Four-Port Crossed-Waveguide Junction Circulators*

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Summary—A detailed account is given of the experimental investigation which has led to the design of 4-port circulators at frequencies from 2.5 to 25 Gc. The complex behaviour of these devices is clarified by establishing the modes of circulation in any particular waveguide passband. The modes are defined in terms of the static magnetic field (H) required, the microwave frequency (f) and the direction of circulation. The shape of the mode characteristic depends upon the ferrite/brass configuration in the center of the junction and the mode charts are given for two possible ferrite arrangements. The fixed-field bandwidths of the two configurations are, respectively, 2–4 per cent and 4–8 per cent. The performances are: isolation (ports 1–4) >20 db, cross-coupling (ports 1–3) >20 db, VSWR <1.2 and insertion loss (ports 1–2), respectively, <0.5 db and <1.0 db for the two configurations. The tunable bandwidth depends upon the mode of circulation and varied from 5 to 15 per cent. The positions of the modes in the waveguide pass-band can be adjusted by changing the diameter of the center ferrite/brass post. This shifting of the center frequency is described in detail for both ferrite arrangements and, for particular modes of circulation, figures are given of the frequency shift per 0.001″ change in ferrite and brass diameter.

I. Introduction

IN 1957, ALLIN AND SMITH[1] proposed that circulator action could be obtained with a symmetrical 4-port H-plane waveguide junction containing a central composite post of polarized ferrite and a conducting material, *e.g.*, brass. In 1958, Chait and Curry[2] demonstrated that circulator action was possible in a symmetrical ferrite-loaded 3-port H-plane junction. Since these proposals, much work has been carried out on 3-port circulators but comparatively little on the 4-port device. If their bandwidth can be improved, these latter devices will have the advantage of greater compactness in applications where at present two 3-port devices are required. However, a symmetrical 3-port circulator requires the correct adjustment of only two independent parameters for circulation at one particular frequency, whereas a 4-port component requires three.[3] This additional parameter increases the problems of broadbanding and considerably complicates the behavior of the device.

If a symmetrical 4-port circulator has the ports numbered cyclicly 1-2-3-4 in the direction of power flow, the following terms are used to express its performance:

isolation (db)	ports 1-4
cross-coupling (db)	ports 1-3
insertion loss (db)	ports 1-2
VSWR	ports 1-1.

It is clear that the insertion loss consists not only of dissipation within the ferrite material but also of power scattered to ports 3, 4 and back into 1. A symmetrical, loss-less, nonreciporcal 3-port junction can be made a circulator by matching the three ports and, therefore, the bandwidth is limited only by the bandwidth of the reflection coefficient. But, in a near-perfect 4-port device, the isolation is (to a 1st order) independent of the reflection coefficient. The signals scattered to port 1 and port 3 are equal and interdependent. By reducing the reflection coefficient to zero the cross-coupling is also reduced to zero and this power instead of being lost is circulated to port 2. By matching in this way, the insertion loss can be reduced by twice the reflective loss of the unmatched junction. However, the isolation remains unaffected and is dependent only on the properties of the central ferrite/brass geometry. Therefore, a broadband 4-port junction circulator is possible only if a central configuration can be found which gives a broadband isolation characteristic and which can then be matched. This point is effectively demonstrated in the performance curves of a 3 Gc circulator shown in Fig. 1. The insertion loss, VSWR and cross-coupling curves are interdependent and broadband but the useful bandwidth of the device is limited by the narrow bandwidth of the isolation curve.

Two arrangements of ferrite and brass have been investigated and these are shown in Fig. 2. When a static magnetic field is applied perpendicular to the broad waveguide wall, the junction becomes asymmetrical and circulator action occurs. Although no simple physical explanation of this behavior exists, it may be regarded as asymmetrical scattering from an anisotropic dielectric rod. It cannot be regarded as a problem of nonreciprocal phase-shift giving signal cancellation at the unwanted ports. This approach can be used to describe the action of the 3-port circulator but it cannot be extended to the 4-port device; yet, the 4-port and 3-port circulators are manifestations of the same principle.

