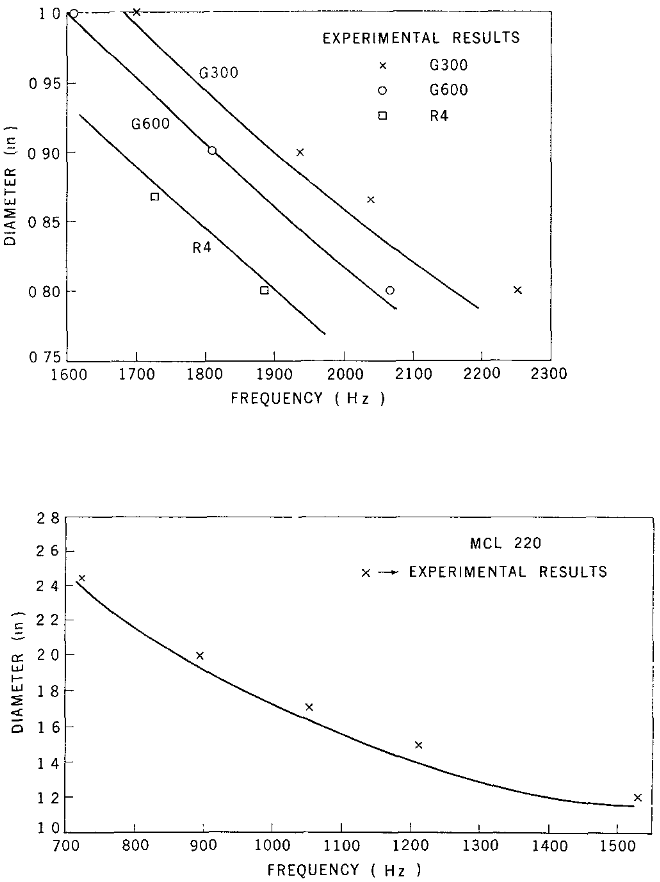

Fig. 9. Computed curves for mode 1 operation.

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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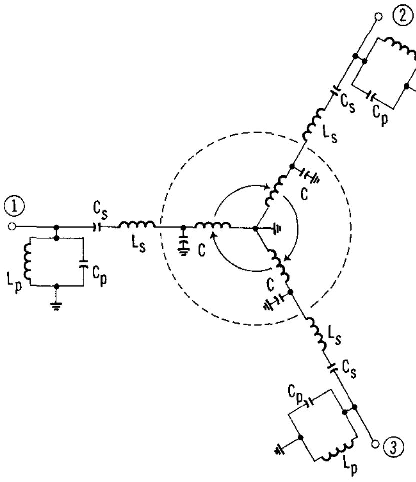

Fig. 1. Equivalent circuit of triple-tuned circulator.

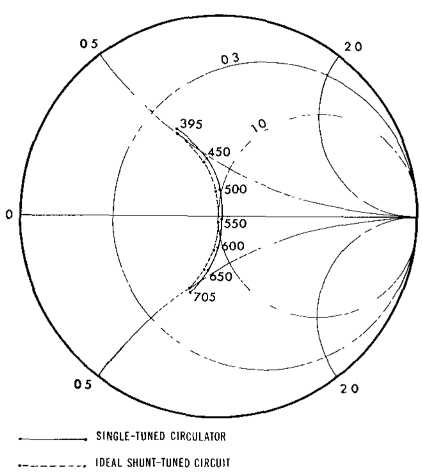

Fig. 2. Impedance response of the single-tuned circulator.

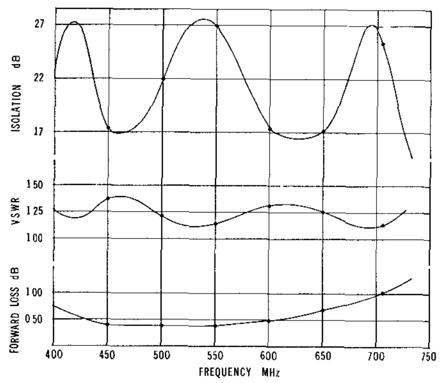

Fig. 3. Performance of triple-tuned circulator.

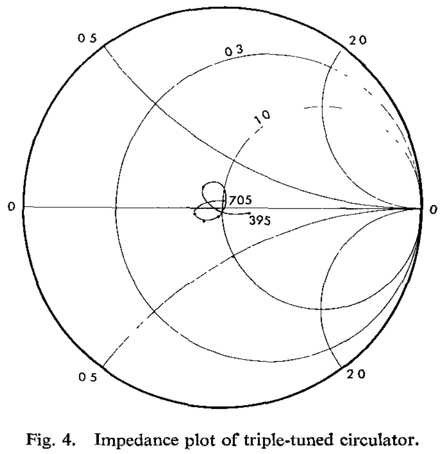

Fig. 4. Impedance plot of triple-tuned circulator.

curves show an equal ripple characteristic with a minimum isolation of 17 dB. The insertion loss reaches a maximum of 1.0 dB at the high end of the band and is typically 0.6 dB or less over most of the band. The corresponding impedance plot is indicated in Fig. 4. The packaged unit is $3\frac{11}{16}$ inches in diameter by $1\frac{1}{4}$ inches in height.

In comparison with previously reported conventional junction circulators, this circulator has greater bandwidth for comparable isolation and insertion loss and has a possible cost advantage in that the ferrite volume required is considerably less.

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Cutoff Characteristics of the Channel Waveguide

Some time ago, Vilmur and Ishii[1] reported the results of an investigation to determine the cutoff characteristics of the channel waveguide. Their analysis was based on the methods of Iashkin and Cohn. However, they found that the two approaches produced appreciably different results. Subsequently, Roth and Ishii[2] attempted to resolve this discrepancy by experiments. Their observations seemed to indicate that there were indeed two modes of propagation, one following Iashkin's method and one following Cohn's method.

The purpose of this correspondence is to verify that over a certain range of channel-width to guide-width ratios there exist two modes with similar cutoff characteristics, to identify these modes by their field configurations and to present accurate cutoff data. These data were obtained using an existing computer program and the accuracy is of the order of 0.1 percent.

Our analysis is based on the method of finite differences which replaces the Helmholtz equation and boundary conditions by a set of algebraic equations in terms of the field values at discrete mesh points. Solutions to the resulting matrix eigenvalue problem are obtained using successive over-relaxation for the field values, a variational expression for the cutoff wavenumber and mesh halving until sufficient accuracy is obtained. Details of the method and the development of a computer program to solve for arbitrarily shaped waveguides have been published in a recent paper.[3]

Figure 1 shows the electric field configuration for the two modes which are of interest to the present discussion. The mode depicted in Fig. 1(a) corresponds to the TE_{10} mode in a rectangular waveguide and the mode of Fig. 1(b) reduces to the TE_{01} mode if the channel is removed. Figure 2 is a graph of the cutoff characteristics for the two modes for a channel waveguide having $b_1/a_1=0.444$, $b_1/b_2=0.5$, and a_2/a_1 varying from 0 to 1. All higher-order modes have cutoff frequencies outside of the range shown on Fig. 2.

The results show that the effect of the channel is to increase the cutoff frequency of the TE_{10} mode and to decrease that of the TE_{01} mode. In fact, over a wide range of a_2/a_1, the TE_{01} mode replaces the TE_{10} mode as the dominant mode in the channel waveguide.

Comparing these results with those obtained by Roth and Ishii,[2] it seems reasonable to conclude that the method of Iashkin gives an approximation to the TE_{10} mode, whereas

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