Complex Gyrator Circuit of an Evanescent-Mode *E*-Plane Junction Circulator Using *H*-Plane Turnstile Resonators

JOSEPH HELSZAJN, MEMBER, IEEE

Abstract —The *E*-plane circulator is of considerable practical interest but its development has lagged somewhat compared to that of the more common *H*-plane device. The purpose of this paper is to experimentally investigate the eigenvalue problem and the complex gyrator circuit of an *E*-plane evanescent-mode junction loaded with one or two *H*-plane turnstile ferrite resonators symmetrically coupled by three standard rectangular waveguides. The condition for which the eigenvalues of the demagnetized junction are in antiphase has been met with the physical variables at hand, but the more important one for which they are also commensurate has not. A transformer coupled device using quarter-wave-long impedance sections at each port is also described. Its frequency coincides with the even solution of two coupled resonators.

I. Introduction

An important class of 3-port waveguide circulators is that comprising an *E*-plane junction employing one or two ferrite resonators. A number of these devices have by now been experimentally described but the literature contains little formal guidance for the design of this class of junctions. The purpose of this paper is to examine in some detail the eigenvalue problem and gyrator circuit of an evanescent-mode *E*-plane junction loaded by one or two *H*-plane turnstile resonators which has some if not all of the features of those described in [5], [7], and [8]. Such an understanding is a prerequisite for design. Some additional references are given in [1]–[4], [6], [9], and [10]. Fig. 1(a) depicts the physical details of the symmetrical *E*-plane junction considered here. The radial wavenumber of each *H*-plane turnstile ferrite resonator was, in this work, chosen in keeping with some prior art in [7] and [8] to coincide with that of the junction formed by the three WR90 waveguides employed to construct the device. It is of note, however, that the radial wavenumber of the resonator in [5] does not coincide with that of the junction. The optimum choice awaits further work. The physical variables available for the design of the device are therefore the length of each resonator, their spacing, and the magnetic variables. The dimensions of the resonator mounts ensured that the junction was cut off when the resonators were removed. The use of some other shape (triangular or semispherical) for the resonator is another possibility. Fig. 1(b) illustrates the asymmetrical geometry. Latched prototypes come readily to mind.

The adjustment of any circulator requires the perturbation of two counterrotating and one in-phase eigennetwork. The solution investigated in this work experimentally displays, in every instance, a passband in the demagnetized state. Devices with stopbands have, however, been described in [10], [11], and [34]. The degenerate counterrotating eigenvalues are in the present geometry determined by that of a quarter-wave-long open circular ferrite or dielectric waveguide propagating the HE_{11} mode with one flat face short-circuited and the other flat face loaded by a magnetic wall. This situation differs from that of the more familiar *H*-plane configuration in that its open flat face is loaded by an electric wall [22]. The frequency of the former arrangement increases as the spacing between the two resonators is reduced; in the latter case it decreases. The corresponding eigennetworks experimentally display magnetic walls at the terminals of the junction. If the junction is propagating for the in-phase eigenvector, symmetry indicates that the corresponding eigennetwork has an electric wall boundary condition at its symmetry axis [34]. The dimensions of the junction can then be adjusted so that this eigennetwork has a magnetic wall boundary condition at its input terminals. In the arrangement considered here, however, measurements indicate that it is evanescent for this excitation and that the in-phase eigennetwork has an approximate electric wall boundary condition at the terminals of the junction which is independent of the physical variables employed in this work. This condition is of course not met in the classic *H*-plane device. Symmetry would otherwise dictate, contrary to the experimental data, that the demagnetized junction would have a bandstop instead of a bandpass response. The value of the susceptance slope parameter of the twin turnstile junction, once the first circulation condition is met, is consistent with the synthesis of quarter-wave coupled devices. Furthermore, that associated with the latter structure is half that of the single turnstile one, again in keeping with the situation encountered in the description of the *H*-plane structure [28]. It may therefore be employed to realize network specifications akin to those achievable with the latter configuration, a fact already demonstrated by Omori [5].

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The author is with the Department of Electrical and Electronic Engineering, Heriot-Watt University, Edinburgh, EH1 2HT Scotland.
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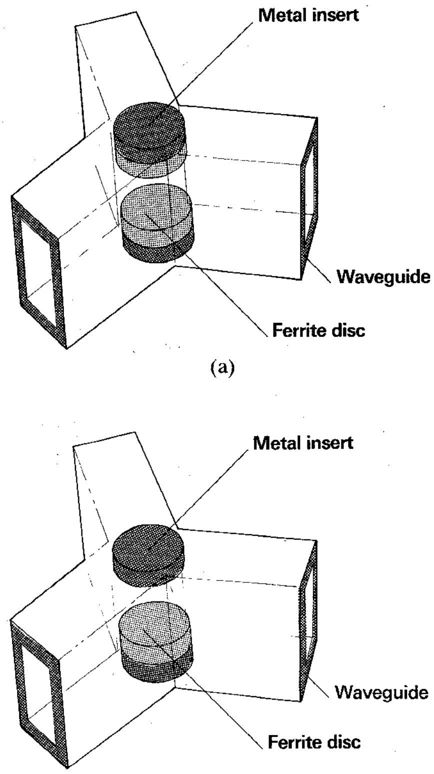

(b)

Fig. 1. (a) Schematic diagram of E-plane junction using coupled quasi-H-plane turnstile resonators. (b) Schematic diagram of E-plane junction using single quasi-H-plane turnstile resonator.

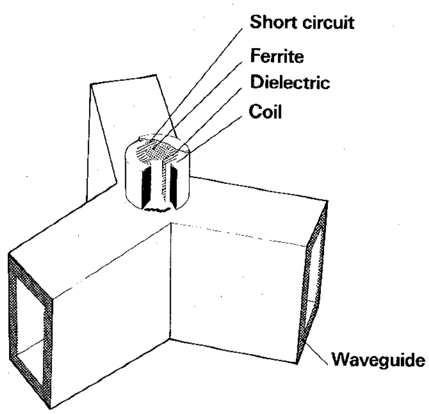

Fig. 2. Schematic diagram of 3-port E-plane junction using single-turnstile resonator.

