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The peculiarities of the Bleustein–Gulyaev wave propagation in structures containing conductive layer

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ABSTRACT

As known, anomalous resisto-acoustic effect is a fundamental property for weakly inhomogeneous piezoactive waves (Bleustein-Gulyaev, Love, and some leaky waves). It consists in that the velocity of aforementioned waves first increases, achieves its maximum, and only then decreases with increasing conductance of a layer placed at the surface of piezoelectric half-space. In this paper we continue to study the peculiarities of the effect appearance and the influence of different electrical boundary conditions on its characteristics. Conditions have been found under which the said effect appears and, respectively, disappears. The magnitude of positive change in velocity with increasing layer conductance is demonstrated to be reduced up to zero as a layer with arbitrary conductance has been moved away from the piezoelectric surface. The positive change in velocity increases when an perfectly conductive screen moves away from the "piezoelectric half-space – conductive layer" structure. The obtained results are useful for a more deep understanding the physical basis of propagation of weakly inhomogeneous piezoactive acoustic waves (Bleustein-Gulyaev, Love, and some leaky waves).

1. Introduction

As it is known [1,2], anomalous resisto-acoustic effect (ARAE) is a fundamental property for weakly inhomogeneous piezoactive waves (Bleustein-Gulyaev (BG), Love, and some leaky waves). It consists in that the velocity of weakly inhomogeneous waves first increases, achieves its maximum, and only then decreases with increasing conductance of a layer placed at the surface of piezoelectric half-space. Earlier it has been demonstrated that the physical cause of this effect is the availability of two processes opposite in direction [1]. On the one hand, the growth of surface conductance σ_s of the layer results in decreasing the depth of wave penetration and in increasing the energy of electric field of the wave near the crystal surface which leads to its velocity increase. On the other hand the gain in σ_s causes the tangential components of electric field at the surface to decrease which induces a lower wave velocity in its turn. These processes are responsible for optimum inherent in the dependence of relation between the flow densities of electrical and mechanical energies of weakly inhomogeneous waves on σ_s. Just this fact accounts for the appearance of ARAE. The appearance of this effect has been experimentally confirmed for weakly inhomogeneous surface acoustic waves with lateral polarization in a "36° Y–X lithium niobate – thin conductive aluminum film" structure [3]. In the presented work we continue to study the peculiarities of this effect and the influence of different electrical boundary conditions on its characteristics.

2. ARAE in a "piezoelectric half-space – vacuum gap – conductive layer" structure

Let's consider the propagation of weakly inhomogeneous surface acoustic wave in the "piezoelectric half-space – vacuum gap – conductive layer" structure (Fig. 1).

To solve the problem we write a system of equations that contains [4]: elastic medium motion equation

$$\rho \partial^2 U_i/\partial t^2 = \partial T_{ij}/\partial x_j, \quad (1)$$

Laplace's equation:

$$\partial D_j/\partial x_j = 0 \quad (2)$$

and piezocrystal state equations:

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$$T_{ij} = C_{ijkl}\partial U_l/\partial x_k + e_{kij}\partial \Phi/\partial x_k, \quad (3)$$
$$D_j = -\varepsilon_{jk}\partial \Phi/\partial x_k + e_{jlk}\partial U_l/\partial x_k \quad (4)$$

Here ρ is the medium density, U_i is the component of mechanical particles displacement, t is the time, T_{ij} is the component of mechanical stress tensor, x_j are coordinates, D_j is component of electrical displacement, C_{ijkl}, e_{ijk}, and ε_{jk} are elastic, piezoelectric and dielectric constants, respectively, and Φ is electrical potential.

We use the condition of quasistatic approximation:

$$E_i = -\partial \Phi/\partial x_i, \quad (5)$$

where E_i is the component of electric field intensity.

Electric displacement in regions I and II must satisfy the Laplace's equation:

$$\partial D_j^I/\partial x_j = 0, \ \partial D_j^{II}/\partial x_j = 0, \quad (6)$$

where $D_j^I = -\varepsilon_0 \partial \Phi^I/\partial x_j$ and $D_j^{II} = -\varepsilon_0 \partial \Phi^{II}/\partial x_j$. Here, indices I and II denote quantities relating to regions $d < x_3 < 0$ and $x_3 > -d$, respectively, and ε_0 is the dielectric constant of vacuum.

Let's write now mechanical and electrical boundary conditions.

$$T_{3j} = 0, \ \Phi = \Phi^{\mathrm{I}}, \ D_3 = D_3^{\mathrm{I}} \text{ at } x_3 = 0, \quad (7)$$
$$\Phi^{\mathrm{I}} = \Phi^{\mathrm{II}}, \ D_3^{\mathrm{I}} - D_3^{\mathrm{II}} = -\delta \text{ at } x_3 = -d. \quad (8)$$

Here, δ is the surface charge density that is connected with the density of surface current within the frames of hydrodynamic approximation using the equation of charge conservation [5]

$$\partial J_1/\partial x_1 = -\partial \delta/\partial t. \quad (9)$$

Here, J_1 is the component of surface current density.

Hence it follows, regarding the expression for the surface current conductivity in the layer [5]:

$$J_1 = -\sigma_S \partial \Phi/\partial x_1, \quad (10)$$

and taking into account that all variables $\sim \exp(j\omega(t - x_1/V))$ one can obtain

$$\delta = -j\sigma_S \Phi_\omega/V^2. \quad (11)$$

Here, σ_S is the surface conductance of the layer, j is the imaginary unit.

