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Magnetoelectric effect in the region of magnetoacoustic resonance in the thickness-longitudinal mode in the structure of YIG/lithium niobate/silicon

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The article is devoted to the theoretical study of the magnetoelectric interaction in the ferrite-piezoelectric-substrate layered structure in the mode of frequency coincidence of ferromagnetic resonance in ferrite and one of the modes of electromechanical resonance of piezoelectric. The results of calculating the magnetoelectric coefficient in the region of magnetoacoustic resonance in the structure of YIG/lithium niobate/silicon in the thickness-longitudinal mode are presented. At a resonance frequency of 1.7 GHz, the magnetoelectric coefficient is 32 V/(cm · Oe). The obtained results can be used in setting up an experimental study.

Keywords: magnetoelectric effect, electromechanical resonance, ferromagnetic resonance, magnetoacoustic resonance, yttrium iron garnet, lithium niobate, layered magnetoelectric structure.

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1. Introduction

Recently the scientific periodicals have been paying more attention to theoretical and applied studies of magnetoelectric (ME) effect in composite materials comprising magnetic and piezoelectric components [1,2]. The primary efforts of the researchers in this area were aimed at searching for methods to increase the ME effect in order to proceed to practical applications. After transition of the ME composite research to the area of electromechanical resonance (EMR) [3–5] and use of a simple gluing technology it was possible to obtain the value of the ME effect that is sufficient for practical applications. In addition to the EMR studies, paper [6] proposed to study the ME effect in the field of magnetoacoustic resonance (MAR), which may be implemented in the match of the EMR frequencies and ferromagnetic resonance (FMR) in a single-crystal ferrite-piezoelectric bilayer. The estimates demonstrated the effective energy transfer between phonons and spin waves in the studied structure and the substantial increase of ME coefficients to the values of 80−480 V/(cm · Oe) at frequencies 5−10 GHz for orthogonal-magnetized bilayers of nickel ferrite/lead zirconate-titanate (PZT) and yttrium-iron garnet (YIG)/PZT. In connection with the complexity of matching the EMR and FMR frequencies to this time it was not possible to experimentally observe the ME effect in the MAR area, therefore, all subsequent studies were aimed at accounting for the features of the effect and search for more convenient configurations of electric and magnetic fields for the experiment [7–13]. In paper [7] the effect was compared in the tangentially and orthogonally magnetized two-layer ME YIG/PZT structures. It was shown that the use of the orthogonally magnetized sample made it possible to achieve higher ME effect compared to the tangentially magnetized one. The accounting for the impact of the exchange interaction in YIG [8] on the effect was conducted, and it was shown that when the exchange field is included into the consideration, the shape of the resonance peak of the ME effect changes substantially. The impact of the substrate on the ME effect value was assessed. In paper [9] the effect was also considered in the ME structure of PZT/YIG on the substrate from the gadolinium-gallium garnet (GGG). It was shown that the ME interaction value substantially decreases with the increase of the substrate thickness. The estimates for PZT/YIG/GGG for the nominal parameters of the film predict MAR at frequency of 5 GHz with ME coefficients of the order of 5−70 V/(cm · Oe). It is evident that to solve the problem of EMR and FMR resonance coincidence it is necessary to either increase the EMR value or to decrease the FMR value. Use of the piezoelectric bimorph based on langatate [10] causes excitation of high-order harmonics that are suppressed differently in ferrite/piezoelectric bilayers. ME coefficient with the value of 470 V/(cm · Oe) at frequency 5 GHz is predicted for the third harmonic in the lamellar structure of YIG and langatate bimorph. MAR in thickness-shear mode is considered in paper [11]. It is shown that the obtained estimated value of the ME coefficient substantially exceeds the values of low frequency ME coefficients: at the resonance frequency of 1.72 GHz the ME coefficient is equal to 64 V/(cm · Oe) for the thickness-shear mode. Another opportunity to observe the effect in the MAR area in the torsional mode is studied in papers [12,13]. As it was noted above, currently the search is in progress for the acceptable variants to experimentally observe the ME effect in the MAR area. In this article the authors presented the results of the theoretical study of the frequency dependence of the ME coefficient for the YIG/lithium niobate/silicon composite in the thickness-longitudinal mode.

