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The characteristics of fundamental shear-horizontal acoustic waves in structure “nanocomposite polymeric film-vacuum gap-piezoelectric plate”

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Abstract

Recently it has been shown that SH_0 wave in structure “piezoelectric plate-nanocomposite polymeric film with Fe nanoparticles” is characterized by the low TCD (~15 ppm/C) and high value of K^2 (~32%). However in the case of the acoustical contact of polymeric material with the plate such structure possesses significant attenuation of the acoustic wave (~1dB/λ). In order to avoid this effect it was suggested to use the structure containing the gap between the polymeric film and plate. As the result of theoretical analysis the dependencies of SH_0 wave velocity versus relative thickness of vacuum gap were obtained. It has been found that there exist such values of gap and dielectric permittivity of the nanocomposite material when the value of TCD of SH_0 wave significantly decreases. At that the attenuation connected with the dissipation factor is practically absent.

Keywords: electro-mechanical coupling coefficient; nanocomposite polymeric film; piezoelectric plate; shear-horizontal acoustic waves; temperature coefficient of delay; vacuum gap

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1. Introduction

As is known for the development of the acoustoelectronic devices the electro-mechanical coupling coefficient (K^2) and temperature coefficient of delay (TCD) of acoustic wave have a great importance. In this connection one of the modern lines of the investigation in acoustics is the search of such wave types and crystallographic orientations of the wave-guides for which the value of K^2 is maximal and value of TCD is minimal. Such combination of the parameters is necessary for the development of the high effective thermo-stable devices. At present there exist the papers showing that fundamental shear-horizontal (SH_0) acoustic waves in thin (in comparison with wavelength) piezoelectric plates possess significantly more electromechanical coupling coefficient than the surface acoustic waves (SAW) in the same material [1]-[3]. For example, it was shown that SH_0 wave has K^2 = 34% for hf = 500 m/s in YX $LiNbO_3$ plate (h = plate thickness, f = wave frequency). In this case although the value of TCD (66 ppm/C)

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[4] is less than TCD of SAW (88 ppm/C) this is not enough for the development of the thermo-stable devices. Thus the problem of decreasing TCD with the high value of K^2 has the practical significance.

It is known that the velocity of SH_0 wave in the piezoelectric plates always decreases when the temperature increases. From the other hand it has been found that the velocity of SH_0 wave in the plate always increases when the dielectric permittivity of the contacting medium decreases. So if the permittivity of this medium decreases with increase in the temperature the velocity of SH_0 wave in the structure "piezoelectric plate – dielectric medium" may also increase with the rise of the temperature. This may allow significant reducing the TCD of SH_0 wave propagating in such structure. The possibility of reducing the TCD of SH_0 wave by using as contacting media the specific liquid (butyl acetate or chlorbenzol) was theoretically and experimentally shown in [5]. However the making such structure and maintenance of the devices developed on its basis meet with some technological difficulties. In this connection the search of the material characterized by the specific dependence of the dielectric permittivity versus the temperature has been carried out. Investigations showed that as such material the nanocomposite polymeric films with various content of Fe nanoparticles can be used.

Recently it has been shown that SH_0 wave in the structure "piezoelectric plate-nanocomposite polymeric film with Fe nanoparticles" is characterized by the low TCD (~15 ppm/C) and high value of K^2 (~32%). However in the case of the acoustical contact of the polymeric material with the plate such structure possesses significant attenuation of the acoustic wave (~1dB/λ) [6]. This may be explained by the high value of the viscosity of the nanocomposite material. In order to avoid this effect it was suggested to use the structure containing the gap between the polymeric film and plate.

Thus, in this paper the theoretical analysis of the influence of the temperature on the velocity of SH_0 wave in the structure "thin piezoelectric plate-vacuum gap-nanocomposite polymeric film" has been carried out.

2. Theoretical Analysis and Results

2.1. Main Equations and Boundary Conditions

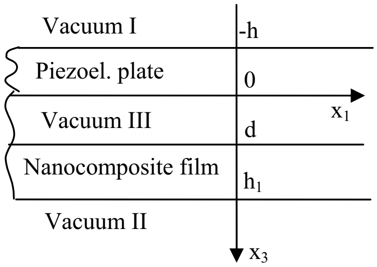

Fig.1 Geometry of the problem.

