$LiNBO_3$ CRYSTAL BASED ELECTROOPTIC PHASE FRONT CORRECTORS FOR ADAPTIVE OPTICAL SYSTEMS: A PERFORMANCE STUDY

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Results of experimental investigations into the possibilities of constructing $LiNbO_3$ crystal based phase front correctors with prescribed spatial modes are presented. A technique for adjusting the shape of driving electrodes is described. It is shown that the suggested corrector is free from several flaws typical of flexible mirrors.

The operational devices most often employed to compensate for nonstationary wavefront disturbances in the adaptive optical systems are controllable mirrors and phase plates.[1] Since designing optical feedback for systems with phase plates is quite a complicated task, at present the most widely used devices employed in adaptive systems of phase conjugation and aperture sensing are mirrors driven by electric signals.[2,3,4]

Along with certain advantages such phase front correctors also have some weak points. First of all, it is rather hard to obtain the response functions of prescribed form using such mirrors. Second, such devices, being in general mechanical, are characterized by hysteresis and phase delays[2,4,5] which limit their application in systems without feedback. As a rule, the response speed of such correctors is also rather low. Obviously, the design and construction of new operational devices for adaptive optical systems is an urgent task. In connection with this it should be noted that one of the promising new directions in the development of adaptive optical systems consists of expanding the phase front in a sum of spatial modes. Taking the statistical properties of nonstationary phase front distortions into account, the optimal basis for such an expansion is seen to be the Karhunen-Loéve basis. A good approximation to such a basis can be obtained by applying orthogonal polynomials to our problem.

This paper presents an experimental analysis of the possibility of building an electrooptical phase front corrector that is capable of correcting a phase front' represented as a combination of prescribed spatial modes.

Let us consider the operating principle of an electrooptical corrector. To control the phase front parameters efficiently, one needs crystals with a strong enough electrooptical effect. One such crystal is $LiNbO_3$. To minimize its driving voltages, its electrodes must be mounted on the crystal normal to its segnetoelectric axis, in order to . make use of the electrooptical coefficient r_{33}, which is maximal for the given crystal. When optical radiation passes through the crystal along its y axis (see Fig. 1) a beam polarized along the z axis acquires an additional phase shift:

$$\varphi_3^{(x)} = \frac{1}{\lambda}\left[n_1 l_0 - \frac{1}{2} n_1^3 r_{33} E_3 l(x) \right]. \quad (1)$$

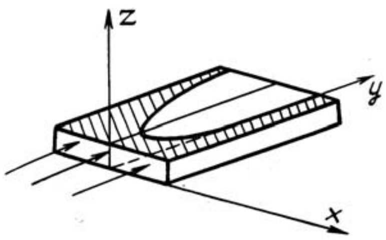

FIG. 1. Beam, path for the $LiNbO_3$ crystal. The axes correspond to the notation: x – 1, y – 2, z – 3.

A beam polarized along the x axis acquires a phase shift of

$$\varphi_1^{(x)} = \frac{1}{\lambda}\left[n_0 l_0 + \frac{1}{2} n_0^3 r_{13} E_3 l(x) \right]. \quad (2)$$

where $l(x)$ is a function that describes the shape of driving electrodes, mounted on the two faces of the crystal.

Proper selection of the electrode shapes can provide the necessary type of phase correction as a single spatial mode that is a function of the coordinate x. Two such correctors introduced in succession will produce a total phase shift of

$$\Delta\varphi(E, x, z) = Al_0\left[2 - \frac{E_3}{l_0}(l(x) + l(z))\right], \quad (3)$$

where $A = \frac{1}{2} n_0^3 r_{33}$.

The dependences $l(x)$ and $l(z)$ are better chosen as

$$l_i(x) = \Phi_i(x);\ l_j(z) = \Phi_j(z);\ i = \overline{1, N_1};\ j = \overline{1, N_2} \quad (4)$$

where $\Phi_i(x)$ and $\Phi_j(z)$ are the respective orthogonal bases in x and z; N_1 and N_2 give the number of orthogonal functions in the chosen expansion. Actually, N_1 and N_2 correspond to the number of chosen spatial modes. To implement a phase front corrector capable of compensating for nonstationary distortions of arbitrary type, one has to properly position the N_1 correctors that introduce correction of the form $l_i(x)$, and the N_2 correctors that introduce correction of the form $l_j(z)$. The total "response" of the corrector is then written in the form

$$\Delta\varphi(x,z) = \sum_{i=0}^{N_1} a_i \Phi_i(x) + \sum_{j=0}^{N_2} b_j \Phi_j(z). \tag{5}$$

It follows from Eq. (2) that the phase change along the wavefront, acquired in the crystal, is equal to the product of the field intensity between the electrodes and the maximum length of the beam path in the interelectrode space in the crystal l

$$\Delta\varphi_{max} \approx \frac{U}{d} l, \tag{6}$$

where d is the crystal thickness, $d \ll l$.

