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Microwave magnetoelectric interactions in ferrite–piezoelectric nanobilayers: Theory of electric field induced magnetic excitations

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Abstract

A theory for magnetic excitations in a yttrium iron garnet (YIG)–lead zirconate titanate (PZT) nanobilayer due to microwave electric field and magnetoelectric (ME) interactions is discussed. The magnetic response is described by ME susceptibility and a technique has been proposed for its determination. The electric field excites elastic modes in PZT that would result in magnetoelastic modes in YIG. The model predicts maximum ME susceptibility when the microwave field is at the coincidence of electromechanical and magnetic resonance. The theory is of importance for new devices such as magnetoelectric spin-acoustic wave generators and power limiters.

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1. Introduction

Materials that are magnetoelectric have an induced polarization in an applied magnetic field or an induced magnetization in an electric field. Single-phase materials such as Cr\textsubscript{2}O\textsubscript{3}, in general, show weak magnetoelectric (ME) effects [1]. Ferromagnetic–ferroelectric composite materials have attracted considerable attention in this regard due to the observation of strong ME effects that is facilitated by their response to electric, magnetic, and elastic forces [2–6]. Two-phase composites consisting of ferrites, manganites, or terfenol for the magnetic phase and lead zirconate titanate (PZT) or lead magnesium niobate–lead titanate (PMN–PT) for the piezoelectric phase have been studied extensively. Since we are interested in the dynamic response of the composites, the frequency dependence of ME interactions is of importance for an understanding of the phenomenon. Several two-phase composites show a giant ME coupling at low frequencies [2–6]. A further enhancement in the strength of the ME coupling is found to occur when the electric subsystem shows electromechanical resonance (EMR) [7–9]. The ME interactions are predicted to be even stronger at the coincidence of EMR and ferromagnetic resonance in the magnetic subsystem and is attributed to efficient transfer of energy between acoustic modes and magnons [10]. We developed the theory for these resonance ME phenomena and measured the strengths of ME interactions at EMR and FMR [7, 11]. The studies also led to design and characterization of a new family of electric field tunable ferrite signal processing devices [12].

This work is concerned with modeling of magnetic excitations in a ferrite–piezoelectric bilayer due to microwave electric field and ME interactions. The magnetic response is described in terms of ME susceptibility and a novel technique has been proposed for its determination for a yttrium iron garnet (YIG)–lead zirconate titanate (PZT) nanobilayer. It is assumed that the sample is positioned at the maximum of microwave electric field. An induced microwave magnetic field (parallel to the electric field) will result from ME interactions and, therefore, will lead to magnetic excitations in the bilayer. One could also understand such magnetic excitations as originating...
from elastic modes in the piezoelectric component. These acoustic modes would in turn excite bound magnetoelastic modes in the ferrite due to ME coupling. The excitations are standing waves along the thickness of the sample and the wave length is determined by the thickness of PZT and YIG, and material parameters. These coupled magnon–phonon modes will be in the microwave region of the electromagnetic spectrum for YIG and only for nanometer thickness for PZT. Thus the focus here is high frequency magnetic excitations, including ferromagnetic resonance (FMR) and ME susceptibility in a ferrite–ferroelectric bilayer. Traditional FMR at high powers in a ferrite will lead to nonlinear effects such as saturation of main resonance and subsidiary absorption. The idea here is to eliminate those effects by locating a bilayer at the position of maximum rf electric field. The rf magnetic field induced due to ME interactions will lead to FMR that will be free of nonlinear effects.

An expressions for the ME susceptibility $\alpha$ has been derived from the rf magnetic field generated due to ME interactions and the resulting magnetization in YIG. The model predicts maximum $\alpha$ and transfer of microwave power to these magnon–phonon excitations when the microwave electric field is applied at the coincidence of electromechanical and magnetic resonance. The theory developed here will enable the determination of ME susceptibility using data on power absorbed by the sample. The theory is of importance for new devices such as magnetoelastic spin-acoustic wave generators and high power devices.

