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PIEZOELECTROMAGNETIC SH-SAWS: A REVIEW

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ABSTRACT

This review has a purpose to acquaint the experimental and theoretical research society with the recent theoretical achievements in the research field of the shear-horizontal surface acoustic wave (SH-SAW) propagation in the two-phase materials. It is well-known that to know the SH-SAW characteristics can be very important for the sensor applications. Since 2007, several contributors have achieved some progress in the theory when it was theoretically demonstrated that several new SH-SAWs can propagate in novel two-phase materials called the piezoelectromagnetics (PEMs) or the magneto-electro-elastic materials. For the last half-decade, a lot of new SH-SAWs were discovered and it was also found that they can propagate in the cubic PEMs and the transversely isotropic piezoelectromagnetic materials of class 6 *mm*. For the same set of the boundary conditions, it is already known that only one SH-SAW can propagate in the cubic PEMs and at least two SH-SAWs can propagate in the hexagonal PEMs of class 6 *mm*. They can have potential applications in the SH-SAW sensors such as biosensors, physical and chemical sensors. It was also discussed that some theoretical results cannot be true.

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INTRODUCTION

The propagation characteristics of various acoustic waves or electromagnetic waves in new composite materials or structures have received an increasing interest in the scientific society due to their importance in the development and design of novel technical devices based on different acoustic waves and optical phenomena. Up to now, much review work (Bichurin *et al*., 2011; Srinivasan, 2010; Özgür *et al*., 2009; Zhai *et al*., 2008; Eerenstein *et al*., 2006; Fiebig, 2005; Fang *et al*., 2008; Sihvola, 2007; Hill and Spaldin, 2000; Prellier *et al*., 2005; Spaldin and Fiebig, 2005; Khomskii, 2006; Smolenskii and Chupis, 1982; Cheong and Mostovoy, 2007; Ramesh and Spaldin, 2007; Kimura, 2007; Kimura *et al*., 2003; Wang *et al*., 2009; Ramesh, 2009; Delaney *et al*., 2009; Gopinath *et al*., 2012; Fert, 2008a,b; Chappert and Kim, 2008; Bibes and Barthélémy, 2008; Bichurin *et al*., 2006; Fetisov *et al*., 2006; Srinivasan and Fetisov, 2006; Priya *et al*., 2007; Grossinger *et al*., 2008; Ahn *et al*., 2009; Petrov *et al*., 2003; Harshe *et al*., 1993; Chu *et al*., 2007; Nan *et al*., 2008; Schmid, 1994; Ryu *et al*., 2002; Chen *et al*., 2012) has been devoted to the two-phase piezoelectromagnetic (PEM) materials, also called the magneto-electro-elastic materials (MEEMs). The two-phase materials are one class of new (composite) materials that exhibit the co-existence of the piezoelectric phase and the piezomagnetic phase. Also, these materials can naturally show an evidence of sizable magnetoelectric coupling at room temperatures. It is well-known that one of the pioneer works (Astrov, 1960; Astrov, 1961; Rado and Folen, 1961; Van Suchtelen, 1972; Van den Boomgaard *et al*., 1974; Van Run *et al*., 1974; Van den Boomgaard *et al*., 1976; Wood and Austin, 1975) on the magnetoelectric effect relates to 1960 (Astrov, 1960). The relatively large magnetoelectric effect was also revealed in several piezoelectromagnetic monocrystals such as Cr_2O_3 (Fiebig, 2005), $LiCoPO_4$ (Rivera, 1994), and $TbPO_4$ (Rado *et al*., 1984). However, the review papers mentioned above did not focus on some problems of the shear-horizontal surface acoustic wave (SH-SAW) propagation in the two-phase materials.

Surface acoustic waves (Gulyaev, 1998) can be defined by the well-known classification accepted in acoustic textbooks: SAW is the wave propagating parallel to the surface of a solid when both the wavevector and the energy flux vector are parallel to the surface and the wave amplitude is quickly (in terms of wavelength) decreasing into the depth of the solid. It is thought that it is possible to supplement this definition. It is well-known that the SAW wavevector can have an imaginary part. This is a SAW feature. Therefore, it is possible to understand the SAWs by the way that there is an equilibrium exchange between the real and imaginary parts resulting in the SAW propagation. It is worth mentioning that several types of SAWs (Gulyaev, 1998) are known. However, this is not the aim of this review to mention all possible

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SAWs in solids and discuss them. The main purpose of this review is to acquaint the reader with some recently obtained SH-SAW characteristics of the transversely isotropic piezoelectromagnetic (composite) materials of class 6 *mm* (hexagonal symmetry) and the cubic PEMs.

It is surprising that the very important SH-SAW characteristics were discovered in the two-phase materials only within the last half-decade, while the SH-SAW characteristics of the single-phase materials such as the pure piezoelectric and pure piezomagnetics are well-known already during more than forty years. Indeed, the SH-SAWs called the surface Bleustein-Gulyaev (BG) waves (Bleustein, 1968; Gulyaev, 1969) are well-accepted. In the transversely isotropic piezoelectrics there are totally two different surface BG-waves: the faster and slower waves propagating on the electrically open and electrically closed surface, respectively, when the surface is also mechanically free. The values of two BG-waves are naturally situated just below the value of the shear-horizontal bulk acoustic wave (SH-BAW). In the two-phase materials, a set of new SH-SAWs (Melkumyan, 2007; Liu *et al*., 2007; Wang *et al*., 2007; Wei *et al*., 2009; Zakharenko, 2010; Zakharenko, 2011a,b; Zakharenko, 2012a) guided by the free surface were recently discovered. The values of all the new SH-SAWs must be also situated just below the value of the PEM SH-BAW.

Melkumyan (2007) has theoretically treated the SH-SAW propagation problems when the waves are guided by the interface between two identical PEM half-spaces of the hexagonal (6 *mm*) symmetry. He has found as many as twelve new SH-SAWs and demonstrated the explicit forms for the SH-SAW velocities in the cases of different electrical and magnetic boundary conditions. In the same year, Liu, Fang, and Liu (Liu *et al*., 2007) as well as Wang *et al*. (2007) have also represented a new SH-SAW propagating along the free surface of the transversely isotropic piezoelectro-magnetics of class 6 *mm*. They also found their explicit forms for the new SH-SAWs. Wei *et al*. (2009) have considered the SH-SAW propagation in the same configuration treated in theoretical works (Liu *at al*., 2007; Wang *et al*., 2007). Using different boundary conditions, the authors of the work (Wei *et al*., 2009) have stated that they have theoretically discovered three new SH-SAWs for the hexagonal PEM half-space and demonstrated the corresponding explicit forms. To complete the list of the new SH-SAWs guided by the free surface of the hexagonal PEM, the author of the work (Zakharenko, 2010) has additionally discovered seven new SH-SAWs for the cases of different electrical and magnetic boundary conditions and also demonstrated the corresponding explicit forms for the wave velocities. Concerning the cubic PEMs, it was revealed in (Zakharenko, 2011b) that seven new SH-SAWs can also propagate and their velocities are different from those in the case of wave propagation in the hexagonal PEMs. Using works (Melkumyan, 2007; Liu *et al*., 2007; Wang *et al*., 2007; Wei *et al*., 2009; Zakharenko, 2010; Zakharenko, 2011a,b; Zakharenko, 2012a), it is thought that one can find the complete list of the SH-SAWs that can propagate along the PEM free surface. However, it is believed that some obtained solutions cannot be true due to the used theoretical method. This will be discussed below.

