circular pad of metallurgical polishing cloth attached to the end of the shaft. The shallow mortar dish, also lined with metallurgical polishing cloth, contains the sphere. The polishing cloths are impregnated with the appropriate polishing compound. The rotating pad is simply lowered into the dish far enough to make contact with the sphere. A horseshoe-type magnet placed directly under the bowl pulls the steel shaft (which has a short axial travel) firmly against the garnet sphere. It is thought the inhomogeneity of the magnets field causes the sphere to constantly change direction searching for an easy crystal axis of alignment. This action, together with the circular motion of the shaft, produces an unstable orbit and a uniform surface finish. With the arrangement properly adjusted, the sphere leaves a track near the outside edge of the pad.

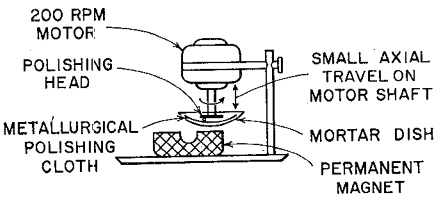

Fig. 1

Samples to be polished should be good spheres with a surface finish comparable to that obtained with no. 0 emery polishing paper. The first stage uses 25-micron diamond paste followed by an 8-micron grit. Time required in each stage depends primarily on the pressure applied to the sphere. If pressure is too great, the sphere does not rotate properly and flat spots occasionally develop. The final polishing procedure is done using $\frac{1}{4}$-micron diamond paste. Microscopic examination is desirable to check on cutting progress in all stages. Generally speaking, 4 to 6 hours in each stage produces a high surface polish.

The unloaded Q's of the finished spheres were measured at a frequency of 4 kMc using the impedance method described by Ginzton.[1] The spheres were mounted loosely in a thin sheet of polyfoam causing the spheres to be aligned along an easy axis of magnetization when placed in the dc magnetic field. The sphere is placed one-half guide wavelength away from the end of a short-circuited section of G-band waveguide. The results of the measurements on the garnet spheres were as follows:

TABLE I

Summary of Measurements of Q_u at 4000 Mc

Sphere Diameter-Inches	Unloaded Q, Q_u at 4000 Mc	Linewidth, $\Delta H = \frac{4000}{Q_u \times 2.8}$ -Oersteds
0.056	2700	0.53
0.060	2670	0.54
0.060	2850	0.50
0.095	2760	0.52

[1] E. L. Ginzton, "Microwave Measurements," McGraw-Hill Book Co., Inc., New York, N. Y., ch. 9, pp. 405–417; 1957.

This method of polishing the garnet spheres using a motor driven polishing head has the advantage, over the commonly employed tumbling technique,[2] that no spheres are now damaged due to chipping, which occurred when the spheres bounced off the wall of the tumbling dish.

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[2] W. L. Bond, "Making small spheres," *Rev. Sci. Instr.*, vol. 22, p. 344; May, 1951.

Miniaturized, Temperature Stable, Coaxial Y-Junction Circulators*

Introduction

The problem of designing a circulator that is extremely small, durable, and lightweight immediately suggests the Y- or T-junction approach. For use with coaxial connectors, the strip transmission line Y-junction suggested by Auld[1] and subsequently demonstrated by Milano, Davis and Saunders,[2] has obvious advantages. A systematic approach to developing such a device calls for the symmetrical alteration of at least two physical characteristics of the junction.[1] The obvious choice for one of these characteristics is the magnitude of the biasing magnetic field. The choice for the complementary characteristics can include any symmetrical change in the geometry of the junction (the adjustable ground plane of Fig. 1 is an example) and the symmetrical placing of isotropic and anisotropic material in the junction. The choice of this complementary characteristic most frequently mentioned in the literature is the diameter of the ferrite post. An alteration of the ferrite post height will also provide adjustment. The use of a metal pin along the axis of symmetry has also been suggested for this purpose.[3] Thaxter and Heller have also reported on the use of a copper sleeve around the ferrite post for operation at 70 and 140 kMc.[4]

The method to be described here involves the magnitude of the biasing field and the use of a dielectric-loading technique that is well suited to the design of very small and rugged devices.

In addition, the problem of temperature stability, high-power behavior, and the crucial role of low field losses in these devices will be treated. In C band, in particular, the use of high-gadolinium content YIG will be shown to offer an attractive solution to temperature problems and high-power problems associated with temperature changes.

