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AN EXAMINATION OF ZERO-ORDER MODES OF PLATE PEM-SH DISPERSIVE ACOUSTIC WAVES: MAGNETICALLY OPEN AND ELECTRICALLY CLOSED PLATE SIDES

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ABSTRACT

This report copes with the examination of dispersive shear-horizontal (SH) wave propagation in the piezoelectromagnetic (PEM) thin film. The studied plate must represent an anisotropic solid with bulk properties. Its symmetry must be hexagonal pertaining to 6 *mm* point group of crystal symmetries. The changes in the velocities of the inspected dispersive waves versus the dimensionless plate thickness *kd* are graphically examined for some values of the coefficient of the magnetoelectromechanical coupling (CMEMC). The obtained results have clarified that the inspected waves are slightly dispersive when the CMEMC < 0.2. The dispersion must be significant for larger values. It was found that the zero-order mode of one inspected dispersive wave can commence only at some *kd* > 0. The same mode of the second inspected dispersive wave can begin at *kd* = 0. For a very large value of *kd*, the wave velocities approach the speed of the nondispersive surface Bleustein-Gulyaev-Melkumyan wave. Also, these academic results can be useful for design of dispersive wave technical devices: chemi-bio-sensors, labs on tiny chips, filters, dispersive delay lines, etc., and their further prospective miniaturization.

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Keywords: Magneto-electro-elastic thin film, magnetoelectric effect, dispersive acoustic anti-plane waves, zero-order modes.

INTRODUCTION

These theoretical examinations are based on and develop the achievements recently obtained in book (Zakharenko, 2012a). This is constructive because allow one to get more complete picture of the behavior of some dispersive waves recognized as the shear-horizontally (SH) polarized processes flowing inside thin solid films, also known as piezoelectromagnetic (PEM) plates. This study uses only the homogeneous case: the lower and upper faces of the PEM plate can be mechanically, electrically, and magnetically conditioned in the same manner. Thus, the mechanical condition at the plate faces is called the mechanically free surface. Besides, the magnetic and electrical ones are the magnetically open and electrically closed surfaces, respectively. The comprehension of assorted boundary conditions is perfectly stated in 1992 by Al'shits *et al.*

The PEM composites, also known as the magneto-electro-elastics are multi-promising for modern employments in a set of technological arenas. These smart solids can concurrently enjoy several effects such as magnetoelectric (ME), piezomagnetic (PM), piezoelectric (PE). Accordingly, these effects and smart solid compounds are reviewed in the academic literature cited in Kimura (2012), Park and Priya (2012), Pullar (2012), Bichurin *et al.* (2012), Zakharenko (2013a), Chen *et al.* (2012), Bichurin *et al.* (2011), Srinivasan (2010), Özgür *et al.* (2009), Zhai *et al.* (2008), Nan *et al.* (2008), Eerenstein *et al.* (2006), Fiebig (2005), Spaldin and Fiebig (2005), Kimura (2007), Kimura *et al.* (2003), Wang *et al.* (2009), Ramesh (2009), Delaney *et al.* (2009), Gopinath *et al.* (2012), Fert (2008), Chappert and Kim (2008), Bibes and Barthélémy (2008), Priya *et al.* (2007), Grossinger *et al.* (2008); Ahn *et al.* (2009); Fang *et al.* (2008) and Prellier (2005).

Today there are the trends toward device microminiaturization and multifunctionality. Therefore, various multiferroic solids that can combine two or more ferroic attributes have been widely applied to sensing, actuating, and storage devices (Nan *et al.*, 2008; Eerenstein *et al.*, 2006). PEM composites, as one typical nature of multiferroic matter, have attracted intensive attention in the last decades because they can possess a large ME constant (Fiebig, 2005; Spaldin and Fiebig, 2005). For that reason, various theoretical and experimental investigations have been carried out on the mechanical behavior of such multiphase compounds in the form of different representative structures. The understanding of wave propagation behavior in the composites (Fiebig, 2005) is very important in designs of acoustic wave devices and related applications.

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It is evident that the PEM solid can be used together or instead of PE or PM solid. It is also apparent that the PEMs are excellent candidates for smart matter technical devices (Özgür *et al*., 2009; Fiebig, 2005) because they possesses electrical, magnetic, and mechanical subsystems and it is possible to control the electrical subsystem by the magnetic one through the mechanical one. The ME solids can be divided into two groups: monocrystals and composites. The relatively large ME effect was revealed in several PEM monocrystals such as Cr_2O_3 (Fiebig, 2005), $LiCoPO_4$ (Rivera, 1994), $TbPO_4$ (Rado *et al*., 1984). However, ME compounds can exhibit a significantly larger ME effect. They possess both the magnetic and electric phases. The famous candidates for the PM phase are Terfenol-D and Metglas and PZT is fitting as the PE phase.

