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Extra two new piezoelectromagnetic SH-SAWs with dramatic dependence on small electromagnetic constant

A.A. Zakharenko

International Institute of Zakharenko Waves (IIZWs), 660014, ul. Chaikovskogo, 20-304 Krasnoyarsk, Russia

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ABSTRACT

It is expected that this theoretical report finalizes the research regarding to the shear-horizontal surface acoustic wave (SH-SAW) propagation along the suitable surface of the transversely isotropic (6 mm) piezoelectromagnetics. This report examines extra two new SH-SAWs, the existence of which dramatically depends on the small electromagnetic constant that is responsible for the magnetoelectric effect. This study also provides some comparison with the previously obtained theoretical results and the phenomenon called the Goldstone excitation. The obtained results can be useful for educational purposes, creation of novel technical devices based on the magnetoelectric effect that can find applications in spintronics, further theoretical treatments of the SH-wave propagation in plates, nondestructive testing and evaluation of apt surfaces and plates, etc.

1. Introduction

Acoustic phonons are collective oscillations in a periodic, elastic arrangement of atoms or molecules in condensed matter. Under action of external exciters, these long wavelength oscillations can result in coupled behavior of groups of atoms that can cause a wave motion propagating far from an excitation spot. It is well-known that in solids, the caused wave motion can be organized in different ways, namely it can possess the in-plane or anti-plane polarization (Auld, 1990; Dieulesaint and Royer, 1980). This theoretical report has an interest in discovery and study of extra new shear-horizontal surface acoustic waves (SH-SAWs) having the anti-plane polarization. This type of polarization can exist only in solids. The studied solids must have the transversely isotropic symmetry of class 6 *mm* and possess both the piezoelectric (PE) and piezomagnetic (PM) effects resulting in appearance of the additional effect called the magnetoelectric (ME) effect. Such ME materials are called the piezoelectromagnetics (PEMs), also known as the magnetoelectroelastics (MEEs). The PEM materials are typically composites of PE materials and magnetic materials. The linear ME effect is the phenomenon of inducing magnetic (electric) polarization by applying an external electric (magnetic) field. Recent review (Hu et al., 2016) summarizes the most recent progresses in the basic principles and possible applications of the interface-based ME effect in multiferroic heterostructures, and presents perspectives on some key issues that require further investigations concerning realizations of their practical device applications.

There is single book (Zakharenko, 2010) regarding to the existence of the SH-SAWs in the transversely isotropic PEMs that was published as a PhD thesis carried out for the International Institute of Zakharenko Waves (IIZWs). Zakharenko (2010) has discovered seven new PEM SH-SAWs. Also, book (Zakharenko, 2010) and theoretical work (Wei et al., 2009) have confirmed the propagation possibility of the other three PEM SH-SAWs discovered by Melkumyan (2007). They are called the surface Bleustein-Gulyaev-Melkumyan (BGM) wave, the piezoelectric exchange surface Melkumyan (PEESM) wave, and the piezomagnetic exchange surface Melkumyan (PMESM) wave. The first surface Melkumyan wave is called the BGM wave to have an analogy with the well-known surface Bleustein-Gulyaev wave (Bleustein, 1968; Gulyaev, 1969) discovered to the end of the 1960s that can propagate in a pure PEs or a pure PMs. The BGM wave and the rest two, PEESM and PMESM, were also studied in papers (Zakharenko, 2011) and (Zakharenko, 2012), respectively. The fifth new SH-SAW discovered in book (Zakharenko, 2010) and studied in paper (Zakharenko, 2012) can exist only in the case when the ME effect is taken into account, namely in the case of nonzero electromag-

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E-mail address: aazaaz@inbox.ru

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netic constant $\alpha \neq 0$. In general, for real known ME materials, the value of α is very small but nonzero. The fifth new SH-SAW relates to the third coupling mechanism responsible for the ME effect such as $(\varepsilon\mu - \alpha^2)$ of the three ones of the coefficient of the magnetoelectromechanical coupling (CMEMC), where ε and μ are the electric and magnetic constants of the PEM solid, respectively. There are also the eighth and tenth new PEM SH-SAWs (Zakharenko, 2013a, 2015a,b) relevant to $(\varepsilon\mu - \alpha^2)$ that have more dramatic dependence on the constant α because the small value of α must be big enough to allow the propagation of the eighth and tenth new PEM SH-SAWs. For these new SH-waves, the values of α smaller than the threshold value α_{th} must lead to the dissipation case when the wave velocity is imaginary. This short theoretical report provides extra new PEM SH-SAWs belonging to the CMEMC coupling mechanism $(\varepsilon\mu - \alpha^2)$ revealing the dissipation at $\alpha < \alpha_{th}$.