The geometry of the problem under consideration is shown in Fig.1. Wave propagates along the x_1 direction of a piezoelectric plate bounded by the planes $x_3=0$ and $x_3 = -h$. The nanocomposite polymeric film is bounded by planes $x_3 = d$ and $x_3 = h_1$. We consider that this film is viscoelastic, nonconductive and isotropic. The regions $x_3 < -h$, $0 < x_3 < d$, and $x_3 > h_1$ correspond to the vacuum. We consider a two dimensional problem in which all field components are assumed to be constant in the x_2 direction. For analysis of the wave propagation we used the motion equation, Laplace's equation, and the constitutive equations for the piezoelectric medium and polymeric film [6]:

$$\rho' \partial^2 U_i / \partial t^2 = \partial T_{ij} / \partial x_j ,\ \partial D_j / \partial x_j = 0 , \qquad (1)$$

$$T_{ij} = C'_{ijkl}\,\partial U_l \big/ \partial x_k + e'_{kij}\,\partial \Phi \big/ \partial x_k \,, \tag{2}$$

$$D_j = -\varepsilon'_{jk}\,\partial \Phi \big/ \partial x_k + e'_{jlk}\,\partial U_l \big/ \partial x_k \,, \tag{3}$$

$$\rho^f\,\partial^2 U_i^f \big/ \partial t^2 = \partial T_{ij}^f \big/ \partial x_j \;\;,\;\; \partial D_j^f \big/ \partial x_j = 0, \tag{4}$$

$$T_{ij}^f = C_{ijkl}^f\,\partial U_l^f \big/ \partial x_k + \eta_{ijkl}^f\,\partial U_l^f \big/ \partial t \partial x_k \,, \tag{5}$$

$$D_j^f = -\varepsilon_{jk}^f\,\partial \Phi^f \big/ \partial x_k \tag{6}$$

Here U_i is the component of mechanical displacement of particles, t is time, T_{ij} is the component of the mechanical stress, x_j is the coordinate, D_j is the component of the electrical displacement, η_{ijkl} is component of viscosity, Φ is the electrical potential. The index f denotes that the appropriate variable refers to polymeric nanocomposite film. Because the considered nanocomposite film is viscoelastic the equation (5) shows that the effective elastic constant is complex and its imaginary part is equal $\omega\eta_{ijkl}$ for the harmonic waves.

The influence of the temperature was considered in the following way. It is known [7] that elastic C'_{ijkl}, piezoelectric e'_{ikl}, and dielectric ε'_{jk} constants and density ρ' of piezoelectric material at the temperature T may be respectively expressed as:

$$C'_{ijkl} = C_{ijkl}^E[1 + C_{ijkl}^T(T - T_R)] \tag{7}$$

$$e'_{kij} = e_{kij}[1 + e_{kij}^T(T - T_R)] \tag{8}$$

$$\varepsilon'_{jk} = \varepsilon_{jk}^S[1 + \varepsilon_{jk}^T(T - T_R)] \tag{9}$$

$$\rho' = \rho[1 - (2\alpha_{11} + \alpha_{33})(T - T_R)] \tag{10}$$

Here C_{ijkl}^E, e_{kij}, ε_{jk}^S and ρ are the elastic, piezoelectric, and dielectric constants and the density of piezoelectric media at the room temperature T_R=20C, respectively; C_{ijkl}^T, e_{kij}^T and ε_{jk}^T are the temperature coefficients of material constants, α_{ij} is the coefficient of the thermal expansion.

Outside of the structure, in the regions I, II, and III, the electrical displacement must satisfy the Laplace's equation:

$$\partial D_j^I \big/ \partial x_j = 0, \quad \partial D_j^{II} \big/ \partial x_j = 0, \quad \partial D_j^{III} \big/ \partial x_j = 0, \tag{11}$$

where $D_j^I = -\varepsilon_0 \partial \Phi^I \big/ \partial x_j$, $D_j^{II} = -\varepsilon_0 \partial \Phi^{II} \big/ \partial x_j$ and $D_j^{III} = -\varepsilon_0 \partial \Phi^{III} \big/ \partial x_j$. Here, ε_0 is the permittivity of vacuum, indices I, II and III denote that the values refer to regions $x_3 < -h$, $x_3 > h_1$, and $0 < x_3 < d$, respectively.

