Correspondence

Dependence of the Resonance Linewidth of Microwave Ferromagnetic Materials on Incident RF Power*

Introduction

The intrinsic resonance linewidth of ferromagnetic materials is a key parameter in delineating the characteristics of these materials. Most of the published data concerning the resonance linewidth of ferrites and garnets are valid for small-signal conditions. However, Suhl's theory has indicated that the linewidth is dependent upon the RF peak power to which the material is subjected.

Experiments performed by Damon[1] have shown that the magnetization vector of a ferromagnetic material fans out at an increasing angle from the direction of the applied dc field as the RF signal amplitude is increased, until some critical angle is reached. The material is then said to be saturated. A further increase in RF power will broaden the resonance absorption curve and decrease the resonance absorption peak value. Under certain conditions a subsidiary resonance absorption curve will appear on the low-field side of the main curve.

These nonlinear characteristics will affect the operation of many microwave devices to a considerable degree. Therefore, an experimental investigation was undertaken to determine the resonance absorption characteristics of several families of polycrystalline ferrite materials, a polycrystalline garnet material, and a single-crystal garnet material. Experiments were made over a wide range of incident power levels. The information obtained will be helpful in predicting the performance of these materials when used in such microwave devices as circulators, power limiters, harmonic generators, and parametric amplifiers.

TABLE I
Composition of Materials

Material	Chemical Composition					
	MgO (Per Cent)	Fe_2O_3 (Per Cent)	Al_2O_3 (Per Cent)	MnO_2 (Per Cent)	Y_2O_3 (Per Cent)	NiO (Per Cent)
Trans-Tech 414	41.19	48.83	5.42	4.56	—	—
General Electric 551-16	50.00	38.50	10.00	1.50	—	—
Trans-Tech Y1-8	—	62.50	—	—	37.5	—
General Ceramics R-1	58.00	36.00	—	6.00	—	—
Trans-Tech 189-1350	35.00	45.00	—	20.00	—	—
Trans-Tech 191-1300	25.00	45.00	—	30.00	—	—
Trans-Tech 447-1100	—	52.00	—	—	—	48

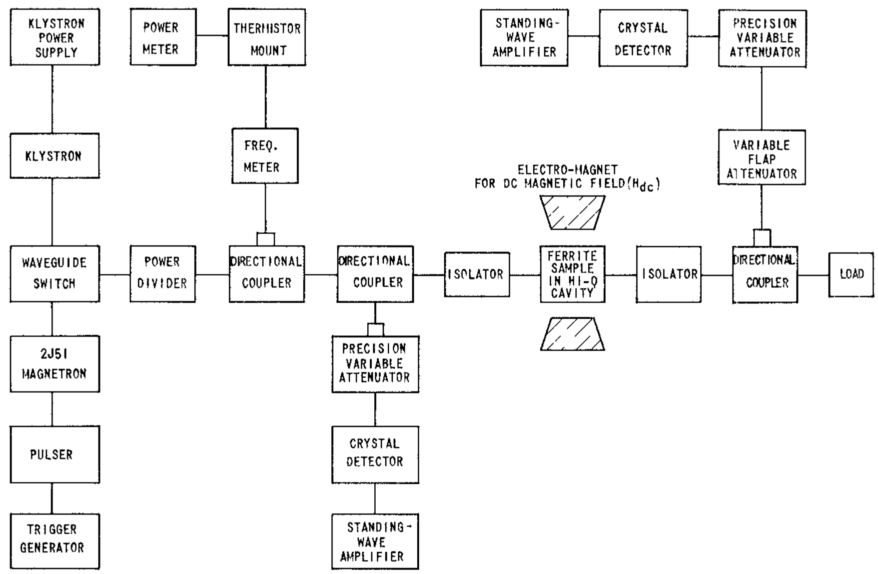

Fig. 1—Block diagram of test equipment setup, high-Q cavity technique.

Discussion

A. Nonlinear Effects

If a pulse of RF power impinges on a ferrite sample that is magnetized perpendicular to the signal field direction, the magnetization vector fans out, dissipates its energy, and relaxes to its equilibrium position. A long relaxation time indicates that a large amount of energy is stored in the spin system of the ferrite sample, analogous to a high-Q resonant circuit. A narrow-linewidth ferrite will have a high peak absorption per unit volume, indicating that a large amount of RF energy is stored in the spin system.

