Octave-Bandwidth UHF/*L*-Band Circulator*

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Summary—**Test data are presented on two aluminum-substituted yttrium-iron-garnet (YIG) materials that have low-saturation magnetizations that permit the extension of ferrite devices well into the UHF/VHF region. In particular, one composition has a saturation magnetization of 300 gauss and a line width of 50 oersteds. Measurements are presented that compare the new materials with previously available higher-saturation magnetization materials.**

A broad-band UHF/*L*-band four-port circulator that operates over a 2-to-1 frequency band has been developed, using this 300 gauss material. Insertion loss is 1 db or less from 665 to 1320 Mc (with constant magnetic field) and 0.5 db or less from 800 to 1150 Mc. A compact and favorable circulator package design was obtained by using coaxial hybrids and dielectric-loaded strip transmission line. Data on the broad-band magic-tee used in the circulator are included. Isolator measurements down to 200 Mc are reported. Reverse-to-forward magnetic-loss ratios of 36 at 600 Mc and 12 at 300 Mc were obtained.

I. Introduction

NONRECIPROCAL ferrite devices—in particular' low-loss circulators—are increasingly difficult to realize at the lower microwave and UHF frequencies [1], [2]. This can be seen by considering the two magnetic-loss mechanisms in microwave ferrites (Fig. 1):

1) The low-field loss that exists at low microwave and UHF frequencies in unsaturated ferrite.
2) The ferrimagnetic resonance loss.

Because the magnetic field required for ferrimagnetic resonance is proportional to the frequency, the low-loss region below ferrimagnetic resonance gradually disappears as the frequency is decreased, thereby increasing the loss in circulators operating in this region. Similarly, the low-field loss will broaden the ferrimagnetic resonance line and deteriorate the ratio of reverse-to-forward loss of low-frequency resonance isolators.

To minimize these effects, it is necessary:

1) to use transversely magnetized thin ferrite slabs, since the demagnetizing factors for this ferrite geometry maximize the applied magnetic field required for resonance,
2) to decrease the saturation magnetization ($4\pi M_s$) of the ferrite material while keeping the resonance line width (ΔH) as narrow as possible.

Previous low-loss *S*-band and *L*-band circulators [3] used a high-density magnesium-manganese ferrite with aluminum substitution (General Ceramics R-6). Measurements show that the loss of R-6 in broad-band circulators increases rapidly when the operating frequency is decreased below 1100 Mc. Therefore, a new material is required for UHF application.

Unfortunately, the addition of aluminum to the magnesium-manganese ferrite, though it lowers the saturation magnetization, will also lower the Curie temperature (about 100°C for R-6). This increases the ferrite sensitivity to temperature variations and limits its use in high-power applications, unless external cooling is provided. The further addition of aluminum to a magnesium-manganese material is therefore undesirable.

II. Development of Materials

A more rewarding approach is to use substituted yttrium-iron garnet (YIG), since reasonable Curie temperatures can be obtained for aluminum-substituted and gallium-substituted YIG without undue line-width deterioration [4]–[6]. Accordingly, we arranged with Microwave Chemicals Laboratory to supply a number of specially prepared YIG compositions with the object of obtaining a satisfactory UHF ferrite material. Two aluminum-substituted YIG compositions were obtained

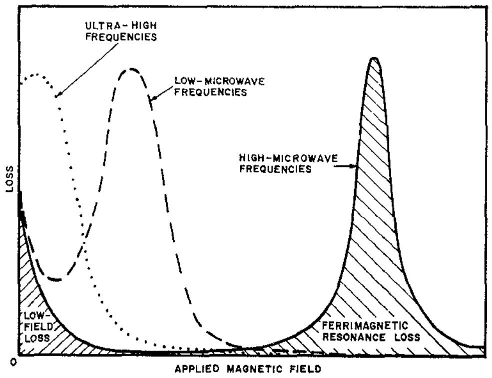

Fig. 1—Ferrite loss vs applied magnetic field.

