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Magnetic polaritons in metamagnet layered structures: Spectra and localization properties

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Abstract

The magnetic polariton propagation in metamagnet layered structures is theoretically studied by using a transfer matrix approach. The layered structures considered here are made up by the stacking of two different layers (also known as building blocks, named A and B), where one of them is a metamagnetic thin film (A), while the other is a non-magnetic insulator thin layer (B). We take into account both the antiferromagnetic (AFM) and ferromagnetic (FM) phases of the metamagnetic material. For the periodic arrangement, the bulk modes are characterized by two large symmetric bands, with non-reciprocal surface modes between them. The quasiperiodic metamagnetic structure is then built up by following the Fibonacci sequence, whose long-range order effect is then investigated, giving rise to an interesting self-similar spectra and a power-law profile.

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1. Introduction

Since the discovery of the icosahedral phase on an Al–Mn alloy by Shechtman et al. [1], researches on the subject of quasiperiodic structures (QPS) have attracted a lot of attention. A fascinating feature of these structures is that they exhibit collective properties not shared by their constituent parts. Furthermore, the long-range correlations induced by the construction of these systems are expected to be reflected to some degree in their various spectra (as in light propagation, electronic transmission, density of states, polaritons, etc.), defining a novel description of disorder. Indeed, theoretical transfer matrix treatments show that these spectra are fractals (for an up to date review see Refs. [2,3]).

Advances in the fabrication of multilayer structures and its characterization, such as neutron diffraction and X-ray scattering, provide the possibility to reveal their novel features, giving a fair physical background, which spans from methods based on numerical simulation to rigorous mathematical demonstrations [4]. Furthermore,they form a new class of intriguing materials, where their macroscopic properties are designed (or controlled) by varying the thickness (or composition) of the constituent films. In fact, some of these properties may be unique to the multilayer structures and provide the potential for device applications [5].

Although the spin waves propagation on anisotropic metamagnets $FeCl_2$ and $FeBr_2$ was already previously studied [6,7], and temperature effects on these spectra were also considered [8,9], for the best of our knowledge nothing was published so far concerning the propagation, in metamagnet layered structures, of the mixed mode which arises from a magnon (the quantum of a spin wave)–photon interaction, the so-called mag-

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netic polaritons, which yields a much richer spectrum. It is therefore our aim to fill this gap by presenting in this work a comprehensive investigation of localization and scaling properties of the magnetic polaritons that can propagate in magnetic multilayer structures made up of materials A (metamagnet) and B (insulator) stacked alternately, by following the Fibonacci quasiperiodic mathematical sequence. Our model is based on a transfer matrix approach, in order to simplify the algebra, which is otherwise quite involved. The metamagnetic materials consist of ferromagnetically ordered layers, with the intralayer ferromagnetic exchange interactions being much stronger than the weak antiferromagnetic interaction between adjacent layers. We consider also the presence of a weak external magnetic field $\vec{H}$ applied perpendicular to the layers. In the regime of low temperatures and for small values of the external magnetic field $\vec{H}$, the adjacent layers of the metamagnet material order antiparallel to one another, giving the antiferromagnetic (AFM) phase. On the other hand, for larger $\vec{H}$ enough to overcome the interlayer antiferromagnetic coupling, the overall ordering is ferromagnetic (FM phase). Both cases will be considered in this work.

The plan of this Letter is as follows: in Section 2, we present the method of calculation employed here, which is based on the transfer matrix approach. The magnetic polariton dispersion relation (bulk and surface modes) is then determined. Section 3 is devoted to the discussion of the polariton's dispersion relation for the periodic and quasiperiodic structures. Further, we present also their localization profiles and the connection with a fractal/multifractal behavior through the scaling law of their bandwidth spectra.

2. General theory

Before to treat the general problem of the QPS, it is more intuitive to deal first with the simpler periodic case, in which the building blocks A (metamagnet) and B (insulator) are arranged in an alternating way $ABAB\cdots$. It is displayed in a geometry such that the z-axis coordinate is placed parallel to the easy-axis of the layers. The thickness of the magnetic (non-magnetic) layer is represented by d_A (d_B), and therefore the unit-cell thickness is given by $L = d_A + d_B$. It fills the semi-space $z \leqslant 0$, with its surface parallel to the xy plane. On the $z \geqslant 0$ region we have vacuum. The surface polariton propagation is restricted to be along the x-axis, parallel to the surface (Voigt geometry). The generalization for the QPS will be considered later.