It is thought that the modern experimental techniques to generate surface waves in piezoelectromagnetics must exist. Indeed, SH-SAWs can be produced by electromagnetic acoustic transducers (EMATs) (Ribichini *et al*., 2010). The EMATs can offer a series of advantages in comparison with the traditional piezoelectric transducers (Thompson, 1990; Hirao and Ogi, 2003). These experimental tools of the SH-SAW (SH-BAW) propagation investigations in the piezoelectromagnetics can be used already today. Also, an optical method can be used. An improved optical method for measurements of both the phase and group velocities described in (Kolosovskii *et al*., 1998) allows one to measure the phase velocity with accuracy ~ 2 m/s. It is well-known that SH-SAWs can be used in sensors and for the non-destructive testing and evaluation of the piezoelectromagnetics. Indeed, because of the capability of energy conversion between the electrical and magnetic fields, PEMs are suitable for novel device applications such as magnetic field sensors, resonators, electric-field-tunable filters, phase shifters, and delay lines. Most of these technical devices are pertaining to the knowledge of the acoustic wave propagation. So, there has been a growing interest in the wave propagation problems in PEM monocrystals and structures within the last half-decade.

It is expected that piezoelectromagnetic (composite) materials can be widely used for sensor applications instead of piezoelectrics or together with them. It is true that SH-SAW sensors can usually have significantly higher sensitivity than that of the BAW devices. This reason is given by the fact that in the case of SAWs the acoustic energy is concentrated at the surface and hence, any perturbations of the surface can have a larger effect than in BAW devices. The piezoelectric sensors were used already for the last three decades. One of the key aims in the design of the sensor is to create the device sensitive only to one particular quantity (in the optimum case.) This is also true for microsensors. Comparing with the older sensor technologies, microsensors can have several advantages such as small size, low cost, and excellent performance (Sze, 1994; Galipeau *et al*., 1997). Development of newer microsensor technologies was caused by the high demand for low-cost and high-performance sensors to measure physical and chemical environmental parameters. Common physical parameters include temperature, pressure, acceleration, and stress. Common chemical parameters can be also measured and include humidity, hazardous gases, and biological materials (Sze, 1994; Galipeau *et al*., 1997; Ballantine *et al*., 1997).

Microelectromechanical systems (MEMSs) can consist of microsensors which can have the mechanical and electrical components (or functions) in a single unit. SAW devices can be associated with the earliest type of MEMSs because of the utilization of electrically generated (and electrically detected) mechanical (acoustic) waves. It is thought that the earliest uses of the SAW devices as the microsensors were reported in 1978 to measure such physical property as pressure (Das *et al*., 1978) and in 1979 to measure chemical properties of thin films (Wohltjen, 1979). Temperature, stress, pressure, electric and magnetic fields (Sze, 1994) can be the external physical parameters that can affect the SAW characteristics. Film properties that can affect the SAW device are as follows: mass, density, conductivity, permittivity, stress, and viscoelasticity (Sze, 1994; Ballantine *et al*., 1997). In addition, an important feature of SAW sensors is that they can be easily used in wireless applications. These sensors can be operated in both active and passive modes, of which the second is particularly interesting because the sensor does not need a power source and can be read using a special FM radar system. The active mode example can be demonstrated with the frequency control element in an oscillator (Das *et al*., 1978). Wireless temperature (Bao *et al*., 1987) and stress (Varadan *et al*., 1996) sensors can be the passive mode examples.

The major sensor markets are military, automotive, industrial and environmental, food industry, and medical. The sensors are based on (bio)chemical and physical sensing properties. It is also necessary to mention that the application area of novel SAW sensors can be extended into micro scale. For instance, a recent paper (Yang *et al*., 2011) designs a novel SAW micro position sensor which can be fabricated with MEMS technology, see also work (Adler and Desmares, 1987). The main countries which have well-developed sensor industry are China, Japan, and the United States. For example, one company of either country mentioned above can produce several million sensors per day. Therefore, this is a very big market and number of relevant patents offering novel sensor devices for the market increases. Some recent patents are cited in (Pereira da Cunha, 2007; Zhang, 2011; Malocha, 2009; Cular, 2011; Cular *et al*., 2011). It is expected that the recent theoretical achievements discussed in this review can help the researchers to be familiar with the SH-SAW characteristics leading to the correct interpretation of experimental results. This can result in the development of a set of different SH-SAW devices and correct description in patent applications. This is true because the wave propagation in the two-phase materials has some very important peculiarities discussed below.

SH-SAWs in Hexagonal PEMs (6 *mm*)

This section acquaints the reader with the recent achievements concerning the wave propagation in the transversely isotropic piezoelectromagnetics. First of all, it is necessary to give a short theory for the SH-SAW propagation in the hexagonal piezoelectromagnetics of class 6 *mm*. The configuration is shown in figure 1. The SH-SAW can propagate only on certain cuts and in certain propagation directions. Therefore, the direction of wave propagation is perpendicular to the sixfold symmetry axis and the wave polarization (anti-plane polarization) is along the axis.

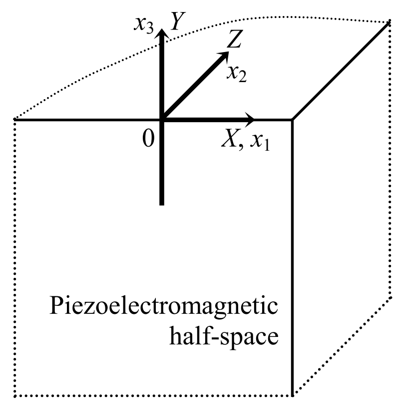

Fig. 1. The rectangular coordinate system for the transversely isotropic (6 *mm*) piezoelectromagnetic half-space. The propagation direction is along the x_1-axis and the wave damps towards the depth of the solid, namely towards the negative values of the x_3-axis. The SH-SAWs are polarized along the x_2-axis directed along the sixfold axis of symmetry. *X*, *Y*, and *Z* are the crystallographic axes.

