PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 81, No. 5
November 2013
pp. 819–827

Fundamental modes of new dispersive SH-waves in piezoelectromagnetic plate

A A ZAKHARENKO
International Institute of Zakharenko Waves (IIZWs), 660037, Krasnoyarsk-37, 17701, Krasnoyarsk, Russia
E-mail: aazaaz@inbox.ru

MS received 3 March 2013; revised 10 July 2013; accepted 13 August 2013
DOI: 10.1007/s12043-013-0609-1; ***e*Publication:** 22 October 2013

Abstract. Fundamental modes of new dispersive shear-horizontal (SH) acoustic waves propagating in the (6 mm) piezoelectromagnetic plate are studied. These SH-waves can propagate when the following boundary conditions are exploited for both the upper and lower surfaces of the plate: (1) when the surfaces are mechanically free, electrically and magnetically closed and (2) when the surfaces are mechanically free, electrically and magnetically open. The SH-waves depend on the electromagnetic wave speed $V_{\rm EM} = 1/\sqrt{(\varepsilon\mu)}$ and can only exist when the electromagnetic constant $\alpha \neq 0$. The calculations (first evidence) were performed for the PZT-5H–Terfenol-D which is a composite with a large value of α. The limit cases of large values of α ($\alpha^2 = 0.5\varepsilon\mu$, $\alpha^2 = 0.9\varepsilon\mu$, and $\alpha^2 = 0.99\varepsilon\mu$) are studied because they satisfy the limitation condition of $\alpha^2 < \varepsilon\mu$.

Keywords. Piezoelectromagnetics; magnetoelectric effect; acoustic SH-waves in plates; wave dispersion; fundamental modes.

PACS Nos 51.40.+p; 62.65.+k; 68.35.Gy; 68.35.Iv; 68.60.Bs; 74.25.Ld; 74.25.Ha; 75.20.En; 75.80.+q; 81.70.Cv

1. Introduction

The magnetoelectric (ME) effect characterized by the value of the electromagnetic constant α can be large in ferroelectric (FE) and/or ferromagnetic (FM) materials and this effect is not restricted to multiferroic materials [1–3]. The linear ME effect is usually very small and can be observed in two classes of materials: single-phase multiferroics possessing simultaneously both FE and FM properties and composites consisting of FE and FM phases. The ME effect in the single-phase materials (Cr_2O_3, $LiCoPO_4$, $TbPO_4$ [2]) is small and arises from the long-range interaction between the atomic moments and electric dipoles in ordered magnetic and FE sublattices. Indeed, none of the ME materials can have combined large and robust electric and magnetic polarizations at room temperature, except for the $Sr_3Co_2Fe_{24}O_{41}$ Z-type hexaferrite [4] discovered in 2010. It is thought that such a single-phase hexaferrite with the realizable ME effect characterized by the constant α can be already sufficient for practical applications. It is well-known that the value of α must be restricted by the following inequality [1,2]: $\alpha^2 < \varepsilon\mu$, where ε and μ stand for the dielectric permittivity coefficient and the magnetic permeability coefficient, respectively. ε and μ are responsible for evaluating the speed of the electromagnetic wave (V_{EM}) in a solid: $V_{\mathrm{EM}} = 1/\sqrt{\varepsilon\mu} < C_{\mathrm{L}}$ where C_{L} represents the speed of light in vacuum, $C_{\mathrm{L}} = 1/\sqrt{\varepsilon_0\mu_0}$. In this short report, V_{EM} and α are important parameters for the study carried out below concerning the acoustic wave propagation coupled with both the electrical and magnetic potentials (electromagnetic waves). This demonstrates some connection between optics and acoustics. In the last decade there has been an explosion of activity in ME materials and devices that can interconvert magnetic and electrical signals. The ME coupling required for this purpose may arise in a single-phase material or at the interface between two materials, for instance, piezoelectric–piezomagnetic (PE–PM) composites. The piezoelectromagnetic (PEM) composite materials (magnetoelectroelastics possessing the PE, PM, and ME effects) are known as a large class of ME materials which can exist as bulk samples and thin films. These smart materials are multi-promising and as a result, many reviews [1–44] are published in the literature on the ME materials and their possible applications in various technical devices. It is also possible to mention the left-handed ME metamaterials ($\varepsilon < 0$ and $\mu < 0$) [45,46] and even three-dimensional bulk materials [46] that can be made into these films (plates).

