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Surface retarded modes of magnetic superlattices with antiferromagnetic coupling

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Abstract

We calculate retarded modes of lateral magnetic superlattices with antiferromagnetic interlayer coupling, which are described with an effective medium theory. There can be two magnetic orderings in these superlattices; the flop spin and parallel spin orderings in an external magnetic field normal to magnetic or nonmagnetic layers. We find that in the Voigt geometry the frequency of surface modes versus the external magnetic field and the interlayer coupling is very different in these two different magnetic orderings. The mode frequency, in the first ordering, is rather sensitive to the interlayer coupling. We also find two critical values of the external field for the presence of the surface mode.

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The magnetic superlattices or multilayers are intriguing materials, which consist of films of a ferromagnetic material with nonmagnetic spacers. Among magnetic superlattices or multilayers, the most interesting systems are of antiferromagnetic interlayer coupling, since one can see the giant magnetoresistive effect or other interesting features in them. In the previous works [1–4], we investigated retarded modes and magnetostatic modes of lateral magnetic/nonmagnetic superlattices and found some distinctive features. Now it has not been difficult to produce a lateral magnetic superlattice or a similar structure. One can imagine growing a common superlattice composed of magnetic layers with nonmagnetic spacer layers, and this structure cut and looked at edge-on is just a lateral magnetic superlattice. In addition, one can also grow a single magnetic film and then produce grooves in this film by the photolithographic or etching technologies [5,6], and the consequent structure may be considered as a lateral magnetic superlattice film. Although we presented some results and discussions on the retarded modes of lateral magnetic superlattices [1,2], the influences of interlayer coupling on such kind of modes have not been considered. For common magnetic/nonmagnetic superlattices with

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an antiferromagnetic interlayer coupling, magnetostatic modes were investigated by using an effective-medium method [7,8], but the magnetostatic waves of such a structure with a lateral surface were discussed with a similar method [3] and it was found that there is a critical value of the applied external field, or say for the existence of surface magnetostatic modes the external field must be larger than this value. In view of theory, magnetostatic modes are obtained in the limitation situation for the retarded modes, in which the retard term in the Maxwell equations is ignored completely, so the investigation of retarded modes in such a structure is of theoretical interest. In general, one is interested in magnetostatic modes of ferromagnets, which can be measured by Brillouin light scattering (BLS) and ferromagnetic resonance (FMR), and retarded modes of antiferromagnets, which can be examined by the attenuated total reflection method (ATR) [9,10], in view of the experiment. In the system used by us, every magnetic layer is of ferromagnetic ordering, but the magnetic orderings of adjoining magnetic layers are of opposite directions in the absence of an applied external field, due to the antiferromagnetic interlayer coupling. This feature in the superlattice is similar to that of an antiferromagnet. It is also one of our objectives to examine retarded modes in this structure. Since many magnetic superlattices are fabricated from very thin films, whose thickness is quite small as compared with the wavelength of spin waves excited in various experiments, one often uses an effective-medium method to describe these superlattices so that some simple and analytical results can be obtained.

In this paper, we calculate and discuss the retarded modes, especially a surface retarded mode, of a lateral ferromagnetic/nonmagnetic superlattice with an antiferromagnetic interlayer coupling. We assume that the wavelength of spin waves is much larger than the thickness of magnetic layers and nonmagnetic layers in the superlattice, so an effective-medium method can be used. The geometry is shown in Fig. 1 where the external field $\mathbf{H}_0$ is normal to the layers and parallel to the z-axis. Each unit cell contains four layers, two magnetic layers of thickness d_1 and two nonmagnetic layers of thickness d_2. In the ground state, the magnetizations $\mathbf{M}^a$ and $\mathbf{M}^b$ of the two magnetic layers are not parallel and rotate away from the z-axis by an angle α, in the presence of the external field $\mathbf{H}_0$ and the antiferromagnetic interlayer exchange. The angle between the z-axis and the magnetizations is determined by [3]