The following section refers the reader to the short theoretical description leading to the existence of the extra two new PEM SH-SAWs. The third section compares the obtained results with the other existing results and the phenomenon called the Goldstone excitation, respectively. It is also necessary to mention that in comparison with the conventional piezoelectrics, the PEM materials are preferable for excitation of the SH-SAWs with the noncontact EMAT method (Thompson, 1990; Hirao and Ogi, 2003; Ribichini et al., 2010). Also, the reader can find some reviews (Zakharenko, 2013b; Pullar, 2012; Srinivasan, 2010; Özgür et al., 2009; Fiebig, 2005; Kimura, 2012) on PEM SH-SAWs, smart PEM materials and their applications that can play their useful role for development of spintronics – the modern electronics free of charges, i.e. a technology utilizing the electron spin. The spin can either be "up" or "down", and this property could be used to store and process information in spintronic devices. Switching spins from up to down can be done using very little energy. Thus, spintronic circuits can be smaller and more efficient than conventional electronic circuits relying on just switching charge. The reader can find some bridges between the low-power spintronics and ME devices in recent work (Fusil et al., 2014). Ceramic materials based on bismuth ferrite (Jartych et al., 2016) represent an example of perspective ME materials. Review (Kimura, 2012) discusses that ME crystals such as ME hexaferrites can be perspective to the ME composite materials.

2. Two new PEM SH-SAWs

Let's treat a bulk hexagonal (6 mm class) PEMs and study the wave propagation in such transversely isotropic ME medium utilizing the rectangular coordinate system $\{x_1, x_2, x_3\}$. Review (Gulyaev, 1998) provides the proper propagation direction in the solid when pure SH-wave (Auld, 1990; Dieulesaint and Royer, 1980; Lardat et al., 1971) coupled with both the electrical (φ) and magnetic (ψ) potentials can be studied: the propagation direction is along the x_1-axis and perpendicular to both the 6-fold symmetry axis managed along the x_2-axis and the x_3-axis aligned along the normal to the free surface of the ME solid when the x_3-axis negative values are managed towards the solid depth. The coordinate beginning is situated at the interface between the solid and a vacuum. For the treated problem, it is natural to apply the quasi-static approximation because the acoustic wave speed is five orders slower than the electromagnetic wave speed. As a result of the used propagation direction (Auld, 1990; Dieulesaint and Royer, 1980; Zakharenko, 2010; Wei et al., 2009; Melkumyan, 2007; Bleustein, 1968; Gulyaev, 1969; Lardat et al., 1971), it is possible to separately consider the differential form of the coupled equations of motion for the pure SH-wave possessing the third mechanical displacement $U = U_2$ directed along the x_2-axis and coupled with both the electrical and magnetic potentials. Besides the mass density ρ there are the following thermodynamically defined material parameters for the PEM solid: the electromagnetic constant α, elastic stiffness constant C, piezomagnetic coefficient h, piezoelectric constant e, magnetic permeability coefficient μ, dielectric permittivity coefficient ε. So, the set of the partial differential equations of the second order (the differential form of the coupled equations of motion) can be written for this case as follows:

$$\begin{cases} C\nabla^2 U + e\nabla^2\phi + h\nabla^2\psi = \rho\partial^2 U/\partial t^2 \\ e\nabla^2 U - \varepsilon\nabla^2\phi - \alpha\nabla^2\psi = 0 \\ h\nabla^2 U - \alpha\nabla^2\phi - \mu\nabla^2\psi = 0 \end{cases} \quad (1)$$

