Conclusions

The preceding analysis has shown that under certain restrictive conditions the electron spins appear able to couple energy from a pulsed magnetic field and radiate it efficiently at some microwave frequency. The analysis has been done for a vastly simplified system where such factors as anisotropy have been neglected. Nevertheless, certain basic limitations such as the geometrical dependence of the initial precession cone angle (θ_T) have become apparent as well as the need to consider carefully the operating temperature.

Several alternate methods of coupling the magnetic energy from the pulsed field have been proposed by the author,[2] and depend on a pulsed RF field coupling energy to the spins before the spin wave spectrum can build up. This RF field would be of lower frequency than the radiation which is desired and so a pulsed magnetic field would raise the system to the desired energy level.

A great deal of fundamental knowledge must be obtained, and many engineering problems solved, before a practical oscillator can be built. With this goal in mind, experiments are being carried out at the Air Force Cambridge Research Center.

A last point worth mentioning is that the possibility of studying the relaxation behavior of the precessional cone angle of the magnetization by means of the observed radiation is an exciting idea which may lead to a more conclusive theory of ferrimagnetic resonance damping.

[2] Presented orally at the International Conference on Solid State Physics as Applied to Electronics and Telecommunications, Brussels, Belgium; June, 1958.

Acknowledgment

The author is deeply indebted to Prof. C. L. Hogan of Harvard University for bringing the subject to his attention, and for continued encouragement and criticism. Mrs. M. R. Hoes of Air Force Cambridge Research Center performed the numerical integrations.

Ferrite High-Power Effects in Waveguides*

E. STERN† AND R. S. MANGIARACINA‡

Summary—**Deterioration of ferrite devices caused by both high power thermal and nonlinear effects are discussed. It is shown that thermal effects can be described, at least qualitatively, by a simple exponential equation. A theoretical maximum power capacity is derived in terms of ferrite configuration parameters. The results of experiments with high peak powers at both *S*-band and *X*-band frequencies are compared with predictions of Suhl's theory on nonlinear, high power effects in ferrites. Steady-state and transient effects are considered. It is shown that high power effects may be eliminated in ferrite devices by properly choosing ferrite properties and geometry.**

LOW POWER ferrite components generally deteriorate when subjected to high power.[1] This paper includes a discussion of the thermal and nonlinear[2] ferrite effects commonly found at high power, and a description of an anamolous transient effect.

Fig. 1 shows the drastic decrease with power in a ferrite resonance attenuation characteristic that, at low power levels, is effectively utilized to build isolators. Methods are indicated to eliminate these undesirable effects.

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[1] N. Sakiotis, H. N. Chait, and M. L. Kales, "Nonlinearity of propagation in ferrite media," Proc. IRE, vol. 43, p. 1011; August, 1955.

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

Thermal Effects

Assuming that the microwave power is absorbed at the top surface of the ferrite, and that the generated heat flows directly through the ferrite and into the waveguide wall, then a simple calculation can be made of the steady-state temperature distribution on the ferrite. As shown in Part A of the Appendix

$$T(X) - T_0 = \frac{0.24\alpha T}{WK} P_{\text{in}} e^{-\alpha X}$$

where

α = attenuation constant
$T(X)$ = temperature of the top surface of the ferrite (Fig. 2) at the longitudinal position x
K = thermal conductivity of the ferrite
W = width of the ferrite slab
t = thickness of the ferrite slab
T_0 = wall temperature.

In applying this equation, special care must be taken in establishing T_0; at high powers a large thermal gradient may exist through the cement between the ferrite and waveguide wall. Fig. 2 shows the theoretical temperature gradient in a specific ferrite. This gradient was qualitatively observed with a temperature indicator.

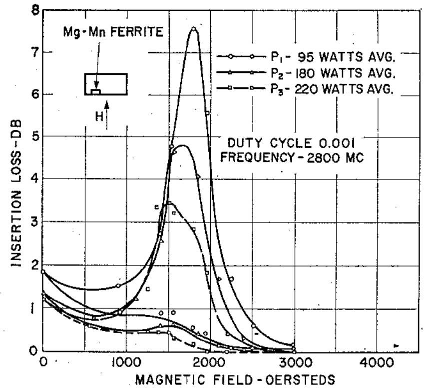

Fig. 1—Insertion loss vs magnetic field for several power levels.