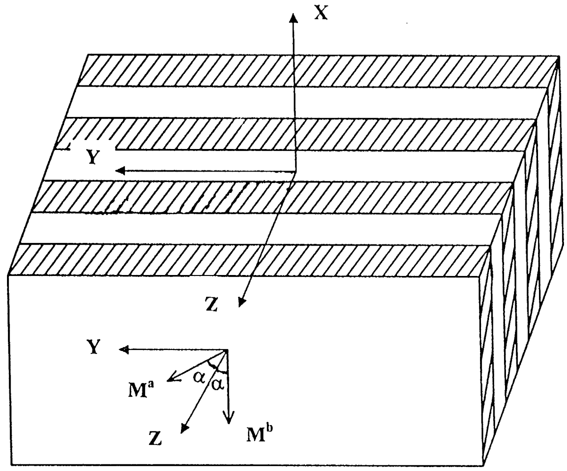

Fig. 1. Geometry for this letter. The superlattice lies in the $x<0$ half space and an external field sets along the z-axis. α is the angle between the magnetizations and the z-axis and the waves propagate along the y-axis.

$$\cos\alpha = \frac{\gamma H_0}{4\pi\gamma M_0 + 2\gamma H_e} = \frac{\omega_0}{\omega_m + 2\omega_e}, \tag{1}$$

where $H_e = H_{ex}/L_m$ is an average coupling strength on every magnetic atomic layer, but H_{ex} and L_m are the interlayer coupling and number of atomic layers contained in the magnetic layers. It is easy to see that when H_0 is larger than $4\pi M_0 + 2H_e$, $\mathbf{M}^a$ and $\mathbf{M}^b$ are parallel to the z-axis. The effective-medium magnetic permeability tensor is described by [3]

$$\overleftrightarrow{\mu} = \begin{bmatrix} \mu_{xx} & i\mu_{xy} & 0 \\ -i\mu_{xy} & \mu_{yy} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

where

$$\mu_{xx} = 1 + \frac{f_1\omega_m(\omega_i\cos\alpha + \omega_m\sin^2\alpha)}{\omega_i^2 + 2\omega_m\omega_e\sin^2\alpha - \omega^2}, \tag{3a}$$

$$\mu_{yy} = 1 + \frac{f_1\omega_m\omega_i\cos\alpha}{\omega_i^2 + 2\omega_m\omega_e\sin^2\alpha - \omega^2} \tag{3b}$$

and

$$\mu_{xy} = \frac{f_1\omega_m\omega\cos\alpha}{\omega_i^2 + 2\omega_m\omega_e\sin^2\alpha - \omega^2}, \tag{3c}$$

with $\omega_i = \omega_0 - \omega_m\cos\alpha$. $f_1 = L_m/(L_m + L_n)$ is the magnetic fraction, and L_m and L_n are the numbers of atomic layers in a magnetic and nonmagnetic layer in a unit cell, respectively. The characteristic frequencies ω_0, ω_e and ω_m are related to the fields H_0, H_e and the magnetization M_0 by $\omega_0 = \gamma H_0$, $\omega_e = \gamma H_e$ and $\omega_m = \gamma M_0$, respectively. The gyromagnetic ratio $\gamma = \gamma_e g/2$, where $\gamma_e = 1.759 \times 10^7$ rad/G is the value of γ for the free electron and g is the spectroscopic splitting factor.

In the flop spin state, the equilibrium angle α is in a range from 0–90° and the condition is $0 \leqslant H_0 \leqslant 4\pi M_0 + 2H_e$. In the spin parallel state $\alpha = 0°$, with the condition $H_0 \geqslant 4\pi M_0 + 2H_e$; the superlattice is then equal to that in Ref. [4].