where t is time and $\nabla^2 = \partial^2/\partial x_1^2 + \partial^2/\partial x_3^2$ is the two-dimensional differentiation operator called the Laplacian.It is blatant that the solution of set (1) can be written in the plane wave form of $U_I = U_I^0 \exp[\mathrm{j}(k_1x_1 + k_2x_2 + k_3x_3 - \omega t)]$, where the index I is equal to 2, 4, 5; $U_4 = \varphi$ and $U_5 = \psi$. The parameters U^0, φ^0, and ψ^0 are the unknown coefficients called the eigenvector components that must be determined. Also, j and ω are the imaginary unity and angular frequency, respectively. $\{k_1,k_2,k_3\} = k\{n_1,n_2,n_3\}$ are the wavevector components, where k is the wavenumber in the propagation direction because the directional cosines are $n_1 = 1$, $n_2 = 0$, $n_3 \equiv n_3$. The last represents the eigenvalue. Substituting the plane wave solutions into set (1), the tensor form of the coupled equations of motion known as the Green-Christoffel equation can be obtained and composed in the form of the following equations' set:

$$\begin{pmatrix} GL_{22} - C(V_{ph}/V_{t4})^2 & GL_{24} & GL_{25} \\ GL_{42} & GL_{44} & GL_{45} \\ GL_{52} & GL_{54} & GL_{55} \end{pmatrix} \begin{pmatrix} U^0 \\ \phi^0 \\ \psi^0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \quad (2)$$

where $V_{ph} = \omega/k$ stands for the phase velocity, $V_{t4} = (C/\rho)^{1/2}$ denotes the purely mechanical bulk acoustic wave (BAW) with the shear-horizontal (SH) polarization. In set (2), the Green-Christoffel tensor components are: $GL_{22} = C(1+n_3^2)$, $GL_{24} = GL_{42} = e(1+n_3^2)$, $GL_{25} = GL_{52} = h(1+n_3^2)$, $GL_{44} = -\varepsilon(1+n_3^2)$, $GL_{55} = -\mu(1+n_3^2)$, $GL_{54} = GL_{45} = -\alpha(1+n_3^2)$. An expansion of the determinant of the coefficient matrix in expression (2) leads to a sixth order polynomial in one indeterminate n_3. Thus, the found six suitable eigenvalues n_3 representing the polynomial roots read: $n_3^{(1,2)} = n_3^{(3,4)} = \pm\mathrm{j}$ and $n_3^{(5,6)} = \pm\mathrm{j}\sqrt{1 - (V_{ph}/V_{tem})^2}$. Here $V_{tem} = \sqrt{C/\rho}(1 + K_{em}^2)^{1/2}$ represents the velocity of the SH-BAW coupled with both the electrical and magnetic potentials via the following coefficient of the magnetoelectromechanical coupling (CMEMC): $K_{em}^2 = (eM_2 - hM_1)/CM_3$. Also, $M_1 = e\alpha - h\varepsilon$, $M_2 = e\mu - h\alpha$, and $M_3 = \varepsilon\mu - \alpha^2$ are the three CMEMC coupling mechanisms discussed in paper (Zakharenko, 2013c).

It is also necessary to state that for the used coordinate system described at the beginning of this section, the three apt eigenvalues of six must have a negative sign because the amplitudes of the solutions U, φ, and ψ defined after equations' set (1) must damp towards the PEM solid depth. Paper (Zakharenko, 2014a) discusses that two suitable sets of the eigenvector components U^0, φ^0, and ψ^0 can be found. The first one reads:

$$\begin{pmatrix} U^{0(1)} \\ \phi^{0(1)} \\ \psi^{0(1)} \end{pmatrix} = \begin{pmatrix} U^{0(3)} \\ \phi^{0(3)} \\ \psi^{0(3)} \end{pmatrix} = \begin{pmatrix} 0 \\ \alpha \\ -\varepsilon \end{pmatrix}, \begin{pmatrix} U^{0(5)} \\ \phi^{0(5)} \\ \psi^{0(5)} \end{pmatrix} = \begin{pmatrix} M_1/CK_{em}^2 \\ \alpha - eh/CK_{em}^2 \\ -\varepsilon + e^2/CK_{em}^2 \end{pmatrix} \quad (3)$$

Using the following equality $e\phi^{0(1)} + h\psi^{0(1)} = e\phi^{0(5)} + h\psi^{0(5)} = M_1$, it is possible to state that the corresponding eigenvector components are coupled via the first coupling mechanism M_1 of the CMEMC.

