Anisotropy Constants and g Value of Nickel Ferrite*

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This paper presents experimental data on the anisotropy constants and g value of nickel ferrite from 4°K to 300°K over a frequency range of 7900 to 11 500 Mc/sec. The observed anisotropy constants agree with those measured by Yager, Galt, and Merritt at K band on the same crystal. Previous measurements by Healy at X band are considerably different, presumably as a result of variations between different single-crystal samples representing the same ferrite. The measured g values show a significant variation with frequency. This has not been observed in previous measurements on single crystals.

INTRODUCTION

THE purpose of work described here was to extend the measurements made on the g value and anisotropy constants of nickel ferrite down to liquid helium temperature, to examine an apparent inconsistency between anisotropy constants measured at X band and K band frequencies, and to test for the possibility of the dependence of these quantities on frequency. The principal study was made on a single crystal loaned us by Dr. John Galt of the Bell Telephone Laboratories. This crystal is one on which he and his colleagues[1] have made extensive measurements at K-band frequencies.

II. EXPERIMENT

Since it is well known that the ferromagnetic resonance phenomenon provides a convenient and accurate means of measuring the g value and magnetic anisotropy constants of ferrites, it does not seem desirable or necessary to discuss the method here.[2-5] However, for purposes of evaluation it may be useful to mention certain details of the experimental procedure.

The sample to be studied (diameter=0.010 inch) was mounted adjacent to the end wall of a rectangular cavity excited in a TE_{10n} mode. Here n was so chosen that the cavity could resonate at eight frequencies between 7900 and 11 500 megacycles per second. This offered the advantage of being able to produce a 40% change in frequency without otherwise altering the experimental conditions to which the ferrite was subjected. The cavity was undercoupled to the wave guide, and electronic resonance in the sample was observed by adjusting the applied steady magnetic field to that value which produced the maximum power

TABLE I. Nickel ferrite single crystal data [$NiO_{0.95}(FeO)_{0.05}Fe_2O_3$].

f Mc/sec	K_1/M	K_2/M	g	H_{eff}	Temp. °K
7937	−265	15	2.317	2447	300
8372	−260	10	2.314	2585	300
8856	−252	35	2.300	2751	300
9376	−252	−10	2.301	2911	300
9925	−257	10	2.291	3095	300
10 501	−255	−5	2.290	3276	300
11 095	−249	−15	2.281	3475	300
24 338[a]	−254	−70	2.196	7917	300
7967	−371	−65	2.374	2397	77
8400	−378	−10	2.356	2547	77
8885	−379	−30	2.343	2709	77
9407	−371	−35	2.336	2876	77
9959	−375	−30	2.326	3067	77
10 537	−399	+15	2.300	3265	77
11 135	−399	+20	2.297	3463	77
24 450[a]	−370	−100	2.198	7942	85
8215	−403	−30	2.41	2425	4
8684	−414	−5	2.37	2615	4
9193	−406	−25	2.35	2794	4
9729	−402	−40	2.35	2955	4
11 480	−435	10	2.31	3545	4
23 880[a]	−392	−120	2.202	7743	4

[a] Data taken by Yager, Galt, and Merritt, Phys. Rev. 99, 1203 (1955).

TABLE II. Critical field above which complete alignment of the magnetization is to be expected.

Direction of applied field, H_0	Critical conditions
|001| axis	$H_0M = -2K_1$
−110| axis	H_0M the larger of $2K_1$ or $2K_1 + \frac{1}{2}K_1$
−111| axis	$H_0M = 12K_1 + (4/9)K_2$

reflection from the resonant cavity containing the sample.

The accuracy of the experiment is critically dependent on the measurement of magnetic field, so that care was taken in measuring the field at the location of the sample. It proved most convenient for us to do this by using the free radical "DPPH" ($\alpha\alpha$ diphenyl-β-picryl-hydrazl) for calibration purposes.[6]

The measurements at liquid helium temperature were made by completely immersing the wave guide and cavity in the liquid helium. The helium was contained in a glass double Dewar flask and heat loss was minimized by including a glass section of wave guide in the heat conduction path between the air and

[1] Yager, Galt, and Merritt, Phys. Rev. 99, 1203 (1955).

[2] L. R. Bickford, Jr., Phys. Rev. 78, 449 (1950).
[3] Galt, Yager, Merritt, and Wood, Phys. Rev. 80, 744 (1950).
[4] D. W. Healy, Jr., Phys. Rev. 86, 1009 (1952).
[5] T. Okamura and Y. Kojima, Phys. Rev. 86, 1040 (1952).
[6] C. H. Townes and J. Turkevich, Phys. Rev. 77, 148 (1950).

the liquid helium.[1] This permitted ample time (nearly 5 hours per filling) to take data before the level of the liquid helium in the Dewar dropped too low.