Also, it is possible to review several studies of ME phenomena that can change the values of the material parameters, such as the value of the constant ε, which affects the wave parameter V_{EM} mentioned above. Indeed, there is a rekindled interest in the development of the ME materials with new multifunctional capabilities called multiferroic systems which are characterized by the simultaneous presence of magnetic and electric order parameters coupled with each other. New classes of artificially structured composite materials that combine dissimilar magnetic and ferroelectric systems are being developed to optimize order parameter coupling [47] that can open new vistas for developing novel ME devices. A variety of ME effects [48] can be observed in multiferroic hexagonal $RMnO_3$ with R = Sc, Y, In. Exploiting absorption and diffraction measurements, Jung [49] has successfully detected the optical ME effect in the polar ferrimagnet $GaFeO_3$: the change of constant ε with the propagation direction of light. Using the density functional theory, Ju and Guo [50] have investigated magnetic ordering dependence of linear and nonlinear optical responses in multiferroic Bi_2FeCrO_6. Arima [51] stated that non-centrosymmetric ferromagnetic materials can actually demonstrate optical and X-ray responses unique to magnetoelectrics. The ME effect has also been demonstrated based on the composite of InGaN/GaN multiple quantum walls (MQWs) and FeCo thin film [52]. The ferromagnetic layer under an external magnetic field can be deformed due to magnetostriction. In the PE layers, this deformation induces electric polarization that changes the strain and the built-in internal electric field in the MQWs. So, the optical and acoustic properties of the MQWs change allowing them to be used in magneto-optical and ME engineering.

This short report studies the new shear horizontal (SH) waves propagating in the PEM transversely isotropic (6 mm) plates such as the PZT-5H–Terfenol-D which is known as a PE–PM composite with a large value of α. These results are not given in [53]. The propagation of these new SH-waves is coupled with both the electrical and magnetic potentials and therefore, they can interact with some of the optical ME phenomena mentioned above and this interaction can generate new acousto-optic phenomena. It is obvious that the SH-waves can be excited by the non-contact method called the electromagnetic acoustic transducers (EMATs) [54–56].

2. Theory and results

It is very important to know the suitable propagation directions of the shear horizontal (SH) elastic waves when they can be coupled with both the electrical and magnetic potentials (electromagnetic waves). For the (6 mm) transversely isotropic material, the suitable propagation direction is given in [57]. The propagating SH-waves are polarized along the six-fold symmetry axis. This is the case of pure waves where the antiplane-polarized SH-waves can be separately studied [58,59] from the in-plane polarized Lamb acoustic waves. To study the SH-wave propagation, the quasistatic approximation [59] must be used. In the case of pure SH-wave propagation, the corresponding tensor form of the equations of motion for the PEM medium can be written [53,60,61]. Also, it is essential to mention the following non-zero material parameters for this case: the elastic stiffness constant C, piezoelectric constant e, piezomagnetic coefficient h as well as ε, μ, and α introduced above. The mechanical, electrical, and magnetic boundary conditions for this case are written for both the upper and lower surfaces of the PEM plate as follows: the mechanically free (the normal component of the stress tensor is vanishing), electrically closed (the electrical potential is vanishing), and magnetically closed (the magnetic induction is vanishing) surfaces. However, they can also exist when the plate surfaces are mechanically free, electrically open (the electric induction vanishes), and magnetically open (the magnetic potential vanishes). The boundary conditions for various cases are perfectly described in [62]. So, these boundary conditions result in the following dispersion relation [53] that must be theoretically investigated in this short work:

$$\sqrt{1-\left(\frac{V_{\mathrm{new6}}}{V_{\mathrm{tem}}}\right)^2}\tanh\left(kd\sqrt{1-\left(\frac{V_{\mathrm{new6}}}{V_{\mathrm{tem}}}\right)^2}\right)-\frac{\alpha^2}{\varepsilon\mu}\frac{K_{\mathrm{em}}^2-K_\alpha^2}{1+K_{\mathrm{em}}^2}=0. \tag{1}$$