As we know, one of the most striking properties of magnetic superlattices composed of magnetic transition metal and nonmagnetic material is that the interlayer coupling oscillates with the thickness of the nonmagnetic layers. Thus, it is possible to determine the type, even the amplitude of the interlayer coupling by specifying the thickness of the nonmagnetic layers. Here we take an antiferromagnetic coupling between two ferromagnetic layers and assume that its amplitude H_{ex} is fixed (or the thickness of the nonmagnetic layers is fixed); so the effects of the interlayer coupling decreases as the thickness of the magnetic layers is increased.

We take the Voigt geometry in which waves propagate along the y-axis and the x-axis perpendicular to the surface, to calculate and discuss the dispersion properties of the retarded modes in this system. In this geometry, the electric field of the modes has a vibration direction perpendicular to the layers in the superlattice, so if we take the nonmagnetic spacer layers of the insulator, the contribution of eddy current to the modes may be slight [5] and this point can be seen later. In this case, we can neglect the eddy influence. The alternating magnetic field of retarded modes in different regions can be written as

$$\vec{h} = \vec{h}_{01}\exp(-\alpha_0 x)\exp(iky - i\omega t) \quad (x > 0), \tag{4a}$$

$$\vec{h} = \vec{h}_{02}\exp(\alpha x)\exp(iky - i\omega t) \quad (x < 0), \tag{4b}$$

in which α_0 and α are real and positive for the surface mode, and are imaginary for the bulk modes. Applying the Maxwell equation $\nabla\times\vec{e} = -\partial\vec{b}/\partial t$ and $\nabla\times\vec{h} = \partial\vec{d}/\partial t$ with $\vec{b} = \overleftrightarrow{\mu}\cdot\vec{h}$ and $\vec{d} = \overleftrightarrow{\varepsilon}\cdot\vec{e}$, one has

$$\alpha_0^2 = k^2 - \varepsilon_0\omega^2 \tag{5a}$$

and

$$\alpha^2\mu_{xx} - k^2\mu_{yy} + \varepsilon_{zz}\omega^2(\mu_{xx}\mu_{yy} - \mu_{xy}^2) = 0, \tag{5b}$$

where ε_0 is the dielectric constant above the superlattice and the effective dielectric coefficient tensor in it is a diagonal matrix with [5]

$$\varepsilon_{zz} = \frac{\varepsilon_1\varepsilon_2}{f_1\varepsilon_2 + f_2\varepsilon_1}, \tag{6a}$$

$$\varepsilon_{xx} = \varepsilon_{yy} = f_1\varepsilon_1 + f_2\varepsilon_2. \tag{6b}$$

As we select such a superlattice composed of metallic ferromagnetic layers and insular nonmagnetic layers, $\varepsilon_1 = \varepsilon_0\left(1 + i\,\sigma/\omega\varepsilon_0\right)$ is the effective dielectric constant of magnetic layers and is very large (or a very large imaginary part), and ε_2 is the constant of nonmagnetic layers and is generally smaller than $\varepsilon_0 \times 10^1$. Therefore Eq. (6a) can be reduced approximately as

$$\varepsilon_{zz} = \frac{\varepsilon_2}{f_2}. \tag{7}$$

We see from Eqs. (7) and (5b) that only this component influences dispersion properties and is real, and the thinner the nonmagnetic layers are, the larger is ε_{zz}. It is not difficult to understand this feature in physics. One may imagine that the thinner the nonmagnetic layers are relatively, the larger the induced electric dipole moments in unit volume is, as electrons in a magnetic layer cannot pass the insular layer to go into another. In addition to these, the nonmagnetic fraction f_2 determines the effective dielectric constant ε_{zz}, and when the relative thickness of nonmagnetic layers is small, one has a large effective dielectric coefficient. Thus f_2 (f_1) may dramatically influence the dispersion properties of the modes. Employing the boundary conditions h_y and e_z continuous at

$x = 0$, and combining Eqs. (5), we get another simple result

$$\alpha\mu_{xx} + k\mu_{yy} + \alpha_0(\mu_{xx}\mu_{yy} - \mu_{xy}^2) = 0. \tag{8}$$

Eqs. (5) and (8) with the requirements of positive α_0 and α can completely determine the dispersion properties of the surface mode. If we take $\alpha = ik_x$ and $k = k_y$ in Eq. (5b), this equation describes the bulk modes propagating in the $x-y$ plane, but if one let $\alpha = 0$ in Eq. (5b), the bulk modes propagating along the y-axis are determined.

