BROADBAND STRIPLINE CIRCULATOR

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ABSTRACT

Performance data on experimental stripline circulators using single-crystal YIG or Li-ferrite discs and external YIG (or Li-ferrite) domes (for achieving a nearly uniform internal magnetic field-strength) are summarized and compared with theoretical expectations. Reasonably good circulator performance is observed in the frequency range from 2.8 to 10.2 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.

INTRODUCTION

The present paper summarizes recent progress in achieving broadband 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 and by other refinements (effect of crystalline anisotropy when the ferrite discs are single crystals, detrimental effect of inhomogeneous demagnetizing fields and how to avoid it).

Figure 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). 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 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.

NEW THEORETICAL RESULTS

After careful analysis of the previous theoretical work we have concluded that the earlier theories are potentially misleading, in as much as they do not recognize the possibility of obtaining

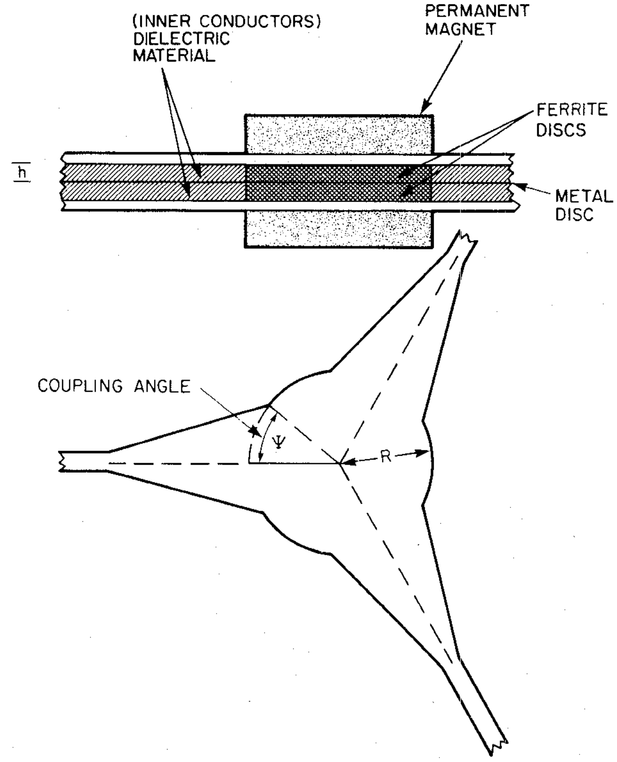

Figure 1 Conventional Stripline Circulator Configuration

useful circulator performance at frequencies lower than f_M. Under the usual operating conditions (when the internal magnetic fieldstrength is much smaller than $4\pi M_s$) the effective permeability $\mu_{eff} = (\mu^2-\kappa^2)/\mu$ (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 disc that is not in contact with one of the stripline inner conductors, and that

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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 discs is "sufficiently small."

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 disc face in the case of YIG or Li-ferrite) is the optimum orientation, because the effective internal magnetic fieldstrength can be reduced to zero in this case. Easy axis orientation ([111] normal to disc face) is not as good, because in the fully magnetized state the effective internal magnetic fieldstrength can not 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 disc 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.

In order to obtain useful circulator performance at frequencies smaller than f_M it is essential to use a magnetic configuration, in which the dc magnetic fieldstrength in the interior of the ferrite discs of the circulator is substantially 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 discs external to the microwave circuit, but in close proximity to the discs. These domes should be separated from the discs by a layer of conductive material, the layer thickness being as small as possible, consistent with the requirement that it should be significantly larger than the skin depth.

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 $\mu_{eff} > 0$ and the newly derived expressions when $\mu_{eff} < 0$. The input parameters required by the program are: the "coupling angle" ψ and disc 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 fieldstrength 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.)

