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Effect of exchange field on the damping of spin-wave resonance modes

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An extension of a previously used calculation has been shown to explain adequately the linewidths and intensities of the higher-order spin-wave resonances in thin films of 75%–25% permalloy. Observations at 9, 22, and 32 GHz have been used to determine that the relaxation frequency, λ, is 0.88×10^8/sec, independent of k.

INTRODUCTION

The results of spin-wave resonance (SWR) experiments at 9.44 GHz on Permalloy thin films have been reported recently by two of us.[1] The positions of the absorption lines and the linewidths of the lowest-order spin-wave modes were adequately explained on the basis of an exchange-conductivity theory[2] using a Landau-Lifshitz-type equation of motion for the magnetization and using partial spin pinning at both surfaces. However, for the higher-order modes there was a systematic deviation between the measured and the calculated linewidths and intensities. The observed SWR linewidths were independent of mode number after the first few modes, whereas the calculations predicted a monotonic decrease in width with mode number. In addition, the observed intensities were less than those predicted for the higher-order modes.

In the present paper we report measurements made on the same films at 22 and 32 GHz. The results again indicate that the linewidths become independent of mode number after the first few modes. Our data over a range of frequencies show that the discrepancy between the actual linewidth at high mode numbers and the calculations is not caused by a thickness variation of the films as had been previously suggested.[1] The discrepancy can be reconciled easily by including the exchange field ($2Ak^2/M_s$) in the effective field in the damping term (in the equation of motion). As is well known, this modification is essentially equivalent to use of a Gilbert-type equation of motion[3] and assures that the relaxation rate is independent of mode number (or k vector).

The present calculations predict for a given alloy and frequency the same linewidth for all of the SWR modes in which the exchange-conductivity contribution to the width is negligible, i.e., resonances in very thin films and in thicker films for mode numbers greater than about 3. This predicted linewidth behavior is in agreement with our experiments at all frequencies studied and, in addition, the calculations produce better accord with the observed intensities. The parameters required to fit the data are essentially the same as those reported previously; however, the damping parameter and the electrical conductivity (in better agreement with direct measurements) have been changed.

RESULTS AND DISCUSSION

The experiments were made at frequencies of 22 and 32 GHz on permalloy films of thicknesses 790, 1300, 2020, and 2700 Å. The film composition was 75 at.% Ni–25 at.% Fe and the films were evaporated[4] onto warm substrates (at 250 °C) in a vacuum of 10^{-7} Torr or better. Because of the large amount of strain present in films of this kind, the type of substrate is found to have some influence on the effective saturation magnetization, on the uniaxial magnetic anisotropy, and on the surface pinning. As a result, these quantities were found to be influenced by annealing even at temperatures of less than 250 °C and by the choice of substrate (soft glass, fused quartz, and single-crystal quartz were used). The experimental linewidths, on the other hand, were found to be insensitive to these factors.

The high-frequency measurements include both parallel and perpendicular geometries, although we will concentrate below on the results for the applied field perpendicular to the film plane. Perpendicular field measurements allow the greatest number of SWR modes to be seen and the results are more readily interpreted. As opposed to X-band measurements, the absolute accuracy of the field measurement is slightly less (~ 0.1%) and the angular misalignment of the samples may have been sufficient to cause errors of like magnitude in the resonant fields. It should also be pointed out that for the thicker samples, especially when the alternate weak modes were conspicuous, the apparent linewidth of the lowest-order modes could be strongly affected by interferences between neighboring modes. The interference effects are more

TABLE I. Experimental data at 22 GHz (all values in Oe).

	2707 Å (20.40 GHz)		2023 Å (22.35 GHz)		1299 Å (22.30 GHz)		790 Å (21.69 GHz)	
Line	Res. Field	Width	Res. Field	Width	Res. Field	Width	Res. Field	Width
1	18 543	105	18 737	68	18 820	51	18 496	74
2	•••	•••	18 605	•••	18 593	43	17 937	43
3	•••	•••	18 406	47	18 140	42	16 730	44
4	18 335	40	18 060	46	•••	•••	14 635	(50)[a]
5	18 150	38	17 624	52	16 313	40	11 788	(71)[a]
6	17 910	37	•••	•••	•••	•••		
7	17 604	42	16 352	50	13 338	(60)[a]		
8	17 233	38	•••	•••				
9	16 782	41	14 556	(55)[a]				
10	16 282	38	•••	•••				
11	•••	•••	12 382	•••				
12	15 052	42	•••	•••				
13	•••		•••					
14	13 557	48						
15	•••	•••						

[a] Weak lines.

pronounced at higher frequencies because of the greater linewidths and larger cavity filling factors.

