Ferromagnetic-bilayer spin-wave resonance: Reassignment of interface-affected lines

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A microscopic theory of standing spin-wave resonance in exchange-coupled bilayer films is presented. The interface-inhomogeneity model (an effective interface exchange coupling and intrinsic uniaxial interface anisotropy parameters are introduced) and the Heisenberg model with spin (exchange and Zeeman) Hamiltonian are used to derive an energy dispersion relation and spin-wave-mode functions for exchange-coupled bilayer ferromagnetic films. The theory is valid for Bravais lattices with arbitrary film-surface or interface orientations in a configuration where the static external field is perpendicular to the film surface and the values of the ferromagnetic and antiferromagnetic interface exchange couplings are arbitrary. The analysis is based on the exact solution of the eigenvalue problem of a bilayer film achieved with the interface rescaling approach. It is shown that the pattern of the resonance spectrum is determined by the nature of the interface exchange-coupling integral J^{AB}, with the first two (high-field side) lines exhibiting pronounced intensities when the interface coupling is antiferromagnetic. We show moreover that the highest-field line arises by excitation of the mode that is localized on the bilayer interface. We also show that this mode represents a complex bilayer vibration formed by the *in-phase* combination of sublayer vibrations, and this result corrects the general belief of experimenters that the mode under consideration is due to an out-of-phase combination of sublayer vibrations.

I. INTRODUCTION

The recent developments in materials science allows one to produce good-quality layered magnetic structures; the resulting sandwiched film may present interesting physical properties since the magnetic collective excitations occurring therein differ from those of its individual magnetic components. The most characteristic feature of the resulting collective spin-wave spectrum resides in the existence of magnetic excitations localized at multilayer interfaces.[1] It is the aim of the present work to study the existence conditions for such interface-localized spin-wave excitations emerging in the simplest case of a multilayer film, i.e., that of two ferromagnetic layers directly coupled (by exchange interactions) at their interface or indirectly coupled by way of a nonmagnetic spacer. We properly take into account the recently revealed fact (see, e.g., Refs. 2 and 3, and references therein) that the interface exchange coupling can be ferromagnetic or antiferromagnetic. Among the various properties of multilayer magnetic films studied in the literature, the resonance investigation of their spin-wave excitations has become of particular interest. We shall show that when a multipeak resonance is observed the highest-field peak is identifiable as the interface spin-wave mode. The nature of this resonance line of the spin-wave resonance spectrum provides a convenient source of direct information concerning the interface coupling.

We shall restrict our discussion from the very beginning to standing spin waves, since only such modes are excited in the ferromagnetic-resonance experiments (performed on thin films) and lie within the scope of our interest. The method of calculation will be presented in detail in a separate paper; here, we give only the results and their discussion. The ferromagnetic-resonance effect observed in multilayer films has hitherto been considered predominantly in papers based on the phenomenological approach.[4-11] In this paper we propose an *exact microscopic* theory of spin-wave resonance in thin bilayer ferromagnetic films, taking into account that the sublayer spins are exchange coupled through the interface; our present work presents a natural extension of our previous results,[12] derived when considering single-layer films only.

II. MODEL

Let us consider a film consisting of two *identical* homogeneous ferromagnetic thin layers (sublayers A and B); the two sublayers form a single magnetic system owing to the interface exchange coupling. We assume that the externally applied static field $\mathbf{H}_{ex}$ is oriented perpendicular to the film surface. We assume its strength lies in a range corresponding to the ferromagnetic-resonance conditions; for such values of the field H_{ex}, one is justified in assuming that all the spins of the bilayer sample are aligned parallel to one other in the direction normal to the film surface. All spins lying in the same lattice plane parallel to the surface are in identical physical conditions, forming a magnetic sublattice to be referred to in brief as a *monolayer*. The two sublayer surfaces that form the interface will be referred to as the *interface monolayers*.

A spin is labeled by an index $l\mathbf{j}$, where l is a number denoting the monolayer and $\mathbf{j}$ is a two-dimensional vector lying in the plane of the film. The index l takes the following values for the respective monolayers: $l=0$ (surface monolayer A), $l=1,2,\ldots,N-2$ (internal planes A), $l=N-1$ (interface monolayer A), $l=N$ (interface monolayer B), $l=N+1,N+2,\ldots,L-2$ (internal planes B), and $l=2N-1$ (surface monolayer B). The

effective field acting on a given spin is defined as the sum of the external static field, the uniaxial bulk-anisotropy field, and the sublayer demagnetization field:

$$\mathbf{H}^{\text{eff}}=\mathbf{H}_{\text{ex}}+\mathbf{H}_a-4\pi\mathbf{M}\ . \tag{1}$$

Here, to emphasize the interface effects, we neglect the surface-anisotropy fields; their inclusion into the model is planned for the extension of this work and poses no mathematical difficulty.

