Resonance Measurements on Nickel-Cobalt Ferrites as a Function of Temperature and on Nickel Ferrite-Aluminates*

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Summary—The variation of line width (ΔH) and effective g factor (g_{eff}) with cobalt content and with temperature is studied in a series of ferrites of composition $Ni_{1-\alpha}Co_{\alpha}Mn_{0.02}Fe_{1.9}O_{4\pm}$. Here α lies between 0 and 0.09; temperatures range from 20°C to 340°C. A minimum in ΔH is observed at $\alpha=0.027$; g_{eff} decreases with increasing α. The temperature dependence of each is qualitatively that which would be expected on the basis of the temperature dependence of the anisotropy of the mixed ferrite. Above room temperature ΔH and g_{eff} increase or decrease, depending on the cobalt content. It is also shown that the shape of the resonance line is determined by the sign of the anisotropy constant. For negative K_1 the line is steeper on the low-field side of resonance—for positive K_1 it is steeper on the high-field side.

Resonance data are presented on several nickel-cobalt ferrite-aluminates, of composition $Ni_{1-\alpha}Co_{\alpha}Mn_{0.02}Fe_{2-t}Al_tO_{4\pm}$, with α varying from 0 to 0.025 for $t=0.3$, 0.4, 0.5, and 0.6. The reduction of ΔH and g_{eff} expected from anisotropy considerations is observed.

Introduction

Nickel ferrite has a negative first-order anisotropy constant K_1 whose magnitude decreases with temperature above room temperature. Cobalt ferrite has a positive anisotropy constant of much greater magnitude, and it also decreases with temperature above room temperature. It might be expected, and it is indeed true, that a solid solution of the proper (small) amount of cobalt ferrite in nickel ferrite would reduce the anisotropy of the mixed ferrite. By varying α in the formula $Ni_{1-\alpha}Co_{\alpha}Fe_2O_4$, ferrites with varying K_1 can be made; K_1 can be caused to vary from the negative value for nickel ferrite through zero to high-positive values. This has been demonstrated by Sirvetz and Saunders[1] in polycrystalline nickel-cobalt ferrite.[2] More direct measurements on single crystals[3] have substantiated this statement. The work of Sirvetz and Saunders suggests that the anisotropy constant of the mixed ferrite is equal to the weighted algebraic sum of the values for the individual ferrites. This would be expected theoretically, also, if it is assumed that the anisotropy is a property of the individual ions arising from crystalline field effects from the surrounding lattice. In such a case it would be true only for small cobalt additions for which the exchange (*i.e.*, Curie temperature) does not change significantly.[4] The temperature variation of K_1 for the mixed ferrite would then be determined by the variation of the *difference* of the K_1 curves for the constituent ferrites. In Fig. 1 $|K_1|$ vs temperature for nickel ferrite is shown (Healy's values[5]). To determine the K_1 for $Ni_{1-\alpha}Co_{\alpha}Fe_2O_4$, K_1 for cobalt ferrite[6] is multiplied by α and plotted, as for the case $\alpha=0.02$ shown in Fig. 1. The net K_1 is then the difference of the two curves (shaded area, for example), and is positive when the cobalt K_1 predominates and negative when the nickel $|K_1|$ is larger. (Actually, the nickel ferrite values should be multiplied by $1-\alpha$, but this is unimportant here). Where the two curves intersect the net K_1 is zero. This intersection moves to higher temperatures as the cobalt content is increased.

Our resonance measurements from room temperature to 340°C on several of these mixed polycrystalline ferrites are reported here. The variation of K_1 is reflected in the effective g factor, line shape, and line width. The smaller K_1, the narrower the line in reasonably high-density materials; for this reason cobalt-doped nickel ferrite, with small K_1, has been used recently in devices where a sharper resonance line was desired. It is well to emphasize that all the ferrites under discussion are high-density, low-loss ferrites (except where noted), suitable for microwave applications.

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[1] M. H. Sirvetz and J. H. Saunders, "Resonance widths in polycrystalline nickel-cobalt ferrites," *Phys. Rev.*, vol. 102, pp. 366–367; April 15, 1956.

[2] L. R. Bickford, Jr., J. Pappis, and J. L. Stull, "Magnetostriction and permeability of magnetite and cobalt-substituted magnetite," *Phys. Rev.*, vol. 99, pp. 1210–1214; August 15, 1955.

C. M. Van der Burgt, "Controlled Crystal Anistropy and Various Mixed Ferrites," presented at Conference on Magnetism and Magnetic Materials, Boston, Mass.; October 16–18, 1956.