The electrode contours determine the field configuration in the crystal to the accuracy of approximately the crystal thickness. The shape of the driving electrode must vary across the crystal, according to the law $\Phi_i(x)$ or $\Phi_j(z)$, wherefore the width of the crystal entrance window must be much larger that the thickness of the crystal. This limitation results in the necessity of narrowing the light beam in the respective planes, using cylindrical lenses for the purpose. The corrector element performing the phase correction of one spatial mode will be a system of the form "cylindrical lens – crystal – cylindrical lens" with the center of the crystal placed at the focus of the lens. It is clear from simple geometric arguments that the width of the cylindrical lens should be not less than the crystal width h_c, and the lens height d_L, should be not less than $d_L \ge d\frac{2F}{l}$, where F is the focal distance.

The above-presented considerations for choosing the electrode shapes are valid for a homogeneous field between the electrodes, $d \ll l_0$. However, in the fabrication of phase correctors from $LiNbO_3$ crystals, one faces edge inhomogeneities of the electric field. The dependences $\Phi_i(x)$ and $\Phi_j(z)$ vary along the beam path through the crystal. The effect can, to a first approximation, be estimated by considering the model problem of the field distortion in a capacitor with circular electrodes of radius R_0

$$\Phi(R) = \frac{1}{U}\int_0^R E(r)\,dr, \tag{7}$$

where U is the inter-electrode potential difference; $E(r)$ is the electric field strength on the mid-plane of the capacitor at a distance r from its center. Then $\Phi(R)$ is expressed in units of the capacitor thickness.

Calculations based on Eq. (7) for different "capacitor thickness–to-electrode radius" ratios are presented in Fig. 2 (each ratio value is indicated in the plot). It can be seen from the figure that the minimum size of the driving electrodes along the y axis Д6 should be not less than d.

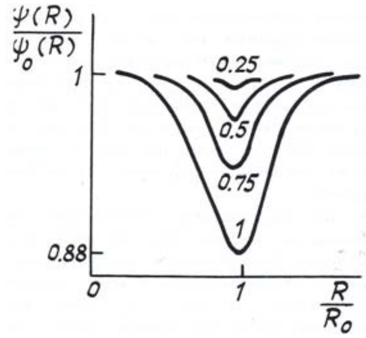

FIG. 2. Electrode shapes.

For $\Delta b > 4d$ field inhomogeneities can be neglected. In other cases this effect must be accounted for by introducing the corresponding corrections into the electrode shapes when the corrector elements are manufactured, according to the results shown in Fig. 2. It should be noted that the distance from the crystal edge to the electrode edge must be greater than or equal to half the crystal thickness.