We perform our calculation within the framework of the Heisenberg localized-spin model assuming a nearest-neighbor exchange interaction, a uniaxial interfacial anisotropy, and a Zeeman Hamiltonian in standard form:

$$\hat{\mathcal{H}}=-\sum_{(l,\mathrm{j};l',\mathrm{j}')} J_{ll'}\hat{\mathbf{S}}_{l\mathrm{j}}\cdot\hat{\mathbf{S}}_{l'\mathrm{j}'}-K^{AB}\sum_{(\mathrm{j};\mathrm{j}')}\hat{S}^z_{N-1;\mathrm{j}}\hat{S}^z_{N;\mathrm{j}'} -g\mu_B H^{\text{eff}}\sum_{l,\mathrm{j}}\hat{S}^z_{l\mathrm{j}}\ , \tag{2}$$

where summations $(l\mathrm{j};l'\mathrm{j}')$ and $(\mathrm{j};\mathrm{j}')$ extend over pairs of neighboring spins and the z axis is chosen perpendicular to the film surface. The exchange integral $J_{ll'}$ between nearest neighbors situated, respectively, in the monolayer l and l' is assumed to be $J_{ll'}=J_{\text{bulk}}$ if both interacting spins belong to the same sublayer (A or B) and $J_{ll'}=J^{AB}$ if the interacting spins belong to different sublayers (i.e., coupling through the interface). The interface exchange integral J^{AB} is allowed to take both positive (ferromagnetic) as well as negative (antiferromagnetic) values, in accordance with recent experimental findings. Similarly, the interface-anisotropy constant K^{AB} is allowed to be either of an easy-axis type ($K^{AB}>0$) or an easy-plane type ($K^{AB}<0$). The Hamiltonian (2) is diagonalized by applying the procedure described in detail in a separate paper.[12] The diagonalization leads to the determination of the wave functions and spin-wave excitation energies permitted in our bilayer film.

In the following sections, we shall restrict ourselves to the presentation of results concerning *standing* spin waves (modes) only, leaving the discussion of propagating spin waves for a separate paper. Having this restriction in mind, we deliberately have not included into our Hamiltonian (2) magnetic dipole-dipole interactions, since it has been shown by Grünberg and co-workers[13,14] that long-range dipolar coupling disappears when the in-plane wave vector of the spin wave is zero.

III. STANDING SPIN WAVES

Standing spin waves are excited in ferromagnetic-resonance experiments performed within thin films. The effect is called "spin-wave resonance" (SWR) and consists of the excitation of consecutive modes, each characterized solely by a unique value of the wave-vector component k perpendicular to the film surface (an in-plane SWR wave vector always vanishes). Note that our Hamiltonian (2) remains symmetric under the transformation $l\leftrightarrow L-1-l$, and because of this symmetry property, one obtains spin-wave modes of only two types, namely, symmetric and antisymmetric. The respective spin-wave-mode functions can be found by applying one of the following three different approaches: recursive interface rescaling approach,[15,16] the interface response-rescaling approach,[17] or the transfer-matrix approach.[18] Here we shall be using the spin-wave functions explicitly expressed by the wave number k in the form given in our paper,[16] which also contains the characteristic equation quantizing the mode number k.

The mode energy E expressed by the wave number k is

$$E(k)=4SJ_{\text{bulk}}z(1-\cos k)+g\mu_B H^{\text{eff}}\ , \tag{3}$$

where S is the spin (in units of $\hbar$) and z is the number of nearest neighbors situated in an adjacent plane. To establish the wave number k, it is instructive first to rewrite the equation given in Ref. 16 in the form of the two equations

$$F(k)\equiv\frac{\cos\{[(2N+1)/2]k\}}{\cos\{[(2N-1)/2]k\}}=\begin{cases}1-2D_{\text{int}} & \text{(4a)}\\ 1-2(D_{\text{int}}+\mathcal{J}^{AB})\ , & \text{(4b)}\end{cases}$$

where we have introduced the new notations $\mathcal{J}^{AB}\equiv J^{AB}/J_{\text{bulk}}$ and $D_{\text{int}}\equiv K^{AB}/2J_{\text{bulk}}$. These two equa-

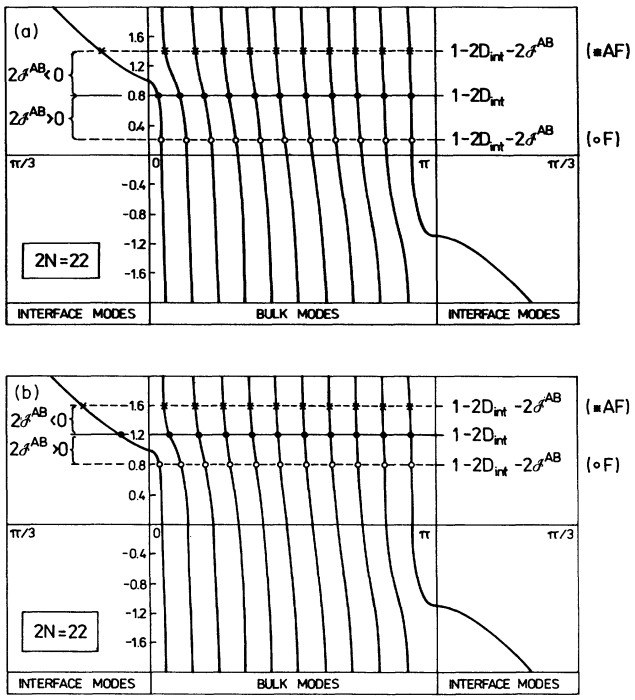


FIG. 1. Accessory graph for the discussion of the characteristic equations (4) when **M** is perpendicular to the film: (a) for interface anisotropy of easy-axis type ($D_{\text{int}}>0$) and (b) for interface anisotropy of easy-plane type ($D_{\text{int}}<0$); we denote here by *AF and oF the roots affected, respectively, by antiferromagnetic and ferromagnetic interfacial coupling. Bilayer thickness is assumed as 22 monolayers. The roots of the characteristic equation are obtained graphically by searching for the points of intersection of the two straight lines and the curves. In the central part, one obtains bulk modes; the root corresponding to the acoustic interface mode is obtained from the graph to the left, while the optical interface mode from that to the right.

