Theory of magnetoelectric effects at microwave frequencies in a piezoelectric/magnetostrictive multilayer composite

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A phenomenological theory is proposed to treat the magnetoelectric (ME) coupling at frequencies corresponding to ferromagnetic resonance in a multilayer composite consisting of alternate layers of piezoelectric and magnetostrictive phases. We discuss two models: (i) a simple two-layer (bimorph) structure and (ii) a generalized approach in which the multilayer structure is considered to be a homogeneous medium. Expressions for the stress induced shift δH in the ferromagnetic resonance field due to an applied electric field E have been obtained for both cases. For a bimorph, δH is directly proportional to the product of the applied electric field and the ME coupling constant. For a nickel ferrite–lead zirconate titanate (PZT) two layer structure, the theory predicts a factor of 5 stronger effect than in yttrium iron garnet-PZT. When the composite is considered to be a homogeneous medium, the corresponding shift δH is given by $2\,M_0\,(B_{33}-B_{31})\,E$, where M_0 is the composite magnetization and B's are the ME coefficients. For this model, a method for the calculation of magnetoelectric coefficients from experimental data is presented.

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I. INTRODUCTION

The magnetoelectric (ME) effect was first predicted by Landau and Lifshitz in 1957. The effect is defined as the dielectric polarization of a material in an applied magnetic field or an induced magnetization in an external electric field.[1] The simultaneous presence of long-range ordering of both magnetic moments and electric dipoles is essential for the realization of ME effects. In a single-phase compound, the magnetoelectric effect is rather weak even at low temperatures.[2–5] A similar ME effect could be accomplished in composites which are of interest for the engineering of materials either with desired properties or new characteristics that are absent in single-phase materials. van Suchtelan proposed ''product property'' two-phase *bulk* composites for the synthesis of high performance materials. For example, a piezomagnetic phase mechanically coupled to a piezoelectric phase will deform in an external magnetic field and will lead to an induced electric field.[6] Such ME composites could also be made with magnetostrictive and piezoelectric phases. van den Boomgaard synthesized composites of magnetostrictive $CoFe_2O_4$ and piezoelectric $BaTiO_3$ by two methods: sintering and unidirectional solidification of eutectic melts.[7–10] Both composites yielded ME coefficients that were a factor 40–60 smaller than calculated values.

Harshe, Dougherty, and Newnham, in their pioneering work on ME composites (i) proposed a theoretical model for *multilayer* hetrostructures with alternating layers of magnetostrictive and piezoelectric phases and (ii) fabricated such structures.[11] A multilayer structure is expected to be far superior to bulk composites for the following reasons. (i) An essential condition for maximizing ME effects is a large dielectric constant (and piezoelectricity). In bulk composites the leakage currents due to low-resistivity ferrite inclusions reduce the overall dielectric constant. (ii) The piezoelectric layer can easily be poled electrically to further enhance the piezoelectricity. The multilayer structures did show an improvement over bulk sintered composites, but the ME coefficient was much smaller than theoretical values.

Most of the published works so far on ME composites have focused on the theoretical modeling and experimental investigation of the effect at low frequencies (10 Hz–10 kHz).[7–13] We proposed, in our earlier work,[14] that layered ferrite-ferroelectric structures are ideal for studies directed at fundamental understanding of ME effects at microwave frequencies through the measurement of electric field assisted shift of ferromagnetic resonance lines.[15–18] The layered composites are also of interest for a variety of device applications including electrically controlled microwave phase shifters or ferromagnetic resonance devices, magnetically controlled electro-optic or piezoelectric devices, broad band magnetic field sensors, smart sensors, actuators, and magnetoelectric memory devices.

In this paper, we develop theoretical models for multilayer ME composites in the microwave range. The phenomenological theory to be presented here is based on the fact that magnetic resonance frequency is strain dependent[19] and that the magnitude of this strain dependence is determined by the piezoelectric and magnetoelastic constants of the piezoelectric and magnetostrictive phases, respectively.