The above boundary problem was solved with the use of the following procedure. Its solution was presented in the form of a set of plane inhomogeneous waves [6,7] and had the form as follows:

$$Y_i(x_1, \ x_3, \ t) = Y_i(x_3)\exp[j\omega(t - x_1/V)], \quad (12)$$

where $i = 1–8$ for the piezoelectric and $i = 1, 2$ for vacuum, V is phase velocity, and ω – is the angular frequency of acoustic wave. We introduce the following normalized variables:

$$Y_i = \omega C_{11}^* U_i/V, \ Y_4 = T_{13}, \ Y_5 = T_{23}, \ Y_6 = T_{33}, \ Y_7 = \omega e^* \Phi/V, \ Y_8 = e^* D_3/\varepsilon_{11}^*, \quad (13)$$

where $i = 1, 2, 3$, C_{11}^*, ε_{11}^* are the normalized material constants of piezoelectric medium in crystallographic coordinate system; $e^* = 1$ and it has the dimensional representation of piezoelectric constant.

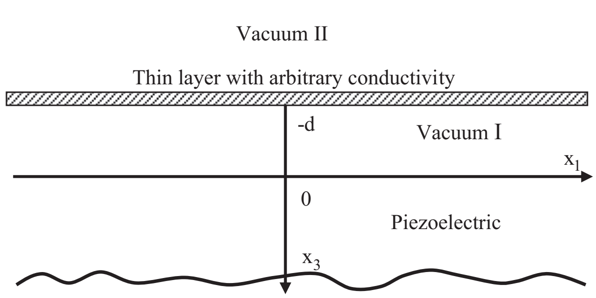

Fig. 1. Geometry of the problem. BG wave propagates along x_1.

Substituting expression (12) into Eqs. (1)–(4) yields a system of eight and of two conventional differential linear equations for piezoelectric medium and vacuum, respectively. Each of the systems can be written in the following matrix form:

$$[A][dY/dx_3] = [B][Y]. \quad (14)$$

Here $[dY/dx_3]$ and $[Y]$ are eight dimensional vectors for the piezoelectric medium and two dimensional vectors for vacuum whose components are defined according the formulae (13). Matrixes $[A]$ and $[B]$ appeared to be squared and have dimensions of 8×8 for the piezoelectric medium and 2×2 for vacuum.

Since matrix $[A]$ is not particular ($det[A] \neq 0$) we can write the following equations for every contacting medium:

$$[dY/dx_3] = [A^{-1}][B][C] = [C][Y]. \quad (15)$$

Then to solve the system of Eq. (15) we need to find the eigenvalues $\beta^{(i)}$ of matrices $[C]$ and corresponding eigenvectors $[Y^{(i)}]$, responsible for the parameters of partial waves, for each of contacting media. General solution would be a linear combination of all partial waves for every medium:

$$Y_k = \sum_{i=1}^{N} A_i Y_k^{(i)} \exp\left(\beta^{(i)} x_3\right) \exp\left(j\omega[t - x_1/V]\right), \quad (16)$$

where the number of eigenvalues $N = 8$ for the piezoelectric medium and $N = 2$ for vacuum and A_i are unknown quantities. Quantities A_i and velocity V can be found using mechanical and electrical boundary conditions (7) and (8) that have been also written in the normalized form with regard to (13). We eliminate the eigenvalues with positive real part from consideration for piezoelectric half-space because all variables should have amplitude decaying deep into the piezoelectric in this case. Thus, only four eigenvalues with negative real part are taken into account for the piezoelectric medium. We estimate both eigenvalues of corresponding matrix $[C]$ for vacuum in region $0 > x_3 > -d$ and exclude the eigenvalues with the negative real part for vacuum in region $x_3 < -d$ from consideration. Since all variables in vacuum must have decaying amplitudes in region $x_3 < -d$.

The use of described procedure helped us to find the wave phase velocity and the amplitudes of all electrical and mechanical variables as a function of coordinate x_3.

We investigated Bleustein-Gulyaev (BG) waves propagating in *YX* barium titanate ($BaTiO_3$). Material constants for barium titanate cited in [8] were used for calculations.

Theoretical analysis provided the dependencies of Bleustein–Gulyaev wave velocity on the layer conductivity for different values of normalized gap d/λ between the layer and the piezoelectric surface (λ is wavelength). The obtained results are shown in Fig. 2. It is seen that anomalous resisto-acoustic effect appears for certain

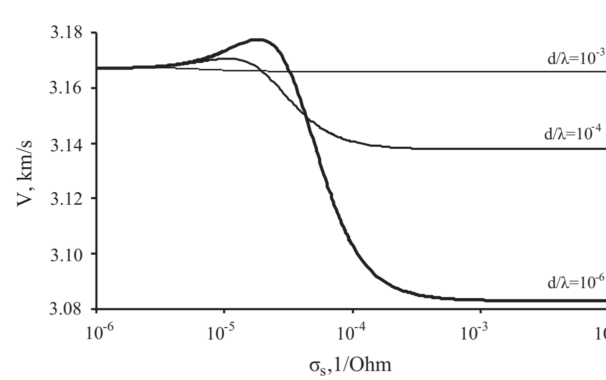

Fig. 2. Velocity of BG wave vs layer conductivity σ_S for different values of normalized gap d/λ between the layer and the piezoelectric surface.