tions *jointly* lead to $2N$ allowed values of the variable k, which can, in general, be complex. Only three types of k are permitted, to each of which there corresponds a different kind of spin wave:

$$\begin{aligned} &\text{(i)}\ k \text{ real (bulk modes)}, \\ &\text{(ii)}\ k = it \text{ (acoustical interface modes)}, \\ &\text{(iii)}\ k = \pi + it \text{ (optical interface modes)}, \end{aligned} \tag{5}$$

where t is a real, positive number. On inserting (5) into (3), one obtains formulas which show that the acoustical and optical interface modes have energies lying, respectively, below and above the energy band of the bulk spin-wave modes.

To visualize the k spectrum, we have plotted (Fig. 1) the function $F(k)$ defined in Eqs. (4) (in the middle for bulk modes, to the right and left for optical and acoustical interface modes, respectively). On fixing some values of the interface-coupling parameter $\mathcal{J}^{AB}$ and the interface-anisotropy parameter D_{int}, the roots of Eqs. (4) are found by searching for the points of intersection of the straight lines parallel to the abscissas and curves $F(k)$. The graph shows that we always obtain $2N$ distinct roots of k provided $\mathcal{J}^{AB} \neq 0$, and half of them are not affected by the interface coupling at all. If the interface coupling is ferromagnetic, all modes not affected by the interface coupling are symmetrical modes, while all those affected are antisymmetrical modes. For antiferromagnetic interface coupling, the reverse holds.

It will be our convention to label the spin-wave modes corresponding to distinct k values by numbers $n = 1, 2, \ldots, 2N$, starting from the energetically lowest mode. In Fig. 2 the *reduced* mode energy (simply, $-\cos k$) is plotted against the interface-coupling parameter $\mathcal{J}^{AB}$ (with the interface anisotropy D_{int} assumed, for simplicity, to be zero) for the eight energetically lowest modes of the spectrum ($n = 1, 2, \ldots, 8$). We see that modes unaffected by interface coupling ($n = 1, 3, 5, 7$ for ferromagnetic coupling and $n = 2, 4, 6, 8$ for antiferromagnetic coupling) have fixed energies, while the affected modes lower their energies as we proceed continuously from strong ferromagnetic coupling to strong antiferromagnetic coupling. However, in the case of antiferromagnetic coupling, we observe a very characteristic feature concerning the mode $n = 1$: Its energy rapidly de-

