Development of a High-Power *L*-Band Resonance Isolator*

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Summary—**Waveguide resonance absorption isolators have been developed for use under high peak and average power conditions at *L* band. Two ferrite materials, one a nickel aluminate ferrite, the other a nickel cobalt ferrite, were developed for this purpose. The characteristics of isolators using these two materials are described.**

Choice of Material

Faced with the problem of developing a high-power isolator for use at about 1300 mc, the resonance-type isolator appeared to be the most promising. Other isolator types which operate off resonance tend to be less feasible at even higher frequencies, at least with ferrite materials presently available.[1]

The principal difficulty in designing a low-frequency resonance isolator is that the applied magnetic fields required for magnetic saturation of the sample and for ferromagnetic resonance are comparable. Thus, care has to be taken to have the sample already magnetically saturated at the resonance field. Otherwise, no distinctive ferromagnetic resonance phenomenon will occur, which is the condition for a satisfactory performance of a resonance isolator. This will be discussed quantitatively.

Although ferrite slabs are used in the practical design, it is somewhat simpler to discuss the relevant facts considering ferrite in disk shape. The sample is mounted in a rectangular waveguide, as shown in Fig. 1, with the dc magnetic field applied normal to its plane. As usual, with respect to its magnetic behavior the disk is approximated by an ellipsoid of revolution. Its dc demagnetizing factor N_z is used for the disk. However, the RF demagnetizing factor N_x is defined by an ellipsoid approximating a disk of twice the original thickness because here the mirror image of the RF H field has to be taken into account. Thus, the sum of the demagnetizing factors is greater than 1.

In order to have the ferrite magnetically saturated, the applied field has to exceed the demagnetizing field,

$$H_{sat} > 4\pi N_z M_s \quad (1)$$

where $4\pi M_s$ = saturation magnetization.

If the applied field were just equal to the demagnetizing field, there still would be a fair degree of misalignment of the magnetization in some grains of the polycrystalline material due to the magnetic anisotropy. The degree of misalignment is proportional to the anisotropy field, H_{anis}, and decreases as the applied field increases. Thus, it is reasonable to define a saturation field

$$H_{sat} = 4\pi N_z M_s + H_{anis} \quad (1a)$$

remembering that this applied field will reduce the misalignment of magnetization in individual grains to a certain degree. Experience has shown that in fairly dense polycrystalline material the ferromagnetic resonance linewidth is of the order of the anisotropy field.

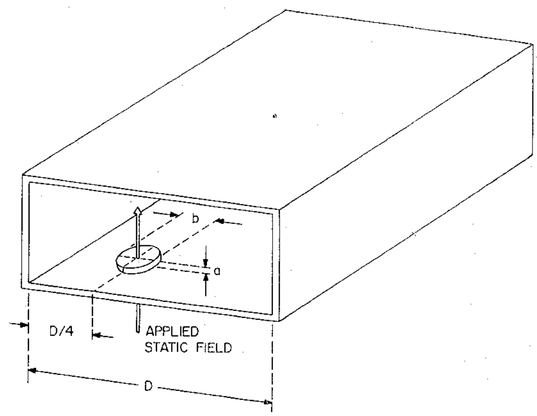

Fig. 1—Illustrating geometry of resonance isolator employing ferrite disk.

The field necessary for resonance is given by Kittel's equation[2]

$$H_{res} = \omega/\gamma + 4\pi(N_z - N_x)M_s. \quad (2)$$

where ω = frequency and γ = gyromagnetic ratio.

If ferromagnetic resonance is to take place in a saturated ferrite, the resonance field (2) has to be greater than the saturation field (1a) or

$$\omega/\gamma > 4\pi N_x M_s + H_{anis}. \quad (3)$$

Given the frequency of operation, this condition can be satisfied by choosing a ferrite material with a) small gyromagnetic ratio γ, b) small saturation magnetization M_s, c) small magnetic anisotropy H_{anis}, and by selecting a flat disk geometry such that there is d) a small demagnetizing factor N_x. Inspecting the ferrite materials

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

[2] C. Kittel, "Interpretation of anomalous Larmor frequencies in ferromagnetic resonance experiment," *Phys. Rev.*, vol. 71, pp. 270–271; February, 1947.

