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HEXAGONAL FERRITES FOR MILLIMETER WAVE APPLICATIONS

FINAL REPORT

January 7, 1991

Contract No. N00014-87-K-0325
June 1, 1987 to May 31, 1990

Funding Agency

Office of Naval Research
Department of the Navy

ONR Technical Contract Officers

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ABSTRACT

This final report presents a review of the work accomplished on this contract. A review of the physics of hexagonal ferrite materials and the effective linewidth concept and the detailed overall research plan are contained in the original proposal document. The focus of the program was on the effective linewidth in millimeter wave materials, including planar hexagonal ferrite Y-type materials, uniaxial M-type materials, and thin ferromagnetic transition metal and alloy films. The key idea in the original proposal was that the ferromagnetic resonance linewidth in hexagonal ferrites is dominated by inhomogeneous and two-magnon scattering losses and that off-resonance measurements of the effective linewidth would (1) show that the FMR losses do not represent the intrinsic losses and (2) that the intrinsic losses are significantly lower. This basic idea was verified. Results were obtained on the off-resonance far-field effective linewidth in planar Zn-Y hexagonal ferrite single crystal platelets, single crystal spheres of Ba- and Sr-hexaferrite materials, and permalloy thin films. Three papers on these results have been published (McKinstry and Patton, 1989; McKinstry, et al., 1989; Moosmüller, et al., 1990). Selected aspects of the results have been presented at the 1989 Intermag Conference in Washington, D.C. (March, 1989) and at the annual Conference on Magnetism and Magnetic Materials Conference in Boston (November, 1989). A summary of technical publications which resulted from the contract and a list of participating personnel are also provided.

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FINAL REPORT

I. INTRODUCTION

Because of requirements which involve the detection of small targets under all possible atmospheric conditions, millimeter wave radar technology has been developing rapidly during this decade. It appears likely that the magnetic material of choice for filter, phase shifter, and other millimeter wave device applications will be some type of hexagonal ferrite. The work under this ONR contract is concerned with the high frequency properties of hexagonal ferrite materials in the millimeter wave frequency range. The major thrust area for the work concerns the off-resonance effective linewidth and the origin of the high frequency losses in this frequency regime.

The key idea in the original proposal was that the ferromagnetic resonance linewidth in hexagonal ferrites is dominated by inhomogeneous and two-magnon scattering losses and that off-resonance measurements of the effective linewidth would (1) show that the FMR losses do not represent the intrinsic losses and (2) that the intrinsic losses are significantly lower. This basic idea was verified. The work accomplished is summarized in Section II. Publications which have resulted from this contract are listed in Section III. Personnel are listed in Section IV.

II. SUMMARY OF RESULTS

This section presents a brief review of the work accomplished on this contract. A review of the physics of hexagonal ferrite materials and the effective linewidth concept and the detailed overall research plan are contained in the original proposal document.

The focus of the program is on the millimeter wave effective linewidth in millimeter wave materials, including planar hexagonal ferrite Y-type materials, uniaxial M-type materials, and thin ferromagnetic transition metal and alloy films. The specific measurements and analyses have been concerned with the field dependence of the high frequency losses as expressed in terms of a field dependent effective linewidth. Results have been obtained on the off-resonance far-field effective linewidth in planar Zn-Y hexagonal ferrite single crystal platelets, single crystal spheres of Ba- and Sr-hexaferrite materials, and permalloy thin films. Three papers on these results have been published (McKinstry and Patton, 1989; McKinstry, et al., 1989; Moosmüller, et al., 1990). Several additional papers on related topics have also been published or are in press. Selected aspects of the results were presented at the 1989 Intermag Conference in Washington DC (March, 1989) and at the annual Conference on Magnetism and Magnetic Materials Conference in Boston (November, 1989).

A. SPECTROMETER

One of the key accomplishments was in the design, construction, and operation of state-of-the-art 10 GHz and 35 GHz effective linewidth spectrometers. The systems use a high resolution microwave frequency synthesizer and scalar network analyzer, with both under computer control. The system is semiautomated to scan over the transmission peak of high-Q microwave/millimeter wave cavity, store data on power vs. frequency, and then analyze the data to extract high accuracy cavity Q-values. Measurements of Q vs. static field are the basis of the effective linewidth technique.

A new high precision Q-measurement procedure was developed in connection with this contract. The procedure utilizes the entire cavity resonance curve profile rather that simply the usual 3 dB points used for conventional Q-determinations. The cavity profile data are cast in the form of normalized frequency and power parameters such that linear graphs yield the 3 characteristic Q-parameters as the slopes from linear least square fits to the data. Q-values in the 20,000 range can be measured with an accuracy of +/- 10.

The data analysis procedures for effective linewidth are tedious. Menu driven software has been developed to facilitate efficient data analysis and interpretation. The software allows the user to examine the frequency and Q data versus applied field, select field ranges for optimum extrapolations for cavity parameters in the absence of magnetic loss, and then analyze the data to obtain effective linewidth parameters.

B. PLANAR MATERIALS

The first results are concerned with the millimeter wave resonance linewidth and off-resonance effective linewidth in "selected" (see below) narrow linewidth planar Zn-Y materials from Purdue University. The narrowest Zn-Y 35 GHz linewidths were typically 60 - 70 Oe. The low field and high field effective linewidths were typically 20 - 40 Oe, with the low field values usually below the high field values. These results are significant for two reasons. (1) The fact that the resonance linewidth is larger than the off-resonance effective linewidths shows rather explicitly that the resonance linewidth contains significant contributions from inhomogeneous linebroadening and two magnon scattering mechanisms. (2) The fact that the low field effective linewidth is larger than the high field effective linewidth demonstrates that there is a significant two magnon scattering contribution from high-k (wavenumber), short wavelength degenerate spin waves.