The second set of the eigenvector components can be introduced as follows:

$$\begin{pmatrix} U^{0(1)} \\ \phi^{0(1)} \\ \psi^{0(1)} \end{pmatrix} = \begin{pmatrix} U^{0(3)} \\ \phi^{0(3)} \\ \psi^{0(3)} \end{pmatrix} = \begin{pmatrix} 0 \\ \mu \\ -\alpha \end{pmatrix}, \begin{pmatrix} U^{0(5)} \\ \phi^{0(5)} \\ \psi^{0(5)} \end{pmatrix} = \begin{pmatrix} M_2/CK_{em}^2 \\ \mu - h^2/CK_{em}^2 \\ -\alpha + eh/CK_{em}^2 \end{pmatrix} \tag{4}$$

Here there is already the coupling of the corresponding eigenvector components through the second coupling mechanism M_2 of the CMEMC: $e\phi^{0(1)} + h\psi^{0(1)} = e\phi^{0(5)} + h\psi^{0(5)} = M_2$.The found eigenvalues and the corresponding eigenvector components are now used for composition of the complete mechanical displacement ($U_2^\Sigma = U^\Sigma$), complete electrical potential ($U_4^\Sigma = \phi^\Sigma$), and complete magnetic potential ($U_5^\Sigma = \psi^\Sigma$). They therefore read: $U_I^\Sigma = \sum_{p=1,3,5} F^{(p)} U_I^{0(p)} \exp[jk(x_1 + n_3^{(p)} x_3 - V_{ph} t)]$, where the index I is equal to 2, 4, 5. It is obvious that the studied case represents a three-partial SH-wave because p = 1, 3, 5. Let's further use F_1, F_2, and F_3 instead of the weight factors $F^{(1)}$, $F^{(3)}$, and $F^{(5)}$, respectively. Let's also to further employ $F = F_1 + F_2$ because there are two identical eigenvalues defined in the context after expression (2) that actually give two identical eigenvectors. Using F and F_3, the studied three-partial case can represent a hidden two-partial SH-wave.

Exploiting the complete parameters in different mechanical, electrical, and magnetic boundary conditions at the interface between the PEM solid and a vacuum, various determinants of the boundary conditions can be composed. Possible boundary conditions for the treated case of the wave propagation along the free surface of the PEM solid were perfectly described by Al'shits et al. (1992). In this study, the used mechanical boundary condition at the interface is for the normal component of the stress tensor: $\sigma_{32} = 0$. The electrical boundary conditions at the interface are the continuity of the electrical potential φ and the continuity of the normal component of the electrical displacement D_3, namely $\varphi = \varphi^f$ and $D_3 = D^f$, where the superscript "f" belongs to the free space. Besides, the used magnetic ones are continuity of the magnetic potential ψ and the continuity of the normal component of the magnetic displacement B_3: $\psi = \psi^f$ and $B_3 = B^f$. It is unnecessary to write down all the explicit forms for the five boundary conditions resulting in a set of three homogeneous equations for the determination of the suitable propagation velocity of a new SH-SAW. To be familiar with the complete procedure, the reader can find book (Zakharenko, 2010) and open access papers (Zakharenko, 2013a, 2015a). It is now possible to give some vacuum parameters: the dielectric permittivity constant $\varepsilon_0 = 8.854187817 \times 10^{-12}$ [F/m] and the magnetic permeability constant $\mu_0 = 12.5663706144 \times 10^{-7}$ [H/m]. These vacuum constants will present below in the final results for the propagation velocity of the SH-wave and are crucial for the wave existence. Indeed, Laplace's equations such as $\Delta\varphi^f = 0$ and $\Delta\psi^f = 0$ must be written for the potentials in a vacuum and they must exponentially vanish in a vacuum far from the free surface of the PEM medium. Utilizing the vacuum constants, let's consider additional two new cases unrecorded in book (Zakharenko, 2010) and papers (Zakharenko, 2013a, 2015a,b).The treated two new cases **(i)** and **(ii)** below pertain to the third coupling mechanism of the CMEMC such as $\varepsilon\mu - \alpha^2$ that is actually responsible for the ME effect. Taking into account the aforementioned vacuum parameters, the third coupling mechanism can be rewritten in the form of $[(\varepsilon + \varepsilon_0)(\mu + \mu_0) - \alpha^2]$ instead.

