Modelling of microwave magnetoelectric effect in a laminate of ferrite and piezoelectric bimorphs

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Abstract. The article discusses the magnetoelectric (ME) effect in a layered structure of ferrite and two piezoelectric bimorphs. Proposed theoretical model predicts a giant microwave ME coupling at the coincidence of high-order harmonics of electromechanical resonance and ferromagnetic resonance for the ferrite. In such structures, ME interaction is known to be a result of mechanical strains. Using two piezoelectric bimorphs results in the excitation of high-order harmonic modes that are suppressed in ferrite-piezoelectric bilayers. ME coefficient of 300 V/(cm Oe) at 5 GHz is predicted for the fifth resonance mode in the laminate of yttrium-iron garnet and two langatate bimorphs. The phenomenon can be used for the realization of ME interaction based microwave devices.

1. Introduction
Magnetoelastic (ME) response of a magnetostrictive/piezoelectric structure can be observed provided that the magnetic and electric parameters are coupled via elastic deformations. Applying an external magnetic field gives rise to the elastic deformations of the magnetic component due to magnetostrictive coupling. The strain transfer to electric component leads to electric polarization due to piezoelectric coupling [1–7].

From a practical standpoint, electromechanical resonance (EMR) for the laminate and ferromagnetic resonance (FMR) for the magnetic component are particularly attractive because they enable one to observe an enhanced ME effect in the EMR region [5–8]. Overlapping of EMR and FMR results in a further increase in ME coupling strength [9]. Magnetoelastic interaction in single-crystal ferrites makes it important to use ferrites as magnetic components for composite multiferroics. According to the theoretical modeling, the strong interaction between phonon spin waves is predicted for the magnetoacoustic resonance (MAR) region. For nickel ferrite - lead zirconate titanate (PZT) and yttrium iron garnet (YIG) - PZT bilayers, the giant value of ME voltage coefficient (80 - 480 V/(cm Oe)) is obtained. Using a laminate composite based on ferrite and piezoelectric bimorph gives rise to the excitation of high-order harmonic modes that are suppressed in ferrite-piezoelectric bilayers. For the laminate of YIG and langatate bimorph, ME coefficients of 470 V/(cm Oe) at 7 GHz is obtained for the third resonance mode [10].

In this work we analyze ME coupling in laminate composites of magnetostrictive ferrite and some piezoelectric bimorphs. Implementing the piezoelectric component as a number of in-series piezoelectric bimorphs with appropriate layer thickness enables one to obtain the desired frequency by using the overlapping of magnetic resonance and higher modes of EMR. We assume the ferrite component to be magnetized to saturation. On this condition, the low acoustic and magnetic losses can
be ensured. A piezoelectric bimorph is used to convert the mechanical energy into electrical energy. A transducer based on a piezoelectric bimorph enables one to significantly increase the ME coefficient at certain types of oscillations. At present, PZT ceramics has wide practical application due to the large values of coefficients. However, piezoelectric ceramics have obvious drawbacks in terms of low Curie temperature, a strong aging effect, and a significant electric field and temperature dependence of piezoelectric coefficients. Piezoelectric single crystals can be used as an alternative to piezoceramics. In present work, the Y-cut single-crystal langatate serves as a piezoelectric phase. This piezoelectric single crystal is known to be the environmentally friendly lead-free piezoelectric material. Piezoelectric bimorph consists of two langatate layers with opposite directions of Y-axis. Langatate has weak piezoelectric coupling coefficient, however the piezoelectric coefficient to dielectric constant ratio exceeds this ratio for PZT. The direct ME effect is known to be proportional to the piezoelectric coefficient to dielectric constant ratio and the use of langatate enables obtaining a strong ME effect. It should be emphasized that the Y-cut langatate is sensitive only to shear stress component. We assume the X-axis of the langatate to be parallel to [100] axis of the ferrite. For our layered structure, the bias magnetic field is perpendicular to the sample plane and ac magnetic field is linearly polarized in the sample plane.

2. Magnetoelectric effect at magneto-acoustic resonance

Since the ME effect is determined by interaction of magnetostrictive and piezoelectric phases through the elastic deformations, we should expect an increased ME coupling in the EMR region. At this point, ME effect in composites has been studied in detail for the longitudinal, flexural, and shear mode regions [6]. In the FMR region, a shift and broadening of magnetic resonance lines can be obtained in applied dc electric field. Overlapping the electromechanical and magnetic resonances results in a further enhancement of the ME coupling [9].

As an example, we consider the laminate composite of ferrite and two single-crystal piezoelectric bimorphs. To model the ME effect at magneto-acoustic resonance and find the ME voltage coefficient, the equations of motion of magnetization, the equations of medium motion for the ferrite and four piezoelectric layers are solved as the starting point taking into account the material relations and elastic equations [9].

Equation for thickness shear vibrations has the following form for the first piezoelectric layer:

\[
\rho_p \frac{\partial^2 u_t}{\partial t^2} = \frac{\partial^2 T_z}{\partial z^2}
\]

with, \( \rho_p, T_z \), and \( u_t \) being the density, stress component, and displacement of the piezoelectric layer.

The thickness shear vibrations of the remaining piezoelectric layers are described by a similar equation. The elasticity equation and material relation for the piezoelectric phase may be written as

\[
\begin{align*}
\rho_s \frac{\partial^2 \varepsilon_p}{\partial t^2} & = \rho_s \frac{\partial^2 \varepsilon_p}{\partial z^2} = \frac{\partial^2 T_z}{\partial z^2} \\
\rho_s \frac{\partial^2 D_p}{\partial t^2} & = \rho_s \frac{\partial^2 D_p}{\partial z^2} = \frac{\partial^2 E_p}{\partial z^2}
\end{align*}
\]

with \( \rho_{s44} \) and \( \rho_d \) being the elastic compliance and piezoelectric coefficient for the piezoelectric layer.