ME multiferroics can couple electric and magnetic dipoles (Kimura, 2012) and so, have a big potential for expected ME devices. Modern discoveries have revealed that ferroelectricity can be induced by complex internal arrangements of magnetic moments in magnetically induced ferroelectrics. Such ferroelectrics can demonstrate giant ME effects: the changes in ferroelectric polarization as soon as an external magnetic field acts. However, none of them can have combined big electric and magnetic polarizations at ~ 20^oC, but the $Sr_3Co_2Fe_{24}O_{41}$ Z-type hexaferrite (Kitagawa *et al*., 2010). A comprehensive review of M, W, X, Y, Z, and U-type hexaferrites can be found in (Pullar, 2012).

A set of wave phenomena in solids can be studied in the frameworks of the multidisciplinary modern ultrasonics (Ensminger and Bond, 2012). Ultrasonics includes the basic science of the energy-matter interaction, the associated technologies for generation and detection, and an increasingly diverse range of applications, which are now encountered in almost every field of engineering, many of the sciences and in medicine. It is also well-known that different SH-SAWs can be produced by the electromagnetic acoustic transducers (EMATs) (Ribichini *et al*., 2010). The noncontact methods such as the EMAT can offer a series of advantages in comparison with the traditional piezoelectric transducers (Thompson, 1990; Hirao and Ogi, 2003).

However, the PEs are widely used, probably, due to the fact that their properties are well-known compared with the PEM solids. For instance, Fu *et al*. (2010) have represented recent developments on the application of ZnO films (6 *mm* PEs) for microfluidics and biosensors based on acoustic waves. Tan *et al*. (2010) have presented a numerical-experimental study of capillary wave motion excited by high frequency SAWs. The plate wave technical devices (Rocha-Gaso *et al*., 2009) can be also used because the interdigital transducers can be formed on the lower side of the plate and the upper side can be in a contact with a fluid. It is thought that employment of suitable PEM thin films can also give a significant rise to various investigations of the complex biosystems. Thus, it is necessary to be familiar with the SAW and plate wave characteristics of the smart substances that can be also apt for wireless tools. Wireless sensing tools (Rocha-Gaso *et al*., 2009) can have the following applications: engine metrology, safety, tracing and tracking, internal and external monitoring, etc. In addition, passive sensors can really have a big potential: it is expected that they can successively replace existing sensors and actually create new sensing applications.

According to recent review (Giannitsis, 2011), chip-like laboratories are a group of miniaturized analytical devices that integrate fluidics, electronics, sensorics, and they are capable of analyzing biochemical liquid samples: solutions of metabolites, proteins, macromolecules, nucleic acids, viruses. In addition to their measuring capabilities, these complex laboratories-devices can facilitate fluidic transportation, mixing, sorting, separation of liquids. It is also possible to mention that the SAWs can result in exhibition of the acoustowetting phenomenon (Rezk *et al*., 2012a) when the SAW propagation causes the formation of a liquid layer from a fluid drop situated on the solid surface. Recent work (Rezk *et al*., 2012b) has studied paper-based microfluidics and stated that it can offer an alternative to typical polymers. Review work (Fair, 2007) discusses the suitability of electrowetting-on-dielectric microfluidics for applications in true chip-like labs. It is well-known that microfluidic devices can offer unique advantages in sample handling, reagent mixing, separation, and detection. Flow-injection analysis method, techniques of microconstruction, and microfluidics are reviewed in (Weigl *et al*., 2003) and interesting work (Yoon and Kim, 2012) reviews pathogen chip-like lab sensors for food safety.

This examination acquaints the reader with some recent accomplishments in the field of the acoustic wave propagation in the PEM thin films. The wave propagation can possess some peculiarities that must be recorded for the research community to make use of the PEM matter in a list of smart practical devices: actuators, filters, sensors, MEMs, laboratories on chips, etc.