[3] P. E. Tannenwald and M. H. Seavey, "Anisotropy of cobalt-substituted Mn ferrite single crystals," PROC. IRE, vol. 44, pp. 1343–1344; October, 1956.

[4] W. P. Wolf, "Origin and temperature dependence of magnetic anisotropy in nonconducting ferromagnetics," *Bull Amer. Phys. Soc.*, ser. II, vol. 2, p. 117; March 21, 1957.

[5] D. W. Healy, Jr., "Ferromagnetic resonance in nickel ferrite as a function of temperature," *Phys. Rev.*, vol. 86, pp. 1009–1013; June 15, 1952.

[6] The cobalt values are from H. Shenker, "The Magnetic Anisotropy of Cobalt Ferrite and Nickel Ferrite," U. S. Naval Ordnance Lab., Navord Rep. 3858; February 8, 1955. Shenker's values were obtained on a crystal of composition $Co_{1.01}Fe_{2.00}O_{3.62}$. The room temperature value is two times larger than that obtained elsewhere (Bozorth, Tilden, and Williams, "Anisotropy and magnetostriction of some ferrites," *Phys. Rev.*, vol. 99, pp. 1788–1798; September 15, 1955) on crystals of slightly different compositions. A simple sum of anisotropies would indicate a minimum anisotropy at room temperature for $\alpha=0.015$, using Shenker's values, whereas our experiments show a minimum for $\alpha=0.027$, as reflected in the line width; this gives a factor of 2 also. Furthermore, K_1 for cobalt ferrite is affected strongly by heat treatment. In any event, the quantitative details of Fig. 1 should not be taken too seriously—the qualitative aspects are of interest here.

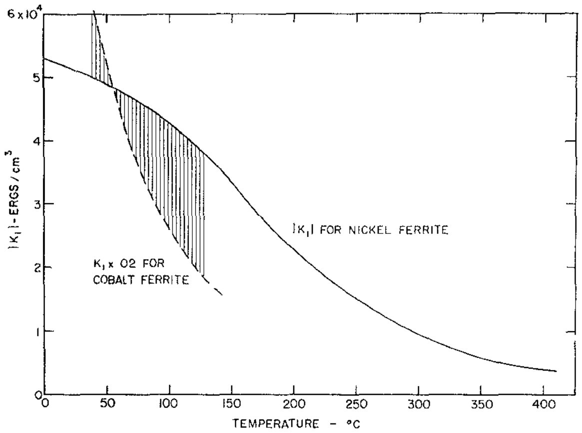

Fig. 1—First order anisotropy constant $|K_1|$ as a function of temperature for nickel ferrite (after Healy), and 0.02 K_1 for cobalt ferrite (after Shenker).

Many of the effects would not be observable were it not for the high density, and the variations with temperature would be different in very porous samples.

Materials

All the ferrites studied were prepared in our laboratory, using ceramic techniques which have been described in detail elsewhere.[7] With the exception of the ferrite-aluminates, all samples were iron-deficient and were of starting composition $Ni_{1-\alpha}Co_{\alpha}Mn_{0.02}Fe_{1.9}O_{4\pm}$, with α varying from zero to 0.09. The ferrite-aluminates had the starting formula $Ni_{1-\alpha}Co_{\alpha}Mn_{0.02}Fe_{2-t}Al_tO_{4\pm}$. Density, magnetic moment, and dielectric loss tangent at 20 mc were measured on all samples as a kind of quality-control. Densities of the nickel-cobalt ferrites varied between 95 per cent and 96 per cent of the theoretical maximum value for stoichiometric nickel ferrite, which is 5.38 gm/cm³; dielectric loss tangents were 0.001 to 0.003. The magnetic moments of samples in this series increased slightly with the small additions of cobalt in the expected way, starting from about 3230 Gauss for the nickel ferrite, corrected to X-ray density. The densities of the ferrite-aluminates were high; they will be given later.

Experimental Procedure

The resonance measurements were made at X band on ferrite spheres, using a reflection-type apparatus similar to that described by Artman and Tannenwald[8] and by Spencer, LeCraw, and Reggia.[9] The small spheres (0.015 inch to 0.040 inch) were mounted about $1\frac{1}{2}$ diameters off the center of the end wall of a rectangular TE_{101} mode cavity, which operated at 9208 mc at room temperature. Brass and copper cavities were used interchangeably at room temperature. For higher temperatures the copper cavity was used, and was flushed continuously with dry nitrogen gas to prevent corrosion. A small furnace surrounding the cavity gave temperatures up to 350°C. The temperatures were measured by means of an iron-constantan thermocouple attached to the cavity wall.