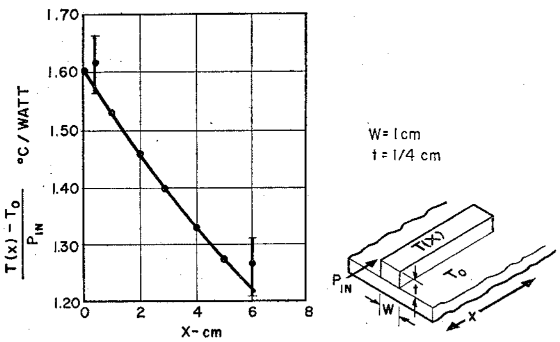

Fig. 2—Calculated thermal gradient for top surface of ferrite slab in waveguide.

If the applied power is very large, then a thermal instability may occur. The mechanism is as follows. The temperature of the first inch of ferrite increases with time until it approaches the Curie temperature. When this happens the saturation magnetization decreases markedly. This causes a proportional decrease of the attenuation constant which in turn increases the power absorbed in the cooler second inch of ferrite. The process continues and an unstable condition is produced. The end result may be a serious deterioration of attenuation of the type shown in Fig. 1.

Using the temperature indicator, an experiment was performed to verify this phenomenon. The attenuation was found to decrease with time in relation to this thermal gradient.

Fig. 3 indicates the variation of saturation magnetization ($4\pi M_s$) with temperature for two different ferrites. Note that the nickel zinc ferrite $4\pi M_s$ and therefore the attenuation remains relatively constant up to temperature T_1. At temperatures greater than T_1, the saturation magnetization drops rapidly. Therefore, it is possible to define the theoretical maximum power capacity for a given ferrite configuration.

$$P_{\max} = \frac{4.17WK}{\alpha t}[T_1 - T_0].$$

This expression holds true if the waveguide wall temperature is maintained at T_0 and the product αt is kept less than 0.01. On the other hand, severe deterioration

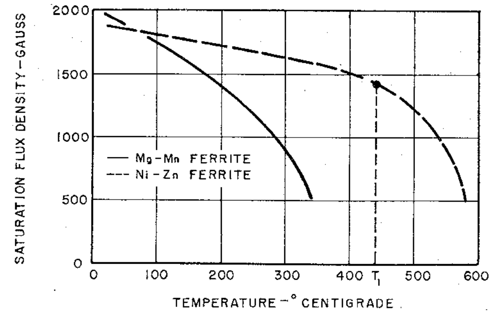

Fig. 3—Saturation magnetization vs temperature for two ferrites.

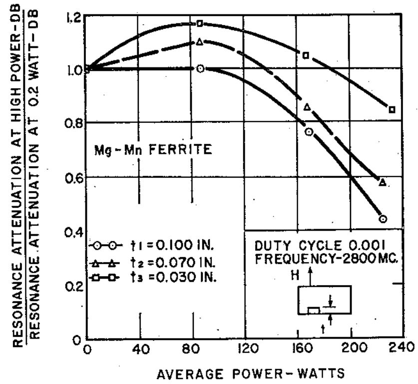

Fig. 4—Resonance deterioration for several ferrite slab thicknesses.

can be expected from the magnesium manganese ferrite at relatively low power.

Fig. 4 shows the relative resonant attenuation as a function of average power for several Mg-Mn ferrite thicknesses. It is anticipated that $P_{\max}$ should vary inversely with ferrite thicknesses. This was corroborated by the measurements shown in this figure. Note that a marked deterioration occurs at a specific power level for each ferrite thickness. Furthermore, at medium power levels, the attenuation ratio exceeds unity. This is a typical thermal effect[3] that is caused in some ferrites by the decrease of anisotropy with increasing temperature.

Nonlinear Effects

The detailed Suhl theory[2] was derived for small ferrite samples immersed in a uniform microwave magnetic field. Ordinary ferrite components use large ferrites in nonuniform microwave magnetic fields. Therefore, a comparison between theory and observations is restricted to estimates of orders of magnitude.

Fig. 5 illustrates the reverse insertion loss vs magnetic field at two peak powers. The average power was held constant to minimize thermal effects. Note that the attenuation decreases somewhat with peak power. The ferrite has a saturation magnetization of 2050 gauss and a full linewidth of 120 oersteds. Suhl's criteria for the coincidence of subsidiary and main resonance for this

[3] B. J. Duncan and L. Swern, "Temperature behavior of ferrimagnetic resonance in ferrites located in waveguide," *J. Appl. Phys.*, vol. 27, pp. 209–215; March, 1956.

