Light Beams' Focusing in Biaxial Ferroelectrics

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Abstract

Among problems of modern optics the elaboration of the methods of formation and control by the space structure of light beams is of great importance. In the papers [1,2] it has been shown that the nonlens focusing and nondiffractional propagation of light, stipulated by the presence of concavity of wave vector surface, are possible near by optical axes of biaxial gyrotropic crystals. The application of external electric field leads to strengthening of concavity and then, increasing of focusing effect for slow waves near binormals [3]. But conducted consideration was limited by the case of the most symmetrical biaxial crystal, namely, orthorhombic one. At the same time many widely used gyrotropic biaxial crystals have lower symmetry. For example, their symmetry is of 2 or m class. Its description is very complex, but at the same time is of essential interest in the connection with enlargement of possibilities of controlling by parameters of optical radiation.
It is known that the big electrooptic effect takes place in ferroelectrics which have orientational spontaneous polarization in definite temperature range in the absence of external electric field. Characteristic peculiarity of given media is strong temperature dependence of optical and electrooptic properties which may be used for control by the focusing of optical radiation.
The aim of the paper is investigation of influence of electric and temperature fields on focusing properties of the lens created on the base of lower symmetrical ferroelectric crystal of 2 class.

1. Introduction

In this paper we analyze the peculiarities of wave vector surface near binormal of biaxial gyrotropic crystal of 2 class symmetry. It has been shown that the presence of gyrotropy leads to appearance of concavity on the wave vector surface for slow light wave and, hence, to possibility of focusing. It has been founded the conditions for this phenomenon. It has been analyzed the influence of temperature and electric field near Curie point on light beam focusing in ferroelectric crystals. It has been grounded that electrooptic interaction in ferroelectric lower symmetrical biaxial crystals may be used for creation of electro- and thermocontrolled crystalline lenses for which one can achieve slow thermochanges of focus length in wide range and fast changes of it by electric field. If the temperature is near Curie point the range of changes of focus length increases abruptly, but the aperture of proposed lenses decreases. By this, it is necessary to thermocontrol of crystalline model. Thus, while creating such elements you must conduct parameter optimization.

2. Peculiarities of Structure of Wave Vector Surface of Monoclinic Crystal near by Optical Axes

It is known [4] that the field of light radiation in the crystal in general case may be presented in the form:

$$\underline{E}(\underline{r},t) = \{(2\pi)^{-2}\int A\,(\underline{q})\,\underline{a}\; exp\; i[(\underline{r}-\underline{U}\,t)\underline{q} - \frac{1}{2}W\,\underline{q}\underline{q}\;t]\}x\;\; exp\; i(\underline{k}_o\,\underline{r} - \omega_o\,t), \qquad (1)$$

Here $\underline{E}$ is the electric vector, A are amplitudes, $\underline{a}$ are polarization vector, $\underline{q} = \underline{k} - \underline{k}_0$; ω_0 and $\underline{k}_0$ are correspondently frequency and wave vector of "central" wave of the beam; $\underline{U} = \partial\omega \big/ \partial\underline{k}$ is group velocity; $W = \partial\omega \big/ \partial\underline{k}\,\partial\underline{k}$ is tensor of divergence of the group velocity which is connected with tensor of divergence of the wave vector surface. In the result of analysis of expression (1) it may be obtained that divergence of arbitrary light beam in the crystal is determined by eigenvalues of W tensor, namely: if $W_a > 0$, then, collimated beam in the medium is defocusing; if $W_a < 0$ it is focusing; by $W_a = 0$ it takes place nondiffractional propagation of radiation[4].

Let us consider the structure of wave vector surface in the case of propagation of light beams in the crystal of 2 class symmetry. For this let us analyze characteristic equation [5]

$$det\,L = 0, \qquad (2)$$

where

$$L_{ie} = (\omega/c)^2\delta_{ie} + \Gamma_{im}(a_{me} + i\delta_{mjl}G_j)$$

with $\Gamma_{im} = k_ik_m - k^2\delta_{im}$ and where $G_j = \dfrac{\pi}{\lambda}\,g_{jm}\,k_m$ is gyration vector [6]; g_{jm} is gyration tensor ; $\underline{n}$ is wave normal; λ is light wavelength; δ_{ie}, δ_{imn} are Kroneker' and Levi- Chivita' symbols; a_{ml} is tensor of dielectric nonpermeability. Differentiating of characteristic equation (2) by components of wave vector $\underline{k}$ one may be obtained for the case of correct coincidence of beam's axis with optical axis:

