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Magnetostatic surface waves in an FM/LH/FM sandwiched structure

Jianing Ma, Hua Li, Qiang Zhang, Yongqi Yin and Xuan-Zhang Wang

Provincial Key Laboratory for Advanced Functional Material and Excited States Processes, School of Physics and Electronic Engineering, Harbin Normal University, Harbin 150025, People's Republic of China

E-mail: limjn@126.com (Hua Li)

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Abstract
Properties of magnetostatic surface waves in a magnetic structure with one left-handed material (LHM) film sandwiched between two ferromagnetic (FM) films are discussed, where FM films are magnetized to be saturated by an external field parallel to the film surfaces and the LHM film has a constant and negative magnetic permeability. Besides the surface magnetostatic wave lying in the same frequency range as that of a single film, two new branches of surface magnetostatic waves with negative group velocity are found in different frequency ranges. The new branches propagate along the inner surface of an FM film, but the other propagates along the outer surface.

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1. Introduction

Over 30 years ago, structures with negative electric permittivity ε and magnetic permeability μ were named 'left-handed material' (LHM) by Veselago [1] to emphasize the fact that the electric field $\vec{E}$, the magnetic field $\vec{H}$ and the wave vector $\vec{k}$ structure a left-handed system. Rapidly growing interest in left-handed metamaterials stems from their recent experimental realization [2–8] by the construction of metamaterials with both effective permittivity and negative permeability. A number of unusual physical properties were observed in experiments, such as superlensing [9–11], an inverse Snell's law [1] or an inverse Doppler effect [1].

On the other hand, most previous investigations on magnetostatic modes or polaritons of magnetic films, multilayers and superlattices were concerned with such structures in which magnetic layers are ferromagnetic (FM) or anti-FM, and nonmagnetic layers are of a common material. We note that the magnetostatic waves are situated in the microwave region for general FM materials [12, 13]; meanwhile practical examples of the LHM are also available in this region. Therefore, we have an idea to investigate magnetic excitations and polaritons in magnetic multilayers, including LHMs. In the present paper, we study the surface magnetostatic waves of an ideal structure of an LHM layer sandwiched between two FM layers in Voigt geometry.

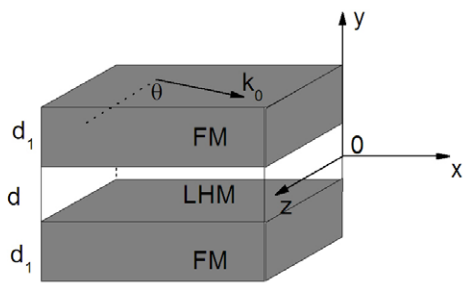

Figure 1. Scheme of an FM/LHM/FM sandwiched structure and coordinate system. $y = 0$ lies in the center of the LHM layer.

For simplicity in discussion, we assume that the LHM layer has a constant and negative magnetic permeability. Our aim is to find the influence on magnetostatic surface waves due to negative equivalent permeability of the LHM layer in the sandwich.

2. Dispersion relations of magnetostatic surface waves

An FM/LHM/FM structure is depicted schematically in figure 1, where the static magnetization (M_0) and the applied field (H_0) are pointed along the z-direction. The y-axis is normal to the layers and $y = 0$ lies in the center of the LHM layer. The surface waves propagate along the x–z plane and have an angle θ with respect to the z-axis. Two FM layers have the same thickness d_1 and are separated by an LHM layer with thickness d and negative permeability constant $\mu_n < 0$.

The permeability tensor of an FM layer in this geometry is given by

$$\mu(\omega) = \begin{pmatrix} \mu_1 & i\mu_2 & 0 \\ -i\mu_2 & \mu_1 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{1}$$

Here, μ_1 and μ_2 are two independent components of the tensor, defined by

$$\mu_1 = 1 + \omega_m\omega_0/(\omega_0^2 - \omega^2), \tag{2}$$

$$\mu_2 = \omega_m\omega/(\omega_0^2 - \omega^2), \tag{3}$$

where ω_m and ω_0 are given in terms of magnetization M_0 and external field H_0 by $\omega_m = 4\pi\gamma M_0$ and $\omega_0 = \gamma H_0$.

The derivation of the dispersion equation is standard. We first introduce a scalar potential φ so that $\vec{h} = \nabla\varphi$ and $\vec{b} = \vec{\vec{\mu}}(\omega)\cdot\vec{h} = \vec{\vec{\mu}}(\omega)\cdot\nabla\varphi$. The magnetic potential in different spaces is indicated by

$$\varphi = A_0 e^{-\alpha_0 y} e^{i\vec{k}\cdot\vec{r}} \quad \left(y > d_1 + \frac{d}{2}\right), \tag{4}$$

$$\varphi = (A_1 e^{-\alpha y} + B_1 e^{\alpha y}) e^{i\vec{k}\cdot\vec{r}} \quad \left(\frac{d}{2} < y \leqslant d_1 + \frac{d}{2}\right), \tag{5}$$

