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PHYSICAL ACOUSTICS

Effect of External Electrical Field on Characteristics of a Lamb Wave in a Piezoelectric Plate

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Abstract—The influence of a homogeneous electrical field **E** on the characteristics and propagation conditions of the Lamb wave in a piezoelectric crystalline plate is considered on the basis of the theory of acoustic wave propagation in piezocrystals under the effect of an external electrical field.

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INTRODUCTION

A theory of and propagation characteristics for acoustic waves in crystalline plates with thickness comparable to wavelength were considered in detail in [1, 2]. These results were used to develop a series of acoustoelectronic devices, in particular, dispersion signal delay lines, phase changers, etc. The influence of a homogeneous electrical field **E** and mechanical stress on the characteristics and conditions of reflection and refraction for bulk acoustic waves at the boundary of piezoelectric crystals is considered in [3–5] on the basis of the theory for bulk acoustic wave propagation in piezocrystals affected by an external electrical field and mechanical stress [6]. Series of papers [7, 8] also studied the influence of a homogeneous electrical field on the propagation anisotropy for zero modes of acoustic Lamb waves in plates of piezoelectric crystals $LiNbO_3$ and $KNbO_3$. The purpose of this work was a detailed analytical and computer investigation of special propagation features for the Lamb and surface-transverse waves in piezoelectrics with cubic symmetry under the effect of a constant electrical field.

PROPAGATION THEORY FOR LAMB WAVES IN A PIEZOELECTRIC CRYSTALLINE PLATE UNDER THE EFFECT OF A HOMOGENEOUS ELECTRICAL FIELD

This paper considers the influence of a homogeneous electrical field on the characteristics and propagation conditions for the Lamb wave in a piezoelectric crystalline plate on the basis of the theory of acoustic wave propagation in piezocrystals under the effect of an external electrical field that is described in detail in [1].

Let us write on the basis of the theory developed in [2] the basic equations describing the effect of an electrical field **E** on propagation conditions for acoustic waves in a piezoelectric medium. In the initial coordinate system, wave equations for small-amplitude waves in homogeneously deformed acentric media and the equation of electrostatics have the form [1]

$$\begin{aligned} \rho_0 \ddot{\tilde{U}}_A &= \tilde{\tau}_{AB,B}, \\ \tilde{D}_{M,M} &= 0. \end{aligned} \tag{1}$$

The following notations are adopted in Eq. (1): ρ_0 is the crystal density in the undistorted (initial) state, $\tilde{U}_A$ is the vector of dynamic elastic displacements, $\tilde{\tau}_{AB}$ is the tensor of thermodynamic stress, and $\tilde{D}_M$ is the vector of electric displacement. The tilde indicates here and below time-dependent variables. A comma after an index means a spatial derivative, and Latin coordinate indices vary from 1 to 3. Here and below, we imply summation over double-repeated indices.

To take into account the effect of an electrical field **E** in a piezoelectric crystal, the equations of state for the dynamic components of thermodynamic stress and electrical induction have the forms, respectively,

$$\begin{aligned} \tilde{\tau}_{AB} &= C^*_{ABCD}\tilde{\eta}_{CD} - e^*_{NAB}\tilde{E}_N, \\ \tilde{D}_N &= e^*_{NAB}\tilde{\eta}_{AB} + \varepsilon^*_{NM}\tilde{E}_M, \end{aligned} \tag{2}$$

where $\tilde{\eta}_{AB}$ is the deformation tensor and the effective elastic, piezoelectric, and dielectric constants are determined by the expressions

$$\begin{aligned} C^*_{ABKL} &= C^{\mathrm{E}}_{ABKL} + \left(C^{\mathrm{E}}_{ABKLQR}d_{JQR} - e_{JABKL}\right)M_J\bar{E}, \\ e^*_{NAB} &= e_{NAB} + \left(e_{NABKL}d_{JKL} + H_{NJAB}\right)M_J\bar{E}, \\ \varepsilon^*_{NM} &= \varepsilon^{\eta}_{NM} + \left(H_{NMAB}d_{PAB} + \varepsilon^{\eta}_{NMP}\right)M_P\bar{E}. \end{aligned} \quad (3)$$

Here $\bar{E}$ is the value of the homogeneous electrical field strength, M_J is the unit vector of the external electrical field direction, and C^E_{ABKLQR}, e_{NABKL}, and H_{NMAB} are nonlinear elastic, piezoelectric, and electrostriction constants (material tensors).

