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Spin waves in a thin film with magnetoelectric coupling at the surfaces

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ABSTRACT

The standing spin waves in a thin ferromagnetic film are calculated when the surface magnetization is influenced by magnetoelectric coupling. At the interfaces, inversion symmetry is broken allowing for an energy term that is linear in the electric polarization in the film. For the two film surfaces, the magnetoelectric coupling is opposite in sign and therefore results in asymmetric pinning of the dynamic magnetization. The magnetoelectric pinning alters the spin wave frequencies and also the power absorbed by the material at these resonances.

1. Introduction

Symmetry-breaking at magnetic surfaces has been investigated intensely over the past few years. Recently, there was much interest in using electric fields to manipulate magnetic surfaces and extremely thin magnetic films [1–4]. This lead to a resurgence of interest in more exotic magnetic interactions, which are not typically symmetry-allowed in bulk materials but are allowed at surfaces. For example, the Dzyaloshinskii–Moriya (DM) interaction that was discovered in the 1950s [5,6] has been found to occur in very thin films [7] and disks [8]. It results in Skyrmion lattices that have suggested applications in spintronic devices since these magnetic objects may be moved using very low power currents [9]. The interfacial DM interaction has also been shown to lead to nonreciprocal spin wave propagation [10] and pinning of dynamic magnetization [11].

In this paper, we theoretically examine how one particular magnetoelectric coupling term that is only allowed at surfaces alters the frequencies and absorption properties of standing spin waves. It has been known for many decades that interface or surface interactions in magnets can be examined by experimentally measuring the resonant absorption of microwaves by spin wave modes [12,13]. Some studies have used such a technique to infer the coupling between a ferromagnetic film and a neighboring multiferroic or ferroelectric film [14,15]. Any interaction at the surface alters the torque acting on the dynamic magnetization and therefore alters the surface pinning of the standing spin waves. This has two effects: firstly, surface pinning changes the wavelength of the standing wave and therefore will alter the frequency; secondly, the pinning – if different at the top and bottom surfaces of a film – results in an asymmetric mode with a net magnetic moment associated with it. This allows much stronger coupling of the mode to uniform driving rf fields.

We find that the magnetoelectric coupling studied here leads to asymmetric pinning of the dynamic magnetization at the top and bottom surfaces of a thin film and therefore allows for higher order standing wave modes to absorb power from an impinging microwave magnetic field. Our main result is that when the effective field produced by the magnetoelectric coupling acts against the demagnetizing field, there is a stronger effect on spin wave frequencies and absorption properties than if the coupling has opposite sign and instead reinforces the demagnetizing field.

The structure of the paper is as follows. Section 2 gives an introduction to the magnetoelectric coupling considered here. Section 3 outlines the theory to calculate linear spin wave frequencies, profiles and absorption spectra. Then, in Section 4 the results of the calculation are presented and discussed. Finally, conclusions are made in Section 5.

2. Interface magnetoelectric coupling

Typically, in bulk materials, the lowest-order energy terms that are symmetry-allowed are quadratic in components of the electric polarization P and quadratic in the components of the magnetization M. This is because a term linear in P violates spatial inversion

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symmetry and a term linear in M violates time reversal symmetry. A detailed account of the symmetry requirements is described in Ref. [16], where the term "multiferroic" was also first coined. However, at a surface, there is no longer any inversion symmetry. Therefore, if the out-of-plane direction is y, terms linear in P_y, namely $P_yM_x^2$, $P_yM_y^2$, $P_yM_z^2$ and $P_y\vec{M}\cdot\vec{M}$, are all allowed.

We assume a thin magnetoelectric film with some out-of-plane y component to the electric polarization. This electric polarization may be spontaneous or induced by an external electric field. We assume that the film is magnetized in the in-plane z direction and we will focus our attention on a $\Gamma P_yM_z^2$ energy density, where ΓP_y is a dimensionless constant that describes the magnetoelectric coupling strength at the surface. We will write $\Gamma P_y = \Gamma P$ as shorthand notation from now on. This energy resembles a magnetocrystalline anisotropy energy. It is varied in the calculations and when the magnetoelectric coupling is greater than the demagnetizing strength ($\Gamma P > 2\pi$ in CGS units) the ground state may be changed. We use magnetic material parameters that are appropriate for iron. This particular magnetoelectric energy density resembles the term found by Rado to describe the magnetodielectric coupling in Cr_2O_3 [17,18]. Even if ΓP is small and does not alter the ground state of the magnet, its effect may be seen on the spin wave spectrum where frequencies may be softened or stiffened.

We consider two cases: (i) magnetoelectric coupling at one surface (this is common in ABC type structures where a different material is joined to the top surface of the film as to the bottom [19]) or (ii) at both surfaces. For case (ii), we assume that the magnetoelectric coupling strength will be the same at the top and bottom of the film. However, the *sign* of the interaction will be switched if we consider the electric polarization vector to be uniform throughout the film and therefore identical at the top and bottom surfaces. This is again due to symmetry and ensures that the film has identical energy when performing a mirror transformation through the central plane of the thin film (hence switching the two surfaces). Such a spatial inversion is illustrated in Fig. 1 with panel (a) showing before the inversion and (b) after. The top surface in (a) must have the same energy as the bottom surface in (b) and therefore a negative sign is needed in the magnetoelectric coupling of the bottom. Similarly, the bottom surface in (a) must have the same magnetoelectric coupling as the top surface in (b). An external electric field or electric poling may be required to have the electric polarization equal on both interfaces.