II. TWO-LAYER STRUCTURE (BIMORPH)

For the sake of clarity, we shall first consider a simple model, i.e., a two-layer (bimorph) structure consisting of a spinel ferrite with cubic ($m3m$) symmetry and a poled lead zirconate titanate (PZT) with a ∞m symmetry about the poling axis. The influence of the electric field upon the piezoelectric phase may be described as follows:

$$ {}^{p}T_{ij} = {}^{p}c_{ijkl}{}^{p}S_{kl} - e_{kij}E_k, \tag{1} $$

where

$$ {}^{p}c = \begin{pmatrix} {}^{p}c_{11} & {}^{p}c_{12} & {}^{p}c_{13} & 0 & 0 & 0 \\ {}^{p}c_{12} & {}^{p}c_{11} & {}^{p}c_{13} & 0 & 0 & 0 \\ {}^{p}c_{13} & {}^{p}c_{13} & {}^{p}c_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & {}^{p}c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & {}^{p}c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2}({}^{p}c_{11} - {}^{p}c_{12}) \end{pmatrix}, \tag{2} $$

$$ e = \begin{pmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{pmatrix}. \tag{3} $$

Here E_k is the electrical-field intensity; ${}^{p}T_{ij}$, ${}^{p}S_{kl}$, e_{kij}, and ${}^{p}c_{ijkl}$ are the stress, strain, piezoelectric coefficient, and stiffness tensors of the piezoelectric phase, respectively.

Substitution of Eqs. (2) and (3) into Eq. (1) and assuming that the electric field is directed along the poling axis, i.e., $E_3 = E$, $E_1 = E_2 = 0$, we get

$$ \begin{aligned} {}^{p}T_{33} &= -e_{33}E + {}^{p}c_{13}({}^{p}S_{11} + {}^{p}S_{22}) + {}^{p}c_{33}{}^{p}S_{33}, \\ {}^{p}T_{11} &= -e_{31}E + {}^{p}c_{11}{}^{p}S_{11} + {}^{p}c_{12}{}^{p}S_{22} + {}^{p}c_{13}{}^{p}S_{33} = 0, \\ {}^{p}T_{22} &= -e_{31}E + {}^{p}c_{12}{}^{p}S_{11} + {}^{p}c_{11}{}^{p}S_{22} + {}^{p}c_{13}{}^{p}S_{33} = 0. \end{aligned} \tag{4} $$

We now assume that the poling axis of the piezoelectric phase coincides with the [111] axis of the magnetostrictive phase. In that case, the elastic constant tensor for the magnetostrictive phase has the form

$$ {}^{m}c = \begin{pmatrix} \frac{{}^{m}c_{11} + {}^{m}c_{12}}{2} + {}^{m}c_{44} & \frac{{}^{m}c_{11} + 5{}^{m}c_{12} - 2{}^{m}c_{44}}{6} & \frac{{}^{m}c_{11} + 2{}^{m}c_{12} - 2{}^{m}c_{44}}{3} & \frac{{}^{m}c_{11} - {}^{m}c_{12} - 2{}^{m}c_{44}}{3\sqrt{2}} & 0 & 0 \\ \frac{{}^{m}c_{11} + 5{}^{m}c_{12} - 2{}^{m}c_{44}}{6} & \frac{{}^{m}c_{11} + {}^{m}c_{12}}{2} + {}^{m}c_{44} & \frac{{}^{m}c_{11} + 2{}^{m}c_{12} - 2{}^{m}c_{44}}{3} & -\frac{{}^{m}c_{11} - {}^{m}c_{12} - 2{}^{m}c_{44}}{3\sqrt{2}} & 0 & 0 \\ \frac{{}^{m}c_{11} + 2{}^{m}c_{12} - 2{}^{m}c_{44}}{3} & \frac{{}^{m}c_{11} + 2{}^{m}c_{12} - 2{}^{m}c_{44}}{3} & \frac{{}^{m}c_{11} + 2{}^{m}c_{12} + 4{}^{m}c_{44}}{3} & 0 & 0 & 0 \\ \frac{{}^{m}c_{11} + 2{}^{m}c_{12} - 2{}^{m}c_{44}}{3} & -\frac{{}^{m}c_{11} - {}^{m}c_{12} - 2{}^{m}c_{44}}{3\sqrt{2}} & 0 & \frac{{}^{m}c_{11} - {}^{m}c_{12} + {}^{m}c_{44}}{3} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{{}^{m}c_{11} - {}^{m}c_{12} + {}^{m}c_{44}}{3} & \frac{{}^{m}c_{11} - {}^{m}c_{12} - 2{}^{m}c_{44}}{3\sqrt{2}} \\ 0 & 0 & 0 & 0 & \frac{{}^{m}c_{11} - {}^{m}c_{12} - 2{}^{m}c_{44}}{3\sqrt{2}} & \frac{{}^{m}c_{11} - {}^{m}c_{12} + 4{}^{m}c_{44}}{6} \end{pmatrix}. \tag{5} $$

