Broad-Band Stripline Circulators Based on YIG and Li-Ferrite Single Crystals

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Abstract —The useful operating range of circulators has been extended by avoiding the "low-field loss" problems usually associated with operating at frequencies smaller than the magnetization frequency f_M, through the use of a device configuration that assures a nearly uniform internal magnetic field. Performance data on experimental stripline circulators using single-crystal YIG or Li-ferrite disks and external YIG (or Li-ferrite) domes (for achieving a nearly uniform internal magnetic field) are summarized and compared with theoretical expectations. Reasonably good circulator performance is observed in the frequency range from 2.8 to 10.20 GHz for the circulator based on YIG and in the frequency range from 5.8 GHz to 18 GHz for the circulator based on Li-ferrite. The external ferrite domes improve the performance significantly when the frequency is near the lower edge of the operating band.

I. Introduction

THE PRESENT PAPER summarizes recent progress in achieving broad-band circulator performance. The theory applicable to stripline circulators has been extended by deriving theoretical expressions for the scattering matrix that are applicable when the effective permeability is negative. In addition, the effect of crystalline anisotropy on circulator performance has been taken into consideration for the case when the ferrite disks are single crystals. Also, the detrimental effect of the demagnetizing field (which is usually inhomogeneous in conventional circulator designs) has been analyzed, and a technique for avoiding performance degradation arising from this source is described. Experimental circulators based on yttrium–iron–garnet (YIG) and Li-ferrite have been built and tested that show useful performance in the frequency range from 2.8 to 10.2 GHz, and from 5.8 to 18 GHz, respectively.

Fig. 1 is a schematic diagram of a conventional stripline circulator. A successful theory of such circulators has been developed by Wu and Rosenbaum [1] based on earlier work by Bosma [2] and others [3], [4]. According to this theory, satisfactory circulator operation can be obtained in the frequency range extending from f_M to $2f_M$. Here, f_M is the "magnetization frequency," defined by $2\pi f_M = \gamma 4\pi M_s$, where γ is the gyromagnetic ratio ($\gamma/2\pi \simeq 2.8$ MHz/Oe) and M_s the saturation magnetization. Available ferrite materials have f_M values from a fraction of a GHz up to approximately 14 GHz; for YIG at room temperature, it is approximately 5 GHz.

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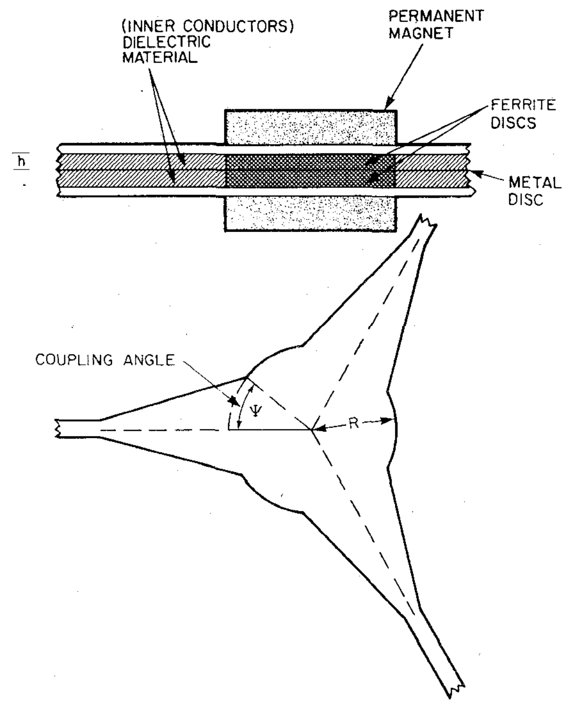

Fig. 1. Conventional stripline circulator configuration.

II. New Theoretical Results

After careful analysis of the previous theoretical work, we have concluded that the earlier theories are potentially misleading, inasmuch as they do not recognize the possibility of obtaining useful circulator performance at frequencies lower than f_M. Under the usual operating conditions (when the internal magnetic field strength is much smaller than $4\pi M_s$) the effective permeability $\mu_e = (\mu^2 - \kappa^2)/\mu$ (μ and $\pm j\kappa$ are the components of the permeability tensor) is negative when $f < f_M$. The theory developed by Bosma [2] and Wu and Rosenbaum [1] is not immediately applicable under these conditions, but it can readily be extended to make it applicable. The resulting extended theory is based on the same approximate boundary conditions as Bosma's theory. It is assumed that the circumferential component of magnetic field h_ϕ is zero at any point along the circumference of the ferrite disk that is not in contact with one of the stripline inner conductors, and that it has a constant value at all points along the circumference that are in contact with one of the inner conductors. These "magnetic wall" boundary conditions are justified provided that the thickness of the ferrite disks is "sufficiently small."