Dispersion relation (1) is valid for $V_{\mathrm{new6}} < V_{\mathrm{tem}}$ and determines the velocity V_{new6} of the sixth new SH-wave propagating in the PEM plate. In eq. (1), the velocity V_{tem} represents the speed of the SH bulk acoustic wave (SH-BAW) coupled with both the electrical and magnetic potentials: $V_{\mathrm{tem}} = \sqrt{C/\rho}\left(1+K_{\mathrm{em}}^2\right)^{1/2}$, where ρ is the mass density. Also, expression (1) depends on the coefficient of the magnetoelectromechanical coupling (CMEMC). The non-dimensional CMEMC K_{em}^2 and the parameter K_α^2 are defined by $K_{\mathrm{em}}^2 = \left(\mu e^2+\varepsilon h^2-2\alpha eh\right)/C\left(\varepsilon\mu-\alpha^2\right)$ and $K_\alpha^2 = \alpha eh/C\alpha^2 = eh/C\alpha$, respectively.

It is necessary to state that dispersion relation (1) is not the single equation that can be found for the treated case of the boundary conditions. Following the numbering of book

[53], the second dispersion relation for determining the velocity V_{new7} of the seventh new SH-wave can be written as follows:

$$\sqrt{1-\left(\frac{V_{\mathrm{new7}}}{V_{\mathrm{tem}}}\right)^2}-\frac{\alpha^2}{\varepsilon\mu}\frac{K_{\mathrm{em}}^2-K_\alpha^2}{1+K_{\mathrm{em}}^2}\tanh\left(kd\sqrt{1-\left(\frac{V_{\mathrm{new7}}}{V_{\mathrm{tem}}}\right)^2}\right)=0. \tag{2}$$

Therefore, there are two dispersion relations, eqs (1) and (2), for further theoretical investigations that will be carried out below. These dispersion relations are suitable for $V_{\mathrm{new6}} < V_{\mathrm{tem}}$ and $V_{\mathrm{new7}} < V_{\mathrm{tem}}$ and can reveal dispersive SH-wave propagation velocities V_{new6} and V_{new7} for the fundamental modes. Indeed, eq. (1) discloses the dependence of the velocity V_{new6} on the dimensionless parameter kd, where k and d are the wavenumber in the propagation direction and the plate half-thickness, respectively. In the same manner, eq. (2) exhibits the dependence of V_{new7} on kd. It is apparent that dispersion relations (1) and (2), which are quite complicated, can be studied only numerically. Also, one can check that when $kd \to \infty$, both relations (1) and (2) can reduce to the following formula for the determination of the velocity of the SH surface acoustic wave (SH-SAW):

$$V_{\mathrm{new}\alpha}=V_{\mathrm{tem}}\sqrt{1-\left(\frac{\alpha^2}{\varepsilon\mu}\frac{K_{\mathrm{em}}^2-K_\alpha^2}{1+K_{\mathrm{em}}^2}\right)^2}. \tag{3}$$