Line widths are estimated to be accurate to 8 per cent. The magnetic field was measured with extreme accuracy by means of nuclear magnetic resonance, so errors in g factor are due primarily to uncertainty in adjusting the magnetic field for maximum absorption and to imperfect spheres. The possible error is about 0.5 per cent in the nickel-cobalt series, and somewhat higher in some of the ferrite-aluminates.

Results and Discussion

The Nickel-Cobalt Ferrites

That crystalline anisotropy broadens the resonance line of a polycrystalline ferrite has been known for some time; Sirvetz and Saunders[1] observed this broadening experimentally in the nickel-cobalt ferrites. Porosity also broadens the line[10] due to the presence of localized demagnetizing fields set up by the pores. These effects have been treated theoretically by Schlömann,[11] who finds for the line broadening due to anisotropy and porosity, respectively,

$$\Delta H_{\text{anis}} = \left| \frac{K_1}{M_s} \right| \tag{1}$$

and

$$\Delta H_{\text{pores}} = 1.5(4\pi M_s)\frac{v}{V} \cdot \tag{2}$$

Here M_s is the saturation moment, V is the total volume of the sample, and v is the volume of the pores alone.

The effective g factor defined by the familiar equation for a sphere

$$\omega_0 = \gamma H_0 \tag{3}$$

(with H_0 being the applied resonance field and $\gamma = g\ e/2\ mc$) varies with porosity and anisotropy. The true polycrystalline g factor should be calculated from[12]

$$\omega_0 = \gamma(H_0 + H_i), \tag{4}$$

where H_i is an "internal field" which depends on anisot-

[7] J. E. Pippin and C. L. Hogan, "The Preparation of Polycrystalline Ferrites," Harvard Univ. Gordon McKay Lab., Cambridge, Mass., Sci. Rep. No. 8, Contract AF 19(604)-1084; July, 1957.

[8] J. O. Artman and P. E. Tannenwald, "Measurement of suceptibility tensor in ferrites," *J. Appl. Phys.*, vol. 26, pp. 1124–1132; 1955.

[9] E. G. Spencer, R. C. LeCraw, and F. Reggia, "Measurement of microwave dielectric constants and tensor permeabilities of ferrite spheres," 1955 IRE Convention Record, pt. 8, pp. 113–121.

[10] S. Blum, J. Zneimer, and H. Zlotnick, "The effects of ceramic parameters on the microwave properties of a nickel ferrite," *J. Amer. Ceram. Soc.*, vol. 4, p. 143; May, 1957.

[11] E. Schlömann, "The Microwave Susceptibility of Polycrystalline Ferrites in Strong DC Fields and the Influence of Nonmagnetic Inclusions of the Microwave Susceptibility," presented at Conference on Magnetism and Magnetic Materials, Boston, Mass.; October, 1956.

[12] This equation was suggested by T. Okamura, Y. Torizuka, and Y. Kojima, "The g factor of ferrites," *Phys. Rev.*, vol. 88, pp. 1425–1426; December 15, 1952.

ropy and porosity.[13–15] Schlömann's theoretical work gives for the internal field

$$H_i = \frac{-K_1}{2M_s} + \frac{4\pi M_s}{2} \frac{1}{\frac{V}{v} + 1}, \tag{5}$$

the anisotropy and porosity contributions being given by the two terms, respectively. The effective g factor defined by (3) is the one of greatest engineering interest, and is the one reported here. Thus it will be expected to vary with cobalt content.

One other effect should be mentioned before the data are presented. It is well known that most ferrites exhibit a resonance line that is steeper on the low-field side of resonance than on the high-field side. Several causes for this have been suggested. Spencer, Ault, and LeCraw[16] have attributed this to anisotropy. Artman[17] has shown that propagation effects (size effects) tend to make the line steeper on the low-field side. Schlömann's[11] theory predicts that the line will be steeper on the low-field side for ferrites with negative anisotropy (the usual case), and steeper on the high-field side for those with positive anisotropy.[18] Furthermore, he shows that porosity effects lead to a line steeper on the low-field side. The present series of ferrites with varying anisotropy can be used to check these ideas.

It is seen that porosity influences these three parameters—line width, effective g factor, and line shape—in much the same way as anisotropy. Since the densities in our nickel-cobalt ferrites are about the same throughout, however, any change in these parameters with cobalt content can be presumed to be due to the change in anisotropy.