III. RESULTS

In Table I we show the value of anisotropy constants; spectroscopic splitting factor, g, and H_{eff} as measured at various X-band frequencies and at three different temperatures, 4°K, 77°K, and 300°K. We also include in this table the results of measurements by Yager, Galt, and Merritt[1] on this particular crystal at K-band frequencies. The principal effect to be noticed here is that whereas the anisotropy constants do not vary appreciably with frequency, the g values certainly do. This is illustrated by Fig. 1. The variation observed is greater than the experimental error involved and the trend of the data seems particularly convincing. At least two effects exist which could possibly give rise to an *apparent* variation of g with temperature. When ferrous ions are an important constituent of the crystal, an electron interchange between ferric and ferrous ions occurs at high temperatures, producing an effective g value which could vary with frequency. We do not

TABLE III. Values of H_i, γ', and g' determined by assuming $\omega = \gamma'(H_{eff} + H_i)$.

Temperature	H_i oe	γ' rad/sec oe	g'
300°K	90±40	19.64×10⁶	2.23±0.02
77°K	280±40	18.70×10⁶	2.13±0.02
4°K	340±60	18.58×10⁶	2.11±0.03

believe this to be true here. We base this judgment on the observation that the variation of g with frequency is observable even at low temperatures. A second possible source of explanation for the existence of a frequency-dependent effective g value is based upon the supposition that the magnetization is not complete in the single-domain sense and parallel to the applied field. There are two reasons why we do not believe this is important here. The first is based upon an analysis of the value of critical field above which complete alignment of the magnetization is to be expected. The results of this analysis are shown in Table II while the analysis itself is discussed in the Appendix.

Referring to Table II, we find that, for our data, the static field was in all cases greater than the critical field. The second reason for doubting the existence of incomplete magnetization is based upon our experimental observation of this very effect at much lower frequencies. We have made a series of resonance observations from S to C to X band employing coaxial cavities and, at frequencies below 5000 Mc/sec, we believe we can observe the effect produced by the existence of several magnetic domains.[7] These effects

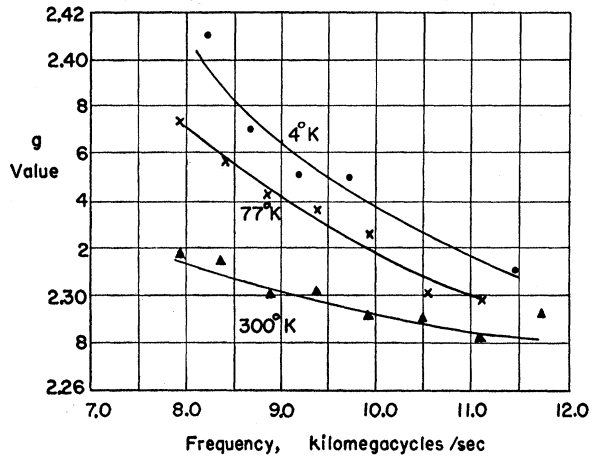[7] P. E. Tannenwald, Phys. Rev. **100**, 1713 (1955).

FIG. 1. Spectroscopic g value vs frequency in $(NiO)_{0.95}(FeO)_{0.05}Fe_2O_3$.

disappear as we go to higher frequencies and therefore higher magnetic fields.

The effect on g of adding a phenomenological constant, H_i, to the effective field, H_{eff}, required for resonance was examined.[8] Specifically, we assumed the following expression for the ferromagnetic resonance frequency:

$$\omega = \gamma'(H_{eff} + H_i). \qquad (1)$$

A least-squares fit of the data to this expression gives rise to the values for H_i, γ', and g' shown in Table III.

In Fig. 2 we plot g' as calculated from the experimental values of ω and H_{eff} and the value of H_i determined from the least-squares fit. Using our values of H_i and the values of ω and H_{eff} measured by Yager et al.,[1] we find the results given in Table IV. It is evident that our results, when extrapolated to K-band
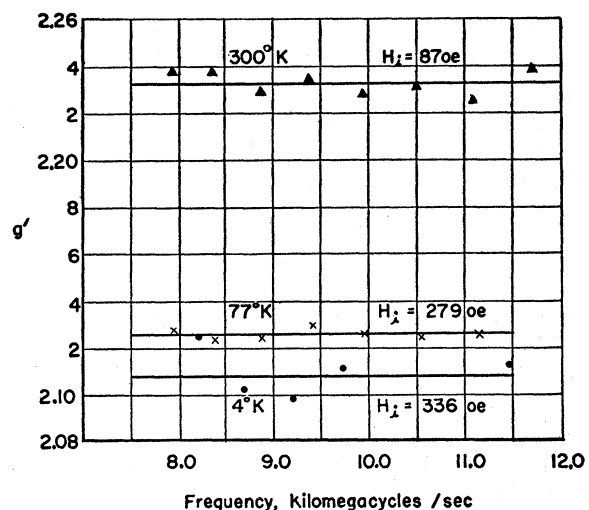

FIG. 2. Derived g' vs frequency in $(NiO)_{0.95}(FeO)_{0.05}Fe_2O_3$ $[\omega = \gamma'(H_{eff} + H_i)]$.