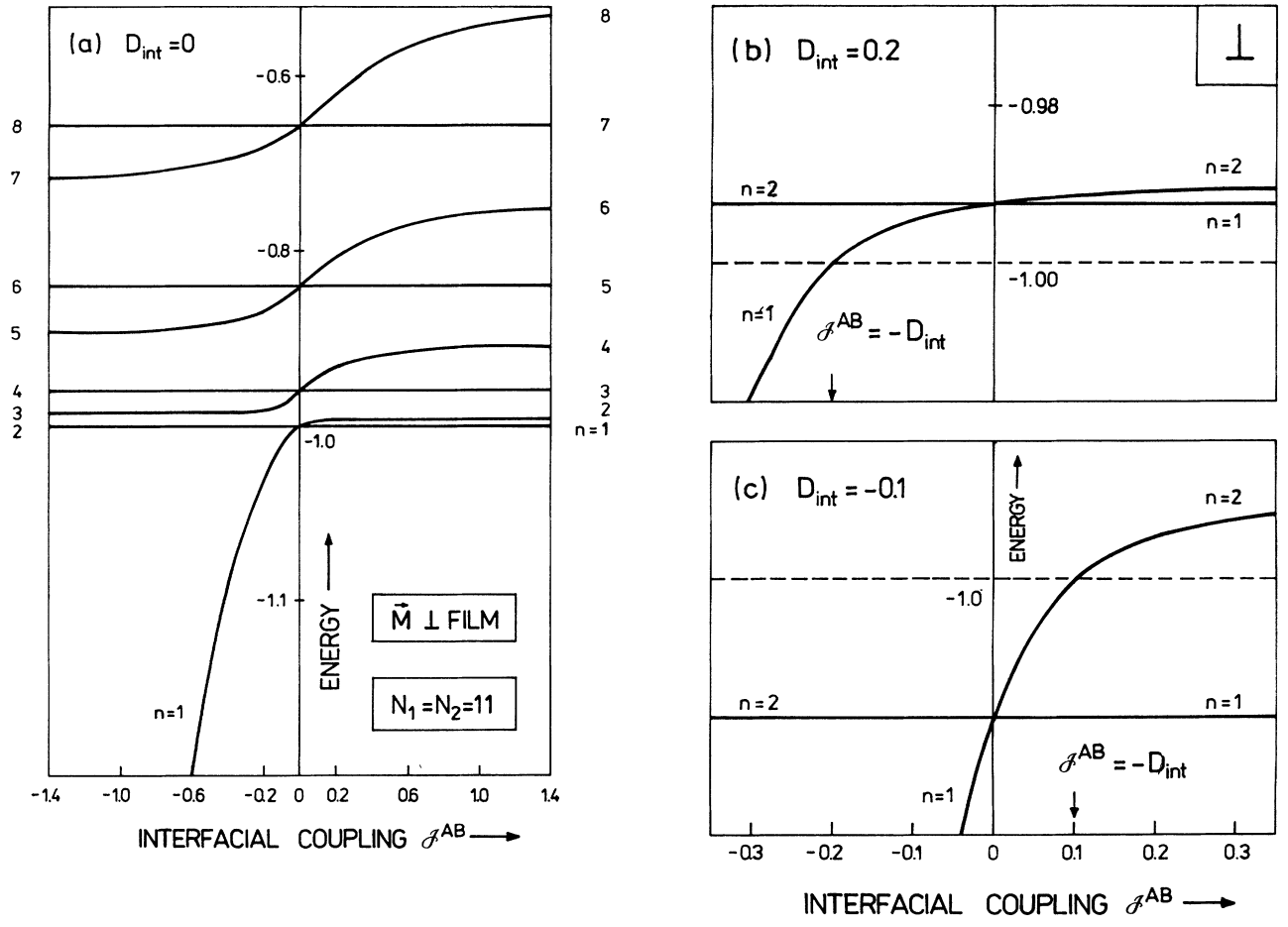


FIG. 2. (a) Bilayer spin-wave mode energies vs the interfacial coupling (n labels the modes) for the case of $D_{\text{int}} = 0$ (i.e., no intrinsic interface anisotropy). Note that for antiferromagnetic coupling the lowest mode ($n = 1$) splits off from the remaining modes: It becomes the interface-localized mode. (b), (c) The same when the interface anisotropy D_{int} is nonzero; the limiting value for the emergence of the interface mode is now $\mathcal{J}^{AB} = -D_{\text{int}}$.

creases with increasing absolute values of antiferromagnetic coupling, always staying *below* the band (in our notation, the bottom band edge corresponds to minus unity). As will be shown later on, the mode $n=1$ becomes, for antiferromagnetic interface coupling, an interface-localized mode. If the interface anisotropy D_{int} is nonzero, the emergence of the interface mode caused by the interface coupling $\mathcal{J}^{AB}$ requires that $\mathcal{J}^{AB} < -D_{\text{int}}$ [see Figs. 2(b) and 2(c)].

IV. EFFECT OF INTERFACE COUPLING ON SPIN-WAVE MODES

First, we shall discuss the formation of coupled bilayer modes for the case when the interface anisotropy is absent ($D_{\text{int}}=0$). In Fig. 3 we show the profiles of the first three eigenmodes supported by each of the sublayers when they are in isolation (sublayer modes). Since we have assumed that no surface (pinning) anisotropy is present in the sublayers, the characteristic feature of the respective spectrum consists in the existence of the *uniform* mode ($n=1$). When the sublayers become coupled, their modes enter into the process of formation of the respective complex modes supported by the newly created (by admitting interface coupling) bilayer structure; these bilayer coupled modes are shown in Figs. 3 and 4, respectively, for weak and strong interfacial coupling. Figure 3 and 4 allow us to formulate the following rules, which are obeyed during the formation of coupled modes: (i) To each of the sublayer modes, there corresponds a pair of bilayer modes, formed as a result of the interface coupling: the lower-energy mode of the pair has its interface amplitudes aligned in phase, while the remaining one (the higher-energy mode) vibrates with interface amplitudes in the out-of-phase state. (ii) As a rule, the in-phase modes are symmetrical ones, and the out-of-phase modes are antisymmetrical.

The shape of a spin-wave mode is dependent on the value of k; as we have seen in the preceding section, some of them are, moreover, dependent on the interface-coupling parameter (by way of the characteristic equation), while the others remain insensitive to that coupling. The following general rule can be stated: For real k, the spin-wave mode amplitudes vary sinusoidally along the thickness of the film (bulk modes), whereas for complex k the modes are localized since their amplitudes vary monotonically from the greatest value at the interface to the smallest values at the film surfaces. It is also readily verified that the mode amplitudes in two adjacent planes l and $l\pm1$ have opposite signs for $k\in(\pi/2,\pi)$ and $k=\pi+it$; we will refer to such modes as *optical* ones. On the other hand, modes corresponding to $k\in(0,\pi/2)$ and $k=it$ will be called *acoustical*. In what follows we shall discuss the effect of interface coupling exerted on some low-energy (i.e., acoustical) modes.

Figure 5 shows profiles of the bilayer-coupled modes assembled into separate sets corresponding to different values of the ferromagnetic or antiferromagnetic coupling; both an easy-axis type of the interface anisotropy [$D_{\text{int}}>0$, Fig. 5(a)] and an easy-plane type [$D_{\text{int}}<0$, Fig. 5(b)] are considered. We see that a given *unaffected* mode is formed by simple repetition of the respective sublayer mode; we should keep in mind that this repetition is symmetrical for ferromagnetic but antisymmetrical for antiferromagnetic interface coupling. Those modes that are sensitive to changes in $\mathcal{J}^{AB}$ (*affected* modes) increase their oscillations as $\mathcal{J}^{AB}$ increases, consistent with the increase of their energies (depicted in Fig. 2). As a rule, odd modes are sensitive to changes of antiferromagnetic coupling, whereas even ones are sensitive to ferromagnetic coupling (they are denoted, respectively, by asterisks and circles on our figures).