Let the X_3 axis in the operated coordinate system be directed along the external normal to the surface of a medium occupying the space $X_3 \le h$ and $X_3 \ge 0$ and the X_1 axis coincide with the direction of wave propagation. In this coordinate system, we represent elastic displacements and electrical potential in the form of plane waves,

$$\begin{aligned} \mathrm{U}_C &= \alpha_C \exp\left[i\left(k_j x_j - \omega t\right)\right], \\ \varphi &= \alpha_4 \exp\left[i\left(k_j x_j - \omega t\right)\right]. \end{aligned} \quad (4)$$

The Green–Christoffel equations in the case of action of an electrical field **E** on a piezocrystal are written down in the form [6]

$$\begin{aligned} \Gamma_{BC} &= \left[C^*_{ABCD} + 2d_{JFC}C^E_{ABFD}M_J\bar{E}\right]k_Ak_D, \\ \Gamma_{C4} &= e^*_{ADC}k_Ak_D, \\ \Gamma_{4C} &= \Gamma_{C4} + 2e_{APD}d_{JPC}M_J\bar{E}k_Ak_D, \\ \Gamma_{44} &= -\varepsilon^*_{IJ}k_Ik_J, \end{aligned} \quad (5)$$

where the effective constants have the form of Eqs. (3).

Propagation of acoustic waves in a piezoelectric plate with the thickness h that is under the effect of an electrical field **E** must satisfy the boundary conditions of equality zero for the normal components of the stress tensor at the crystal–vacuum boundary. Continuity for the components of the vector of electrical field strength that are tangential to the boundary surface is provided by the continuity condition for the electrical potential φ and the continuity condition for the normal components of the electric displacement vector **D**,

$$\begin{aligned} &\tau_{3k} = 0 \quad \text{at} \quad x_3 = 0; \quad x_3 = h; \\ &\varphi = \varphi^{[\mathrm{I}]} \text{ at } x_3 < 0; \;\; \varphi = \varphi^{[\mathrm{II}]} \text{ at } x_3 > h; \\ &\mathrm{D} = \mathrm{D}^{[\mathrm{I}]} \text{ at } x_3 < 0; \;\; \mathrm{D} = \mathrm{D}^{[\mathrm{II}]} \text{ at } x_3 > h. \end{aligned} \quad (6)$$

The upper index I concerns the half-space $X'_3 > h$, and the index II concerns the half-space $X'_3 < 0$. Substituting solutions to Eqs. (4) into Eqs. (6) and keeping only the terms linear with respect to **E**, we obtain a determinant of equation system for the boundary conditions for the operated coordinate system,

$$\begin{aligned} &\sum_{n=1}^{8} C_n\left(C^*_{3jkl}k_1^{(n)}\alpha_k^{(n)} + e^*_{k3j}k_k^{(n)}\alpha_4^{(n)}\right) \\ &\qquad \times \exp\left(ik_3^{(n)}h\right) = 0; \\ &\sum_{n=1}^{8} C_n\left[e^*_{3kl}k_l^{(n)}\alpha_k^{(n)} - (\varepsilon^*_{3k}k_k^{(n)} - i\varepsilon_0)\alpha_4^{(n)}\right] \\ &\qquad \times \exp\left(ik_3^{(n)}h\right) = 0; \\ &\sum_{n=1}^{8} C_n\left(C^*_{3jkl}k_l^{(n)}\alpha_k^{(n)} + e^*_{k3j}k_k^{(n)}\alpha_4^{(n)}\right) = 0; \\ &\sum_{n=1}^{8} C_n\left[e^*_{3kl}k_l^{(n)}\alpha_k^{(n)} - (\varepsilon^*_{3k}k_k^{(n)} + i\varepsilon_0)\alpha_4^{(n)}\right] = 0. \end{aligned} \quad (7)$$

It is necessary to note that the equations given for the boundary conditions are obtained from an assumption on application of a homogeneous external electrical field without taking into account boundary effects. The obtained equations take into account all changes in the configuration of an anisotropic continuous medium that are connected with its static deformation and, in particular, the change of the crystal shape, i.e., extension and rotation of elementary lines parallel to the sample ribs [1, 6].