[8] Okamura, Torizuka, and Kojima, Phys. Rev. **88**, 1425 (1952).

TABLE IV. Comparison of g' values obtained from
K-band and X-band data.

Temperature	g' (K-band data)	g' (X-band data)
300°K	2.17	2.23
77°K	2.12	2.13
4°K	2.11	2.11

frequency according to Eq. (1), yield values consistent with experimental data taken at those frequencies.

IV. CONCLUSIONS

The measurements at liquid helium temperature show no significant changes from those made at higher temperatures. The first order anisotropy constant K_1 which we measured agrees very well with that measured by Yager et al. There is a slight inconsistency between their measurement of K_2 and ours, however, even here the disagreement is not serious since the discrepancy is just about equal to the limit of error. These results differ quite appreciably with the earlier results of Healy,[4] where K_2 was an important term in the anisotropy energy even at liquid nitrogen temperature and was significant at room temperature. We must conclude that the observed difference is attributable to some difference between the sample crystals both of which were nominally single crystals of nickel ferrite.

We also conclude from our data that the measured g varies with frequency. McGuire[9] at the Naval Ordnance Laboratory has informed us that he has made measurements on another sample of nickel ferrite and did not observe any change in g with frequency. Measurements made on manganese ferrite also give rise to a g independent of frequency.[8] However, in this ferrite, since the measured g is essentially 2.00, it is not likely that its behavior is typical of other binary ferrites.

The addition of the constant H_i seems to indicate that such a term can account for a frequency variation of g. However, our results are not sufficiently accurate to establish the fact that a linear addition of a constant term to H_{eff} is correct and unique. Other phenomenological equations may also lead to a frequency-independent effective g value.

APPENDIX

In analyzing the resonance condition without the assumption of parallel alignment of the magnetization and applied field, the equilibrium position of the magnetization may be determined as a function of the magnitude of the applied field and its orientation relative to the crystal axes. This is most easily done by finding the orientation (or orientations) of the magnetization which are energetically stable. The total

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[9] T. R. McGuire, Naval Ordnance Laboratory (private communication).

magnetic energy of a sample may be written:

$$E = E_{\text{anis}} - \mathbf{H} \cdot \mathbf{M}$$
$$= K_0 + K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2) + K_2\alpha_1^2\alpha_2^2\alpha_3^2$$
$$- H_0 M(\alpha_1\beta_1 + \alpha_2\beta_2 + \alpha_3\beta_3). \quad (1)$$

Here, K_i are the anisotropy constants: α_i are the direction cosines of the magnetization vector, $\mathbf{M}$; and β_i are the direction cosines of the applied field H_0. Note that this expression for energy implicitly makes the following assumptions:

(a) We have a perfect ferromagnetic single crystal.

(b) The sample shape is spherical (with equal demagnetizing factors in all directions). This then makes the energy associated with the demagnetizing field a constant independent of the orientation of M.

(c) We have magnetic saturation in the sense that the sample consists of a single domain with M equal to the saturation value.

(d) The crystal has cubic magnetic symmetry and therefore cubic magnetic anisotropy.

(e) Two anisotropy terms are sufficient to specify the anisotropy energy.

The problem of finding the stationary values of the energy for a given applied field is somewhat simpler if we make the substitutions:

$$\alpha_1 = \rho \cos\phi,$$
$$\alpha_2 = \rho \sin\phi, \qquad 0 \leqslant |\rho| \leqslant 1, \qquad (2)$$
$$\alpha_3 = \pm(1-\rho^2)^{\frac{1}{2}}, \quad 0 \leqslant \phi \leqslant \pi.$$

The energy then becomes

$$E = K_0 + K_1\{\rho^2 - \tfrac{1}{8}\rho^4 | 7 + \cos4\phi |\}$$
$$+ \tfrac{1}{8}K_2(\rho^4 - \rho^6)(1 - \cos4\phi)$$
$$- H_0 M[\beta_1\rho \cos\phi + \beta_2\rho \sin\phi \pm \beta_3(1-\rho^2)^{\frac{1}{2}}]. \quad (3)$$

Inserting the magnitude (H_0) and orientation (β_i) of the applied field, we can then find the values of ρ and ϕ which make E stationary.

In general we find a number of energetically stable orientations, and the actual direction of the magnetization will depend on its original orientation as well as the magnitude and direction of the applied field $\mathbf{H}$. For $\mathbf{H}$ along the principal axes (i.e., cube edge, face diagonal, and body diagonal), the parallel alignment of $\mathbf{M}$ and $\mathbf{H}$ is always an orientation of stable equilibrium for very large H. As H is decreased, the parallel alignment becomes an orientation of unstable equilibrium at a critical field which depends on the magnitude and sign of the anisotropy constants. These are the fields listed in Table II above which the alignment is expected to be perfect. These criteria for stability are experimentally meaningful since the conditions may be readily satisfied. In performing the resonance experiment here, the field, H_0, was sufficiently large that no difference was noted as the resonance value was approached from above or from below.