For a two-phase material, it is possible to use a thermodynamic potential to describe its thermodynamic properties. The thermodynamic process can be naturally considered as adiabatic with the constant entropy. Also, it is thought that it is convenient to choose the following thermodynamic variables written in the tensor forms: stress σ_{ij}, strain η_{ij}, electrical field E_i, electrical induction D_i (electrical displacement), magnetic field H_i, magnetic flux B_i (magnetic displacement) where the indexes *i* and *j* run from 1 to 3. In this case, the well-known strain-displacement relation and the quasi-static approximations can be also applied. Using the Gibbs thermodynamic potential, the constitutive relations (Zakharenko, 2010; Zakharenko, 2011b) for a linearly piezoelectromagnetic solid can be then written. As a result, the following material constants can be thermodynamically determined:

the elastic stiffness constant C, piezoelectric constant e, piezomagnetic coefficient h, dielectric permittivity coefficient ε, magnetic permeability coefficient μ, and electromagnetic constant α. It is noted that the constants mentioned above are written already in the treated case (Zakharenko, 2010).

Exploiting the Maxwell equations such as div**B** = 0 and div**D** = 0, the governing mechanical, magnetostatic, and electrostatic equilibriums can be also used in order to write the equations of motion. It is thought that it is convenient to use the tensor form of the coupled equations of motion. Leaving only those equations of motion which relate to the SH-wave propagation, it is possible to determine all the eigenvalues and corresponding eigenvector components for a suitable phase velocity. The very important fact is that in a two-phase material, two different sets of the eigenvector components can exist. This can result in such unique situation when two solutions can be found. Therefore, it is necessary to state that SH-SAWs can propagate guided by the mechanically free surface (normal component of stress σ_{32} = 0) when different electrical and magnetic boundary conditions are also applied at the vacuum-solid interface. The realization of the boundary conditions for the two-phase materials possessing both the piezoelectric and piezomagnetic phases is perfectly described in (Al'shits *et al*., 1992). It is obvious that this peculiarity is present only in the two-phase materials and cannot be revealed in the single-phase materials for the case of the pure SH-wave propagation. Therefore, it is indispensable to review the obtained results of the SH-SAW propagation in the transversely isotropic piezoelectromagnetic materials.

The case of $\sigma_{32} = 0$, $\varphi = 0$, and $\psi = 0$

This is the case of the mechanically free, electrically closed (φ = 0) and magnetically open (ψ = 0) surface. This case was theoretically considered in (Melkumyan, 2007; Wei *et al*., 2009, Zakharenko, 2010). In 2007, Melkumyan was the first researcher discovered in his theoretical work (Melkumyan, 2007) that with this set of the boundary conditions, the new SH-SAW can propagate along the interface of two identical PEMs. He also found an explicit form for the new SH-SAW velocity. In 2009, the authors of the paper (Wei *et al*., 2009) have treated the case of wave propagation along the vacuum-PEM interface and received the same formula for the SH-SAW velocity. However, they did not mention work (Melkumyan, 2007) and stated that they have found the new SH-SAW. Also, their explicit form for the velocity was given in a complicated form. It is thought that a convenient explicit form for the new SH-SAW velocity discovered by Melkumyan was obtained in the book (Zakharenko, 2010). This book theoretically studied the wave propagation problems in a transversely isotropic PEM. Also, (Zakharenko, 2010) has stated that the new SH-SAW propagating in a two-phase material can be called the surface Bleustein-Gulyaev-Melkumyan (BGM) wave to have an analogy to the slower surface BG-wave propagating in a single-phase material. Indeed, in a two-phase PEM, two solutions for the SH-SAW velocity can be found. However, for this set of the boundary conditions, two solutions coincide and both can be represented in the same convenient form (Zakharenko, 2010; Zakharenko, 2011a) written below:

$$V_{BGM} = V_{tem}\left[1-\left(\frac{K_{em}^2}{1+K_{em}^2}\right)^2\right]^{1/2} \quad (1)$$

In equation (1), the velocity denoted by V_{tem} is the speed of the shear-horizontal bulk acoustic wave (SH-BAW) coupled with both the electrical potential and the magnetic potential. It reads:

$$V_{tem} = V_{t4}\left(1+K_{em}^2\right)^{1/2} \quad (2)$$

In equations (1) and (2), the very important material parameter denoted by K_{em}^2 is called the coefficient of the magnetoelectromechanical coupling or CMEMC. It couples all the material constants listed above, but the mass density ρ. It has the following form:

$$K_{em}^2 = \frac{\mu e^2 + \varepsilon h^2 - 2\alpha e h}{C\left(\varepsilon\mu - \alpha^2\right)} \quad (3)$$

Also, the velocity V_{t4} in equation (2) is written as follows:

$$V_{t4} = \sqrt{C/\rho} \quad (4)$$

In definition (4), the velocity V_{t4} represents the SH-BAW speed in the case of zero value of the CMEMC. It is obvious that the SH-BAW in equation (4) is uncoupled with both the electric and magnetic potentials and therefore, represents a purely mechanical SH-wave.

Also, the electromagnetic constant α in equation (3) can be very small. As a result, α = 0 can lead to the following natural decoupling between the characteristics of the piezoelectric and piezomagnetic phases:

$$K_{em}^2 = K_e^2 + K_m^2 \quad (5)$$

In expression (5), the CMEMC reduces to the well-known single-phase parameters defined by the following formulae:

$$K_e^2 = \frac{e^2}{\varepsilon C} \quad (6)$$

$$K_m^2 = \frac{h^2}{\mu C} \quad (7)$$

The first material parameter defined by the relation (6) is called the coefficient of the electromechanical coupling (CEMC) and characterizes a purely piezoelectric material. The second parameter defined by the relation (7) is called the coefficient of the magnetomechanical coupling (CMMC) and represents an important characteristic for a purely piezomagnetic crystal.

It is well-known that in a single-phase piezoelectric material, the corresponding SH-SAW called the slower BG-wave can propagate along the mechanically free and electrically closed surface. In this case, the formula for the surface BG-wave can be written as follows:

$$V_{BGEC} = V_{te}\left[1-\left(\frac{K_e^2}{1+K_e^2}\right)^2\right]^{1/2} \quad (8)$$

In equation (8), the SH-BAW velocity V_{te} propagating in a pure piezoelectrics is defined by the following expression:

$$V_{te} = V_{t4}\left(1+K_e^2\right)^{1/2} \quad (9)$$

where the velocity V_{t4} is defined by relation (4).

It is worth noting that the formula (8) for the slower surface BG-wave can be obtained from equation (1) by setting $h = 0$ and $\alpha = 0$ in the definitions (2) for V_{tem} and (3) for K_{em}^2. It is obvious that formulas (1) and (8) have the same mathematical structure. However, formula (8) cannot reduce to a formula (1) and they represent different cases.