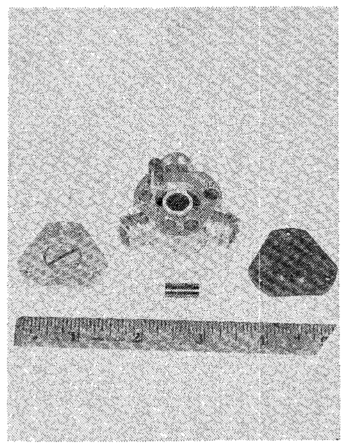

Fig. 1—The C-band circulator.

The C-Band Circulator

Physical Description

The structure of the C-band circulator is shown in Fig. 1. The housing is made of a nonmagnetic material, and the cover plates, which complete the magnetic path through the solid state material, are made of magnetic steel. Exclusive of connectors the device is 1.5 inches in diameter and 0.75 inches in height. The weight is approximately 3.75 ounces. This structure has a slight sensitivity to the proximity of magnetic material. This effect has been shown to be negligible except at the center of band frequencies where isolation between arms may exceed 35 db.

An alternate design can be used to overcome even this slight sensitivity. The exterior of this alternate design is composed entirely of magnetic steel. When fully temperature compensated, this shielded circulator constitutes an exceptionally durable and dependable solid-state device.

Electrical Characteristics

The characteristics of the C-band circulator adjusted for use in the 5.4- to 5.9-kMc range are shown in Fig. 2. These results are typical; slight asymmetries in the structure will generally cause variation in the characteristics from arm to arm. The synthesis procedure provides for design at a single frequency only; the bandwidth is consequently a characteristic of each individul circulator that must be adjusted experimentally.

The Design Technique

The synthesis procedure calls for the alteration of two physical characteristics in order to make the junction a circulator at a

* Received by the PGMTT, January 3, 1961; revised manuscript received, March 2, 1961. The research for this paper was supported in part by Contract No. DA-36-039-78909 of the U. S. Army Signal Corps., Fort Monmouth, N. J.

[1] B. A. Auld, "The synthesis of symmetrical waveguide circulators," IRE Trans. on Microwave Theory and Technique, vol. MTT-7, pp. 238–246; April, 1959.

[2] L. Davis, Jr., V. Milano, and J. Saunders, "A strip-line L-band compact circulator," Proc. IRE (Correspondence), vol. 48, pp. 115–116; January, 1960.

[3] C. Montgomery, R. H. Dicke, and E. M. Purcell, "Principles of Microwave Circuits," McGraw-Hill Book Co., Inc., New York, N. Y., ch. 12; 1948.

[4] J. B. Thaxter and G. S. Heller, "Circulators at 70 and 140 kmc," Proc. IRE (Correspondence), vol. 48, p. 110; January, 1960.

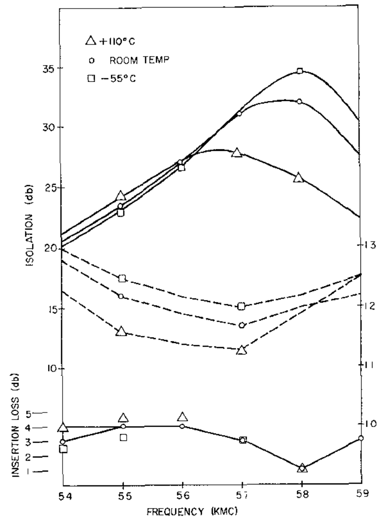

Fig. 2—Typical performance of the C-band circulator in the 5.4 kMc to 5.9-kMc range.

given frequency. This assumes that the range of adjustment afforded by this technique includes the desired frequency. It is thus advantageous to employ a technique that will yield a broad range of adjustment.

The technique employed with the miniaturized circulators discussed here involves the magnitude of the biasing field and the dielectric sleeves. (Fig. 1). It is structurally desirable to hold the outer and inner diameter of the dielectric sleeves constant, since these two physical characteristics serve to center the solid state element, thus eliminating one possible source of asymmetry. This leaves the dielectric constant and the height of the sleeves available for adjustment.