Fig. 2 shows measured values of line width and effective g factor as a function of cobalt content. ΔH decreases to a minimum near $\alpha = 0.027$ and then increases with more cobalt addition, in the manner observed by Sirvetz and Saunders. The narrowest line width obtained was 175 oersteds. The scatter near the minimum is probably due to nonuniform distribution of cobalt throughout the ferrite, and therefore incomplete cancellation of K_1. It is assumed that K_1 starts at about -5×10^4 ergs/cm^3 at $\alpha = 0$, becomes less negative and passes through zero at $\alpha \doteq 0.027$, and then increases positively. The results are in fairly good agreement with

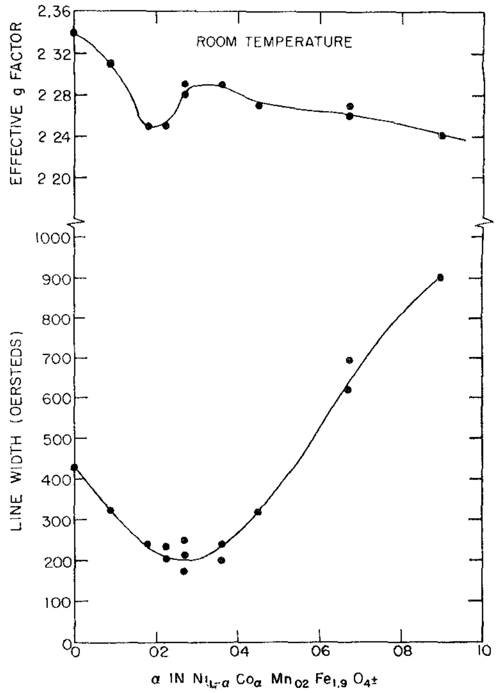

Fig. 2—Line width and effective g factor as a function of α in $Ni_{1-\alpha}Co_{\alpha}Mn_{0.02}Fe_{1.9}O_{4\pm}$.

(1) and (2). The line width at the minimum should be about 200 oersteds for 96 per cent density, according to (2); this is the case experimentally. Also (1) predicts that the anisotropy contribution to ΔH for nickel ferrite is about 200 oersteds, so that the line width for $\alpha = 0$ should be about 400 oersteds, adding in the effect of porosity. The observed value is 430. The *exact* amount by which anisotropy broadens a line is probably open to question, and may, in general, be a function of the density.[19]

Eqs. (3)–(5) predict a continuous decrease in effective g factor with cobalt content, in view of the uniform density of the samples. Eq. (3) gives

$$g_{\text{eff}} = \frac{f_0}{1.4H_0}. \tag{6}$$

Let it be assumed that $H_{i_{anis}} = -AK_1/M_s$ rather than $0.5(K_1/M_s)$, as indicated in (5). Then assuming density and M_s do not change significantly for small α, and that $K_1(\alpha)$ is a simple sum of the constituent K_1's, (4) and (6) combine to give

$$g_{\text{eff}}(\alpha) = g_{\text{eff}}(\alpha = 0) - 6.4A\alpha = 2.34 - 6.4A\alpha \tag{7}$$

for small α. Here we have used $K_1 = -5 \times 10^4$ for nickel ferrite and $K_1 = +2 \times 10^6$ for cobalt ferrite (see Bozorth, *et al.*[6]). Fig. 2 shows the decrease in g_{eff} with cobalt content. The dip near minimum anisotropy is not explained—perhaps it is due to inhomogeneities also. Except for the dip, the curve is more nearly fitted for $A = 0.2$ in

[13] Y. Kojima, "The g factor of ferromagnetic spinels," *Sci. Rep. Res. Inst., Tohoku University*, vol. A-6, pp. 614–622; December, 1954.

[14] P. A. Miles, "Ferromagnetic resonance in ferrites," *Nature*, vol. 174, pp. 177–178; July 24, 1954.

[15] T. R. McGuire, "The frequency dependence of g values in ferrites," *Proc. AIEE Conf. on Magnetism and Magnetic Material*, pp. 43–46; 1955.

[16] E. G. Spencer, L. A. Ault, and R. C. LeCraw, "Intrinsic-tensor permeabilities on ferrite rods, spheres, and disks," Diamond Ordnance Fuze Labs. Rep. No. TR-343; April 20, 1956.

[17] J. O. Artman, "Effects of size on the microwave properties of ferrite rods, disks, and spheres," *J. Appl. Phys.*, vol. 28, pp. 92–98; January, 1957.

[18] C. A. Morrison and N. Karayianis of Diamond Ordnance Fuze Labs. independently obtained a similar result, using a somewhat different model; private communication.