CALCULATION FOR THE EFFECT OF AN EXTERNAL ELECTRICAL FIELD ON THE PROPAGATION CONDITIONS FOR ACOUSTIC WAVES IN A PIEZOCRYSTAL PLATE

On the basis of the given basic dispersion equations describing acoustic wave propagation in piezoelectric plates, we analyze the variation of characteristics for an acoustic waves in a piezoplate due to variation of crystal symmetry and the rise of modified material constants by the example of a $Bi_{12}GeO_{20}$ crystal (the point group of symmetry 23) at application of an electrical field **E**. Let us consider the case of field application and acoustic wave propagation in the direction [100] in the plane (001). We write down the dispersion equation with respect to k_3 (in the absence of an electrical field) for the symmetrical and antisymmetrical modes of the Lamb wave in the form

$$\begin{aligned} &(C^E_{11}k_1^2 + C^E_{44}k_3^2 - \rho_0\omega^2)(C^E_{44}k_1^2 + C^E_{11}k_3^2 - \rho_0\omega^2) \\ &\qquad - (C^E_{12} + C^E_{44})^2k_1^2k_3^2 = 0. \end{aligned} \quad (8)$$

Solving Eq. (8) together with the boundary conditions of Eqs. (7) makes it possible to obtain in this case equations describing propagation of a symmetrical mode,

$$\frac{\tanh(iq_3h/2)}{\tanh(iq_1h/2)} = \frac{q_3\left[C_{11}^E\left(k^2-k_L^2\right)-C_{12}^Eq_1^2\right]\left\{C_{12}^E\left(C_{12}^E+C_{44}^E\right)k^2-C_{11}^E\left[C_{11}^E\left(k^2-k_L^2\right)+C_{44}^Eq_3^2\right]\right\}}{q_1\left[C_{11}^E\left(k^2-k_L^2\right)-C_{12}^Eq_3^2\right]\left\{C_{12}^E\left(C_{12}^E+C_{44}^E\right)k^2-C_{11}^E\left[C_{11}^E\left(k^2-k_L^2\right)+C_{44}^Eq_1^2\right]\right\}} \tag{9}$$

and an antisymmetrical mode for the Lamb wave,

$$\frac{\tanh(iq_3h/2)}{\tanh(iq_1h/2)} = \frac{q_1\left(C_{11}^E\left(k^2-k_L^2\right)-C_{12}^Eq_3^2\right)\left(C_{12}^E\left(C_{12}^E+C_{44}^E\right)k^2-C_{11}^E\left(C_{11}^E\left(k^2-k_L^2\right)+C_{44}^Eq_1^2\right)\right)}{q_3\left(C_{11}^E\left(k^2-k_L^2\right)-C_{12}^Eq_1^2\right)\left(C_{12}^E\left(C_{12}^E+C_{44}^E\right)k^2-C_{11}^E\left(C_{11}^E\left(k^2-k_L^2\right)+C_{44}^Eq_3^2\right)\right)} \tag{10}$$

analogously to equations for the Lamb waves in an isotropic medium [10]. Here k_L is the wave vector of a longitudinal bulk wave and $q_n \equiv k_3^{(n)}$ are solutions to a biquadratic dispersion equation (Eq. 8). Figure 1 gives the dispersion curves of phase velocities for the first modes of the Lamb and *SH* waves that are calculated with the help of Eqs. (9) and (10) as the functions of the product h/λ for a $Bi_{12}GeO_{20}$ crystal plate in the direction [100] in the plane (001).

Application of an electrical field **E** to a crystalline plate along the second-order axis reduces the effective symmetry of a cubic crystal down to the monoclinic one (class 2) inducing the rise of new elastic, piezoelectric, and dielectric constants,

$$C_{15}^* = C_{155}d_{14} - e_{134}; \quad C_{35}^* = C_{166}d_{14} - e_{124};$$
$$C_{46}^* = C_{456}d_{14} - e_{156}; \quad e_{16}^* = e_{156}d_{14} + H_{44}; \tag{11}$$
$$\varepsilon_{13}^* = H_{44}d_{14} + \varepsilon_{123}.$$