A. Effect of Crystalline Anisotropy on Circulator Performance

In order to make circulator theory applicable to single-crystal ferrites, the effect of crystalline anisotropy has to be taken into consideration. It can be shown that hard-axis orientation ([100] normal to the disk face in the case of YIG or Li-ferrite) is the optimum orientation, because the effective internal magnetic field strength can be reduced to zero in this case. Easy-axis orientation ([111] normal to disk face) is not as good, because in the fully magnetized state the effective internal magnetic field strength cannot be made smaller than 2/3 of the anisotropy field ($2|K_1|/M_s$) and this restricts the frequency band of circulator operation. Other orientations (for instance, [110] normal to disk face) will generally induce ellipticity of the spin precession, which implies that the circulator performance depends upon the orientation of the in-plane crystal axes to the port locations of the device.

B. Effect of Magnetic Field Inhomogeneity on Circulator Performance

The assumption that μ_e must be positive for useful circulator performance has generally been made in most theoretical work. This is probably attributable to the fact that the measurements on experimental circulators generally show that they have a high insertion loss when $f < f_M$ and the internal magnetic field strength H is very small, i.e., $f_H \ll f_M$, where $2\pi f_H = \gamma H$, a phenomenon usually referred to as low field loss. Although some authors have considered the possibility of operating circulators under conditions when $\mu_e < 0$ [5]–[9], the broad-band performance actually achieved with these experimental circulators appears to have been inferior to that obtained with the Wu–Rosenbaum circulator [1] or similar designs [10].

In order to operate circulators under conditions in which $f < f_M$ and $f_H \ll f_M$, low field loss has to be avoided, and for that purpose it is imperative to understand its origin. In this context, it is important to realize that in the conventional stripline circulators, the magnetic field strength within the ferrite disks is nonuniform. The disks are usually located in a magnet structure that creates a substantially uniform field (before the disks are put in place) at the site of the disks. It is well known, however, that the total field inside the ferrite disks consists of the applied fields and the "demagnetizing field." The latter field is generated by the magnetic poles at the disk surfaces; its direction is substantially opposite to that of the applied magnetic field; and it is highly nonuniform in samples that are not ellipsoidal. Detailed calculations on the subject [11] have shown that for disks with a height-to-diameter ratio of 1:10, the demagnetizing factor is approximately 0.9 near the disk center and approximately 0.4 near the perimeter. This implies that when the external field has the value at which the internal field is substantially zero at the disk center, the internal field near the perimeter will be approximately $0.5 \times 4\pi M_s$. A "local resonant frequency" f_{res} can generally be defined as the frequency at which the effective permeability becomes infinite in a lossless ferrite medium. This frequency is related to the previously defined frequencies f_H and f_M by

$$f_{res} = \sqrt{f_H(f_H + f_M)}. \tag{1}$$

In a conventional circulator structure, f_H is adjusted to be nearly zero at the disk center and is therefore approximately $0.5 f_M$ near the perimeter. Thus, according to (1) under these conditions

$$f_{res,center} \simeq 0$$
$$f_{res,perimeter} \simeq \frac{\sqrt{3}}{2} f_M = 0.87 f_M. \tag{2}$$

Alternatively, the externally applied magnetic field could be reduced to a value that is smaller than the demagnetizing field to be expected at the center of a uniformly magnetized disk. In this case, the resonant frequency at the perimeter would be smaller than the value given by (2), but the disk will not be uniformly magnetized, particularly near the center. Instead, the magnetization will break up into domains having different magnetization directions. Previous theoretical and experimental work on the microwave properties of partially magnetized ferrites [12], [13] has shown that such materials are lossy when the frequency is smaller than f_M.

Equation (2) implies that for an ideal ferrite with an infinitely narrow resonance linewidth, low field loss will be present at all frequencies less than $0.87 f_M$. The ferrites used in practice have, of course, a finite linewidth. The low field loss will then set in at a somewhat higher frequency of the order of, or perhaps slightly larger than, f_M. The experimental observation of high loss in circulators operated under conditions of $f < f_M$, $f_H \ll f_M$ can thus be explained as arising from resonant absorption near the disk perimeter. This absorption does not represent a fundamental limitation of circulator bandwidth because it should be possible to substantially eliminate this loss by using a design for which the magnetic field is uniform throughout the interior of the ferrite disks.