The behavior of 4-port junction circulators is complex but it can be clarified by establishing the various modes of circulation. Each mode is defined in terms of the diameters of the ferrite (d_f) and brass (d_b), the

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[1] P. E. V. Allin and F. W. Smith, "Waveguide Circulators," British patent specification No. 852, 751; application date December 2, 1957.

[2] H. N. Chait and T. R. Curry, "Y circulator," *J. Appl. Phys.*, supplement to vol. 30, pp. 1525–1535; April 1959.

[3] B. A. Auld, "The synthesis of symmetrical waveguide circulators," IRE Trans. on Microwave Theory and Techniques, vol. 7, pp. 238–246; April, 1959. See p. 245.

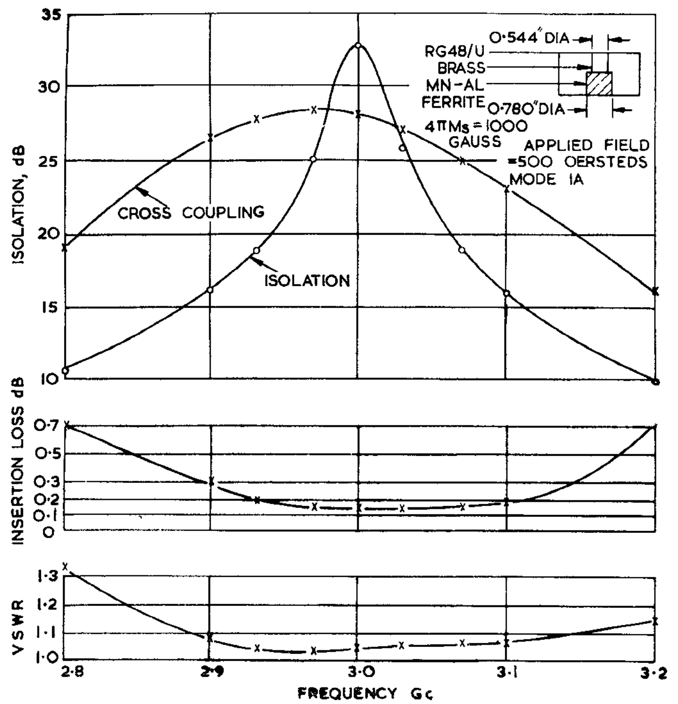


Fig. 1—The performance of a 4-port circulator for operation at 3.0 Gc.

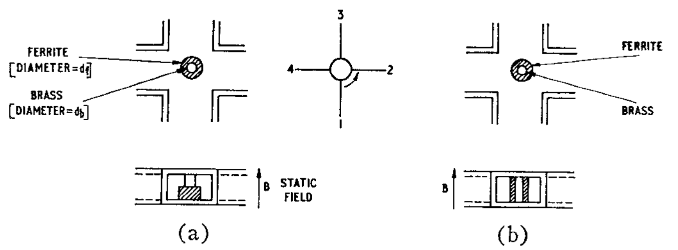


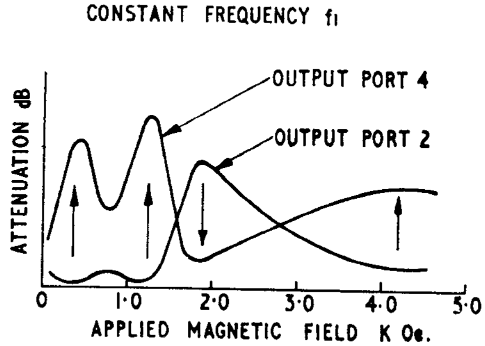
Fig. 2—4-port H-plane waveguide junction circulator. (a) Half-height configuration. (b) Full-height configuration.

applied static magnetic field (H), the microwave frequency (f) and the direction of circulation.