Some appreciation of the operation of the symmetrical E-plane junction employing H-plane turnstile resonators may be gained by recognizing that it is essentially a 7-port circuit comprising three rectangular waveguide ports and two orthogonal ports for each round turnstile waveguide. Since the output terminals of the round waveguides are short-circuited, its overall matrix description reduces in the usual way to a symmetrical 3-port network. By the same token, the conventional H-plane waveguide circulator is a 7-port junction comprising an H-plane junction and E-plane turnstile resonators [11]–[13]. The asymmetric E-plane circulator is a 5-port circuit. In the E-plane device, with the direction of propagation taken along the z axis, H_z rather than H_x is perpendicular to the symmetry axis of the device. The magnetic fields corresponding to the counterrotating eigenvectors are therefore circularly polarized at the side instead of the top and bottom walls of the waveguide. Fig. 2 illustrates one possible turnstile arrangement.

A possible broad-band network for the complex gyrator circuit of this type of device is a conventional quarter-wave coupled device. While the nature of the complex gyrator circuit rather than the matching problem is the issue of this paper, the realization of the latter problem provides a further confirmation of the topology of the former one.

II. Eigennetworks of E-plane Junction Circulator

An understanding of the nature of the in-phase and counterrotating eigenvalue problems is a prerequisite to the adjustment of any junction circulator. If the reflection eigenvalues of the in-phase and degenerate counterrotating eigennetworks are in phase, then the demagnetized junction behaves as a bandstop filter. If the in-phase eigenvalue is out of phase with the degenerate counterrotating ones, it has a bandpass response, which is the usual situation encountered in the design of H-plane devices using either planar or turnstile resonators. The in-phase and for that matter the counterrotating eigennetworks may have either electric or magnetic walls at the symmetry axis of the junction. There are therefore altogether four possible ideal eigenvalue diagrams of degree 1, each of which is associated with a unique complex gyrator circuit. Fig. 3 depicts the different possibilities. The mode nomenclature of these different solutions has been discussed in [34]. The experimental transition from a bandstop circuit to a bandpass one mentioned in [5] may be catered for by either rotating the in-phase or counterrotating eigenvalues by 180 degrees on the eigenvalue diagram. The situation for which the eigennetworks are commensurate is the so-called first calculation condition; the second condition is met by magnetizing the junction with a suitable direct magnetic field, as is well understood.

The device experimentally investigated in this paper has a bandpass response in its demagnetized state. Scrutiny of the eigenvalue diagrams in Fig. 3 indicates that this condition is satisfied if its in-phase and counterrotating eigennetworks form either an $e,2m$ or an $m,2e$ eigenvalue diagram. Whether one or the other case prevails requires a theoretical or experimental appreciation of the eigenvalue problem. The former has not at this time been fully grasped; it is therefore deduced experimentally. Of course, whether an eigenvalue exhibits an electric or a magnetic wall depends on the choice of the reference terminals. The ones adopted in this work coincide with those defined by the three WR90 waveguides used to form the junction. There is, however, no assurance that these in fact correspond to the electrical or characteristic planes of this class of structure. The experimental in-phase and degenerate

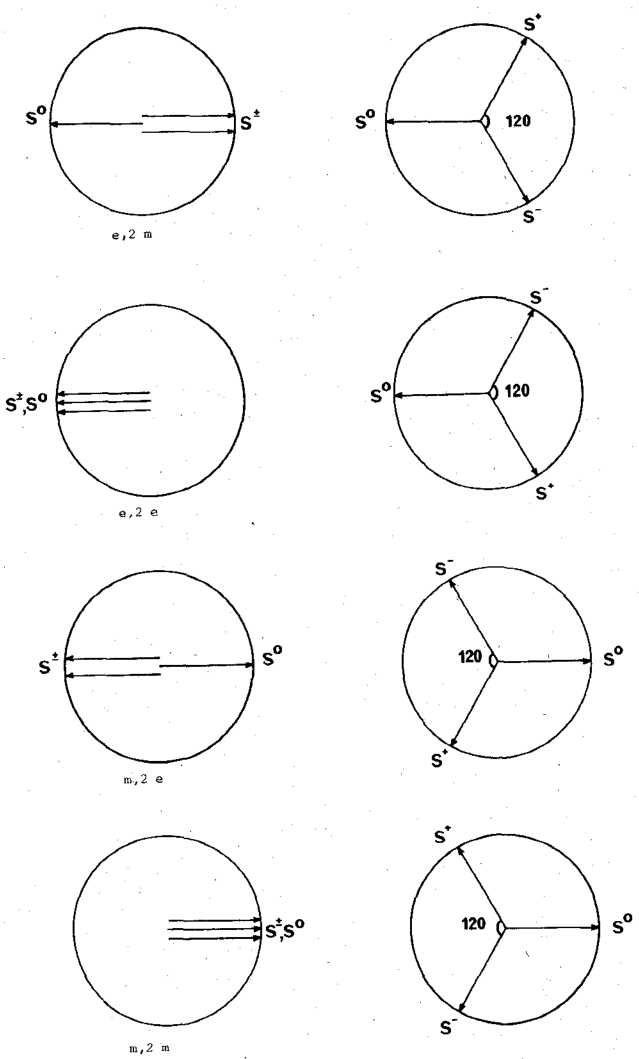

Fig. 3. Eigenvalue diagrams of 3-port symmetrical junction circulator.

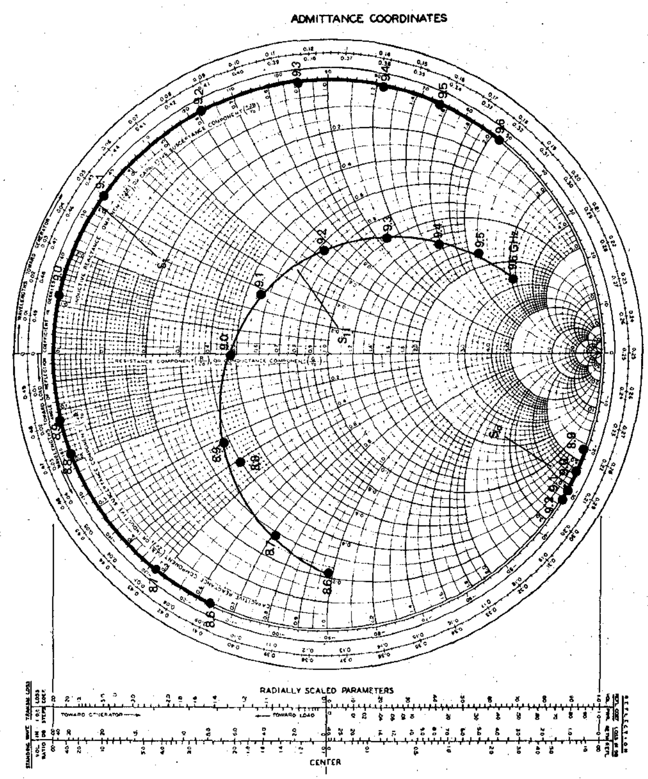

Fig. 4. Smith chart (admittance coordinates) of in-phase and degenerate counterrotating eigenvalues and demagnetized frequency response of E-plane junction using coupled H-plane $HE_{11\frac{1}{2}}$ turnstile resonators ($\epsilon_f = 15.0$, $R = 6.0$ mm, $R/L = 2.49$, $L/b_1 = 0.44$).

