III. Tests with a Doublet of Pure YIG Disks

Another test with a pure YIG doublet was subsequently tried, using continuously variable spacing and a [111] orientation of the axes. This resulted in a smooth variation in resonant field with relative orientation of the two disks. The frequency range was extended to 3000 MHz, since higher frequencies are to undoped material what lower frequencies are to Ga YIG. A differential gaussmeter was used to show that the individual disks were initially very similar in $4\pi M_s N_z$ at a number of fixed frequencies. Since the procedure here involved inserting and removing the disks one at a time, in a bandstop-filter structure, orientations relative to the applied magnetizing field were probably not perfectly reproduced. Nevertheless, the measurements were repeatable within ± 3 Oe at 1200 MHz and above.

Resonances of this doublet were strong, and all data were clear cut and reproducible. In the octave 1500–3000 MHz, the variation of the effective $4\pi M_s N_z = H_{dc} - f_0/2.8$ with spacing was examined in detail and found to decrease by several tens of oersteds as the second disk was brought in from relatively far away to almost touching. This observation is consistent with theory. Most of the change occurs for spacings in the range 0.006 to 0.040 inch, for 0.150-inch diameter by 0.005-inch-thick disks. Figure 2 shows a few representative plots, at selected frequencies, of relative resonant field against disk spacing. The vertical limit marks represent a combination of experimental error and a "hysteresis" effect that will be explained soon by reference to Fig. 3.

Unfortunately, the observed change in effective $4\pi M_s N_z$ was neither constant nor even proportional to H_{dc} as the frequency varied. Actually, it dropped from about 45 Oe out of 2270 Oe at 1900 MHz, to about 25 Oe out of 2690 Oe at 3000 MHz. Thus, if we were to plot the resonant field against frequency for several disk spacings, all on one graph, then these several curves would not be parallel, though at the higher fields or frequencies they become more nearly parallel. This result means that if two unequal "inner" disks on opposite sides of a bandpass filter are "equalized" at one frequency by introducing two more "outer" disks at whatever spacing is appropriate to each side, they would not remain equalized at another frequency, and the filter would not be "tracking." As yet, no theory is available to apply to the aforementioned observed details; so far one can only predict approximately for the end-points, that is, for infinite and zero spacing.

An unusual phenomenon, observed at the lower frequencies, is exemplified in Fig. 3 for frequencies of 800 MHz and 1200 MHz. Below about 1500 MHz ($H_{dc} \approx 2100$ Oe) the resonant field for a given frequency and spacing is lower when the disks are approaching one another than when separating. This effect, which disappeared at higher fields and frequencies and therefore probably arises from some incomplete saturation condition, was always distinct and reproducible.

IV. Conclusions

Until doublets per se can be studied further, they cannot be used as adjustable resonators in bandpass filters. Instead, equality of $4\pi M_s N_z$ may have to depend on selecting pairs of "matched" disks from a large batch of disks.

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Bandstop Filter Formulas[1]

This correspondence summarizes a few simple formulas for single-resonator bandstop filters. We have found the formulas useful mainly in the tuning procedure or to determine the individual resonator Qs of multiresonator bandstop filters [1]–[5]. These equations arose and were developed at the Stanford Research Institute during various applications; the exact formulas have not been published before.

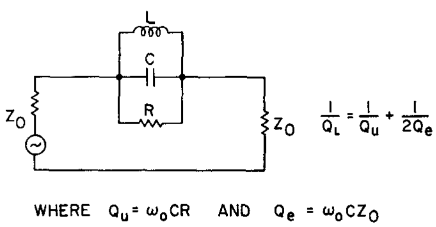

Fig. 1. Single-resonator bandstop filter.

Consider the single-resonator bandstop filter shown in Fig. 1, with the unloaded Q, Q_u, and external Q, Q_e, as defined in the figure. The source and load impedances (Z_0) are assumed to be equal. Let

$(L_A)_{\max}$ = maximum attenuation in dB of bandstop filter (with single resonator).

$V_{\max}$ = maximum input VSWR of bandstop filter (with single resonator).