Concerning the other single-phase materials such as the pure piezomagnetics, the slower BG-wave can propagate along the mechanically free and magnetically open surface. The velocity V_{BGMO} of the surface BG-wave can be written in the following form:

$$V_{BGMO} = V_{tm}\left[1-\left(\frac{K_m^2}{1+K_m^2}\right)^2\right]^{1/2} \quad (10)$$

Formula (10) can be also obtained from equation (1) by setting $e = 0$ and $\alpha = 0$ in V_{tem} and K_{em}^2. In equation (10), the SH-BAW velocity V_{tm} propagating in a pure piezomagnetics is written as follows:

$$V_{tm} = V_{t4}\left(1+K_m^2\right)^{1/2} \quad (11)$$

where the expression for the SH-BAW velocity V_{t4} is written in the formula (4).

The case of $\sigma_{32} = 0$, D = 0, and B = 0

This is the case of the mechanically free, electrically open, and magnetically closed surface. This case of the boundary conditions was also considered in (Melkumyan, 2007; Wei *et al*., 2009; Zakharenko, 2010). These theoretical works soundly demonstrated that no SH-SAW solutions can be found. The single possibility is the propagation of the well-known SH-BAW velocity V_{tem} defined by expression (2).

The case of $\sigma_{32} = 0$, $\varphi = 0$, and B = 0

This is the case of the SH-wave propagation guided by the mechanically free, electrically closed, and magnetically closed surface. In this case, an explicit form for the propagation velocity of the new SH-SAW was also obtained in (Melkumyan, 2007). His theoretical work was published in 2007. In two years, Wei, Liu, and Fang (Wei *et al*., 2009) have also obtained some of the theoretical results by Melkumyan. Note that the authors of the paper (Wei *et al*., 2009) have studied the SH-wave propagation along the vacuum-solid interface and did not cite the work (Melkumyan, 2007). As a result, they have written that they have obtained the new results. This is true, but they have only confirmed the previously obtained result (Melkumyan, 2007). Therefore, the new SH-SAW was discovered in (Melkumyan, 2007) for this case of the boundary conditions. (Zakharenko, 2010) has also confirmed the results of works (Melkumyan, 2007; Wei *et al*., 2009), and (Zakharenko, 2012a) has introduced some further theoretical investigations of the new SH-SAW velocity. This new SH-SAW was then called the piezoelectric exchange surface Melkumyan wave or PEESM-wave (Zakharenko, 2012a). It is essential to state that this solution corresponds to the first set of the eigenvector components. However, it doesn't matter which set of two can be called the first. It is noted that the second SH-SAW solution will be also given in this subsection below.

It is thought that the convenient explicit form for the velocity V_{PEESM} is given in (Zakharenko, 2010, Zakharenko, 2012a) and expressed as follows:

$$V_{PEESM} = V_{tem}\left[1-\left(\frac{K_{em}^2-K_m^2}{1+K_{em}^2}\right)^2\right]^{1/2} \quad (12)$$

It is thought that the explicit form in equation (12) can be convenient for understanding of the physical sense. Indeed, the following term $K_{em}^2 - K_m^2$ in equation (12) represents a subtraction of two material parameters. The second parameter called the CMMC (K_m^2) represents the purely piezomagnetic phase defined by the presence of the piezomagnetic effect. The first parameter called the CMEMC (K_{em}^2) couples the piezoelectric and piezomagnetic effects via the magnetoelectric effect. The last can be understood as some exchange between the piezoelectric and piezomagnetic phases. So, $K_{em}^2 - K_m^2$ can represent a purely piezoelectric phase plus some exchange between these two phases. This means that for α <> 0 one copes here with both the phases because some exchange remains.

However, the theoretical method used in excellent works (Melkumyan, 2007; Wei *et al*., 2009) was unable to reach the second SH-SAW solution. This is true because the authors of papers (Melkumyan, 2007; Wei *et al*., 2009) did not illustrate that this problem of the SH-wave propagation in the two-phase materials is more complicated. Also, they did not demonstrate the eigenvalues and eigenvectors. Therefore, they did not find these two different sets of the eigenvector components. Book (Zakharenko, 2010) has demonstrated that the formula (12) can be obtained and it corresponds to one of the possible two sets of the eigenvector components. Using the second set and the electrical and magnetic boundary conditions of this subsection, work (Zakharenko, 2010) has naturally revealed the following explicit form for the velocity of the new SH-SAW which can also propagate in the two-phase materials:

$$V_{new} = V_{tem}\left[1-\left(\frac{\alpha^2}{\varepsilon\mu}\frac{K_{em}^2-K_\alpha^2}{1+K_{em}^2}\right)^2\right]^{1/2} \quad (13)$$

where the non-dimensional value of K_α^2 can be first met in the book (Zakharenko, 2010). This exchange coefficient, K_α^2, couples only two terms in the CMEMC, K_{em}^2, which contain the electromagnetic constant α. It is defined by the following relation:

$$K_\alpha^2 = \frac{\alpha e h}{C\alpha^2} = \frac{eh}{\alpha C} \quad (14)$$

It is clearly seen in relation (14) that the value of K_α^2 can approach infinity as soon as the value of the electromagnetic constant α vanishes. However, this undesirable situation is compensated by the factor of ($\alpha^2/\varepsilon\mu$) in equation (13). This factor can be also introduced as the relation of two velocities. These velocities can be denoted by V_α and V_{EM} and are defined by the following formulas:

$$V_\alpha^2 = \frac{1}{\alpha^2} \quad (15)$$

$$V_{EM}^2 = \frac{1}{\varepsilon\mu} \quad (16)$$

It is noted that relation (16) represents the well-known speed of the electromagnetic wave propagating in a bulk solid. Usually, the speed V_{EM} is approximately five orders higher than the SH-BAW speed defined by expression (2).

It is crucial to discuss the new result given in the formula (13). It is apparent that as soon as the value of the constant α vanishes, the new SH-SAW velocity in expression (13) reduces to the SH-BAW velocity V_{tem}. This can mean that the propagation of this new SH-SAW is caused by the magnetoelectric effect. It was mentioned above that the electromagnetic constant α is very small. Also, this value is restricted by the following inequality (Özgür *et al*., 2009; Fiebig, 2005; Wei *et al*., 2009):

$$\alpha^2 < \varepsilon\mu \quad (17)$$

As a result, the value of this new SH-SAW can be situated too close to the SH-BAW value due to the small value of α. Also, (Zakharenko, 2012a) discusses the case when the new SH-SAW velocity in expression (13) can also reduce to the SH-BAW velocity V_{tem} for a large value of α where $\alpha > 0$. This peculiarity does not exist for $\alpha < 0$. In equation (13), it is obvious that this can happen as soon as the following condition occurs: $K_{em}^2 - K_\alpha^2 = 0$. Also, the solution (13) exists in the case of the other electrical and magnetic boundary conditions considered in the following subsection.