Expression (3) is true because $\tanh(kd \to \infty) \to 1$ occurs in relations (1) and (2). The SH-SAW velocity $V_{\mathrm{new}\alpha}$ was recently discovered in [60]. However, this SH-SAW has a peculiarity that this SH-SAW speed is slightly smaller than the SH-BAW speed V_{tem}. So, the value of $V_{\mathrm{new}\alpha}$ can be significantly closer to the value of V_{tem} than the other SH-SAWs discovered in [60] because the value of α is very small. It is also necessary to state that the magnetoelectric effect is crucial for the existence of the sixth and seventh new dispersive SH-waves because as soon as α becomes zero, the other new SH-waves given in [53] can exist, except the case of dispersion relations (1) and (2). There is also a recent work [63] that theoretically investigates the non-dispersive SH-wave defined by expression (3). It is also blatant in expression (3) and relations (1) and (2) that the non-dispersive SH-SAW velocity $V_{\mathrm{new}\alpha}$ and the dispersive plate SH-wave velocities V_{new6} and V_{new7} depend on the speed V_{EM} of the electromagnetic wave in a PEM solid. As a rule, the electromagnetic wave speed V_{EM} is slightly lower than the speed C_{L} of light in vacuum. Also, the value of the speed V_{EM} is approximately five orders larger than the speed of elastic wave propagating in a solid. This huge difference in the speeds is the reason for using the quasistatic approximation [59,64] for the case. It is worth noticing that the propagation of the elastic SH-BAW coupled with both the electrical and magnetic potentials can be slightly increased by coupling with both the potentials. It is also clearly seen that SH-SAW speed $V_{\mathrm{new}\alpha}$ is smaller than the SH-BAW speed $V_{\mathrm{tem}} = \sqrt{C/\rho}\left(1+K_{\mathrm{em}}^2\right)^{1/2}$. The difference between the speeds $V_{\mathrm{new}\alpha}$ and V_{tem} was graphically given in [63] as a function of α. It is obvious in expression (3) that $V_{\mathrm{new}\alpha} = V_{\mathrm{tem}}$ for $\alpha = 0$. However, in [63] it is demonstrated that the speed $V_{\mathrm{new}\alpha}$ can reach the speed V_{tem} for some large values of α restricted by the inequality [1,2] $\alpha^2 < \varepsilon\mu$.

This short report deals with the theoretical investigations of the fundamental modes of the new dispersive SH-waves defined by dispersion relations (1) and (2). Formulae (1) and (2) were first obtained in [53], but in this work, the investigation was not thorough and therefore, some peculiarities were not demonstrated. This lacuna is partly filled with the results obtained in this short theoretical work. For simplicity, this work treats the concrete PEM material such as the PZT-5H–Terfenol-D composite. The PZT-5H–Terfenol-D material constants were compared with $BaTiO_3$–$CoFe_2O_4$, another well-known composite (see table in [63]). The PZT-5H–Terfenol-D and $BaTiO_3$–$CoFe_2O_4$ composites possess very large and small values of α, respectively. One can find that the value of $\varepsilon\mu$ for $BaTiO_3$–$CoFe_2O_4$ is more than an order larger than that for PZT-5H–Terfenol-D. This means that the value of α can be significantly closer to the value of $\varepsilon\mu$ for PZT-5H–Terfenol-D assuming that the restriction [1,2] $\alpha^2 < \varepsilon\mu$ is satisfied. This is the reason for investigating PZT-5H–Terfenol-D. Table 1 lists the values of the SH-BAW and SH-SAW velocities such as V_{tem} and $V_{\mathrm{new}\alpha}$, respectively. The dependence of the velocities on the value of α is tabulated for PZT-5H–Terfenol-D. It is convenient to introduce the α-value as a part of the $\varepsilon\mu$-value in the first column of table 1. It is clearly seen in table 1 that when the value of α is small ($\alpha^2 \ll \varepsilon\mu$ and $\alpha^2 \sim \varepsilon\mu$) the value of the SH-SAW velocity $V_{\mathrm{new}\alpha}$ is a little less than the value of the SH-BAW velocity V_{tem}. For $\alpha^2 > 0.5\varepsilon\mu$, the difference between the velocities V_{tem} and $V_{\mathrm{new}\alpha}$ becomes significant. For $\alpha^2 = 0.99\varepsilon\mu$, the value of V_{tem} is already more than twice as much. It is worth noting that when $\alpha^2 = 0.99\varepsilon\mu$, the optic (electromagnetic) contribution such as ($\varepsilon\mu$–α^2) in the denominator of the CMEMC K^2_{em} becomes dominant. It is obvious that when α^2 is also closer to $\varepsilon\mu$ than the case of $\alpha^2 = 0.99\varepsilon\mu$, one can deal with the case of $V_{\mathrm{tem}} \to \mathrm{V_{EM}}$. However, when $V_{\mathrm{tem}} \to V_{\mathrm{EM}}$, the value of the SH-SAW velocity $V_{\mathrm{new}\alpha}$ can be approximately one order smaller than the value of the SH-BAW velocity V_{tem} and hence, the quasistatic approximation can be still satisfied only for $V_{\mathrm{new}\alpha}$. Therefore, it is possible to state that PEM (composite) materials are good candidates for verifying the upper threshold of the applicability of the quasistatic approximation. For $\alpha^2 \to \varepsilon\mu$, this threshold can be demonstrated for $V_{\mathrm{tem}} \to V_{\mathrm{EM}}$. This fact can be used as a bridge between optics/photonics and acoustics.