Discrete values of dielectric constant presently available in low loss material can be used for broad range, course adjustment. The sleeve height, however, provides fine adjustment and can be made equally effective over a broad range. With the use of Stycast K-20 sleeves, for example, the C-band circulator can be made to operate at any selected frequency in the band from 4.4 kMc to beyond 10 kMc by a simple adjustment in the height of the sleeves and a complementary adjustment in the biasing field.

Temperature Stability

Use of unsaturated Alnico-V magnets as biasing elements can give a constant biasing field over a broad range of temperature. This leaves the effects of temperature change on the solid-state material as the principle source of instability in fixed field Y-junction circulators. This instability has been observed in below-resonance operation to be the result of a "drift" in optimum frequency of operation as a function of temperature and/or a drift in optimum required biasing field as a function of temperature.

Temperature compensation in the C-band circulator was accomplished simply by the selection of a material which minimized these drifts. Figs. 3, 4(a) and 4(b) are plots

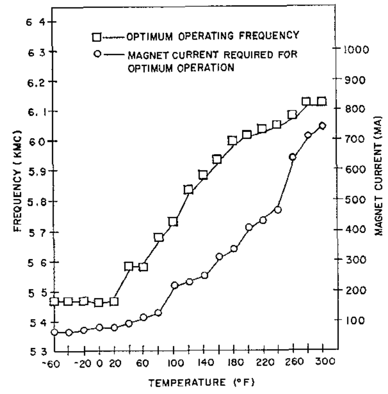

Fig. 3—Optimum operating frequency and required magnet current as a function of temperature for a circulator using an Mg-Mn ferrite.

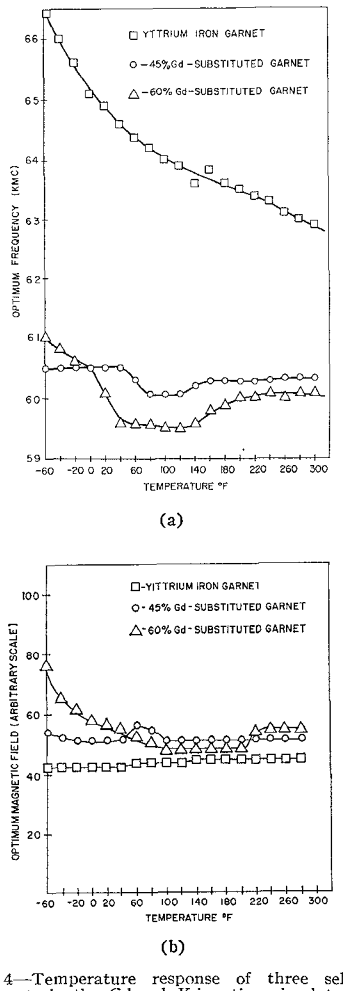

Fig. 4—Temperature response of three selected garnets in the C-band Y-junction circulator. (a) Drift in optimum operating frequency with temperature. (b) Drift in optimum magnetic field with temperature.

of optimum operating frequency and required biasing field as functions of temperature for four compositions. The Mg-Mn ferrite[5] is thought to be a good example of a temperature-unstable material for use in junction circulators. At the other extreme the 45 per cent and 60 per cent gadolinium-substituted garnets exhibit a minimum of temperature instability. The yttrium-iron garnet displayed stability in optimum biasing field but the optimum operating frequency is seen to drift over a relatively broad band. The high-gadolinium-content garnets were selected for experimentation on the basis of the observed temperature behavior of these materials in other devices involving resonance and phase shift phenomena.

The characteristics of Fig. 2 were obtained using 60 per cent gadolinium. In another test using 45 per cent gadolinium, the isolation alone was monitored. This isolation remained above 20 db in all three arms of the circulator over the temperature range −60°F to 300°F. In addition, the 60 per cent Gd garnet provides good circulation with low insertion loss in most of the bands under investigation, and should display temperature behavior in these bands that is comparable with that obtained in C band.

There are two primary considerations in the operation of these devices at high-power levels; they are high-peak-power breakdown and heating due to absorption of power. Tests revealed that high-power break-down occurs in the C-band circulator at approximately 30 kw peak power, 30 watts average, when the unit is fitted with Type N connectors, and operated unpressurized. Now, to determine heating and possibly high-power nonlinear effects, the electrical characteristics of the devices were investigated at low- and high-power levels. At 5.560 kMc, the frequency at which the high-power tests were to be run, the circulator exhibited the following low-power characteristics:

Isolation	35 db
Insertion Loss	0.2 db
Input VSWR	1.05 db.