[19] See, *e.g.*, S. Geschwind and A. M. Clogston, "Narrowing effect of dipole forces on inhomogeneously broadened lines," *Phys. Rev.*, vol. 108, pp. 49–53; October 1, 1957.

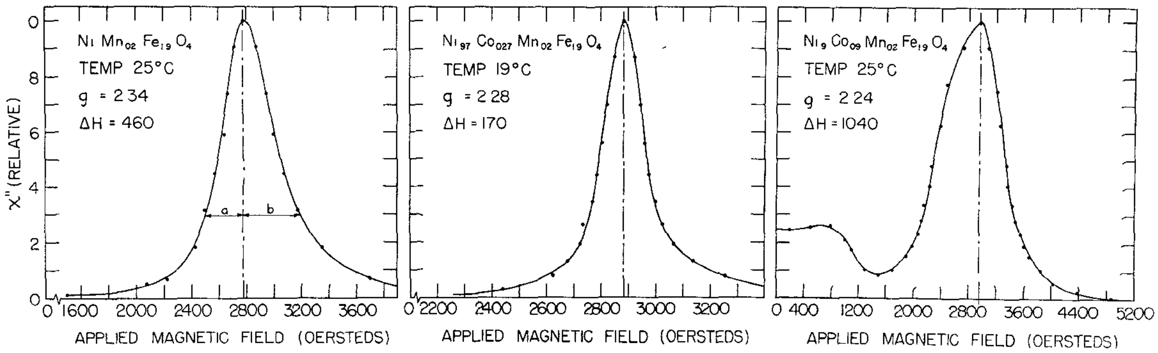

Fig. 3—Normalized resonance lines, illustrating dependence of asymmetry on the sign of K_1. For the line at left K_1 is negative; for that in the center K_1 is presumed zero; for the line at right, K_1 is positive.

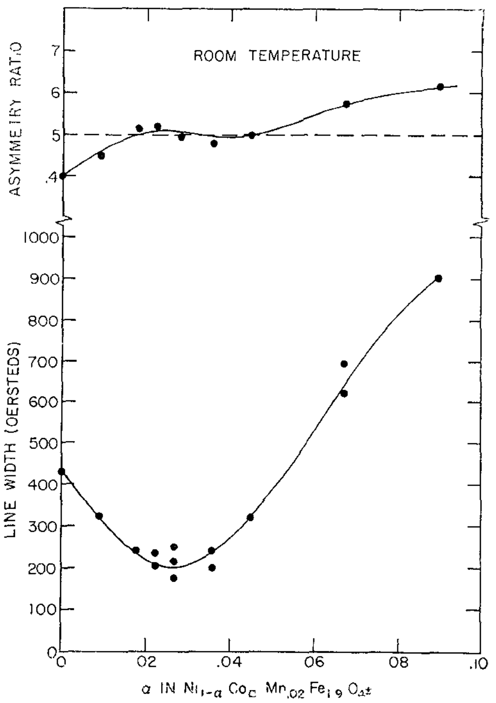

Fig. 4—Asymmetry ratio and line width vs α in $Ni_{1-\alpha}Co_{\alpha}Mn_{0.02}Fe_{1.9}O_{4\pm}$.

(7), as suggested by Miles,[14] rather than for Schlömann's value of 0.5.

Fig. 3 shows normalized resonance lines for three values of α, and illustrates the asymmetry dependence on the sign of the anisotropy constant. For the first curve α is zero and K_1 is negative; the line is steeper on the low-field side of resonance. The second curve, for $\alpha=0.027$ and K_1 presumably zero, is almost symmetrical. The third curve, steeper on the high side, is for $\alpha=0.09$ and K_1 positive. The very slight asymmetry in the center curve may be due to porosity or inhomogeneity—sphere sizes were such that the size effect probably does not occur. In order to see how this asymmetry varies continuously with α, we may define an "asymmetry ratio" with reference to Fig. 3, first curve, as

$$\text{A.R.} = \frac{a}{a+b}. \tag{8}$$

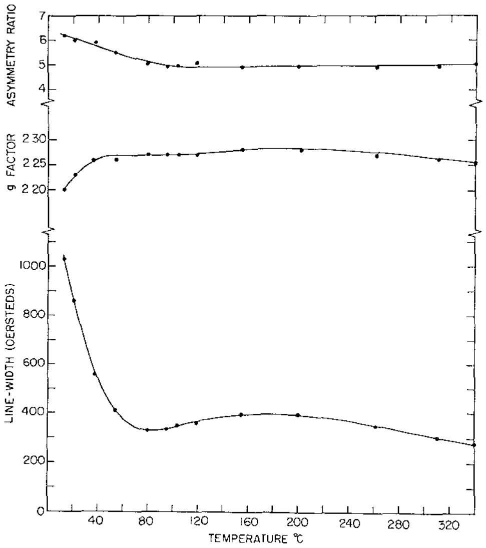

Fig. 5—Line width, effective g factor, and asymmetry ratio vs temperature for $Ni_{0.9}Co_{0.09}Mn_{0.02}Fe_{1.9}O_{4\pm}$.