TABLE I
Properties of Materials

Material	Saturation Magnetization (Gauss)	Line Width (Oersteds at S-Band)	Dielectric Loss Tangent (at 20 Mc)	Dielectric Constant	Curie Temperature (°C)
Al-YIG*	400	60	0.0037	13.5	140
Al-YIG*	300	50	0.0016	11.7	125
Pure YIG	1750	40 to 50	0.002	16	275
R-6 (Mg-Mn-Al)	730	90	0.0015	—	100

* Measurements by L. M. Silber, Polytechnic Inst. of Brooklyn, N. Y.

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that combined low-saturation magnetization (400 and 300 gauss), narrow line width, reasonable Curie temperature, and low dielectric-loss tangent. Table I shows the measured magnetic and dielectric properties of these materials, and compares them to the properties of pure (unsubstituted) YIG and R-6. It was possible to obtain a material having a saturation magnetization of only 300 gauss, a line width of 50 oersteds, a dielectric-loss tangent of 0.0016, and a Curie temperature of 125°C. This proved to be the best material for UHF circulators and had extremely good performance (reverse-to-forward loss ratio) when measured as an isolator at frequencies down to 200 Mc.

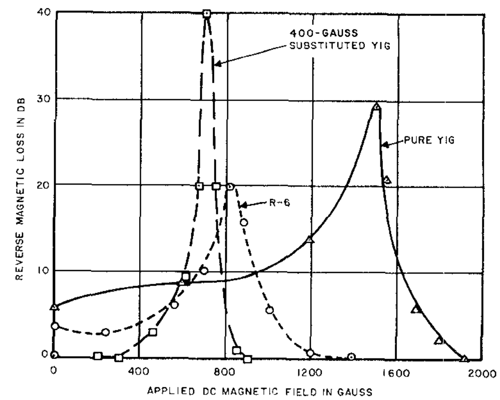

Fig. 2—Comparison of magnetic loss (1200 Mc).

III. Microwave and UHF Measurements

The magnetic loss at 1200 Mc as a function of applied magnetic field for R-6, pure YIG, and the 400-gauss substituted YIG material are compared in Fig. 2. The 400-gauss material shows a narrow line width, a very low zero-field loss, and a high-resonance loss. The dimensions of the various samples were not identical, but the conclusions are qualitatively correct.

TABLE II
Microwave Measurements on Substituted-YIG Materials

Test Frequency (mc)	Material (Gauss)	Test Section*	Resonant Loss per 6-Inch Length (db)	Zero Field Loss per 6-Inch Length (db)	Differential Phase Shift per 12-Inch Length (Degrees)	Figure of Merit (Degrees per db)
900	400	A	9.0	0.8	33.4	420
900	400	B	23.2	2.4	88.0	440
900	300	B	15.6	0.4	112	410
1200	400	C	10.8	0.2	50.4	505
1200	400	B	24	0.4	97.6	490
1200	300†	B	16	0.1	111	520

* Test sections are designated as: A) 9.2 by 1 inch (inside dimension) waveguide; B) dielectric-loaded strip transmission line (Fig. 4) C) 6.5 by 1 inch (inside dimension) waveguide.

† Phase-shift measurements were made with the magnetic field above ferrimagnetic resonance, except for the measurements with the 300-gauss material.

Microwave measurements at 900 and 1200 Mc for the 300- and 400-gauss materials are given in Table II. The substituted-YIG compositions show high figures of merit for both circulator and isolator application in the UHF region. Note that only in the case of the 300-gauss material was it possible to obtain low-loss phase-shift data below resonance. Reverse magnetic-loss measurements of the 300- and 400-gauss materials at 900 Mc are compared in Fig. 3. The 300-gauss material, with lowest saturation magnetization and good line width, shows a broader low-loss region than the 400-gauss material, and hence can be used to lower frequencies. Therefore, the 300-gauss material is the most suitable for broad-band UHF circulators and isolators.