The above results validate the basic thesis of the original proposal - that the measured linewidth in single crystal hexaferrites (1) may contain significant contributions related to inhomogeneous and two magnon losses, and (2) may not represent purely intrinsic losses.

Some of the Zn-Y platelets had very large linewidths and are not included in the "selected" category discussed above. For these materials, the 35 GHz linewidths were generally in the 200 Oe range. For these samples, the off resonance effective linewidths were typically in the 20 - 70 Oe range. These results also corroborate the key hypothesis of the proposal. In this case, we have very "dirty" materials with very large linewidths. Nevertheless, the off-resonance, high field and low field effective linewidths are much lower and indicate that even in "dirty" materials, the intrinsic losses are respectable. In most cases, the high field effective linewidth appears to be higher than the low field values. This is opposite from what one would expect from high-k scattering considerations.

C. UNIAXIAL MATERIALS

Data were also obtained on relatively high anisotropy uniaxial materials in the form of Sr- and Ba-hexaferrite spheres. In these cases, the actual ferromagnetic resonance (FMR) could not be observed at 35 GHz. It was still possible, however, to make below resonance effective linewidth determinations. The 35 GHz effective linewidth values were in the 66 - 80 Oe range.

D. PERMALLOY THIN FILM EFFECTIVE LINEWIDTH

In addition to the first millimeter wave effective linewidth measurements in hexagonal ferrite materials, it has also been possible to apply the effective linewidth technique to metals for the first time. Even though the focus of the contract was on ferrites, this work on metals was undertaken because of the recent developments at the Naval Research Laboratory concerning narrow linewidth epitaxial iron films. The very high saturation induction in iron makes such films attractive candidates for nonreciprocal millimeter wave planar device applications.

Because of various substrate problems, the target material for the current work was permalloy on glass. The basic measurement was the same - Q vs. static field. The analysis was quite different. It was necessary to solve the complete electromagnetic boundary value problem for metal film FMR, relate the field dependent Q to a field dependent Landau-Lifshitz damping parameter, and use the data to map out the field dependence of that damping. It was possible to use the Q-data in the near field tails of the FMR absorption to determine off-resonance values of the Landau-Lifshitz damping - values which appear to be comparable to those expected for very good single crystal platelets or whiskers.

These results indicate that one can use the effective linewidth technique in relatively imperfect metals like polycrystalline permalloy films, and determine near-intrinsic microwave loss properties.

III. PUBLICATIONS

A. PUBLICATIONS ON EFFECTIVE LINEWIDTH

"Methods for Determination of Microwave Cavity Quality Factors from Equivalent Electronic Circuit Models." K. D. McKinstry and C. E. Patton, Rev. Sci. Instrum., 60, 439-443 (1989).

"Off Resonance Loss Measurements in Ferrites at 35 GHz." K. D. McKinstry, C. E. Patton, M. A. Wittenauer, M. Sankararaman, J. Nyenhuis, F. J. Friedlaender, H. Sato, and A. Schindler, IEEE Trans. Magnetics 25, 3482-3484 (1989).

"Microwave Effective Linewidth in Thin Metal Films." H. Moosmüller, K. D. McKinstry, and C. E. Patton, J. Appl. Phys. 67, 5521-5523 (1990).

B. RELATED PUBLICATIONS ON FERRITES

"Hexagonal Ferrite Materials for Phase Shifter Applications at Millimeter Wave Frequencies," C. E. Patton, IEEE Trans. Magnetics 24, 2024-2028 (1988).

"The Second-Order Spin-Wave Instability Threshold in Single Crystal Yttrium Iron Garnet Films Under Perpendicular Pumping," Y. T. Zhang, C. E. Patton, and G. Srinivasan, J. Appl. Phys. 63, 5433-5438 (1988).

"Observation of Auto-oscillations and Chaos in Subsidiary Absorption in Yttrium Iron Garnet," G. Srinivasan, M. Chen, and C. E. Patton, J. Appl. Phys. 64, 5480-5482 (1988).

Brillouin Light Scattering Observation of Anomalous Parametric Spin-wave Character in Subsidiary Absorption," W. D. Wilber, J. G. Booth, C. E. Patton, G. Srinivasan, and R. W. Cross, J. Appl. Phys. 64, 5477-5479 (1988).

"Ferromagnetic Resonance Foldover and Spin Wave Instability in Single Crystal YIG Films," M. Chen, C. E. Patton, G. Srinivasan, and Y. T. Zhang, IEEE Trans. Magnetics 25, 3485-3487 (1989).

"Anomalous Low Frequency Butterfly Curves for Subsidiary Absorption and FMR Overlap at 3 GHz," R. W. Cross, C. E. Patton, G. Srinivasan, J. G. Booth, and M. Chen, J. Appl. Phys., in press (1991).

"First Order Instability Theory for Magnetostatic Modes in Ferromagnetic Spheres," M. Chen and C. E. Patton, J. Appl. Phys., in press (1991).

"Oscillations in the Stokes-anti-Stokes Ratio in Brillouin Scattering from Magnons in Thin Permalloy Films," H. Moosmüller, J. R. Truedson, and C. E. Patton, J. Appl. Phys., in press (1991).

IV. PERSONNEL

The personnel supported on this project in one form or another (salary, materials, etc.) are listed below.

Principal Investigator:	Carl E. Patton Professor of Physics
Postdoctoral Fellow:	Gopalan Srinivasan Research Assistant Professor
Postdoctoral Fellow:	Hans Moosmüller Postdoctoral Fellow
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Undergraduate Students:	Christopher Springfield Mike Crawford Ralph Cross
High School Students:	Eric Shink Scott Andre Eric Lindloff