Acoustic waves propagating in aforementioned structure must also satisfy the mechanical and electrical boundary conditions:

$$x_3 = -h:\; T_{i3} = 0\,;\; \Phi = \Phi^I\,;\; D_3 = D_3^I \tag{12}$$

$$x_3 = 0:\; T_{i3} = 0\,;\; \Phi = \Phi^{III}\,;\; D_3 = D_3^{III} \tag{13}$$

$$x_3 = d:\; T_{i3}^f = 0\,;\; \Phi^f = \Phi^{III}\,,\; D_3^f = D_3^{III} \tag{14}$$

$$x_3 = -h_1:\; T_{i3}^f = 0\,;\; \Phi^f = \Phi^{II}\,,\; D_3^f = D_3^{II} \tag{15}$$

Here $i=1\div3$, h, h_2, and d are the thicknesses of the piezoelectric plate, nanocomposite film and vacuum gap, respectively. Substituting the solution as the plane inhomogeneous wave in equations system (1) - (3), (4)-(6) and (11) yields the systems of the ordinary differential equations for each aforementioned media. The numbers of the equations are the following: 8 for the piezoelectric plate, 6 mechanical and 2 electrical for the nanocomposite film and 2 electrical for each vacuum regions [5]. At first the phase velocity (V) is considered as the unknown parameter of these systems. This allows finding the eigenvalues and eigenvectors as the functions of unknown velocity and writing the matrix of boundary conditions by using (12) - (15). The sought value of the phase velocity is that value for which the determinant of this matrix is equal zero.

When we have defined the value of the velocity it can be found the temperature coefficient of the phase velocity (TCV) and delay (TCD). The expressions for the TCV and TCD have the following form [7]:

$$TCV = \frac{v_{ph}(T) - v_{ph}(T_R)}{v_{ph}(T_R)(T - T_R)} \tag{16}$$

$$TCD = \alpha_{11} - TCPV \tag{17}$$

We used the material constants of lithium niobate and their temperature coefficients from [8] and [7], respectively. The material constants of the nanocomposite polymeric films containing Fe nanoparticles have been measured by the authors previously in [9]. These constants are presented in the Table 1. Moreover the authors measured the temperature dependence of dielectric permittivity of the used nanocomposite films. These data is also presented in the Table 1.

Table 1. Parameters of Nanocomposite Polymeric Films Containing Fe nanoparticles

%	ρ, kg/m^3	C_{11}, 10^8 Pa	η_{11}, Pa*s	C_{66}, 10^8 Pa	η_{66}, Pa*s	$\varepsilon_{ii}/\varepsilon_0$	
						10^{0}C	20^{0}C
0	879.5	16	24	1.4	2.9	2.32	2.29
2	884.1	23.2	24.6	2.6	2.2	2.21	2.16
5	918.6	20.1	6.2	2.8	2.3	2.39	2.32
7	972.6	17.8	4	3.4	2.4	2.27	2.20
12	993.7	15.1	7.6	3.5	1.1	2.33	2.29
15	991.3	14	4	3.4	0.7	2.43	2.39
17	986.6	12.8	11.3	3.0	1.3	3.20	3.17
20	1052	10.2	17.6	3.3	1.1	2.66	2.61

3. Theoretical Results

As a result of the conducted calculation the velocity and TCD have been found for SH_0 wave propagating in the structure “piezoelectric plate – vacuum gap –nanocomposite polymeric film”.

Fig. 2 shows the dependencies of the velocity (a) and TCD (b) of SH_0 wave propagating in the structure “Y-X plate of lithium niobate – vacuum gap - nanocomposite polymeric film” on the parameter d/h. At that the thickness of film $h_1 = 0.1h$.The nanocomposite polymeric film contains 15% of Fe nanoparticles. One can see that with moving away the nanocomposite film from the piezoelectric plate the velocity of SH_0 wave increases and reaches the value of the wave for the electrically open plate surface. It has been also found that with approaching the nanocomposite film to the surface of the piezoelectric plate the temperature coefficient of delay decreases and the wave attenuation is absent. However the value of the change in the TCD is not enough for the development of the thermo-stable structure.