At high signal powers, the uniformity of the spin precessional motion is disturbed. This disturbance causes a time lag in the precessional motion of adjacent spins, and creates spin waves within the sample. Suhl[2] has shown that, as the RF power is increased, a critical RF field h_c is obtained because of these spin waves. The relationship for this critical RF field is given by

$$h_c = 2\Delta H \sqrt{\frac{2\Delta H_k}{4\pi M_s}},$$

where ΔH is the linewidth of the resonance as measured at low power, ΔH_k is the linewidth of the first unstable spin-wave mode, and $4\pi M_s$ is the saturation magnetization of the ferrite sample. After this critical field is reached, further increases in RF power cause the main resonance to decline and the resonance linewidth to increase.

B. Experimental Procedure

Ferrite linewidth measurements were made at both high- and low-power levels on a number of ferromagnetic materials as a function of incident power level (and thus RF magnetic field). The measurements were made with a high-Q, nondegenerate waveguide cavity. The samples used and their chemical compositions are listed in Table I.

A block diagram of the equipment used in making measurements by the high-Q cavity technique is shown in Fig. 1. A pulsed magnetron provided the high-power RF source. Measurements were made at a pulse repetition rate of 30 cps and a pulse length of one microsecond. This very low duty cycle was used in order to eliminate any spurious effects which might be caused by heating of the ferrite sample.

The ferrite samples were in the shape of small, accurately ground spheres varying in diameter from 0.015 inch to 0.090 inch.[3] The choice of dimension was determined by the dispersion effect of the sample in the cavity. A spherical form factor was used since, for a spherical geometry, the internal demagnetization factors are equal along each of the three mutually perpendicular axes of the sphere.

The power divider permitted the incident power level to be varied over a wide range. Ferrite isolators were used to isolate the cavity from the rest of the microwave circuitry and to insure matched conditions for stable magnetron operation.

Measurements were also made (with the same technique and experimental arrangement) using a low-power reflex klystron. A waveguide switch with high isolation

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[1] R. W. Damon, "Relaxation effects in the ferromagnetic resonance," *Rev. Mod. Phys.*, vol. 25, pp. 239–245; January, 1953.

[2] H. Suhl, "The nonlinear behavior of ferrites at high microwave signal levels," Proc. IRE, vol. 44, pp. 1270–1284; October, 1956.

[3] J. L. Carter, E. V. Edwards, D. L. Fresh, and I. Reingold, "Ferrite sphere grinding technique," *Rev. Sci. Instr.*, vol. 30, pp. 946–947; October, 1959.

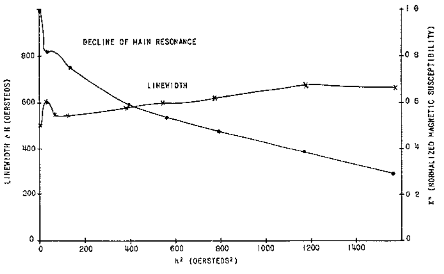

Fig. 2—Observed linewidth and decline of the main resonance as a function of incident power (square of RF field) for type-R-1 material.

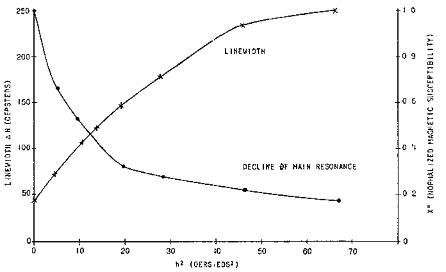

Fig. 3—Observed linewidth and decline of the main resonance as a function of incident power (square of RF field) for type-YIG material.

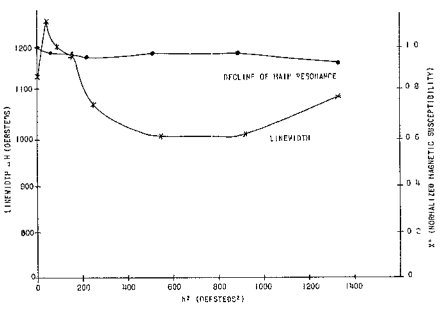

Fig. 4—Observed linewidth and decline of the main resonance as a function of incident power (square of RF field) for type 447-1100 material.

