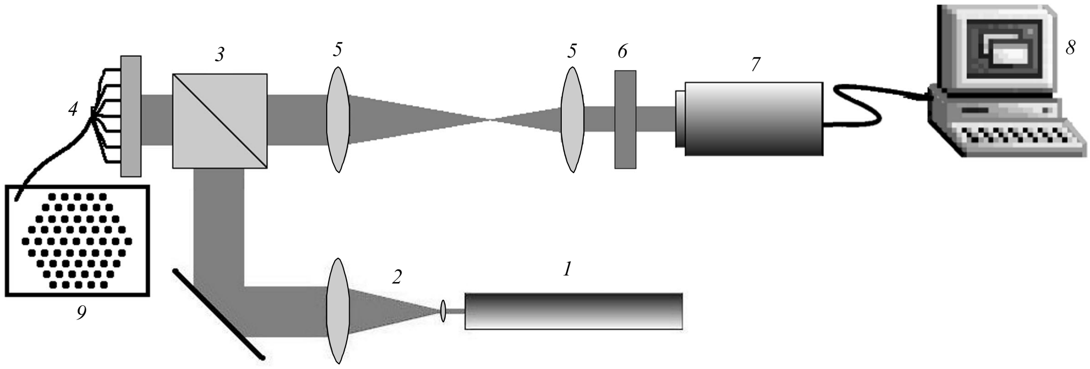

Figure 6. Scheme of a polarisation interferometer for studying the wavefront shape: (*1*) He–Ne laser; (*2*) collimator; (*3*) beamsplitter; (*4*) LC corrector; (*5*) lens; (*6*) polaroid; (*7*) CCD camera; (*8*) personal computer; (*9*) voltage generator.

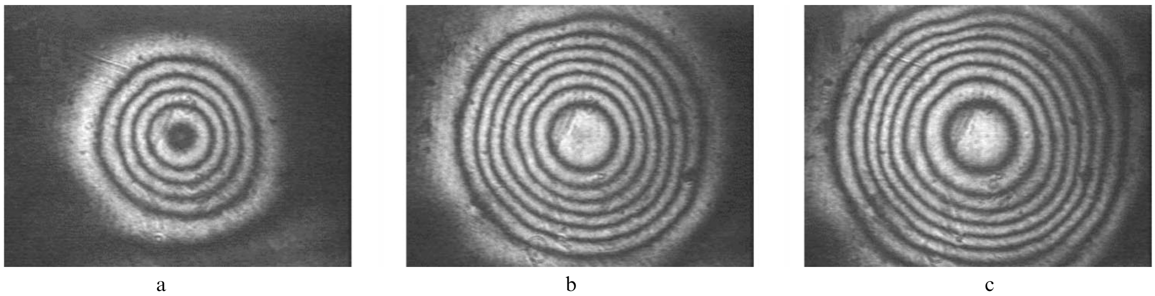

Figure 7. Interferograms of the wavefront produced by the central electrode for electrode voltages at the frequency 10 kHz and amplitudes 20 (a), 40 (b), and 69 V (c).

the LC layer determined by calibrated spacers was 12.5 μm and the maximum range of phase variation was 10λ. The electrodes had different diameters and were located at different distances from the LC layer. They were arranged in a hexagonal structure. The corrector response was studied by the interferometric method in a scheme with crossed polaroids (Fig. 6). The corrector was oriented so that its optical axis was directed at an angle of 45° to the polarisation plane of the incident laser beam. A voltage supply was an audio-frequency sine-wave generator.

We found that the response of the LC corrector in the frequency range from 1 to 100 kHz was independent of the voltage frequency, which is caused by the absence of the dispersion of permittivity of the LC and ceramic layers. This confirms the validity of the quasi-stationary field approximation used to explain the corrector operation. Because of this, we performed all studies only at one voltage frequency equal to 10 kHz. The results are presented in Figs 7–12.

One can see from Fig. 7 that the phase delay profile of the corrector for one electrode is close to axially symmetric. In this case, the width of the phase distribution will depend on the voltage difference at the picture centre and the threshold voltage for the S effect below which the spatial reorientation of NLC molecules does not occur. The phase delay depends only on the applied voltage. As this voltage is increased, the drop of the phase distribution increases.