The distances a and b are taken at a height which is 0.3 of maximum on the curve, where the asymmetry is fairly pronounced. Negative anisotropy should give a value less than 0.5 for A.R., zero anisotropy should give 0.5, and positive anisotropy a value greater than 0.5. This asymmetry ratio is plotted in Fig. 4 vs α, with ΔH on the same graph for emphasis. A.R. is 0.4 for nickel ferrite, increases to 0.5 in the region where ΔH is a minimum corresponding to zero anisotropy, and increases above 0.5 to the right of the ΔH minimum where K_1 is positive. It seems, then, that the line asymmetry in this case, where the anisotropy field is small compared to the resonance field and appreciably greater than the single-crystal line width, is caused primarily by anisotropy.

Since K_1 changes with temperature, ΔH, g_{eff}, and A.R. change with temperature. In Fig. 5 these quantities are shown for $\alpha=0.09$ for temperatures up to 340°C. The variations can be explained, qualitatively at least, purely in terms of anisotropy. Near room temperature K_1 is positive and decreasing towards zero. From the data it would appear that $K_1=0$ near 100°C; then it becomes negative with further increase in temperature and ultimately, of course, starts to drop to-

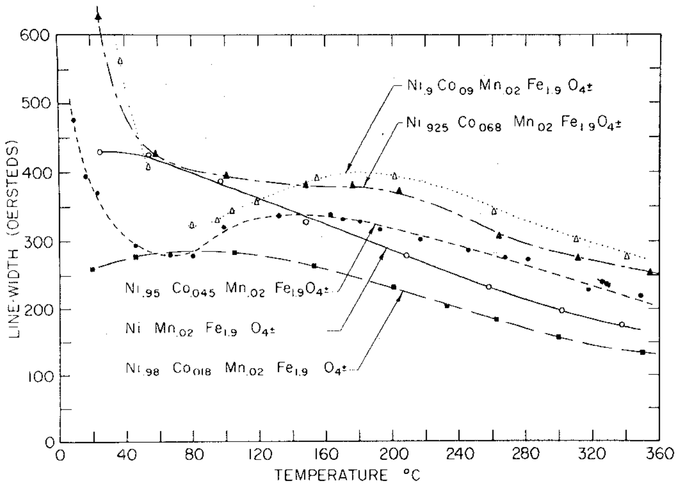

Fig. 6—Line width vs temperature for five nickel-cobalt ferrites.

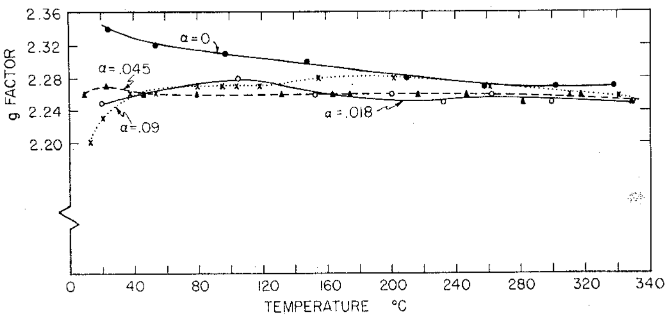

Fig. 7—Effective g factor vs temperature for four nickel-cobalt ferrites.

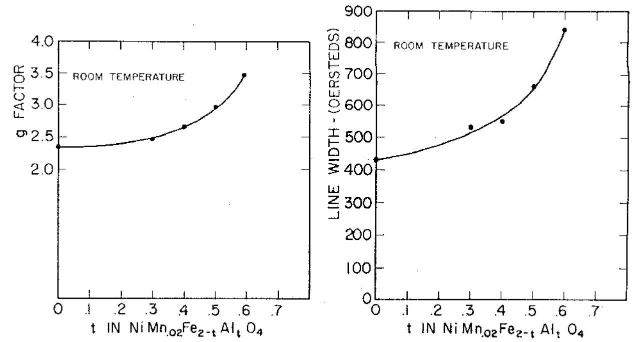

Fig. 8—Line width and effective g factor vs t in nickel ferrite-aluminate of composition Ni $Mn_{0.02}Fe_{2-t}Al_tO_{4\pm}$. Note that the point for $t=0$ was taken on composition Ni $Mn_{0.02}Fe_{1.9}O_{4\pm}$.