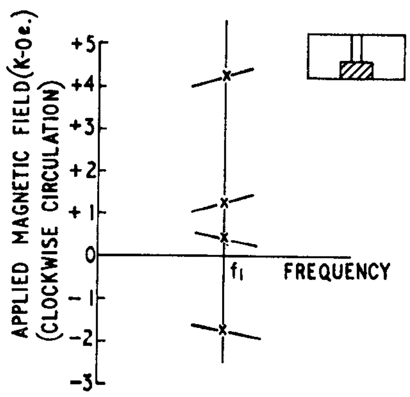
II. The Half-Height Configuration

A. The Modes of Circulation

This configuration is shown in Fig. 2(a) and consists of a central polarized ferrite post, which is half the waveguide height, on top of which is a cylindrical brass post. These cylinders make firm flat contact with each other and with the waveguide walls. To obtain circulation at a specified frequency, the three independent variables chosen were the ferrite diameter, brass diameter and the magnetic field. To distinguish the modes of circulation the microwave frequency (f) was increased in discrete steps and at each frequency the outputs from ports 2 and 4 were monitored as the applied magnetic field (H) was swept from zero to approximately 3000 oersteds. A typical sketch of the output at f_1 from ports 2 and 4 is shown in Fig. 3(a) in which two features are apparent: that not all modes are equally useful and that at a single frequency circulation may be obtained in either direction by adjusting the value of the applied



(a)



(b)

Fig. 3—(a) The output from ports 2 and 4 as the magnetic field is varied. (b) Modes of circulation. The negative and positive magnetic field values, required for circulation in a constant direction, plotted against frequency.

field. This information may be presented in another way by plotting H against f, with the circulation in a reverse sense represented by a negative applied field. In this way, the indicated circulation is always in the same sense and the graph is self-consistent [Fig. 3(b)]. By repeating this plot each time as the frequency is increased in discrete steps, a mode chart (H vs f) may be built up as shown in Fig. 4. Thus, a picture is obtained of the regions of circulation which are possible in any waveguide pass-band, but without any indication of performance. Although the modes have been arbitrarily numbered, the distinction in direction has been made by giving all modes in one sense odd numbers and in the other sense even numbers. The best performance is usually obtained on the sloping parts of the mode 1 and 1A characteristics and the fixed field bandwidth is about 3 per cent. Only poor performance is obtained over the flat regions of the mode 1 characteristic where broadband operation might be expected. At a constant value of applied field ($\pm H$), circulation at two very different frequencies ($f_1 f_2$) can be obtained but in opposite directions. This should not be confused with the diplexing action reported by Brown and Clarke.[4]

[4] J. Brown and J. Clark, "A unique solid state diplexer." IRE Trans. on Microwave Theory and Techniques, (*Correspondence*), vol. 10, p. 298; July, 1962.

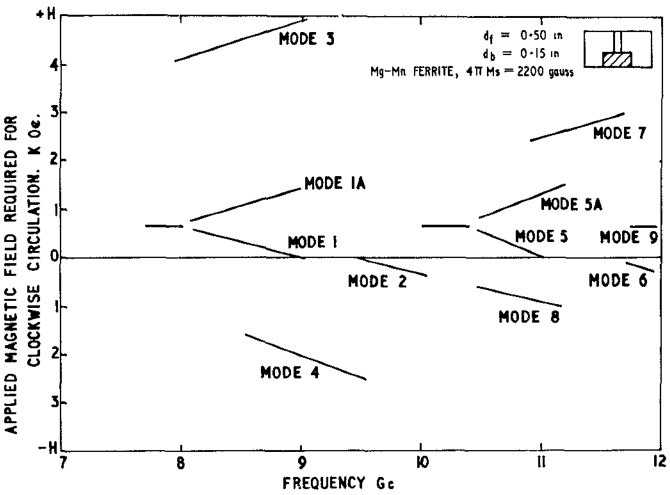


Fig. 4—The complete mode chart, 8–12 Gc and 0–4 kOe, for the "half-height" configuration.