For the magnetostrictive phase, taking into account Eq. (5), we get

$$ \begin{aligned} {}^{m}T_{11} &= \left(\frac{{}^{m}c_{11} + {}^{m}c_{12}}{2} + {}^{m}c_{44}\right){}^{m}S_{11} + \frac{{}^{m}c_{11} + 5{}^{m}c_{12} - 2{}^{m}c_{44}}{6}\,{}^{m}S_{22} + \frac{{}^{m}c_{11} + 2{}^{m}c_{12} - 2{}^{m}c_{44}}{3}\,{}^{m}S_{33} + \frac{{}^{m}c_{11} - {}^{m}c_{12} - 2{}^{m}c_{44}}{3\sqrt{2}}\,{}^{m}S_{23}, \\ {}^{m}T_{22} &= \frac{{}^{m}c_{11} + 5{}^{m}c_{12} - 2{}^{m}c_{44}}{6}\,{}^{m}S_{11} + \left(\frac{{}^{m}c_{11} + {}^{m}c_{12}}{2} + {}^{m}c_{44}\right){}^{m}S_{22} + \frac{{}^{m}c_{11} + 2{}^{m}c_{12} + 4{}^{m}c_{44}}{3}\,{}^{m}S_{33}, \\ {}^{m}T_{33} &= \frac{{}^{m}c_{11} + 2{}^{m}c_{12} - 2{}^{m}c_{44}}{3}\,{}^{m}S_{11} + \frac{{}^{m}c_{11} + 2{}^{m}c_{12} - 2{}^{m}c_{44}}{3}\,{}^{m}S_{22} + \frac{{}^{m}c_{11} + 2{}^{m}c_{12} - 2{}^{m}c_{44}}{3}\,{}^{m}S_{33} - \frac{{}^{m}c_{11} - {}^{m}c_{12} - 2{}^{m}c_{44}}{3\sqrt{2}}\,{}^{m}S_{23}, \\ {}^{m}T_{23} &= \frac{{}^{m}c_{11} + 2{}^{m}c_{12} - 2{}^{m}c_{44}}{3}\,{}^{m}S_{11} - \frac{{}^{m}c_{11} - {}^{m}c_{12} - 2{}^{m}c_{44}}{3\sqrt{2}}\,{}^{m}S_{22} + \frac{{}^{m}c_{11} - {}^{m}c_{12} + {}^{m}c_{44}}{3}\,{}^{m}S_{23}. \end{aligned} \tag{6} $$

Here ${}^{m}T_{ij}$ and ${}^{m}S_{kl}$, are the stress and strain tensors of the magnetostrictive phase, respectively.

To calculate the resonant ME effect for the bimorph, the approach taken is as follows: (i) Determine the strain ${}^{m}S_{33}$ as a function of the stress ${}^{m}T_{33}$; (ii) Determine the stress ${}^{p}T_{33}$ as a function of the strain ${}^{p}S_{33}$; (iii) Determine the stress ${}^{m}T_{33}$, using boundary conditions for the interface; (iv) Determine the resonance line shift, using well-known relations for the stress dependence of the resonance magnetic field. Therefore the problem reduces to the solution of the elastostatic equations under specified boundary conditions.

Next, following Harshe *et al.*,[11] we consider the structure consisting of mechanically clamped magnetostrictive-piezoelectric discs without interface friction (case II in Ref. 11):

$$ {}^{p}T_{33} = {}^{m}T_{33}, \quad {}^{p}S_{33} = -{}^{m}\nu/{}^{p}\nu \cdot {}^{m}S_{33}, \tag{7} $$

where ${}^{m}\nu$ and ${}^{p}\nu$ are the volume fraction of magnetostrictive phase and piezoelectric phase, respectively. From Eqs. (4), (6), and (7), we obtain

$$ {}^{m}T_{33} = \frac{E_3\left(\dfrac{2\,{}^{p}c_{13}e_{31}}{{}^{p}c_{11}+{}^{p}c_{12}} - e_{33}\right)}{1+\dfrac{{}^{m}\nu}{{}^{p}\nu}\left(\dfrac{1}{3\,{}^{m}c_{44}}+\dfrac{{}^{m}c_{44}}{3({}^{m}c_{11}+2\,{}^{m}c_{12})}\right)\left({}^{p}c_{33}-2\dfrac{{}^{p}c_{13}^{2}}{({}^{p}c_{11}+{}^{p}c_{12})}\right)}. \tag{8} $$

