Magnon decay and observed nonlinear microwave transmission phenomena

G. Dewar
Physics Department, University of North Dakota, Grand Forks, North Dakota 58202
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Holmes and Alexandrakis observed nonlinear phenomena in the transmission of microwave energy through moderately thick samples of polycrystalline iron. In these experiments the sample, in the shape of a thin disk, formed part of the common wall between two microwave cavities. Microwaves polarized with the rf magnetic field parallel to a large, static magnetic field in the plane of the sample was incident on one cavity. Any energy passing through the sample and generating microwaves polarized perpendicular to, and at half the frequency of, the incident microwaves entered the second cavity and was subsequently detected. For incident microwaves of frequency 18.74 GHz, they observed a transmission feature ≈ 100 Oe wide at an applied field of 2.2 kOe. Misalignment of the rf magnetic field with the magnetization allowed the incident microwaves to excite spin waves. At 2.1 kOe one magnon can decay into two phonons that propagate in the same direction as the original magnon. It is these phonons that were responsible for the observed transmission.

I. INTRODUCTION

Holmes and Alexandrakis[1,2] reported on the transmission of microwave energy through moderately thick samples of iron and nickel. In one particular experimental arrangement they observed nonlinear phenomena in iron. In these experiments, the sample, in the shape of a thin disk, formed part of the common wall between two microwave cavities. Microwave energy was incident on one cavity; energy passing through the sample entered the second cavity and was subsequently detected. Holmes and Alexandrakis detected transmitted microwaves at half the frequency of the incident microwaves. At the time there was no satisfactory explanation for the observed transmission.

Alexandrakis and colleagues[1,3,4] attempted to show that their observations could be explained by a nonlinear theory: this theory was shown to be untenable.[5,6] In addition, Kurn *et al.*[7] were unable to reproduce several of the other Holmes and Alexandrakis results. The experiment in which the detected signal was at a subharmonic of the incident microwave frequency was neither challenged nor satisfactorily explained.

II. RELEVANT FEATURES OF THE EXPERIMENT

In the subharmonic transmission experiment of Holmes and Alexandrakis, a polycrystalline iron disk ≈ 3 μm thick and 99.9% pure separated two microwave cavities. One cavity,the transmitter cavity, was connected to a microwave source operating at 18.74 GHz. The other cavity, the receiver cavity, was connected to a heterodyne receiver which was sensitive to the amplitude and phase of the 9.37-GHz microwave power emerging from this cavity. The local oscillator for the receiver also supplied power to a frequency doubler and amplifier chain which was the source of the 18.74-GHz microwaves. Both cavities operated in the TE_{101} mode. The polarizations of the rf magnetic fields in the two cavities were orthogonal to each other at the position of the sample. A static magnetic field was applied in the plane of the sample and parallel to the rf magnetic field in the transmitter cavity, i.e., the transmitter cavity operated in the $H_{\parallel,\parallel}$ configuration. The receiver cavity had the polarization of the rf magnetic field perpendicular to the static field, the $H_{\parallel,\perp}$ configuration.

Holmes and Alexandrakis observed a subharmonic transmission feature approximately 100 Oe wide centered at an applied magnetic field of 2.2 kOe. This feature was 5–10 dB greater than the system noise level. The precise shape of the transmission feature, as shown in plots of transmission amplitude versus applied field, differed from measurement to measurement. In a modification of this experiment the receiver cavity was rotated so that the polarization of the rf magnetic field was parallel to that of the transmitter cavity and both were parallel to the applied field, i.e., both the transmitter and receiver cavities operated in the $H_{\parallel,\parallel}$ mode. The transmission feature at 2.2 kOe was absent in this configuration.

The thesis of J. B. Holmes[8] contains further relevant experimental detail. In addition to looking for the subharmonic feature with both cavities operating in the $H_{\parallel,\parallel}$ mode, he rotated the magnetic field so that both cavities operated in the $H_{\parallel,\perp}$ mode. In this mode "no real transmission signal could be identified."[9] Holmes also performed conventional ferromagnetic resonance reflection measurements (FMR) at both 18.74 and 9.37 GHz. He observed the iron samples to show absorption maxima at applied fields of ≈ 1.5 and 0.45 kOe, respectively, with the cavities operating in the $H_{\parallel,\perp}$ mode.[10] Further, he carried out the FMR measurements with the transmitter cavity operating at 18.74 GHz in the $H_{\parallel,\parallel}$ configuration and found that the strength of the FMR absorption was $\approx \frac{1}{3}$ the strength of the absorption in the $H_{\parallel,\perp}$ configuration.