2. Theory

We consider a ferrite–PZT bilayer as in Fig. 1 that is subjected to a bias field $H_0$ perpendicular to its plane, along the $z$-axis. The piezoelectric phase is electrically polarized with a field $E_0$ parallel to $z$. It is assumed that $H_0$ is high enough to saturate the ferrite to a single domain state for minimization of magnetic losses. The expression for space-variant microwave magnetization $m_z$ can be found using the equations of motion for ferrite and piezoelectric phases and equation of motion of magnetization. Equations of motion for ferrite and piezoelectric composite phases can be written in the following form:

$$\partial^2(m_{u_z})/\partial t^2 = \partial^2(m_{W})/(\partial x \partial m_{S_1}) + \partial^2(m_{W})/(\partial y \partial m_{S_2}) + \partial^2(m_{W})/(\partial z \partial m_{S_3})$$

(3)

$$\partial^2(m_{u_z})/\partial t^2 = \partial^2(m_{W})/(\partial x \partial m_{S_1}) + \partial^2(m_{W})/(\partial y \partial m_{S_2}) + \partial^2(m_{W})/(\partial z \partial m_{S_3})$$

(4)

$$\partial^2 m_z/(\partial t)^2 = \partial^2(m_{W})/(\partial x \partial m_{S_1}) + \partial^2(m_{W})/(\partial y \partial m_{S_2}) + \partial^2(m_{W})/(\partial z \partial m_{S_3})$$

(5)

The equation of motion of magnetization for ferrite phase has the form

$$\partial M/\partial t = -\gamma [M \times H_{eff}],$$

(4)

where $H_{eff} = -\partial(m_{W})/\partial m$.

In the absence of external ac magnetic field, the electric field induced magnetization $m_k$ in terms of circularly polarized mechanical displacement $m_{u_z}$ of the ferrite is obtained by solving the above equations and substituting in

$$m_k = \frac{B_2 \gamma}{\omega - \omega_k} a(m_{u_z}),$$

(5)

where $\omega$ is angular frequency, $\omega_k$ is frequency for magnetoelectric modes, and $\gamma$ is the gyromagnetic ratio. The magnetic modes will have uniform magnetization in the plane of the film and a standing wave structure perpendicular to the film plane.
Substituting the value for $m u^\pm$ into Eq. (5) yields:

$$m_q = \frac{B_2 p c_{44} \mu_m k \sin(m_\parallel k L) [1 + \cos(k L)]}{(p_c^{44} k \sin(\pi k L) \cos(m_\parallel k L) + p_m c_{44} k \sin(m_\parallel k L) \cos(k L)) [\omega - \omega_0]}$$

(6)

where

$$m_k = \omega \sqrt{\frac{m \rho}{c_{44}}} \quad p_k = \omega \sqrt{\frac{p \rho}{c_{44}}}$$

$$m c_{44}^{\pm} = m c_{44} + \gamma (B_2^2 + \omega^2 \mu M_0 H_z) / [M_0(\omega - \gamma H_0 - 4\pi \gamma M_0)]$$

where $m_{c_{ij}}$ and $p_{c_{ij}}$ are elastic moduli of ferrite and piezoelectric layers, respectively, $m \rho$ and $p \rho$ are densities of the two phases, $m L$ and $p L$ are ferrite and piezoelectric layer thicknesses, and $p E$ is microwave electric field applied to the piezoelectric layer. The term $c_{44}$ is the stiffness tensor component that relates the shear stress $T_k(T_3)$ with shear strain $S_k$ and $e_{15}$ is the piezoelectric coefficient tensor component that relates the stress $T_k(T_3)$ with in-plane electric field $E_2(E_1)$.

Signal attenuation is taken into account by introducing a complex frequency and an imaginary component of $\omega = 10^{-2} \omega_0$. This imaginary component corresponds to a Q-value of 1000 for resonance absorption in the ferrite.

3. Results and discussion

Next we apply the theory to the specific case of YIG–PZT bilayer and calculate the ME susceptibility given by $\alpha = \mu_0 \partial m_k / \partial p E$. The choice of YIG for the ferrite is because of low losses at microwave frequency, a necessary condition for the observation of the enhancement in the ME coupling that is predicted by the theory. Fig. 2(a) shows the susceptibility $\alpha$ vs frequency $f$ calculated from Eq. (2). We choose 31-nm YIG and 134-nm PZT so that the fundamental EMR will be around 6 GHz [7] for material parameters in Ref. [10]. A bias field of $H_0 = 2$ kOe is assumed so that it is smaller than the field $H_c$ for the excitation of magnetic modes that include FMR. There are peaks in $\alpha$ at the fundamental EMR and higher order thickness modes. The susceptibility at the fundamental mode is an order of magnitude higher than the value at the higher harmonics.