The case of σ_{32} = 0, D = 0, and ψ = 0

This case of the mechanically free, electrically open, and magnetically open surface also results in the possibility of propagation of two SH-SAWs with different velocities. Using the first set of the eigenvector components, book (Zakharenko, 2010) also revealed the explicit form for the new SH-SAW velocity, for which the formula is coinciding with formula (13) corresponding to the second set of the eigenvector components in the case of the previous subsection. This is a unique case when one can find for the different sets of the boundary conditions that the SH-SAW propagation velocity will be the same. Therefore, all the peculiarities discussed in the previous subsection are true in this case. However, the second set of the eigenvector components together with this set of the boundary conditions can reveal the other SH-SAW velocity.

Using the second set of the eigenvector components, work (Zakharenko, 2010) has also confirmed the theoretical result of work (Melkumyan, 2007). In 2009, theoretical work (Wei *et al*., 2009) has also found the result obtained in (Melkumyan, 2007). However, the authors of the work (Wei *et al*., 2009) did not cite the work by Melkumyan and did not compare their results with the previous discoveries. As a result, (Wei *et al*., 2009) stated that the new SH-SAWs were discovered by the authors. (Zakharenko, 2010) has stated that this new SH-SAW was discovered by Melkumyan in his theoretical work (Melkumyan, 2007). (Zakharenko, 2012a) carried out further investigations and the new SH-SAW by Melkumyan was called the piezomagnetic exchange surface Melkumyan wave or PMESM-wave, because this solution is very important similar to the others and it is already necessary to distinguish it from the other new SH-SAWs which can propagate in the PEMs. It is worth noting that works (Melkumyan, 2007; Wei *et al*., 2009) have used the theoretical method with which it is possible to reveal the only single solution of two. It is interesting that the V_{PEESM} in equation (12) corresponds to one set of the eigenvector components, while the V_{PMESM} in equation (18) written below corresponds to the other set. This can mean that this theoretical method used in (Melkumyan, 2007; Wei *et al*., 2009) can confuse these two sets of the eigenvector components. This can give incorrect results in some complicated cases. This will be also discussed in the following subsection. However, this theoretical method revealed three SH-SAWs in the correct forms written in equations (1), (12), and (18).

It is thought that the most convenient explicit form for the PMESM-wave velocity, V_{PMESM}, was given in (Zakharenko, 2010; Zakharenko, 2012a) and it reads as follows:

$$V_{PMESM} = V_{tem}\left[1-\left(\frac{K_{em}^2-K_e^2}{1+K_{em}^2}\right)^2\right]^{1/2} \quad (18)$$

In equation (18), $K_{em}^2 - K_e^2$ can mean that the remaining product of this subtraction can represent the piezomagnetic phase plus some exchange between the piezoelectric and piezomagnetic phases. It is apparent that something from the piezoelectric phase is present in the exchange form. For $\alpha <> 0$, one consequently deals with both the piezoelectric and piezomagnetic phases coupled through the magnetoelectric effect. Also, it is possible that when one has $K_{em}^2 - K_e^2 = 0$ in equation (18), the value of this SH-SAW velocity reduces to the value of the SH-BAW velocity denoted by V_{tem}. Perhaps, this can happen for a relatively large value of α when $\alpha > 0$.

The case of $\sigma_{32} = 0$, $\varphi = \varphi^f$, $D = D^f$, $\psi = \psi^f$, $B = B^f$

It is thought that this is the most complicated case for the theoretical investigations of the SH-wave propagation in the transversely isotropic PEM materials. The acoustic SH-waves are guided by the mechanically free surface. This surface is in contact with the free space, also called a vacuum. Therefore, it is necessary to account the vacuum characteristics. However, it is well-known that the elastic constant C_0 of a vacuum is approximately thirteen orders smaller than that of a solid. Its value is given in (Kiang and Tong, 2010): C_0 = 0.001 Pa. For this reason, the material parameter of a vacuum can be neglected. This is usual for many theoretical descriptions. However, the free space also possesses the electrical and magnetic material constants and they cannot be neglected. The vacuum magnetic permeability constant, μ_0, is defined by $\mu_0 = 4\pi\times10^{-7}$ [H/m] = $12.5663706144\times10^{-7}$ [H/m]. Also, the vacuum dielectric permittivity constant, ε_0, is defined by $\varepsilon_0 = 10^{-7}/(4\pi C_L^2) = 8.854187817\times10^{-12}$ [F/m] where the parameter C_L represents the speed of light in a vacuum and is expressed as follows:

$$C_L^2 = \frac{1}{\varepsilon_0\mu_0} \quad (19)$$

It is possible to use the superscript "*f*" for a vacuum. It is necessary to account that the electrical potential in a vacuum denoted by φ^f and the magnetic potential denoted by ψ^f must vanish far from the surface. Also, the following conditions must be satisfied at the vacuum-solid interface: $\varphi = \varphi^f$, $D = D^f$, $\psi = \psi^f$, $B = B^f$. This means that the electrical characteristics such as the electrical potential and the electric displacement must continue at the interface. The same must be required for the magnetic characteristics such as the magnetic potential and the magnetic flux. These boundary conditions at the vacuum-solid interface lead to the existence of two different SH-SAWs. They correspond to two different sets of the eigenvector components. Zakharenko (2010) provides both complicated solutions written in the original convenient forms. Following work (Zakharenko, 2010), the velocity of the new SH-SAW can be given in the following explicit form:

$$V_{new} = V_{tem}\left[1-\left(\frac{K_{em}^2-K_e^2+\alpha^2 C_L^2\frac{\varepsilon_0}{\varepsilon}\left(K_{em}^2-K_\alpha^2\right)}{\left(1+K_{em}^2\right)\left(1+\frac{\mu}{\mu_0}\right)}\right)^2\right]^{1/2} \quad (20)$$

In equation (20), the term $K_{em}^2 - K_e^2$ represents a subtraction of the purely piezoelectric phase from the coupled piezoelectromagnetic phase. Also, the following factor $\alpha^2 C_L^2(\varepsilon_0/\varepsilon)$ demonsofates the dependence on the speed of light in a vacuum. It is obvious that this factor can be very small for a small value of α and large value of ε. They are the material parameters of the piezoelectromagnetics. It is necessary to mention that the value of α is restricted by inequality (17). This means that the value of the velocity V_α in equation (15) must be always larger than that of the velocity V_{EM} of the bulk electromagnetic wave defined by the formula (16). Therefore, it is expected that $\alpha^2 C_L^2(\varepsilon_0/\varepsilon) < 1$ or even $\alpha^2 C_L^2(\varepsilon_0/\varepsilon) \ll 1$. Also, the value of K_α^2 decreases when the value of α increases. It is worth noting that the value of α can have a positive or negative sign depending on the direction of the applied magnetic field. In general, the value of the electromagnetic constant α is very small. So, it is also possible to write the velocity of the new SH-SAW for the case of $\alpha = 0$ in the following simplified form:

$$V = V_{tem0}\left[1-\left(\frac{K_m^2}{\left(1+K_e^2+K_m^2\right)\left(1+\mu/\mu_0\right)}\right)^2\right]^{1/2} \quad (21)$$

where the SH-BAW velocity V_{tem0} is defined by the following expression:

$$V_{tem0} = V_{t4}\left(1+K_e^2+K_m^2\right)^{1/2} \quad (22)$$

In expression (22), the SH-BAW velocity V_{t4} is defined by formula (4). As soon as the piezoelectric constant e equals to zero in equations (21) and (22), equation (21) reduces to the velocity V_{BGpm} of the faster surface BG wave (Bleustein, 1968; Gulyaev, 1969) propagating in a pure piezomagnetics:

$$V_{BGpm} = V_{tm}\left[1-\left(\frac{K_m^2}{\left(1+K_m^2\right)\left(1+\mu/\mu_0\right)}\right)^2\right]^{1/2} \quad (23)$$