admittance eigenvalues, as well as the frequency response of the demagnetized junctions, are depicted in Fig. 4 for one situation. The configuration investigated may therefore with some adjustment of the in-phase eigenvalue be characterized by a degree 1 $e,2m$ R-STUB circuit [34], the topology in fact associated with the more common H-plane device using E-plane turnstile resonators. The experimental eigenvalue problem has been dealt with in [12] and [25]; it will not be repeated here. The type of measurement described here also provides a precise method of determining the operating frequencies and susceptance slope parameters of the eigennetworks of the demagnetized junction.

The nature of the eigenvalue problem may also be understood from a knowledge of the immittance of the complex gyrator circuit at different direct magnetic fields. If the junction has a passband when demagnetized and if the real part of its complex gyrator immittance is asymptotic to an electric wall as it is magnetized, then it displays an $e,2m$ eigenvalue diagram and a degree 1 $e,2m$ R-STUB gyrator circuit. If it is asymptotic to a magnetic wall, it coincides with an $m,2e$ eigenvalue diagram and an $m,2e$ R-STUB circuit [34]. Fig. 5 shows this result for the

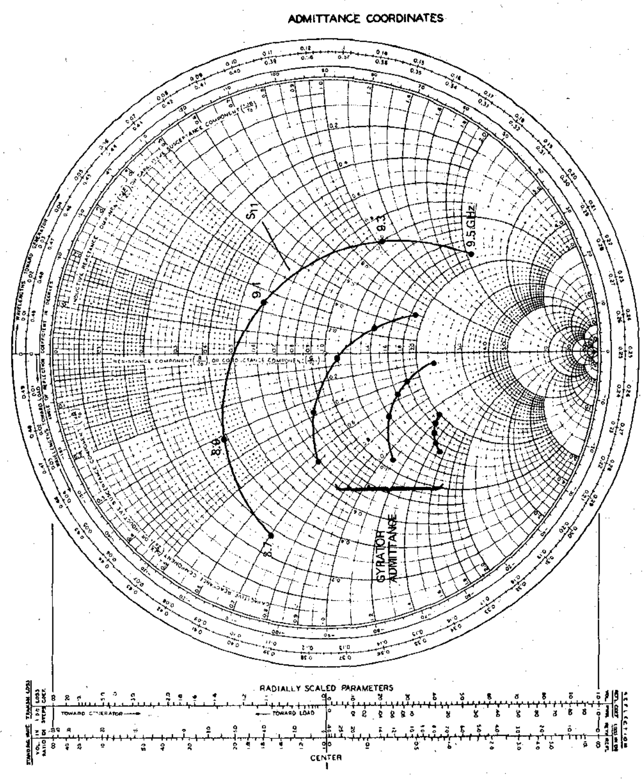

Fig. 5. Smith chart (admittance coordinates) of demagnetized and magnetized complex gyrator immittance of E-plane junction using coupled H-plane $HE_{11\frac{1}{2}}$ turnstile resonators ($\epsilon_f = 15.0$, $R = 6.0$ mm, $R/L = 2.49$, $L/b_1 = 0.44$).

eigenvalue solution in Fig. 4. These immittances do not move along constant-conductance circles on this diagram because the in-phase eigennetwork is in this instance somewhat overlength. This feature is further studied in the section on the in-phase eigenvalue. It may, however, be partly offset by employing an undersized quarter-wave transformer for matching purposes, a possibility already recognized in [5].

III. Mode Chart

The resonator employed to establish the counterrotating modes in the construction of the E-plane turnstile junction is an open ferrite resonator with one flat face open-circuited and the other short-circuited. Modes in cylindrical cavities with ideal magnetic walls are either TE or TM in type and are described by a three-digit notation as $\mathrm{TE}_{l,m,n}$ or $\mathrm{TM}_{l,m,n}$. Here, l is the number of full-period variations of E_r with respect to θ, m is the number of half-period variations of E_θ with respect to r, n is 1 for a half-wave-long resonator open-circuited at each end, and n is $1/2$ for a quarter-wave-long resonator open-circuited at one end and short-circuited at the other end. The resonator mode employed in the design of this class of device has not always been identified, but that utilized in [5], [7], and [8] and in this work is the limit $\mathrm{TM}_{11\frac{1}{2}}$ or, more strictly speaking, the hybrid $\mathrm{HE}_{11\frac{1}{2}}$ one with its open face loaded by a magnetic wall. The one employed in [9] is the $\mathrm{TM}_{21\frac{1}{2}}$. It is of note, however, that the radial wavenumbers in the former works are all significantly different. It differs, therefore, from that associated with an H-plane junction using E-plane turnstile resonators in that its open flat face is loaded by a magnetic instead of an electric wall. The characteristic equation for the frequency of the degenerate counterrotating modes of the E-plane junction using H-plane turnstile resonators therefore coincides with the even eigenvalue of two $\mathrm{HE}_{11\frac{1}{2}}$ resonators coupled by a section of round waveguide with a contiguous magnetic wall below cutoff; the frequency of the conventional H-plane junction using E-plane turnstile resonators corresponds to the odd eigenvalue of the same geometry. These two arrangements are illustrated in Figs. 6(a) and 6(b), respectively.