With regard to energy (3), the interface modes lie beyond the energy band of bulk modes (in the scheme of reduced energy used in Fig. 2, the bottom band edge corresponds to minus unity, while the upper one corresponds to plus unity). In particular, the acoustic mode lies below and the optical mode above the band. The nature of the interface mode is best explained by considering the changes undergone by the mode profiles as a result of changes in interface coupling. We will use this procedure to explain the nature of the acoustic mode. Since this mode always lies at the bottom of the energy band, we only have to consider the changes undergone by the

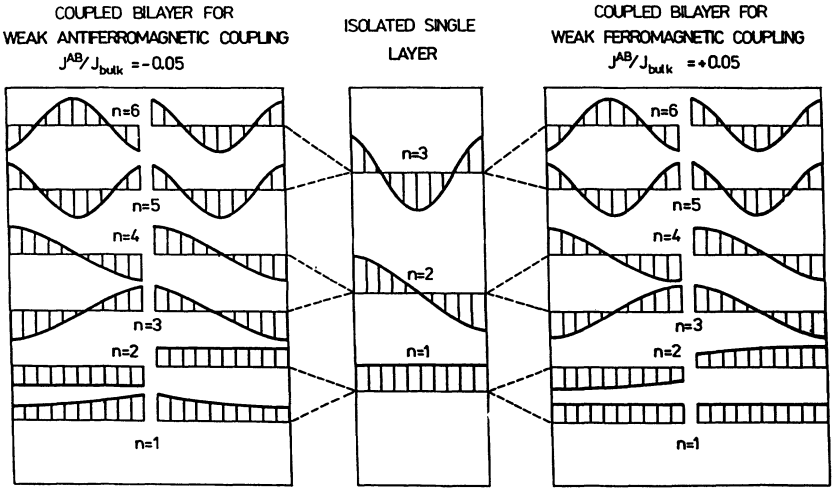


FIG. 3. Formation of bilayer-coupled modes in dependence on the nature of the interfacial exchange coupling of the sublayers (the case with $D_{\text{int}}=0$). For ferromagnetic (antiferromagnetic) interfacial coupling, symmetric (antisymmetric) modes are unaffected by the coupling.

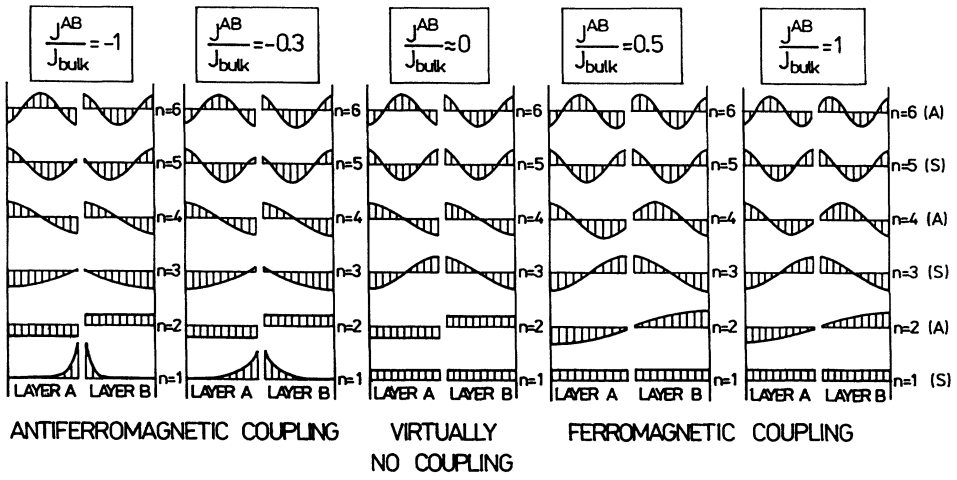


FIG. 4. Profiles of the low-energy bilayer spin-wave modes collected into separate sets corresponding to different values of the ferromagnetic or antiferromagnetic interface coupling. Both sublayers A and B have equal thickness (11 monolayers each); the interface anisotropy $D_{\text{int}}=0$. For the ferromagnetic type of interface coupling, the lowest mode ($n=1$) corresponds to the uniform mode, while for antiferromagnetic coupling this mode becomes interface localized. S and A denote, respectively, symmetric and antisymmetric modes.

lowest affected modes (i.e., $n=1$ for antiferromagnetic and $n=2$ for ferromagnetic interface coupling).