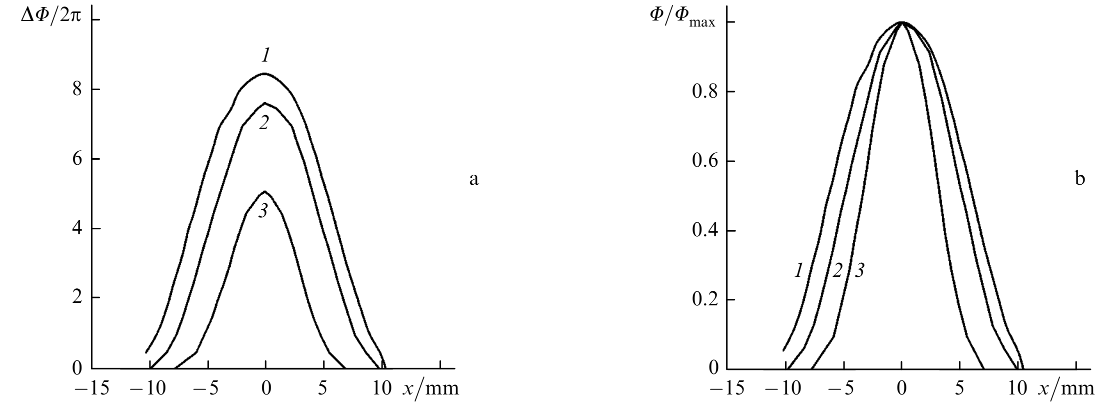

Figure 8. Real (a) and normalised (b) profiles of the wavefront formed by one electrode of the corrector on a ceramic substrate for voltage amplitudes 60 (*1*), 40 (*2*), and 20 V (*3*).

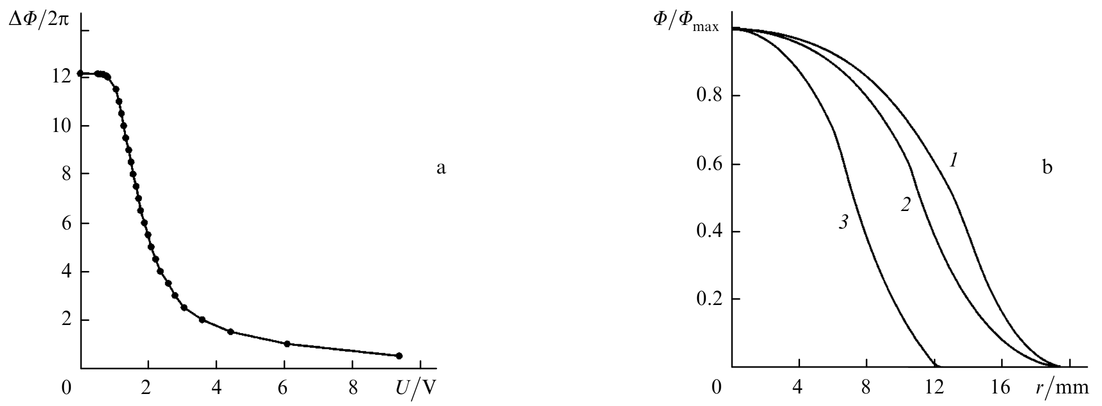

Figure 9. Volt – phase characteristic of a 25-μm-thick BL037 LC layer (a) and normalised profiles of the wavefront formed by one electrode of the corrector on a ceramic substrate (b) for the voltage amplitude 60 (*1*), 40 (*2*), and 20 V (*3*).