THEORETICAL PART AND RESULTS

The theory of the shear-horizontally (SH) polarized wave processes in the 6 *mm* PEM plates is given in (Zakharenko, 2012a). This theory naturally starts with the consideration of the suitable thermodynamic variables and functions, writes the corresponding constitutive relations, and thermodynamically defines the PEM material constants. Next, the mechanical equilibrium equations must be written together with the Maxwell equations for electrostatics and magnetostatics in the quasi-static approximation. The coupled equations of motion in the differential forms can be then constituted. With the solutions in the plane wave form for them, the tensor form of the equations of motion can be represented.

It is now necessary to discuss the suitable propagation direction in order to cope with propagation of pure waves (Lardat *et al*., 1971; Dieulesaint and Royer, 1980) with the anti-plane polarization (perpendicular to the sagittal plane.) The propagations of pure SH-waves are possible only in the high symmetry directions (Lardat *et al*., 1971; Dieulesaint and Royer, 1980). For the hexagonal (6 *mm*) solids (Nye, 1989, Newnham, 2005, Lovett, 1999, Auld, 1990) the wave process direction must be parallel to the free surface and perpendicular to both the surface normal and the six fold symmetry axis. The mentioned normal must be also perpendicular to the mentioned axis. All such apt propagation directions are true for PEs, PMs, and PEMs when they relate to the broaden family of the 6 *mm* solids. In these directions, the PEM SH-wave process must also attach the magnetic (ψ) and electrical (φ) potentials.

Using the coupled equations of motion written in the tensor form and the suitable high symmetry propagation direction in the PEM plate, it is possible to find the eigenvalues and the corresponding eigenvectors (Zakharenko, 2013b; Zakharenko, 2013c; Zakharenko, 2014) for the problem of the SH-wave propagation. Also, it is worth noting that in such direction, the following independent nonzero material constants exist: the stiffness constant C, PM coefficient h, PE constant e, dielectric permittivity coefficient ε, magnetic permeability coefficient μ, and electromagnetic constant α, where $C = C_{44} = C_{66}$, $e = e_{16} = e_{34}$, $h = h_{16} = h_{34}$, $\varepsilon = \varepsilon_{11} = \varepsilon_{33}$, $\mu = \mu_{11} = \mu_{33}$, and $\alpha = \alpha_{11} = \alpha_{33}$ (Zakharenko, 2010; Zakharenko, 2012a; Zakharenko, 2012b). The found eigenvalues and eigenvectors are employed to figure the complete mechanical displacement, complete magnetic and electrical potentials dependent on the weight factors that can be calculated treating the boundary conditions. The mechanical, electrical, and magnetic boundary conditions for the lower and upper PEM plate sides are as follows: the mechanically free, electrically closed (φ = 0), and magnetically open (ψ = 0) faces. The boundary conditions in the case when the treated medium concurrently owns the PM, PE, and ME effects are perfectly recorded by Al'shits *et al*. (1992). With the book by Zakharenko (2012a), the following dispersion relation for the determination of the phase velocity V_{new1} of the first new plate SH-wave can be written:

$$\sqrt{1-\left(V_{new1}/V_{tem}\right)^2}\tanh(kd)-\frac{K_{em}^2}{1+K_{em}^2}\tanh\left(kd\sqrt{1-\left(V_{new1}/V_{tem}\right)^2}\right)=0 \tag{1}$$

where *kd* is the normalized plate thickness: *k* and *d* are the wavenumber in the direction of wave process propagation and the plate half-thickness, respectively.

The dispersion relation written above pertains to the case when the velocity V_{new1} is smaller than the SH bulk acoustic wave (BAW) speed V_{tem} tied with the magnetic and electrical potentials. This is the case of the lowest or zero-order mode. The V_{tem} is defined by

$$V_{tem}=\sqrt{C/\rho}\left(1+K_{em}^2\right)^{1/2} \tag{2}$$

where ρ is the mass density.

In expressions (1) and (2), K_{em}^2 stands for the coefficient of the magnetoelectromechanical coupling (CMEMC) that equals to

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

For this set of the boundary conditions mentioned above, it is necessary to state that there is the second dispersion relation (Zakharenko, 2012a). For the case when the propagation velocity is smaller than the speed V_{tem}, the second dispersion relation can be extra determined. The velocity V_{new2} for the second-type lowest mode ($V_{new2} < V_{tem}$) of the second new plate SH-wave can be calculated with the following formula:

$$\tanh\left(kd\sqrt{1-\left(V_{new2}/V_{tem}\right)^2}\right)\sqrt{1-\left(V_{new2}/V_{tem}\right)^2}-\frac{K_{em}^2}{1+K_{em}^2}\tanh(kd)=0 \tag{4}$$