For general ferromagnets and magnetic superlattices without the interlayer antiferromagnetic coupling, the frequency of surface modes increases with external magnetic field H_0, since the resonant frequency increases as H_0 is strengthened. If the bulk modes are reciprocal or $\omega(k) = \omega(-k)$, the surface mode is nonreciprocal. For our system, an angle between two magnetizations in a unit cell appears and changes with the field H_0, so the mode frequency may change with the field in a different manner. In addition, we also want to know how the exchange coupling influences dispersion properties of the retarded modes.

In numerical calculations, we assume the metal ferromagnetic layers are of Fe with the parameters $4\pi M_0 = 17.6\,\text{kG}$ and $\gamma = 1.85 \times 10^7$ rad/G and L_n is fixed at $L_n = 4$, but the values of H_{ex}, H_0 and L_m can be selected. In addition, the dielectric constant $\varepsilon_2 = 1.5$ for the insular nonmagnetic layers and $\varepsilon_0 = 1.0$ and $\mu_0 = 1.0$ in the space above the superlattice. For numerical calculations and results, we use kG as the unit of frequencies and wave number, so there are two conversions, $1\,\text{kG} = 2.94\,\text{GHz}$ for the frequencies and $1\,\text{kG} = 9.8\,\text{m}^{-1}$ for wave number k.

We, first, present Fig. 2 to show the spectrum structure. The shaded areas are the bulk continua and the curves represent the surface mode. The surface mode with k positive starts from the top boundary of the bottom bulk continuum and corresponds to $\mu_{xx} = 0$, or the starting frequency is

$$\omega = [\omega_i(\omega_i + f_1\omega_m\cos\alpha) + (2\omega_e + f_1\omega_m)\omega_m\sin^2\alpha]^{1/2}. \tag{9}$$

Substituting this value into Eq. (5) or Eq. (8), we get the wave number at this frequency, i.e.:

$$k = [\omega_i^2 + 2\omega_m\omega_e\sin^2\alpha + f_1\omega_m(\omega_i\cos\alpha + \omega_m\sin^2\alpha)] \times c\tan\alpha\sqrt{\frac{\varepsilon_{zz}}{\omega_m(\omega_i\cos\alpha + \omega_m\sin^2\alpha)}}. \tag{10}$$

The frequency of this surface mode increases with wave number, and possesses a magnetostatic limit. The surface mode with k negative, however, begins from such a point at which $\alpha_0 = 0$ (or $-k = \omega$) and ends at the boundary line of the upper bulk continuum, $\alpha^2 = 0$. Using Eqs. (7) and (8) we can also determine the expressions of ω and k corresponding to these points, but they are rather complicated, so are not shown here. Fig. 2a is related to the superlattice in which every magnetic layer contains more magnetic atomic layers, $L_m = 40$ that means $f_2 = 0.09$ and $\varepsilon_{zz} = 16.67$, but Fig. 2b corresponds to that with $L_m = 20$ related to $f_2 = 0.125$ and $\varepsilon_{zz} = 12.0$. These two figures have similar patterns, but are numerically different. We should also note that the surface mode for k negative is of low dispersion and for $\omega = -k$, there is no dispersion.