ward zero at still higher temperatures, as the Curie temperature is approached. The line width varies in this way, decreasing to a minimum, then increasing to a maximum, and decreasing at higher temperatures. The g factor increases as K_1 becomes less positive, reaches a plateau where ΔH is a minimum, and increases slightly as K_1 becomes negative. The asymmetry ratio behaves in the expected way, except that at higher temperatures it remains at 0.5. This is because the asymmetry ratio plotted in Fig. 5 was measured at the half-point of the line rather than at the 0.3 point, and here the asymmetry is not so sensitive to K_1.

The temperature variation of ΔH for five of the nickel-cobalt ferrites is shown in Fig. 6, while Fig. 7 shows the g factor vs temperature for four of the materials. All these curves can be explained qualitatively by considering anisotropy.

The Nickel-Cobalt Ferrite-Aluminates

In ferrites for microwave devices it would be desirable to be able to control the saturation moment, line width, and g factor independently. It was shown sometime ago[20] that the magnetization of nickel ferrite can be reduced by the substitution of aluminum for part of the iron, with some decrease in the Curie temperature. However, the line width and g factor increase rapidly when this is done,[21] and for some applications (*e.g.*, most low-frequency applications) this is undesirable. Fig. 8 shows these parameters at room temperature as a function of t in Ni $Mn_{0.02}Fe_{2-t}Al_tO_{4\pm}$. (Note that the point for $t=0$ was taken on a ferrite of starting composition Ni $Mn_{0.02}Fe_{1.9}O_{4\pm}$ rather than Ni $Mn_{0.02}Fe_2O_{4\pm}$.) The trend is the same as that shown by McGuire, but the numbers are different, due probably to the higher densities of our samples.

The possibility of adding cobalt to nickel ferrite-aluminate to reduce the line width and, to some extent, the effective g factor immediately arises, and it should be possible to do this without changing the saturation moment appreciably. The results for our samples of starting composition $Ni_{1-\alpha}Co_\alpha Mn_{0.02}Fe_{2-t}Al_tO_{4\pm}$ are shown in Fig. 9 and Fig. 10, with α between 0 and 0.025 and t between 0 and 0.6. The expected decrease in line width is observed although the magnitude of the decrease is not great for the higher aluminum contents. This could be a practical consequence of the ceramic techniques employed in making the materials; the saturation moment is lower for higher t, so that $|K_1|/M_s$ is large. Then slight inhomogeneities in the K_1 of the mixed ferrite would be more serious than for higher magnetizations. On the other hand, single-crystal measurements of line widths for nickel ferrite-aluminates are not available —it may be that the natural line width is larger for higher t.

The peculiar behavior of the $t=0.4$ and $t=0.5$ curves is not explained. However, Schlömann[22] has shown that these low magnetization ferrites may have shoulders on the resonance curve. In this event the line width is not very meaningful and the entire curve should be studied. Shoulders were observed on some of our samples, but complete lines were not plotted for all of them.

The g factor decreases as expected when cobalt is added. Of course, even in the absence of anisotropy, the

[20] L. R. Maxwell and S. J. Pickart, "Magnetization in nickel ferrite-aluminates and nickel ferrite-gallates," *Phys. Rev.*, vol. 92, pp. 1120–1126; December 1, 1953.

[21] T. R. McGuire, "Microwave resonance absorption in nickel ferrite-aluminate," *Phys. Rev.*, vol. 93, pp. 682–686; February 15, 1954.

[22] E. Schlömann, "Shape of the ferromagnetic resonance line in polycrystalline ferrites," *Bull. Amer. Phys. Soc.*, ser. II, p. 238; April 25, 1957.

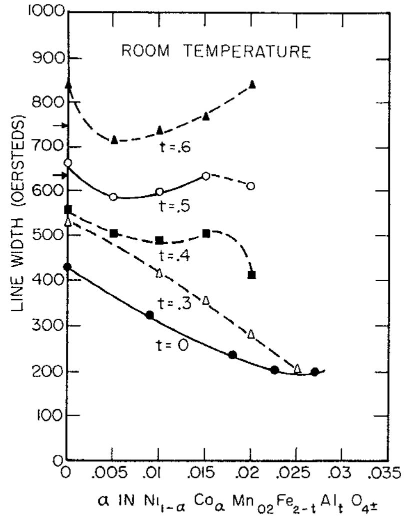

Fig. 9—Line width vs α in $Ni_{1-\alpha}Co_\alpha Mn_{0.02}Fe_{2-t}Al_tO_{4\pm}$. See text for comment on $\alpha=0$ values.