One can find in (1) and (4) that for a very big value of *kd*, the velocities V_{new1} and V_{new2} for both the new plate SH-waves will approach the SH-SAW velocity corresponding to the surface Bleustein-Gulyaev-Melkumyan (BGM) wave (Melkumyan, 2007; Zakharenko, 2011). The speed of the nondispersive BGM-wave can be evaluated with the following explicit formula:

$$V_{BGM}=V_{tem}\left[1-\left(\frac{K_{em}^2}{1+K_{em}^2}\right)^2\right]^{1/2} \tag{5}$$

The main purpose of this report is to examine the behaviors of the velocities V_{new1} and V_{new2} versus the dimensionless parameter *kd*. These dependencies of $V_{new1}(kd)$ and $V_{new2}(kd)$ are defined by dispersion relations (1) and (4) that can be investigated only numerically. Also, it is convenient to carry out the numerical study for different values of K_{em}^2 which couples all the PEM

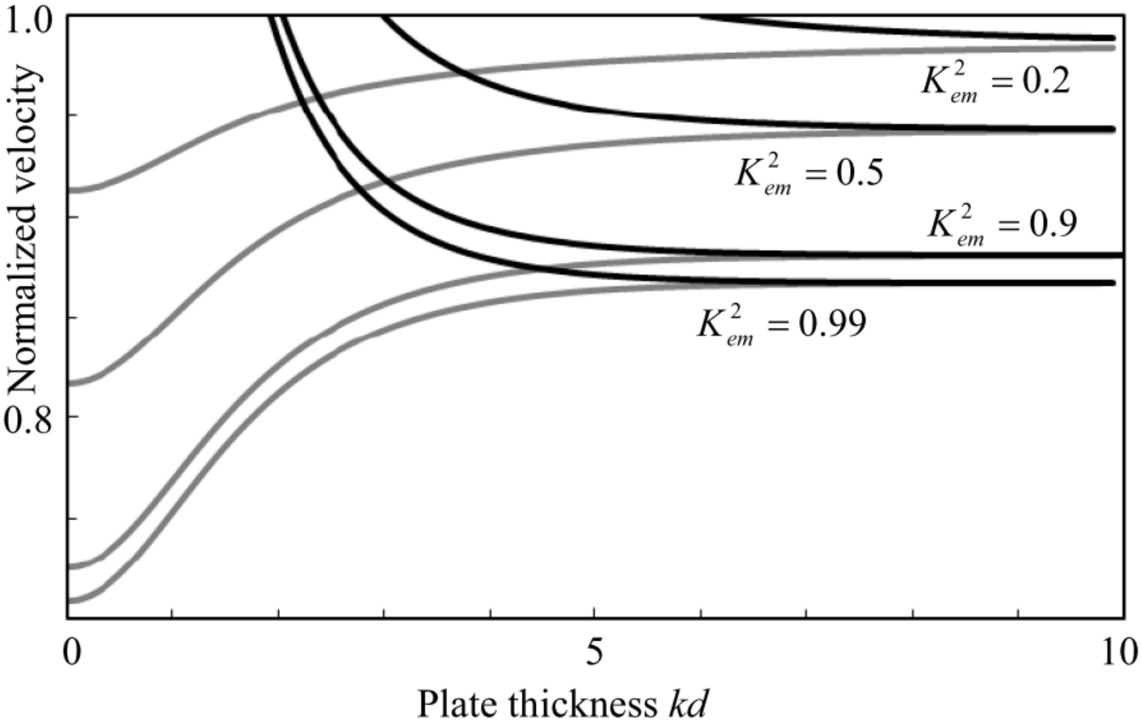

Fig. 1. The zero-order modes for K_{em}^2 several values: the normalzed velocities V_{new1}/V_{tem} and V_{new2}/V_{tem} are shown by the black and grey lines, respectively.

constants, see formula (3). In the book by Zakharenko (2012a), the dependencies of $V_{new1}(kd)$ and $V_{new2}(kd)$ for the lowest modes were performed only for K_{em}^2 = 0.3. The study of book (Zakharenko, 2012a) is incomplete because the following questions remain: what is the *kd* threshold minimum for the first lowest mode corresponding to the V_{new1} and what is the minimum value of the V_{new2} of the second lowest mode for $kd \rightarrow 0$. It is also essential to say that $K_{em}^2 < 1$.