$$W\underline{q}\underline{q} = (V^2/\omega)\,p_\pm\,q^2. \qquad (3)$$

Here

$$p_\pm = (n_o^2/2)[a_1 + a_2 \pm a_o^2/G], \qquad (4)$$

with

$$a_{3,1} = \{\,a_{11} + a_{33} \pm A^{1/2}\}/2\,, \qquad (5a)$$

$$a_2 = a_{22}\,, \qquad (5b)$$

$$A = [a_{11} - a_{33}]^2 + 4\,a_{13}^2, \qquad (5c)$$

$$a_o = [(\,a_2 - a_3)\,(a_3 - a_1\,)]^{1/2}\,, \qquad (5d)$$

where $n_o^2 = V^2/c^2 = a_3 \pm G$; n_0 and V are correspondently refraction index and phase velocity of light wave in the direction of optical axis in gyrotropic crystal of 2 class symmetry; G is projection of gyration vector on optical axis; $q^2.=.q_1^2 + q_2^2$. By this we consider that $a_2 > a_3 > a_1$ and plane of optical axes coincidences with (X_1X_2) crystallographic one. How it is evident, tensor W in the direction of optical axis has two equal eigenvalues: $W_{11} = W_{33} = W_\pm = (V^2/\omega)\, p_\pm$.

By influence of external electric field along ferroelectric axis X_2 dielectric constants are changed:

$$a_{ii}(E) = a_{ii} + r_{i2}E \tag{6a}$$

$$a_{13}(E) = a_{13} + r_{52}E\,, \tag{6b}$$

where r_{ij} are linear electrooptic coefficients. By this wave vector surface has deformation. Let's consider that the influence of external electric field is weak. By this, eigenvalues of tensor of derivative of group velocity may be determined from (3) by following changes: $a_{ij} \longrightarrow a_{ij}(E)$, $A \longrightarrow A(E)$. Then, how it follows from (3), by the case

$$a_1(E) + a_2(E) < a_o(E)^2/G, \tag{7}$$

eigenvalues of W tensor for slow waves are negative and, hence, in conformity with (1) focusing of slow light wave takes place. In conformity with [7-9] parameters of anisotropy and gyrotropy near Curie temperature in ferroelectric phase of crystal have essential temperature dependence. But correct analytical analysis of wave surface deformation by simultaneous influence of electric and temperature field near point of phase transition has essential difficulties. Let us estimate the focusing properties of ferroelectric crystals on the base of experimental data about physical constants of widely used crystal $NaNO_2$, for example, near Curie temperature.

How it follows from (3), decreasing of gyrotropy parameter G near Curie point Tc leads to strenthening of concavity of the wave vector surface for slow waves. Calculation that coefficient of thermostrenthening of concavity of wave vector surface $\Gamma = p_-(T) / p_-(T_n)$, where $T_n = 20\,^\circ$, for $NaNO_2$ by $T=140^o$ achieves 1.3. Considered peculiarities of electrooptic interaction in lower symmetrical ferroelectric crystals may be used for creating of crystalline lenses. If divergent Gaussian beam falls into the crystal, in accordance with results of [2], the beam is focusing twice: into and out of the crystal on the distance $F_1 = -Z_1 n_o/p_-$ and $F_2 = -(Z_1 + Lp_-/n_o)$ from its entrance correspondently. Here Z_1 is distance from the weak point of entrance beam to crystal with the L length. Then, changes of focus length by variation of p_- are determined by correlations $F_1 = Z_1 n\Delta\, p/\, p_-^2$, $F_2 = L\Delta\, p_-^n/n$ and near Curie temperature may be great. For example, for $NaNO_2$ crystal $F_2 \sim 89\ cm$ by change of temperature from $T_n = 20\,^\circ$ to $T=140^o$ and L=1 cm.

3. Conclusions

In this paper, it is shown that electrooptic interaction in ferroelectric lower symmetrical biaxial crystals may be used for creation of electro- and thermocontrolled crystalline lenses for which one can achieve slow thermochanges of focus length in wide range and fast changes of it by electric field. If the temperature is near Curie point the range of changes of focus length increases abruptly, but the aperture of proposed lenses decreases. By this, it is necessary to thermocontrol of crystalline model. Thus, while creating such elements you must conduct parameter optimization.

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