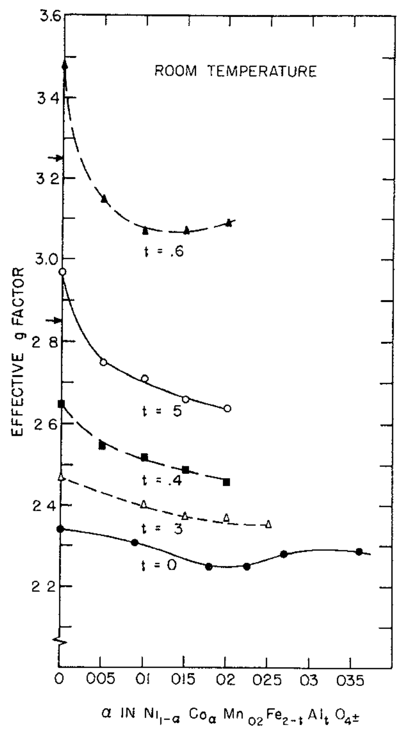

Fig. 10—Effective g factor vs α in $Ni_{1-\alpha}Co_\alpha Mn_{0.02}Fe_{2-t}Al_tO_{4\pm}$. See text for comment on $\alpha=0$ values.

g factor would be expected to increase with t, as the compensation point in the magnetization is approached.

The saturation moment and other properties of nickel ferrite-aluminates are very sensitive to the firing cycle. The ferrite-aluminates for $\alpha=0$ were prepared earlier and in a slightly different manner from those for $\alpha\neq0$. As a result their moments are somewhat different from those for corresponding t with $\alpha\neq0$. The properties of the samples are presented for comparison in Table I. If the differences in magnetization are taken into account, it is estimated that the intercepts (for $\alpha=0$) of the $t=0.6$ and $t=0.5$ curves of Fig. 9 and Fig. 10 should occur at the small arrows along the vertical scales.

TABLE I

PROPERTIES OF THE FERRITE-ALUMINATES OF COMPOSITION $Ni_{1-\alpha}Co_\alpha Mn_{0.02}Fe_{2-t}Al_tO_{4\pm}$. THE VALUES FOR $\alpha\neq0$ ARE AVERAGE VALUES.

Composition α	t	X-Ray Density[20]	Per Cent of X-Ray Density	Measured $4\pi M_s$ Corrected to X-Ray Density
0	0.3	5.27 gms/cm³	94.4%	1970
$\neq0$	0.3		97.4	1980
0	0.4	5.23	97.0	1490
$\neq0$	0.4		97.0	1570
0	0.5	5.19	95.7	1040
$\neq0$	0.5		96.6	1190
0	0.6	5.15	93.8	710
$\neq0$	0.6		96.6	840

CONCLUSION

The performance of microwave ferrite devices with large average power variations or in fluctuating ambient temperatures depends strongly on the temperature dependence of the properties of the ferrite. Here, this dependence of g and ΔH for several nickel-cobalt ferrites has been presented. It is perhaps worth while remarking that the resonance field for an isolator operating at high temperatures will be shifted not only because of the variation of M_s, as reflected through the demagnetizing fields, but also because of a change in the g factor itself. For certain cobalt contents it is also true that g and ΔH show little temperature dependence.

The reduction of ΔH and g_{eff} by addition of cobalt to nickel ferrite-aluminates has been demonstrated; another advantage that should result from this addition is a significant reduction of the maximum frequency at which low-field losses occur, in view of the reduction of $|2K_1|/M_s$—which is comparable to $4\pi M_s$ in some of the ferrite-aluminates. These examples again point up the fact that it is possible to tailor ferrite materials for a particular application, sometimes within wide limits. Thus, by adding cobalt and aluminum to nickel ferrite, $4\pi M_s$, g_{eff}, ΔH, and low-field losses can be varied; an additional control of ΔH, almost independent of the other parameters, can be realized by controlling firing temperature to obtain the desired density. The ferrite-aluminates above were fired at 1400°C in oxygen, and had relatively high dielectric losses. By using a deficiency of iron, adding some copper, and firing at 1250°C in oxygen, excellent dielectric loss tangents can be obtained with 96 per cent density.

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