TABLE I
SUMMARY OF FERRITE PROPERTIES

Ferrite	$NiO(Fe_2O_3)_{0.50}(Al_2O_3)_{0.45}$	$(NiO)_{0.975}(CoO)_{0.025}(Fe_2O_3)$
Saturation magnetization, $4\pi M_s$ (gauss)	300	3000
Curie temperature, T_c (°C)	260	590
Linewidth, ΔH, measured at 10 kmc with spherical samples (oersteds)	825	200
Linewidth, ΔH^*, defined as twice the high field half linewidth, measured with thin disks at 1.2 kmc (oersteds)	780	380
Gyromagnetic ratio, γ, measured at 10 kmc with spherical samples (mc/gauss)	2.0	3.2
Thermal conductivity, k, at 100°C, (cal/sec cm. °C)	0.01	0.04

presently available and excluding those with a Curie temperature close to room temperature, there appear to exist two classes of ferrites satisfying condition (3) at 1300 mc.

The first class consists of certain members of the family of nickel aluminate ferrites. They have been studied in detail by Gorter[3] and by Maxwell and coworkers.[4,5] If we write the generic formula as $NiAl_xFe_{2-x}O_4$, the pertinent data may be summarized as follows.

1) The Curie temperature drops proportionally to x, from 590°C for $x=0$ to 200°C for $x=1$, which is about the limit of usefulness.

2) The saturation magnetization drops from a value of 3000 gauss for $x=0$ to zero at $x=0.625$ (magnetization compensation point), and then rises again to a maximum value at $x=1$. This maximum value at $x=1$ depends somewhat on the processing and in our case is about 500 gauss.

3) The effective g factor is equal to 2.3 at $x=0$, increases with increasing x, and reaches very large values just below the compensation point. Above compensation g drops to an approximately constant value of 1.5.

4) The polycrystalline linewidth is large near the compensation point, because the anisotropy energy remains finite as the magnetization goes to zero and the effective anisotropy field becomes very large.[6]

Suitable materials for application in L-band resonance isolators may be found for values of x greater than required for magnetic compensation. Conditions a) and b) of small gyromagnetic ratio and saturation magnetization are then met. The anisotropy turns out to be sufficiently small for the purpose. Also, it is not even necessary to choose a very flat geometry because of the small magnetization.

The properties of one such material,

$$NiO(Fe_2O_3)_{0.50}(Al_2O_3)_{0.45},$$

are given in Table I. The resonance isolator data to be given below were obtained with it. The low value of $4\pi M_s$ is a consequence of high porosity in this particular material; when corrected to zero porosity the value of $4\pi M_s$ becomes 500 gauss. The linewidth may be decreased to 600 oersteds by firing the material to high density. After these measurements were completed, it was found that relatively high density materials with measured magnetization of 500 gauss and linewidth below 300 oersteds could be obtained by rather slight compositional and processing variations which did not affect adversely the other properties.

The second type of material that has been investigated is exemplified by nickel ferrite modified by a small cobalt substitution such as to cancel the first order anisotropy at the operating temperature. Sirvetz and Saunders[7] have shown that a decrease in polycrystalline linewidth from 400 oersteds to less than 200 oersteds is achieved by means of a 2.5 mole per cent substitution of cobalt for nickel. The ferrite does not satisfy the first two conditions: the gyromagnetic ratio has practically the free electron value and the saturation magnetization is essentially that of nickel ferrite. However, condition c) of small magnetic anisotropy is fulfilled, and condition d) may be satisfied by choosing a very flat geometry so that the small demagnetizing factor N_x can compensate for the large magnetization. The properties of this material are also given in Table I.

PERFORMANCE OF THE NICKEL ALUMINATE FERRITE ISOLATOR

Isolator and Magnet Geometry

The typical design of such an isolator is shown in Fig. 2. Fig. 3 is a photograph of one version of the isolator which demonstrates the placement of the Alnico V magnets. Reduced height waveguide is used because it is easier to maintain the biasing H field over the smaller gap. Also, the effectiveness of the ferrite is increased because in reducing the height the RF H field within the ferrite increases. The reduction in height is limited by the onset of arcing which should be avoided at the peak power used. In practice, half-height guide, $1\frac{5}{8}\times 6\frac{1}{2}$ inches, is used without difficulty at least up to 2.5 megw.

The optimum biasing field at room temperature is about 800 gauss. As a consequence of the large reson-

[3] E. W. Gorter, "Saturation magnetization and crystal chemistry of ferrimagnetic oxides," *Philips Res. Reps.*, vol. 9, pp. 403–443; November, 1954.