TABLE II

FIGURE OF MERIT AS A FUNCTION OF INCIDENT POWER LEVEL FOR EIGHT POLYCRYSTALLINE FERROMAGNETIC MATERIALS

Material	h_s	p_t	ΔH	F_R	%	F_P	%
1) 414	0.02	50×10^{-3}	166	6000	100	38.7	100
	11.3	18×10^{3}	207	3844	64	31.0	80
	22.8	70×10^{3}	266	2300	38	24.0	62
	36.0	180×10^{3}	288	1980	33	22.2	57
2) 551-16	0.02	50×10^{-3}	143	8100	100	45.0	100
	12.5	21×10^{3}	283	2000	24	27.8	51
	21.6	65×10^{3}	431	885	11	15.0	33
	30.5	130×10^{3}	428	890	11	15.0	33
3) R1	0.02	50×10^{-3}	505	645	100	12.7	100
	10.8	15×10^{3}	550	545	85	11.9	92
	23.4	75×10^{3}	609	440	68	10.5	83
	34.2	160×10^{3}	676	360	56	9.5	75
4) 189-1350	0.02	50×10^{-3}	300	1840	100	21.5	100
	11.4	18×10^{3}	290	1980	108	22.0	102
	16.1	35×10^{3}	354	1350	73	18.7	85
	36.0	180×10^{3}	565	520	28	11.4	53
5) YIG	0.02	50×10^{-3}	44	86,000	100	136.5	100
	3.0	1.2×10^{3}	104	15,350	18	62.0	46
	5.2	3.5×10^{3}	172	5620	7	37.5	28
	8.2	9×10^{3}	250	2640	3	25.5	19
6) Y1-8	0.02	50×10^{-3}	56	57,120	100	119.5	100
	4.8	3×10^{3}	157	6700	12	41.0	34
	8.2	9×10^{3}	315	1680	3	20.5	17
	10.6	15×10^{3}	353	1360	2	18.2	15
7) 191-1300	0.02	50×10^{-3}	44	1400	100	18.7	100
	2.8	1×10^{3}	369	1200	86	17.3	93
	10.2	14×10^{3}	298	1850	132	21.5	116
	25.5	90×10^{3}	561	530	38	11.5	62
	36.0	180×10^{3}	670	370	265	9.6	52
8) 447-1100	0.02	50×10^{-3}	1130	128	100	5.7	100
	21.5	21×10^{3}	1182	119	93	5.4	96
	21.6	65×10^{3}	1006	147	115	6.0	107
	36.0	180×10^{3}	1094	141	110	5.9	105

h_s = RF field at sample, oersteds
P_t = peak transmitted power in waveguide, watts
ΔH = linewidth of sample, oersteds
F_R = figure of merit for resonance absorption device
F_P = figure of merit for phase-shift device

between ports permitted either the reflex klystron or the magnetron output power to be incident upon the cavity.

A rectangular, transmission-type cavity in 1.25 inch × 0.60 inch cross-section waveguide was used in these experiments. The cavity, which was coupled to the transmission line by means of asymmetric, inductive-type irises, operated in the TE_{102} mode at a resonance frequency of 8957 megacycles and a loaded Q of 2239. A sample holder, containing a polystyrene rod with the ferrite material cemented to its tip, was mounted on the narrow side of the waveguide cavity so that the specimen was located at the point of maximum RF field. The perturbation caused by the polystyrene rod was minimal.

The transmission-type cavity permits linewidth measurements to be made at a constant RF field. As the energy absorbed in the ferrite sample increased, the monitored power at the output termination of the cavity decreased. Increasing the input power until the output power level reached an appropriate reference level thus enabled maintenance of a constant RF field in the cavity over the complete range of measurements.

RESULTS

The change in the observed linewidth and the decline of the main resonance (decrease in magnetic susceptibility) as the incident RF power is increased are shown in several curves (Figs. 2–4) for some of the polycrystalline ferromagnetic samples evaluated. These two parameters are plotted as functions of the square of the RF field, and the decline of the main resonance is compared to the low power normalized value of the magnetic susceptibility, X''. Figs. 2 and 3 are representative of the common types of ferrite materials in which there is a substantial decline of the main resonance and a corresponding broadening of the linewidth as the incident power level is increased.

