Appendix

Part A

The microwave power that is absorbed per differential ferrite segment is

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

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),

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

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

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

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*

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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.

shows the relation between the applied magnetic field and the ferromagnetic resonance frequency for several commonly used ferrite shapes. The X's in Fig. 1 denote abscissa values for which the applied field is sufficiently large to overcome internal demagnetizing fields for each shape, so that saturation may be produced. The range over which low field magnetic losses occur in a demagnetized sample of any shape is shown. Fig. 1 is useful in comparing the various shapes commonly used in devices. Choice of a shape is easily made on the basis of requirements for low frequency operation, low applied magnetic field, or a particular ferrite. Points above the lines correspond to operation below ferromagnetic resonance field (or above ferromagnetic resonance frequency) and include most low field devices such as Faraday rotators and differential phase shifters.

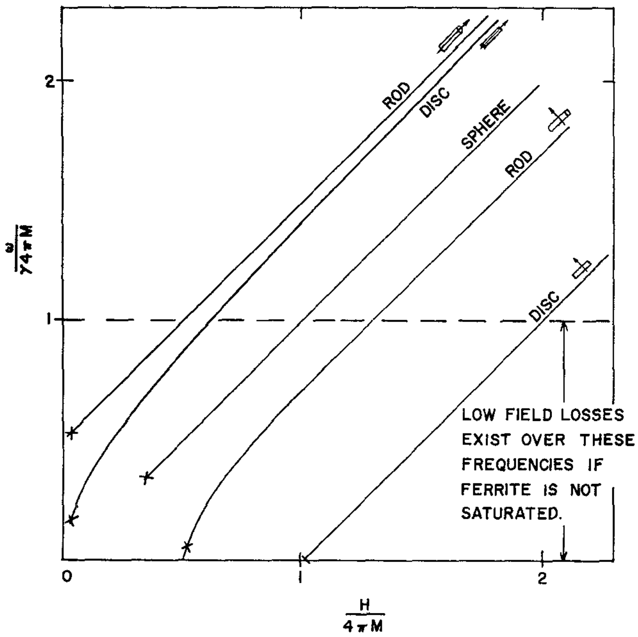

Fig. 1—Resonance frequency as a function of applied field and saturation magnetization for different ferrite shapes.

As the temperature increases, due to ambient conditions or power absorption, a typical ferrite's saturation magnetization is found to decrease as shown in Fig. 2. Measurements made on a Mg-Mn-Al ferrite show the magnetization dropping from 900 gauss at room temperature to zero at a Curie temperature of 92°C. Two effects will be noted on microwave device characteristics as the saturation magnetization decreases. First, the nonreciprocal property, absorption or phase shift, for example, decreases in magnitude because of the reduction in saturation magnetization. Second, a change in magnetization causes the ferromagnetic resonance frequency to shift in a manner which can be predicted from Kittel's equation. By proper choice of ferrite shape it is possible to minimize this shift in resonance frequency. Figs. 3(a) and (b) show the shift in resonance frequency as a function of saturation magnetization for two com-