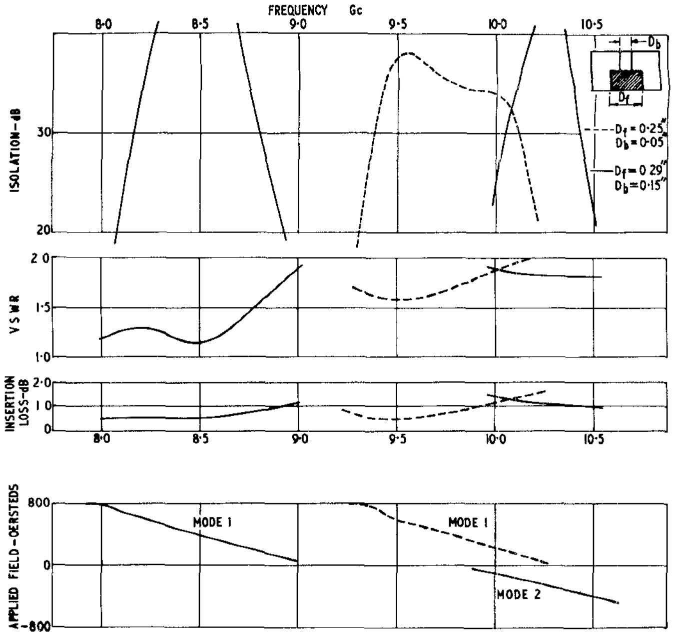


Fig. 5—A comparison of performance of two similar unmatched configurations. The need to distinguish the mode and direction of circulation is clear. Mn-Mg ferrite, $4\pi M_s = 2200$ gauss. To avoid confusion the performance of mode 1A is not shown.

They obtained opposite directions of circulation in a stripline circulator at two frequencies, because the circulator was below resonance at one frequency and above resonance at the other. However, from Fig. 4, it can be seen that with the "half-height" 4-port circulator opposite directions of circulation at two frequencies can occur with the magnetic field not only below resonance but also below saturation. Some circulation has been measured with only the remanent flux in a 0.25″ diameter post of manganese-magnesium ferrite with a 0.20″ diameter post of brass. The isolation was 12 db, insertion loss 4 db, cross-coupling 12 db, VSWR 2.5. Another interesting feature of the mode chart is the demonstration of higher-order modes of circulation, as shown by the repetition of modes 1–4 at the higher frequencies. The performance in these modes has not yet been investigated in detail.

TABLE I

FREQUENCY SHIFT PER 0.001″ CHANGE ON DIAMETER FOR HALF-HEIGHT CONFIGURATION

Frequency	W/g Size	Ferrite	Ferrite Δf	Brass Δf
(*Gc*)		4πMs(Gauss)	(Mc)	(Mc)
3.0	RG48/U	Mn−Al 1000	−2	−0.5
9.0	RG52/U	Mn−Mg 2200	−20	−5
22.0	RG53/U	Ni−Zn 5000	−160	−30