Figure 1 shows the dependence of the normalized velocities V_{new1}/V_{tem} and V_{new2}/V_{tem} of the new dispersive SH-waves propagating in the 6 *mm* PEM plate. The figure graphically shows the zero-order mode dispersion relations for K_{em}^2 = 0.2, 0.5, 0.9, 0.99. The velocities V_{new1}/V_{tem} and V_{new2}/V_{tem} are shown by the black and grey lines, respectively. First of all, it is necessary to state that at very big values of *kd*, the values of both the velocities approach the value of the surface BGM-wave. It is also clearly seen in the figure that for a relatively small value of K_{em}^2 = 0.2, the values of the velocities are situated quite close to the value of the V_{tem} (2). This is so due to the fact that for a small K_{em}^2, the value of V_{BGM} (5) is situated slightly below the value of V_{tem}. For K_{em}^2 = 0.2, the velocity V_{new1} starts at $kd \sim 6.0$ and the relation V_{BGM}/V_{tem} is ~ 0.986. For large values of K_{em}^2 = 0.9 and 0.99, this mode shown by the black lines starts at $kd \sim 2.04$ and ~ 1.92, respectively. Therefore, it is possible to state that this report has determined the minimum threshold value of $kd \sim 1.9$. This is a quite large value.

It is also possible to further analyze the behavior of the second zero-order mode shown by the grey lines. For K_{em}^2 = 0.2, the V_{new2} starts with the minimum value of $V_{new2}/V_{tem} \sim 0.913$ at $kd = 0$ and can reach V_{BGM}/V_{tem} at a big *kd*. This means that the second lowest mode with such small value of K_{em}^2 = 0.2 cannot exist below the minimum value of $V_{new2}/V_{tem} \sim 0.913$. Therefore, the V_{tem} value must be certainly large to deal with significant velocity dispersion. For K_{em}^2 = 0.9 and 0.99, the second lowest mode starts at $kd = 0$ with the following minimum values: $V_{new2}/V_{tem} \sim 0.726$ and $V_{new2}/V_{tem} \sim 0.709$. This means that the velocity V_{new2} cannot have values smaller than $\sim 0.7V_{tem}$. This is very important finding and differs this type of the dispersive SH-wave with the anti-plane polarization from the dispersive Lamb type waves with the in-plane polarization because the Lamb wave asymmetric mode starts with zero speed at $kd = 0$.

Based on the results revealed in this work, it is also possible to discuss some 6 *mm* PEM composites. The material characteristics of the $BaTiO_3$-$CoFe_2O_4$ composites can be borrowed from (Aboudi, 2001; Annigeri *et al*., 2006). These compounds can be classified as the composites with (0-3) connectivity when the 3D matrix consisting of the $BaTiO_3$ PE phase or the $CoFe_2O_4$ PM phase has the PM or PE 0D inclusions, respectively. For the $BaTiO_3$-$CoFe_2O_4$ composites with 20% and 80% volume part of $BaTiO_3$, the V_{BGM} values (~2794.045 m/s and ~2956.340 m/s) are very close to the corresponding V_{tem} values (~2794.094 m/s and ~2956.343 m/s) and K_{em}^2 << 0.2. Therefore, the plate SH-waves characterized by the velocities V_{new1} and V_{new2} will be weakly dispersive and the velocity V_{new1} for the first lowest mode can start at kd >> 6.0. On the other hand, it is also possible to discuss the other composite plate such as PZT-5H–Terfenol-D with the (2-2) connectivity when the 2D planes of the PZT-5H PE phase and the Terfenol-D PM phase follow each other to form a sandwich structure. It has K_{em}^2 ~ 0.788, V_{tem} ~ 1746.253 m/s, and V_{BGM} ~ 1644.243 m/s (Wang and Mai, 2007; Liu and Chue, 2006; Zakharenko, 2012c). This value of K_{em}^2 is close to 0.9 shown in the figure. Therefore, it is possible to say that using figure 1, it is possible to compare different composites. It is also possible to state that to study the PEM plates instead of the corresponding bulk solids is more preferable because at $kd \rightarrow 0$ the V_{new2} values can be significantly smaller than the V_{BGM} value. This fact can be convenient for experimentalists to study these waves. Also, it is obvious that the PEM plates can be used to further miniaturize the technical devices based on such smart matter. Indeed, they are good candidate to constitute new technical devices. The most famous tools on the dispersive SH-waves are delay lines, bio-chemi-sensors, and the devices with a higher level of integration: chip-like complex laboratories, etc. These waves can be readily generated and detected in the noncontact manner with the electromagnetic acoustic transducers (Ribichini *et al*., 2010; Thompson, 1990; Hirao and Ogi, 2003).

