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Internal dipolar field and soft magnons in periodic nanocomposite magnets

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ABSTRACT

We study spin wave excitations in a three-dimensional nanocomposite magnet of exchange coupled hard ($SmCo_5$) and soft (FeCo) phases. The dipolar interaction splits the spin wave energies into the upper and lower branches of the spin wave manifold. When the amount of the soft phase is increased the energy of low-lying spin excitations is considerably softened due to two reasons: (i) the low- lying mode locked into the soft phase region with a spin wave gap at $\mathbf{k} = 0$ which scales approximately proportional to the anisotropy constant of the soft phase and (ii) the internal dipolar field which comes from magnetic charges forming at hard-soft boundaries with normals parallel to the magnetization displaces the spin wave manifold toward the lower energies. With adding more soft phase the spin wave gap closes and the system moves to another ground state characterized by the magnetization mismatch between spins of the hard and soft phases.

1. Introduction

Materials with periodically modulated magnetic and geometric properties are of special interest recently from the viewpoint of applications, which aim to manipulate propagating spin waves [1–5]. Spin waves propagating in nonhomogeneous magnetic nanostructures serve as information carriers and show the existence of allowed frequency ranges and forbidden band gaps [6–11]. The periodic modulation of magnetic properties are also realized in nanocomposite magnets composed of exchange-coupled hard and soft magnetic phases [12–14]. The hard phase provides the immense magnetic anisotropy that stabilizes the exchange-coupled soft phase against demagnetization. In multi-layer geometry it gives the increase in the remnant magnetization and the ultimate gain in the energy product with increasing amount of the soft phase material [15]. However, in a geometry where the nanocomposite is magnetized perpendicular to the hard-soft boundary, the anticipated increase in the remanence does not occur partly because the hard and soft phase magnetization vectors are never completely parallel to each other [16].

In a nonhomogeneous magnetic material values of the saturation magnetization M_S, anisotropy constant K and the direction of the magnetization $\mathbf{n}_0$ are, in general, functions of the position vector $\mathbf{r}$. In a magnonic crystal the applied uniform magnetic field usually forces all the magnetic moments to be magnetized in the direction of the applied field [18–20]. In a nanocomposite hard-soft magnet the behavior of the magnetization vector $\mathbf{M}(\mathbf{r}) = M_S(\mathbf{r})\mathbf{n}_0(\mathbf{r})$ depends on the demagnetizing effects and mutual arrangement of easy axes of constituent ferromagnets. For an arrangement with easy axis (in the z direction) perpendicular to the hard-soft boundary the homogeneously magnetized state $\mathbf{M}(\mathbf{r}) = M_S(\mathbf{r})\hat{z}$ is energetically unfavorable from the magnetostatic point of view. Because of the discontinuity of the magnetization at the hard-soft boundary, a magnetic charge $\rho_M = -\nabla \cdot \mathbf{M}$ is developed. This increases the dipolar energy which can be written in the form [21] $E_{dip} \propto \int d^3r d^3r' \rho_M(\mathbf{r})\rho_M(\mathbf{r}')/|\mathbf{r} - \mathbf{r}'|$. For sufficiently low soft phase content a strong anisotropy field of the hard phase and exchange forces at soft-hard boundaries enforce the whole magnet to be magnetized in the z direction. With adding more soft phase with considerably smaller value of anisotropy constant the soft phase spins become tilted from the easy direction and their averaged direction are misaligned with spins of the hard phase. Monte Carlo simulation at finite temperatures [22] reveals that this misorientation grows with temperature and as the amount of the soft phase is increased. Such a misalignment, usually, is not considered in the context of magnonic crystals where the nonuniform static demagnetizing filed is assumed to be homogeneously averaged throughout the sample [18].