The preceding discussion shows that the low field loss observed in conventional stripline circulators can be attributed to the fact that the dc magnetic field near the disk perimeter is considerably larger than the field at the disk center, giving rise to resonant absorption when f is approximately equal or less than f_M. It follows that low field loss can be eliminated or at least substantially reduced by using a device configuration in which the internal magnetic field is uniform.

A convenient way of achieving this desired uniformity is to position spherical caps, or "domes," of a material with the same saturation magnetization as the disks external to the microwave circuit, but in close proximity to the disks. These domes should be separated from the disks by a layer of conductive material; the thickness of this layer should be as small as possible, consistent with the requirement that it should be significantly larger than the skin depth.

C. Circulator Analysis

It was first pointed out by Bosma [2] that the stripline circulator can be conveniently analyzed by introducing a Green's function $G(r,\phi; R,\phi')$ that relates the axial component of electric field $e_z(r,\phi)$ within the ferrite disk to the circumferential component of magnetic field $h_\phi(R,\phi')$ at the periphery (R,ϕ') of the disk. This Green's function is derived from a solution of Maxwell's equation for the region occupied by the ferrite disk. In order to facilitate calculation of the impedance and scattering matrices, the Green's function is required only for $r = R$. For $\mu_e > 0$, the Green's function derived by Bosma can be expressed as

$$G(\phi;\phi') = V_0 + \sum_{n=1}^{\infty} V_n \cos n(\phi-\phi') + U_n \sin n(\phi-\phi') \tag{3}$$

where

$$V_0 = -j\frac{\zeta_e}{2\pi}\frac{J_0(x)}{J_0'(x)} \tag{4}$$

$$V_n = -j\frac{\zeta_e}{\pi}\frac{J_n'(x)J_n(x)}{[J_n'(x)]^2 - \left[\frac{\kappa}{\mu}\frac{nJ_n(x)}{x}\right]^2} \tag{5}$$

$$U_n = \frac{\zeta_e}{\pi}\frac{(\kappa/\mu)n[J_n(x)]^2/x}{[J_n'(x)]^2 - \left[\frac{\kappa}{\mu}\frac{nJ_n(x)}{x}\right]^2}. \tag{6}$$

Here

$$x = \frac{\omega}{c_0}\sqrt{\epsilon_f\mu_e}\,R \tag{7}$$

$$\zeta_e = \sqrt{\frac{\mu_0\mu_e}{\epsilon_0\epsilon_f}} \tag{8}$$

$J_n(x)$ is the Bessel function of the first kind of order n, and the prime denotes differentiation with respect to the argument. In (5)–(8), μ and $\pm j\kappa$ are the elements of the permeability tensor, ϵ_f is the relative dielectric constant of the ferrite, R is the radius of the ferrite disk, $\omega = 2\pi f$, c_0 is the velocity of light in vacuum, and μ_0 and ϵ_0 are the permeability and permittivity of vacuum.

It can similarly be shown that for $\mu_e < 0$ eq. (3) still applies, but now

$$V_0 = j\frac{\bar{\zeta}_e}{2\pi}\frac{I_0(\bar{x})}{I_0'(\bar{x})} \tag{9}$$

$$V_n = j\frac{\bar{\zeta}_e}{\pi}\frac{I_n'(\bar{x})I_n(\bar{x})}{[I_n'(\bar{x})]^2 - \left[\frac{\kappa n I_n(\bar{x})}{\mu\bar{x}}\right]^2} \tag{10}$$

$$U_n = -\frac{\bar{\zeta}_e}{\pi}\frac{(\kappa/\mu)n[I_n(\bar{x})]^2/\bar{x}}{[I_n'(\bar{x})]^2 - \left[\frac{\kappa n I_n(\bar{x})}{\mu\bar{x}}\right]^2}. \tag{11}$$

Here

$$\bar{x} = \frac{\omega}{c_0}\sqrt{\epsilon_f(-\mu_e)}\,R \tag{12}$$

$$\bar{\zeta}_e = \sqrt{\frac{\mu_0(-\mu_e)}{\epsilon_0\epsilon_f}} \tag{13}$$

and $I_n(\bar{x})$ is the modified Bessel function of the first kind of order n.