Finale note

For any peculiarities' documentation, this analysis of the dispersive wave propagation (anti-plane polarized zero-order modes) in the solid magneto-electro-elastic plates was carried out for several K_{em}^2 values. It was solidly recorded that the propagation velocity cannot be equal to zero even for $kd = 0$ and when K_{em}^2 ~ 1. With K_{em}^2 ~ 1, the corresponding inspected wave velocity approaches some original velocity ~ $0.7V_{tem}$ at $kd = 0$. Concerning the second inspected wave process, the velocity never starts at $kd = 0$ for the reason that this zero-order mode is connected with the other branch existing above the V_{tem}. For a large K_{em}^2, both the inspected wave velocities approach the BGM wave rapidity. Also, these discussions can be useful in the constitution of list of dispersive wave technical tools. The delay lines can be the right application. Besides, the anti-plane polarized waves are exhaustively exploited to constitute sensors, filters, smart matter technical devices, complex laboratories on a single chip, etc., and can supplementary develop the device miniaturization.

REFERENCES

Aboudi, J. 2001. Micromechanical analysis of fully coupled electro-magneto-thermo-elastic multiphase composites. Smart Materials and Structures. 10(5):867-877.

Ahn, CW., Maurya, D., Park, CS., Nahm, S. and Priya, S. 2009. A generalized rule for large piezoelectric response in perovskite oxide ceramics and its application for design of lead-free compositions. Journal of Applied Physics. 105(11):114108, pp6.

Al'shits, VI., Darinskii, AN. and Lothe, J. 1992. On the existence of surface waves in half-infinite anisotropic elastic media with piezoelectric and piezomagnetic properties. Wave Motion. 16(3):265-283.

Annigeri, AR., Ganesan, N. and Swarnamani, S. 2006. Free vibrations of simply supported layered and multiphase magneto-electro-elastic cylindrical shells. Smart Materials and Structures. 15(2):459-467.

Auld, BA. 1990. Acoustic Fields and Waves in Solids. Krieger Publishing Company (vol. I and II, 2nd edi.). pp878.

Bibes, M. and Barthélémy, A. 2008. Multiferroics: Towards a magnetoelectric memory. Nature Materials. 7(6):425-426.

Bichurin, M., Petrov, V., Zakharov, A., Kovalenko, D., Yang, SCH., Maurya, D., Bedekar, V. and Priya, SH. 2011. Magnetoelectric interactions in lead-based and lead-free composites. Materials. 2011(4):651-702.

Bichurin, MI., Petrov, VM. and Petrov, RV. 2012. Direct and inverse magnetoelectric effect in layered composites in electromechanical resonance range: A review. Journal of Magnetism and Magnetic Materials. 324(21):3548-3550.

Chappert, C. and Kim, JV. 2008. Metal spintronics: Electronics free of charge. Nature Physics. 4(11):837-838.

Chen, T., Li, S. and Sun, H. 2012. Metamaterials application in sensing. MDPI Sensors. 12(3):2742-2765.

Delaney, KT., Mostovoy, M. and Spaldin, NA. 2009. Superexchange-driven magnetoelectricity in magnetic vertices. Physical Review Letters. 102(15):157203.

Dieulesaint, E. and Royer, D. 1980. Elastic waves in solids: Applications to signal processing. J. Wiley, New York, USA. (Translated by Bastin, A. and Motz, M., Chichester). pp511.

Eerenstein, W., Mathur, ND. and Scott, JF. 2006. Multiferroic and magnetoelectric materials. Nature. 442(7104):759-765.

Ensminger, D. and Bond, LJ. 2012. Ultrasonics: Fundamentals, Technologies, and Applications. (3rd edi.). A series of textbooks and reference books on mechanical engineering. Ed. Faulkner, LL. CRC Press: Taylor & Francis Group, Boca Raton – London – New York. pp728.

Fair, RB. 2007. Digital microfluidics: is a true lab-on-a-chip possible? Microfluid and Nanofluid. 3(3):245-281.

Fang, D., Wan, YP., Feng, X. and Soh, AK. 2008. Deformation and fracture of functional ferromagnetic. ASME Applied Mechanics Review. 61(2):020803. pp23.

Fert, A. 2008. Origin, development, and future of spintronics (Nobel lectures). Reviews of Modern Physics. 80(4):1517-1530.