In equation (23), the SH-BAW velocity V_{tm} is defined by expression (11). It is well-known that the value of the velocity V_{BGpm} is situated slightly below the value of the velocity V_{tm}. In the case of $h = 0$ and $\alpha = 0$, equation (20) also reduces to the SH-BAW velocity V_{tm} defined by expression (11) which is the wave characteristic for a pure piezomagnetics. Indeed, it is natural that a piezoelectromagnetics can possess incorporative properties of the piezoelectric phase and the piezomagnetic phase.

For the other set of the eigenvector components, the explicit form for the velocity of the other new SH-SAW, which can propagate along the surface, was also introduced in the book (Zakharenko, 2010). It is thought that (Zakharenko, 2010, 2011a) provide the convenient form of the solution. The velocity of the new SH-SAW can be then written in the following form (Zakharenko, 2010; Zakharenko, 2011a):

$$V_{new} = V_{tem}\left[1-\left(\frac{K_{em}^2 - K_m^2 + \alpha^2 C_L^2 \frac{\mu_0}{\mu}\left(K_{em}^2 - K_\alpha^2\right)}{\left(1+K_{em}^2\right)\left(1+\frac{\varepsilon}{\varepsilon_0}\right)}\right)^2\right]^{1/2} \quad (24)$$

It is thought that the term $K_{em}^2 - K_m^2$ in equation (24) can be interpreted as a subtraction of the purely piezomagnetic phase from the coupled piezoelectromagnetic phase. Also, the following factor $\alpha^2 C_L^2(\mu_0/\mu)$ can be very small due to a small value of α. However, this is not always true. For instance, when $\alpha^2 \to \varepsilon\mu$ occurs and $\varepsilon\mu$ is quite large due to $\mu/\mu_0 \sim 100$ and $\varepsilon/\varepsilon_0 \sim 100$, it is possible that the following factor $\alpha^2 C_L^2(\mu_0/\mu)$ can approach such large number as 100. On the other hand, large values of μ and ε can result in a very small value of the CMEMC, K_{em}^2. As a result, the value under the square root in expression (24) can be larger than zero. This means that this new SH-SAW can propagate in such PEM materials.

Also, in the case of a negligibly small value of the electromagnetic constant α, it is possible to write the velocity of this new SH-SAW in the following simplified form:

$$V = V_{tem0}\left[1-\left(\frac{K_e^2}{\left(1+K_e^2+K_m^2\right)\left(1+\varepsilon/\varepsilon_0\right)}\right)^2\right]^{1/2} \quad (25)$$

where the SH-BAW velocity V_{tem0} is defined by expression (22). For the zero value of the piezomagnetic coefficient h, formula (25) also reduces to the well-known velocity V_{BGpe} of the faster surface BG wave (Bleustein, 1968; Gulyaev, 1969) propagating in a pure piezoelectrics:

$$V_{BGpe} = V_{te}\left[1-\left(\frac{K_e^2}{\left(1+K_e^2\right)\left(1+\varepsilon/\varepsilon_0\right)}\right)^2\right]^{1/2} \quad (26)$$

It is worth noticing that the value of the velocity V_{BGpe} is situated slightly below the value of the velocity V_{te}. Also, one can verify that with $e = 0$ and $\alpha = 0$, equation (24) reduces to the SH-BAW velocity V_{te} defined by expression (9) which is the wave characteristic for a pure piezoelectrics.

It was demonstrated in this subsection that two solutions can always exist in this set of the electrical and magnetic boundary conditions. They were obtained following the theoretical method used in the book (Zakharenko, 2010) and they correspond to two different sets of the eigenvector components. However, the reader can find works (Liu *et al*., 2007; Wang *et al*., 2007) in which the authors have used the other theoretical method. Unfortunately, this method can give only single solution for the velocity of the new SH-SAW and this solution differs from those written above in formulae (20) and (24). The authors of theoretical works (Liu *et al*., 2007; Wang *et al*., 2007) have found the following formula in the case:

$$V_{new} = V_{tem}\left[1-\left(\frac{\frac{\varepsilon_0}{\varepsilon}\left(K_{em}^2 - K_m^2\right)+\frac{\mu_0}{\mu}\left(K_{em}^2 - K_e^2\right)+\frac{\varepsilon_0\mu_0}{\varepsilon\mu}K_{em}^2}{\left(1+K_{em}^2\right)\left(1-\delta+\frac{\varepsilon_0\mu_0}{\varepsilon\mu}+\frac{\varepsilon_0}{\varepsilon}+\frac{\mu_0}{\mu}\right)}\right)^2\right]^{1/2} \quad (27)$$

In expression (27), one can find that work (Wang *at al*., 2007) provides $\delta = 0$, but work (Liu *at al*., 2007) offers $\delta = \alpha^2/(\varepsilon\mu)$. It is noted that the explicit form for the new SH-SAW velocity defined by expression (27) is also given in a convenient form to compare with the results of Zakharenko (2010) given in the formulae (20) and (24). The reader can also find that (Liu *et al*., 2007; Wang *et al*., 2007) provide the new SH-SAW velocity expressed by convenient explicit form (27) in very complicated forms.

The work of Liu *et al*. (2007 and Wang *et al*. (2007) have also stated that the expression (27) represents a new result. This means that they have found the new SH-SAW propagating in a transversely isotropic piezoelectromagnetic material. To obtain a formula (27), they probably used the theoretical method which can mix both the different sets of the eigenvector components. As a result, they have reached only single solution (27) instead of possible two solutions (20) and (24) for the two-phase materials. It is thought that their method is somewhat inaccurate because the two sets should be separately used. Therefore, the author of this review cannot agree with the result demonstrated in formula (27) by the authors of papers Liu *et al*. (2007) and Wang *et al*. (2007). Indeed, to obtain an SH-SAW velocity is not easy in the case of the two-phase materials.