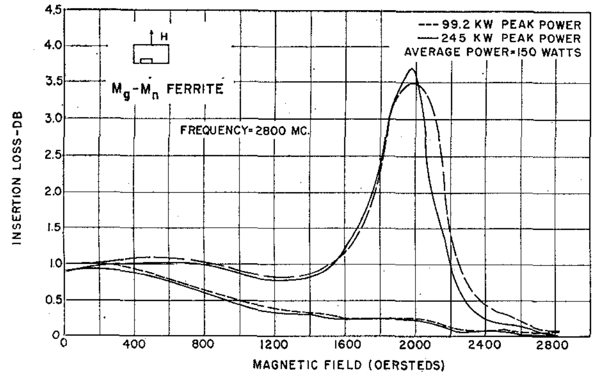

Fig. 5—The decline of the main resonance with peak power at a fixed average power level.

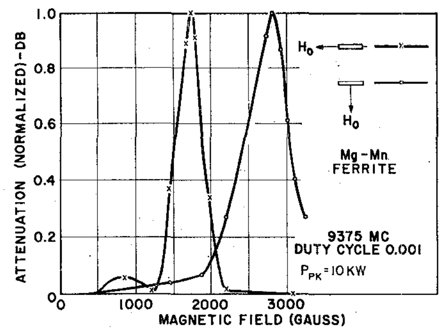

Fig. 6—The dependence of subsidiary resonance on ferrite geometry in waveguide.

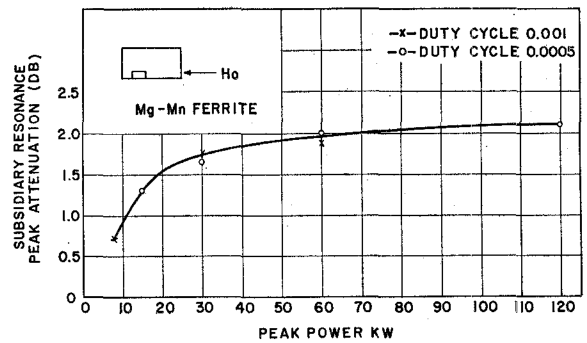

Fig. 7—The variation of subsidiary resonance with peak power.

ferrite geometry predicts that coincidence does not occur. Therefore, h_{crit}^2 is equal to

$$h_{\text{crit}} = \Delta H \sqrt{\frac{2\Delta H}{(4\pi M_s)}}$$

where ΔH is the half width of the main resonance line.

This defines the threshold for the deterioration of the main resonance. If this equation is solved for the given frequency and waveguide size (see Part B of the Appendix), it is found that the critical power is equal to 150 kw. This agrees approximately with the data shown in this figure. Note that for the slab configuration magnetized as shown, subsidiary resonance is not evident.

The normalized resonance attenuation as a function of dc field for two orientations of the field is shown in Fig. 6. Note that a subsidiary resonance peak is observed if the magnetic field lies in the plane of the slab. However, if the field is transverse to the slab, the subsidiary resonance is partially suppressed. This agrees qualitatively with Suhl's theory since it is expected that a very thin slab will not exhibit subsidiary resonance. These measurements were made at 9375 mc with a peak power of 10 kw. The main resonance did not deteriorate with peak power since it lies below the calculated instability threshold of 15 kw.

The maximum amplitude of the subsidiary resonance for the field lying in the plane of the ferrite slab as a function of peak power is shown in Fig. 7. Note that the data was taken at two duty cycles. Since the two sets of data fall on the same curve, it is clear that heating and other extraneous effects are negligible. Note also that the subsidiary resonance tends to saturate. This agrees qualitatively with the observations made by Scovil of Bell Telephone Laboratories with small single crystal samples. The calculated critical power for the onset of subsidiary resonance is equal to 30 kw. In this calculation N_x equals 1 in order to arrive at a minimum critical power level. This prediction is completely out of line with the experimental data. If h_{crit} is calculated for subsidiary and main resonance coincidence,

$$h_{\text{crit}} = \frac{(\Delta H)^2}{4\pi M_s}$$

where ΔH is the half width of the resonance line, and the critical power equals 250 watts. This calculation provides a much better approximation of the critical power for subsidiary resonance.

On the basis of the studies described above, a material and dimensions were chosen to minimize the Suhl and thermal effects in an *S*-band isolator.

The attenuation as a function of magnetic field for two power levels is seen in Fig. 8. Note that the attenuation is virtually unaffected by the power in the region lying slightly above resonance. The resonance shift with power can be attributed to a slight decrease of $4\pi M_s$ with temperature. The slight decrease of attenuation below resonance may be due to subsidiary main resonance coincidence. A field should be chosen that places the operating point in this region of minimum deterioration.