Fiebig, M. 2005. Revival of the magnetoelectric effect. Journal of Physics D: Applied Physics. 38(8):R123-R152.

Fu, YQ., Luo, JK., Du, XY., Flewitt, AJ., Li, Y., Markx, GH., Walton, AJ. and Milne, WI. 2010. Recent developments on ZnO films for acoustic wave based biosensing and microfluidic applications: A review. Sensors and Actuators B: Chemical. 143(2):606-619.

Giannitsis, AT. 2011. Microfabrication of biomedical lab-on-chip devices. A review. Estonian Journal of Engineering. 17(2):109-139.

Gopinath, SCB., Awazu, K. and Fujimaki, M. 2012. Waveguide-mode sensors as aptasensors. MDPI Sensors. 12(2):2136-2151.

Grossinger, R., Duong, GV. and Sato-Turtelli, R. 2008. The physics of magnetoelectric composites. Journal of Magnetism and Magnetic Materials. 320(14):1972-1977.

Hirao, M. and Ogi, H. 2003. EMATs for science and industry: Non-contacting ultrasonic measurements. Boston, MA, Kluwer Academic.

Kimura, T., Goto, T., Shintani, H., Ishizaka, K., Arima, T. and Tokura, Y. 2003. Magnetic control of ferroelectric polarization. Nature. 426(6962):55-58.

Kimura, T. 2007. Spiral magnets as magnetoelectrics. Annual Review of Materials Research. 37(1):387-413.

Kimura, T. 2012. Magnetoelectric hexaferrites. Annual Review of Condensed Matter Physics. 3(1):93-110.

Kitagawa, Y., Hiraoka, Y., Honda, T., Ishikura, T., Nakamura, H. and Kimura, T. 2010. Low-field magnetoelectric effect at room temperature. Nature Materials. 9(10):797-802.

Lardat, C., Maerfeld, C. and Tournois, P. 1971. Theory and performance of acoustical dispersive surface wave delay lines. Proceedings of the IEEE. 59(3):355-364.

Liu, TJCh. and Chue, ChH. 2006. On the singularities in a bimaterial magneto-electro-elastic composite wedge under antiplane deformation. Composite Structures. 72(2):254-265.

Lovett, DR. 1999. Tensor properties of crystals. (2nd edi.). Taylor and Francis. pp480.

Melkumyan, A. 2007. Twelve shear surface waves guided by clamped/free boundaries in magneto-electro-elastic materials. International Journal of Solids and Structures. 44(10):3594-3599.

Nan, CW., Bichurin, MI., Dong, SX., Viehland, D. and Srinivasan, G. 2008. Multiferroic magnetoelectric composites: Historical perspective, status, and future directions. Journal of Applied Physics. 103(3):031101.

Newnham, RE. 2005. Properties of Materials: Anisotropy, Symmetry, Structure. (Kindle edi.). Oxford University Press Inc., Oxford-New York. pp391.

Nye, JF. 1989. Physical Properties of Crystals. Their Representation by Tensors and Matrices. Oxford, Clarendon Press. pp385.

Özgür, Ü., Alivov, Ya. and Morkoç, H. 2009. Microwave ferrites, part 2: Passive components and electrical tuning. Journal of Materials Science. Materials in Electronics. 20(10):911-952.

Park, ChS. and Priya, Sh. 2012. Broadband/Wideband Magnetoelectric Response. Advances in Condensed Matter Physics. Hindawi Publishing Corporation. 2012:323165. pp12.

Prellier, W., Singh, MP. and Murugavel, P. 2005. The single-phase multiferroic oxides – from bulk to thin film. Journal of Physics: Condensed Matter. 17(30):R803-R832.

Priya, S., Islam, RA., Dong, SX. and Viehland, D. 2007. Recent advancements in magnetoelectric particulate and laminate composites. Journal of Electroceramics. 19(1):147-164.

Pullar, RC. 2012. Hexagonal ferrites: A review of the synthesis, properties and applications of hexaferrite ceramics. Progress in Materials Science. 57(7):1191-1334.

Rado, GT., Ferrari, JM. and Maisch, WG. 1984. Magnetoelectric susceptibility and magnetic symmetry of magnetoelectrically annealed $TbPO_4$. Physical Review B. 29(7):4041-4048.

Ramesh, R. 2009. Materials science: Emerging routes to multiferroics. Nature. 461(7268):1218-1219.