The characteristic equation of the odd-mode solution of two coupled resonators from which the length of each resonator (L) may be calculated from a knowledge of its radius (R), the spacing ($2S$) between the two, the propagation constants (α and β), and the constitutive parameters (ϵ_{eff} and ϵ_d) of the two regions is

$$\frac{\epsilon_{\mathrm{eff}}}{\beta}\cot(\beta L)-\frac{\epsilon_d}{\alpha}\tanh(\alpha S)=0 \tag{1}$$

where

$$\beta^2=k_0^2\epsilon_{\mathrm{eff}}-\left(\frac{1.84}{R}\right)^2 \tag{2}$$

$$\alpha^2=\left(\frac{1.84}{R}\right)^2-k_0^2\epsilon_d. \tag{3}$$

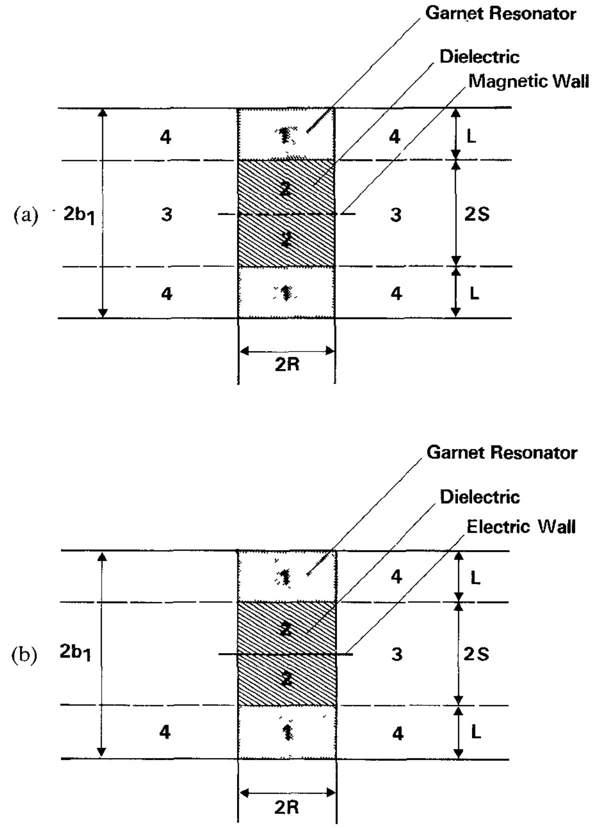

Fig. 6. (a) Even-mode geometry of coupled turnstile resonators (magnetic wall arrangement). (b) Odd-mode geometry of coupled turnstile resonators (electric wall arrangement).

The propagation constant β is determined by solving the characteristic equation for the HE_{11} mode of the open demagnetized ferrite or dielectric waveguide from a knowledge of ϵ_f and R [15], [16]. The parameter ϵ_{eff} is the effective dielectric constant of an equivalent round waveguide with an ideal magnetic wall; it is obtained from a knowledge of β and k_0R in (2). The solution adopted here satisfies the boundary conditions between regions 1 and 4 and 1 and 2 in Fig. 6(a) but neglects those between 3 and 4 and 2 and 3.

The characteristic equation for the even-mode solution of the two coupled resonators in Fig. 6(b) is of course well understood and is reproduced for completeness only [15], [19]–[22]:

$$\frac{\epsilon_{\mathrm{eff}}}{\beta}\cot(\beta L)-\frac{\epsilon_d}{\alpha}\coth(\alpha S)=0. \tag{4}$$

The even and odd theoretical solutions of two coupled resonators for three different values of R/L are summarized in Fig. 7. The upper branch in this illustration is the resonance solution of the E-plane junction using coupled H-plane turnstile resonators; the lower branch is that of the dual H-plane junction employing E-plane resonators. The experimental relationship of the upper branch may be accurately evaluated by the method in [25]. The overall dimension of the resonator ($2b_1$) is related to the dimensions L and S of the junction in the manner indicated in Fig. 6.

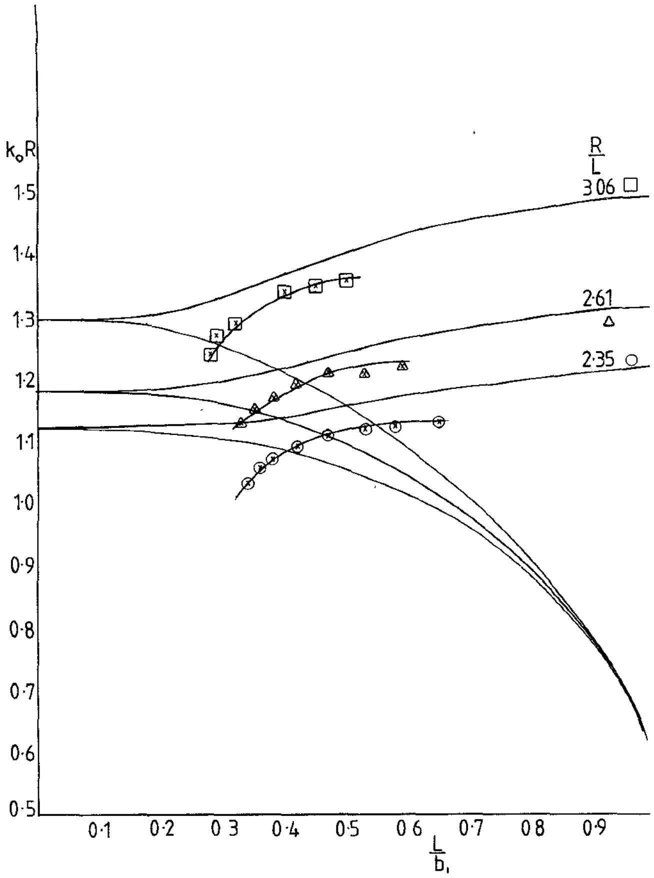

Fig. 7. Even- and odd-mode charts of coupled $HE_{11\frac{1}{2}}$ turnstile resonators ($\epsilon_f = 12.7$).