From the standpoint of practical application, it is probably more meaningful if variations in linewidth and resultant figures of merit[4] are presented as functions of the incident power rather than the microwave RF field. Therefore, the RF fields for the various samples were converted to the equivalent power in X-band waveguide, based upon the derivation of Stern and Mangiaracina,[5] and the calculated figures of merit and percentage change in figures of merit were compared to those at low-power-level conditions for the different incident peak-power levels.

The somewhat astronomical figures of merit achieved with the YIG and Y1-8 materials at low power levels [Table II, 5) and 6)] would ordinarily indicate the desirability of using narrow linewidth materials for high-power devices. However, because of line broadening, the figures of merit decrease rapidly with increased power, indicating that poor device performance will result at high power levels. Therefore, a narrow linewidth material must be chosen judiciously. It should also be noted that the use of narrow linewidth materials introduces the problem of maintaining a high degree of magnetic field stability, since a comparatively small shift in the magnetic field may result in a complete loss of the resonance condition.

The curve for type 447-1100 material (Fig. 4) is surprising, inasmuch as there is no appreciable decline of the main resonance and the linewidth becomes narrower with increasing RF field. A first explanation of this anomalous behavior is to attribute it to heating effects. Therefore, measurements were made over a range of duty cycles varying from 12.5×10^{-5} to 3×10^{-5} for constant peak power, and no change in the results were noted. No theory has been offered to explain the peculiar behavior noted for the type 447 material. The fact that this material is relatively porous and has small grain size may account, in part, for the observed results. The peculiar behavior of this

[4] B. Lax, "Frequency and loss characteristics of microwave ferrite devices," PROC. IRE, vol. 44, pp. 1368–1386; October, 1956.

[5] E. Stern and R. S. Mangiaracina, "Ferrite high power effects in waveguides," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, Vol. MTT-7, pp. 11–15; January, 1959.

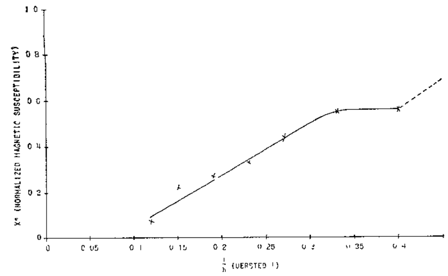

Fig. 5—Dependence of magnetic susceptibility on the reciprocal of the RF magnetic field at high power levels for type-YIG material.

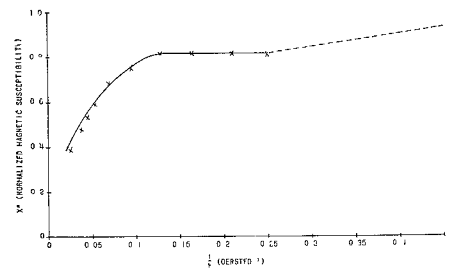

Fig. 6—Dependence of the magnetic susceptibility on the reciprocal of the RF field at high power levels for type R1 material.

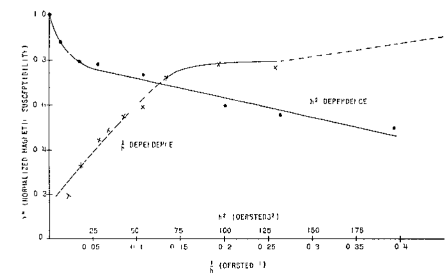

Fig. 7—Dependence of the magnetic susceptibility on the square of the RF field at low power levels, and on the reciprocal of the RF field at high power levels for type-414 material.

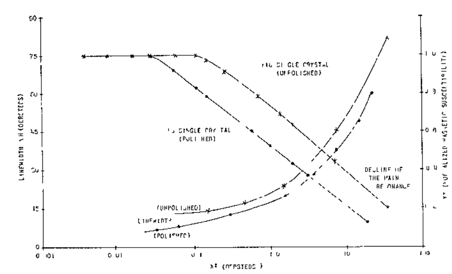

Fig. 8—Observed linewidth and decline of the main resonance as a function of incident power (square of RF field) for single crystal type-YIG material.

material is naturally reflected in its figure of merit [Table II, 8)] which, rather than decreasing in the expected manner, increases with incident power.