The most critical parameter, isolation, was monitored during the high-power tests. Successive readings were taken at 5-kw increments with the power maintained for five minutes before each reading. No significant change in isolation was observed throughout the test until arcing occurred. Since isolation remained essentially constant, there is no real basis to expect that other characteristics might vary. The material used in this test was 60 per cent gadolinium garnet.

A similar test was run using the Mg-Mn ferrite. The low-power isolation at 5.650 kMc was 31.5 db. At 25 kw peak power and 25 watts average power, the isolation had dropped to 26 db. At this point the power was removed and the device allowed to cool to room temperature. A reapplication of the 25 kw peak power resulted in an isolation of 31.5 db, which gradually decreased as the power was maintained. The somewhat poor performance of the Mg-Mn ferrite at high power was thus apparently due to temperature instability.

Application to Other Frequency Bands

The techniques developed for C and X bands were found to be useful in the design of circulators at lower microwave frequencies. Satisfactory circulator performance has been obtained at frequencies as low as 200

[5] Commercial General Ceramics R-5 Ferrite.

Mc in larger structures. Devices that have been designed in S band down to about 2 kMc are quite similar to those in C band and X band. Circulators constructed below approximately 2 kMc differ in one essential feature that warrants further treatment.

Below and Above Resonance Operation

For most frequencies in the microwave spectrum, the ferrimagnetic materials employed in Y-junction circulators can be biased in a low-loss region with a field that is either below or above that required for ferrimagnetic resonance. With a specific material and geometry this suggests the possibility that the conditions for circulation can be satisfied at two widely-separated values of biasing field. In general we must also expect two different frequencies of circulation to be involved.

These suppositions have, indeed, been found to be true. Experience indicates that circulation occurs in opposite directions for the two fields and that the above-resonance biasing field corresponds to a lower frequency of optimum circulator performance. For example, in the "C-band Circulator" use of 60 per cent gadolinium-content garnet posts 0.400 inches in diameter results in good performance at 4.9 kMc with an above resonance field of approximately 1550 gauss. At this field, isolation exceeds 40 db and insertion loss is less than 0.2 db. Another point of good performance is found at 6.3 kMc with a below-resonance field of approximately 100 gauss. Isolation in this case is greater than 40 db and insertion loss less than 0.6 db. Circulation at the two frequencies is in opposite directions.

From the standpoint of miniaturization, below-resonance operation is obviously desirable because of the very appreciable difference in the size of the required biasing magnets. This assumes, of course, that operation below resonance is practical, which is not necessarily the case.

The Role of Low Field Losses

Unfortunately, presently-known material technology results in a low frequency limit to the utility of below-resonance operation. This limit is the frequency at which low field losses become intolerable. Since the below-resonance biasing fields are quite small, this situation can be roughly approximated by an unmagnetized medium, in which case the limiting frequency is given by[6]

$$f_{mc} = \gamma(H_a + 4\pi M_s),$$

where

$4\pi M_s$ = saturation magnetization
H_a = anisotropy field
γ = gyromagnetic ratio.

For the 60 per cent gadolinium-content garnet, $H_a \approx 80$ oersteds,[7] $4\pi M_s = 700$ and $\gamma = 2.8$ Mc/oersted. Thus, $f_{mc} \approx 2200$.

[6] D. Polder and J. Smit, "Resonance phenomena in ferrites," *Revs. Mod. Phys.*, vol. 25, p. 89; 1953.
[7] G. P Rodrigue, Thesis, Harvard University, Cambridge, Mass.; 1958.

In actual tests with this garnet the authors have been able to achieve below-resonance circulation with insertion loss in the neighborhood of 1 db down to about 2100 Mc. Below this frequency, using the above material, satisfactory results have thus far been achieved only with above-resonance operation.

Conclusion

For use in coaxial circulators, a perturbation technique which employs the magnitude of the biasing field and symmetrical dielectric loading is considered to be of exceptional utility.

The problem of temperature instability in junction-type circulators is thought to be solved by the use of "temperature favorable" materials such as medium- to high-percentage gadolinium substituted yttrium-iron garnets. Yttrium-iron garnet is somewhat less temperature favorable, but will suffice for many applications.