(i) Using first eigenvectors (3) for the aforementioned five boundary conditions ($\sigma_{32} = 0$, $\varphi = \varphi^f$, $D_3 = D^f$, $\psi = \psi^f$, $B_3 = B^f$) it is possible to construct corresponding five homogeneous equations with the weight factors F_1, F_2, F_3, F_E and F_M. It is usual to find function $F_E(F_1, F_2, F_3)$ from one suitable equation and the function $F_M(F_1, F_2, F_3)$ from the other one and to substitute them into the rest equations in order to exclude the vacuum weight factors F_E and F_M. So, one naturally deals now with three homogeneous equations in three unknowns F_1, F_2, and F_3. Finally, it is possible to compose three consistent equations when the first one represents a sum of the rest two. Using $F = F_1 + F_2$, they read:

$$\begin{cases} (\varepsilon\mu + \varepsilon_0\mu + \varepsilon\mu_0 + \varepsilon_0\mu_0 - \alpha^2)[F + F_3 b(1 + K_{em}^2)/K_{em}^2] = 0 \\ \varepsilon_0(\mu + \mu_0)[F + F_3(K_{em}^2 - K_\alpha^2)/K_{em}^2] = 0 \\ F[\varepsilon(\mu + \mu_0) - \alpha^2] + F_3\varepsilon\mu_0(K_{em}^2 - K_e^2)/K_{em}^2 = 0 \end{cases} \tag{5}$$

where $b^2 = 1 - (V_{ph}/V_{tem})^2$; the nondimensional parameter $K_e^2 = e^2/C\varepsilon$ is called the coefficient of the electromechanical coupling (CEMC) and $K_\alpha^2 = eh/C\alpha$ is also the nondimensional coefficient combining the terms with the electromagnetic constant α in the CMEMC.

To obtain the first new result, it is indispensable in set (5) to successively subtract the second and third equations form the first. As a result, the explicit form for the calculation of the velocity of the fourteenth new SH-SAW is given by the following expression:

$$V_{new14} = V_{tem}\left[1 - \left(\frac{\frac{\mu_0}{\mu}(K_{em}^2 - K_e^2) + \frac{\varepsilon_0}{\varepsilon}\left(1 + \frac{\mu_0}{\mu}\right)(K_{em}^2 - K_\alpha^2)}{(1 + K_{em}^2)\left(1 + \frac{\varepsilon_0}{\varepsilon} + \frac{\mu_0}{\mu} + \frac{\varepsilon_0\mu_0 - \alpha^2}{\varepsilon\mu}\right)}\right)^2\right]^{1/2} \tag{6}$$

If one would like to consider only dependence on ε_0, i.e. $\mu_0 = 0$ in expression (6), the velocity V_{new14} reduces to the following form:

$$V_{new14}(\mu_0 = 0) = V_{tem}\left[1 - \left(\frac{\varepsilon_0\mu}{(\varepsilon + \varepsilon_0)\mu - \alpha^2}\frac{K_{em}^2 - K_\alpha^2}{1 + K_{em}^2}\right)^2\right]^{1/2} \tag{7}$$

(ii) Exploiting second eigenvectors (4) for the same boundary conditions, three consistent equations can be also constructed when the first equation represents a sum of the other two. The equations read:

$$\begin{cases} (\varepsilon\mu + \varepsilon_0\mu + \varepsilon\mu_0 + \varepsilon_0\mu_0 - \alpha^2)[F + F_3 b(1 + K_{em}^2)/K_{em}^2] = 0 \\ F[(\varepsilon + \varepsilon_0)\mu - \alpha^2] + F_3\varepsilon_0\mu(K_{em}^2 - K_m^2)/K_{em}^2 = 0 \\ (\varepsilon + \varepsilon_0)\mu_0[F + F_3(K_{em}^2 - K_\alpha^2)/K_{em}^2] = 0 \end{cases} \tag{8}$$