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

[5] T. R. McGuire, "Magnetic resonance absorption in nickel ferrite-aluminates," *Phys. Rev.*, vol. 91, p. 206; July, 1953.

[6] E. Schlomann and J. R. Zeender, "Ferromagnetic resonance in polycrystalline nickel ferrite aluminate," *J. Appl. Phys.*, vol. 29, pp. 341–343; March, 1958.

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

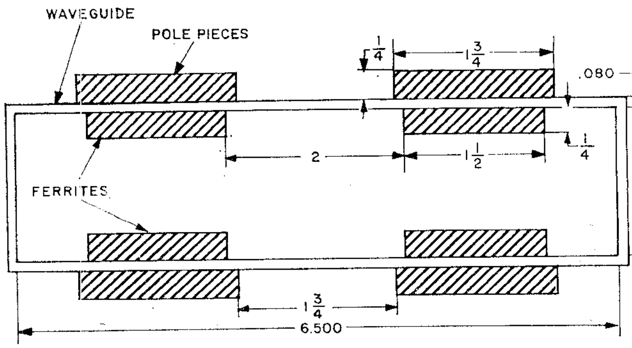

Fig. 2—Dimensions of the L-band isolator using nickel aluminate ferrite.

ance linewidth, no great homogeneity is required. Therefore, it is possible to have ferrite slabs at the four possible positions within the guide despite the resulting inhomogeneities in the biasing field. The applied biasing field actually is made somewhat lower, between 700 and 750 gauss, beause the device will work at elevated temperatures due to the power dissipated in the ferrite. At higher temperatures the saturation magnetization decreases and so does the field necessary for resonance.

The ferrite dimensions used are determined experimentally as a compromise between various factors. The best figure of merit is achieved with ferrites having a small and flat cross section. The dissipation of power absorbed in the ferrite is also favored by this geometry: that is, small thickness and large area in contact with the guide wall. On the other hand, a large reverse attenuation per unit length of the isolator requires a large ferrite cross section.

Using the ferrite cross-sectional dimensions shown, slabs $\frac{1}{4} \times 1\frac{1}{2}$ inches, an isolation of 10 db was obtained in a length of 15 inches while the insertion loss was 1 db or slightly less. With reduction of ferrite thickness to $\frac{1}{8}$ inch the isolation decreased to one half the above value, but the back-to-front ratio increased from 10 to a value of 15 to 18. Improvement in back-to-front ratio thus involves an increase in length while decreasing thickness for a given amount of isolation, but if lower peak powers were being considered, waveguide of smaller height could be used and the improved back-to-front ratio could be obtained without such a large increase in length.

It seems worth mentioning that the reverse loss per unit length of this isolator can be predicted reasonably well by waveguide perturbation theory. In this theory the change of the wave vector k (in empty guide, $k=2\pi/\lambda_g$) due to perturbations in the waveguide cross section is calculated. The procedure is quite analogous to cavity perturbation theory where the change in resonant frequency is computed. Empty guide RF H field is assumed, in particular circularly polarized field inside the ferrite. Magnetic loss is introduced in the form $\mu''+\kappa''=8\pi M_s/\Delta H$. The reverse loss calculated in this way agrees with the experimental data to within 20 per cent. Good agreement should be expected considering the boundary conditions. The RF H field is tangential to the broad face of the ferrite, hence should be the same inside the ferrite as in empty guide.

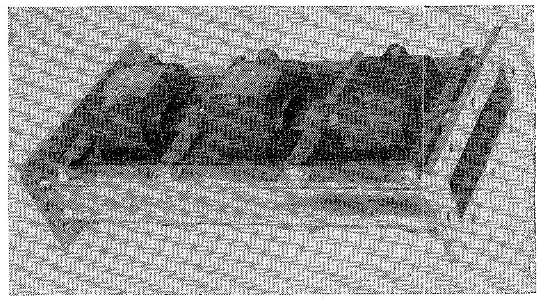

Fig. 3—Photograph of the L-band isolator using nickel aluminate ferrite.