2. Calculation of thickness-longitudinal mode of ME effect

The structure of the studied ME composite (see Figure 1): on the substrate from silicon with thickness of $300\,\mu$m a layer of lithium niobate is placed with thickness of 600 nm, and an YIG plate is glued on top of the lithium niobate with thickness of $50\,\mu$m. The axis Z is perpendicular to the plane of YIG, the magnetizing field H_0 is directed at the angle of β to axis Z in the plane ZY, to provide for the thickness-longitudinal MAR mode. The alternating microwave magnetic field is directed along axis X in the YIG plane. FMR excites the thickness-longitudinal mode of mechanical strain, which, changing to piezoelectric, creates electric voltage on the top and on the bottom of lithium niobate at the expense of MAR.

Let us write down the motion equation for the spherical angles of magnetization direction in YIG [14]:

$$\frac{\partial\theta}{\partial t} = -\frac{\gamma}{\mu_0 M_s \sin(\theta)}\frac{\partial W}{\partial\varphi},$$
$$\frac{\partial\varphi}{\partial t} = \frac{\gamma}{\mu_0 M_s \sin(\theta)}\frac{\partial W}{\partial\theta}, \quad (1)$$

where γ — gyromagnetic ratio for YIG, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m — a magnetic constant, M_s — YIG saturation magnetization.

Let us write down the density of free energy of YIG with the magnetizing field H_0 and alternating microwave field in accordance with Figure 1:

$$W = -\mu_0 H_0 M_s \big(\cos(\theta)\cos(\beta) + \sin(\theta)\sin(\varphi)\sin(\beta)\big) + \mu_0 M_s^2 \cos^2(\theta)/2 + B_1^m S_3 \cos^2(\theta) + {}^m c_{33}\, {}^m S_3^2/2 - \mu_0 h_1 M_s \sin(\theta)\cos(\varphi), \quad (2)$$

where B_1 — the first magnetic elastic constant for YIG, ${}^m c_{33}$ — the longitudinal component of YIG hardness tensor, ${}^m S_3$ — the longitudinal component of YIG strain tensor determined as

$${}^m S_3 = \partial\, {}^m u_3/\partial z, \quad (3)$$

where ${}^m u_3$ — the longitudinal component of the YIG strain vector.

The longitudinal component of YIG strain tensor:

$${}^m T_3 = \partial W/\partial\, {}^m S_3 = B_1 \cos^2(\theta) + {}^m c_{33}\, {}^m S_3. \quad (4)$$

To determine the equilibrium angles of magnetization φ_0 and θ_0 let us write down the equations (1) for the density of free energy of YIG W_0 not taking into account the members

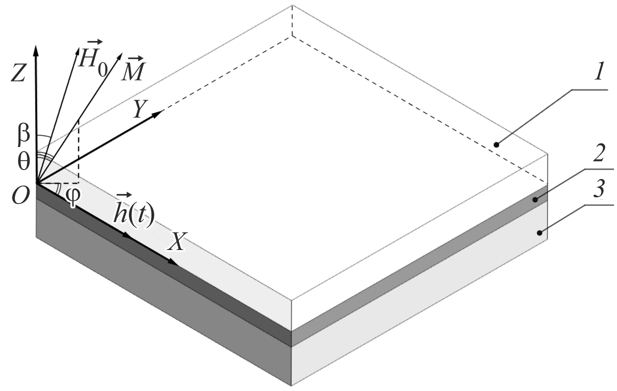

Figure 1. Structure of the studied ME composite: *1* — YIG, *2* — lithium niobate, *3* — silicon

with magnetoelasticity and alternating microwave magnetic field:

$$W_0 = -\mu_0 H_0 M_s \big(\cos(\theta)\cos(\beta) + \sin(\theta)\sin(\varphi)\sin(\beta)\big) + \mu_0 M_s^2 \cos^2(\theta)/2 + {}^m c_{33}\, {}^m S_3^2/2,$$
$$\partial W_0/\partial\varphi = 0,$$
$$\partial W_0/\partial\theta = 0. \quad (5)$$