In the case of application of an electrical field $\mathbf{E} \parallel [010]$, the Green–Christoffel tensor has the form

$$\Gamma_{ij} = \begin{pmatrix} a_{11} & 0 & a_{13} & 0 \\ 0 & a_{22} & 0 & a_{24} \\ a_{31} & 0 & a_{33} & 0 \\ 0 & a_{24} & 0 & a_{44} \end{pmatrix}, \tag{12}$$

where

$$a_{11} = C_{11}^Ek_1^2 + C_{44}^Ek_3^2 + \left[\left(C_{12}^E + C_{44}^E\right)d_{14} + 2C_{15}^*\right]k_1k_3;$$
$$a_{13} = \left(C_{12}^E + C_{44}^E\right)k_1k_3 + C_{11}^Ed_{14}k_1^2 + C_{15}^*k_1^2 + \left(C_{44}^Ed_{14} + C_{35}^*\right)k_3^2;$$
$$a_{31} = \left(C_{12}^E + C_{44}^E\right)k_1k_3 + C_{44}^Ed_{14}k_1^2 + C_{15}^*k_1^2 + \left(C_{11}^Ed_{14} + C_{35}^*\right)k_3^2; \tag{13}$$
$$a_{22} = C_{44}^E\left(k_1^2 + k_3^2\right) + 2C_{46}^*k_1k_3;$$
$$a_{24} = 2e_{14}k_1k_3 + e_{16}^*\left(k_1^2 + k_3^2\right);$$
$$a_{33} = C_{44}^Ek_1^2 + C_{11}^Ek_3^2 + \left[\left(C_{12}^E + C_{44}^E\right)d_{14} + 2C_{35}^*\right]k_1k_3;$$
$$a_{44} = -\varepsilon_{11}^{\eta}\left(k_1^2 + k_3^2\right) - 2\varepsilon_{13}^*k_1k_3.$$

Thus, in this version, only already existing components of the Green–Christoffel tensor (Eq. (5)) are changed. This results in the fact that the wave structure almost does not change, i.e., the Lamb and *SH* waves remain "pure" modes. However, the dispersion equation in this case stops being biquadratic and derivation of separate equations for symmetrical and antisymmetrical modes becomes impossible. It is necessary to note that exactly the terms in Eqs. (13), which are connected with the effect of an electrical field, characterize all changes in the configuration of an anisotropic continuous medium caused by static deformation. We have to note also that the effects connected with the change of the crystal geometry and taken into account in Eqs. (2)–(6) lead to the violation of symmetry for the Green-Christoffel tensor. Figure 2 presents calculated coefficients for controllability of phase velocities,

$$\alpha_{\nu_i} = \frac{1}{\nu_i(0)}\left(\frac{\Delta\nu_i}{\Delta\bar{E}}\right)_{\Delta\bar{E}\to 0}. \tag{14}$$

It is necessary to note that the values of the coefficients α_ν for zero modes are significantly smaller than for the waves of the first and next orders both for the Lamb waves of both types and *SH* waves. A difference in the sign for the values of α_ν ("symmetry") for symmetrical and antisymmetrical Lamb waves, for example, S_1 and A_1, S_2 and A_2, and so on that is caused by the effect of hybridization of acoustic modes, is a characteristic feature. In the absence of an external electrical field, there are two points where the phase velocities of the S_1 and A_1 modes (S_2 and A_2) are equal (Fig. 3). The effect of hybridization—that is, the existence of coupled modes and energy exchange in the conditions of space-time synchronism—was observed in [11] for a metalized surface of potassium niobate. At $\mathbf{E} = 0$, the point of intersection for different modes exists in dispersion curves for phase velocities and interaction (hybridization) between these modes is absent. Application of an electrical field leads to "repulsion" of dis-