Just because a particular magnetoelectric coupling term is symmetry-allowed in a system, does not necessarily mean that the magnetoelectric coupling will be large enough to have an appreciable effect on the system. This has been the main problem in designing magnetoelectric and multiferroic systems that have strong enough coupling to realize devices where magnetization may be controlled with electric fields or vice versa. Strain-mediated coupling between very thin films has so far been used to create the largest magnetoelectric couplings. In this work, we do not investigate the microscopic mechanisms that give rise to the magnetoelectric coupling and instead focus on what effect such a phenomenological coupling would have on the spin waves in the system.

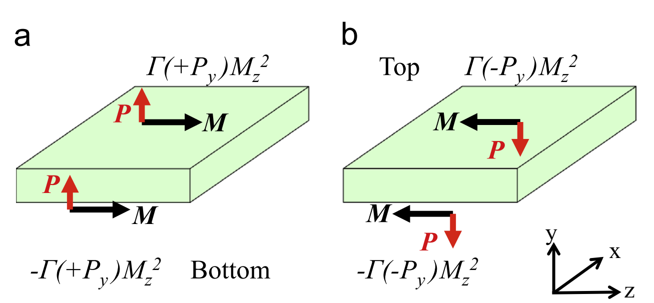

Fig. 1. Schematic of a spatial inversion through the x–z thin film plane. This is to demonstrate that the magnetoelectric coupling must have opposite sign on the top and bottom surfaces if the electric polarization is uniform through the film. (a) Before inversion and (b) after inversion.

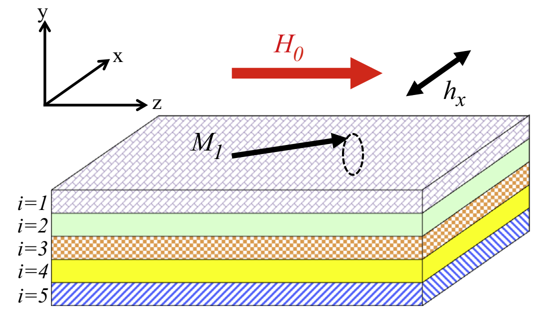

Fig. 2. Schematic of the magnetic thin film. In this case $N=5$ is the number of thin film layers considered to make up the film. In the top ($i=1$) layer the magnetization $\vec{M}_1$ is drawn and precesses about its equilibrium z direction.

3. Theory

The geometry of the thin film is shown in Fig. 2. The film is finite in the y direction and infinite in the x–z plane. The film is split into N thin film slices or layers that are indexed by i. The magnetization is assumed to be uniform within each plane and we only consider variations through the thickness of the film.

The total energy of the film is made up of a sum over the slices that includes contributions from the exchange, demagnetizing, applied field and magnetoelectric energies. The energy density of the film is given in CGS units by

$$E = -J\sum_{\langle i,j\rangle}\vec{M}_i\cdot\vec{M}_j - H_0\sum_{i=1}^{N}M_{iz} - h_xe^{-i\omega t}\sum_{i=1}^{N}M_{ix} + 2\pi\sum_{i=1}^{N}M_{iy}^2 + \Gamma PM_{1y}^2 - \Gamma PM_{Ny}^2. \tag{1}$$

The first term is the exchange energy density. The sum is over nearest neighbor pairs of slices i and j. It is assumed that the exchange constant J is constant throughout the material. J can be related to the exchange energy per unit length A via $J = A/(\delta^2M^2)$, where δ is the thickness of each thin film slice.

The second term in Eq. (1) is due to the static applied field H_0 in the z (in-plane) direction, and the next term is the Zeeman energy due to the oscillating rf field in the x direction. The angular frequency of the rf driving field is ω. Next, the demagnetizing energy for each individual layer is included. Finally, the last two terms in Eq. (1) represent the magnetoelectric coupling at the top ($i=1$) and bottom ($i=N$) layers of the thin film. Notice that these terms have the same magnitude but opposite signs due to the symmetry of the two surfaces. For $\Gamma P > 0$, the magnetoelectric coupling at the top restricts the magnetization's motion out-of-plane whilst at the bottom surface it acts to lower the thin film demagnetizing effects.

The damped equation of motion for the magnetization in layer i is given by

$$\frac{\partial\vec{M}_i}{\partial t} = -|\gamma|\vec{M}_i\times\vec{H}_i - \alpha\frac{\vec{M}}{M}\times\frac{d\vec{M}}{dt}, \tag{2}$$

where γ is the gyromagnetic ratio of the material, and α is the Gilbert damping parameter. $\vec{H}_i$ is the total effective magnetic field acting on layer i, and is found by differentiating the energy density