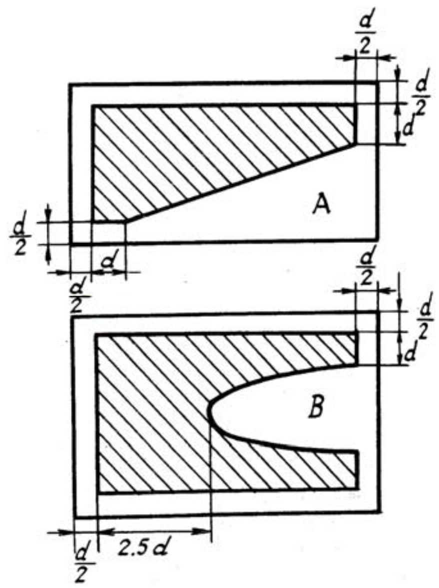

FIG. 3. Electrode shapes for $LiNbO_3$ samples, d is the crystal thickness

To carry out the experimental studies we manufactured $LiNbO_3$ phase corrector elements of 30×20×2 mm size. Their shape is shown in Fig. 3. The electrodes were produced by cathode vacuum deposition of platinum. Pre-selected crystals of minimal inhomogeneity were used. To further eliminate possible inhomogeneities, the crystals were subjected to polarization processing following a technique described in Ref. 6. The contours of the phase correction spatial modes were then studied on an experimental setup, a block diagram of which is presented in Fig. 4. The laser beam, which is first polarized by the polarizer 2, passes through the crystal 3, which has a driving voltage of 2 kV fed to its electrodes. In such a case the refractive index of the part of the crystal that is inside the generated electric field becomes different from that in the unaffected part of the crystal. The laser beam is refracted at the two resulting inner interfaces, changes its direction by an angle $\alpha(x)$ proportional to the derivative of the spatial mode of the corrector element at the given point $\bar{x}$. The value of $\alpha(x)$ may be determined from the shift of the beam position on the screen.

$$\alpha(x) = \beta \frac{\Delta h}{L}, \tag{8}$$

where Δh is the shift itself, and β is a normalizing coefficient.

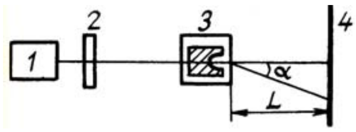

FIG. 4. Block diagram of the experimental setup: 1) LGN-105 laser; 2) polarizer; 3) crystal; 4) screen; α is the laser bear, deviation angle (when the driving voltage is fed to the electrodes)

Two samples A and B were examined experimentally (see Fig. 3). The laser beam was shifted parallel to the major (longer) crystal face (y axis, Fig. 1) stepping at the beam thickness (1 mm). The actual spatial modes of the corrector elements were reconstructed by numerically integrating the experimental data. To reduce the measurement errors the experiment was repeated several times and its data processed using statistical techniques. An analysis of the results demonstrated that the actual spatial modes of the corrector elements correspond to the electrode shapes to within an error of 20%. Such a low level of accuracy is apparently the result of inhomogeneities in the $LiNbO_3$ crystals and from insufficient experimental accuracy.

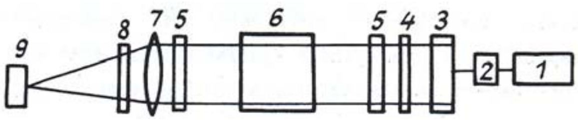

FIG. 5. Block diagram of the experimental setup: 1) LGN-105 laser; 2) modulator; 3) collimator; 4) phase plate; 5) cylindrical lenses; 6) $LiNbO_3$ crystal; 7) circular, *lens; 8) polarizer; 9) photodetector*

To study the practical possibility of using $LiNbO_3$ crystals in adaptive optical systems, a separate experiment was carried out on the setup shown in Fig. 5. The beam from the LGN-105 laser 1 is modulated, collimated, and then stationary phase distortions are introduced into it. The beam thus formed enters the corrector of the above-described design ("cylindrical lens – crystal – cylindrical lens") and then, after passing through the polarizer and the circular lens, is focused upon a point photodetector,. The essence of the experiment consists in the following. The envelope of the photodetector signal is recorded in the absence of a driving voltage at the corrector crystal. *A-priori* known phase distortions are then introduced into the beam and the amplitude of the photodetector signal corrector elements. The crystal electrode shapes examined in the experiment are shown in Fig. 3. The first one corresponds to the overall phase front tilt, and the second – to defocusing of kx^2 type. As a result of the experiment we were able to increase the beam intensity at the photodetector by a factor of 1.5–1.7 while compensating for phase front tilts, and by 1.7–2.0 – while compensating for defocusing.

CONCLUSIONS

The foregoing experiments demonstrate the fundamental possibility of using electrooptical crystals to correct phase distortions. One of the advantages of such crystals is their lack of hysteresis. Optical losses in bleached crystals are as low as 2%. Note however a fundamental flaw of the lithium niobate crystals – their low radiation strength ($\xi \leq 100$ MW/cm^2), which limits their operational power density to 30–50 MW/cm^2 (Ref. 7). Electrooptical crystals can serve as a basis for phase correctors of prescribed capabilities, since their spatial mode profile and type depend on the driving electrode shape only, which in turn can be quite arbitrary. A significant advantage of adaptive optical systems with correctors built around electrooptical crystals is the complete independence of the control channels. By applying algorithms of aperture sensing to organize such control, the rate of convergence of the system to its maximum figure of merit is increased.

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