Figure 1 shows the fundamental modes of the new dispersive SH-waves propagating in the PEM plate made of the PZT-5H–Terfenol-D material. Dispersion relations (1) and

Table 1. The material characteristics of the PZT-5H–Terfenol-D composite for various values of α.

α^2 (s/m)	α (ns/m)	K^2_{em}	K^2_{α}	V_{tem} (m/s)	$V_{\mathrm{new}\alpha}$ (m/s)
$\to \varepsilon\mu$	$\to (\varepsilon\mu)^{1/2}$	$\to \infty$	$eh/C\alpha$	$\to \infty$	$\ll V_{\mathrm{tem}}$
$0.99\varepsilon\mu$	139.2093747	15.12242913	0.3528795244	5244.327158	2209.379614
$0.9\varepsilon\mu$	132.7309308	1.837400471	0.3701031676	2200.061679	1947.258747
$0.5\varepsilon\mu$	98.93179469	0.7067604902	0.4965455047	1706.321365	1703.082705
$0.1\varepsilon\mu$	44.24364361	0.6976264992	1.110309503	1701.749420	1701.246523
$0.01\varepsilon\mu$	13.99106858	0.7875794053	3.511106936	1746.253178	1746.050487
$0.0001\varepsilon\mu$	1.399106858	0.8429878349	35.11106936	1773.110382	1773.107317

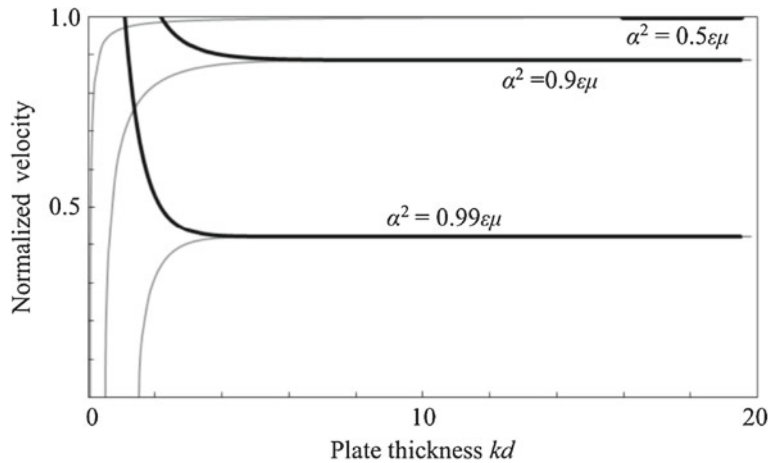

Figure 1. The fundamental modes' dispersion relations for several values of α^2. $V_{\mathrm{new6}}/V_{\mathrm{tem}}$ and $V_{\mathrm{new7}}/V_{\mathrm{tem}}$ in eqs (1) and (2) are shown by the thin grey and thick black lines, respectively.