It is also possible to discuss the result given in expression (27). For simplicity, it is necessary to use $\delta = 0$ (Wang *et al*., 2007). For $\alpha = 0$, expression (27) can be rewritten in the following simplified form:

$$V = V_{tem0}\left[1-\left(\frac{K_e^2}{\left(1+K_e^2+K_m^2\right)\left(1+\varepsilon/\varepsilon_0\right)}+\frac{K_m^2}{\left(1+K_e^2+K_m^2\right)\left(1+\mu/\mu_0\right)}\right)^2\right]^{1/2} \quad (28)$$

The explicit form in equation (28) is convenient for comparison with those in equations (21) and (25). It is flagrant that for $e = 0$, the SH-SAW velocity in expression (28) reduces to the velocity V_{BGpm} of the faster BG-wave (23) in a pure piezomagnetics. For $h = 0$, the velocity in expression (28) also reduces to the velocity V_{BGpe} of the faster BG-wave (26) in a pure piezoelectrics. Also, two fractions with the following factors $(1 + \varepsilon/\varepsilon_0)$ and $(1 + \mu/\mu_0)$ in the denominators are present under the square root in expression (28). However, only one corresponding fraction of two is present in the expression (21) or (25). Comparing with these two expressions, formula (28) looks like it can give a value of the SH-SAW velocity situated not closer to the value of the SH-BAW velocity, V_{tem0}. It is expected that this fact can also occur when the expression (27) is compared with expressions (20) and (24).

SH-SAWs in Cubic PEMs

It is thought that SH-SAWs can also propagate in cubic piezoelectromagnetics. There is currently the single work concerning the wave propagation in the cubic PEMs (Zakharenko, 2011b). The theory of the wave propagation in the cubic PEMs is significantly more complicated than that for the hexagonal PEMs. In the case of the cubic PEMs, two sets of the eigenvector components also exist. However, they always result in the single solution because the two solutions coincide. This is unlike the transversely isotropic PEMs and can be useful for experimentalists when the presence of the second solution is not desirable. Also, experimental evidence of any SH-SAW propagation in the transversely isotropic PEMs or cubic PEMs is still not available. Probably, this is due to the fact that the SH-SAW propagation in the hexagonal PEMs was discovered only half-decade ago.

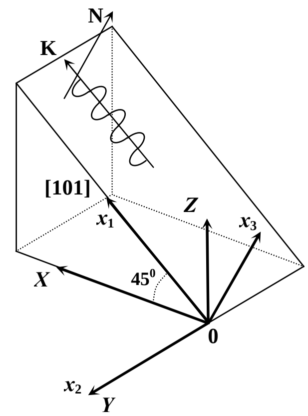

Fig. 2. The SH-SAW propagation along direction for the cubic piezoelectromagnetics. **K** is the wavevector in the direction of wave propagation and **N** is the vector of the surface normal. *X*, *Y*, and *Z* are the crystallographic axes.

Figure 2 shows the configuration for the wave propagation in the cubic PEM. The SH-SAW can propagate in the direction or relevant. The wave polarization is perpendicular to both the propagation direction and the surface normal. All the theoretical procedures sketchy described in the previous section are also used here. The forms of the eigenvalues and the eigenvectors can be very complicated. The eigenvalues are purely imaginary for $K_{em}^2 < 1/3$ and can be complex for $K_{em}^2 > 1/3$. In a cubic PEM with $K_{em}^2 < 1/3$, SH-SAW solutions can be found just below the value of the SH-BAW velocity V_{tem} defined by expression (2). However, SH-SAW solutions for the cubic PEM with $K_{em}^2 > 1/3$ are situated just below the value of some velocity V_K where $V_K < V_{tem}$. As a result, all the cubic PEMs can be divided into two groups: the first group is for the cubic PEMs with $K_{em}^2 < 1/3$ and the second is for those with $K_{em}^2 > 1/3$. For both the groups, the SH-SAW velocities cannot be represented in explicit forms. This is unlike the transversely isotropic PEMs. However, Zakharenko, (2011b) has found that the surface BGM can also propagate in the cubic PEMs for the corresponding set of the boundary conditions. It is thought that it is useful to start the review of the cubic PEMs with this case.

The case of $\sigma_{32} = 0$, $\varphi = 0$, and $\psi = 0$

For the mechanically free, electrically closed ($\varphi = 0$) and magnetically open ($\psi = 0$) surface of the cubic PEM, work (Zakharenko, 2011b) has revealed that the surface BGM-wave is solidly found when either of two sets of the eigenvector components is used. It is thought that the explicit form for the surface BGM-wave velocity defined by expression (1) can be rewritten in the following simplified form:

$$V_{BGM} = V_{tem}\left[\frac{1+2K_{em}^2}{\left(1+K_{em}^2\right)^2}\right]^{1/2} \quad (29)$$

It is thought that this form is more convenient when a digital calculator is used for evaluation of the value of the surface BGM-wave velocity. It is thought that this is the single case when the SH-SAW solution can be represented in an explicit form. It is possible to review the other boundary conditions for the problem of SH-wave propagation in the cubic PEMs.

The case of σ_{32} = 0, D = 0, and B = 0

Zakharenko (2011b) has also theoretically verified a possibility of propagation of SH-SAWs guided by the mechanically free, electrically open, and magnetically closed surface. It was found that for both the sets of the eigenvector components, the phase velocity solution denoted by V_K can be revealed. This solution corresponds to two equal eigenvalues which naturally give equal eigenvectors. Therefore, the value of the determinant of the boundary conditions can equal to zero as soon as the equal eigenvalues are utilized. The details can be found in Zakharenko (2011b).

The velocity V_K is defined by the following explicit form:

$$V_K = a_K V_{t4} \quad (30)$$

where

$$a_K = 2\sqrt{K_{em}\left(1+K_{em}^2\right)^{1/2} - K_{em}^2} \quad (31)$$

In equation (30), the SH-BAW velocity V_{t4} is defined by the expression (4).

It is necessary to acquaint the reader with the fact that this solution is always present and does not depend on the applied boundary conditions. This is similar to the solution corresponding to the SH-BAW velocity V_{tem}. It is also expected that the SH-wave propagating with the velocity V_K can be generated in the cubic PEM. Concerning experimental measurements of SAWs, it is also thought that some elements of crystals symmetry (screw axis or glide reflection) must be broken near the surface. Thus, to experimentally distinguish different types of SAWs can be very complicated and unclear.

Other Sets of the Boundary Conditions

For the other sets of the boundary conditions, two SH-SAW solutions (Zakharenko, 2011b) are also found. However, each pair of the solutions gives the same value of the new SH-SAW velocity. This can mean that in each case only single new SH-SAW can propagate. This is unlike the problem of the SH-wave propagation in the transversely isotropic PEMs reviewed in the previous section. For the cubic piezoelectromagnetics, the value of the velocity V_{new} can be written in the following common form:

$$V_{new} = V_{tem}\sqrt{1-b^2} \quad (32)$$

where the parameter b is defined below in expression (33). Zakharenko (2011b) has also demonstrated the following compact form for the parameter b:

$$b = n_3^{(3)} n_3^{(5)} = -\frac{\mathrm{j}B\left[n_3^{(5)}\left(m^{(2)}-\gamma_K^2\right) - n_3^{(3)}\left(m^{(3)}-\gamma_K^2\right)\right]}{A\left(m^{(3)}-m^{(2)}\right)} \quad (33)$$

where j is the imaginary unity, j = $(-1)^{1/2}$.