Let us first consider the case of an easy-axis type of the interface anisotropy ($D_{\text{int}}>0$). From the characteristic equation (4) (see also Fig. 1), the root k corresponding to the lowest affected mode is seen to be real for $(\mathcal{J}^{AB}+D_{\text{int}})>0$, equal to 0 at $\mathcal{J}^{AB}=-D_{\text{int}}$ and imaginary for $\mathcal{J}^{AB}<-D_{\text{int}}$. Figure 5(a) shows the respective changes undergone by this mode when the parameter $\mathcal{J}^{AB}$ is made to vary. It is of bulk character for positive (ferromagnetic) coupling as well as for negative (antiferromagnetic) coupling greater than $-D_{\text{int}}$, but becomes interface localized for stronger antiferromagnetic coupling. The interface mode has its maximum amplitude on the interface monolayers and exhibits exponential monotonic changes in amplitude within each sublayer. The strength of localization of the interface mode increases with growing absolute value of the negative interface exchange integral (see also Fig. 4), i.e., with growing freedom of the interface spins. For the case of an easy-plane type of interface anisotropy ($D_{\text{int}}<0$), one can have two interface-localized modes originating separately in each

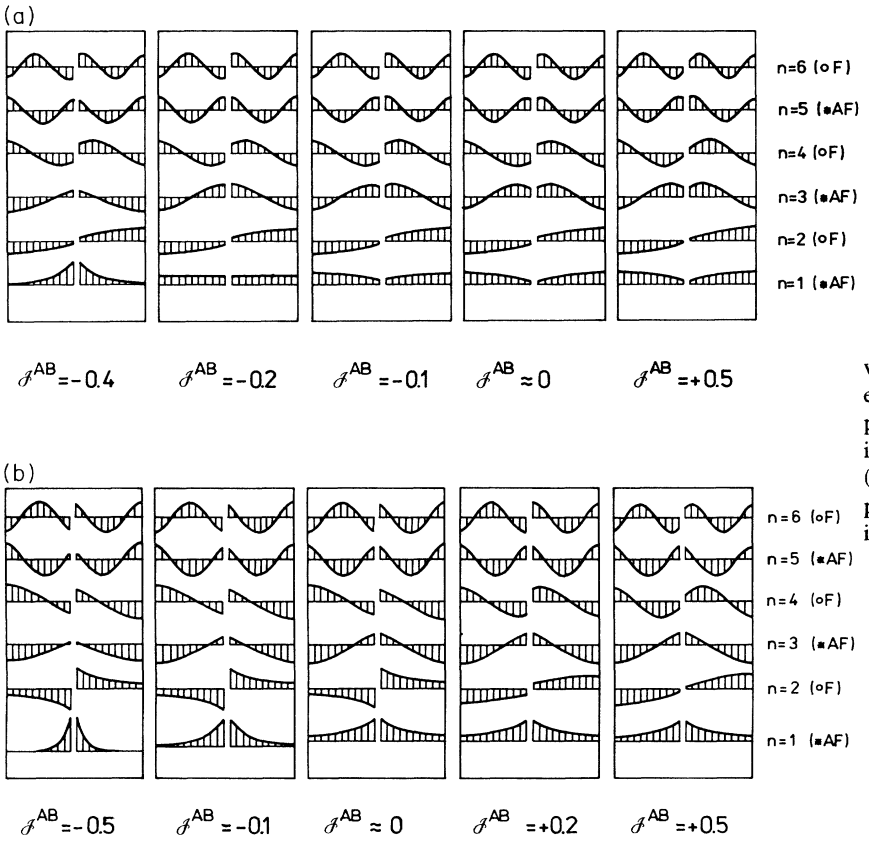


FIG. 5. Mode profiles vs interface coupling with **M** perpendicular to the film for (a) an easy-axis type ($D_{\text{int}}=0.2$) and (b) for an easy-plane type ($D_{\text{int}}=-0.1$) of the interface anisotropy. Affected modes are denoted *AF (modes sensitive to antiferromagnetic coupling) and oF (those sensitive to ferromagnetic interface coupling).

of the two Eqs. (4). Such a situation is shown in Fig. 5(b) and can be easily understood by having recourse to Fig. 1(b). The in-phase mode $n=1$ is always interface localized, even in the regime of ferromagnetic interface coupling; this fact is due to the interface anisotropy $D_{\rm int}$, which (being of easy-plane type) gives some freedom to the interface spins (oriented *perpendicularly* to the film surface). The second out-of-phase (antisymmetric) mode $n=2$ emerges when the interface coupling $\mathcal{J}^{AB}$ falls below $-D_{\rm int}$ and, when $\mathcal{J}^{AB}$ becomes negative, the mode $n=2$ becomes an unaffected one, while the mode $n=1$ becomes sensitive to the antiferromagnetic coupling.

In general, an interface mode is more strongly localized at higher values of t (remember that $k=it$). Hence t is termed the "localization increment" of the mode. It is also important, for practical reasons, to draw attention to the fact that the uniform mode $k=t=0$ defines that limit beyond which interface modes always emerge.

V. SPIN-WAVE RESONANCE SPECTRUM

It is well known that in magnetic thin films, because of the emergence of standing spin waves in the direction perpendicular to the film, an overall nonzero transversal magnetization component can arise with which the alternating field interacts. The intensity of the resonance line is proportional to the square of the overall transversal component of magnetization; in other words, the intensity of the resonance peak corresponding to a given nth spin-wave mode is directly proportional to the squared sum over its amplitudes across the bilayer film (cf. Ref. 12), i.e.,

$$I(k_n)\sim\left[\sum_{l=0}^{2N-1}u_l(k_n)\right]^2. \tag{6}$$

By Eq. (6), the resonance intensity is directly related to the profile of the mode; since the profile is essentially determined by the interface conditions (see Sec. IV), we can expect the calculated SWR spectrum to be determined unequivocably by the values of the interface coupling $\mathcal{J}^{AB}$ and the interface anisotropy $D_{\rm int}$. All the SWR spectra presented in the following have been calculated using the formula (6) with numerically normalized amplitudes $u_l(k)$. These spectra become easily understandable if, when interpreting them, we turn our attention to the respective mode profiles shown in Figs. 4 and 5.