In the limit when $\mu_e \to 0$ (and $\kappa \to \mu$), the coefficients V_n and U_n all approach finite limiting values (the same value for $\mu_e < 0$ as for $\mu_e > 0$). In this limit, the Green's function simplifies considerably and is given by

$$G(\phi;\phi') = \frac{j}{\pi\epsilon_0\epsilon_f\omega R} - \frac{j\mu_0\mu\omega R}{\pi}\sum_{n=1}^{\infty}\frac{e^{jn(\phi-\phi')}}{n}$$
$$= \frac{j}{\pi\epsilon_0\epsilon_f\omega R} + \frac{j\mu_0\mu\omega R}{\pi}\ln\left[1-e^{j(\phi-\phi')}\right]. \tag{14}$$

On the basis of the extended theory, a computer program has been developed that calculates the performance parameters of a stripline circulator such as shown in Fig. 1 as a function of frequency, using the expressions derived by Wu and Rosenbaum [1] when $\mu_e > 0$ and the newly derived expressions when $\mu_e < 0$. The input parameters required by the program are the "coupling angle" ψ and disk radius R (see Fig. 1), the dielectric constants of the dielectric material of the stripline and of the ferrite, the magnetization frequency f_M, the magnetic field frequency f_H (internal magnetic field strength expressed as a frequency), and the number of terms to be taken into account in certain series expansions in terms of Bessel functions. (Wu and Rosenbaum chose this number to be three. In the present computer program, this number can be selected at will; the results illustrated in Fig. 2 are derived using nine terms. If only three terms had been used, the results would be somewhat different, but the principal features would be the same.)

The theory described so far is expected to be applicable to a stripline circulator in which the width of the inner conductor w equals the width of the contact at which the inner conductor is connected to the central metal disk. Thus, w is related to the disk radius R and coupling angle ψ by

$$w = 2R\sin\psi. \tag{15}$$

Since the coupling angles required for broad-band performance are typically quite large ($\simeq 0.75$ rad or larger) the stripline width w calculated from (15) is also relatively large (e.g., 0.164 in); hence, the characteristic impedance of the stripline is relatively small (e.g., 8 Ω). Suitable matching circuits are therefore required in order to connect the circulator to stripline or other transmission lines having 50-Ω characteristic impedance.

The scattering matrix of the circulator with matching circuits can be expressed in terms of the scattering matrix of the "bare" circulator (no matching circuits) and the