It is well known that the applied stress causes the shift of the resonance magnetic field.[19] We will confine ourselves to the case where both magnetic and electric fields are along the poling axis of the piezoelectric layer in a [111] direction of the magnetostrictive layer; then the result becomes simply

$$ \delta H_E = \frac{3\lambda_{111}\,{}^{m}T_{33}}{M_s} = AE_3, \tag{9} $$

where A is a magnetoelectric constant and M_s is a saturation magnetization of the magnetostrictive layer.

From Eqs. (8) and (9) it is possible to estimate the shift in the resonance field for a bilayer of a magnetostrictive-piezoelectric composite. Theoretical values of the magnetoelectric constant $A=\delta H_E/E_3$ were determined for two composites of importance, nickel ferrite-PZT and yttrium iron garnet (YIG)-PZT. For the computations, the material parameters assumed for the two phases are as follows:

PZT:

$$ {}^{p}c_{11} = 12.6\times 10^{10}\ \mathrm{N/m^2};\ {}^{p}c_{12} = 7.95\times 10^{10}\ \mathrm{N/m^2}; $$

$$ {}^{p}c_{13} = 8.4\times 10^{10}\ \mathrm{N/m^2};\ {}^{p}c_{33} = 11.7\times 10^{10}\ \mathrm{N/m^2}; $$

$$ e_{31} = -6.5\ \mathrm{C/m^2};\ e_{33} = 23.3\ \mathrm{C/m^2}. $$

$NiFe_2O_4$:

$$ {}^{m}c_{11} = 21.99\times 10^{10}\ \mathrm{N/m^2};\ {}^{m}c_{12} = 10.94\times 10^{10}\ \mathrm{N/m^2}; $$

$$ {}^{m}c_{44} = 8.12\times 10^{10}\ \mathrm{N/m^2};\ \lambda_{111} = -21.6\times 10^{-6}; $$

$$ 4\pi M_s = 3200\ \mathrm{G}. $$

YIG

$$ {}^{m}c_{11} = 26.9\times 10^{10}\ \mathrm{N/m^2};\ {}^{m}c_{12} = 10.77\times 10^{10}\ \mathrm{N/m^2}; $$

$$ {}^{m}c_{44} = 7.64\times 10^{10}\ \mathrm{N/m^2}; $$

$$ \lambda_{111} = -2.8\times 10^{-6};\ 4\pi M_s = 1750\ \mathrm{G}. $$

Figure 1 shows the estimated ME constant A as a function of the ratio of the volume of the two phases in the bilayer. The composite with nickel ferrite is predicted to show a stronger microwave ME effect than YIG because of a relatively high magnetostriction for the ferrite. Another remarkable feature in Fig. 1 is the fact that the numerical value of the field shift increases from zero with increasing volume fraction of the piezoelectric phase. But we need to realize that the magnetic resonance line becomes weak if the concentration of the magnetostrictive phase is too low.

At low frequencies, however, the largest ME effect is observed at approximately 50:50 volume percent composition.[11,13] For ${}^{m}\nu/{}^{p}\nu=1$, the resonance line shift resulting from the applied electric field is given by

$$ \delta H = A\cdot E,\ \text{with } A\approx 2\ \mathrm{Oe\,cm/kV}\ \text{for } NiFe_2O_4\ \text{PZT}, \tag{9a} $$

$$ \delta H = A\cdot E,\ \text{with } A\approx 0.45\ \mathrm{Oe\,cm/kV}\ \text{for YIG PZT}, \tag{9b} $$

where δH is in Oe and E in kV/cm. The estimated resonance line shift for YIG PZT is in good agreement with our previous experimental results.[14] The line shift 0.45 Oe cm/kV is to be compared with the measured value of 0.2–0.56 Oe cm/kV depending on the properties of the piezoelectric phase. Thus