(2) were exploited to obtain the dependencies of the normalized velocities $V_{\mathrm{new6}}/V_{\mathrm{tem}}$ and $V_{\mathrm{new7}}/V_{\mathrm{tem}}$ of the new dispersive SH-waves on the dimensionless plate thickness kd. The figure compares the dispersion relations for $\alpha^2 = 0.5\varepsilon\mu$, $\alpha^2 = 0.9\varepsilon\mu$, and $\alpha^2 = 0.99\varepsilon\mu$. The velocity $V_{\mathrm{new6}}/V_{\mathrm{tem}}$ defined by relation (1) is shown by thin grey lines. The velocity $V_{\mathrm{new7}}/V_{\mathrm{tem}}$ defined by relation (2) is shown by thick black lines. It is clearly seen in the figure that when the value of α increases, the fundamental modes corresponding to the velocity $V_{\mathrm{new7}}/V_{\mathrm{tem}}$ (thick black lines) start with $V_{\mathrm{new7}} = V_{\mathrm{tem}}$ at smaller values of kd. When $\alpha^2 = 0.99\varepsilon\mu$, the value of $kd \sim 1$ is still significantly larger than zero. It is also apparent that for $\alpha^2 \ll \varepsilon\mu$, this fundamental mode will start with a very large value of kd, namely $kd \gg 20$ according to the figure. In contrast, the other fundamental modes corresponding to the velocity $V_{\mathrm{new6}}/V_{\mathrm{tem}}$ (thin grey lines) commence with $V_{\mathrm{new7}} = 0$ at larger values of kd. When a fundamental mode commences when $kd > 0$, it is said that a 'silence zone' occurs because the corresponding SH-wave cannot be excited. It is thought that for $V_{\mathrm{new6}}/V_{\mathrm{tem}}$, this 'silence zone' can be negligible in the case of $\alpha^2 \ll 0.5\varepsilon\mu$ because already for $\alpha^2 = 0.5\varepsilon\mu$ (see the figure) the fundamental mode dispersion relation looks like a δ-function: the velocity V_{new6} is zero at $kd \to 0$ and then the velocity V_{new6} rapidly approaches the SH-SAW speed$V_{\mathrm{new}\alpha}$, where $V_{\mathrm{new}\alpha} \to V_{\mathrm{tem}}$ occurs. Therefore, it is expected that for $\alpha^2 \ll 0.5\varepsilon\mu$, the dispersion relation will approach the δ-function behaviour. One can also find that for $\alpha^2 = 0.99\varepsilon\mu$, the velocity V_{new6} starts already at a larger threshold value of kd than that for the velocity V_{new7}. Also, this threshold value of kd can be significantly larger when the value of α is closer to the value of $\varepsilon\mu$ than when $\alpha^2 = 0.99\varepsilon\mu$. So, these illuminated peculiarities discussed above can be used for developing various new acousto-optoelectronic technical devices based on smart PEM materials (sensors, filters, delay lines, lab-on-a-chip, etc.) when the optic and acoustic wave phenomena is completely understood. Also, it is well-known that plates can be

used for further miniaturization of technical devices and the plate SH-waves exited and detected with the EMATs can be utilized for non-destructive testing and evaluation of thin films (plates).

3. Conclusion

In this original study, it is possible to conclude that to deal with the PEM plate SH-waves is preferable in comparison with the investigation of the SH-SAW because the plate SH-wave velocity for a small value of kd can be significantly below the SH-BAW speed. It is thought that the new dispersive SH-waves studied can be a useful tool for various theoretical and experimental studies of optic and acoustic phenomena because these acoustic SH-waves are coupled with both the electrical and magnetic potentials but the Lamb waves in this case represent purely mechanical waves. However, it is necessary to account for the peculiarities such that the fundamental modes of the new dispersive SH-waves can commence at $kd > 0$ and therefore, 'silence zones' can occur. Constitution of various new acousto-optoelectronic technical devices can be a natural consequence of further investigations of the wave phenomena.