In (8), the nondimensional characteristic $K_m^2 = h^2/C\mu$ is called the coefficient of the magnetomechanical coupling (CMMC). A successive subtraction of the second and third equations from the first in set (8) leads to the second new result. Indeed, the velocity of the fifteenth new SH-SAW can be calculated with the following formula:

$$V_{new15} = V_{tem}\left[1 - \left(\frac{\frac{\varepsilon_0}{\varepsilon}(K_{em}^2 - K_m^2) + \frac{\mu_0}{\mu}\left(1 + \frac{\varepsilon_0}{\varepsilon}\right)(K_{em}^2 - K_\alpha^2)}{(1 + K_{em}^2)\left(1 + \frac{\varepsilon_0}{\varepsilon} + \frac{\mu_0}{\mu} + \frac{\varepsilon_0\mu_0 - \alpha^2}{\varepsilon\mu}\right)}\right)^2\right]^{1/2} \tag{9}$$

In the case of $\varepsilon_0 = 0$, it reduces to the following form:

$$V_{new15}(\varepsilon_0 = 0) = V_{tem}\left[1 - \left(\frac{\varepsilon\mu_0}{\varepsilon(\mu + \mu_0) - \alpha^2}\frac{K_{em}^2 - K_\alpha^2}{1 + K_{em}^2}\right)^2\right]^{1/2} \tag{10}$$

It is now essential to stress the peculiarity existing in final results (6) and (9). It is clearly seen in expressions (6) and (9) that they depend on the coefficient $K_\alpha^2 = eh/C\alpha$. This coefficient approaches an infinity when $\alpha = 0$. If K_α^2 is large enough, i.e. the electromagnetic constant α is small enough, the propagating new SH-SAWs cannot exist due to the dissipation, i.e. the velocities V_{new14} in (6) and V_{new15} in (9) become imaginary. This means that there can exist a dramatic dependence on small values of α. In general, the value of α is small for real PEM solids. It is expected that these new SH-SAWs can propagate only in selective PEM solids with the strong enough ME effect. However, this peculiarity vanishes when $\varepsilon_0 = 0$ in expression (6) and $\mu_0 = 0$ in expression (9). Therefore, the corresponding vacuum parameters are crucial for the existence of the peculiarity. The following section compares the obtained new results with the previously found wave phenomena.

3. Comparison with previous results and the phenomenon called the Goldstone excitation

First of all, it is natural to compare the obtained 14th and 15th new SH-SAWs in this report with the 8th and 10th new SH-SAWs discovered in papers (Zakharenko, 2013a) and (Zakharenko, 2015a), respectively. These all mentioned four new SH-SAWs allow some dissipation at small enough values of the electromagnetic constant α. This phenomenon was briefly discussed to the end of the previous section. This phenomenon of dissipation can exist for the 14th and 10th new SH-SAWs only if the vacuum electric constant ε_0 is taken into account. Moreover, the dependence of the 10th new SH-SAW on ε_0 is vital because $\varepsilon_0 = 0$ cancels the SH-BAW instability, i.e. $V_{new10}(\varepsilon_0 = 0) = V_{tem}$, see formula (60) in paper Zakharenko, 2015a. Also, $V_{new14}(\varepsilon_0 = 0)$ in formula (6) written in the previous section does not reduce to V_{tem}. It is now possible to compare 15th and 8th new SH-SAWs. The phenomenon of dissipation exists for these new waves only if the vacuum magnetic constant μ_0 is taken into account. Analogically, $\mu_0 = 0$ actually annuls the SH-BAW instability, i.e. $V_{new8}(\mu_0 = 0) = V_{tem}$, see formula (73) in paper Zakharenko (2013a). However, it is allowable for the 15th new SH-SAW existence: $V_{new15}(\mu_0 = 0) \neq V_{tem}$.