Fig. 9 gives the effect produced on the resonance line of ferrite at low power by the introduction of dielectric. Note that the apparent resonance for the ferrite-dielectric combination is shifted to a somewhat higher field and the attenuation is increased. If this principle is incorporated into a high power isolator and the ferrite and dielectric dimensions are chosen so that nonlinear effects and thermal instabilities are minimized, a high power isolator can be obtained that has minimum size and weight.

A picture of high power *S*-band isolator that requires only forced air cooling is shown in Fig. 10. With a peak power of 5 megawatts and an average power of 5 kw looking into a mismatch of 1.8 at 2900 mc, the measured

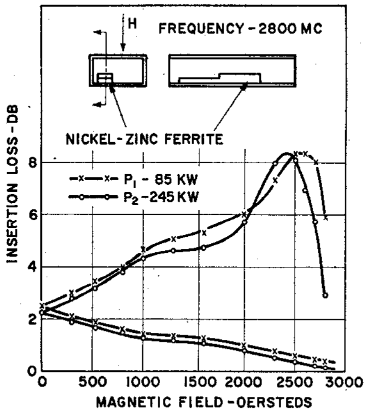

Fig. 8—Attenuation vs magnetic field for special ferrite configuration.

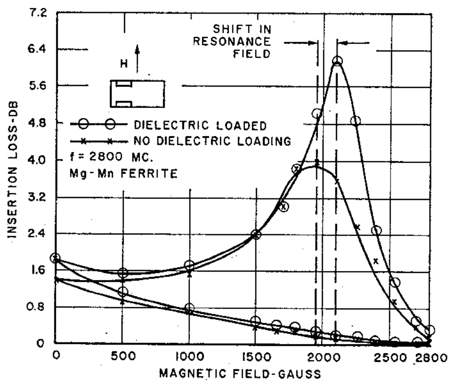

Fig. 9—The effect of dielectric loading on the main resonance.

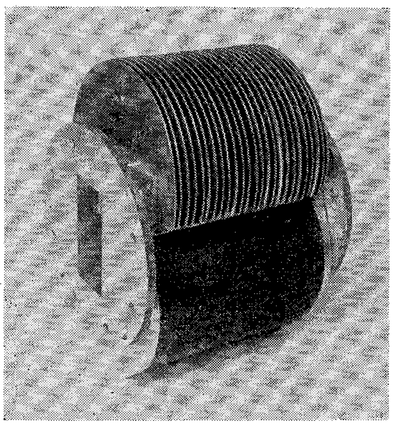

Fig. 10—Air-cooled, 5-mw peak, 5-kw average power, S-band isolator.

forward loss was less than 0.2 db and the reverse loss was greater than 10 db. The isolator is six inches long. Its bandwidth extends from 2700 mc to 2900 mc.

During these high power investigations an anomalous effect was observed at X band, especially with oversize ferrites. Fig. 11 shows the magnetizing field and the attenuation of the ferrite as a function of time. Now the expected behavior is a slight increase of attenuation, and later on a decrease. However, when the field is increased, the attenuation drops sharply within 70 milliseconds

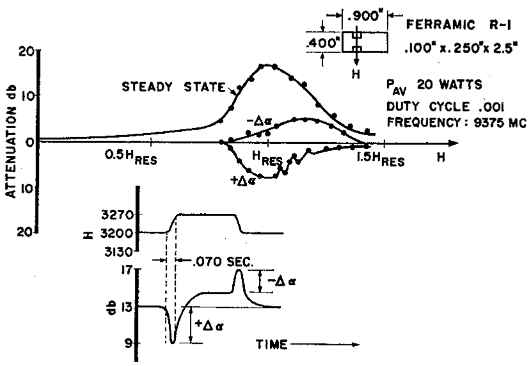

Fig. 11—The transient effect produced at high power with oversize ferrite slabs.

and then drifts slowly to the expected steady-state value above the initial attenuation. When the field is switched back to its initial value, a sharp increase in attenuation is first observed and then a slow decrease of attenuation occurs back to the expected initial level. The amplitude of the sharp increase in attenuation produced by a decrease in field is $-\Delta\alpha$ and the resultant decrease in attenuation with an increase of magnetic field is $+\Delta\alpha$. The graph in the upper portion of Fig. 11 shows the steady-state attenuation as a function of field and a plot of $+\Delta\alpha$ and $-\Delta\alpha$ that is produced at the indicated field by switching the field by a small increment.