B. Circulator Design

The mode chart shown in Fig. 4 shows a large number of modes because the diameter of the ferrite post was large, 0.5″. In practice, many of these modes are eliminated and the behavior is simplified by using a smaller ferrite diameter. If the diameter of the ferrite or conducting post is changed, the operating frequency of the circulator is altered. Decreasing the diameter, increases the frequency; increasing the diameter, decreases the frequency. Thus, the mode chart may be shifted along the frequency axis. By reducing the diameter of the ferrite post in waveguide RG-52/U from 0.5″ to 0.30–0.25″, modes 1–4 are shifted up to the center of the waveguide pass-band and modes 5–8 are eliminated. If now the performances of ferrites of 0.25″ diameter and 0.29″ diameter are compared in Fig. 5, we see not only a simplification in the mode pattern (see Fig. 4) but also a possible source of confusion. The 0.29″ ferrite operates in mode 2 over a similar frequency band to the 0.25″ ferrite operating in modes 1 and 1A. That is to say, these two similar configurations have similar performances over a common frequency band but in opposite directions. Therefore, the two performances can only be compared properly when accompanied by a knowledge of the mode structure. The approximate figures of frequency shift per 0.001″ change in ferrite and brass diameter when operating in mode 1 are given in Table I. They were obtained by plotting the mode 1 characteristic for various ferrite diameters with a constant brass diameter and by plotting the characteristics for various brass diameters with a constant ferrite diameter. Then, at a level of constant applied field where the circulation was optimum, a line was drawn across each set of characteristics intersecting each mode at a different frequency. The graph of these frequencies vs their associated ferrite or brass diameters was in general a straight line, the slope of which gave the frequency shift per 0.001″ change in diameter.

By adjusting the composite post to obtain the desired center frequency in mode 1 or 1A, 4-port circulators with the half-height configuration have been completed in the frequency ranges of around 3, 9 and 22 Gc. The performance at 3 Gc is shown in Fig. 1. In realizing a practical device, it may be possible to shift the desired mode to the required frequency by adjusting only the ferrite or the brass diameter, but in general it is necessary to adjust both in order to optimize both the isolation and the VSWR. Also, it may not be sufficient to consider only the shift of the modes along the frequency axis. It is important to consider the position of the optimum operating frequency within each mode. The position of the best performance on the characteristics may change as the modes are shifted along the frequency axis. Although a characteristic may be shifted up in frequency by decreasing the diameter of the composite post, the optimum position on the characteristic may be moved down by a larger amount. Thus, decreasing the diameter may lower the optimum frequency instead of increasing it.

A circulator using polycrystalline yttrium iron garnet has been operated successfully in liquid nitrogen. The insertion loss at 77°K was not significantly different to that at 293°K, provided that the applied magnetic field was readjusted. The magnitude of the insertion loss depended upon the mode of operation. Modes 1 and 2 appeared to be promising with losses of less than 0.40 db, *i.e.*, a noise contribution of less than 10°K at 77°K over tunable bandwidths of 10 per cent.

III. The Full-Height Configuration

With this configuration, shown in Fig. 2(b), the brass post is the full height of the waveguide and is surrounded by a closely fitting ferrite tube of the same height. The static magnetic field is again applied perpendicular to the broad walls. Since it can now be assumed that the microwave fields do not vary in this direction, this type of 4-port circulator is more amenable to theoretical solution. The structure has other advantages over the half-height configuration: the brass may be used for pinning the ferrite and it may be hollow to pass a coolant. It would also be less prone to high peak-power breakdown, particularly if the top and bottom and inner surfaces of the ferrite tube are plated integrally with the waveguide junction.

To obtain circulation at any specified frequency, the three variables were again the ferrite, brass diameter and the applied magnetic field. Using the technique described earlier for the half-height configuration, the mode chart shown in Fig. 6(a) was established for a circulation in RG-52/U *X*-Band. As before, all modes in one sense have even numbers and in the other sense, odd numbers. Keeping the brass diameter constant, 0.10″, and increasing the ferrite diameter from 0.3″ to 0.40″, modes 5 and 3 are shifted to lower frequencies until they are eliminated as shown in Fig. 6(b) and (c). With a ferrite diameter of 0.45″, mode 4 is introduced at the higher frequencies, as shown in Fig. 6(d). Good