$w_{x\text{-}dB}$ = fractional bandwidth between x-dB points on a guide wavelength basis. (The suffix 1 is used to emphasize that this is the bandwidth of a single cavity of possibly a multi-cavity filter in which the other cavities have been decoupled.)

$$A = \text{antilog}_{10}\left[\frac{(L_A)_{\max}}{20}\right] = 10^{(L_A)_{\max}/20}.$$

The resonator normalized slope parameter[1] is

$$\frac{b}{Y_0} = \frac{1}{2}\frac{Q_u}{A-1}.$$

Then,

$$A = \tfrac{1}{2}(V_{\max} + 1)$$

$$\frac{Q_u}{Q_e} = 2(A-1) = V_{\max} - 1$$

$$Q_u = \frac{1}{w_{3\text{-db}}}\sqrt{A^2 - 2}.$$

More generally,

$$Q_u = \frac{1}{w_{L_A\text{-}dB}}\sqrt{\frac{A^2 - 10^{L_A/10}}{10^{L_A/10} - 1}}$$

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Design Data for UHF Circulators

Introduction

Davies and Cohen [1] have described detailed calculations based upon the theoretical investigations of Bosma [2] into stripline circulator operation. The calculations yielded design curves for various modes of circulation but were applicable only for a particular relationship between center conductor width and ferrite radius. This correspondence describes an extension of their calculations to a wide range of stripline geometries, permitting greater freedom in circulator design.

Design Curves

The circulator geometry is depicted in Fig. 1, with the radius of the center conducting plane R being taken equal to the ferrite radius. Curves have been obtained as solutions of Bosma's circulation equations with the aid of a digital computer, using a technique which separates the required data from the singularities associated with solutions.

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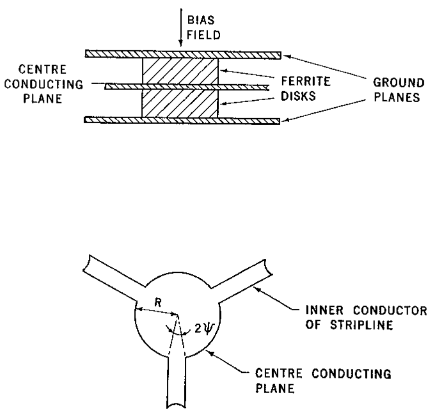


Fig. 1. Arrangement for 3-port ferrite circulator.

Parameters of interest in the design curves are x, Z_{eff}/Z_d, κ/μ, and ψ defined as:

$$x = kR \tag{1}$$

$$\frac{Z_{eff}}{Z_d} = \left[\frac{\mu_{eff}\epsilon_d}{\mu_d\epsilon}\right]^{1/2} \tag{2}$$

$$k = \frac{2\pi f \mu_{eff}\epsilon}{c} \tag{3}$$

where

$\mu_{eff} = \mu^2 - \kappa^2/\mu$

μ, $i\kappa$ = diagonal and off-diagonal elements of ferrite permeability tensor

ϵ = ferrite relative permativity

μ_d, ϵ_d = relative permeability and permativity of dielectric filling stripline

c = velocity of light (cm/s)

f = frequency (Hz).

Figures 2 and 3 are plots of x against κ/μ for modes 1, 2, and 3 following the mode nomenclature given in Davies and Cohen [1]. Figures 4, 5, and 6 are the corresponding plots of Z_{eff}/Z_d against κ/μ. The dotted lines in Figs. 2 and 3 indicate the singularity loci of the solutions [1], and S_1, S_2, S_3, and S_4 double singularities. Some slight differences from the corresponding curves of Davies [1] and Cohen for $\psi = 20$ degrees are discernible in the figures. These appear to arise from the earlier termination by Davies and Cohen [1] of the infinite series expressions occurring in the circulator equations.

To minimize ferrite diameter and, therefore, dissipation loss, circulators are often operated above resonance. This will correspond to mode 1 operation at low values of κ/μ. As a design aid this region has been replotted in Figs. 7 and 8, using an expanded scale. It can be seen from Fig. 8, that the following approximate relation holds.

$$\frac{Z_{eff}}{Z_d} = \frac{\pi}{3\psi} \cdot \frac{\kappa}{\mu}.$$

This is in agreement with equation (69) of Bosma [3].

Design Technique

The design curves are used to ascertain values of Z_{eff}/Z_d satisfactory for circulator design and hence, derive the corresponding ferrite radius and biasing field. With the aid of the lossfree Polder Tensor formulation curves of Z_{eff}/Z_d and internal field strength are plotted against κ/μ, for a given ferrite ma-