References

[1] Ü Özgür, Ya Alivov and H Morkoç, *J. Mater. Sci.: Mater. Electron.* **20**, 911 (2009)
[2] M Fiebig, *J. Phys. D: Appl. Phys.* **38**(8), R123 (2005)
[3] M Fiebig, V V Pavlov and R V Pisarev, *J. Opt. Soc. Am. B* **22**(1), 96 (2005)
[4] T Kimura, *Ann. Rev. Condens. Matter Phys.* **3**(1), 93 (2012)
[5] Ch-S Park and Sh Priya, *Advances in condensed matter physics* (Hindawi Publishing Corporation, 2012) Vol. 2012, 12 pages
[6] R C Pullar, *Prog. Mater. Sci.* **57**(7), 1191 (2012)
[7] M I Bichurin, V M Petrov and R V Petrov, *J. Magn. Magn. Mater.* **324**(21), 3548 (2012)
[8] A A Zakharenko, *Canad. J. Pure & Appl. Sci. (SENRA Academic Publishers)* **7**(1), 2227 (2013), ISSN: 1715-9997
[9] T Chen, S Li and H Sun, *Sensors (MDPI)* **12**(3), 2742 (2012)
[10] M Bichurin, V Petrov, A Zakharov, D Kovalenko, S Ch Yang, D Maurya, V Bedekar and Sh Priya, *Materials* **2011**(4), 651 (2011)
[11] G Srinivasan, *Ann. Rev. Mater. Res.* **40**(1), 153 (2010)
[12] J Zhai, Z-P Xing, Sh-X Dong, J-F Li and D Viehland, *J. Am. Ceram. Soc.* **91**(2), 351 (2008)
[13] C W Nan, M I Bichurin, S X Dong, D Viehland and G Srinivasan, *J. Appl. Phys.* **103**(3), 031101 (2008)
[14] W Eerenstein, N D Mathur and J F Scott, *Nature* **442**(7104), 759 (2006)
[15] N A Spaldin and M Fiebig, *Science* **309**(5733), 391 (2005)
[16] D I Khomskii, *J. Magn. Magn. Mater.* **306**(1), 1 (2006)
[17] S-W Cheong and M Mostovoy, *Nature Mater.* **6**(1), 13 (2007)
[18] R Ramesh and N A Spaldin, *Nature Mater.* **6**(1), 21 (2007)
[19] T Kimura, *Ann. Rev. Mater. Res.* **37**(1), 387 (2007)
[20] T Kimura, T Goto, H Shintani, K Ishizaka, T Arima and Y Tokura, *Nature* **426**(6962), 55 (2003)
[21] K F Wang, J-M Liu and Z F Ren, *Adv. Phys.* **58**(4), 321 (2009)
[22] R Ramesh, *Nature* **461**(7268), 1218 (2009)