III. ORIGIN OF THE SUBHARMONIC TRANSMISSION

These experimental results have a simple explanation. The key observations are (1) that the alignment of the rf magnetic field with the magnetization was imperfect and (2) that, at 2.1 kOe, one magnon of frequency 18.74 GHz can decay, with the conservation of crystal momentum, into two forward propagating longitudinal phonons of frequency 9.37 GHz. See Fig. 1. The decay process occurs at this particular applied field when the magnetization lies close to a [111] axis, a magnetically hard direction.

Since the polarization of the magnetic field of the incident microwaves in the experiment was nominally parallel to the static magnetic field, one would naively expect no generation of either spin waves or the extraordinary electromagnetic wave at the fundamental frequency of 18.74 GHz. (The microwave power was far below the threshold for parallel pumping.[5,11]) The reason for this is that the transverse response of the magnetization is responsible for most of the "interesting" magnetic effects. In the $H_{\parallel,\parallel}$ configuration, one observes the longitudinal response of the magnetization. This response is limited by the small longitudinal susceptibility of the ferromagnet and leads to a slight modification of the classical skin depth. Thus, the material should behave like an ordinary metal. However, Holmes' observation of a substantial ferromagnetic resonance signal in the $H_{\parallel,\parallel}$ configuration indicates that there was a considerable misalignment between the rf magnetic field and the magnetization over a large fraction of the sample and that magnons were indeed excited. The primary source of this misalignment was the magnetocrystalline anisotropy in the individual crystals of the polycrystalline material.

The strength of the magnetocrystalline anisotropy of iron[12] leads to the conclusion that FMR at 18.74 GHz can be observed for magnetic fields of 1.1 or 2.1 kOe with the magnetization directed along a [100] axis or a [111] axis, respectively. For other directions, FMR occurs at

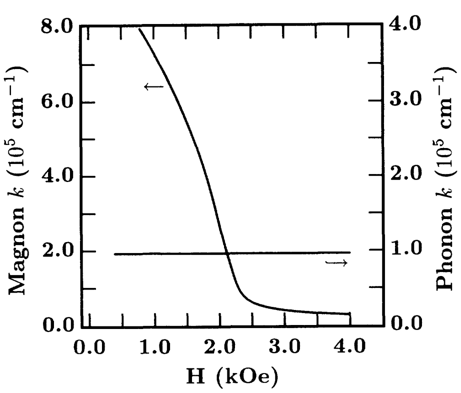

FIG. 1. Propagation constant for magnons and phonons in iron vs applied magnetic field. Note the different vertical scales. The magnon frequency is 18.74 GHz and the phonon frequency is 9.37 GHz. As shown, the dispersion relation crossing corresponds to one magnon decaying into two phonons with $\omega_{\rm magnon}=2\omega_{\rm phonon}$ and $k_{\rm magnon}=2k_{\rm phonon}$. In the calculation, the magnetization is assumed to lie along a [111] direction and in the plane of a disk-shaped sample. The magnons and the longitudinal phonons propagate along a [110] direction, which is perpendicular to the plane of the disk. Details of the calculation are contained in Refs. 13 and 14.

intermediate fields. The anisotropy gives rise to effective fields which shift FMR from the 1.5 kOe calculated in the absence of any anisotropy. This anisotropy is usually represented as an energy, dependent on the direction of the magnetization, in the form

$$E_{\rm anis}=K_1(\alpha_1^2\alpha_2^2+\alpha_2^2\alpha_3^2+\alpha_3^2\alpha_1^3)+\cdots , \qquad (1)$$

where the ellipsis represents higher-order terms and the α's are the direction cosines of the magnetization referred to the crystal axes. This energy has a zero derivative with respect to angle in the [100], [110], and [111] directions. The second derivative, which determines the restoring torques (or effective fields) on the magnetization, varies relatively slowly in the neighborhood of the [100] and [111] directions. Thus, crystals randomly oriented with respect to an external magnetic field will exhibit effective anisotropy fields clustered near those expected for [100] and [111] directions.