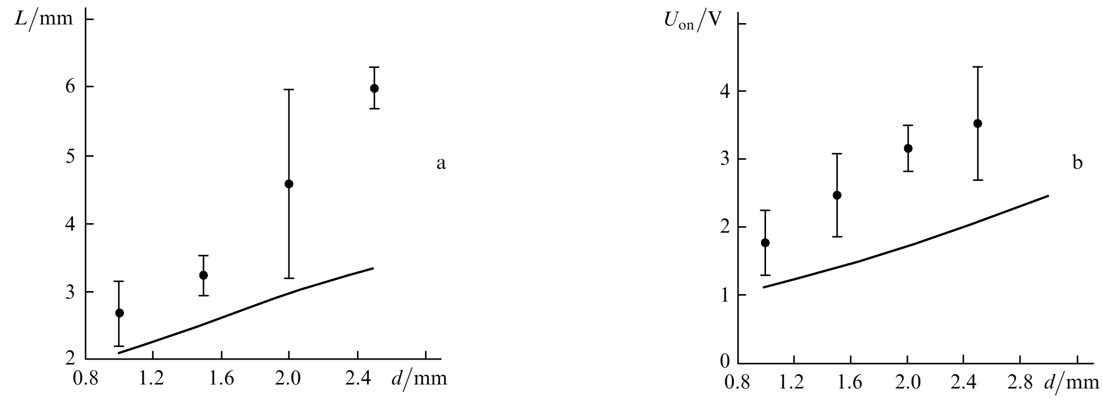

Figure 10. Experimental (points) and theoretical (solid curves) dependences of the phase distribution half-width (a) and the switching voltage (b) on the distance *d* between the electrode end and the LC layer.

Figure 8 presents the corresponding wavefront profiles in the cross section along the line passing through the centre of symmetry of the interference pattern.

One can see from the normalised wavefront phase distributions that the profile width increases with the voltage applied to the electrode. This is caused by the nonlinear dependence of the phase delay in the LC layer on voltage (volt – phase characteristic) (Fig. 9). Thus, for large voltages on the electrode, the voltage drop in the LC layer corresponds to the nonlinear region of the volt – phase characteristic (the operating voltage above 2 V). The dependence of the phase delay in the LC layer on voltage in this region is flatter than that in the linear region. As a result, the phase decrease rate in the wavefront profile will be considerably smaller that that in the linear region for the same voltage distribution. Therefore, even for identical voltage distributions in the case of high potentials, the phase distribution will have a greater width.

As pointed out above upon simulations, the width of the phase delay distribution depends on the distance of the electrode from the LC layer. It was found experimentally that the phase distribution width increased with distance, which is confirmed by theoretical calculations (Fig. 10a). The theoretical dependences presented in Fig. 10 were obtained from normalised voltage distributions calculated by using the proposed model. The experimental data are presented for electrodes of diameter 1.5 mm. For the electrode diameter of 1.0 mm, these dependences are similar.

We estimated from experimental data the switching voltage U_{on}, i.e. the minimal voltage that should be applied to the corrector electrodes to induce the LC reorientation. The threshold voltage for the LC itself is 0.82 V. Because the voltage applied to the electrode in our corrector is divided between the capacity of ceramic and LC layers, the switching voltage for the corrector will be higher than the threshold voltage for the LC layer. Figure 10b shows its dependence on the distance between the electrode and the LC layer.

In the cases considered above, voltage was fed only to one electrode. By applying voltage to all electrodes, we can form arbitrary distributions of the potential and phase delay. Figure 11 presents phase delay distributions for the case when the same voltage was fed to three electrodes. This situation was simulated in the single-contact approximation. The potential distribution was found by the summation of distributions from each of the electrodes assuming that they have the same response function. The value of the voltage applied to electrodes was selected to match the range of the phase distribution with experimental values. The dimensions of the theoretical and experimental patterns in Fig. 11 are the same and equal to 22×16 mm.

Thus, we have demonstrated experimentally the efficiency of the LC wavefront corrector based on a ceramic substrate. The mathematical model correctly qualitatively describes the dependences of the voltage and phase profiles on the corrector design.

a b c

Figure 11. Phase delay distributions: calculated phase profile (a) and interference pattern (b), and the interference pattern obtained in the scheme with crossed polaroids (c).

6. Conclusions

We have confirmed theoretically and experimentally the possibility of manufacturing a multichannel modal LC corrector of a new type based on a ceramic substrate with the high permittivity. We have developed the technology for manufacturing substrates with built-in electrodes, which is simpler than the manufacturing technology of glass substrates with built-in electrodes used in modal LC correctors that we developed earlier. The efficiency of the new corrector has been demonstrated experimentally. It has been shown that the spatial distribution of the phase delay depends on the voltage applied to electrodes and is independent of the voltage frequency. The width of the optical response function is mainly determined by the distance between the LC layer and the electrode end. The most suitable are electrodes of diameter 1.5 mm located at a distance of 1.5 mm from the LC layer. The method of manufacturing multielement modal correctors proposed in the paper offers some advantages both over zonal and modal LC correctors developed earlier.

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