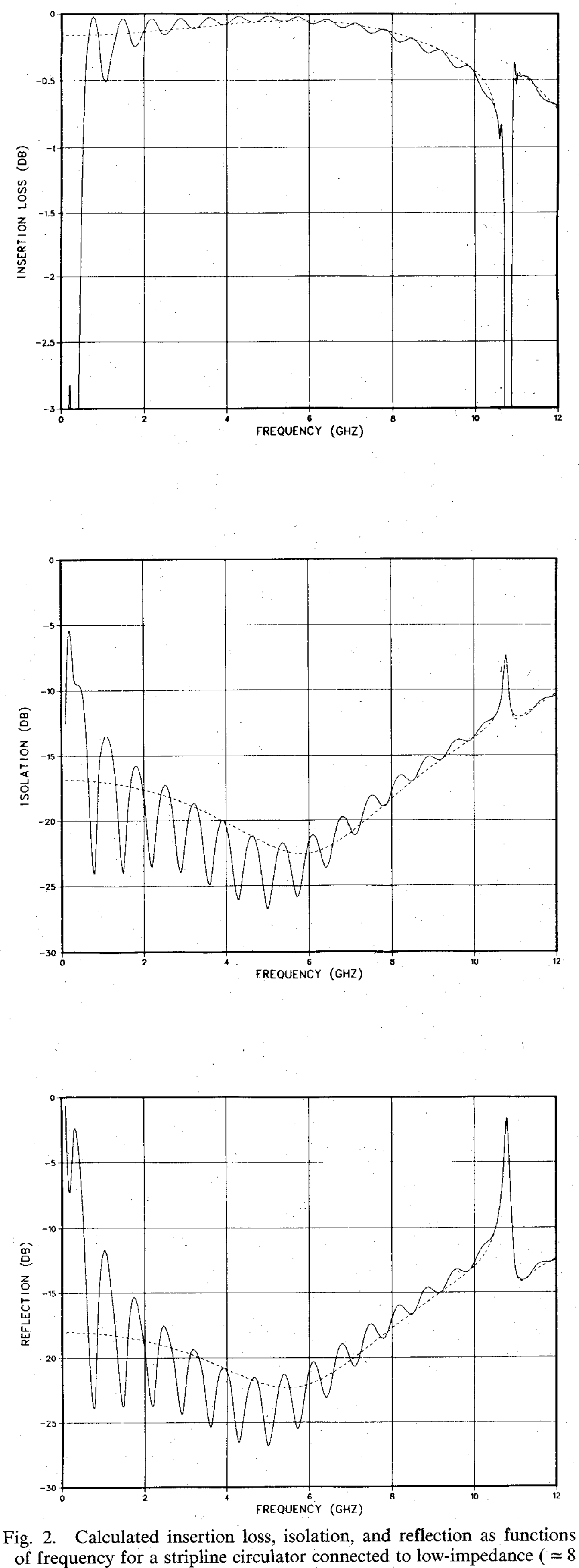

Fig. 2. Calculated insertion loss, isolation, and reflection as functions of frequency for a stripline circulator connected to low-impedance ($\simeq 8$ Ω) stripline (broken lines) and a circulator connected to 50-Ω striplines by means of simple exponential tapes (solid lines) 72 mm in length.

transfer scattering matrices of the matching circuits. Fig. 2 illustrates the results derived for a simple exponential taper [14] and using the materials and device parameters that correspond approximately to one of the circulators for which the performance is reported below:

Dielectric constant of ferrite:	$\epsilon_f = 14$
Dielectric constant of substrate:	$\epsilon_d = 10$
Magnetization frequency:	$f_M = 4.99$ GHz
Magnetic field frequency:	$f_H = 0$
Coupling angle:	0.75 rad $\simeq 43°$
Disk radius R:	3 mm $\simeq$ 0.118 in
Stripline height b:	1.25 mm $\simeq$ 0.050 in
Outer stripline width w_1:	0.25 mm $\simeq$ 0.10 in
Inner stripline width w_2:	4.17 mm $\simeq$ 0.164 in
Length of taper L:	72 mm $\simeq$ 2.835 in

In Fig. 2, the insertion loss, isolation, and reflection are shown in dB as functions of frequency between zero and 12 GHz. The broken lines apply to the "bare" circulator assuming an 8-Ω system impedance; the wavy, solid lines apply to a circulator having identical tapers attached to each port matching to a 50-Ω system. At frequencies where the two sets of curves intersect, the tapers present a purely resistive 8-Ω resistance to the circulator. It is apparent from these curves that the circulator junction impedance is more optimally matched at the lower frequencies with impedances somewhat different from 8 Ω.

The broken lines in Fig. 2 (applicable to the "bare" circulator) appear to indicate surprisingly good circulator performance in the limit $f \to 0$. This is due to the somewhat unrealistic assumption $f_H = 0$ (which implies that $\kappa \to \infty$ as $f \to 0$) used in the calculation. For any finite value of f_H, the predicted device performance will not be that of a circulator in the limit $f \to 0$. Comparison with the experimental data described in Sections III and IV shows that at low frequencies (for $f < f_M/2$) the theory described here is apparently invalid for different reasons.

The strong peak in the insertion loss at approximately 10.8 GHz is due to the excitation of a higher order dielectric resonance ($n = 2$) in the disk. It is interesting to note that the theoretical curves shown in Fig. 2 have no singularity whatever at the frequency at which μ_e changes sign (5 GHz in the present case).

III. Results of Experimental Work Using YIG

Broad-band stripline circulators were built using either YIG ($f_M \simeq 5$ GHz) or Li-ferrite ($f_M \simeq 10.4$ GHz). With YIG as the active material, good circulator performance was achieved in the frequency band from approximately 2.8 GHz to 10.2 GHz, whereas with Li-ferrite the band extended from approximately 5.8 GHz to 18.0 GHz.

Fig. 3 shows the central part of the circulator using YIG disks in cross section (top half) and the shape of the inner conductor (the metal "spider") drawn approximately to scale. The single-crystal YIG disks have a [100] crystal axis normal to the disk surface and have a diameter of 0.240 in and a height of 0.025 in. The polycrystalline YIG domes were ground into the desired, nearly hemispherical shape