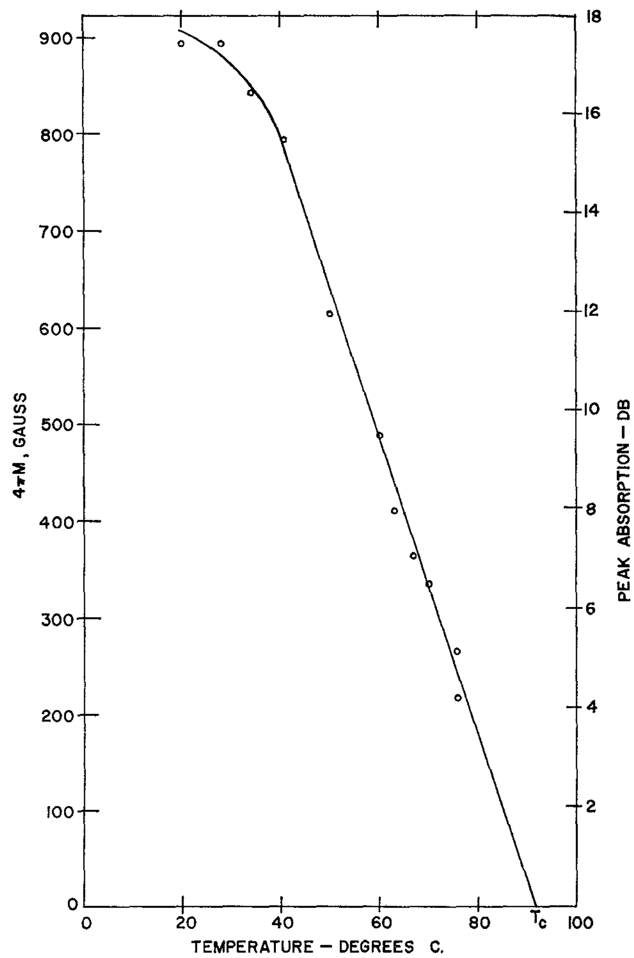

Fig. 2—Absorption vs temperature for thin slab of Mn-Mg-Al ferrite with saturation magnetization of 900 gauss and Curie temperature, T_c, of 92°C.

monly used ferrite-loaded waveguide geometries. Fig. 3(c) shows the possible results which can be obtained with a more suitable choice of ferrite shape. It is seen in this case that the resonance frequency remains almost independent of saturation magnetization.

Discussion

As shown by the ferromagnetic resonance absorption characteristics of Fig. 3, the operating frequency range of an isolator depends on the applied magnetic field, the saturation magnetization of the material used, and the demagnetizing factors associated with the choice of geometry. These quantities are related through Kittel's equation.

Since most ferrite devices use geometries which are long compared to a wavelength and vary only in transverse shape, the demagnetizing factor N_y, where y is along the waveguide axis, has been assumed to be zero. For this geometry Kittel's equation normalized to the applied field becomes

$$\left(\frac{\omega}{\gamma H}\right)^2 = \left[1 - N_z \frac{4\pi M}{H}\right]\left[1 + (1 - 2N_z)\frac{4\pi M}{H}\right] \quad (1)$$

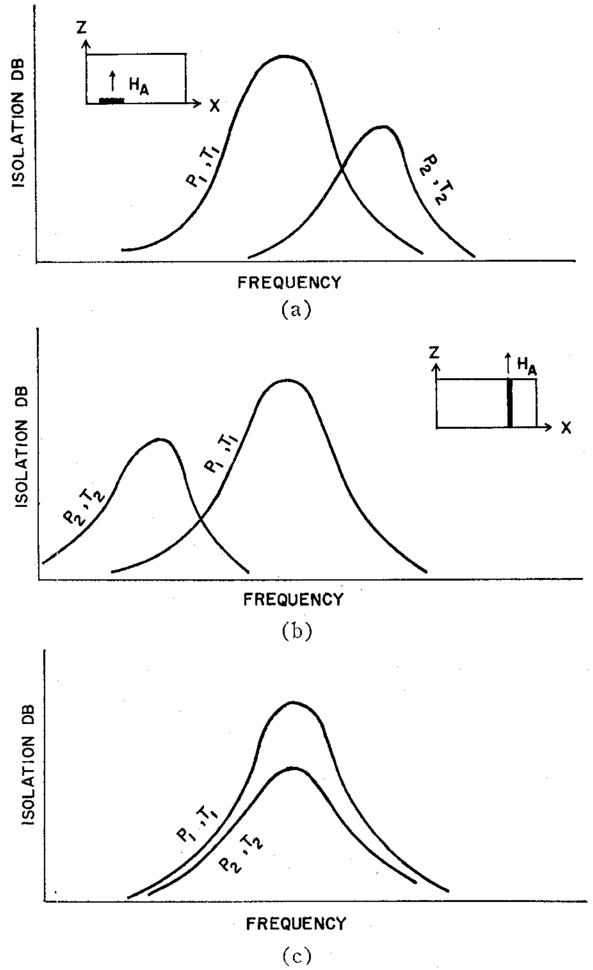

Fig. 3—Isolator characteristics for ferrite slabs magnetized (a) normal to plane, (b) parallel to plane, and for (c) ferrite shape chosen for minimum dependence of resonance frequency on magnetic moment. P_2 and T_2 are greater than P_1 and T_1.