The measurements were taken at 9375 mc with 20 watts average power and a duty cycle of 0.001. Note that the attenuation transient is sensitive to the sense of the magnetic field transient and to magnetic bias. In addition, the transients are ferrite size dependent. If the ferrite thickness is made less than 0.050 inch, the transients are suppressed. The intrinsic rise time of the effect is known now.

In conclusion, high power effects can be eliminated by choosing the appropriate ferrite geometry. A ferrite with a broad linewidth, a high Curie temperature, a slow decline of the saturation magnetization with temperature, a low $4\pi M_s$ and a transversely magnetized slab configuration should enable the engineer to build a very high power component. If a large amount of power is to be dissipated in the ferrite, it is recommended that the ferrite be soldered directly to the waveguide wall and that the coolant be applied in a fashion such that the thermal gradient between coolant and ferrite is minimized. The ferrite dimensions should be adjusted so that neither thermal nor nonlinear critical powers are reached. The judicious use of dielectric should help to overcome some of the effects produced by high power.

The anomalous effect can be prevented from occurring in high power switches, variable attenuators, and modulators if the switching speed is made long or if the ferrite dimensions are reasonably small.

Special care must be taken in all high power devices where the transverse demagnetizing coefficients are greater than zero because the subsidiary resonance peak is then likely to occur.

APPENDIX

Part A

The microwave power that is absorbed per differential ferrite segment is

$$dP_x = -\alpha P_{in} e^{-\alpha x} dx. \qquad (1)$$

If it is assumed that all the microwave energy is absorbed in the top surface of the ferrite and that all the heat flows directly into the waveguide wall at temperature T_0, then the following expression holds true:

$$d\dot{Q}_x = 0.24 dP_x = \frac{WK}{t}[T_x - T_0]dx \qquad (2)$$

where

K = thermal conductivity of ferrite
W = width of the ferrite slab
t = thickness of the ferrite slab
T_0 = wall temperature.

Substituting (1) in (2),

$$[T_x - T_0] = 0.24 \frac{\alpha t}{WK} P_{in} e^{-\alpha x}.$$

The assumption has been made that the heat flows directly to the waveguide wall. The assumption is justified if

$$\frac{\dfrac{d[T_x - T_0]}{dx}}{\dfrac{d[T_x - T_0]}{dy}} = \alpha t \ll 1.$$

Part B

Microwave magnetic fields in waveguide may be expressed as

$$H_x = 0.0719\sqrt{\frac{P_t}{ab}}\sqrt{1 - \left(\frac{\lambda}{\lambda_0}\right)^2} \sin\left(\frac{\pi}{a}x\right) \sin \omega t \text{ oersteds}$$

$$H_z = 0.0719\sqrt{\frac{P_t}{ab}} \frac{1}{\sqrt{1 - (\lambda/\lambda_0)^2}} \cdot \frac{\lambda}{\lambda_0} \cos\left[\frac{\pi}{a}x\right] \cos \omega t \text{ oersteds}$$

where

P_t = transmitted power in watts
a, b = waveguide dimensions in inches
λ = free space wavelength
λ_0 = cutoff wavelength for the TE_{10} waveguide mode.

Part C

The coincidence of main and subsidiary resonance is achieved provided that

$$(N_x + N_y + \sqrt{N_x^2 + N_y^2 + 14N_xN_y}) \frac{4\pi M_s}{3} > \frac{\omega}{\gamma}$$

where

the demagnetizing factors $N_x + N_y + N_z = 1$
$4\pi M_s$ = saturation magnetization in gauss
ω = applied angular frequency
$\gamma = 2\pi \times 2.82 \times 10^6$ radians/oersted.

Temperature Effects in Microwave Ferrite Devices*

J. L. MELCHOR† AND P. H. VARTANIAN†

Summary—**With proper choice of shape, it is possible to minimize the frequency shift of ferromagnetic resonance in microwave ferrite components operating over a wide range of ambient temperatures. Calculations have been made for minimum resonance frequency shift with change in saturation moment. Curves relating the resonance frequency shift as a function of saturation magnetization are plotted for several ferrite geometries. Design curves are presented for reducing dependence of resonance frequency on temperature.**

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INTRODUCTION

IN THE DESIGN of microwave devices containing ferrites, the choice of ferrite shape can have an important effect on the characteristics achieved. The ferrite dimensions should be chosen to give optimum performance. Fig. 1, derived from Kittel's equation,[1]

$$\omega^2 = \gamma^2[H + (N_y - N_z)4\pi M][H + (N_x - N_z)4\pi M]$$

[1] C. Kittel, "On the theory of ferromagnetic resonance absorption," *Phys. Rev.*, vol. 73, pp. 155–161; January, 1948.