Electric field control of surface spin waves

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Abstract

A mean field theory is used to calculate spin wave frequencies for canted antiferromagnets with magnetoelectric coupling to a ferroelectric polarisation. Effects of electric fields on magnetic resonance frequencies and nonreciprocities are discussed. Possibilities for hybrid magnetoelectric modes in multilayer geometries are examined, where magnetoelectric effects arise through dynamic coupling via dipolar magnetic fields.

1. Introduction

Great interest in possibilities for electric control of magnetic properties has renewed investigations into multiferroic classes of materials displaying simultaneous ordering of magnetic and electric polarizations. Many of these materials have at least two magnetic sublattices antiferromagnetically coupled, and display weak ferromagnetism through canting of the sublattices, as illustrated in Fig. 1 for a weakly coupled two sublattice multiferroic such as $BaMnF_2$. The weak ferromagnetism is depicted by the vector ***M***, and is perpendicular to the electric polarization ***P***.

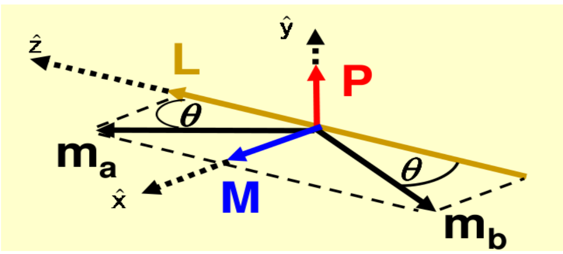

Fig. 1: Orientation of electric and magnetic polarizations in a multiferroic with a canted spin structure such as that expected for $BaMnF_2$. Vectors **L** and **M** represent the sum and difference of the two sublattice magnetizations.

These materials are especially interesting because of magneto-electric coupling between ***M*** and ***P***. The simultaneous existence of, and coupling between, magnetism and ferroelectricity appears in a number of complex oxides, but its manifestation is subtle and complex. It is now understood that the electronic states responsible for magnetism and ferroelectricity are associated with different atoms in the oxides, and are in some sense incompatible.[1] In some systems, magneto-electric coupling of the Dzyaloshinskii-Moriya form arises primarily through spin obit effects and is typically weak and strongly dependent upon local site symmetry.

2. Electric control of surface spin waves

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Early work showed that magnetic polaritons in bulk media can display interesting and potentially useful properties, [2-4] but little has been discussed regarding surface excitations until now. We show that, for single phase materials whose magnetic structure is canted antiferromagnetic, surface magnetic polaritons can exist in the GHz range and that the magnetoelectric interaction leads to "leaky" surface modes (pseudosurface waves that dissipate energy into the bulk). [5] Most significantly, we can show that the surface mode nonreciprocity, where $\omega(k) \neq \omega(-k)$, can be controlled with an applied *electric* field.

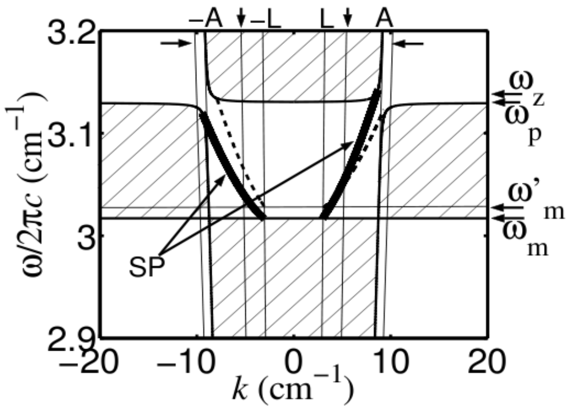

Fig. 2: Bulk and surface mode dispersions calculated for $BaMnF_2$. Surface modes are indicated by SP and the shaded regions represent bulk bands. The dashed lines represent surfaces branches when an electric field (−5 × 109 V/m) is applied. Note that the magnetic resonance ω_m shifts upon application of an electric field. (Reproduced with permission from Ref. [5])

A calculated example is shown in Fig. 2 for the frequencies of TE polarised surface magnetic polaritons propagating perpendicular to the direction of weak magnetisation on $BaMnF_2$. Surface localised modes, associated with the weak ferromagnetism, correspond to magnetostatic waves and exist in a window of frequencies inside the light line and bounded by characteristic resonances that delineate the bulk bands. The surface branch is non-reciprocal with respect to the propagation direction perpendicular to ***M*** (note that bulk modes can exhibit nonreciprocities for other geometries [3]). Reversal of ***P*** through application of an electric field causes the weak magnetisation to reverse, thereby reversing directional dependence of the surface modes. A shift of the magnetic resonance frequency also occurs.