For the parts of the polycrystal where the magnetization was aligned near a [111] direction, it is possible for a magnon to decay spontaneously into two longitudinal phonons which subsequently generate microwaves. This decay process occurs close to the applied magnetic field which satisfies the FMR condition. At a field $\approx$20 Oe greater than that for FMR, the propagation constant of the 18.74-GHz magnon, $k_{\rm magnon}$, is twice the propagation constant of the 9.37-GHz phonon. See Fig. 1. Details of the calculation as well as the values of the necessary parameters can be found in Refs. 13 and 14. At smaller magnetic fields, the propagation constant of the magnon is so large ($k_{\rm magnon}>2k_{\rm phonon}$) that this decay mode is not allowed; at larger magnetic fields ($k_{\rm magnon}<2k_{\rm phonon}$) conservation of crystal momentum requires the phonons to propagate at a nonzero angle with respect to the forward direction; i.e., the phonons must have equal and opposite nonzero components of their wave vectors perpendicular to the direction of the magnon. If the sound waves do not propagate perpendicular to the plane of the sample, i.e., parallel to the original magnon, then the microwaves produced by the phonons will vary in phase from place to place on the sample and will destructively interfere. The transmission is further limited to applied magnetic fields near FMR because the spin waves are most strongly excited when the FMR condition is satisfied. The width of the transmission feature is dependent on the lifetime of the magnons [$\mathrm{Im}(k)\approx\frac{1}{3}\mathrm{Re}(k)$ at 2.1 kOe] as well as the distribution of anisotropy fields seen by the magnetization.

This decay process can occur via a magnetoelastic interaction between magnons and phonons.[15] The magnons are heavily attenuated and do not propagate more than a few tenths of a micrometer into the iron. The phonons, which are relatively unattenuated,[13] freely traverse the sample. In fact, $4\frac{1}{2}$ sound wavelengths closely match the 3-μm sample thickness and it is quite likely that an acoustic resonance existed in the samples. These phonons radiate microwaves upon reflection at the back surface. This microwave generation is mediated by the ordinary magnetoelastic coupling, usually parameterized by

B_1 and B_2, which enters into the boundary conditions.[13,16,17] It was these microwaves, polarized with the rf magnetic field perpendicular to the static magnetization, which were subsequently detected.

Kraus and Fraitová have shown that magnons generated near FMR and propagating at an oblique angle with respect to the magnetization can penetrate $1-2$ μm into iron.[18] It is unlikely that these magnons play a role in the transmission discussed here. These oblique magnons are relatively few in number since they must be produced at surface irregularities. Although they are able to penetrate to relatively great depths into the sample, the would have to decay into energy at half their frequency in order to be detected. Since it is the spontaneous decay of magnons which gives rise to phonons at half the magnon frequency, it is irrelevant whether the magnons decay within 0.1 or 1 μm of the surface. The far more numerous magnons propagating perpendicular to the surface wold swamp any oblique magnon contribution to the microwave transmission.

The magnon decay process in incoherent. The microwave receiver in the experiment, however, was a coherent detector. The transmission appeared as excess power added in random phase to the receiver's local oscillator. It is only because the transmission occurred over a narrow range of applied field that it was readily discernible from receiver noise. From several plots of transmission versus applied field[2] it is apparent from the irreproducibility of the line shape that there was no coherence between the transmitted signal and the local oscillator.

For the parts of the polycrystal where the magnetization was aligned along a [100] direction, there could be no detected signal in the Holmes and Alexandrakis experiment. Even if a magnon decayed into two longitudinal phonons, these phonons would not exhibit any ordinary magnetoelastic coupling when propagating perpendicular to the [100] direction. Thus, there would be no microwaves excited when the phonons reflected off the back surface of the sample.

In the experiment in which Holmes and Alexandrakis rotated the receiver cavity so that it operated in the $H_{\|,\|}$ mode, they detected no subharmonic transmission. This is in agreement with the mechanism proposed here since the transmitted microwaves were polarized such that they could not enter the receiver cavity when it was rotated into this configuration.

In the experiment in which both the transmitter and receiver cavities operated in the $H_{\|,\perp}$ mode, Holmes[8] should have seen a transmission signal at least three times larger than the one he and Alexandrakis did report for the mixed configuration.[1,2] This is because the generation of magnons would not depend on the misalignment of the magnetization with the rf magnetic field of the transmitter cavity as it did when that cavity operated in the $H_{\|,\|}$ mode. As the FMR measurements showed, the excitation of the magnons was at least three times greater when the transmitter cavity operated in the $H_{\|,\perp}$ mode. However, the transmission signal in this configuration would not be identical to that of the mixed configuration. The transmission through crystals for which the magnetization was not near the [111] direction would be stronger also. Thus, there should have been a broad transmission feature stretching from somewhat more than 1 to 2.2 kOe. Since this transmission would be incoherent it would imitate a $5-15$ dB increase in *receiver noise* for magnetic fields in this range. It is possible that Holmes did not recognize this transmission since he was looking for a sharp feature at 2.2 kOe which, at the time, was believed to represent a coherent signal.

IV. CONCLUSIONS

The subharmonic generation of microwaves in the transmission experiment of Holmes and Alexandrakis[1,2] is due to the decay of 18.74-GHz magnons into 9.37-GHz longitudinal phonons. It is these phonons which propagated across their samples and radiated microwaves into the receiver.

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