Typical experimental results, at 300 K, are collected together in Tables I and II for 22 and 32 GHz, respectively. In addition, one should note: (i) The relative intensities are somewhat sensitive to the position of the sample in the cavity,[4] and this can affect the apparent width of the lower-order modes in the thickest films. However, the primary purpose of the present investigation is to study the widths of the higher-order modes and these are fairly insensitive to the sample position. (ii) At a given frequency, *the linewidths of the higher modes are the same for all the films*; the linewidth variation with frequency is linear. (iii) Some of the samples were thermally cycled to about 250 °C; there is no observable change in the 300 K widths of the higher-order modes although the relative intensities and the positions are affected slightly. (iv) Including all the experimental effects, the linewidths of the higher-order modes are determined to about 10%.

The earlier calculations[2] were done using the Landau-Lifshitz equation with the damping term $(\lambda/\gamma M_s^2)\,[\vec{M}\times(\vec{M}\times\vec{H}_0)]$, where H_0 is the so-called internal field and was taken to be $H_{app} - 4\pi M_s$ for the perpendicular geometry. With this assumption, one gets a linewidth for the higher-order SWR modes which varies as $(\lambda/\gamma M_s)\,H_0$ and clearly decreases with increasing mode order. In Ref. 1 it was suggested that the apparent deviation between the calculated and observed linewidths was the re-

TABLE II. Experimental data at 32 GHz (all values in Oe).

	2707 Å (32.38 GHz)		2023 Å (31.21 GHz)		1299 Å (31.30 GHz)		790 Å (31.30 GHz)	
Line	Res. Field	Width	Res. Field	Width	Res. Field	Width	Res. Field	Width
1	22 562	175	21 723	109	22 210	101	21 874	85
2	22 343	74	21 571	•••	21 965	•••	21 201	70
3	22 210	•••	21 411	63	21 528	78	20 419	70
4	21 930	76	21 104	(41)	20 803	74	19 687	68
5	21 620	68	20 645	65	19 756	69	18 012	•••
6	21 259	85	20 066	•••	18 453	68		
7	20 806	70	19 346	68	16 862	67		
8	20 285	74						
9	19 710	68						
10	19 051	69						
11	18 316	•••						
12	17 540	77						
13	•••	•••						
14	15 757	70						

sult of a thickness variation in the film. However, using the present data it is clear that this explanation is inadequate because the additional linewidth due to film taper will be independent of frequency and such a term does not account for the observed deviations at all frequencies.

It is now realized that in addition to H_0 in the damping term, one must include a contribution from the exchange field $(2A/M_s^2)\,\nabla^2\vec{M}$. Neglect of this term is not very significant for the main mode or the low-order modes. However, it becomes very important for the higher-order modes. In fact, when the exchange term is omitted, the calculation for high orders is equivalent to computing the linewidth at progressively lower frequencies.

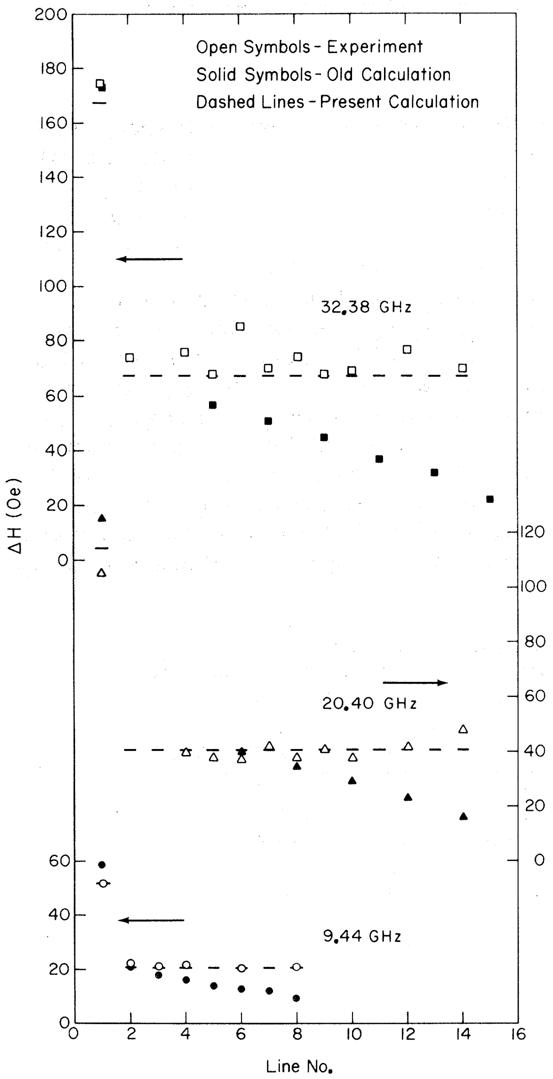

FIG. 1. Comparison of the observed and calculated linewidth of spin wave resonances in a 2700-Å-thick film of 75 at.%–25-at.% Permalloy.

TABLE III. Parameters used for the calculations.