Figure of Merit

The figure of merit is defined as the ratio of reverse attenuation to insertion loss (back-to-front ratio). For this number Lax,[1] under a number of assumptions, arrived at a theoretical upper limit:

$$F = (2\omega\tau)^2. \tag{4}$$

Here τ is the relaxation time. The underlying assumptions are: a) the ferrite is magnetically saturated; b) the insertion loss is due to magnetic losses only; c) the loss with applied resonance dc field, but with the nonresonant circular RF excitation, is given by a Lorentzian tail-off of the resonance absorption described by the relaxation time τ; d) the perturbation approach is valid and, especially, the RF H field inside the ferrite is circularly polarized. The relaxation time may be correlated with the observed ferromagntic resonance linewidth. Then the upper limit for the figure of merit reads

$$F = (4\omega/\gamma\Delta H)^2. \tag{4a}$$

Inserting the data for nickel aluminate ferrite, the limiting figure of merit would be 10.5. Experimental figures lie in the range from 10 to 18. The reason for this discrepancy seems to be that the basis of arriving at the theoretical limit is questionable. Most important probably is the fact that the line shape is not Lorentzian. At 10 kmc, the line is found to be asymmetric, with the slope at the low field side larger than that at the high field side. In fact, the assumption of Lorentzian shape far from resonance seems to have no firm theoretical foundation, even for single crystals where distortions due to anisotropy, etc., are absent. It appears that at present there is no reliable basis for estimating a limiting figure of merit under the given circumstances.

Dielectric Losses

Since the ferrite fills an appreciable fraction of the waveguide cross section for an appreciable length, dielectric losses would adversely influence the figure of merit of the isolator if they exceeded a certain value. In this case it may be estimated that microwave resistivity of the ferrite should be higher than 10^4 ohm-cm.

It is known that in ferrites such as considered here, conduction is caused by the presence of divalent iron ions. In order to keep the resistivity high, the ferrite is made slightly iron deficient and is fired at a rather low temperature (1250°C) in oxygen. Cavity measurements of complex dielectric constant at 10 kmc show that indeed the microwave resistivity of this ferrite is higher than 10^4 ohm-cm.

Bandwidth

From the plot shown in Fig. 4 of attenuation vs applied field, it appears that small changes in applied field and, by the same token, of operating frequency, do not appreciably change the performance of the isolator. This is indeed the case. No special provisions were necessary to achieve a satisfactory performance over a 10 per cent band (1250 to 1350 mc).

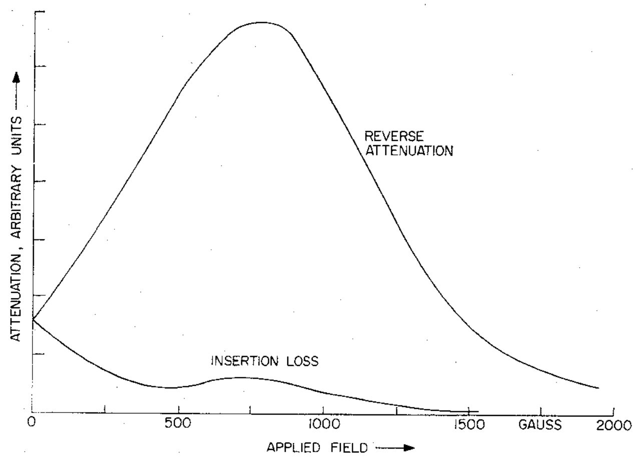

Fig. 4—Typical performance of resonance isolator employing nickel aluminate ferrite.

Peak Power Performance

At high-power levels there occur nonlinear phenomena in ferrites which tend to deteriorate the performance of devices operating satisfactorily at low-power levels. For single crystals, the onset of nonlinearities has been explained by Suhl[8] theoretically in terms of instabilities leading to growth of spin wave amplitudes. In this isolator geometry, nonlinearities should set in at an RF H field

$$h = \Delta H_o(2\Delta H_k/4\pi M_s)^{1/2}. \quad (5)$$

Here ΔH_o and ΔH_k are the intrinsic linewidths of the uniform precession and of spin waves with wave number k, respectively. In applying this result to polycrystalline material, it is difficult to estimate these intrinsic linewidths. But even if they are twenty times smaller than the observed macroscopic linewidth, it turns out that this field hardly can be realized in this isolator with the highest power levels presently attainable. In practice no deterioration in performance has been noted at peak powers of 2 megw in the forward direction (1.5 to 1 mismatch) or with 1.5 megw in the reverse direction.