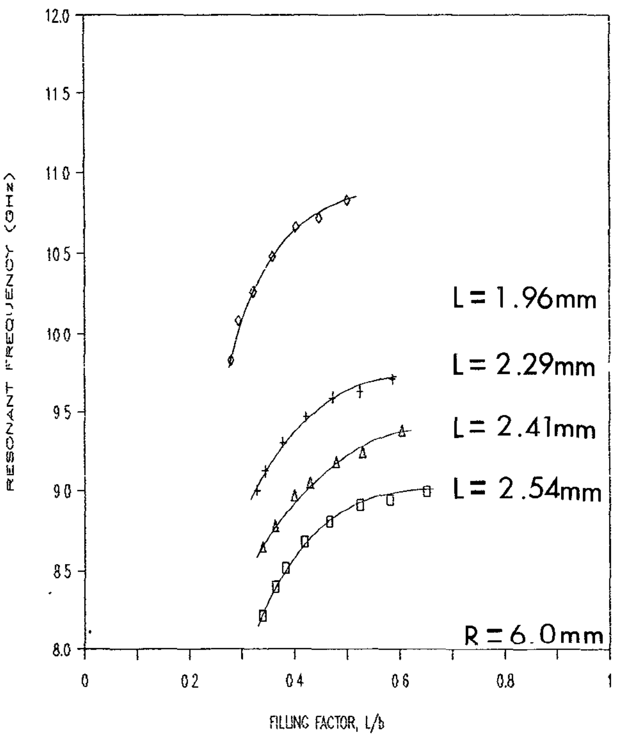

Fig. 8. Experimental mode chart for the design of 9-GHz E-plane junction using coupled H-plane $HE_{11\frac{1}{2}}$ turnstile resonators ($\epsilon_f = 15.0$, $R = 6.0$ mm, $R/L = 2.36$, 2.49, 2.62, and 3.06).

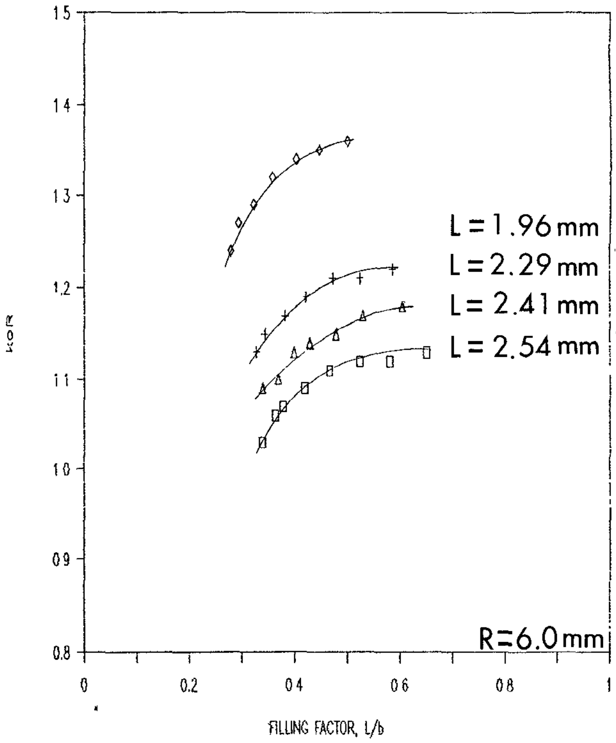

Fig. 9. Experimental normalized mode chart of E-plane junction using coupled H-plane $HE_{11\frac{1}{2}}$ turnstile resonators ($\epsilon_f = 15.0$, $R = 6.0$ mm, $R/L = 2.36$, 2.49, 2.62, and 3.06).

The operating frequency of any junction for which the frequency variation of the in-phase eigennetwork may be neglected compared to that of the degenerate counterrotating ones is usually not very different from that of the latter eigennetworks. It may be experimentally deduced by noting that at which the device displays either bandpass or bandstop characteristics. In the former case, the counterrotating eigenvalues are out of phase with the in-phase one; in the latter case, they are in phase with it. The situation in which the eigennetworks are commensurate is, although a more demanding requirement, always desirable in a well-designed device. The structure investigated here in fact exhibits a bandpass characteristic in its demagnetized state. A higher order bandpass response circulating in the opposite direction has also been noted in [7]; a bandstop solution has been described in [9] and [10].

Fig. 8 depicts the experimental mode chart of an E-plane circulator in WR90 for four different values of R/L; three possible solutions for the design of a 9.0-GHz device are noted. Fig. 9 indicates the same data in normalized form. The discrepancy between this latter relationship and the theoretical one illustrated in Fig. 7 is in part due to the fact that the former coincides with the frequency at which the in-phase and counterrotating eigennetworks are in antiphase rather than commensurate. The optimum circulation solution is that for which the in-phase and the degenerate counterrotating eigenvalues are commensurate, but this problem awaits a solution. A more precise knowledge of the frequency of the degenerate eigennetworks may be derived by constructing a family of solutions of the type indicated in Fig. 4.

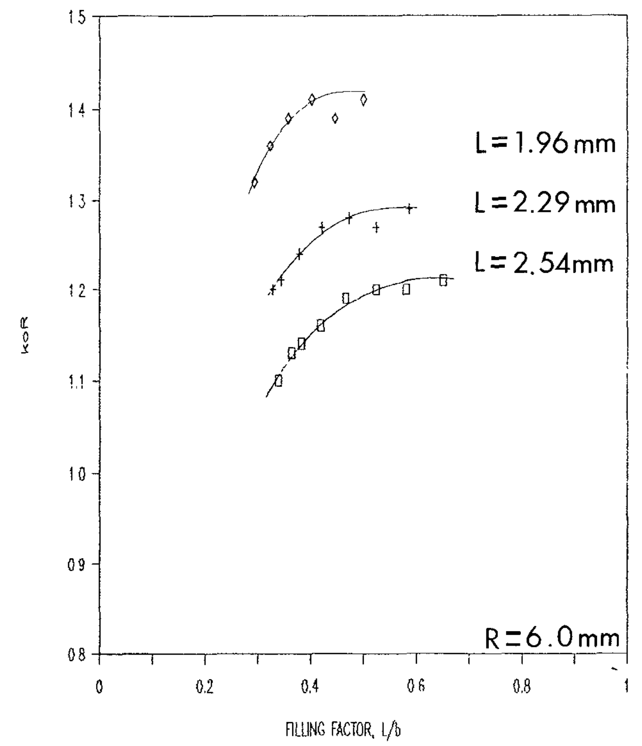

Fig. 10. Experimental mode chart of E-plane junction using single H-plane $HE_{11\frac{1}{2}}$ turnstile resonator ($\epsilon_f = 15.0$, $R = 6.0$ mm, $R/L =$ 2.36, 2.62, and 3.06).