We first consider the case $D_{\rm int}=0$. Figure 6 shows SWR spectra calculated for the following values of the interface coupling: $\mathcal{J}^{AB}=+1.0$, $+0.5$, -0.1, -0.2, -0.3, and -1.0. One notes that, if the interface coupling is ferromagnetic, the resonance intensities corresponding to $k_n\neq 0$ vanish, and only the single-line intensity $k=0$ is nonzero; this is the case of ordinary ferromagnetic resonance, when the spectrum presents but one (uniform mode) resonance line. Multipeak bilayer SWR therefore requires (if intrinsic interface anisotropy is absent) *antiferromagnetic* interface coupling.

The respective SWR spectra calculated for (two) cases with nonzero interface anisotropy $D_{\rm int}\neq 0$ are shown in Figs. 7(a) and 7(b). Multipeak resonance spectra are now obtained even if the interface coupling is ferromagnetic, and this is so because the interface anisotropy acts as an independent cause by itself for evoking the SWR effect. There exists, however, a difference between the spectrum obtained for ferromagnetic interface coupling and that related to antiferromagnetic coupling: While the former does not change with (positive) coupling, the latter is strongly sensitive to any change of the (negative) coupling $\mathcal{J}^{AB}$. Moreover, we also find that if the interface anisotropy is of easy-axis type, there exists the so-called critical effect of SWR consisting in the excitation of but one resonance line; this takes place exactly when $\mathcal{J}^{AB}=-D_{\rm int}$

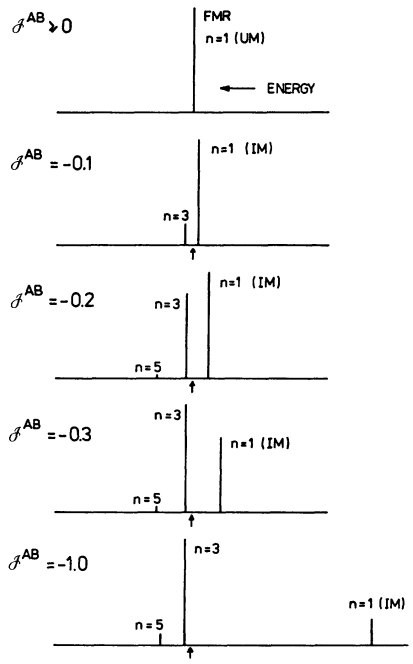


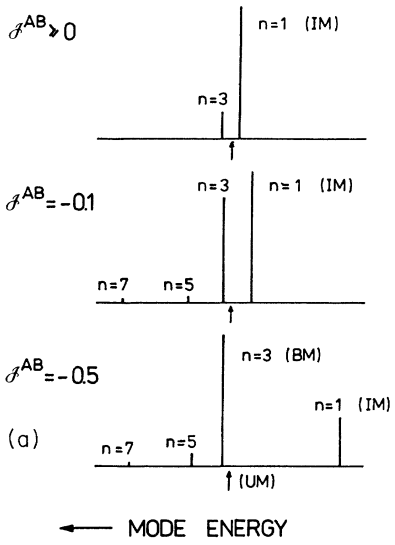
FIG. 6. Stick spin-wave resonance spectra calculated for various strengths of the interfacial coupling of the bilayer AB film for the case when interface anisotropy is absent ($D_{\rm int}=0$). The spectra exhibit only peaks corresponding to the symmetric modes (of odd numbers $n=1,3,5,\ldots$). The calculations are performed for the case when both sublayers A and B have equal thicknesses (11 monolayers each). For the ferromagnetic type of interface coupling, the spectrum always consists of only one single ferromagnetic-resonance (FMR) peak, irrespective of the strength of the coupling; this mode corresponds to the uniform mode (UM). For the antiferromagnetic type of interface coupling, the multipeak spectra always exhibit the presence of the interface-localized mode (IM), which is located on the low-energy side of the spectrum. The units of the horizontal axis are proportional to the normalized energy; the peak intensities have also been normalized by assuming the intensity of the highest peak as unity (in each spectrum separately). Note that for some critical value of $\mathcal{J}^{AB}$ (between -0.2 and -0.3) the intensities of the first two modes ($n=1,3$) become inverted. The findings of this figure are easily understood by referring them to Fig. 4, where the profiles of all modes (both resonant and nonresonant) are shown separately for each strength of the interfacial coupling.

[see Fig. 7(b)]; no such effect is predicted to exist for the case of easy-plane interface anisotropy [cf. Fig. 7(a)].

The analysis of the spectra shown in Figs. 6 and 7 leads to further important statements.

(i) The multipeak spectra corresponding to antiferromagnetic interface coupling *always* contain the interface-localized-mode peak, identified as the energetically lowest one ($n=1$).

(ii) The intensity of the interface-mode peak decreases when antiferromagnetic coupling becomes more intense.