	Old Parameters	New Parameters
M_s	922.8 Oe	922.8 Oe
g	2.10	2.10
A	1.14×10^{-6} erg/cm	1.14×10^{-6} erg/cm
λ	0.75×10^{8}/sec	0.88×10^{8}/sec
$K_s^{(0)}$	0.55 erg/cm^2	0.55 erg/cm^2
$K_s^{(d)}$	0.435 erg/cm^2	0.435 erg/cm^2
σ	$0.63\times10^{5}/\Omega$ cm	$0.49\times10^{5}/\Omega$ cm

With the use of the exchange field along with H_0, the secular equation for the propagation constants given in Ref. 2 is changed in the following way: a is replaced by $a-(2Ak^2/M_s^2)(\lambda/\gamma)$ and d is replaced by $d-(2Ak^2/M_s^2)(\lambda/\gamma)$. These modifications affect only the *damping* of the spin waves. Thus the linewidths and relative intensities are altered but the line centers are affected only slightly.

In Fig. 1 we have collected together the linewidths for the 2700-Å-thick film at 9, 22, and 32 GHz. It should be noted that the numbers on the abscissa are purely for designation since an integer order number is meaningless when the surface spins are neither completely pinned nor completely free. For the sake of comparison, the linewidths calculated on the old model as well as the new model are included in Fig. 1. The values of the parameters used for the calculations are given in Table III. It is important to note that for best fit to the data at all the frequencies, one had to change the parameters λ and σ in the new calculations. However, even with the λ and σ unaltered the new calculation would give a much better fit to experiment. For instance, for line No. 9 at 32 GHz the calculated values are 57 and 67 Oe for the old and new parameters, respectively, in comparison with the observed linewidth of 68 Oe.

The present choice of λ and σ was made as follows. First, the linewidths of the higher-order modes (which are rather insensitive to σ) were used to fix λ. The conductivity σ was then adjusted to give the best fit to the linewidths for the main mode and the low-order modes at 9.44 GHz. Unfortunately the interference between the low-order modes at 22 and 32 GHz makes their linewidth determination rather inaccurate. Further, we have also measured the dc conductivity of our samples, using a four-probe method, and it is very gratifying to note that the chosen value of σ is very close to that measured directly.

For the sake of brevity we have not presented the calculated linewidths for all thicknesses. However, as noted earlier the linewidths of the higher-order modes are the same for all the films. Thus the calculated values shown in Fig. 1 give a fair idea of the precision with which λ can be determined.

TABLE IV. Calculated and experimental resonance parameters (2707 Å, 9.44 GHz).

H_n (Oe)			ΔH_n (Oe)			I_n		
Expt.	Old Calc.	New[a] Calc.	Expt.	Old Calc.	New[a] Calc.	Expt.	Old Calc.	New[a] Calc.
14780	14780	14781	52	59	53	100	100	100
14569	14580	14580	22	21	24	24	23	18
14390	14392	≈14390	21	18	≈20	0.03	0.02	0.01
14151	14147	14147	22	16	22	5.2	6.8	4.6
b	13840	≈13847	b	14	20	b	0.03	0.014
13481	13466	13466	21	13	21	1.3	3.3	1.3
b	13028	13028	b	12	≈20	b	0.03	0.01
12536	12525	12524	21	9	21	0.44	2.7	0.58
b	11955	11956	b	7	21	b	0.06	0.004

[a] New values for the conductivity and the damping constant were used, see text.

[b] The line intensities were too small to give reliable values for this parameter.

In short, considering all the measurements the value of λ is uncertain to about 10%. It should also be noted that the value of λ is rather insensitive to the choice of σ and K_s.[5]

In Table IV we have presented the entire spectrum at 9.44 GHz. The results of both the old and the new calculations are included for direct comparison with the listed experimental values. It is clear that the calculated line centers are not altered significantly but the new intensities for the higher-order modes are in better agreement with experiment.

CONCLUSIONS

The discrepancy between the calculated and measured SWR linewidths at high orders, noted in Ref. 1, has been successfully explained by including the exchange field in the damping term of the Landau-Lifshitz equation. By combining SWR measurements at three frequencies we have established that the optimal value of the relaxation parameter for 75 at.%–25 at.% Permalloy is 0.88×10^8/sec.

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[1] G. C. Bailey and C. Vittoria, Phys. Rev. B 8, 3247 (1973), and references therein.

[2] C. Vittoria, R. C. Barker, and A. Yelon, J. Appl. Phys. 40, 1561 (1969).

[3] C. H. Wilts (private communication) has used the Gilbert equation to analyze some of the data of Ref. 1.

[4] G. C. Bailey, J. Appl. Phys. 41, 1012 (1970).

[5] If K_s varies spatially along the sample surface it will give rise to an inhomogeneous broadening. Although this possibility has not been ruled out, it is difficult to believe that such a variation will produce the same linewidth for the higher-order modes in all of our films especially when all the films do not have the same value of K_s. Further, thermal cycling to 250 °C does not affect the linewidths of the high-order modes but alters the relative intensities. This suggests that K_s is changed on thermal cycling. If the width were due to spatial variation in K_s one would have expected to see a linewidth variation on thermal cycling.