Consider the results in Fig. 2(b) for a bias field $H_0$ corresponding to magnetic resonance in YIG. In general, there is a set of resonance fields corresponding to inhomogeneous precessions for $H$ in the range $\omega / \gamma + 2\pi M_0$ to $\omega / \gamma + 4\pi M_0$ for a thin disk magnetized perpendicular to its plane. Variation in $\omega$ or $H_0$ results in the excitation of these modes. When $H_0$ is set equal to $H_r = \omega / \gamma + 4\pi M_0$, $\alpha$ is expected to show a dramatic increase in magnitude, as in Fig. 2(b) and (c), due to coincidence of resonance character for the mechanical displacement and magnetization. When the frequencies of magnon and phonon modes are matched, there is efficient transfer of energy between the electric and magnetic subsystems. In Fig. 2(b) for $H_0 = 3.86$ kOe, the fundamental acoustic mode coincides with uniform precession magnon mode that results in a sixty-fold increase in $\alpha$. When the $H_0$ is increased to 6 kOe so that uniform precession frequency coincides with the higher order EMR mode, one expects two orders of magnitude increase in $\alpha$ as in Fig. 2(c).

The $z$-dependence of the ME susceptibility is shown in Fig. 3. The high frequency excitation profile in YIG corresponds to a series of magnetostatic modes including uniform precession. The results for 31-nm YIG–134-nm PZT bilayer shows the average value of the ME susceptibility at each $z$, with $z = 0$ representing the interface. As one moves along $+z$ away from the interface, the susceptibility decreases linearly to zero on the outer surface of YIG. One possible option for having a constant ME susceptibility in YIG (i.e., a uniform precession mode) is when two YIG–PZT bilayers are arranged back-to-back to form a trilayer of PZT–YIG–PZT. Fig. 3 also shows the ME susceptibility profile for a PZT–YIG–PZT trilayer. Calculation for this trilayer is similar to that for the bilayer. We assumed 31-nm YIG and 67-nm thick PZT layers. The ME
susceptibility will then remain practically constant at each point along the depth of YIG as shown in the figure.

Next we consider measurements of ME susceptibility for the case of a PZT–YIG–PZT trilayer. One could use a resonant cavity with the sample located at the ac electric field maximum. The dc magnetic bias field is selected so that homogeneous precession frequency coincides with the fundamental EMR mode. Thus the microwave electric field will result in FMR in YIG and absorption of microwave power. The electric field induced magnetization is equivalent to that induced by a microwave magnetic field

$$H = m_k \frac{\gamma H_0 - 4\pi \gamma M_0 - \omega}{\gamma M_0}.$$  \hspace{1cm} (7)

Eq. (3) is obtained by solving the equation of motion of magnetization for a YIG plate being placed in an antinode of ac magnetic field. The absorbed power $P$ is given by:

$$P = k_1 H^2 \quad \text{with} \quad k_1 = \frac{\pi M_0}{\Delta H} \omega V,$$  \hspace{1cm} (8)

where $V$ is volume of YIG and $\Delta H$ is half-width of resonance absorption. Thus, $H$ can be determined from Eq. (8) and substituted in Eq. (7) to obtain $m_k$. The ME susceptibility $\alpha = \mu_0 m_k/E$ can be determined from data on power absorbed.

### 4. Conclusion

A theory is discussed for magnetic excitations due to ME interactions in YIG–PZT bilayers and trilayers. The ME interactions will generate a microwave field when the sample is placed in electric field maximum, resulting in magnetic excitations in YIG. The microwave ME susceptibility for the trilayer can be estimated from the theoretical estimates and data on power absorption. A family of ferrite devices with high power handling capacity can be designed based on the model discussed here. Traditional YIG devices show saturation effects, but the proposed devices with the trilayer located at microwave electric fields will show saturation effects only at very high power levels.

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