The frequency of the surface mode as a function of external magnetic H_0 is illustrated in Fig. 3, with fixed wave numbers. Fig. 3a with $k = 9$ obviously shows two magnetic orderings, the spin flop and parallel states. In the first state, the mode frequency decreases as the field is strengthened. In the second state, it increases with the field. The decrease of the frequency with the increase of the field, in the flop state, results from the interlayer exchange coupling. This feature of the ferromagnetic/nonmagnetic superlattices with interlayer antiferromagnetic coupling is quite unique. In addition, we see a critical value of the field, which means that the surface mode cannot exist in the flop spin structure as the field is smaller than this value. At this value, the starting mode frequency is equal to its magnetostatic limit. This critical value is determined by

$$H_{0c} = \frac{1}{\sqrt{1 + f_1}}(4\pi M_0 + 2H_e). \tag{11}$$

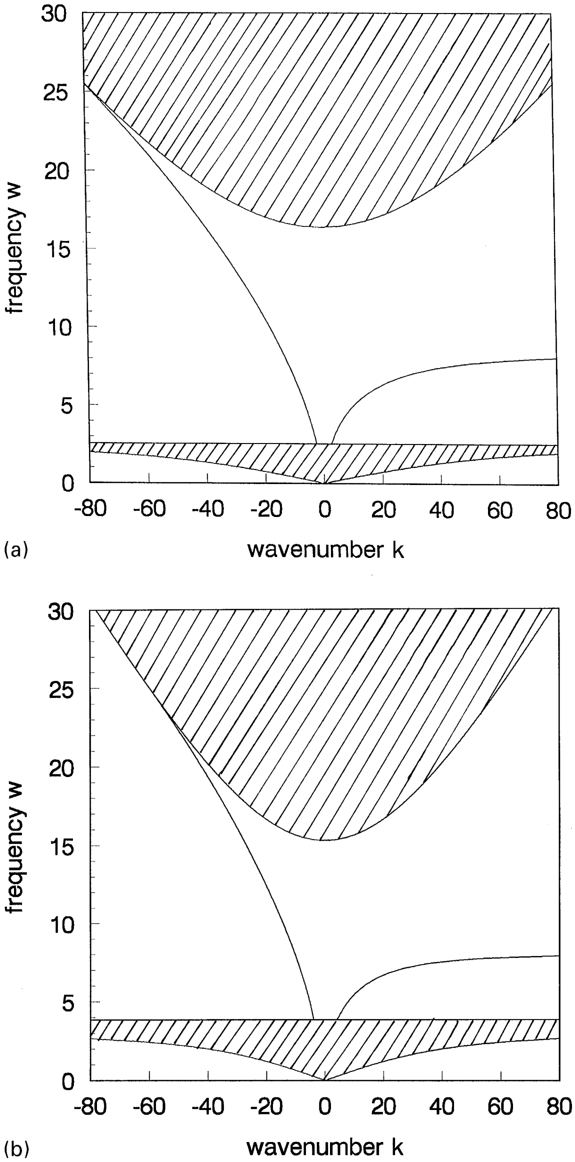

Fig. 2. Spectrum structure of retarded modes for $H_0 = 18.0\,\text{kG}$ and $H_{ex} = 6.0\,\text{kG}$; (a) $L_m = 40$ and (b) $L_m = 20$. The shaded areas represent the bulk continua and the curves show the surface mode.