Fig. 1 shows the dependencies of the velocities of the nondispersive 8th, 10th, 14th, and 15th new SH-SAWs on the small values of the electromagnetic constant α. The material parameters for the PEM composite materials $BaTiO_3$–$CoFe_2O_4$ and PZT-5H–Terfenol-D were borrowed from papers (Zakharenko, 2011, 2014b, 2015b). The first and second solids are relatively weak and significantly stronger PEMs, respectively, that provides a contrast for comparison. It is clearly seen in the figure that the dissipation phenomenon corresponding to imaginary velocity appears at significantly smaller values of the constant α for the weaker PEM $BaTiO_3$–$CoFe_2O_4$. The reader can readily evaluate the threshold values of $(\alpha^2/\varepsilon\mu)_{th}$ from the figure. Also, it is natural that at small values of the α, the normalized velocities of the 8th and 15th new SH-SAWs only slightly differ from each other and this difference is larger for the stronger PEM PZT-5H–Terfenol-D. It worth mentioning that for this pair of the new SH-SAWs, the vacuum parameter μ_0 is crucial for the existence of the dissipation phenomenon. For PZT-5H–Terfenol-D, the normalized velocities of the 8th and 15th new SH-SAWs are equal to zero at $\alpha^2/\varepsilon\mu = 0.86$ and 1.0, respectively. Concerning the 10th and 14th new SH-SAWs' normalized velocities at small values of $\alpha^2/\varepsilon\mu$, they look like they coincide for both the studied composites. For this pair of new SH-SAWs, the vacuum parameter ε_0 is vital for the existence of the dissipation phenomenon. However, for $\alpha^2/\varepsilon\mu \to 1$, the 10th and 14th new SH-SAWs' normalized velocities approach 1 and 0, respectively. With the found characteristics of the 14th and 15th new SH-SAWs, it is also necessary to perform a further theoretical study on dispersive wave propagation in plates similar to research (Zakharenko, 2015c), in which the speeds of the corresponding new dispersive waves approach the nondispersive 8th new SH-SAW speed at large values of the plate thickness. It is expected that new disposition relations can be more complicated than those obtained in paper (Zakharenko, 2015c). The two-dimensional structures (plates) can be suitable for further miniaturization of some technical devices including ones with a high level of integration. It is also natural to use the dissipation phenomenon around the threshold values of $(\alpha^2/\varepsilon\mu)_{th}$ for constitution of various smart technical devices such as switches, delay lines, computer logics, etc.Next, it is possible to compare the obtained theoretical results (6) and (9) with those theoretically obtained in 2007 papers (Wang et al., 2007; Liu et al., 2007). The authors of references (Wang et al., 2007; Liu et al., 2007) have used the same coupled equations of motion (1) for the PEM SH-wave propagation coupled with both the electrical and magnetic potentials. Their final results for the PEM SH-wave propagation velocities also depend on both the vacuum parameters ε_0 and μ_0 but different from each other, see formula (27) introduced in review (Zakharenko, 2013b) in the convenient form for comparison. This is similar to results (6) and (9) obtained in this short report. Review (Zakharenko, 2013b) has also stated that their results are incorrect, even fake, because they have mixed different eigenvectors (3) and (4). So, their incorrect results for the propagation velocities do not allow any dissipation at some small values of the electromagnetic constant α because there is no dependence on the coefficient K_α^2. Instead of that, they have even introduced their results in very complicated forms unsuitable for any comparison.