[8] H. Suhl, "The theory of ferromagnetic resonance at high signal powers," *J. Phys. Chem. Solids*, vol. 1, pp. 209–227; 1957.

Average Power Handling

In addition to the nonlinearities mentioned, heating of the isolator due to the energy absorbed in the ferrite can lead to deterioration of the performance at high power levels. Assuming uniform absorption of power throughout the ferrite cross section, the inner surface will be warmer than the one adjacent to the wall by

$$\Delta T = Qd/2Ak \quad (6)$$

with a parabolic distribution in between. Here Q = total power absorbed, d = ferrite thickness, A = total ferrite area, and k = thermal conductivity. Where a large fraction of the power is being absorbed in the reverse direction ΔT is, of course, a function of position along the length of the ferrite and the above formula must be modified. If α is the fraction of energy absorbed, it is only required to multiply ΔT as given above by ln $\alpha/(1-\alpha)$ to get the maximum temperature rise at the end of the ferrite nearer to the load. With absorption of a few hundred watts, this computed temperature gradient only amounts to a few degrees. This is so because the imaginary part of the suceptibility, $8\pi M_s/\Delta H$, is small in this ferrite and hence the absorption per unit area is small.

The present isolator is operated without external cooling. Practically no heating is observable in the application for which it was designed where the total dissipation is of the order of 150 watts, most of this due to forward insertion loss. When 580 watts was applied in the reverse direction (over 500 watts dissipated), the waveguide temperature rose to 115°C, but the isolation was still 10 db. It seems clear that with external cooling and good thermal contact between ferrite and waveguide, power dissipation of up to 5 kw could be realized.

Performance of the Nickel Cobalt Ferrite Isolator

Isolator and Magnet Geometry

The design of this isolator is shown schematically in Fig. 5. The waveguide height is reduced further to one inch without the danger of arcing because samples are very thin.

As was shown in the introduction, this is necessary because the transverse demagnetizing factor N_x has to be small. A typical ratio of width to thickness of the ferrite slabs is 15.

The field required for resonance is about 3000 gauss. It has to be rather homogeneous in order to have the magnetization aligned perpendicular to the slab plane. This is demonstrated in Fig. 6. There, the attenuation shown by the isolator is measured as a function of applied field while the isolator guide is tilted slightly with respect to the homogeneous applied field. It is seen that even small misalignments of ferrite with field are detrimental to its performance, the tolerance being about 0.3 degrees. It is safe to say that the tolerable degree of inhomogeneity of the applied field is of the same order. The difficulty of constructing the magnet and aligning it with the isolator within close toler-

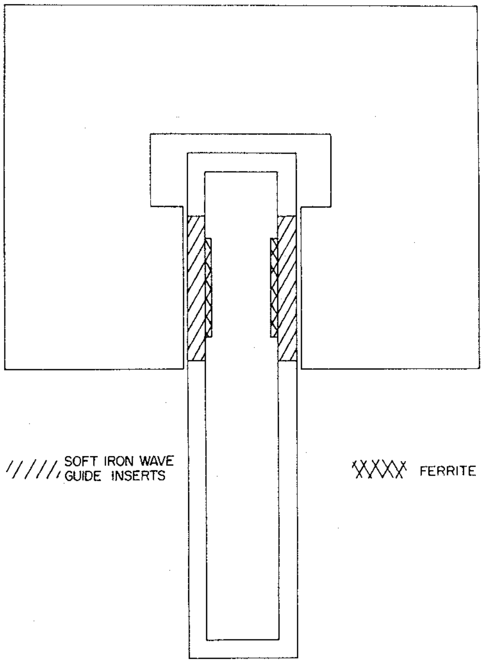

Fig. 5—Schematic cross section of low-frequency isolator with nickel cobalt ferrite.

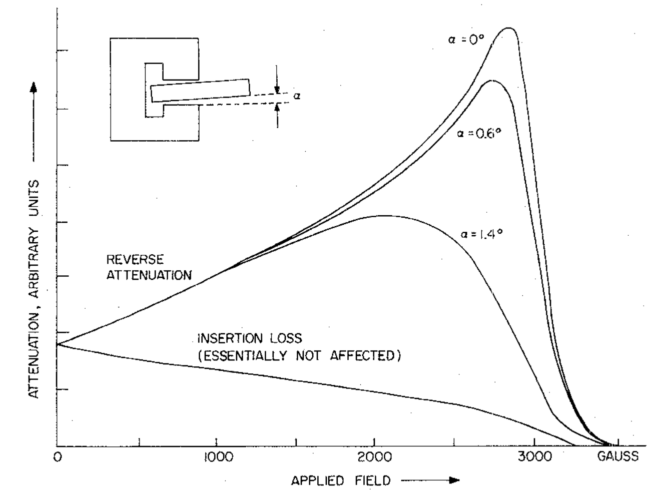

Fig. 6—Demonstrating the effect of misaligning magnet and isolator on reverse attenuation of nickel cobalt ferrite isolator.