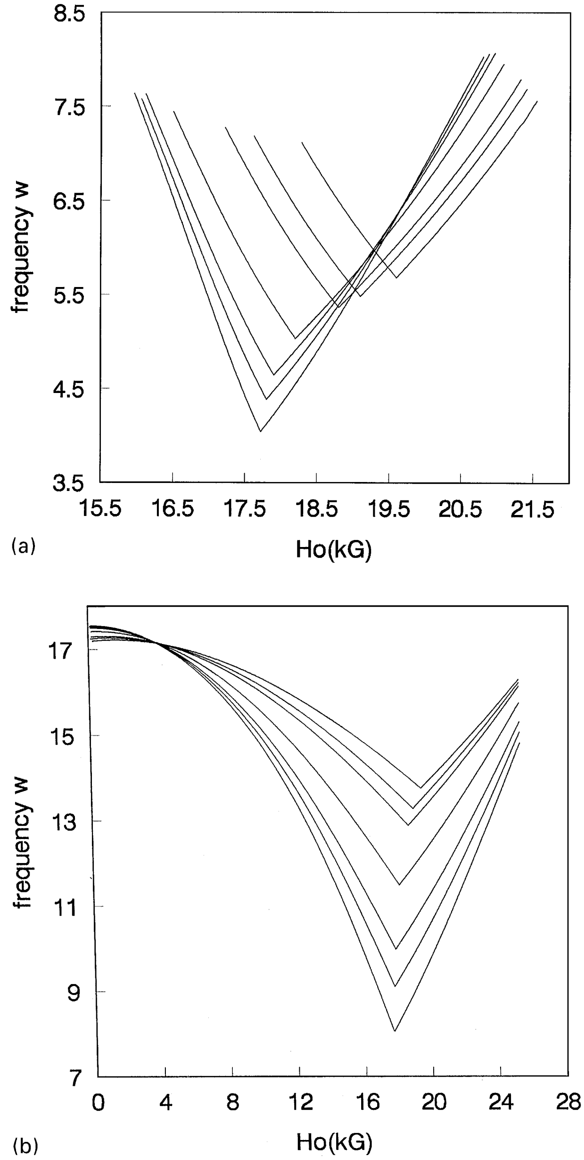

Fig. 3. Frequency of surface mode versus external field H_0 for $H_{ex} = 6.0\,\text{kG}$; (a) $k = 9\,\text{kG}$ and (b) $k = -18\,\text{kG}$. Curves from bottom to top correspond to $L_m = 100$, 60, 40, 20, 10, 8, and 6, respectively.

Practically, this surface mode and its magnetostatic limit both do not exist for $H_0 < H_{0c}$ [3]. In the parallel spin state, the mode frequency increases with H_0, but if H_0 is larger than a finite value, the condition $\alpha_0 > 0$ is no longer satisfied, so the surface mode terminates at this value. Fig. 3b shows that the surface mode versus H_0 for that wave number is negative and $k = -18$ (kG). The $-k$ surface mode changes more sensitively with H_0 in the two states than $+k$ surface mode. From this figure we can also see such a point at which this mode frequency does not change with f_1.