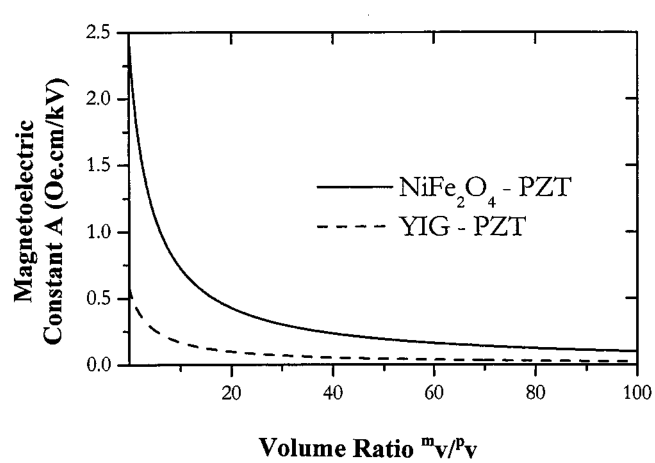

FIG. 1. The dependence of the magnetoelectric constant A as a function of the ratio of the volumes of magnetostrictive and piezoelectric phases ${}^{m}\nu/{}^{p}\nu$. The estimates are for bilayers of nickel ferrite-PZT and yttrium iron garnet (YIG)-PZT.

we infer from the treatment that the volume fraction of the piezoelectric phase must be sufficiently high and that it is necessary to use a piezoelectric component with a large piezoelectric coefficient, a magnetostrictive component with small saturation magnetization, and high magnetostriction.

III. GENERAL THEORY: MACROSCOPIC HOMOGENEOUS MODEL

Let us assume that the composite as a whole can, from a point of view of the ME properties, be considered macroscopically as a homogeneous material, i.e., the magnetoelectric composites can be considered as a real "material" with the ME effect which is not present in the constituent phases. In this case the influence of an external constant electric field **E** upon the magnetic resonance spectrum can be generally described by means of an additional term in the thermodynamic potential:[20]

$$W=\int_V (W_0+\Delta W_{\mathrm{ME}})d^3\mathbf{x}, \tag{10}$$

where W_0 is the thermodynamic potential density at $\mathbf{E}=0$, and

$$\Delta W_{\mathrm{ME}}=B_{ijk}E_iM_jM_k, \tag{11}$$

where B is ME coefficients. ΔW_{ME} can be found by means of a similar approach as in Refs. 11 and 20, taking into account elastic, magnetoelastic, magnetostrictive, piezoelectric, and electrostrictive contributions under certain specified boundary conditions. As a practical example, we consider specifically the case described above, that is a cubic magnetostrictive phase with magnetization in the (110) plane and making the angle θ with the [001] cubic axis. Considerable simplification of the theory results further if the direction of magnetization coincides with a uniaxial stress ${}^mT_{33}$ (see above). Then the additional energy term can be represented by

$$\begin{aligned}\Delta W_{\mathrm{ME}}=&\frac{3}{8M^2}[\lambda_{111}-\lambda_{100}+(\lambda_{100}-\lambda_{111})\cos 2\theta]M_1^2\,{}^mT_{33}\\&+\frac{9}{32M^2}[\lambda_{111}-\lambda_{100}+(\lambda_{100}-\lambda_{111})\cos 4\theta]M_2^2\,{}^mT_{33}\\&+\frac{3}{8M^2}\left((\lambda_{100}-\lambda_{111})\sin 2\theta+\frac{3}{2}(\lambda_{100}\right.\\&\left.-\lambda_{111})\sin 4\theta\right)M_2M_3\,{}^mT_{33}\\&+\frac{3}{8M^2}\left[\left(\frac{-9\lambda_{111}-7\lambda_{100}}{4}\right)+(\lambda_{111}-\lambda_{100})\cos 2\theta\right.\\&\left.+\frac{3}{4}(\lambda_{111}-\lambda_{100})\cos 4\theta\right]M_3^2\,{}^mT_{33}.\end{aligned} \tag{12}$$