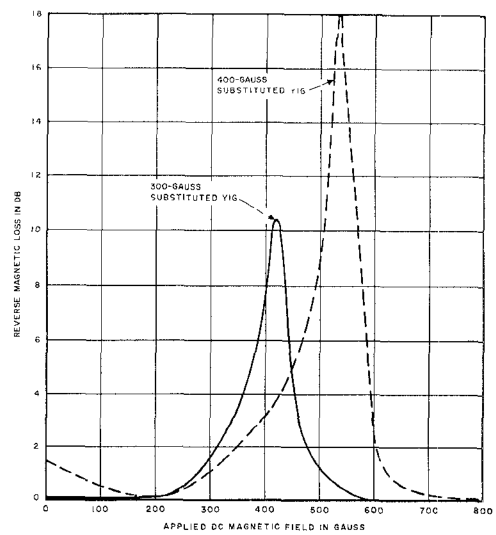

Fig. 3—Comparison of magnetic loss (900 Mc).

IV. Broad-Band Circulator Design

To obtain as large a bandwidth as possible, and in view of its superiority for use with broad-band maser and parametric amplifiers, a four-port differential phase-shift type circulator was developed. The feasibility of a very broad-band coaxial S-band circulator has previously been demonstrated [7]. To achieve large bandwidth as well as a compact unit, TEM-mode transmission lines were used. Strip transmission lines using partial dielectric loading (Fig. 4) were used for the nonreciprocal phase-shift sections, thereby distorting the TEM mode [8], [9] sufficiently to produce a longitudinal component of the RF magnetic field. The strip transmission line was chosen instead of coaxial line because it is easier to fabricate the structure and shape the ferrite and dielectric pieces, and the dielectric pieces can be readily adjusted and interchanged for optimum circulator performance during testing.

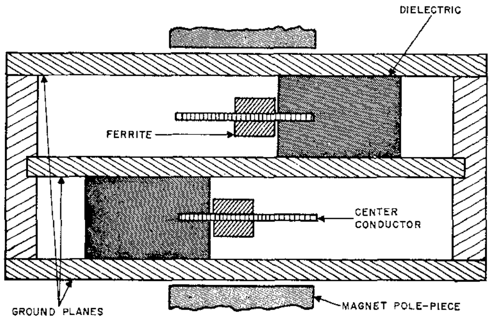

Fig. 4—Cross section of strip-transmission-line circulator structure.

The mode resulting from the dielectric loading does not have a complete circularly-polarized RF magnetic field [10]. However, the field produced is almost circularly polarized—sufficiently so to produce efficient nonreciprocal action when the structure is loaded with ferrite. The ellipticity (deviation from circular polarization) results in increased length and deteriorates the figure of merit (degrees of differential phase shift per db of loss) of the ferrite nonreciprocal phase-shift section. Thus, an ellipticity of 1.2 will reduce the figure of merit by 17 per cent. For an isolator it would limit the reverse-to-forward loss ratio to 20 to 1. The calculated ellipticity at the dielectric interface for our structure was from 1.1 to 1.3 in the frequency range of interest.

A slowing factor of 2.2 was measured over the desired frequency range, thereby reducing the length of the ferrite section by the same factor. To match the 16-ohm dielectric-loaded line to the 50-ohm input and output over the desired frequency band, three quarter-wave transformers which had a Tchebycheff response were used [11]. Matching was accomplished by using a 400- to 1200-Mc sweep oscillator and was checked point by point. The SWR of the dielectric line with the transformers averaged 1.15.

V. Hybrids

To construct a four-port phase-shift circulator, two hybrids are required to connect two 90-degree nonreciprocal phase-shift sections. For the best design, one hybrid should give a 90-degree phase difference and a 3-db power split; the other should give a 180-degree phase difference and a 3-db power split.

A 180° hybrid was developed based on previous work [12], [13]. This coaxial magic-tee is basically a broadband four-port ring hybrid where all arms are $\lambda/4$ long. Reversing the inner and outer conductors on one of the arms introduces the extra 180 degrees of phase shift required for hybrid action. Since the 180° phase shift introduced in the crossover arm is not frequency sensitive, the bandwidth of the resulting hybrid is wider than the conventional ring hybrid. Neglecting the discontinuities caused by the reversal at the crossover arm and the wire connections, the calculation shows that for a 40-per cent bandwidth, an input SWR slightly less than 1.10 can be obtained at all ports. Since all line lengths in this hybrid are equal, we can obtain high isolation to the decoupled port and an even power split to the two coupled ports over a large frequency range.