The ferrite material utilized in this work was a garnet one with a saturation magnetization (M_0) to equal to 0.1600 T and a relative dielectric constant (ϵ_f) of 15.0. The relative dielectric constant (ϵ_d) of the region between the two resonators was unity. The radius of the resonator was arbitrarily made equal to that of the junction formed by the three WR90 waveguides ($R = 6$ mm).

Some additional measurements on the frequency of an E-plane junction using a single $HE_{11\frac{1}{2}}$ resonator are illustrated in Fig. 10. Its operating frequency is obviously again related to that of a single decoupled resonator supporting the $HE_{11\frac{1}{2}}$ mode. No correlation between theory and practice has, however, been attempted. The quantity b_1 has the same meaning here as in Fig. 6, i.e., $b_1 = (S + L)$.

Scrutiny of the mode chart of an idealized open garnet waveguide having a radial wavenumber ($k_0 R\sqrt{\epsilon_f}$) equal to that of the resonator (4.38), as is the case here, indicates that the phase constants of its TM_{11}, TE_{01}, and TM_{21} modes are equal to ω_0, $1.08\omega_0$ and $1.26\omega_0$, respectively. This means that the fractional bandwidth (δ) of such an idealized resonator operating in the $TM_{11\frac{1}{2}}$ mode is limited by the onset of the $TE_{01\frac{1}{2}}$ mode. The spacing between these frequencies may of course be widened by employing a resonator with a somewhat smaller radius than that defined by the junction. The choices employed in [5] and [8] are $k_0 R\sqrt{\epsilon_f} = 2.43$ and 4.16, respectively. In the former geometry, the terminals of the junction are ill defined and it is of note that the transformer section is reported to be substantially undersized. The optimum radius for use in this type of junction must be the subject of further work. The value used in the design of H-plane devices is typically between 2.73 and 3.48. Using a ferrite material instead of a garnet one is another possibility. In this instance, $k_0 R\sqrt{\epsilon_f} = 3.96$ and the phase constants of the TM_{11}, TE_{01}, and TM_{21} modes are equal to ω_0, $1.11\omega_0$, and $1.39\omega_0$, respectively.

IV. In-Phase Eigenvalue

The correct adjustment of the in-phase eigennetwork is in this as well as in other junctions desirable in order for it to display a suitable gyrator circuit for the synthesis of quarter-wave coupled devices. The effect of a nonideal in-phase eigenvalue has been noted in [24] and [25]; it may be incorporated in the gyrator circuit without too much difficulty [34]. The topology of this circuit (Fig. 11) is reproduced for completeness from the material in [34]; it involves the in-phase impedance eigenvalue (Z^0) and counterrotating split admittance eigenvalues ($Y^{\pm}$). Although it is possible to absorb the effect of a nonideal in-phase immittance in the matching network, this should be avoided if at all possible. It has, however, been found necessary to do so in this work. Scrutiny of the data in the Smith chart in Fig. 4 indicates that the in-phase eigennetwork approximately displays an electric wall at the terminals of the junction, more strictly speaking a short section of a short-circuited stub or series inductance. It also indicates that the frequency variation of the in-phase eigennetwork may be neglected compared to that of the degenerate ones. The parameters of the in-phase eigennetwork do not therefore appear in the complex gyrator circuit of this class of device provided it is commensurate with that of the degenerate counterrotating ones. Provisions for the adjustment of this eigenvalue may at first sight be made by noting that the physical variables of the degenerate counterrotating ones are not unique, as is readily appreciated by scrutinizing the mode charts in Figs. 7–10. This suggests that the spacing between the resonators may be employed to tune the in-phase eigennetwork and that the thickness of each resonator may be used to trim the degenerate counterrotating ones. Fig. 12 indicates the variation of the admittance associated with S_{11}, with frequency for three different combinations of R/L and L/b_1 for which $k_0 R\sqrt{\epsilon_f} = 4.38$ at 9.0 GHz. The frequency dispersion of each of these different solutions is in keeping with the values of the susceptance slope parameter noted in the next section, but the reference terminals of each appear to be independent of the details of the junction. One explanation for this situation, in keeping with the transition between the stopband and passband solutions noted by Omori, is that the junction is evanescent for the in-phase eigenvector over this field of variables. In the absence of the resonator mounts, on the other hand, it is propagating for this eigenvector, and its eigennetwork exhibits an electric wall at the symmetry axis or, equivalently, a magnetic wall at the reference terminals [34]. In the former case the junction has a bandpass characteristic; in the latter instance it has a stopband one.

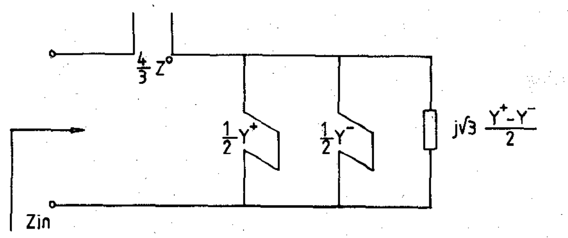

Fig. 11. Complex gyrator circuit of 3-port junction circulator in terms of immittance eigenvalues.

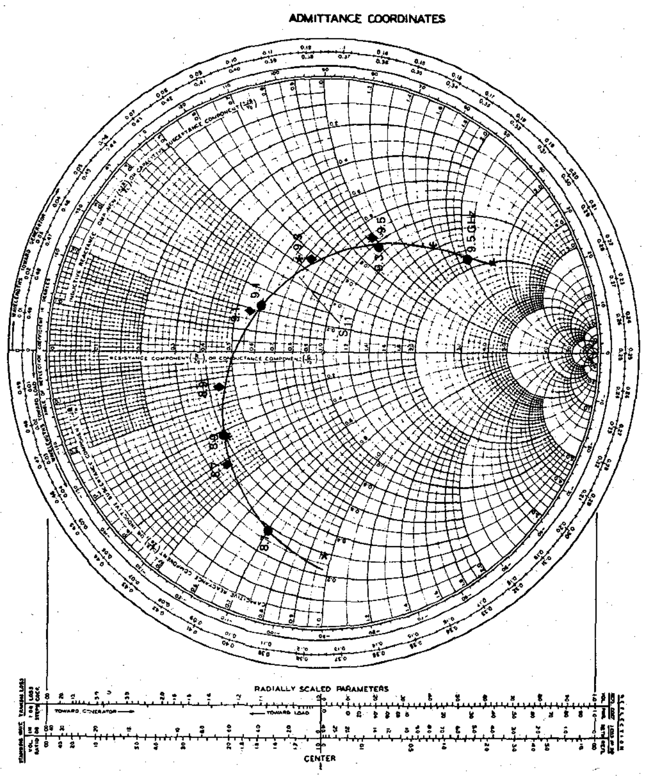

Fig. 12. Smith chart (admittance coordinates) of demagnetized junction for different values of R/L and L/b_1 ($R/L = 2.43$, $L/b_1 = 0.48$, $R/L = 2.49$, $L/b_1 = 0.44$, $R/L = 2.55$, $L/b_1 = 0.36$).