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The dependence of the ground state magnetization in composite permanent magnets on the demagnetizing effects has been discussed previously for a single soft inclusion in a matrix of hard phase [23]. These calculations reveal that the remnant magnetization sensitively depends on the size of the inclusion. With increasing of the fraction of the soft phase the long-range stray field destroys the parallel alignment of the soft magnetic moments and creates magnetic vortex-like structures. These calculations are based on computational micromagnetism [24–26] and yield a stable magnetization distribution by minimizing the total energy of magnetic system.

Micromagnetic calculations [23] as well as an analytic estimate of the nucleation field and the remanence enhancement [15] have not discussed the thermally activated tilting of spins and the resulting magnetization mismatch. The effect of thermal activation can be understood if one knows the low-lying spin wave energies $E_j(\mathbf{k})$. The fluctuation of the magnetization is determined by the density of the magnons which in turn is governed by the Boltzmann factor $\exp(-E_j(\mathbf{k})/k_BT)$. The lower the energy of spin excitations, which turns out to be concentrated in the soft phase, the more fluctuations of the soft phase spins and more reduction in the remnant magnetization of the composite appears. Due to the fluctuation of soft phase spins the remanence does not increase proportional to the fraction of the soft phase, $M_r = v_s M_s + v_h M_h$ $(v_s + v_h = 1)$, as it can be for a composite with homogeneous magnetization.

To further elucidate the physics involved in the instability of the homogeneously magnetized state, $\mathbf{M}(\mathbf{r}) = M_S(\mathbf{r})\hat{z}$, in the present work we consider the spin wave spectrum in a three-dimensional (3D) composite composed of a periodic array of hard phase cubes immersed into a soft phase matrix. We incorporate the effect of the nonhomogeneous saturation magnetization $M_S(\mathbf{r})$ and internal magnetic chargers into the formalism of spin wave excitations. We explicitly construct operators of spin-wave excitations and calculate the corresponding eigenfrequencies. We anticipate that the dipolar interaction will lower the spin wave energy, which in turn enhances the fluctuation of the magnetization at finite temperatures as these spin waves are thermally excited.

A comparison of the behavior of low-lying spin excitations with Monte Carlo simulation results [16] show the crucial dependence of the low-lying spin excitations on dipolar effect in a hard-soft composite. Because of the low magnitude of the anisotropy of the soft phase the spin excitations are highly sensitive to the local magnetic ordering induced by dipolar interaction [17]. In this paper we extend our previous analysis [27] of a composite with homogeneous exchange interaction, in which $J_{ij} = const$ for any nearest neighbors i and j, for the case of position-dependent exchange interaction $J(\mathbf{R}_i, \mathbf{R}_j)$ and present the clarifying details of incorporating the dipolar part of interaction into the formalism of spin-wave excitations for nonhomogeneous ferromagnets. We focus on the study of the dependence of the spin wave manifold on the internal dipolar magnetic field that comes from magnetic charges developing at hard-soft boundaries. For this we shall extract the effective demagnetizing field H_{dip} from the spin-wave dispersion behavior.

The paper is organized as follows. In Section II we present the general theory of linear spin-waves in a nonhomogeneous two-phase periodic structure of exchange-coupled hard and soft phases. We first linearize the spin Hamiltonian in the position space and then perform the diagonalization in the Fourier space. We then proceed in comparing the analytical results obtained for the behavior of low-lying spin excitations in a nonhomogeneous composite with the spin-wave spectra for homogeneous ferromagnets. We discuss the implication of H_{dip} for spin-wave manifolds in two-phase and one-phase ferromagnets. In Sec. III we discuss results of our calculation and the effect of the internal demagnetizing field on the spin wave dispersion of the two-phase magnet. And Sec. IV contains our conclusion.

2. Theoretical model

2.1. Two-phase composite magnet

We model the hard-soft composite as a periodic array of identical cubes of hard phase embedded into a soft phase matrix, as illustrated in Fig. 1. The easy axes of both phases are in the z direction. Each cube has a linear dimension l_h and separated from the adjacent one by a soft phase with linear dimension l_s, so there is a periodicity in the x,y and z directions with a period $w = l_h + l_s$. We shall refer to this periodicity as w- periodicity.