Type 447 material has been successfully used in high-power device applications. Since the linewidth and resonance absorption remain fairly constant with incident power, one would expect this material to provide satisfactory device characteristics at high power levels.

TABLE III

Critical RF Fields (h_c) and Corresponding Spin-Wave Resonance Linewidth (ΔH_k)

Material	$4\pi M_s$ Oersteds	ΔH Oersteds	h_c Oersteds	ΔH_k Oersteds
414	650	166	5.2	0.13
551-16	1100	143	4.9	0.16
YIG	1800	44	1.6	0.3
R1	2100	505	9.2	0.09
Y1-8	1800	56	1.8	0.23
Single-Crystal YIG, Unpolished	1750	13.5	0.33	0.13
Single-Crystal YIG, Polished	1750	6.5	0.17	0.16

$4\pi M_s$ = saturation magnetization
ΔH = linewidth of sample
h_c = RF field
ΔH_k = spin-wave resonance linewidth

The curves in Figs. 2 and 4 show an erratic behavior at "medium" field and power levels, which is not caused by experimental deviations. The fine structure noted in this region should be investigated further in order to determine the reason for the anomalous behavior.

Green and Schlömann[6] have shown that at fairly low power levels the susceptibility varies linearly with the square of the RF magnetic field strength, and that at high power levels, the susceptibility is inversely proportional to the amplitude of the RF magnetic field strength. The representative data presented in Figs. 5 and 6 tend, in general, to confirm these results.

The dependence of the susceptibility on $1/h$ at high power levels was compared to the linear relationship with the h^2 dependence at low power levels. The results for a representative sample are shown in Fig. 7. In all cases, the values for the magnetic susceptibility X'' are normalized to the low-power value.

The data presented can also be used to determine the critical field strength and the corresponding spin-wave resonance linewidth by use of the method of Schlömann, Saunders, and Servetz.[7] These values for the materials investigated are presented in Table III. It is interesting to note that the variations in ΔH_k are much smaller than those in ΔH.

The only single-crystal material investigated was yttrium-iron garnet One sample of this material was checked both before and after it was polished. The results, which are given in Fig. 8, show the dependence of the linewidth and the decline of the main resonance on incident RF power. The results also show the expected effect of surface finish for narrow linewidth materials. The effectiveness of a polished surface in reducing linewidth is evident.

Conclusions

Information has been obtained concerning the dependence of linewidth and the decline of the main resonance on incident microwave power level for several common types of ferromagnetic materials.

The anomalous behavior noted in these experiments indicates the need for additional theoretical and experimental study. An indication has also been obtained of the direction to be taken in ferromagnetic material research in order to achieve optimized performance of microwave ferromagnetic devices, such as isolators, circulators, power limiters, and parametric amplifiers.

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[6] J. J. Green and E. Schlomann, "High Power Ferromagnetic Resonance at X-Band in Polycrystalline Garnets and Ferrites," Raytheon Co., Waltham, Mass., Tech. Memo. T-168; 1959.

[7] E. Schlomann, J. Saunders, and M. Servetz, "*L*-Band Ferromagnetic Resonance Experiments at High Peak Power Levels," Raytheon Co., Waltham, Mass., Tech. Memo. T-167; 1959.

Green's Function Techniques for Inhomogeneous Anisotropic Media*

In many problems involving the guiding and radiation of electromagnetic waves the solution for the field quantities at points in space is given in terms of integrals of the field quantities over their values on a closed surface. These integrals are often derived through the application of vector Green's theorems. The Green's function used in any particular application is usually determined by the special considerations of that problem, but it is convenient to use, as the Green's function, a solution of the vector wave equation which is singular at the point where the field is to be computed. In this article the concept is extended to include media which are anisotropic and may be inhomogeneous as well. Use is made of the generalized reciprocity relationships for anisotropic media.[1] This involves the use of the media of a given problem termed "original media" and those characterized by transposed tensor parameters and termed "transposed media."

If the media for a given problem are anisotropic with tensor constitutive parameters which are not necessarily symmetric, the following identity forms a convenient starting point:

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[1] R. F. Harrington and A. T. Villeneuve, "Reciprocity relationships for gyrotropic media," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp 308–310; July, 1958.