V. Complex Gyrator Circuit

The complex gyrator circuit of any junction is defined as that exhibited by the device at port 1 with port 3 decoupled from port 2 by terminating the latter port by a variable complex load. The relationships outlined in Figs. 4 and 5 indicate, as already noted, that it may in this instance be approximated by an $e,2m$ R-STUB network. The elements of this circuit are usually specified in terms of a normalized susceptance slope parameter (b'), a normalized gyrator conductance (g), and a loaded Q factor (Q_L). A knowledge of these parameters is a prerequisite for the network problem or for the description of directly coupled devices. Since the field of variables employed in this work does not provide a means of idealizing the in-phase eigennetwork, the discussion is restricted to the latter situation. If the frequency variation of the in-phase eigennetwork may be neglected compared to that of the degenerate counterrotating one, these parameters are related in a simple way in terms of the split frequencies of

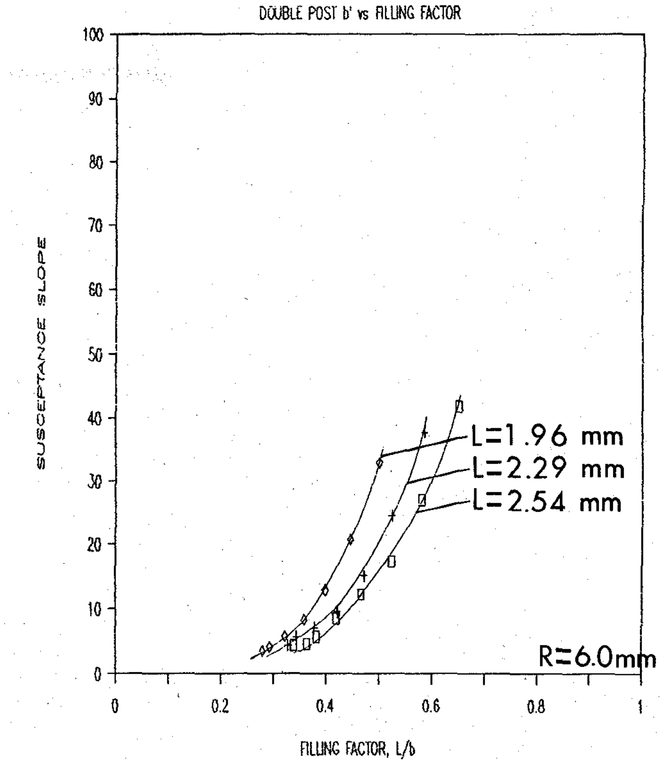

Fig. 13. Susceptance slope parameter of E-plane junction using coupled H-plane $HE_{11\frac{1}{2}}$ turnstile resonators ($\epsilon_f = 15.0$, $R = 6.0$ mm, $R/L = 2.36$, 2.62, and 3.06).

the magnetized resonator by

$$g = \sqrt{3}\, b' \left(\frac{\omega_+ - \omega_-}{\omega_0} \right) \tag{5}$$

provided again that the in-phase and degenerate eigennetworks are commensurate.

This relationship may be utilized to define the Q factor of the gyrator circuit in terms of the split frequencies [23]

$$\frac{1}{Q_L} = \sqrt{3} \left(\frac{\omega_+ - \omega_-}{\omega_0} \right). \tag{6}$$

The measurements of these quantities are discussed in some detail in [25]–[27].

Fig. 13 illustrates the relationship between the susceptance slope parameter and the physical variables of the symmetrical circuit. This quantity may be evaluated from a knowledge of the frequency response of directly coupled devices in terms of the frequencies ($f_{1,2}$) on either side of the circulation one in the mode charts (f_0) at which the VSWR has some convenient value:

$$b' = \frac{(\mathrm{VSWR} - 1)}{2\delta_0 \sqrt{\mathrm{VSWR}}}. \tag{7}$$

Although this measurement assumes that the in-phase and degenerate counterrotating eigennetworks are commensurate, a condition not altogether satisfied here, it is on past experience good enough for engineering purposes. A comparison between the value obtained in this manner for the specific case treated in Fig. 4 and that derived

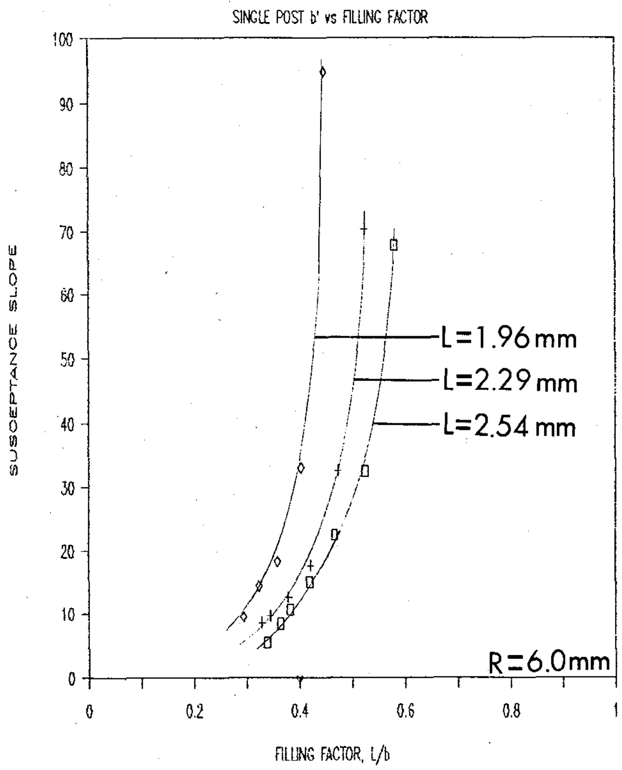

Fig. 14. Susceptance slope parameter of E-plane junction using single H-plane $HE_{11\frac{1}{2}}$ turnstile resonator ($\epsilon_f = 15.0$, $R = 6.0$ mm, $R/L =$ 2.36, 2.62, and 3.06).