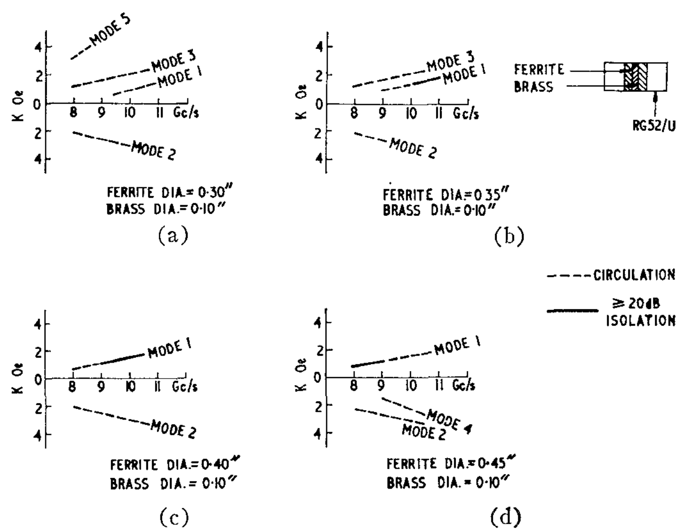


Fig. 6—The mode charts for "full-height" configurations. Mn-Mg ferrite, $4\pi M_s = 2200$ gauss. Heavy lines indicate isolation >20 db. Brass diameter, $d_b = 0.10$.″ Ferrite diameter (d_f) in (a) 0.30″, (b) 0.35″, (c) 0.40″ (d) 0.45″.

circulation can be obtained in mode 1 (VSWR∼1.7) with ferrite diameters 0.3–0.4″ or in mode 3 (VSWR ∼1.9) with ferrite diameters near 0.2″. Mode 1 has the advantage that smaller applied field values are required. The regions of circulation in each mode move from higher to lower frequencies as the ferrite diameter is increased. If the brass diameter is increased with the ferrite diameter held constant, the effect is equal and opposite. The operating frequency increases. That is to say, it is the thickness not the diameter of ferrite which governs the circulating frequency. With manganese-magnesium ferrite, a 0.32″ diameter ferrite with 0.050″ diameter brass post has a performance similar to a 0.38″ diameter ferrite with a 0.100″ brass post. The operating frequency shifts −20 Mc per 0.001″ change in diameter. It is surprising that a specific increase (or decrease) in the ferrite thickness produces approximately the same frequency shift whether it occurs on the inside or outside radius. With ferrite posts larger than about 0.50″ outer diameter, the mode chart becomes complex; up to eight modes have been identified but circulation in mode 1 has remained appreciably better than in any other mode. In general, the larger the brass diameter, the larger the reflection coefficient. The usefulness of decreasing the brass diameter to lower the optimum frequency appears to reach a limit with a diameter of approximately 0.030″. Reducing the brass diameter further does very little to shift the center frequency, but if it is removed completely the performance deteriorates abruptly.

The performance of an unmatched "full-height" 4-port circulator is shown in Fig. 7. The broader band isolation provides isolation >20 db over the frequency range 9.3–10.0 Gc. The ferrite material is nickel-manganese ferrite, $4\pi M_s = 2800$ gauss. If the VSWR is re-