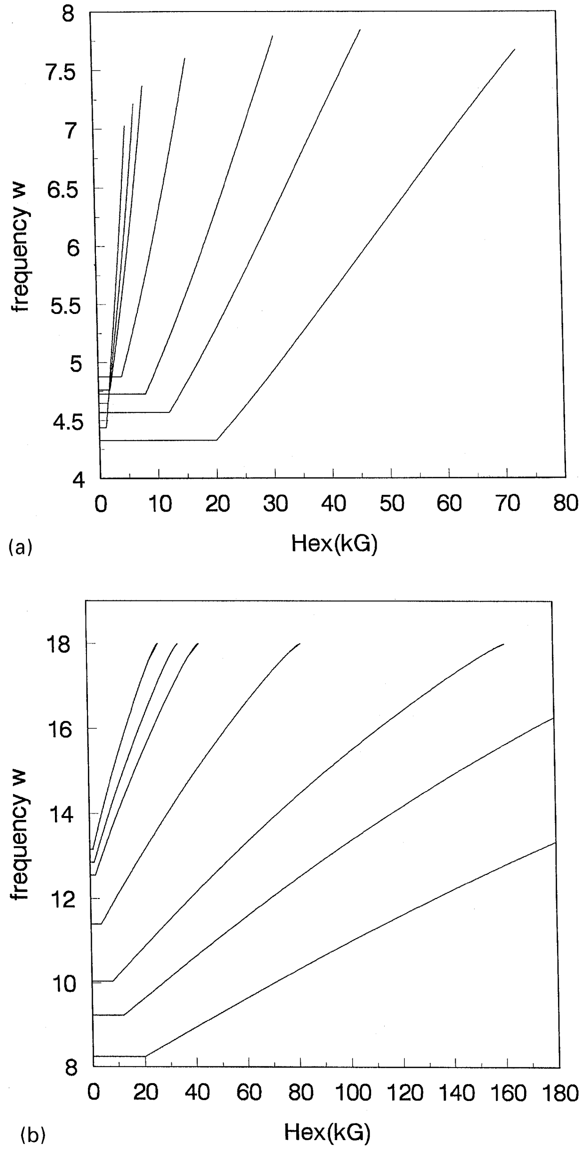

Fig. 4. Frequency of surface mode as a function of interlayer coupling field H_{ex} for $H_0 = 18\,\text{kG}$; (a) $k = 9.0\,\text{kG}$ and (b) $k = -18.0\,\text{kG}$. Curves from the right to left are related to $L_m = 100$, 60, 40, 20, 10, 8 and 6, respectively.

Figs. 3a and b show that at the transition point from the flop spin state to the parallel spin state, the surface mode is softened.

It is also interesting to note how the surface mode varies with the interlayer coupling. Figs. 4a and b show the frequency of surface mode versus H_{ex}, for $H_0 = 18$ (kG). For $k = 9$ (kG), a positive value, Fig. 4a illustrates that the surface mode changes rapidly with the interlayer coupling field H_{ex}, especially for smaller L_m. When this coupling field is decreased and smaller than a finite value, the state is changed from the flop into the parallel spin state so that effects of the coupling field on the modes disappear and the frequency does not vary with it. It may be possible that one can obtain information of interlayer antiferromagnetic coupling by the measurement of the frequency of the surface retarded mode, as the frequency is sensitive to the coupling field. For $k = -18\,\text{kG}$, a negative value, Fig. 4b shows that mode frequency varies much more obtusely with the coupling field and the curves terminate at $\omega = 18\,\text{kG}$ since $\alpha_0 > 0$.

We have investigated retarded modes, especially the surface mode, of ferromagnetic/nonmagnetic superlattices with antiferromagnetic interlayer coupling in the Voigt geometry. We assume the external magnetic field H_0 to be in the lateral surface and transverse to metallic magnetic and insulated nonmagnetic layers in the superlattices, and the surface mode also to be propagating in this surface and perpendicular to H_0. Because of the external magnetic field and antiferromagnetic interlayer coupling the superlattices can be in one of the two spin states, or the flop spin and parallel spin states, depending on the values of H_0. In different states, the modes have different properties. In the flop spin state, the frequency of the surface mode decreases as the applied field is strengthened, but for the parallel state, the frequency increases as the field is strengthened. At the transition point, the mode is softened. The mode is very sensitive to the interlayer coupling in the flop state, but is not influenced by this coupling, in the parallel state. When H_0 is smaller than a finite value, the surface mode cannot exist, but it also cannot appear for H_0 larger than its other critical value for a fixed value of k.

For this magnetic/nonmagnetic superlattice selected for numerical calculation, the sample dimension, for $k = 10\,\text{kG}$, is required to be much larger than 1.0 mm to guarantee the existence of such kinds of nonuniform modes. If this requirement cannot be satisfied, one may observe only the uniform modes by the ferromagnetic resonance experiments (FMR). Now the attenuated total reflection (ATR) experiment has been used to study retarded modes of antiferromagnets and the obtained results are very well consistent with that predicted by the theory [9,10]. Until now, we have not observed the experimental measurements of retarded modes of ferromagnets with the ATR method. The main difficulty is that the measurements need high quality ferromagnetic samples. For our system, the effective dielectric coefficient ε_{zz} is about ten times as large as that of common materials and one can further increase this coefficient by choosing the nonmagnetic insular layers of a high dielectric constant and decreasing the relative thickness of these layers. Generally speaking, for a given frequency, a large dielectric constant corresponds to a large wave number, so the necessary dimension of a sample can be reduced for the existence of the retarded modes. Here one needs only $\lambda \gg 1.0\,\mathrm{mm}$.

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