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, $f_{mc} \approx 2200$.

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.

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[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.

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.

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[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.

RECIPROCAL FERRITE PHASE MODULATOR

A cross-sectional view of the reciprocal phase modulator for 23 to 25 kMc is illustrated in Fig. 1. The ferrite rod used as the phase-shifting element consists of a low-loss Ni-Zn ferrite, having a useful range of diameters from 0.080 to 0.100 inch. It is tapered at both ends for impedance matching and centrally located inside the rectangular waveguide section by a polyfoam dielectric support. The demagnetizing factor of this 3 inch-long ferrite rod, for a longitudinal magnetizing field, is very small.

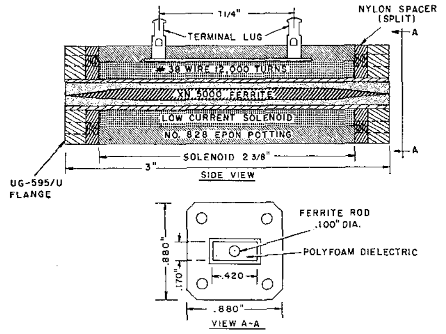

Fig. 1.

The low-current solenoid supplying the magnetic control field consists of 12,000 turns of No. 38 wire wound around the $\frac{1}{4}\times\frac{1}{2}$-inch rectangular waveguide section. The total length of the solenoid is $2\frac{3}{8}$ inches, and its normal operating currents are from 0 to 50 ma, corresponding to a magnetic field strength from 0 to 120 oersteds. A control power of approximately 1 watt was required to obtain a field strength of 60 oersteds. An Epon resin is used to pot the modulator winding.

The phase-shifting characteristics at 23,640 Mc as a function of the applied magnetic field and diameter of the Ni-Zn ferrite rods are shown in Fig. 2. These rods were all 3.00 inches long, including the 9/16 inch impedance matching tapers at both ends, and were taken from the same piece of ferrite material. As seen in the figure, only small phase changes are obtained for rod diameters less than 0.080 inch. When the rod diameter is increased above this value, large phase changes are seen to occur, particularly for fields less than 50 oersteds. It is also seen that the phase shift does not increase linearly with an increase in the rod diameter. This is due to the increased effectiveness of the high dielectric constant ($\epsilon \approx 14$) of the ferrite in concentrating the microwave energy as the rod diameter is increased.[4] For rod diameters greater than 0.100 inch, little increase in phase shift is obtained and large amplitude modulations begin to occur. The phase-shift characteristics of a 0.090-inch MgMn ferrite rod ($4\pi M_s = 1760$ gauss) is also shown in the figure (dashed curve) for comparison. The zero-field insertion loss for each of the three rods indicated in the figure was less than 0.5 db, and less than 0.2-db amplitude modulation was observed at the output. The figure of merit for the phase modulator using a 0.100-inch-diameter NiZn ferrite rod was greater than 3000.

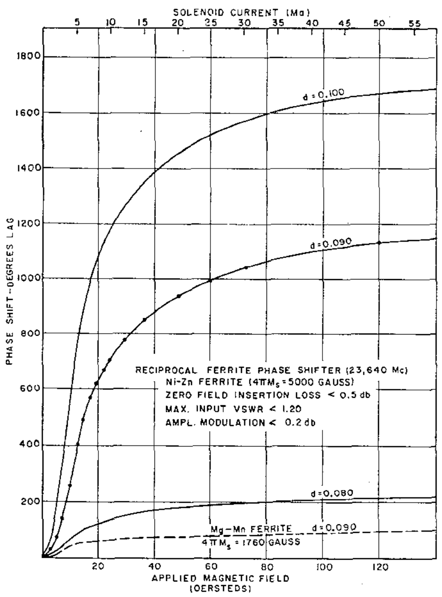

Fig. 2.

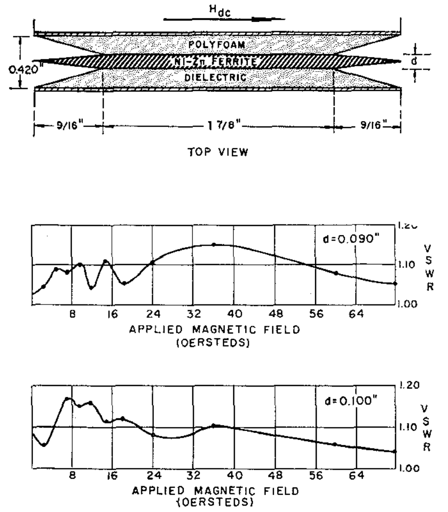

Fig. 3.

A simplified drawing of the rectangular waveguide phase modulator is shown in Fig. 3(a). Linear tapers were used at both ends of the ferrite rod and polyfoam dielectric support for impedance matching. The input VSWR of this phase modulator at 23,640 Mc, using a 0.090-inch- and 0.100-inch-diameter ferrite rod as a function of the applied magnetic field, is shown in Fig. 3(b) and 3(c).

The peak power handling capability and average power rating of the phase modulator are estimated to be approximately 5 kw and 25 w respectively. The maximum average power rating, which depends upon the RF losses in the ferrite, can be increased as better microwave ferrites become available.

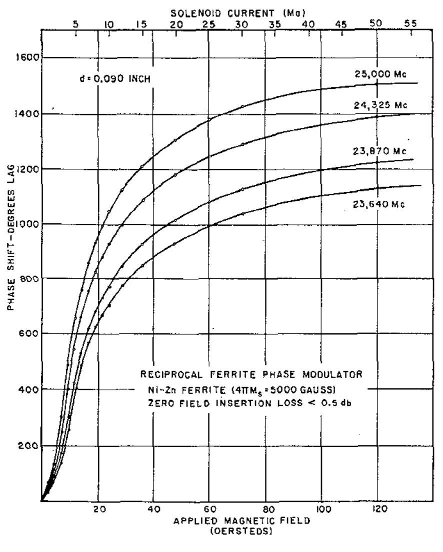

Fig. 4.

The bandwidth characteristics of the reciprocal phase modulator using a 0.090-inch-diameter rod [Fig. 3(a)], are shown in Fig. 4. Phase shifts vs applied magnetic field are given for several frequencies over a bandwidth of greater than 1300 Mc. As seen in the figure, the phase shift obtained increases appreciably with frequency. Above 25,000 Mc, higher-order modes[4] begin to occur, which cause large amplitude variations. The zero-field insertion loss for this rod was approximately 0.4 db, and the variation in transmitted power as a function of applied field was less than 0.3 db. An input VSWR over the bandwidth shown was no greater than 1.2.

A photograph of the reciprocal-phase modulator used for the measurements is shown in Fig. 5. The tapered ferrite rod (0.100-inch-diameter) and polyfoam dielectric insert are shown in the foreground. Standard UG-595/U K-band flanges were used at both ends of the phase modulator. The phase modulator and the ferrite rod were 3 inches long, and the total weight was 5 ounces.

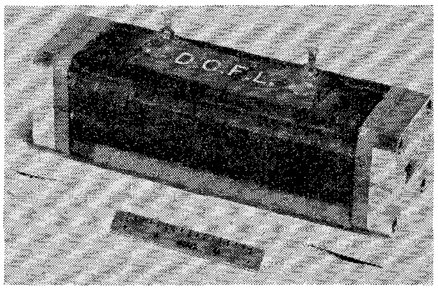

Fig. 5.

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