The equation of medium motion for the ferrite phase has the following form:

\[
\rho_m \frac{\partial^2 (\varepsilon_{m})}{\partial t^2} = \frac{\partial^2 (\varepsilon_{m})}{\partial x^2} + \frac{\partial^2 (\varepsilon_{m})}{\partial y^2} + \frac{\partial^2 (\varepsilon_{m})}{\partial z^2} + \varepsilon_{m} \gamma \left[ M, H_{at} \right],
\]

We assume the free energy density of the ferrite phase \( \varepsilon_{m} \) in (3) to include the magnetostatic energy, magnetic anisotropy energy and magnetoelastic energy.

The equation of magnetization motion for the ferrite layer can be written as follows:

\[
\frac{\partial M}{\partial t} = - \gamma \left[ M, H_{at} \right].
\]
The effective magnetic field in (4) is the derivative of the free energy density with respect to magnetization: $H_{\text{eff}} = - \frac{\partial (\mu W)}{\partial M}$.

For the simultaneous solution of above equations, the standard boundary conditions are used. According to these conditions, we take into consideration continuity of strain and stress components at the interfaces. The final expression for the ME voltage coefficient is not given here due to its inconvenience.

3. Application: magnetoelectric effect in layered structure of yttrium iron garnet and two langatate bimorphs at magneto-acoustic resonance

As an example, the presented theoretical model is applied to obtain the numerical estimates for the laminate composite of YIG layer and two Y-cut langatate bimorphs. The YIG layer thickness equals 0.4 μm and the each langatate bimorph thickness equals 0.52 μm (2 layers of 0.26 μm each). Figure 1 shows the frequency dependence of the ME voltage coefficient for the fifth resonant frequency with a magnetizing field $H_0 = 3520$ Oe. For comparison, the similar graphs are shown for the YIG-langatate bilayer and for the laminate of YIG and two langatate bimorphs.

![Figure 1](image)

**Figure 1.** Frequency dependence of ME voltage coefficient for the laminate of YIG and two langatate bimorphs (1), for the YIG-langatate bilayer (2), and for the laminate of YIG and langatate bimorph (3) for bias field $H_0 = 3520$ Oe.

The graphs in figure 1 show that ME effect is suppressed at the resonance frequency of 4.96 GHz for the YIG-langatate bilayer and for the laminate of YIG and langatate bimorph, while a sharp increase in the ME voltage coefficient is observed for the laminate composite formed by YIG layer and two Y-cut langatate bimorphs. The observed effect is related to the vibrational mode structure. Figure 2 shows the thickness dependence of the electric field induced in the piezoelectric layers.
Figure 2. Distribution of induced electric field over the thickness of piezoelectric phase for the laminate of YIG and Y-cut langatate bimorph (1) and YIG - langatate bilayer (2) for $H_0 = 3520$ Oe and ac magnetic field of 1 Oe.

Using the graphs in figure 2 one can conclude that for the YIG-langatate bilayer, the average induced voltage vanish for the fifth resonant frequency. This is associated with the fact that the piezoelectric component thickness equals two wavelengths for a specified resonant frequency. Induced electric field is governed by (2) and the average electric field over the oscillation period is zero. Similarly, the average electric field induced across the piezoelectric layers vanish for the laminate of YIG and Y-cut langatate bimorph since average induced voltage continues to be zero.

The possibility of obtaining the giant ME voltage emerges for the laminate composite of YIG and two langatate bimorphs. Figure 3 shows the thickness dependence of the electric field induced in the piezoelectric layers for this case.
Figure 3. Distribution of induced electric field over the thickness of piezoelectric phase for the laminate of YIG and two langatate bimorph (1) and YIG - langatate bilayer (2) for $H_0 = 3520$ Oe and an ac magnetic field of 1 Oe.

It can be seen from the graphs in figure 3 that the average electric field induced across the piezoelectric phase is nonvanishing for the laminate of YIG and two langatate bimorph since the direction of Y-axis of langatate layers follows the stress direction. Thus induced electric field maintains the sign over the thickness of piezoelectric component.

The obtained effect can be used to study the enhanced ME effect in the region of overlapping the magnetic resonance and higher modes of EMR. It should be noted that implementing the piezoelectric component as a number of in-series piezoelectric bimorphs with appropriate layer thicknesses enables one to use a higher mode with desired frequency.

From the data in figure 1, it follows that, a significant increase in the ME voltage coefficient is observed at the fifth resonant frequency for the laminate of YIG and two Y-cut langatate bimorphs compared to the YIG-langatate bilayer with the same total thickness of langatate.

4. Conclusion

Proposed theoretical model predicts a giant microwave ME coupling at the coincidence of high-order harmonics of electromechanical resonance for the electrical subsystem and ferromagnetic resonance for the ferrite. Implementing the piezoelectric component as two piezoelectric bimorphs results in the excitation of high-order harmonic modes that are suppressed in ferrite-piezoelectric bilayers. ME coefficient of 300 V/(cm-Oe) at 5 GHz is predicted for the fifth resonance mode in the laminate of YIH and two langatate bimorphs. Implementing the piezoelectric component as a number of in-series piezoelectric bimorphs enables one to use a higher mode with desired frequency. The phenomenon can of interest for the investigation of the energy exchange between spin waves and phonons and for the realization of ME interaction based microwave devices.
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