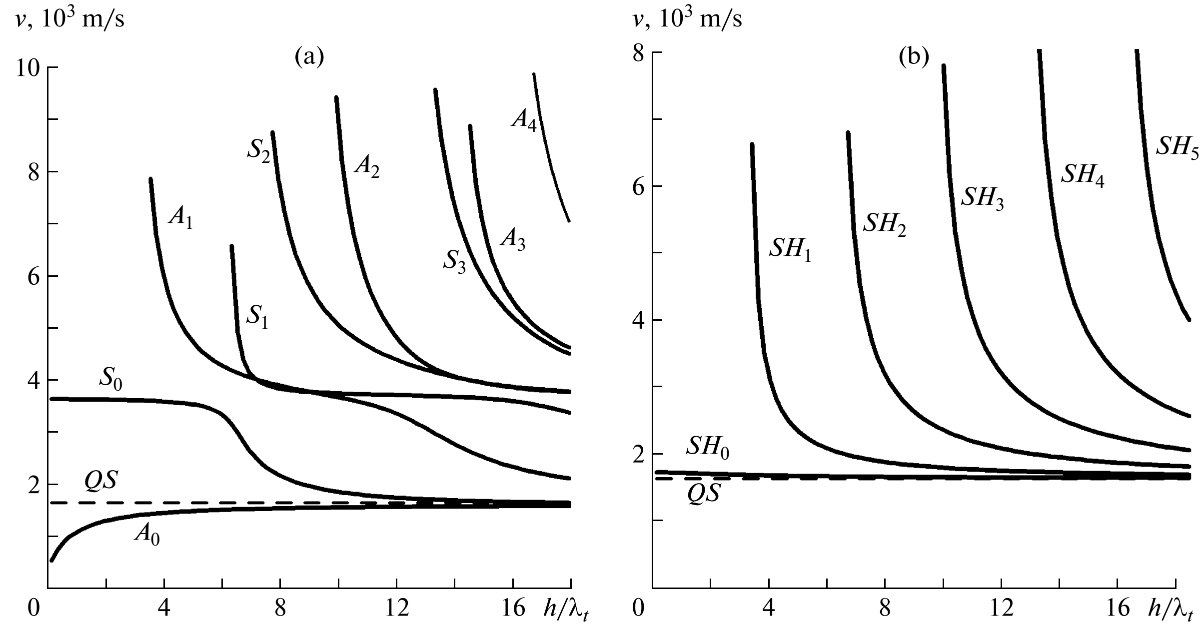

Fig. 1. Dispersion dependences for phase velocities of symmetrical and antisymmetrical modes for the Lamb and *SH* waves in a $Bi_{12}GeO_{20}$ plate in the direction [100] of the plane (001); λ_t is the shear wavelength. (a) Dispersion dependences for the symmetrical and antisymmetrical modes of the Lamb wave and (b) dispersion dependences for the modes of *SH* waves.

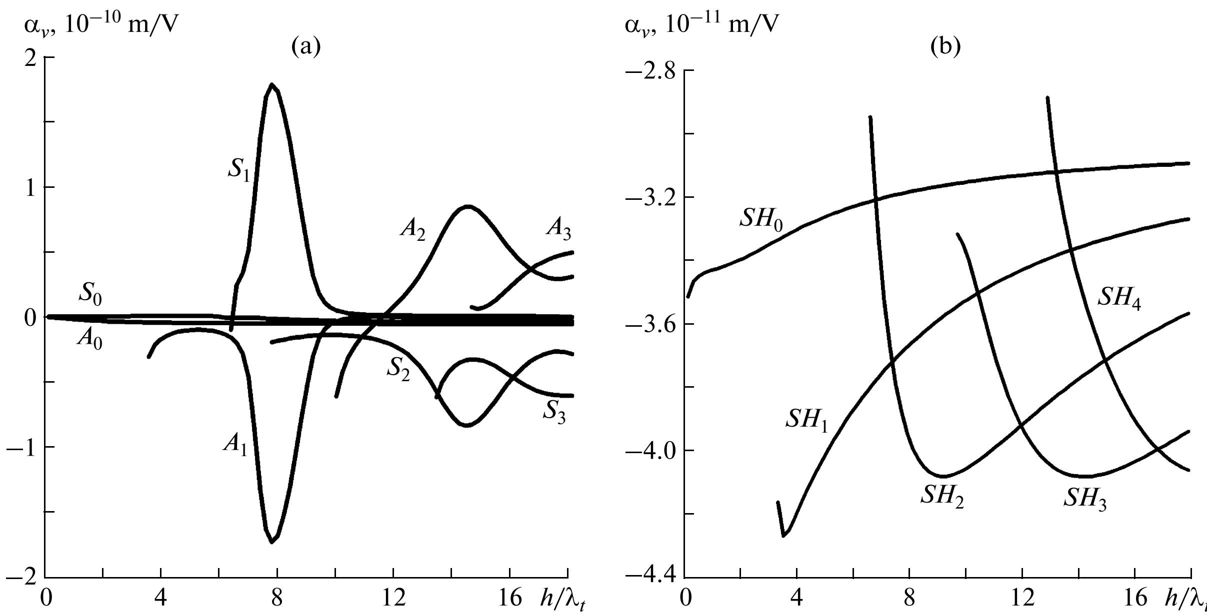

Fig. 2. Controllability coefficients for (a) the Lamb (*S* and *A* modes) and (b) *SH* waves in a plate in the direction [100] of the plane (001) in $Bi_{12}GeO_{20}$ in the case of electrical field application **E** ‖ [010].

persion dependences for phase velocities and removal of degeneration for the hybrid acoustic modes of the Lamb wave (Fig. 3), which leads naturally to the significant increase of values for the coefficient α_v for the hybrid modes but with different signs.