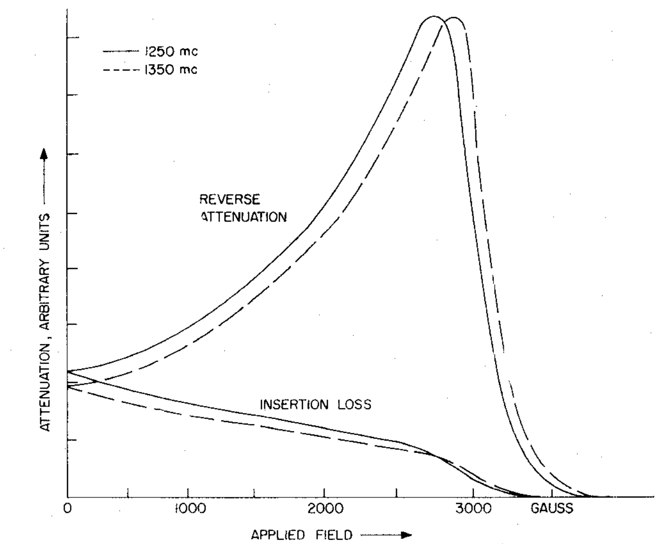

Fig. 7—Reverse attenuation and insertion loss of typical nickel cobalt ferrite isolator at two frequencies as a function of applied field.

ances is considerably reduced by making the pole pieces part of the isolator guide rather than of the magnet.

The required high degree of magnetic field homogeneity makes it impossible to use two magnets with opposing fields side by side as in the nickel aluminate ferrite isolator. Thus, only two of the four possible ferrite locations are used in this isolator.

The total length of this isolator can be kept small. In order to achieve the same reverse attenuation, 10 db, it can be about five inches long. This can be understood on the basis of the attenuation per ferrite volume which is proportional to the imaginary part of the resonance susceptibility, $8\pi M_s/\Delta H$. This quantity is much greater for nickel cobalt ferrite.

The reverse loss per unit length of this isolator was computed by waveguide perturbation theory. The agreement with the measured value was better than 10 per cent. A better agreement than in the nickel aluminate ferrite case should be expected since the higher aspect ratio of this ferrite justifies the perturbation approach even more.

Figure of Merit

The measured ratio of reverse attenuation to insertion loss is of the same order or greater than the value obtained from (4a) which is 24. Again, this agreement is probably not too significant because the theoretical basis of (4a) is not too realistic.

The most important limitation of the figure of merit in this isolator is the competition of magnetic saturation with ferromagnetic resonance. This was shown by experiments in which further reduction of thickness by grinding the ferrite samples results in further improvement of the figure of merit. Another check is the observation that for higher frequencies the insertion loss is lower.

For a typical ratio of ferrite width to thickness of 15, the figure of merit at 1200 mc may be 15 increasing to over 30 at 1300 mc.

Bandwidth

This isolator works satisfactorily over a 10 per cent band without special provisions. The curves of absorption vs applied field are given in Fig. 7 for 1250 and 1350 mc. With properly chosen applied field the isolation is practically constant over this band. The insertion loss, as mentioned before, however, tends to be somewhat greater at the lower frequency.

Dielectric Losses

The fraction of waveguide cross section occupied by ferrite is small. From electrostatic arguments, the electrical field within the ferrite is reduced by some factor greater than 10. Therefore, the dielectric loss tangent tolerable for this isolator is considerably larger than for the one described first. In terms of resistivity, about 10^2 ohm-cm could be tolerated. The actual microwave resistivity of this ferrite is somewhat higher. In manufacturing the ferrite material, it is rather fortunate that the requirement of resistivity is not very stringent. Thus, all attention can be concentrated on obtaining a narrow ferromagnetic linewidth. Experience has shown that narrow lines can only be obtained in dense material. Consequently, the processing and firing parameters are optimized with respect to producing a very dense ferrite ceramic.