In this connection the influence of the temperature on the characteristics of SH_0 wave in the structure “nanocomposite polymeric film – vacuum gap - Y-X plate of lithium niobate – vacuum gap - nanocomposite polymeric film” has been studied. Fig. 3 shows the dependence of the TCD on parameter d/h at the fixed relative value of the second vacuum gap 0.001. It can be seen that in this case the change in the TCD is two times more than for one vacuum gap. However in this case the value of the TCD also does not reach zero level.

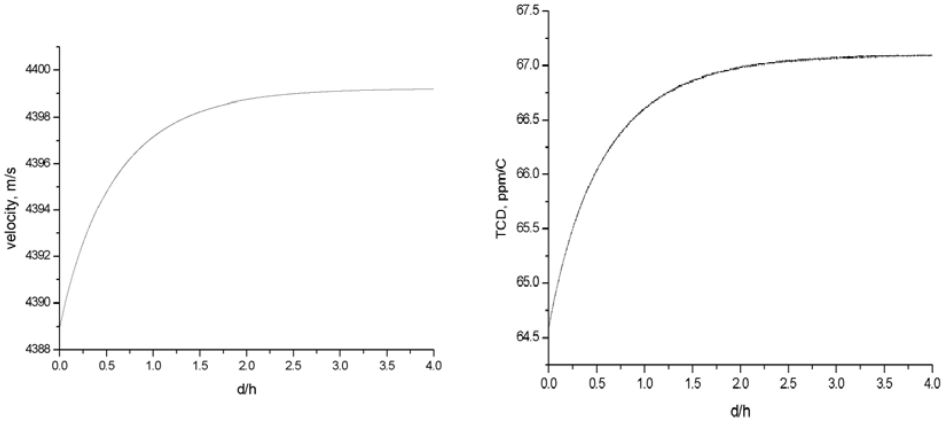

Fig.2 The dependence of the velocity (a) and TCD (b) of SH_0 wave propagating in the structure "Y-X plate of lithium niobate – vacuum gap - nanocomposite polymeric film" on parameter d/h. At that $h_l = 0.1h$.

Then the search of the temperature dependence of the dielectric permittivity of the nanocomposite material needed for zero value of the TCD was performed. It has been found that the zero value of the TCD may be reached for the structure with two nanonocomposite films separated by vacuum gaps if the temperature rise of 10^0C decreases the permittivity of films on 6%. Fig.4 presents the dependence of TCD on the parameter d/h at the values of the dielectric permittivity of the nanocomposite material 4.26 and 4.0 under T = 10^0C and 20^0C, respectively. Accordingly for one nanocomposite film the decrease in the permittivity with the aforementioned rise of the temperature must be equal 12%.

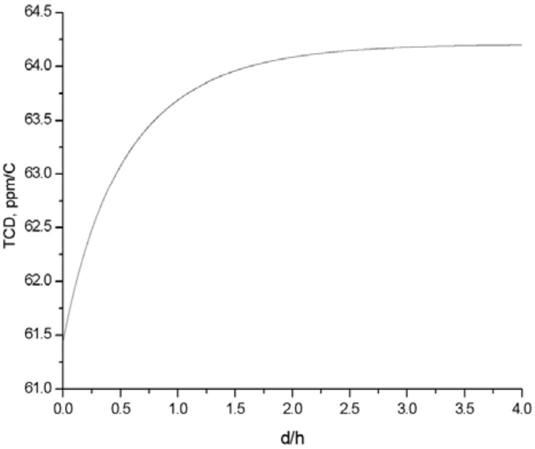

Fig.3 The dependence of TCD of SH_0 wave propagating in the structure "nanocomposite polymeric film - vacuum gap - Y-X plate of lithium niobate – vacuum gap - nanocomposite polymeric film" on the parameter d/h. The relative value of the second vacuum gap is equal 0.001.