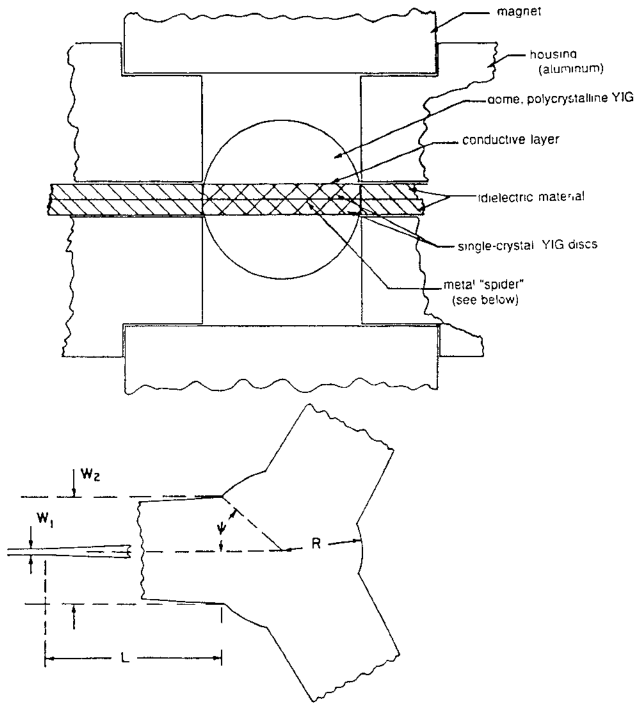

Fig. 3. Experimental broad-band stripline circulator configuration.

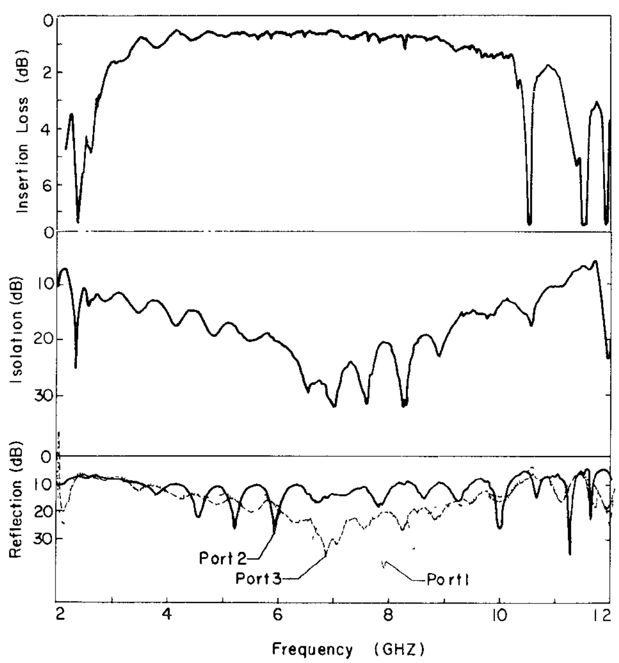

Fig. 4. Insertion loss, isolation, and reflection measured on broad-band stripline circulator illustrated in Fig. 3 based on YIG.

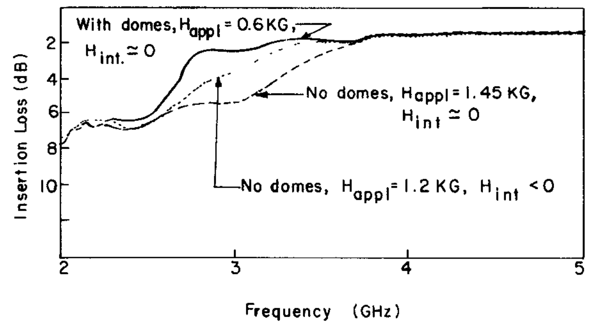

Fig. 5. Insertion loss versus frequency for experimental circulator based on YIG measured with external ferrite domes either present or absent.

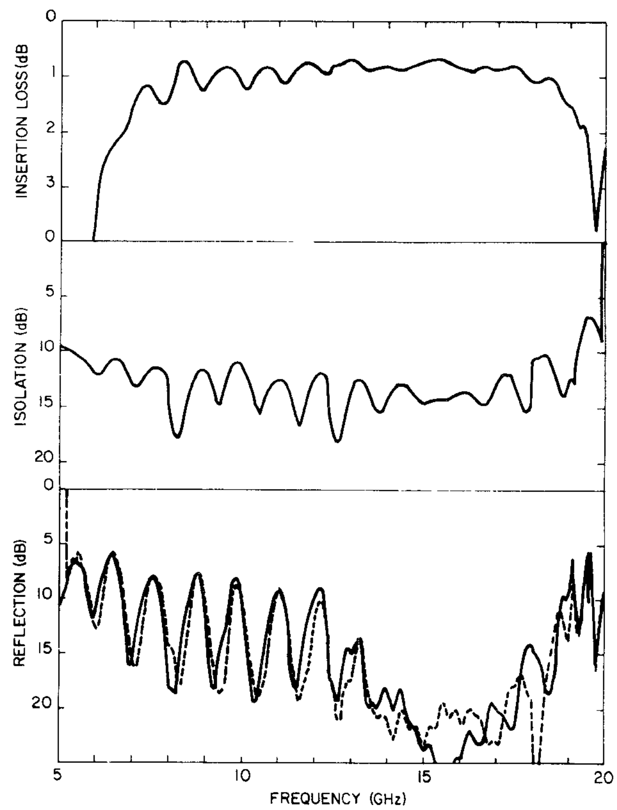

Fig. 6. Insertion loss, isolation, and reflection measured on broad-band circulator based on Li-ferrite.