[23] K T Delaney, M Mostovoy and N A Spaldin, *Phys. Rev. Lett.* **102**(15), 157203 (2009)
[24] S C B Gopinath, K Awazu and M Fujimaki, *Sensors (MDPI)* **12**(2), 2136 (2012)
[25] A Fert, *Rev. Mod. Phys.* **80**(4), 1517 (2008)
[26] A Fert, *Physics – Uspekhi (Moscow)* **51**(12), 1336 (2008)
[27] C Chappert and J-V Kim, *Nature Phys.* **4**(11), 837 (2008)
[28] M Bibes and A Barthélémy, *Nature Mater.* **7**(6), 425 (2008)
[29] W Prellier, M P Singh and P Murugavel, *J. Phys.: Condens. Matter* **17**(30), R803 (2005)
[30] M I Bichurin, V M Petrov, D A Filippov, G Srinivasan and S V Nan, *Magnetoelectric materials* (Academia Estestvoznaniya Publishers, Moscow, 2006)
[31] Y K Fetisov, A A Bush, K E Kamentsev, A Y Ostashchenko and G Srinivasan, *The IEEE Sensor J.* **6**(4), 935 (2006)
[32] G Srinivasan and Y K Fetisov, *Integrated Ferroelectrics* **83**(1), 89 (2006)
[33] S Priya, R A Islam, S X Dong and D Viehland, *J. Electroceram.* **19**(1), 147 (2007)
[34] R Grossinger, G V Duong and R Sato-Turtelli, *J. Magn. Magn. Mater.* **320**(14), 1972 (2008)
[35] C W Ahn, D Maurya, C S Park, S Nahm and S Priya, *J. Appl. Phys.* **105**(11), 114108 (2009)
[36] V M Petrov, M I Bichurin, V M Laletin, N Paddubnaya and G Srinivasan, Modeling of magnetoelectric effects in ferromagnetic/piezoelectric bulk composites, in: *Proceedings of the 5th International Conference on Magnetoelectric Interaction Phenomena in Crystals* (MEIPIC-5) (Sudak, Ukraine, 21–24 September 2003), arXiv:cond-mat/0401645
[37] G Harshe, J P Dougherty and R E Newnham, *Int. J. Appl. Electromag. Mater.* **4**(1), 161 (1993)
[38] Y H Chu, L W Martin, M B Holcomb and R Ramesh, *Mater. Today* **10**(10), 16 (2007)
[39] H Schmid, *Bull. Mater. Sci.* **17**(7), 1411 (1994)
[40] J Ryu, Sh Priya, K Uchino and H-E Kim, *J. Electroceram.* **8**(2), 107 (2002)
[41] D Fang, Yo-P Wan, X Feng and A K Soh, *ASME Appl. Mech. Rev.* **61**(2), 020803 (2008)
[42] A Sihvola, *Metamater.* **1**(1), 2 (2007)
[43] N A Hill (N A Spaldin) *J. Phys. Chem. B* **104**(29), 6697 (2000)
[44] G A Smolenskii and I E Chupis, *Sov. Phys. Uspekhi (Moscow)* **25**(7), 475 (1982)
[45] A M Shuvaev, S Engelbrecht, M Wunderlich, A Schneider and A Pimenov, *Eur. Phys. J. B* **79**(2), 163 (2011)
[46] W T Chen, Ch J Chen, P Ch Wu, Sh Sun, L Zhou, G-Y Guo, Ch T Hsiao, K-Y Yang, N I Zheludev and D P Tsai, *Opt. Express* **19**(13), 12837 (2011)
[47] H J A Molegraaf, J Hoffman, C A F Vaz, S Gariglio, D van der Marel, C H Ah and J-M Triscone, *Adv. Mater.* **21**(34), 3470 (2009)
[48] M Fiebig, Magnetoelectric correlations in multiferroic manganites revealed by nonlinear optics, in: *Advances in solid state physics* (Springer-Verlag, Berlin-Heidelberg, 2007) Vol. 46, pp. 255–267
[49] J H Jung, *J. Korean Phys. Soc.* **46**(2), 508 (2005)
[50] Sh Ju and G-Y Guo, *Appl. Phys. Lett.* **92**(20), 202504 (2008)
[51] T Arima, *J. Phys.: Condens. Matter* **20**(43), 434211 (2008)
[52] C M Wei, H Y Shih, Y F Chen and T Y Lin, *Appl. Phys. Lett.* **98**(13), 131913 (2011)
[53] A A Zakharenko, *Thirty two new SH-waves propagating in PEM plates of class 6 mm* (Saarbruecken–Krasnoyarsk, LAP LAMBERT Academic Publishing GmbH & Co. KG, 2012) 162 pages
[54] R Ribichini, F Cegla, P B Nagy and P Cawley, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **57**(12), 2808 (2010)
[55] R B Thompson, Physical principles of measurements with EMAT transducers, in: *Physical acoustics* edited by W P Mason and R N Thurston (Academic Press, New York, 1990) Vol. 19, pp. 157–200
[56] M Hirao and H Ogi, *EMATs for science and industry: Non-contacting ultrasonic measurements* (Kluwer Academic, Boston, MA, 2003)

[57] Yu V Gulyaev, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **45**(4), 935 (1998)

[58] C Lardat, C Maerfeld and P Tournois, *Proceedings of the IEEE* **59**(3), 355 (1971)

[59] E Dieulesaint and D Royer, *Elastic waves in solids: Applications to signal processing*, translated by A Bastin, M Motz and Chichester (English) (J Wiley, New York, 1980) 511 pages

[60] A A Zakharenko, *Propagation of seven new SH-SAWs in piezoelectromagnetics of class 6 mm* (Saarbruecken–Krasnoyarsk, LAP LAMBERT Academic Publishing GmbH & Co. KG, 2010) 84 pages

[61] A A Zakharenko, *Twenty two new interfacial SH-waves in dissimilar PEMs* (Saarbruecken–Krasnoyarsk, LAP LAMBERT Academic Publishing GmbH & Co. KG, 2012) 148 pages

[62] V I Al'shits, A N Darinskii and J Lothe, *Wave Motion* **16**(3), 265 (1992)

[63] A A Zakharenko, *Pramana – J. Phys*. **79**(2), 275 (2012)

[64] B A Auld, *Acoustic fields and waves in solids*, 2nd edn (Krieger Publishing Company, 1990) Volumes I and II (set of two volumes) 878 pages