For the special case considered above when $\mathbf{M}_0\|[111]$, we get

$$\begin{aligned}\Delta W_{\mathrm{ME}}=&\left(\frac{\lambda_{111}-\lambda_{100}}{2}\right)M_1^2\,{}^mT_{33}+\left(\frac{\lambda_{111}-\lambda_{100}}{2}\right)M_2^2\,{}^mT_{33}\\&+\left(\frac{-\lambda_{111}-\lambda_{100}}{2}\right)M_3^2\,{}^mT_{33}.\end{aligned} \tag{13}$$

The magnetic resonance condition has the well-known form[21]

$$\omega=\gamma\left\{\left[H_3+\sum (N_{11}^i-N_{33}^i)M_0\right]\left[H_3+\sum (N_{22}^i-N_{33}^i)M_0^i\right]-\left(\sum_i N_{12}^iM_0\right)^2\right\}^{1/2}, \tag{14}$$

where ω is the resonance frequency, γ is the gyromagnetic ratio, H_3 is the projection of an external magnetic field towards the equilibrium orientation of the magnetization M_0; $N_{kl}^{i=m}$ are the geometrical demagnetization factors; $N_{kl}^{i=a}$ are the effective demagnetization factors due to the magnetic crystalline anisotropy; $N_{kl}^{i=E}$ are the effective demagnetization factors due to the ME interaction. Using Eq. (14) it is easily shown that the resonance line shift under the influence of the electric field to the first order in N_{kl}^E has the form

$$\delta H_E=-\frac{M_0}{Q_1}[Q_2(N_{11}^E-N_{33}^E)+Q_3(N_{22}^E-N_{33}^E)-Q_4N_{12}^E], \tag{15}$$

where

$$Q_1=2H_3+M_0\sum_{i\neq E}[(N_{11}^E-N_{33}^E)+(N_{22}^E-N_{33}^E)];$$

$$Q_2=\left[H_3+M_0\sum_{i\neq E}(N_{22}^E-N_{33}^E)\right];$$

$$Q_3=\left[H_3+M_0\sum_{i\neq E}(N_{11}^E-N_{33}^E)\right];\quad Q_4=2M_0\sum_{i\neq E}N_{12}^i.$$

Equation (15) enables us to determine the ME constants of the composite and consequently to interpret the data on the resonant ME effect.

Uniaxial structure ($\infty m+m3m\rightarrow 3m$)

Attention will now be restricted to the uniaxial structure with $3m$ symmetry point group. In this case Eq. (11) for the thermodynamic potential density can be written as follows:

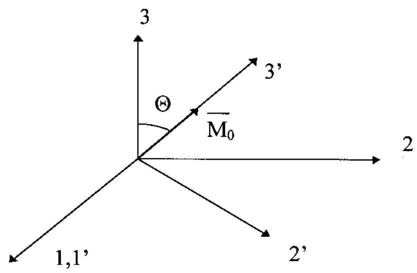

FIG. 2. Coordinate system for a uniaxial multilayer structure.

$$\Delta W_{\mathrm{ME}}=E_1[B_{11}(M_1^2-M_2^2)-2B_{22}M_1M_2+2B_{14}M_2M_3+2B_{15}M_1M_3]+E_1[B_{22}(M_2^2-M_1^2)-2B_{11}M_1M_2+2B_{15}M_2M_3-2B_{14}M_1M_3]+E_3(B_{33}-B_{31})M_3^2. \tag{16}$$

The usual two-index notation is introduced:

$$B_{ijk}=B_{i\lambda}$$

with $\lambda=1,2,3,4,5,6$ corresponds to $j=1$ and $k=1$, $j=2$ and $k=2$, $j=3$ and $k=3$, $j=2$ and $k=3$, $j=1$ and $k=3$, $j=1$ and $k=2$, respectively, and

$$B_{ijk}=B_{\lambda\mu}$$

where $ij\Leftrightarrow\lambda=1\cdots6$, $kl\Leftrightarrow\mu=1\cdots6$.