The limit to below ferrimagnetic resonance operation of junction type circulators is thought to be the frequency at which low field losses become intolerable. The lowest practical below-resonance operation using presently available materials appears to be around 2000 Mc. Circulators constructed at lower frequencies and requiring high-level performance, have required above-resonance biasing fields.

Acknowledgment

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K-Band Reciprocal Ferrite Phase Modulator*

Introduction

A rectangular waveguide reciprocal phase modulator, making use of a longitudinal magnetic control field, was reported by Reggia and Spencer[1] in 1957. This X-band phase modulator consisted of a longitudinally magnetized ferrite rod centrally located inside a rectangular waveguide excited in its fundamental TE_{01} mode. The outstanding advantages of this type modulator are the large phase shifts per unit length obtainable, simple geometric configuration, the high figure of merit[2] possible, and the small magnetic control fields required. These modulators have since been designed for use at frequencies ranging from 3000 Mc to 70,000 Mc.

A simplified theoretical analysis of the above phase modulator was made by Weiss.[3] Another theoretical analysis by Tompkins[4] resulted in exact solutions for the field configuration and energy distribution of longitudinally magnetized ferrite rods in circular waveguide as a function of rod diameters. This analysis also included a comparison between the theoretical solutions and the results obtained with the rectangular waveguide phase modulator.

It is the purpose of this paper to present the design data of a K-band phase modulator and the experimental results obtained at 23,640 Mc to 25,000 Mc.

Design Procedure

Beginning with the design data[1] available at X-band and choosing a standard rectangular waveguide (0.170×0.420 inch) for 23 to 25 kMc, it was first necessary to select a suitable ferrite material. A small dielectric and magnetic loss tangent at the operating frequency was required in order to obtain a phase modulator with low insertion loss. Also, since the amount of phase shift obtained is proportional to the magnitude of the saturation magnetization ($4\pi M_s$), a Ni-Zn ferrite[5] having a line width of 40 oersteds and $4\pi M_s$ of 5000 gauss was selected.[6] This material has made possible a phase modulator with a figure of merit in excess of 3000.

The next problem was to determine the minimum rod diameter (d_{min}) required to obtain sufficient concentration of the microwave energy in the ferrite,[4] a necessary condition for obtaining large phase shifts, and the maximum rod diameter (d_{max}) such that the generation of spurious modes in the ferrite-loaded waveguide would not be permitted. Both the maximum and minimum rod diameters are critically dependent on the narrow dimension (0.170 inch) of the rectangular waveguide. With the particular Ni-Zn ferrite chosen, it was found that d_{min} was 0.080 inch and d_{max} was 0.100 inch.

Impedance matching was accomplished by tapering both ends of the ferrite rod and dielectric polyfoam support. An input VSWR of less than 1.20 for the phase modulator for all values of applied magnetic field was considered satisfactory.

* Received by the PGMTT, November 21, 1960; revised manuscript received January 30, 1961. The work reported here was sponsored by the U. S. Army Signal Corps.
[1] F. Reggia and E. G. Spencer, "A new technique in ferrite phase shifting for beam scanning of microwave antennas," Proc. IRE, vol. 45, pp. 1510–1517; November, 1957.

[2] Figure of merit

$$= \frac{\text{maximum phase shift in degrees}}{\text{maximum insertion loss in decibels}}.$$

[3] J. A. Weiss, "A phenomenological theory of the Reggia-Spencer phase shifter," Proc. IRE, vol. 47, pp. 1130–1137; June, 1959.
[4] J. E. Tompkins, "Energy Distribution and Field Configuration in Ferrites," Solid State Physics in Electronics and Telecommunications, Academic Press, Ltd., London, England, pp. 169–180, 1960.
[5] BTL XN5000 (1244, 5131-6). The formula for this Ni-Zn ferite, obtained from L. G. Van Uitert of Bell Telephone Labs., Inc., is

$$Ni_{0.5}Cu_{0.1}Zn_{0.4}O.Fe_{1.9}Mn_{0.1}O_3.$$

[6] L. G. Van Uitert, "Resonance line widths of sintered nickel ferrites having low porosities," *J. Appl. Phys.*, Suppl. to vol. 31, p. 2265; April, 1960.