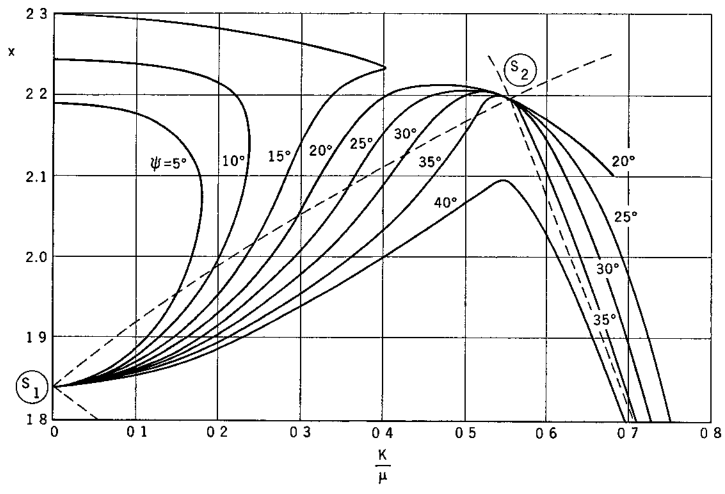


Fig. 2. 'x' as a function of κ/μ (mode 1).

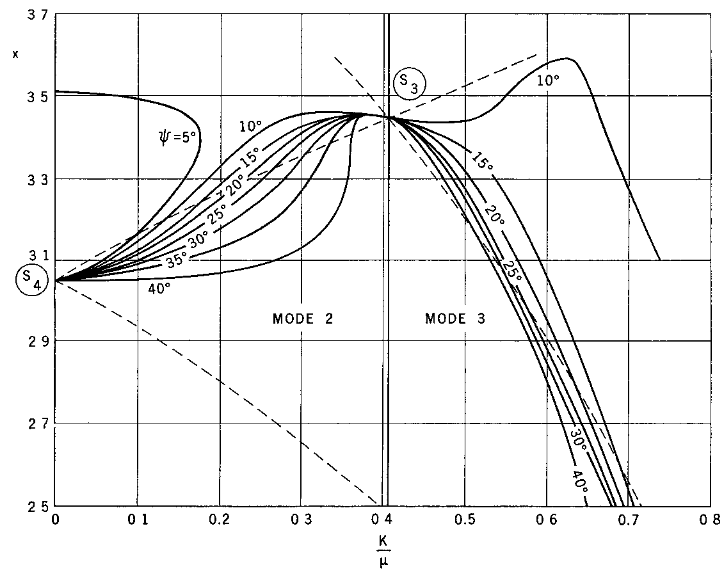


Fig. 3. 'x' as a function of κ/μ (modes 2 and 3).

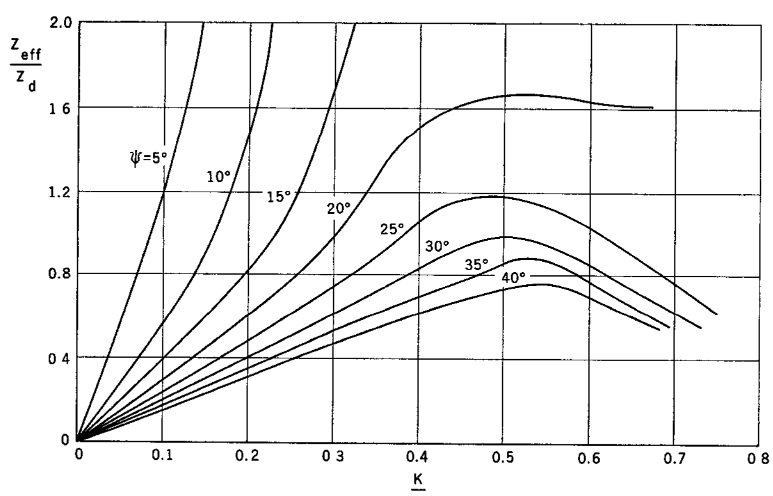


Fig. 4. Z_{eff}/Z_d as a function of κ/μ (mode 1).

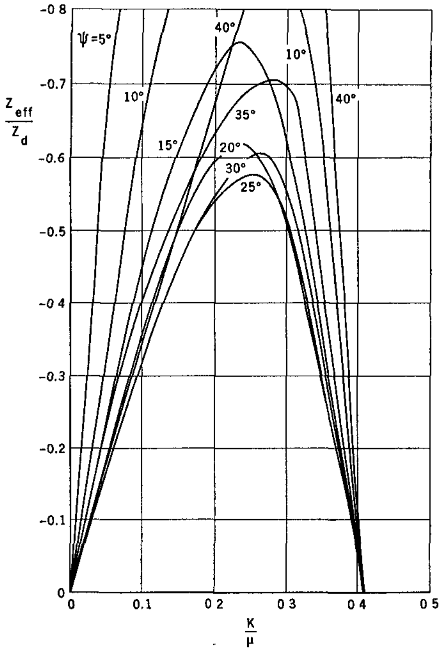


Fig. 5. Z_{eff}/Z_d as a function of κ/μ (mode 2).