According to the demagnetization factors method, an effective magnetic field is computed as follows:[21]

$$\overline{H}_E=-\partial W_{\mathrm{ME}}/\partial\overline{M}=-N^E\overline{M}. \tag{17}$$

Equation (17) has to be written in the coordinate system ($1'$, $2'$, $3'$) for which the axis $3'$ coincides with the equilibrium magnetization direction M_0. The components of $H_{K'}^E$ are given by

$$H_{K'}^E=\beta_{K'K}H_K^E, \tag{18}$$

where the matrix $\hat{\beta}$ can be taken as follows (see Fig. 2):

$$\hat{\beta}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\Theta & -\sin\Theta\\ 0 & \sin\Theta & \cos\Theta\end{pmatrix}. \tag{19}$$

It is clear that

$$M_K=\beta_{K'K}M_{K'}. \tag{20}$$

Substitution of Eq. (17) into Eq. (18) and taking into account Eqs. (19) and (20) yields

$$\begin{aligned}N_{11}^E-N_{33}^E&=4(B_{11}E_1-B_{22}E_2)+2g_2\cos^2\Theta+2g_3\sin 2\Theta;\\ N_{22}^E-N_{33}^E&=2g_2\cos 2\Theta+4g_3\sin 2\Theta;\\ N_{12}^E&=[-2(B_{11}E_2+B_{22}E_1)]\cos\Theta+[2((B_{14}E_2-B_{15}E_1)]\sin\Theta;\end{aligned} \tag{21}$$

where

$$g_2=-B_{11}E_1+B_{22}E_2+(B_{31}-B_{33})E_3;$$

$$g_3=-B_{14}E_1.$$

For the sake of clarity the primes in Eq. (21) are omitted. It is necessary to note that the indices on the right-hand side of Eq. (21) correspond to the crystallographic coordinate system. Without loss of generality, we shall consider a case when the electric field is directed along a symmetry axis of a structure, i.e.

$$E_1=E_2=0,\ \ E_3=E.$$

So, we get

$$\begin{aligned}N_{11}^E-N_{33}^E&=2[(B_{31}-B_{33})E]\cos^2\Theta;\\ N_{22}^E-N_{33}^E&=2[(B_{31}-B_{33})E]\cos 2\Theta;\\ N_{12}^E&=0.\end{aligned} \tag{22}$$

Taking into consideration a cubic and geometrical anisotropy of the magnetostrictive phase[17] and assuming that the we have (111)-magnetostrictive layers, for $\mathbf{E}\|\mathbf{H}\|[111]$, we get

$$\omega/\gamma=H_3+M_0[4/3\cdot H_A/M_0-4\pi+2(B_{31}-B_{33})E]. \tag{23}$$

The resonance field shift resulting from the applied electric field is equal to

$$\delta H_E=-2M_0(B_{33}-B_{31})E. \tag{24}$$

Note that in Eq. (24) M_0 is the magnetization of a multilayer composite as a whole.

Using experimental data on the resonant ME effect and the expression (24) it is possible to determine ME constants describing the behavior of multilayers in an external electrical field that will allow us to get additional information about the nature of ME interaction in the structures. In Nickel ferrite-PZT composites, for example, one obtains from Eqs. (24) and (9a)

$$(B_{33}-B_{31})\approx 7.7\times10^{-3}\ \mathrm{cm/kV}. \tag{25}$$

Similar analysis could be carried out to obtain the expressions for all other ME constants by using appropriate orientations for **E** and **H**.

IV. CONCLUSIONS

We presented here (i) theoretical analysis of high-frequency ME effects for a simple two-layer structure and (ii) a detailed treatment for electric-field-induced shift for ferromagnetic resonance field in multilayers. Our calculations predict a strong microwave ME effect in composites consisting of a magnetic phase that has a large magnetostriction and a small magnetization. The results obtained in this study are of importance for quantitative information on microwave ME effects and for potential device applications based on multilayer composites. Microwave devices based on ME effects have unique advantages over traditional ferrite and semiconductor analogs.[22]

Based on these models, we conclude that nickel ferrite-PZT composite is the system of choice for realizing strong ME effects at microwave frequencies. Followup works now underway include experimental investigation of magnetoelectric effects in multilayer of nickel ferrite-PZT and nickel zinc ferrite-PZT and fabrication of tunable microwave devices of magnetic type with electrical control, such as a microstrip phase shifter. In general, the control parameter can be variations associated with electric and magnetic fields, temperature, and their combined effects. The theory presented here is likely to lead to composites with strong ME effects at microwave frequencies for signal processing devices.

ACKNOWLEDGMENTS

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