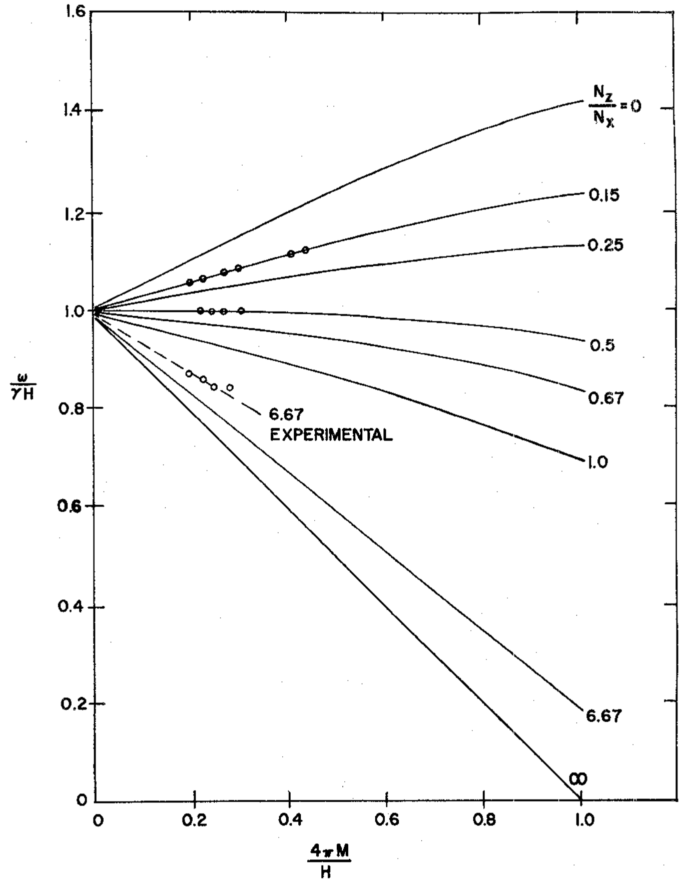

Fig. 4—Resonance frequency vs saturation magnetization for different demagnetizing factors.

where

ω = ferromagnetic resonance frequency

γ = gyromagnetic ratio

$N_z = 1 - N_x$ = demagnetizing factor along direction of field

$4\pi M$ = saturation magnetization of the ferrite.

Calculated curves based on (1) for different values of N_z/N_x are shown in Fig. 4. Here it can be seen that for a ferrite shape chosen such that $N_z/N_x = 0.5$, the saturation magnetization can decrease from half the applied resonance field value to zero without an appreciable change in resonance frequency. For any value of N_z/N_x less than 0.5 the curves of Fig. 4 will have maxima; and in the neighborhood of these maxima the moment can change over wide ranges with little effect on resonance frequency. Experimental points are plotted for ferrite samples chosen with $N_z/N_x = 0.15$, 0.5 and 6.67. Correlation between calculated and experimental data for the first two shapes is found to be quite good. However, for the latter shape there is a discrepancy between calculation and measurement. The values for N_z/N_x were determined from Osborn,[2] assuming the slabs to be ellipsoids. For the dimensions used, it is found that N_z/N_x is approximately equal to the ratio of the x dimension to the z dimension. However, since the ferrite was mounted flat on a waveguide wall, one should use double the z dimension because of the RF image dipole required by the metal surface boundary conditions.[3] Consequently, the points labeled "6.67 experimental" should be for an effective N_z/N_x of 3.33, and again, agreement between theory and experiment would be good.

For each operating microwave frequency there is a corresponding combination of geometry, applied magnetic field, and saturation magnetization to give minimum temperature dependence. Fig. 5 shows the locus of points derived from Kittel's equation when $d\omega/dM$ is zero. These curves provide the necessary information to design a microwave ferrite device with minimum dependence of resonance frequency on temperature. As an example, assume we have need for an isolator at 5600 mc which is subjected to a variable ambient temperature. Now, if we choose a low loss ferrite with a saturation magnetization of 2000 gauss, $\omega/4\pi M\gamma$ is 2.0. The optimum choice of N_z/N_x is seen to be 0.415 and $4\pi M/H$ is

[2] J. A. Osborn, "Demagnetizing factors," *Phys. Rev.*, vol. 67, pp. 351–357; March, 1945.

[3] Private communication, M. Sirvetz and H. Sharfman, Raytheon Manufacturing Co.