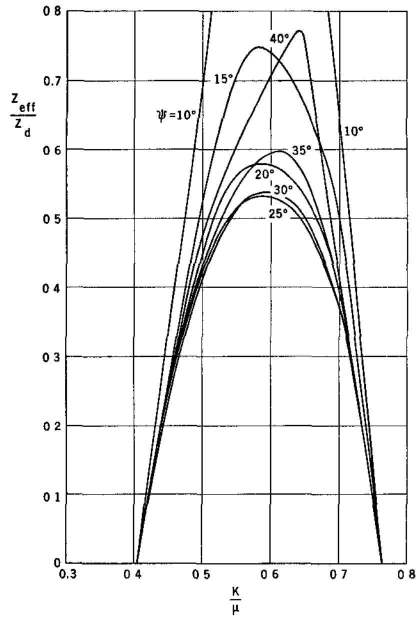


Fig. 6. Z_{eff}/Z_d as a function of κ/μ (mode 3).

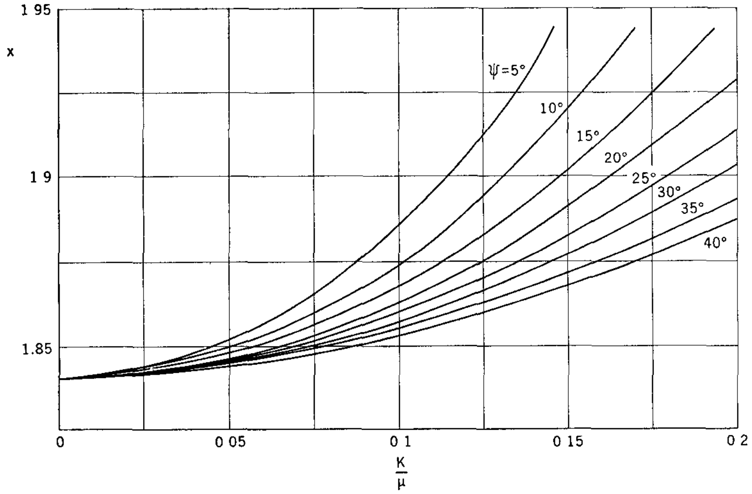


Fig. 7. Expanded plot of x against κ/μ (mode 1).

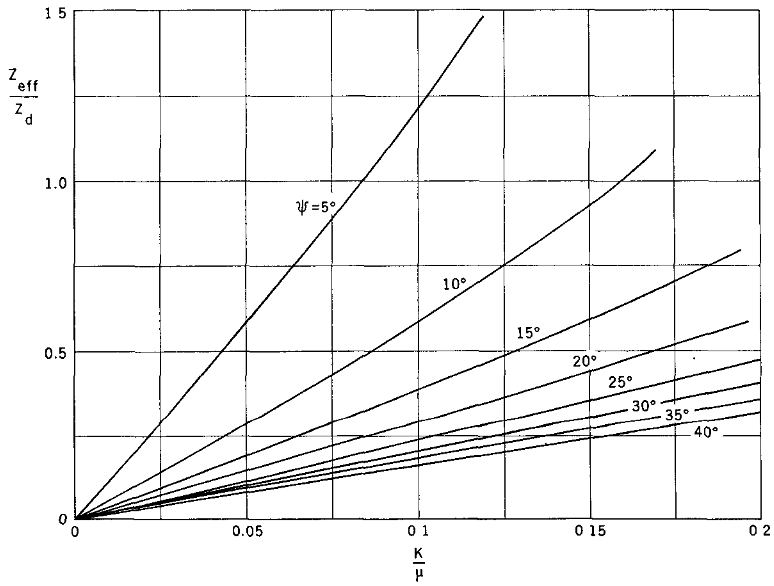
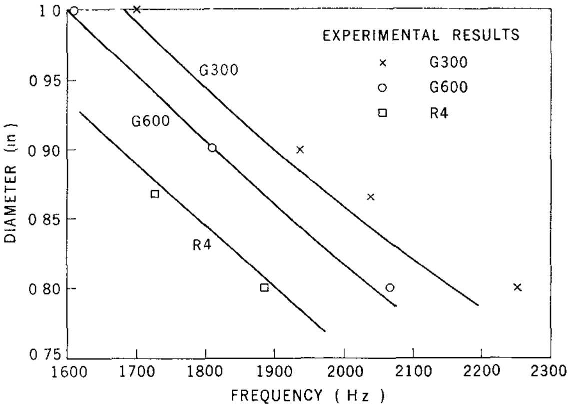


Fig. 8. Expanded plot of Z_{eff}/Z_d against κ/μ (mode 1).