Equations (32) and (33) represent recursive formulae for the determination of the suitable phase velocity for each case of the electrical and magnetic boundary conditions. In equation (33), the material parameters A and B represent complicated functions on all the material constants and their explicit forms can be found in Zakharenko (2011b). Also, the eigenvalues in equation (33) are defined by the following formula:

$$n_3^{(3,5)} = -\mathrm{j}\sqrt{1-m^{(2,3)}} \quad (34)$$

where

$$m^{(2,3)} = \frac{B_t \pm \sqrt{B_t^2 - 16K_{em}^2(1+K_{em}^2)}}{2(1+K_{em}^2)} \quad (35)$$

$$B_t = \left(1+K_{em}^2\right)\left(\frac{V_{ph}}{V_{tem}}\right)^2 + 4K_{em}^2 \quad (36)$$

In equation (33), the non-dimensional parameter γ_K, which represents the normalized phase velocity V_{ph} of the new SH-SAW, is defined as follows:

$$\gamma_K = \frac{V_{ph}}{V_{t4}} \quad (37)$$

It is thought that it is unnecessary to give the complicated theory for each case of the boundary conditions. The reader can find the theory in Zakharenko (2011b). This all mentioned above relates to the propagation problems of different SH-SAWs for the usual cases when the values of the SH-SAW velocities are situated just below the value of the SH-BAW velocity V_{tem}. However, in cubic piezoelectromagnetics there is the case when the value of the SH-wave velocity can be slightly larger than that of V_{tem}. This case is discussed in the following subsection.

Surface Electromagnetic Wave or SH-SAW

In this problem of wave propagation, the SH-wave also propagates in the direction in the cubic piezoelectromagnetics. In this case, one of three suitable eigenvalues is real, but not imaginary or complex. Fortunately, it does not participate in the complete displacements. For the mechanically free surface, several combinations of the following electrical and magnetic boundary conditions can be used: electrically closed, electrically open, magnetically closed, magnetically open surface. For some boundary conditions, this new SH-wave can represent a purely electromagnetic wave and some sets of the electrical and magnetic boundary conditions promise that the new SH-wave can represent really new SH-SAW (Zakharenko, 2012b). This new SH-SAW can propagate with the speed slightly larger than that of the SH-BAW V_{tem}. The existence conditions for the new SH-wave can be very complicated and depend on all the material parameters. It is also expected that these theoretical results can be applied to some problems the SH-wave propagation in the left-handed metamaterials because three-dimensional metamaterials Chen *et al*. (2011) can be created. The recent review of the sensor applications of metamaterial can be found in Chen *et al*. (2012).

Following the theoretical work (Zakharenko, 2012b), the solution for the velocity of the new SH-wave is given in the following explicit form:

$$V_{new} = V_{t4}\sqrt{2} = V_{tem}\sqrt{\frac{2}{1+K_{em}^2}} \quad (38)$$

where V_{tem} and V_{t4} are the speeds of the SH-BAWs coupled and uncoupled with both the electrical and magnetic potentials, respectively. In equation (38), it is clearly seen that $V_{tem} < V_{new}$ for $K_{em}^2 < 1$. This fact allows one to state that the velocity of the new SH-wave is positioned in the velocity range where leaky acoustic SH-waves can exist.

For the electrical and magnetic boundary conditions such as $\varphi = 0$ and $\psi = 0$ as well as $D = 0$ and $B = 0$, the new SH-wave can represent a purely electromagnetic wave propagating with the slow speed defined by expression (38). Indeed, the new SH-wave can be purely electromagnetic due to the existence condition such as $h\varepsilon = e\alpha$ (Zakharenko, 2012b) resulting in zero value of the mechanical displacement (eigenvector component): $U \rightarrow (h\varepsilon - e\alpha)K_{em}^2 = 0$ (Zakharenko, 2012b). It was also discussed in Zakharenko (2012b) that this situation can also mean that this slow wave can be truly acoustic, and the piezoelectromagnetic properties can compensate the mechanical ones resulting in zero value of the mechanical displacement during the wave propagation. Indeed, this slow electromagnetic SH-wave propagates with the speed slightly above the V_{tem}. It is well-known that acoustic wave speeds including V_{tem} and V_{new} in equation (38) are approximately five orders slower than the speed of the electromagnetic wave propagating in a bulk solid defined by the relation (16). This extreme slowness of the new SH-wave exemplifies that some connection with the mechanical displacement is conserved. Therefore, the new SH-wave can be called the surface acoustic magnetoelectric wave (Zakharenko, 2012b). This can illuminate that this SH-wave relates to an acoustic branch, but not an optic one.

This new electromagnetic wave can relate to the surface acoustic-phonon polaritons (SAPPs) and it is necessary to distinguish them from the surface optic-phonon polaritons (SOPPs.) The SOPPs (Huber *et al*., 2008) are well-known because SOPPs on crystal substrates have applications in microscopy, biosensing, and photonics. The SOPPs are defined as electromagnetic surface modes formed by the strong coupling of light and optical phonons in polar crystals. They are generally excited using IR or THz radiation. Generation and control of the SOPPs are essential for realizing novel applications in microscopy, data storage, thermal emission, or in the field of metamaterials. However, a comparatively little attention is still given to the SOPPs. They have certain advantages including their ability to be generated in a wide spectral range, from IR to THz wavelengths at the surface of a large variety of semiconductors, insulators, and ferroelectrics (Huber *et al*., 2008). Minin and Minin (2010) have also mentioned that surface electromagnetic effects can enhance the efficiency of numerous physical and chemical processes (Schatz and van Duyne, 2002), as these effects can lead to an increase of the electromagnetic fields at the surface. This can give rise to an improved experimental sensitivity.

CONCLUSION

This review work has acquainted the reader with the recent achievements in the theory of SH-SAW propagation in the two-phase cubic and transversely isotropic (class 6 *mm*) piezoelectromagnetic materials. The reader can find in this review that using the same set of the electrical and magnetic boundary conditions, two SH-SAWs can propagate in the transversely isotropic PEM materials and only single SH-SAW can propagate in the cubic PEMs. To know this fact can be useful for the case when the presence of the second SH-SAW is not desirable, or vice versa, i.e. this fact can help in design of novel technical devices. Also, in the cubic PEMs, the other solutions can exist. They were also discussed. For instance, it was discussed the case when the SH-wave solution can represent a purely electromagnetic wave or true SH-SAW. Finally, it is necessary to state that this review relates to the wave propagation guide by the PEM free surface. However, the reader can find book (Zakharenko, 2012c) which discusses the propagation problems of new interfacial SH-waves when two dissimilar PEMs are used.

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