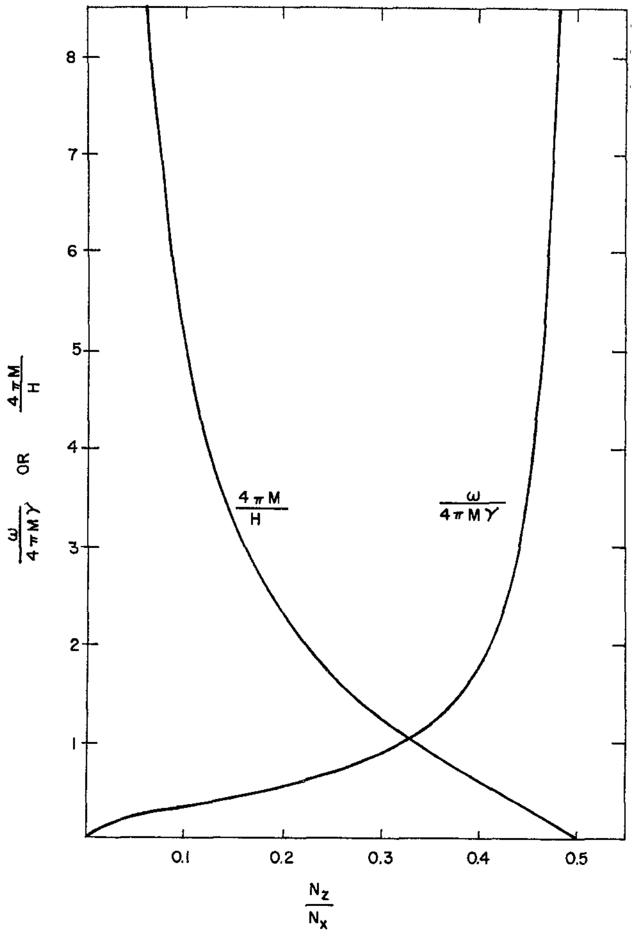

Fig. 5—Resonance frequency or magnetic field value vs N_z/N_x for $d\omega/dM=0$.

0.50, or the field to be applied is 4000 gauss. Suppose, however, we choose to use a high Curie temperature ferrite with a saturation magnetization of 3500 gauss. Then, $\omega/4\pi M\gamma$ is 0.57, N_z/N_x is 0.20 and $4\pi M/H$ is 2.25. Here the field required for resonance is 1555 gauss.

Conclusions

Ferrite shapes can be chosen to minimize change in microwave resonance frequency whenever saturation moment decreases due to ambient temperature changes. However, if the temperature rise is due to power absorption within the ferrite, several additional factors must be considered in designing a device for minimum shift of resonance frequency. First is the cooling effect of the metallic wall on the ferrite. This sets up a thermal gradient across the ferrite and consequently the optimum N_z/N_x varies, since $4\pi M$ varies throughout the material. Second, presence of the metallic wall tends to stabilize the ferrite temperature, and it will probably be found that the optimum shape for the extremely high average power device is a compromise between maximizing the area between the ferrite and waveguide wall for heat transfer reasons, and choosing an optimum shape for minimizing the thermally caused shift in resonance frequency. For applications where environmental temperature of the device is to vary over wide ranges, choice of N_z/N_x, as shown in Fig. 5, is optimum.

Discrepancies between the resonance frequency predicted by Kittel's equation and that measured for the configuration of Fig. 3(a) can be attributed to an RF image at the waveguide wall.

Characteristics of Ferrite Microwave Limiters*

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***Summary*—Microwave ferrites that exhibit a nonlinear RF absorption as a function of RF power level can be utilized in the construction of a passive microwave device which will allow small RF signals to be transmitted with very little attenuation but which will attenuate large RF signals considerably. Such a device tends to "limit" the amplitude of the microwave energy passing through the device and is therefore called a ferrite microwave limiter.**

One application of the ferrite limiter is in the protection of crystal detectors in pulsed radar sets. However, when a rectangular pulse of *X*-band RF energy is transmitted through the limiter, the output waveform is no longer rectangular but consists of a leading edge spike of 0.1-μsec duration followed by a plateau of highly attenuated RF energy. At the present time the leading edge spike is the major obstacle in the successful use of the ferrite microwave limiter as a TR cell in the protection of crystal detectors.

Experimental techniques used to improve the performance of the limiter are presented, and the performance characteristics of an *X*-band ferrite microwave limiter are shown.

Principle of Operation

The nonlinear properties of ferrites were first observed in cavity experiments conducted by Damon[1] and by Blombergen and Wang[2] in 1950 and 1951. Similar observations in ferrite-loaded waveguide

* Manuscript received by the PGMTT, July 1, 1958; revised manuscript received, September 2, 1958.
† Systems Dev. Labs., Hughes Aircraft Co., Culver City, Calif.

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

[2] N. Blombergen and S. Wang, "Relaxation effects in para- and ferromagnetic resonance," *Phys. Rev.*, vol. 93, pp. 72–83; January, 1954.