Peak Power Performance

In nickel cobalt ferrite, having high magnetization M_s and small linewidth ΔH, the onset of nonlinearities should occur at comparatively low power levels. To be specific, if the linewidths to be used in (5) are assumed one fifth of the macroscopic linewidth, the nonlinearities should set in below 1 megw.

This seems reasonable in view of some preliminary experiments. Although it was not possible to make very extensive high-power measurements with this isolator, it was found that in the range of 300 to 500 kw the reverse attenuation was about 35 per cent lower than at low powers and was substantially independent of power in this range. The figure of merit did not decrease drastically. So this isolator still might be useful even at high power. One would have to make up for the loss in reverse attenuation by greater length of the isolator.

Average Power Handling

With respect to average power dissipation, the two isolators are about equivalent. In the nickel cobalt ferrite isolator, considerably more power is absorbed per volume of ferrite, but heat conduction is enhanced by the higher thermal conductivity of this denser material and by the smaller thickness. With provisions for efficient cooling of the guide wall, it should be possible to dissipate about 5 kw without difficulties.

Conclusions

In this work two distinct and, in a sense, rather extreme approaches have been taken. In the first a low magnetization material, a nickel aluminate ferrite, was developed especially for the purpose. Although its linewidth was greater than might have been desired, it gave an adequate ratio of isolation to insertion loss for many high-power applications. For example, in amplitron systems,[9] the isolator should provide isolation equal to the amplification of the amplitron in order to reduce the VSWR seen by the driver tube to the value given by the antenna mismatch. Typically, 10 db of isolation is required, and 1 db of insertion loss is ordinarily permissible.

One major advantage of nickel aluminate ferrite is that its low saturation magnetization permits operation with relatively small biasing fields. This is particularly important since pressurization is frequently not available in high power systems, and the magnet gap is consequently large. The fact that the isolation per unit ferrite volume if relatively small is to a great extent overcome by the fact that the geometrical conditions are not very stringent. That is, the transverse demagnetizing factor need not be very small, and a relatively large fraction of the waveguide cross section may be utilized.

The Curie temperature of the nickel aluminate ferrite is rather low, which might appear to be a disadvantage where large amounts of power must be dissipated, but in practice this turns out to be a minor consideration. In high-power systems forced flow liquid cooling will nearly always be available to provide waveguide temperature well below 100°C. Since it has been shown that the temperature difference across the ferrite thickness may be kept small even for several kilowatts of dissipation, there seems to be no strong reason to require a Curie temperature in excess of about 200°C. Finally, it should be noted that no evidence of degradation has been observed at peak powers of 1 to 2 megw. There seems to be every reason to expect good behavior at considerably higher power levels.

The second approach consisted of the use of a material, nickel cobalt ferrite, which had high Curie temperature, high saturation magnetization, and small linewidth. As predicted from the linewidth, a better ratio of isolation to insertion loss was found than could be obtained with the nickel aluminate ferrite. On the other hand, an inconveniently large magnetic field was needed with extremely stringent requirements on accuracy and uniformity as computed on a percentage basis.

In the initial stages of this work it was felt that the high Curie temperature would be very advantageous. Materials like the low magnetization magnesium aluminate ferrites, which were then available for L-band use, had Curie temperatures of the order of 100°C and were quite unsuitable for high-power applications. Since the development of the nickel aluminate ferrites, with Curie temperature in excess of 200°C, the importance of the high Curie temperature of nickel cobalt ferrite has been greatly decreased, as explained above. Indeed, the advantages may in practice prove to be rather illusory. Since the resonance field, as given by Kittel's formula, is very nearly equal to the saturation magnetization, rather slight temperature rises, relative to the Curie temperature, will produce significant changes in resonance fields; that is, changes corresponding to an appreciable fraction of the linewidth. With respect to behavior at high peak powers, the present evidence is not clear and experiments are under way to study peak power effects under conditions where heating is negligible. It is expected that nonlinear effects will become important at lower levels than for the nickel aluminate ferrite and some evidence of this may already have been obtained at about 500 kw.

[9] W. C. Brown, "Description and operating characteristics of the planiotron—a new microwave tube device," Proc. IRE, vol. 45, pp. 1209–1222; September, 1957.