The electric and magnetic fields are given by (s polarization):

$$\vec{H}_j(x,y,z) = (H_{xj}, 0, H_{zj}) \exp(ik_x x - i\omega t), \tag{1}$$

$$\vec{E}_j(x,y,z) = (0, E_{yj}, 0) \exp(ik_x x - i\omega t), \tag{2}$$

where for the magnetic layer we have

$$H_{xA}(z) = A^n_{1A} g_A + A^n_{2A} \bar{g}_A, \tag{3}$$

$$H_{zA}(z) = (-i/\mu_0)\big[\mu^-_{\text{eff}} A^n_{1A} g_A + \mu^+_{\text{eff}} A^n_{2A} \bar{g}_A\big], \tag{4}$$

$$E_{yA}(z) = (i/k_x)(\omega/c)\big[\mu^- A^n_{1A} g_A + \mu^+ A^n_{2A} \bar{g}_A\big], \tag{5}$$

where $g_A = \exp(k_A z)$ and $\bar{g}_A = g_A^{-1}$. Also,

$$\mu_0 = -k_x^2 + \mu_1 \varepsilon_A \omega^2/c^2, \tag{6}$$

$$\mu^\pm_{\text{eff}} = \pm k_x k_A + \mu_2 \varepsilon_A \omega^2/c^2, \tag{7}$$

$$\mu^\pm = \mu_2 - \mu_1 \mu^\pm_{\text{eff}}/\mu_0, \tag{8}$$

$$k_A = \big[k_x^2 - \mu_V \varepsilon_A \omega^2/c^2\big]^{1/2}, \tag{9}$$

$$\mu_V = \mu_1 - \mu_2^2/\mu_1, \tag{10}$$

with μ_V being the Voigt permeability. Here k_x is the in-plane wave-vector, ω is the angular frequency, c is the speed of light in vacuum, and ε_A is the dielectric constant of medium A. One can show that for the metamagnetic material

$$\mu_1 = 1 + \frac{4\pi(A_1\omega^2 - B_1)}{(\omega^2 - \omega_1)(\omega^2 - \omega_2)}, \tag{11}$$

$$\mu_2 = \frac{4\pi(A_2\omega^2 - B_2)}{(\omega^2 - \omega_1)(\omega^2 - \omega_2)}, \tag{12}$$

with A_p, B_p, ω_p ($p = 1, 2$) defined elsewhere [10]. It is worthwhile to mention that $\omega_{1,2}$ represent the two resonant frequencies of the metamagnetic material. The first one, ω_1, is related to the precession of the magnetization vector, $\vec{M}$, around the effective static field, defining the ferromagnetic phase. The second one, ω_2, which is related to the precession of $\vec{M}$ around the exchange field H_E, defines the antiferromagnetic phase.

On the other hand, for the non-magnetic layer we have

$$H_{xB}(z) = A^n_{1B} g_B + A^n_{2B} \bar{g}_B, \tag{13}$$

$$H_{zB}(z) = (-ik_x/k_B)\big[A^n_{1B} g_B - A^n_{2B} \bar{g}_B\big], \tag{14}$$

$$E_{yB}(z) = (i/k_B)(\omega/c)\big[A^n_{1B} g_B - A^n_{2B} \bar{g}_A\big], \tag{15}$$

where $g_B = \exp(k_B z)$ and $\bar{g}_B = g_B^{-1}$. Also, $k_B = [k_x^2 - \varepsilon_B \omega^2/c^2]^{1/2}$, with ε_B being the dielectric constant of medium B.

Defining, for each medium, the two column-vectors

$$|A^n_j\rangle = \begin{bmatrix} A^n_{1j} \\ A^n_{2j} \end{bmatrix}, \tag{16}$$

and using Maxwell's boundary conditions on the interfaces $z = nL + d_A$ and $z = (n+1)L$, we find, in matrix form, the following equations for the amplitudes of the electromagnetic fields:

$$M_A|A^n_A\rangle = N_B|A^n_B\rangle, \tag{17}$$

$$M_B|A^n_B\rangle = N_A|A^{n+1}_A\rangle, \tag{18}$$

where

$$M_A = \begin{pmatrix} f_A & \bar{f}_A \\ \mu^- f_A & \mu^+ \bar{f}_A \end{pmatrix},$$

$$M_B = \begin{pmatrix} f_B & \bar{f}_B \\ -(k_x/k_B) f_B & (k_x/k_B)\bar{f}_B \end{pmatrix}, \tag{19}$$

$$N_A = \begin{pmatrix} 1 & 1 \\ \mu^- & \mu^+ \end{pmatrix}, \qquad N_B = \begin{pmatrix} 1 & 1 \\ -k_x/k_B & k_x/k_B \end{pmatrix} \tag{20}$$