by means of a suitable grinding tool. The metal spider was fabricated photolithographically from copper foil 0.0005 in thick. The conductive layer between the YIG disks and the YIG domes was copper foil approximately 0.0005 in thick.

Fig. 4 shows the insertion loss, isolation, and reflection (in dB) as measured between 2 and 12 GHz. It may be seen that fairly good performance has been obtained at all frequencies between 3 and 10 GHz. At the lower edge of this band, the insertion loss rises gradually to 2 dB, but approximately 1 dB of this loss is attributable to reflections. It should therefore be possible to improve the insertion loss in this range by better matching.

The data summarized in Fig. 4 show that good circulator performance can indeed be realized for $f < f_M$, i.e., in the region previously thought to be "forbidden." The bandwidth of the present experimental circulator is almost two octaves.

The effect of the ferrite domes on circulator performance has been investigated by making measurements of insertion loss versus frequency at various field strengths and by comparing results obtained with and without domes. Fig. 5 summarizes the results of this investigation. With the domes in place, an applied field of 0.6 kG is expected to result in an internal field near zero (since $4\pi M_s \simeq 1.75$ kG and the demagnetizing factor for a sphere is 1/3). The insertion loss obtained under these conditions is shown as

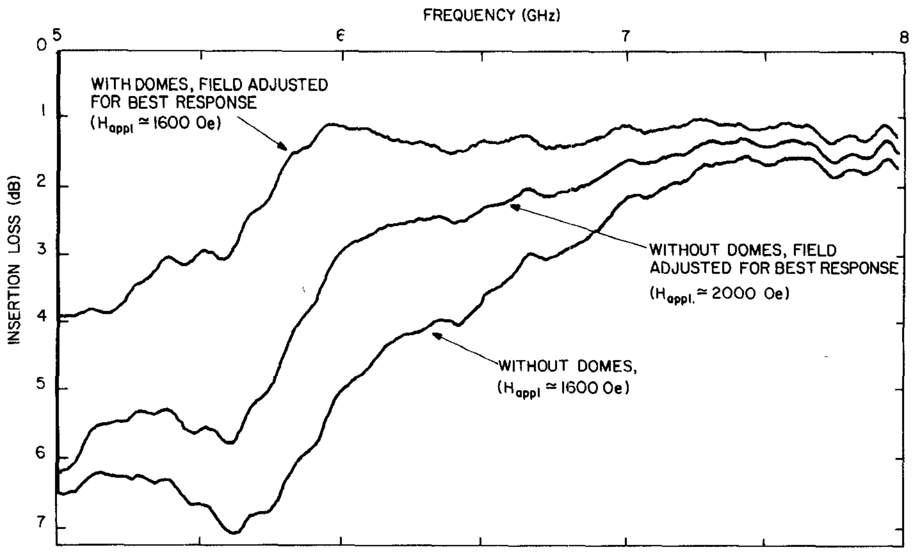

Fig. 7. Insertion loss of circulator based on Li-ferrite measured with external ferrite domes either present or absent.

a solid line in Fig. 5. When the domes are removed, the demagnetizing factor of the two disks is approximately 0.8 (see [11, figs. 11 and 12]). Thus, an applied field of 1.45 kG should result in a near zero internal magnetic field near the disk center. The insertion loss obtained under these conditions, shown as a dashed line in Fig. 5, is substantially larger (for $f < 3.5$ GHz) than the insertion loss obtained with the domes in place. It was found that the insertion loss obtained without the domes could be somewhat reduced by using a smaller applied magnetic field, for instance, 1.2 kG. The insertion loss obtained under these conditions, shown as a dotted line in Fig. 5, falls between the results obtained in the other two cases.

This demonstrates that the realization of a substantially uniform magnetic field in the interior of the ferrite disks will improve circulator performance when $f < f_M$.