Let us define from (5) the equilibrium angles $\varphi_0 = 90°$ and $\theta_0 = 74.5°$ at $\beta = 20°$, using the YIG saturation magnetization value $M_s = 11.15$ kA/m [2] and the value of the constant magnetic field $H_0 = 44.9$ kA/m, providing for the condition of MAR existence. Let us further linearize the magnetization motion equation (1) at equilibrium angles of magnetization direction $\varphi_0 = 90°$ and $\theta_0 = 74.5°$, leaving only the members of the first order of smallness. Then we receive the following system of linear heterogeneous equations:

$$i\omega\delta\theta = -\gamma \sin(\beta) H_0 \delta\varphi - \gamma h_1,$$
$$i\omega\delta\varphi = -\gamma/(\mu_0 M_s)\big(-2B_1\, {}^m S_3 \cos(\theta_0)\big) + \big[\mu_0 M_s^2 \sin(\theta_0) + \mu_0 H_0 M_s \sin(\beta)/\sin^2(\theta_0)\big]\delta\theta. \quad (6)$$

Solution to the system of equations (6):

$$\delta\varphi = -\frac{\gamma\big(\gamma\mu_0 M_s^2 \sin^3(\theta_0) h_1 + \gamma\mu_0 H_0 M_s \sin(\beta) h_1 + 2iB_1\omega\cos(\theta_0)\sin^2(\theta_0)\big)}{\mu_0 M_s\big(\gamma^2 H_0^2 \sin^2(\beta) + \gamma^2 H_0 M_s \sin(\beta)\sin^3(\theta_0) - \sin^2(\theta_0)\omega^2\big)},$$

$$\delta\theta = \frac{\gamma\big(2B_1\gamma H_0 \sin(\beta)\cos(\theta_0)\, {}^m S_3 - i\mu_0 M_s \omega h_1 \sin^2(\theta_0)\big)}{\mu_0 M_s\big(\gamma^2 H_0^2 \sin^2(\beta) + \gamma^2 H_0 M_s \sin(\beta)\sin^3(\theta_0) - \sin^2(\theta_0)\omega^2\big)} \quad (7)$$

Let us expand the equation for the longitudinal component of the YIG strain tensor (4) in a row around the equilibrium value of the angle θ_0, limiting to the members of the first order. Let us remove the permanent member, because we are only interested in the values that harmonically depend on the time:

$$ {}^mT_3 = {}^mc_{33}\,{}^mS_3 - 2B_1\cos(\theta_0)\sin(\theta_0)\delta\theta. \quad (8) $$

Let us add (7) in (8) and get

$$ {}^mT_3 = {}^mc_{33\text{eff}}\,{}^mS_3 + T, $$

$$ {}^mc_{33\text{eff}} = {}^mc_{33} - \frac{4\gamma^2B_1^2H_0\sin(\beta)\cos^2(\theta_0)\sin^3(\theta_0)}{\mu_0M_s\left(\gamma^2H_0^2\sin^2(\beta)+\gamma^2H_0M_s\sin(\beta)\times \times\sin^3(\theta_0)-\sin^2(\theta_0)\omega^2\right)}, $$

$$ T = \frac{2i\gamma\omega B_1\cos(\theta_0)\sin^3(\theta_0)}{\gamma^2H_0^2\sin^2(\beta)+\gamma^2H_0M_s\sin(\beta)\sin^3(\theta_0)-\sin^2(\theta_0)\omega^2}. \quad (9) $$

Let us write down the motion equation for the longitudinal strain in YIG:

$$ {}^m\rho\,\frac{\partial^2\,{}^mu_3}{\partial t^2} = \frac{\partial\,{}^mT_3}{\partial z}, \quad (10) $$

where ${}^m\rho$ is YIG density.