Rezk, AR., Manor, O., Friend, JR. and Yeo, LY. 2012^a. Unique fingering instabilities and soliton-like wave propagation in thin acoustowetting films. Nature Communications. 3:1167. pp7.

Rezk, AR., Qi, A., Friend, JR., Li, WH. and Yeo, LY. 2012^b. Uniform mixing in paper-based microfluidic systems using surface acoustic waves. Lab on a Chip. 12(4):773-779.

Ribichini, R., Cegla, F., Nagy, PB. and Cawley, P. 2010. Quantitative modeling of the transduction of electromagnetic acoustic transducers operating on ferromagnetic media. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control. 57(12):2808-2817.

Rivera, JP. 1994. The linear magnetoelectric effect in $LiCoPO_4$ revisited. Ferroelectrics. 161(1):147-164.

Rocha-Gaso, MI., March-Iborra, C., Montoya-Baides, Á. and Arnau-Vives, A. 2009. Surface generated acoustic wave biosensors for the detection of pathogens: A review. MDPI Sensors. 9(7):5740-5769.

Spaldin, NA. and Fiebig, M. 2005. The renaissance of magnetoelectric multiferroics. Science. 309(5733):391-392.

Srinivasan, G. 2010. Magnetoelectric composites. Annual Review of Materials Research. 40(1):153-178.

Tan, MK., Friend, JR., Matar, OK. and Yeo, LY. 2010. Capillary wave motion excited by high frequency surface acoustic waves. Physics of Fluids. 22(11):112112.

Thompson, RB. 1990. Physical principles of measurements with EMAT transducers. In: Physical Acoustics. Eds. Mason WP. and Thurston, RN. Academic Press, New York, USA. 19:157-200.

Wang, BL. and Mai, YW. 2007. Applicability of the crack-face electromagnetic boundary conditions for fracture of magnetoelectroelastic materials. International Journal of Solids and Structures. 44(2):387-398.

Wang, KF., Liu, JM. and Ren, ZF. 2009. Multiferroicity: The coupling between magnetic and polarization orders. Advances in Physics. 58(4):321-448.

Weigl, BH., Bardell, RL. and Cabrera, CR. 2003. Lab-on-a-chip for drug development. Advanced Drug Delivery Reviews. 55(3):349-377.

Yoon, JY. and Kim, BS. 2012. Lab-on-a-chip pathogen sensors for food safety. MDPI Sensors. 12(8):10713-10741.

Zakharenko, AA. 2010. Propagation of seven new SH-SAWs in piezoelectromagnetics of class 6 *mm*. LAP LAMBERT Academic Publishing GmbH & Co. KG, Saarbruecken-Krasnoyarsk. pp84.

Zakharenko, AA. 2011. Analytical investigation of surface wave characteristics of piezoelectromagnetics of class 6 *mm*. ISRN Applied Mathematics (India). 2011:408529. pp8.

Zakharenko, AA. 2012^a. Thirty two new SH-waves propagating in PEM plates of class 6 *mm*. LAP LAMBERT Academic Publishing GmbH & Co. KG, Saarbruecken-Krasnoyarsk. pp162.

Zakharenko, AA. 2012^b. Twenty two new interfacial SH-daves in Dissimilar PEMs. LAP LAMBERT Academic Publishing GmbH & Co. KG, Saarbruecken – Krasnoyarsk. pp148.

Zakharenko, AA. 2012^c. On wave characteristics of piezoelectromagnetics. Pramana – Journal of Physics. 79(2):275-285.

Zakharenko, AA. 2013^a. Piezoelectromagnetic SH-SAWs: A review. Canadian Journal of Pure & Applied Sciences. 7(1):2227-2240.

Zakharenko, AA. 2013^b. Peculiarities study of acoustic waves' propagation in piezoelectromagnetic (composite) materials. Canadian Journal of Pure and Applied Sciences. 7(2):2459-2461.

Zakharenko, AA. 2013^c. New nondispersive SH-SAWs guided by the surface of piezoelectromagnetics. Canadian Journal of Pure and Applied Sciences. 7(3):2557-2570.

Zakharenko, AA. 2014. Some problems of finding of eigenvalues and eigenvectors for SH-wave propagation in transversely isotropic piezoelectromagnetics. Canadian Journal of Pure and Applied Sciences. 8(1):2783-2787.

Zhai, J., Xing, ZP., Dong, Sh-X., Li, JF. and Viehland, D. 2008. Magnetoelectric laminate composites: An overview. Journal of the American Ceramic Society. 91(2):351-358.

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