In the case of application of an electrical field **E** ‖ [100], i.e., along the direction of wave propagation, new material constants are induced,

$$\begin{aligned} C^*_{14} &= C_{144}d_{14} - e_{114}; \quad C^*_{56} = C_{456}d_{14} - e_{156};\\ C^*_{24} &= C_{155}d_{14} - e_{134}; \quad e^*_{11} = e_{114}d_{14} + H_{11};\\ e^*_{35} &= e_{156}d_{14} + H_{44}; \quad e^*_{13} = e_{134}d_{14} + H_{21}. \end{aligned} \tag{15}$$

Thus the Green–Christoffel tensor takes on a general form, i.e., it does not contain zero components.

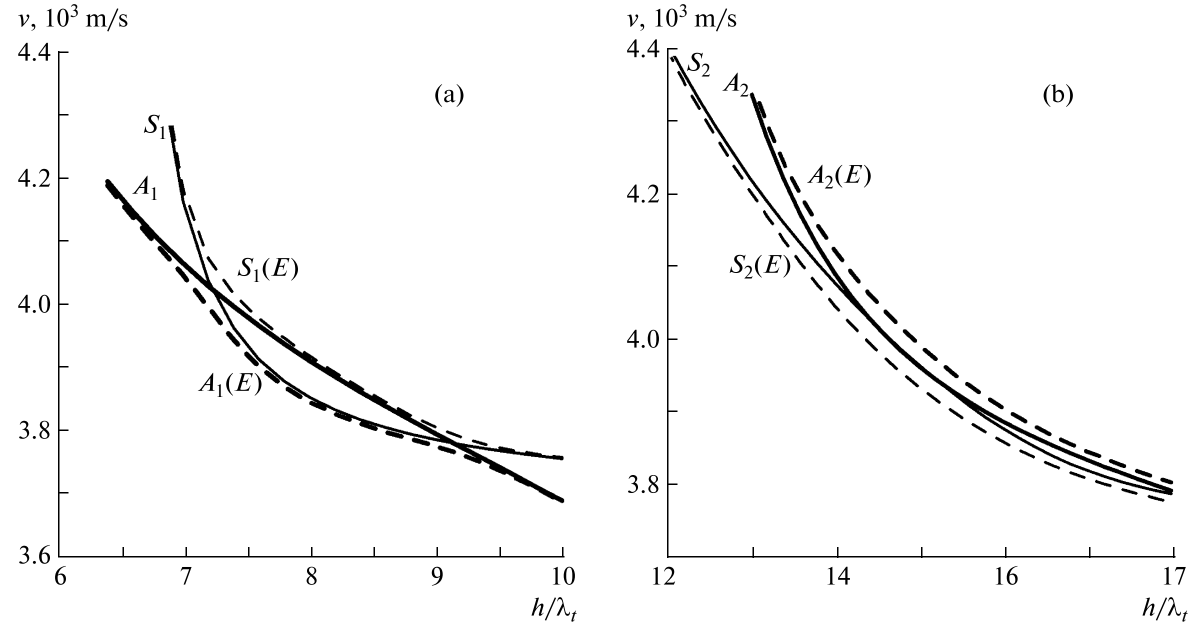

Fig. 3. Dependences of phase velocities for the modes of the Lamb wave in a $Bi_{12}GeO_{20}$ plate in the direction [100] of the plane (001) at $\mathbf{E} \parallel [010]$ and $\mathbf{E} = 0$. (a) A_1 and S_1 modes and (b) A_2 and S_2 modes.