$$\varphi = (A e^{-\alpha_1 y} + B e^{\alpha_1 y}) e^{i\vec{k}\cdot\vec{r}} \quad \left(-\frac{d}{2} < y \leqslant \frac{d}{2}\right), \tag{6}$$

$$\varphi = (A'_1 e^{-\alpha y} + B'_1 e^{\alpha y}) e^{i\vec{k}\cdot\vec{r}} \quad \left(-d_1 - \frac{d}{2} < y \leqslant -\frac{d}{2}\right), \tag{7}$$

$$\varphi = A'_0 e^{\alpha_0 y} e^{i\vec{k}\cdot\vec{r}} \quad \left(y < -d_1 - \frac{d}{2}\right), \tag{8}$$

where $\vec{k}$ and $\vec{r}$ are the two-dimensional vectors in the x–z plane. By using the magnetostatic wave equation $\nabla\cdot\vec{b} = 0$, the attenuation constants are

$$\alpha_0 = \alpha_1 = k_0, \tag{9}$$

$$\alpha = \sqrt{k_x^2 + k_z^2/\mu_1}, \tag{10}$$

where $k_x = k_0 \sin\theta$ and $k_z = k_0\cos\theta$. The boundary conditions of φ and b_y continuous at the interfaces lead to a group of linear equations of the amplitudes in solutions (4)–(8), and the coefficient determinant of this group equal to zero gives us the dispersion relation

$$\sinh(k_0 d)C + \cosh(k_0 d)D = 0 \tag{11}$$

with

$$\begin{aligned} C = {} & [-(\mu_1\alpha)^2 + (\chi_2\sin\theta)^2 - \mu_n^2] \\ & \times [(\mu_1\alpha)^2 - (\chi_2\sin\theta)^2 + 1] \\ & \times \sinh^2(k_0\alpha d_1) - (1+\mu_n^2)(\mu_1\alpha)^2 - \mu_1\alpha\sinh(2k_0\alpha d_1) \\ & \times [(\mu_1\alpha)^2 - (\chi_2\sin\theta)^2 + \mu_n^2], \end{aligned} \tag{12}$$

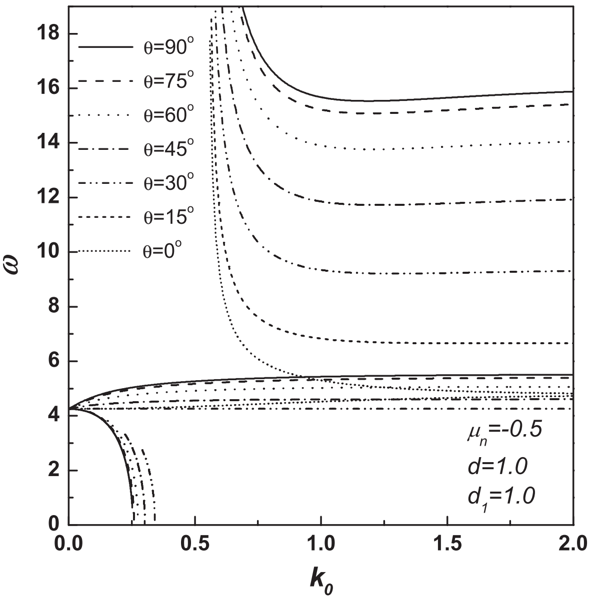

Figure 2. Surface mode frequency as a function of k_0 for various values of θ and $\mu_n = -0.5$.

$$\begin{aligned} D = {} & \mu_1\mu_n\alpha\{[-(\mu_1\alpha)^2 + (\chi_2\sin\theta)^2 - 1]\sinh(2k_0\alpha d_1) \\ & - 2\mu_1\alpha\cosh(2k_0\alpha d_1)\}. \end{aligned} \tag{13}$$

For the surface modes, a necessary condition is that α must be real and positive, implying the inequality

$$\sin^2\theta + \cos^2\theta/\mu_1 > 0. \tag{14}$$

Equations (11) and (14) completely determine the dispersion properties of the magnetostatic surface modes, that is, the mode frequency as a function of the propagation direction and external static field. Equation (11) must imply completely different results for $\mu_n < 0$, due to the presence of an odd-power term of μ_n in the coefficient D.

3. Numerical results and discussion

In this section, we numerically illustrate the results for an FM/LHM/FM sandwiched structure, with the FM parameters being $4\pi M_0 = 5.6$ kG, $\gamma = 1.97\times10^{10}$ rad s^{-1} kG^{-1} and $H_0 = 2.0$ kG.

In figure 2, we plot the surface mode frequencies as functions of k_0, with θ as a changeable parameter. Besides the surface magnetostatic wave lying in the same frequency scope as that of a single FM film, there appear two new branches of the surface magnetostatic wave for a negative value of μ_n, $\mu_n = -0.5$. The surface branch situated in the low-frequency region decreases in frequency and finally ends at the point of $\omega = 0$ and a finite value of k_0, as k_0 is increased; meanwhile it obviously has a negative group velocity $\partial\omega/\partial k_0 < 0$ that in the high-frequency range also decreases in frequency as k_0 is increased, i.e. this branch has a negative group velocity too. One interesting thing is that for $\theta = 0°$, the high-frequency surface wave smoothly enters into the frequency range of the middle branch by changing k_0. What is more, the low-frequency branch of the surface wave does not exist for $\theta = 0°$ and $15°$, and the middle-frequency branch does not either.