The unit gave a power split of ± 0.10 db or better (from 700 to 1200 Mc), an isolation of 27 db or more, and an input SWR averaging 1.1.

For the 90° hybrid, we used a special unit supplied by Sage Laboratories that is a miniaturized version of a broad-band parallel strip-transmission-line hybrid [14].

VI. Circulator Package and Performance

Measurements on differential phase shift and loss on the ferrite section shows that good circulator operation can be obtained with 400-gauss material at 700 gauss (above resonance) or with 300-gauss material near 100 gauss (below resonance). This is shown in Table II. Operation below resonance is, of course, preferred because magnet weight is reduced substantially and broad-band operation can be readily achieved.

Fig. 5 shows the completely assembled circulator with the hybrids distinguishable at each end. The two nonreciprocal phase-shift sections are located one on top of the other (Fig. 4). This results in a compact and easily packaged geometry. The strip transmission lines have a 3.6° jog to obtain the proper physical locations for connecting the hybrids.

Performance data taken on the assembled circulator are shown in Fig. 6. The measured insertion loss was 0.5 db or less from 800 to 1150 Mc (with optimized magnetic field), and 1.0 db or less from 665 to 1320 Mc (with constant applied magnetic field).

Thus, a UHF/L-band circulator was realized that has an octave of coverage with constant magnetic field. The electromagnet can, of course, be replaced by a permanent magnet.

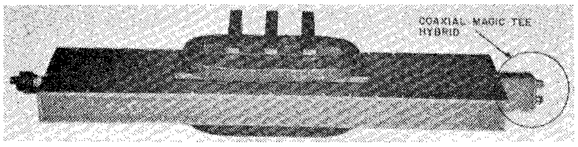

Fig. 5—UHF/L-band circulator.

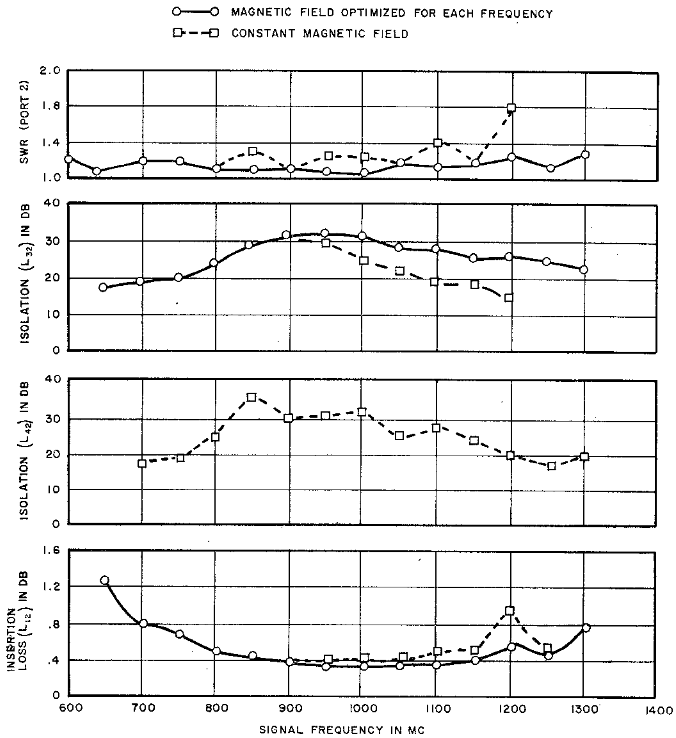

Fig. 6—Performance data for UHF/L-band circulator.

This circulator was tested with an experimental broadband parametric amplifier 15 and provided the large bandwidth necessary to accurately measure the low noise figures obtained. The amplifying region of the parametric amplifier is considerably greater than its 3-db bandwidth. Therefore, the circulator bandwidth should at least equal the gain-bandwidth product of the parametric amplifier so that a good match is provided to the amplifier until the gain drops to unity.

VII. Isolator Measurements

Isolator measurements of the 300-gauss material are shown in Fig. 7 with magnetic field optimized at each frequency. The measurements were obtained in the dielectric-loaded strip transmission line (Fig. 4) with a ferrite only 12 inches long. As is shown, high-reverse losses and good reverse-to-forward loss ratios (db) are obtained down to a frequency of 300 Mc. The figure of merit (reverse-to-forward loss ratio in db) was 38 at 800 Mc, 36 at 600 Mc, 20 at 400 Mc, and 12 at 300 Mc.