The author has to state that the final part of this section is written for further discussions and is based on some interesting comments of one of the first readers (referees, namely Professor Dr. V.G. Shavrov) of my previous work (Zakharenko, 2013a, 2015a,b). It concerns the theory developed in the 1960s (Wagner, 1966; Goldstone, 1961; Nambu, 1960), namely the Goldstone excitation phenomenon pertaining to quantum nongap long-wavelength elementary excitations. These excitations can be associated with some longitudinal phonons in crystals, phonons in the superfluid helium-II and superconductors, magnons in magnetic systems. Following the Shavrov comments and using the condition of thermodynamic stability $\alpha^2 < \varepsilon\mu$ (Özgür et al., 2009; Fiebig, 2005), the threshold of the Goldstone excitation is defined by

$$\frac{\varepsilon\mu eh}{C\varepsilon\mu + \mu e^2 + \varepsilon h^2} > \alpha \text{ or } \frac{K_\alpha^2}{1 + K_e^2 + K_m^2} > 1 \qquad (11)$$

It is clearly seen in inequality (11) that the fraction numerator depends on the electromagnetic constant α because the coefficient $K_\alpha^2 = eh/C\alpha$ defined after Eq. (5) depends on the α. Concerning the

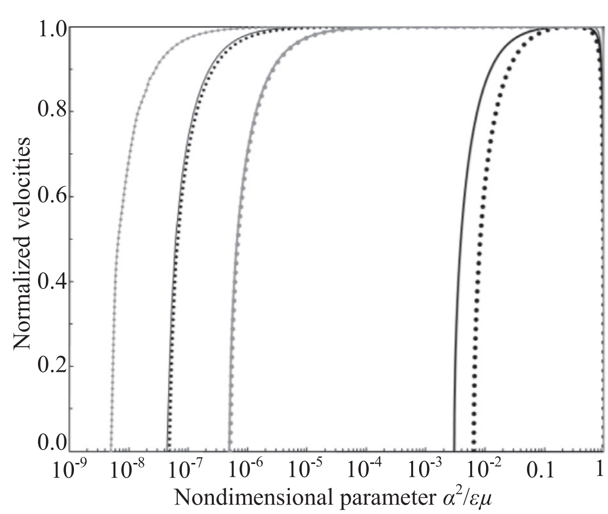

Fig. 1. The normalized velocities V_{new8} (big dots), V_{new10} (smaller dots), V_{new14} (thin solid lines), and V_{new15} (thick solid lines) versus $\alpha^2/\varepsilon\mu$: for $BaTiO_3$–$CoFe_2O_4$ (grey) and PZT-5H–Terfenol-D (black).

fraction denominator in inequality (11), it does not depend on the α because $K_{em}^2(\alpha = 0) = K_e^2 + K_m^2$. It is also possible to discuss that the α can have a negative sign and therefore, it is possible to deal with the absolute values to compare the left and right sides in inequality (11). If the reader would also like to associate one of the four new SH-SAWs discussed in this section with the Goldstone excitation, the author has to state that Goldstone excitation threshold (11) and therefore, their theory leading to the threshold is incorrect because this theory does not take into account any vacuum parameters, ε_0 or μ_0. Indeed, the dissipation phenomenon discussed in the context above can exist for the four new SH-SAWs at small enough values of the electromagnetic constant α only if the corresponding vacuum constants are taken into account and therefore does not relate to the Goldstone excitation phenomenon. Also, it is necessary to mention that there are three different branches of the acoustic excitations in solids and they can relate to the possible three bulk acoustic waves (BAWs). So, the discovered different new SH-SAWs caused by different mechanisms, for instance, by the ME effect, represent an instability of the same SH-BAW under action of various mechanical, electrical, and magnetic boundary conditions and relate to the same SH-BAW branch but not to some additional branches.

4. Conclusion

This short theoretical report has examined extra two new SH-SAWs, the propagation of which in the transversely isotropic PEM solids can dramatically depend on the magnetoelectric effect characterized by the electromagnetic constant α. It was discussed that taking into account the corresponding vacuum parameter in the new SH-SAW velocity expression allows the existence of the dissipation phenomenon at small values of α. So, some comparison with the previously obtained theoretical results and the phenomenon called the Goldstone excitation was performed. The theoretically obtained new results can be handy for educational purposes and even creation of suitable technical devices based on the ME effect for spintronics. Also, it is recommended that further theoretical researches of the SH-wave propagation in plates must be carried out that can be called for nondestructive testing and evaluation of apt surfaces and plates, etc. It is possible that some gravitational phenomena can be applied as an addiction to the electromagnetic properties or instead of them. These gravitational phenomena were discussed in recently developed theory (Zakharenko, 2016).

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