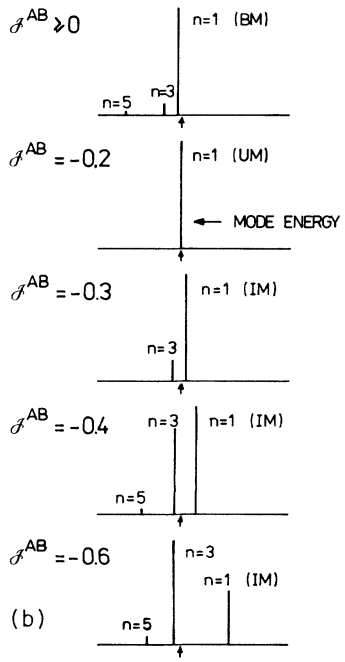


FIG. 7. Same as in Fig. 6 for cases when interface anisotropy does exist in the system: (a) as an easy-plane type ($D_{\text{int}}=-0.1$) and (b) as an easy-axis type ($D_{\text{int}}=0.2$). For a detailed explanation see the text.

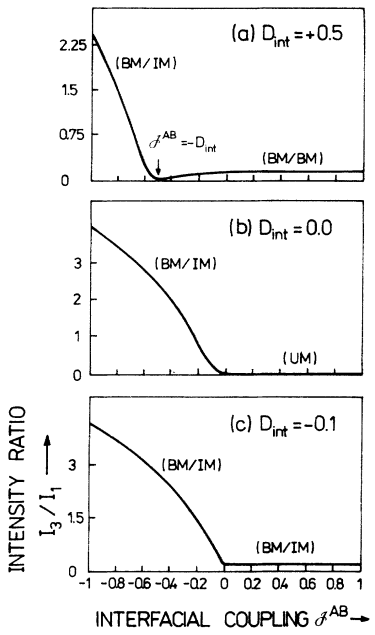


FIG. 8. Intensity ratio of the first two resonance modes vs exchange interfacial coupling $\mathcal{J}^{AB}$ for various values of the intrinsic interface-anisotropy parameter D_{int} (the bilayer consists of 22 monolayers). In the whole range of variability of negative $\mathcal{J}^{AB}$ values, the first mode ($n=1$) is always the interface-localized mode (IM), while the third one is of bulk nature (BM); note that the intensities I_3 and I_1 become inverted around some critical values of $\mathcal{J}^{AB}$. In the range of variability of *positive* values of $\mathcal{J}^{AB}$, the intensity ratio becomes stabilized (being insensitive to any changes of the interfacial coupling).

At sufficiently great (absolute) values of $\mathcal{J}^{AB}$, it can become equal to, or less than, the intensity of the next resonant (bulk) mode ($n=3$).

(iii) No peak corresponding to the uniform mode ($k=0$) appears in multipeak SWR. This peak appears only in one-peak resonance.

When determining the values of the interface coupling, it is best to have recourse to the resonance-line intensities (cf. Ref. 12). In Fig. 8 we show the dependence of the *relative* intensities of the resonance peaks for the first and third modes. One sees that we do have strict one-to-one correspondence between the two values involved, $I_{\text{bulk}}/I_{\text{interface}}$ and negative $\mathcal{J}^{AB}$. By having recourse to this correspondence, one is able to determine the value of the antiferromagnetic interface coupling from the measured relative intensities of the respective resonance peaks.

VI. EXPERIMENTAL IMPLICATIONS FROM THE REASSIGNMENT OF THE SWR LINES AND OUTLOOKS

We note that the multipeak bilayer resonance spectrum by no means resembles the SWR spectrum from a single-layer film: Easily perceptible intensities in the spectrum are obtained only for the first two high-field resonance lines so that experiment reveals but a "double ferromag-

netic resonance." These two lines originate in *collectivized* excitations of the bilayer composed into an *in-phase* oscillating mode. Our reassignment of the SWR lines shows that for very strong antiferromagnetic coupling the energetically lowest mode (here it is the one corresponding to the greatest value of the resonance field) possessing the nature of the interface-localized mode is excited with an intensity lower than the next successive mode, which has the nature of a bulk mode, thus producing the "inverted intensity pattern" spectra so often observed in experiment.

The reason why antiferromagnetic (and *not* ferromagnetic) interface coupling leads to localization of the spin wave on the interface is quite obvious. The interface spins achieve some sort of freedom owing to the antiferromagnetic coupling between them, and their reversal (the onset of the collective spin-wave process) becomes easier. This is equivalent to an increase in the probability of reversal at the interface and an enhancement of the interface spin-wave amplitude, apparent experimentally as the interface mode.

The presence in the SWR spectrum of a resonance line due to the interface mode is a potential source of information concerning the interface. Thus, e.g., Fig. 8 proves that by fitting the intensity ratio $I_{\text{bulk}}/I_{\text{interface}}$ derived from our theory to the experimental data one can easily determine the value of the antiferromagnetic interface exchange integral. Similarly, by applying the same fitting procedure to the intensity ratio derived from our theory in the region of *positive* (ferromagnetic) coupling $\mathcal{J}^{AB}$ (see Fig. 8), one is able to determine the interface-anisotropy parameter D_{int}. Obviously, in the most general case, corresponding to real specimens, one will have to take into consideration the surface anisotropies[19] as well as the eventuality that these anisotropies may cause the boundary conditions to be asymmetric. Also, the external field may be conceived of as directed at an arbitrary angle to the surface of the film. Calculations extending to such fields are now under way.

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