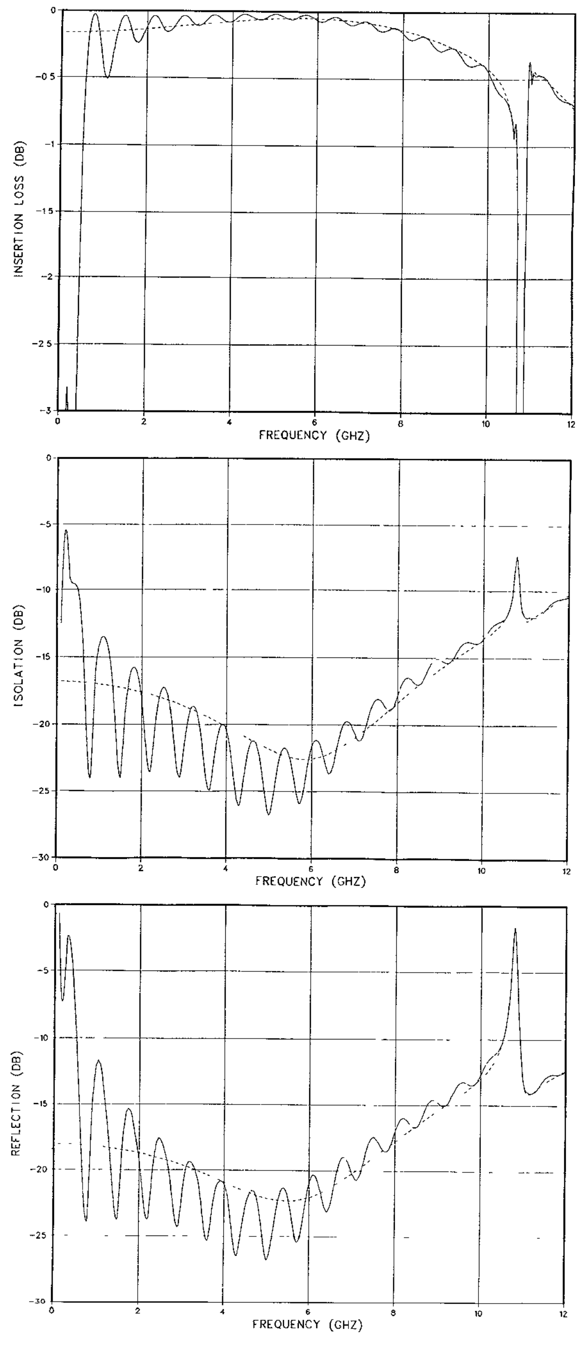

Figure 2 Calculated insertion loss, isolation and reflection as functions of frequency for a stripline circulator connected to low-impedance (≈8 Ohm) stripline (broken lines) and a circulator connected to 50 Ohm striplines by means of means of simple exponential tapers (solid lines) of 72 mm length.

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 disc. Thus w, is related to the disc radius R and coupling angle ψ by

$$w = 2R \sin\psi \quad (1)$$

Since the coupling angles required for broadband performance are typically quite large ($\simeq$.75 radians or larger) the stripline width w calculated from (1) is also relatively large (e.g., .164") and hence the characteristic impedance of the stripline is relatively small (e.g., 8 Ohm). Suitable matching circuits are therefore required in order to connect the circulator to stripline or other transmission lines, having 50 Ohm 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 transfer scattering matrices of the matching circuits. Figure 2 illustrates the results derived for a simple exponential taper (4) and using the materials and device parameters, that correspond approximately to the circulator for which the performance is reported below:

Dielectric constant of ferrite:		ε_f = 14
Dielectric constant of substrate:		ε_d = 10
Magnetization frequency:		f_M = 4.99 GHz
Magnetic field frequency:		f_H = 0
Coupling angle:	0.75 radians	$\simeq$ 43^o
Disc radius R:	3 mm	$\simeq$ .118"
Stripline height b:	1.25 mm	$\simeq$ .050"
Outer stripline width w_1:	0.25 mm	$\simeq$ .010"
Inner stripline width w_2:	4.17 mm	$\simeq$ .164"
Length of taper L:	72 mm	$\simeq$ 2.835"

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, the wavy, solid lines to the circulator having identical tapers attached to each port.

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

RESULTS OF EXPERIMENTAL WORK

Broadband, stripline circulators were built using either YIG or Lithium ferrite. 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 GHz. In the present paper (as contained in the Conference Digest) only the results obtained with YIG discs are described in detail. A related paper submitted for publication in the Conference Proceedings gives further information on the results obtained using Li-ferrite.