Having found the private derivatives in both parts of equation (10), we get

$$ -{}^m\rho\omega^2\,{}^mu_3 = {}^mc_{33\text{eff}}\frac{\partial^2\,{}^mu_3}{\partial z^2}. \quad (11) $$

Having divided both parts of equation (11) in ${}^mc_{33\text{eff}}$ and moved the left part of the obtained equation to the right, we get the following harmonic equation:

$$ \frac{\partial^2\,{}^mu_3}{\partial z^2} + k_1^2\,{}^mu_3 = 0, \quad (12) $$

where $k_1 = \omega\sqrt{{}^m\rho/{}^mc_{33\text{eff}}}$ — wave number for YIG.

The general soluition to equation (12) provides a formula for the longitudinal component of YIG strain vector:

$$ {}^mu_3 = A_1\cos(k_1z) + B_1\sin(k_1z). \quad (13) $$

Let us now consider the motion equation for the longitudinal strain in lithium niobate. The longitudinal component of strain tensor ${}^pS_3$ is determined similarly to equation (3), and the longitudinal component of mechanical stresses is determined with account of the open contour condition ($D_3 = 0$) using formula

$$ {}^pT_3 = {}^pc_{33}^D\,{}^pS_3, $$

$$ {}^pc_{33}^D = \frac{\varepsilon_{33}\varepsilon_0}{{}^ps_{33}\,\varepsilon_{33}\varepsilon_0 - d_{33}^2}, \quad (14) $$

where d_{33} — longitudinal piezoelectric coefficient of lithium niobate, $\varepsilon_0 = 8.85\cdot10^{-12}$ F/m — electric constant, ε_{33} — the necessary component of tensor of dielectric permittivity of lithium niobate, ${}^ps_{33}$ — longitudinal mechanical ductility lithium niobate.

Similarly to the calculations with YIG, we will get the motion equation for the longitudinal strain in lithium niobate:

$$ \frac{\partial^2\,{}^pu_3}{\partial z^2} + k_2^2\,{}^pu_3 = 0, \quad (15) $$

where $k_2 = \omega\sqrt{{}^p\rho/{}^pc_{33}^D}$ — wave number for lithium niobate, ${}^p\rho$ — density of lithium niobate.

From (15) we get the general solution to the harmonic equation for lithium niobate:

$$ {}^pu_3 = A_2\cos(k_2z) + B_2\sin(k_2z). \quad (16) $$

Let us now consider the motion equation for the longitudinal strain in silicon. The longitudinal component of strain tensor ${}^sS_3$ is determined similarly to equation (3), and the longitudinal component of silicon mechanical stresses tensor is determined using formula

$$ {}^sT_3 = {}^sS_3/{}^ss_{33}, \quad (17) $$

where ${}^ss_{33}$ — longitudinal component of silicon mechanical ductility tensor.

Similarly to the previous calculations, we get the general solution to the harmonic equation for silicon:

$$ {}^su_3 = A_3\cos(k_3z) + B_3\sin(k_3z), \quad (18) $$

where $k_3 = \omega\sqrt{{}^s\rho\,{}^ss_{33}}$ — wave number for silicon, ${}^s\rho$ — silicon density.

To determine the unknown constants A_1, A_2, A_3, B_1, B_2, B_3 let us make a system of 6 equations in accordance with the boundary conditions for a free ME composite. Having determined the unknown constants A_2 and B_2 from the system of equations, we will find the electrical voltage in the layer of lithium niobate, having integrated the electric field intensity determined using the formula

$$ E_3 = -h_{33}\,{}^pS_3, $$

$$ h_{33} = \frac{d_{33}}{\left({}^ps_{33}\varepsilon_0\varepsilon_{33} - d_{33}^2\right)}, \quad (19) $$

based on lithium niobate thickness with account of the open contour condition. Having divided the electrical voltage by the thickness of lithium niobate and amplitude of microwave magnetic field, we get the ME voltage coefficient at MAR for the studied ME composite at thickness-longitudinal mode:

$$ \begin{aligned} \alpha = {} & 2i\gamma B_1\cos(\theta_0)\sin^3(\theta_0)h_{33}\left(\cos(\eta_m)-1\right) \\ & \times\left(\left(\cos(\eta_p)-1\right)k_2\,{}^pc_{33}^D\,{}^ss_{33}\cos(\eta_s) - k_3\sin(\eta_p)\sin(\eta_s)\right)\Big/ \\ & \Big(\Big[{}^ss_{33}\,{}^pc_{33}^Dk_2\big(\sin(\eta_p)\cos(\eta_m){}^pc_{33}^Dk_2 + \cos(\eta_p) \\ & \times\sin(\eta_m)k_1\,{}^mc_{33\text{eff}}\big)\cos(\eta_s) + k_3\sin(\eta_s)\big({}^pc_{33}^Dk_2\cos(\eta_m) \\ & \times\cos(\eta_p) - k_1\,{}^mc_{33\text{eff}}\sin(\eta_m)\sin(\eta_p)\big)\Big]\Big[{}^pt\big(\gamma^2H_0^2\sin^2(\beta) \\ & + \gamma^2H_0M_s\sin(\beta)\sin^3(\theta_0) - \sin^2(\theta_0)\omega^2\big)\Big]\Big), \end{aligned} \quad (20) $$

where $\eta_m = k_1 {}^m t$, $\eta_p = k_2 {}^p t$, $\eta_s = k_3 {}^s t$, ${}^m t$ — YIG thickness, ${}^p t$ — thickness of lithium niobate, ${}^s t$ — silicon thickness.

3. Calculation results

Figure 2 shows the theoretical diagram of frequency dependence of ME voltage coefficient diagram, obtained using formula (20) for the studied ME composite of YIG/lithium niobate/ silicon at MAR in case of thickness-longitudinal MAR mode. The calculations adopted Q factor of EMR $Q = 500$, Q factor of FMR $Q_H = 564$.

YIG parameters:

$$ {}^m c_{33} = 76.4\,\text{GPa},\ \ {}^m\rho = 5170\,\text{kg/m}^3, $$

$$ B_1 = 564900\,\text{J/m}^3,\ \ {}^m t = 50\,\mu\text{m},\ \ \gamma = 2.2\cdot 10^5\,\text{m/(A}\cdot\text{s)}, $$

$$ M_s = 11.15\,\text{kA/m},\ \ H_0 = 44.9\,\text{kA/m}. $$

Lithium niobate parameters:

$$ {}^p s_{33} = 4.94\cdot 10^{-12}\,\text{m}^2/\text{N},\ \ {}^p\rho = 4700\,\text{kg/m}^3,\ \ \varepsilon_{33} = 43.6, $$

$$ d_{33} = 16.1\,\text{pm/V},\ \ {}^p t = 600\,\text{nm}. $$

Silicon parameters:

$$ {}^s s_{33} = 7.7\cdot 10^{-12}\,\text{m}^2/\text{N},\ \ {}^p\rho = 2330\,\text{kg/m}^3,\ \ {}^s t = 0.3\,\text{mm}. $$

Material parameters of YIG are taken from [2], of lithium niobate — from [15], silicon — from [16].

The magnetoelectric voltage coefficient is equal to $32\,\text{V/(cm}\cdot\text{Oe)}$ at resonance frequency of 1.7 GHz.

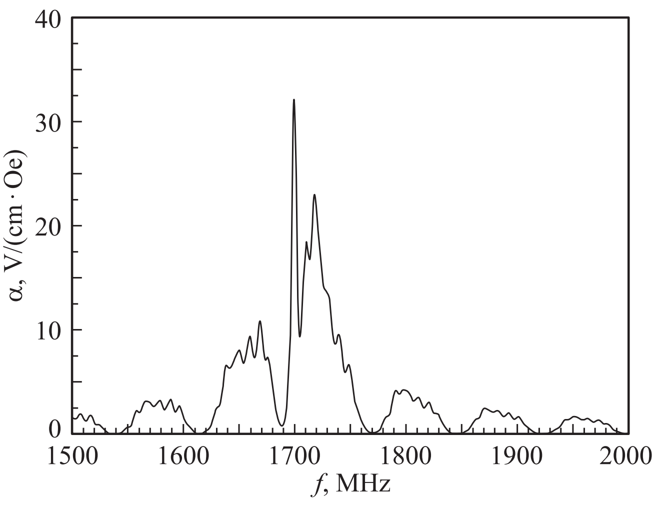

Figure 2. Frequency dependence of ME voltage coefficient of the studied ME composite of YIG/lithium niobate/silicon at thickness-longitudinal MAR mode.