A comparison of the experimentally observed performance (Figs. 4 and 5) with the theoretically expected performance (Fig. 2) shows generally good agreement at frequencies above 2.5 GHz, but considerable disagreement at frequencies below 2.5 GHz. The calculated insertion loss is, of course, much smaller than the observed insertion loss, even at frequencies larger than 2.5 GHz, as may be expected since energy dissipation is completely neglected on the theory.

The periodicity in the experimental data agrees quite well with the periodicity in the theoretical curves and is determined by the length of the tapers and the dielectric constant of the substrates. In the experimental curves, the periodicity is more pronounced at the higher frequencies, whereas in the theoretical curves it is more pronounced at the lower frequencies. This may be attributable to unavoidable discontinuities at the coax to stripline transition and to the assumption of exponential tapers in the theoretical calculations, not straight-edge tapers as actually used.

The theoretical insertion loss shows a strong peak at 10.8 GHz due to excitation of a higher order dielectric resonance. This resonance apparently produces a pair of peaks (at approximately 10.4 and 11.4 GHz) in the experimental data.

IV. Results of Experimental Work Using Li-Ferrite

The structure of the circulator using Li-ferrite is similar to that shown in Fig. 3. Since the expected operating frequency is about two times higher for Li-ferrite than for YIG, the ferrite disk diameter was reduced to 0.120 in (from 0.236 in for YIG), whereas the height remained the same (0.025 in). The length of the tapers was reduced to 1.6 in $\simeq$ 41 mm. The Li-ferrite disks were single crystals with a [100] axis normal to the disk face.

Fig. 6 summarizes measurements of insertion loss, isolation, and reflection in the frequency range from 5 to 20 GHz. The curves are very similar to the ones obtained with YIG (and a larger disk diameter) except that the frequency band is shifted up by about a factor of two. With better matching (which can be achieved by multistage quarter-wave transformers), we expect that the insertion loss can be reduced to values comparable to the minimum shown in Fig. 6, and the isolation increased to values comparable to the maximum shown in Fig. 6.

Fig. 7 illustrates the effect of the external ferrite domes on insertion loss for this circulator. The lowest insertion loss was measured with the external domes present and the external magnetic field adjusted to approximately 1600 Oe. This value of magnetic field is consistent with the saturation magnetization ($4\pi M_s \simeq 3700$ Oe) and the anisotropy field ($H_a \simeq 500$ Oe) of this material. For a perfect sphere in [100] orientation, the effective internal magnetic field would be zero when the external field equals $4\pi M_s/3 + H_a$ $\simeq 1733$ Oe. The actual shape of the composite sphere (disks plus domes) was that of a slightly elongated sphere, which accounts for the small difference between the field values at which optimal performance is expected and those at which it is actually observed.

Fig. 7 also shows that, with the domes removed and the applied field constant at 1600 Oe, the insertion loss is increased considerably. An intermediate situation exists when the applied field is adjusted for lowest insertion loss without the domes present (which was the case at a field value of approximately 2000 Oe). These results again demonstrate that the realization of a substantially uniform field in the interior of the ferrite disks improves circulator performance substantially.

V. Discussion

The low-frequency edge of the usable frequency band for the type of circulator described here appears to be given by $f_M/2$ (2.5 GHz for YIG, 5.4 GHz for Li-ferrite). We attribute this behavior to the excitation of magnetostatic surface modes at the ferrite–dielectric interface. It can be shown that in the limit of zero internal magnetic field such modes have resonant frequencies of approximately $f_M/2$. The detrimental effect of such modes has not been taken into consideration in any of the theoretical analyses of circulator performance. Excitation of these modes indicates a breakdown of the validity of the "magnetic wall" boundary condition, which is invoked in most theoretical treatments of the problem as a plausible but not rigorously justifiable simplifying assumption. The broad-band circulator design described here is thus limited to a two-octave bandwidth, i.e., one octave more than the conventional design.

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Dr. Schloemann has published over 110 scientific papers, and has been granted twelve U.S. patents and several foreign patents. From 1970 to 1973, he was a member of the editorial board of the IEEE Transactions on Microwave Theory and Techniques, and from 1974 to 1976, he served on the editorial board of the *Journal of Applied Physics* and *Applied Physics Letters*. In 1978, he was elected a Fellow of IEEE "for contributions to the theory and development of microwave ferrite materials and devices." He is also a Fellow of the American Physical Society and a member of the IEEE Magnetics Society, the IEEE Microwave Theory and Techniques Society, and Sigma Xi.

Ronald E. Blight (SM'72), photograph and biography unavailable at the time of publication.