We focus on the low-lying spin excitations that occur gradually over a large distance. The magnetization, $\mathbf{M}(\mathbf{r})$, for a coarse-grained system, is defined on a discrete set of sites $\mathbf{R}_i$ in terms of block spin variables $\mathbf{S}_i = \mathbf{S}(\mathbf{R}_i)$, $|\mathbf{S}_i| = 1$, as $\mathbf{M}(\mathbf{r}) \simeq M(\mathbf{R}_i)\mathbf{S}_i$, with $M(\mathbf{R}_i) = M_S(\mathbf{R}_i)$ being the saturation magnetization density of the hard (M_h) or soft (M_s) phase at site i. Spins of the hard and soft phases are arranged in a three-dimensional cubic lattice with an effective lattice constant a. The effective magnetic moment of site i is $M(\mathbf{R}_i)v$, where $v = a^3$ is the volume of a block spin cell.

The interaction between two spins $\mathbf{S}_i, \mathbf{S}_j$ located at $\mathbf{R}_i, \mathbf{R}_j$ is described by the Hamiltonian for a classical spin system, including the nearest-neighbor exchange energy, the uniaxial magnetic anisotropy term and the dipole–dipole interaction:

$$H = -\frac{1}{2}\sum\nolimits'_{i,j} J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j - \sum_i K_i \left(S_i^z\right)^2 - \frac{g}{2}\sum\nolimits'_{i,j} D^{\alpha\beta}(\mathbf{R}_{ij})M'(\mathbf{R}_i)M'(\mathbf{R}_j)\, S_i^\alpha S_j^\beta, \quad (1)$$

where $\mathbf{R}_{ij} = \mathbf{R}_i - \mathbf{R}_j$, and the summations are over all distinct magnetic sites i and j with the restriction that $\mathbf{R}_{ij} \neq 0$. Indices α and β denote the Cartesian components x,y or z, and $D^{\alpha\beta}(\mathbf{R}_{ij}) = (3R_{ij}^\alpha R_{ij}^\beta - R_{ij}^2\delta_{\alpha\beta})/R_{ij}^5$ is the dipolar interaction tensor. In Eq. (1) positions vectors $\mathbf{R}_i$ are given in units of the lattice spacing a. The exchange constant J_{ij}, is equal to J_h (J_s) for the nearest neighbor spins of hard (soft) phase and zero otherwise. The two phases are exchange-coupled with a coupling constant J_{hs} which can be estimated as the geometric mean of J_h and J_s, $J_{hs} = (J_h J_s)^{1/2}$. K_i is

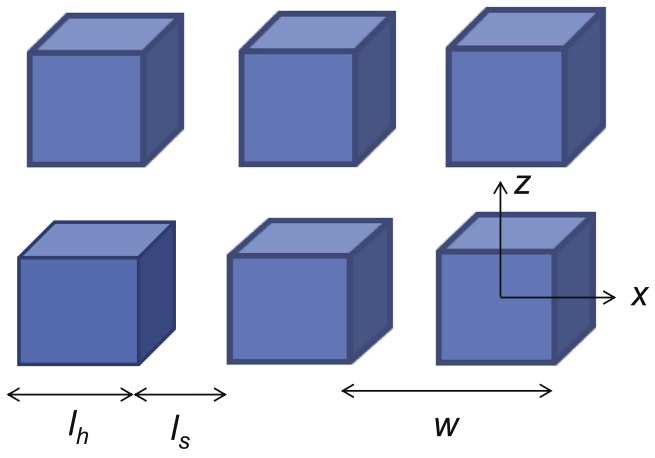

Fig. 1. Geometry of hard-soft periodic structure. The z axis is the easy axis for the hard and soft phases.