4. Conclusion

As a result of the conducted theoretical study, the following conclusions were made. 1) conducted calculations make it possible to compare the MAR value for different EMR modes and different substrates to select the most effective combinations for the experimental study; 2) comparison with the previous estimates of ME effect in the MAR area showed lower values of ME coefficients, which is due to the accounting for the silicon substrate and selected arrangement of electrodes on the upper and lower plane of the lithium niobate film. It should be noted that such approach is practically more realizable in case of the experimental study; 3) compared to the values of low frequency ME coefficients the obtained estimated value of ME coefficient exceeds them substantially: at the resonance frequency of 1.7 GHz the ME coefficient is equal to $32\,\text{V/(cm}\cdot\text{Oe)}$ for the thickness-longitudinal mode, but is two times lower than the ME coefficient for the thickness-shear mode.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M.I. Bichurin, O.V. Sokolov. Theory of magnetoelectric phenomena in composites, in: G. Srinivasan, S. Priya, N. Sun (Eds.), Magnetoelectric Composites, Chapter 1, Woodhead Publishing, USA. (2025). pp. 1-47.

[2] M.I. Bichurin, V.M. Petrov, R.V. Petrov, A.S. Tatarenko. Magnetoelectric composites. Jenny Stanford Publ. (2019). 296 p.

[3] J. van Suchtelen. Philips Res. Rep. **27**, *1*, 28 (1972).

[4] M.I. Bichurin, D.A. Filippov, V.M. Petrov, V.M. Laletsin, N. Paddubnaya, G. Srinivasan. Phys. Rev. B **68**, *13*, 132408 (2003).

[5] C.-W. Nan, M.I. Bichurin, S. Dong, D. Viehland, G. Srinivasan. J. Appl. Phys. **103**, *3*, 31101 (2008).

[6] M.I. Bichurin, V. Petrov, O.V. Ryabkov, S.V. Averkin, G. Srinivasan. Phys. Rev. B **72**, *6*, 060408 (2005).

[7] O.V. Ryabkov, V.M. Petrov, M.I. Bichurin, S.V. Averkin, G. Srinivasan. Vestn. Novgorod. gos. un-ta **36**, 30 (2006). (in Russian).

[8] O.V. Ryabkov, V.M. Petrov, M.I. Bichurin, G. Srinivasan. Pisma v ZhTF **32**, *23*, 48 (2006). (in Russian).

[9] M.I. Bichurin, V.M. Petrov, S.V. Averkin, A.V. Filippov, E. Liverts, S. Mandal, G. Srinivasan. J. Phys. D: Appl. Phys. **42**, 215001 (2009).

[10] V.M. Petrov, A.F. Saplev, G. Srinivasan. Ferroelectrics **569**, 196 (2020).

[11] M.I. Bichurin, O.V. Sokolov, S.V. Ivanov, I.Yu. Markov. Chelyabinskiy fiziko-matematicheskiy zhurnal **10**, *2*, 207 (2025). (in Russian).
[12] M.I. Bichurin, O.V. Sokolov, V.N. Lobekin. IEEE Magn. Lett. **13**, *1*, 1 (2021).
[13] I.Yu. Markov, O.V. Sokolov, M.I. Bichurin. IBCM 2025 Abstract Book. BFU Kaliningrad. (2025). P. 95.
[14] A.G. Gurevich and G.A. Melkov, Magnitnye kolebaniya i volny. Fizmatlit, M. (1994). 464 s. (in Russian).
[15] G. Xu, S. Xiao, Y. Li, Y. Long. Journal of Magnetism and Magnetic Materials, **616**, 172833 (2025).
[16] A.A. Blistanov, V.S. Bondarenko, N.V. Perelomova, F.N. Strizhevskaya, V.V. Chkalova, M.P. Shaskolskaya. Akusticheskie kristally. Nauka, M. (1982). 632 s. (in Russian).

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