3. Dynamic coupling in multilayers

Multilayers can facilitate strong interactions between films that can drastically modify the properties of excitations. For example, it is possible to obtain electric field induced frequency shifts of several GHz in ferromagnet/$BiFeO_3$ multilayers. [4] In fact, it turns out that multilayering can, in the case of multiferroics, create an indirect form of magneto-electric coupling that appears in the spin wave *dynamics*.

We demonstrate this possibility within an effective medium description of a heterostructure composed of alternating ferromagnetic and weak ferromagnetic ferroelectric films. [6] In this description, one considers the long wavelength, average magnetic and electric response of a multilayer, taking into account Maxwell's electromagnetic boundary conditions for the dynamic electric and magnetic fields at each interface.

The antiferromagnetic component of the multiferroic supports two types of resonances: "acoustic" and "optic", in analogy to phonons in a diatomic lattice. The optic mode for the canted sublattices produces a weak dynamic magnetisation which can couple linearly to an oscillating component of $\boldsymbol{P}$. The strength of the electro-magnetic coupling is proportional to ΓM^2 and $\Gamma P_o M^2$, where Γ is the magneto-electric coupling strength and P_o is the equilibrium polarisation. This dynamic coupling vanishes when the canting angle goes to zero. Even if exchange coupling is neglected between the ferromagnetic and multiferroic films, one finds that magnetic dipolar fields serve to hybridize the canted antiferromagnetic optic mode with the ferromagnetic resonance via coupling to a ferroelectric resonance. As a result, a low frequency magneto-electric mode appears that depends upon the relative film thicknesses, and applied magnetic and electric fields.

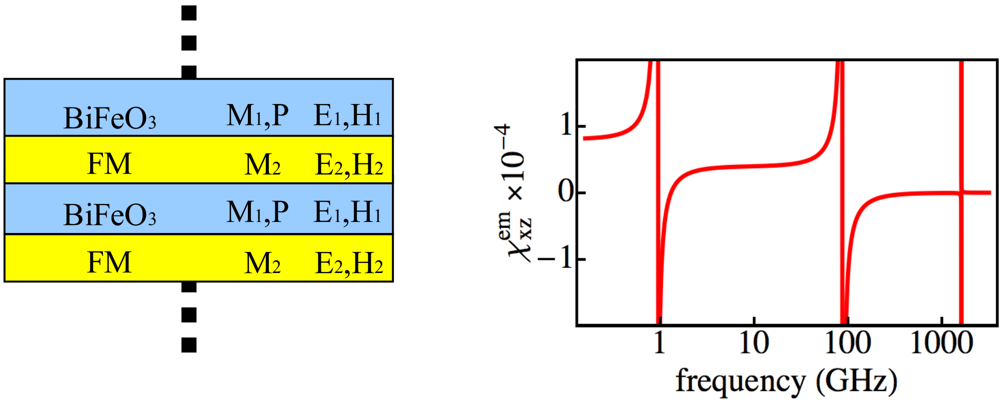

Fig. 3: (Left) Sketch of a multilayered ferromagnet/canted multiferroic. (Right) Dipolar coupling between the ferromagnetic resonance and the electromagnon mode produces a new resonance at 1 GHz.

Example calculated results are shown in Fig. 3. Using parameters appropriate for $BiFeO_3$ and NiFe, one finds an electromagnon mode at 4.07 GHz for films of equal thickness. This is a shift downward of the bare NiFe resonance by nearly 2 GHz. This is a significant result in that the magneto-electric coupling is transferred to the NiFe via dipolar interactions solely in this model. A new magneto-electric spin wave resonance is thereby created, whose frequency provides a direct measure of the magneto-electric coupling strength and which will be directly affected by electric as well as magnetic fields through canting angle.

3. Conclusions

We have discussed different possibilities for using magnetoelectric coupling in multiferroics to introduce electric field control of magnetic spin waves. We close by noting that the possible connection of displacive coupling to magnetostriction leads naturally to the idea of enhancing magnetoelectric coupling through strain engineering in a multilayer geometry. [7]

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