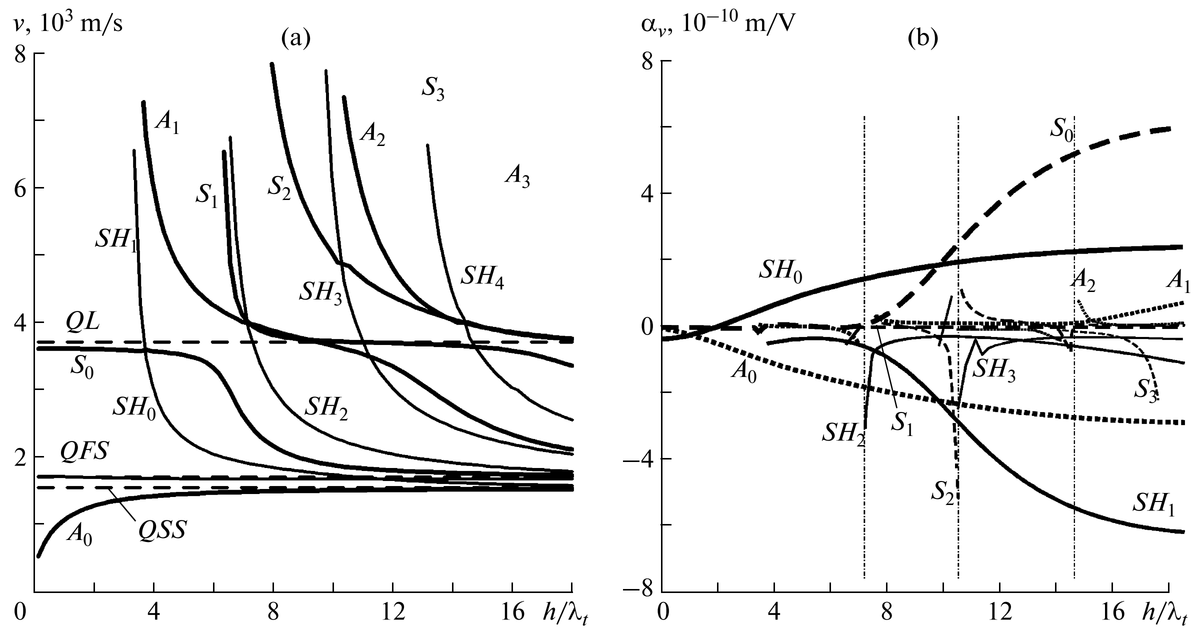

Fig. 4. Dependences of phase velocities and controllability coefficients for the Lamb wave in a $Bi_{12}GeO_{20}$ plate in the direction [100] of the plane (001) in the case of electrical field application $\mathbf{E} \parallel [100]$.

As demonstrated earlier [4], the effect of an electrical field $\mathbf{E}$ in this configuration has almost no influence on the value of the phase velocity for a longitudinal bulk wave. However, removal of degeneration for shear waves occurs along the direction [100], that is, the acoustic axis in an unperturbed case and the last is split into two conical ones with the Poincaré index $\pm 1/2$, splitting of the acoustic axis occurring in the plane (110). Therefore, the Lamb waves stop being pure modes, i.e., oscillations along the X_2 axis are present in wave displacements. An analogous situation arises also with *SH* waves.

Figure 4a presents dispersion curves for the phase velocities of acoustic waves and the controllability coefficients α_v as the functions of the product h/λ or application of an electrical field $\mathbf{E} \parallel [100]$ to a piezo-