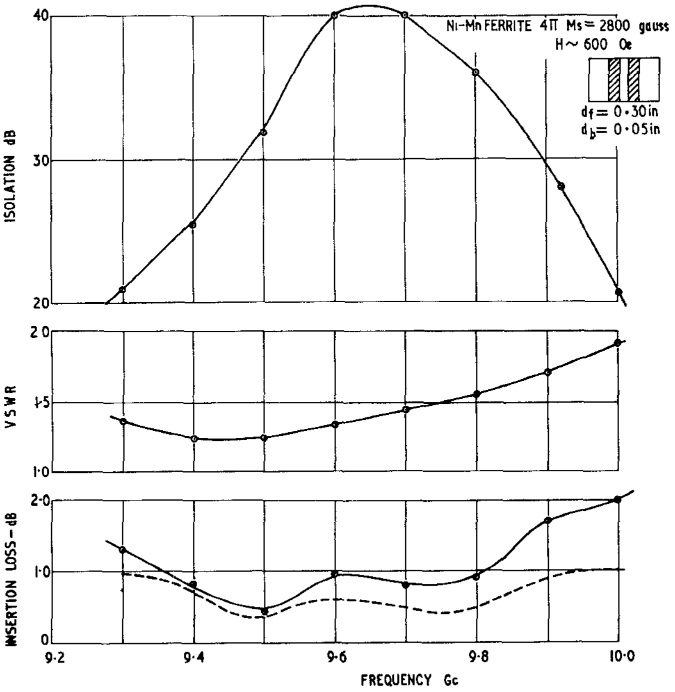


Fig. 7—The performance of an unmatched 4-port circulator. The isolation curve shows an 8 per cent bandwidth. The realizable insertion loss after matching is shown by the broken line.

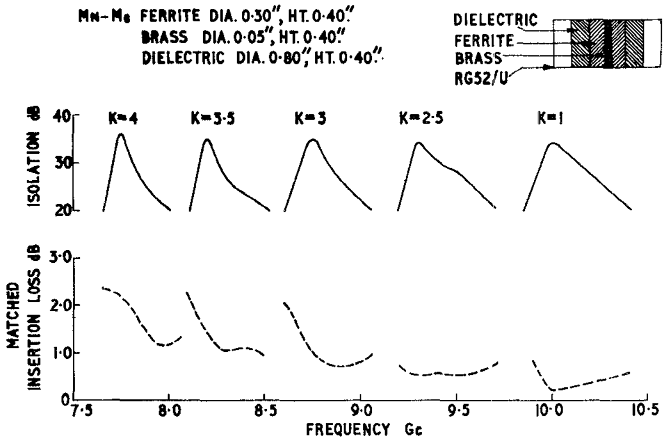


Fig. 8—The effect of loading the circulator with coaxial dielectric cylinders.

duced by external matching elements until it makes a negligible contribution to the insertion loss as described in the introduction, the realizable insertion loss with this material will be approximately as shown by the dotted curve. It should be emphasized that this theory applies only to a near-perfect circulator. It has been found in practice that, when a 4-port circulator with a VSWR$\geq$1.5 is matched, the improvement in insertion loss is rather better than that predicted by this theory.

Since the correct adjustment of three variables is required in a symmetrical 4-port junction for circulation at a particular frequency, at least one more variable must be introduced for operation over a broader band. The parameters which have been introduced in turn are the height of the ferrite and an additional coaxial tube of dielectric around the ferrite. Reducing the height of the ferrite shifted the mode curves to higher levels of magnetic field, due to the increased demagnetizing factor. The addition of dielectric (up to $K=4$) around the ferrite lowers the frequency of circulation as shown in Fig. 8, but the effect upon the bandwidth is not yet clear, since the brass, ferrite and dielectric diameters should be optimized with each configuration.

IV. Conclusions

The circulator action of a symmetrical ferrite-loaded 4-port H-plane waveguide junction has been demonstrated. The complex behavior of these devices has been clarified by establishing the modes of circulation within a waveguide pass-band. These modes depend entirely on the particular configuration of ferrite and conducting material at the center of the junction and a technique by which these modes may be distinguished has been described in detail. Two composite ferrite-brass posts have been investigated and their mode charts have been established. Design data have been compiled which enable these circulators to be operated in their optimum modes at frequencies about 9 Gc with the "full-height" configuration and at frequencies about 3, 9 and 22 Gc with the "half-height" configuration.

It has been established that the bandwidth of a 4-port junction circulator depends upon the bandwidth of the isolation curve. The isolation is substantially independent of the reflection coefficient; thus the bandwidth is entirely governed by the properties of the central composite ferrite post. The broadest bandwidth obtained with the two 4-port configurations described above is 8 per cent. If this can be improved, these devices offer the advantage of compactness where otherwise two 3-port circulators would be required.

V. Acknowledgment

The authors would like to thank J. Sapp who made many of the waveguide junctions and C. V. George who ground the ferrite material.