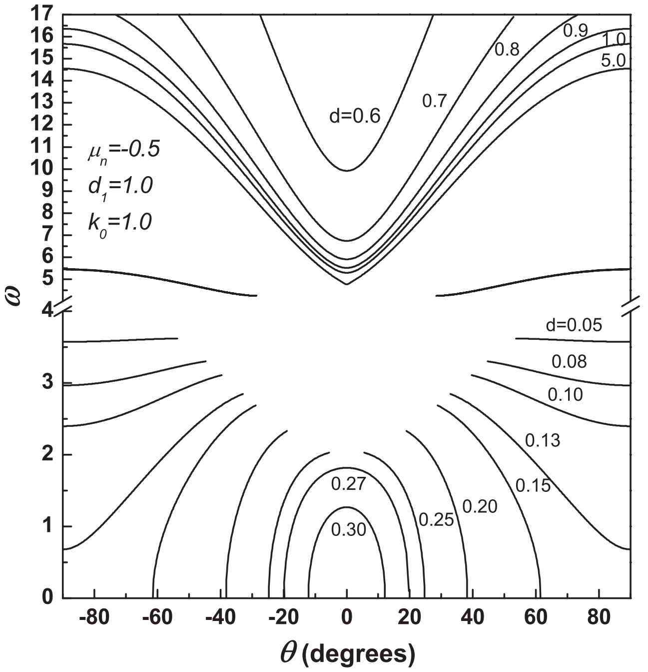

Figure 3. Surface mode frequency versus θ for various values of d and $\mu_{\mathrm{n}} = -0.5$.

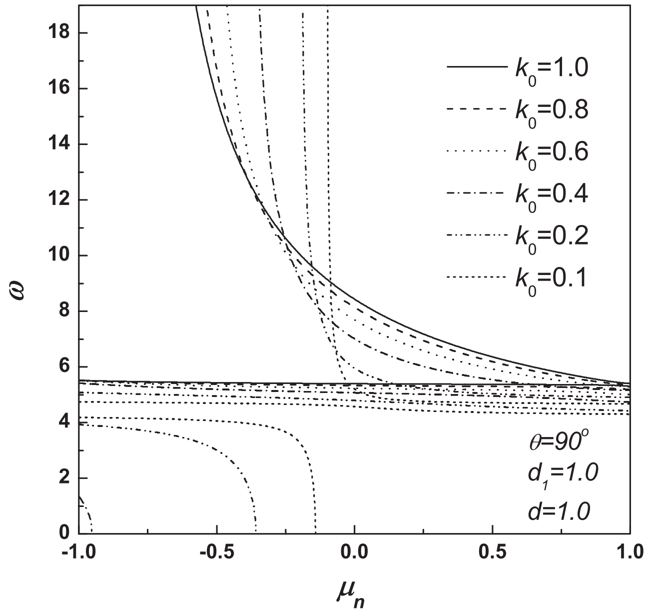

Figure 4. Surface mode frequency versus μ_{n} for various values of k_0.

As an alternative, we show in figure 3 surface mode frequencies versus θ with d as a changeable parameter, where we also see the two new surface wave branches besides the middle surface wave branch. When a relatively small value of d is taken, a new surface mode appears at the low-frequency range. As d further decreases, the LHM perturbation becomes small and the surface wave curves close up to the curves corresponding to that of a single FM film. When the thickness of the LHM layer takes a relatively big value, the other new surface mode will appear at the high-frequency range.

Finally, we examine magnetostatic waves versus permeability μ_{n} for various values of wave vector k_0, as shown in figure 4. It is indeed that the low-frequency mode can be seen only for negative values of μ_{n}, but the high-frequency branch can exist in a wider range of $\mu_{\mathrm{n}} < 1.0$. For $\mu_{\mathrm{n}} > 1.0$, the high-frequency mode and middle branch merge into a mode. For both low and high branches, the mode frequency clearly decreases as μ_{n} increases, implying that the two branches propagate along the inner surface of an FM layer. The middle-frequency branch does not change obviously with μ_{n}, showing that this mode is localized at the outer surface of an FM layer.

In summary, we have investigated the magnetostatic surface modes of a sandwiched structure composed of a left-handed medium and two ferromagnetic layers in Voigt geometry. According to the numerical results, in contrast to the conventional FM sandwich, the sandwiched structure with the LHM layer discussed in this paper could provide two new interesting branches of magnetostatic surface modes situated over the low-frequency and high-frequency regions, respectively. Both of them have negative group velocity and propagate along the inner surface of an FM layer. The middle-frequency branch possesses a positive group velocity and propagates along the outer surface, occupying a small frequency region. If it is possible to manufacture such a sandwich over some frequency range, it may be used to control the dispersive effects of materials in metamaterial modeling.

Acknowledgments

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