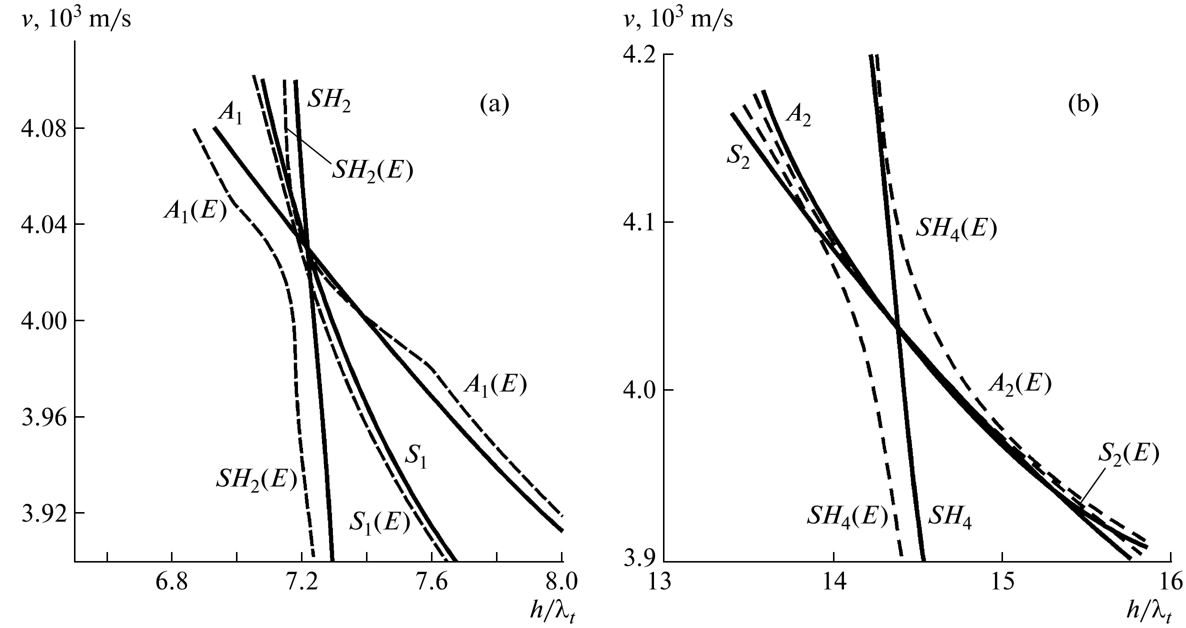

Fig. 5. Phase velocities for the Lamb and *SH* waves in a plate in the direction [100] of the plane (001) for $Bi_{12}GeO_{20}$ in the case of external electrical field application $\mathbf{E} \parallel [100]$. (a) A_1, SH_2, and S_1 modes and (b) S_2, SH_4, and A_2 modes.

plate. Figure 4b gives the controllability coefficients α_v only for the modes with large values of α_v, since the values of α_v for other modes are not distinctive in the plot. It is necessary to note that the most distinctive values of α_v belong to the first modes of acoustic waves, the values of α_v for the modes A_0 and SH_0 tending to the value of α_v for the Rayleigh wave, which is $\alpha_v = -3.17 \times 10^{-10}$ m/V in this case, while the value of α_v for the modes SH_1 and S_0 is almost twice as large as the value of α_v for the Rayleigh wave.

Application of an electrical field $\mathbf{E} \parallel [100]$ to a piezoplate leads to transformation of the acoustic modes S_0 and SH_1—i.e., in the process of transmission through the region of space–time synchronism, a smooth change of mode polarization occur—and, therefore, of its type (Fig. 4). A distinctive feature at $\mathbf{E} \parallel [100]$ is also the manifestation of the hybridization effect with increase of h/λ, in particular, for the modes A_0 and SH_0 with the values of phase velocities tending to the velocity of a surface acoustic wave with increase of h/λ. Degeneration (equality of phase velocities) is absent. However application of an electrical field **E** to a crystalline plate leads to coupling of the modes A_0 and SH_0 and "repulsion" of dispersion dependences that explains the symmetry of the controllability coefficient α_v for these modes.

Another version of hybridization rise is observed immediately for three modes, in particular, the modes S_2, SH_4, and A_2 (A_1, SH_2, and S_1). Their degeneration at $\mathbf{E} = 0$ occurs at a single point (Fig. 5). Application of an electrical field $\mathbf{E} \parallel [100]$ leads to transformation of the acoustic modes S_2 and SH_4 analogous to the one described above and removal of degeneration for the velocities of these modes. There is no change for the mode A_2, but at the point of degeneration for phase velocities of acoustic modes, a change of sign for α_v occurs, i.e., the value of the wave phase velocity under the influence of an electrical field **E** is smaller before the degeneration point and larger after it. The change character in the vicinity of the hybridization region for all three modes is exponential. Similar hybridization regions are indicated in Fig. 4 by vertical dotted lines.

CONCLUSIONS

Thus, using the results given in this paper, it is possible to analyze in detail the dispersion character of acoustic modes in a piezoelectric plate in the conditions of homogeneous finite influences if the constants of linear and nonlinear electromechanical properties for a crystal are known. It was demonstrated that, at different versions of electrical field application, mode interaction may arise in a single propagation direction. The character of acoustic wave hybridization can manifest itself also as removal of degeneration for phase velocities and in the region of space–time synchronism without a direct contact of phase velocities for acoustic modes. The obtained data can be useful for development of controllable devices and finding new effects important for practice.

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