The YIG discs were single-crystal in [100] orientation (0.240" diameter and .025" height) and were used in combination with alumina substrates and external YIG "domes" (for realizing a uniform magnetic fieldstrength inside the ferrite discs).

Figure 3 shows the central part of the circulator in cross-section (top half) and the shape of the inner conductor (the metal "spider") drawn approximately to scale. The single-crystal YIG discs have a [100] crystal axis normal to the disc surface. The polycrystalline YIG domes were ground into the desired, nearly hemispherical shape by means of a suitable grinding tool. The metal spider was fabricated photolithographically from copper foil of .0005" thickness. The conductive layer between the YIG discs and the YIG domes was copper foil of approximately .0005" thickness.

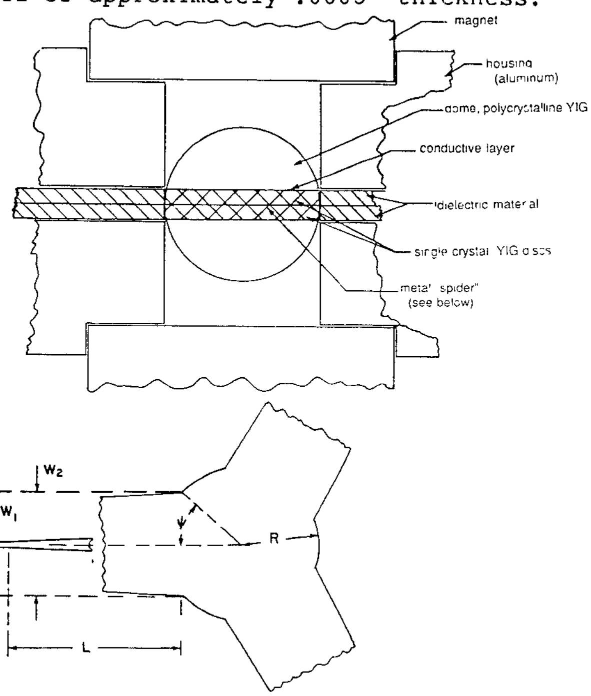

Figure 3 Experimental Broadband Stripline Circulator Configuration

Figure 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. 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 fieldstrengths and by comparing results obtained with and without domes. It was shown in this way that the realization of a substantially uniform magnetic fieldstrength in the interior of the ferrite discs will improve circulator performance when $f < f_M$ (see complete paper in conference proceedings).

A comparison of the experimentally observed performance (Fig. 4) 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 in the theory.

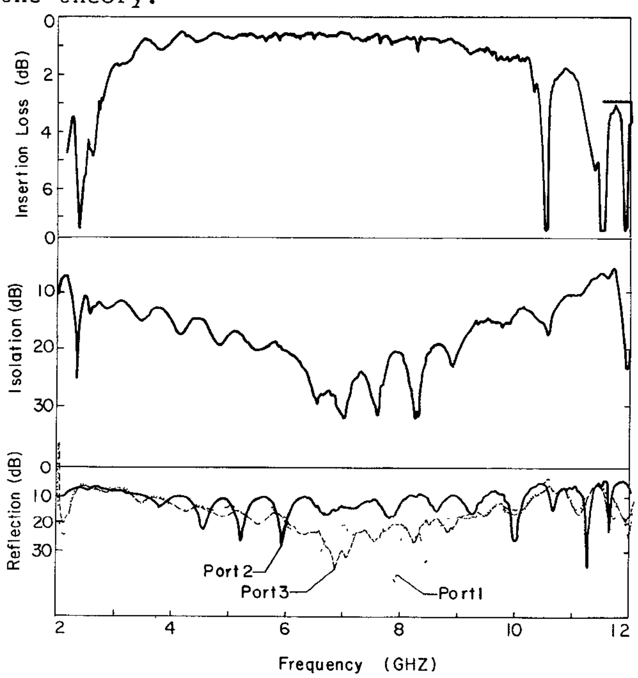

Figure 4 Insertion loss, isolation, and reflection measured on broadband stripline circulator illustrated in Fig. 3.

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 co-ax to stripline transition and to the assumption of exponential tapers in the theoretical calculations, not straightedge 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.

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). We attribute this behavior to the excitation of magneto-static 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 broadband 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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