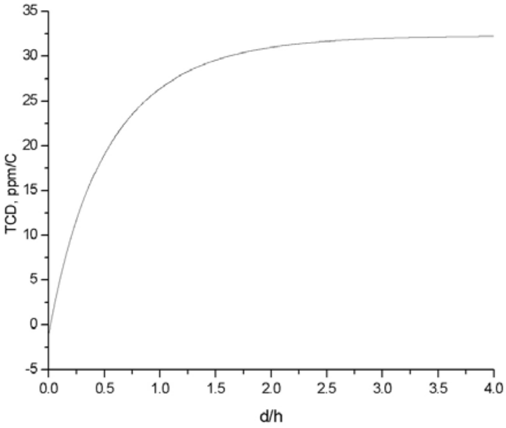

Fig.4 The dependence of TCD of SH_0 wave propagating in structure "nanocomposite polymeric film - vacuum gap - Y-X plate of lithium niobate – vacuum gap - nanocomposite polymeric film" on parameter d/h. The values of the permittivity of the films are equal 4.26 and 4.0 under T = 10^0C and 20^0C, respectively

4. Conclusión

As the result of theoretical analysis the dependencies of SH_0 wave velocity versus the relative thickness of the vacuum gap were obtained. They show that when vacuum gap increases the wave velocity increases and reaches the value of the wave velocity in the mechanically free piezoelectric plate. This is connected with decreasing the effective permittivity of the structure when the film moves away from the piezoelectric plate. Moreover, it has been found that with decrease of the vacuum gap the value of TCD of SH_0 wave decreases. At that the attenuation connected with the dissipation factor is practically absent. We have also found the temperature dependence of the permittivity of nanocomposite film provided zero value of the TCD of the structure.

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References

[1] B. D. Zaitsev, S. G. Joshi, and I. E. Kuznetsova, “Propagation of QSH (quasi shear horizontal) acoustic waves in piezoelectric plates,” IEEE Trans. Ultrason. Ferroel. and Freq. Control, vol. 46, pp. 1298-1302, 1999.

[2] I. E. Kuznetsova, B. D. Zaitsev, S. G. Joshi, and I. A. Borodina, “Investigation of acoustic waves in thin plates of lithium niobate and lithium tantalate,” IEEE Trans. Ultrason. Ferroel. and Freq. Control, vol. 48, pp. 322 – 328, 2001.

[3] I. E. Kuznetsova, B. D. Zaitsev, S. G. Joshi, and I. A. Borodina, “Acoustic plate waves in potassium niobate single crystal,” Electronic Letters, vol. 34, pp. 2280 – 2281, 1998.

[4] I. E. Kuznetsova, B. D. Zaitsev, and S. G. Joshi, “Temperature characteristics of acoustic waves propagating in thin piezoelectric plates,” Proc. of IEEE Ultrason. Symp., vol. 1, pp. 157-160, 2001.

[5] B. D. Zaitsev, I. E. Kuznetsova, S. G. Joshi, and A. S. Kuznetsova, “New method of change in temperature coefficient delay of acoustic waves in thin piezoelectric plates,” IEEE Trans. Ultrason. Ferroel. and Freq. Control, vol. 48, pp. 322 – 328, 2001.

[6] I. E. Kuznetsova, B. D. Zaitsev, A. S. Kuznetsova, and A. M. Shikhabudinov, “Development of temperature stable acoustic line based on piezoelectric plate and nanocomposite polymeric film,” Proceedings of IEEE Ultrasonics Symp., Nov. 2-5, 2008, Beiging, China, pp. 920-923, 2008.

[7] A. J. Slobodnik, “The Temperature Coefficients of Acoustic Surface Wave Velocity and Delay on Lithium Niobate, Lithium Tantalate, Quartz, and Tellurium Dioxide,” Phys. Sci. Res. Pap., no.477, 1977.

[8] G. Kovacs, M. Anhorn, H. E. Engan, G. Visintini, and C. C. W. Ruppel, “Improved material constants for LiNbO3 and LiTaO3,” Proc. IEEE Ultrasonics Symp., vol. 1, pp. 435-438, 1991.

[9] I. E. Kuznetsova, B. D. Zaitsev, N. M. Ushakov, I. D. Kosobudskii. and A. M. Shikhabudinov, “Acoustical characteristics of polymeric nanocomposite films,” in Program and Abstracts of Int. Congress on Ultrasonics, April 9-12, 2007, Vienna, Austria, 2007, p.166.