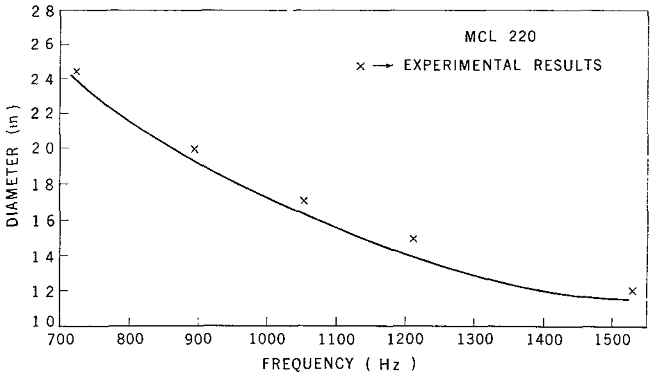


Fig. 9. Computed curves for mode 1 operation.

terial at the design center frequency. Intersects of the derived Z_{eff}/Z_d curve with the curves for a chosen mode of circulation yield a set of κ/μ values for different ψ. Corresponding x values can be obtained from Figs. 2 or 3, as appropriate. The optimum radius for the desired stripline geometry can then be selected, using (1)–(3), and the corresponding internal field also determined.

An approximation for the external bias field required can be derived from the calculated internal field applying published data on demagnetizing factors for disks [4].

Standard matching techniques, using dielectric transformers [5], [6] can then be applied to increase operational bandwidth, if necessary.

Experimental Results

Figure 9 gives computed curves for various ferrite materials operating above ferromagnetic resonance in mode 1 with experimental results for comparison. In most cases the discrepancy between experimental and computed results is less than 3 percent. Experimental bias fields were about 10–15 percent lower than calculated values, but it is expected that field errors will be higher because of demagnetizing factor approximations and measurement errors.

Similar results have been obtained for modes 2 and 3, although errors in ferrite diameter tend to be somewhat higher. Because of the negative sign for Z_{eff}/Z_d mode 2 circulation is in the opposite sense to modes 1 and 3. Measured bandwidths exceeded predicted values by amounts varying from 30 to 100 percent, but nevertheless demonstrated the validity of the proportionality with κ/μ, deduced by Bosma [3]. These discrepancies can be expected as the theory neglects dissipative losses in the ferrite.

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Broadband, Lumped Element UHF Circulator

A triple-tuned, broadband circulator covering the 400–700 MHz range has been developed utilizing lumped element techniques.[1]

The basic design is a shunt-tuned, lumped constant circulator biased above ferromagnetic resonance and triple tuned by means of two additional resonant circuits at each port. The equivalent circuit for this unit is shown in Fig. 1.

The single-tuned circulator was designed and constructed using the techniques described by Dunn and Roberts[2] and Konishi.[3] According to the lumped constant circulator theory presented in these papers, the Q, and hence the bandwidth, of a basic single-tuned circulator is related to the bias field and saturation magnetization of the ferrite by

$$Q = \frac{\mu^+ + \mu^-}{\sqrt{3}\,(\mu^+ - \mu^-)}$$

where

$$\mu^\pm = 1 + \frac{\omega_m}{\omega_0 \mp \omega}$$

ω is the center frequency of the circulator, ω_0 is the frequency of ferromagnetic resonance, and ω_m is $\gamma 4\pi M_s$. This expression indicates that the bandwidth increases as the frequency of resonance approaches the operating frequency. Unfortunately, magnetic losses also increase as resonance is approached setting a limit to the bandwidth that can be achieved with tolerable losses. The basic single-tuned circulator was designed to operate as close to resonance as possible without introducing objectionable losses in the desired operating frequency band. The ferrite material was a polycrystalline garnet material with $4\pi M_s = 1000$ gauss. The impedance response of the single-tuned circulator is plotted in Fig. 2. It is seen that the response approximates very closely that of an ideal parallel resonant circuit, also shown in Fig. 2.

To realize the full bandwidth for the given single-tuned plot it was necessary to triple tune by adding the appropriate series and shunt-tuned circuits. The parameters of these circuits can be determined graphically, or from filter theory by using the circulator as a shunt resonator in a three-resonator bandpass filter with the desired Tchebyscheff response. Results for the triple-tuned circulator are plotted in Fig. 3. These performance

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