Since this structure is designed for higher frequencies,

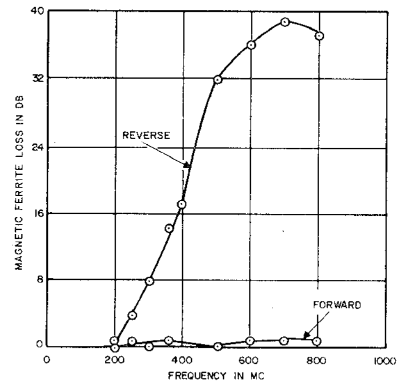

Fig. 7—Isolator performance at UHF/VHF frequencies.

it did not give optimum elliptical polarization below 500 Mc. Hence, substantial improvements should be possible over those previously reported [15] by optimizing the circuit design.

VIII. Conclusions

Measurements are reported on two aluminum-substituted YIG materials that can be used for ferrite devices in the VHF, UHF and L-bands.

One composition with a saturation magnetization of 300 gauss permits the extension of circulators and isolators to lower frequencies than has been possible in the past.

A four-port circulator has been developed using the 300-gauss material that can be operated over a 2-to-1 frequency band. An insertion loss of 1 db or less was obtained from 665 to 1320 Mc with constant magnetic field. Insertion loss with optimized magnetic field was 0.5 db or less from 800 to 1150 Mc.

A specially compact and favorable circulator package design was achieved that used coaxial hybrids and a dielectric-loaded strip-transmission-line ferrite structure.

Favorable reverse-to-forward loss ratios were obtained in isolator measurements to 300 Mc.

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A Five-Port Matched Pseudo-Magic Tee*

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Summary—**The five-port matched pseudo-magic tee consists of an input waveguide, two load arm waveguides which are coupled into the input waveguide with +90° and −90° phase shifts, respectively, and an output waveguide which is split into two load waveguides by a septum.**

The improvements include a much broader matching and isolation bandwidth, higher isolation between arms, better matching into arms, and a variety of modifications for different applications.

These characteristics have been obtained by employing frequency-insensitive phase shifters. Hence, frequency coverage is mainly limited by mechanical asymmetry and the characteristics of the directional coupler in the magic tee.

While this type of hybrid junction is not a true magic tee because the load arms are not used as the input arm, it does have several applications which an ordinary magic tee does not have.

***X*-, *K*-, and *M*-band models were examined experimentally, and highly sensitive and accurate impedance measurements were made.**

INTRODUCTION

CONVENTIONAL magic tees are not as well matched nor as well isolated over as broad a frequency range as one would like. The sensitivity and accuracy of impedance bridges and the sensitivity of microwave mixers are quite often limited by the aforementioned factors. Several attempts at modifying conventional matched magic tees have been made. However, the main difficulties, which arise from the fundamental restrictions of the structure itself, have remained.

A solution of this problem has been obtained in the following ways.

PRINCIPLES OF OPERATION

The new-type magic tee (type 1) is shown in Fig. 1(a) and 1(b) (page 218). Input-microwave power is split equally by a septum in the input waveguide and then introduced into load arm waveguides 1 and 2 through directional couplers. The waves reflected from loads 1 and 2 meet at the output arm.

One can see that the waves going into loads 1 and 2 are out of phase with each other, if the condition $L_{i1}=L_{i2}$ is satisfied. Hence, the wave coming from the output arm has zero amplitude if loads 1 and 2 are identical and $L_{o1}=L_{o2}$. The geometrical conditions $L_{i1}=L_{i2}$ and $L_{o1}=L_{o2}$ are satisfied independently of the input frequency. This condition has enabled us to build a frequency-insensitive magic tee.

The matching conditions of the input waveguide depend mainly upon the matched load of the directional couplers. The necessity for the matched loads at waveguide junctions of the load arms is easily seen by circuit theory.[1] The mismatches at the junction cause fre-

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