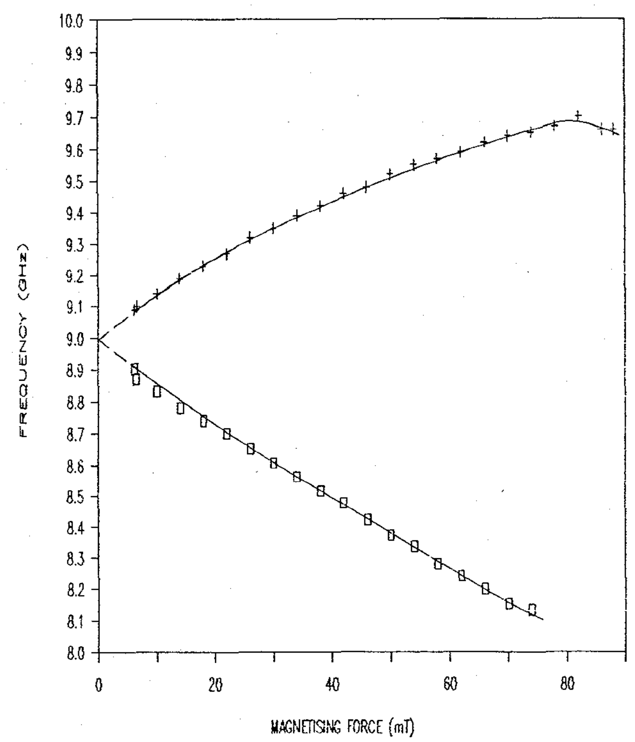

Fig. 15. Split frequencies of E-plane junction using coupled H-plane $HE_{11\frac{1}{2}}$ turnstile resonators ($\epsilon_f = 15.0$, $M_0 = 0.1600$ T, $R = 6.0$ mm, $R/L = 2.36$, $L/b_1 = 0.44$).

using its more formal definition in terms of the susceptance (b_1), of the degenerate counterrotating immittance eigenvalues

$$b' = \frac{\omega}{2} \frac{\partial b_1}{\partial \omega}\bigg|_{\omega = \omega_0} \tag{8}$$

indicates that this is indeed so. Interestingly enough, the susceptance slope parameter of the one-disk configuration is twice that of the coupled-disk geometry (Fig. 14), a feature also met in the description of the H-plane structure [28]. The values for the three possible solutions at 9.0 GHz for which $k_0 R\sqrt{\epsilon_f} = 4.38$ ($R/L = 2.36$, $L/b_1 = 0.65$, $R/L = 2.49$, $L/b_1 = 0.44$, and $R/L = 2.62$, $L/b_1 = 0.33$) are 30, 12, and 1.5, respectively. The susceptance slope parameter is, however, not an independent parameter since it is essentially fixed by the physical parameters employed to satisfy the first circulation condition; the optimum value awaits a solution of the in-phase eigennetwork.

Scrutiny of (5) or of the data in Fig. 5 indicates that the gyrator conductance may be adjusted in the usual way by the magnetic variables of the resonator. This parameter may be evaluated from a knowledge of the quantities in (5) or by utilizing one or the other of the methods described in [26] and [27]. Fig. 15 gives the split frequencies for one solution. The theoretical development of the magnetized resonator follows routinely from the derivation of the related problem in [37].

VI. Quarter-Wave Coupled E-Plane Junction Circulator

The main endeavour of this paper is to establish the eigenvalue problem of an E-plane junction circulator using an evanescent-mode junction loaded by single or coupled quarter-wave-long open circular gyromagnetic waveguides propagating the HE_{11} mode open-circuited at one end and short-circuited at the other; a secondary task is to investigate the matching problem and, if possible, to quarter-wave couple it. Scrutiny of the element values of the gyrator circuit of the E-plane device examined in this work indicates that these are in keeping with those associated with the more common H-plane one. It is therefore expected that, if the in-phase eigennetwork in the complex gyrator circuit in Fig. 11 is absorbed in the matching network, network specifications akin to those realizable with the latter junction should also be achievable with the former device. This problem has in fact been dealt with in [35]. Network solutions are tabulated in [24] and [29]–[34]. Experimental solutions to this problem are noted in [5] and [8].

Since the complex gyrator of this junction is, after all, a nearly ideal degree-1 circuit, it may be matched using slightly foreshortened quarter-wave-long reduced-height waveguide sections. Ridge or alternate line transformers represent two other possibilities. The impedance level of the transformer sections was initially fixed by employing half-height waveguide but as Fig. 5 suggests, an impedance level somewhat higher than that would have been a more

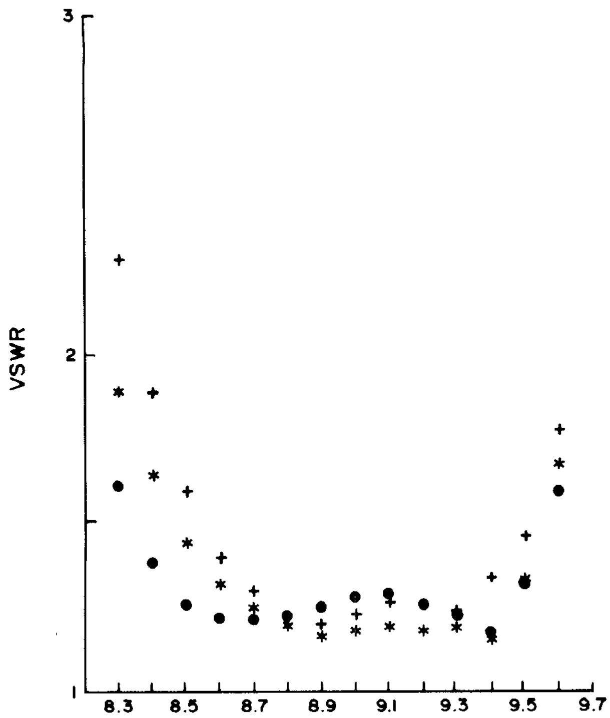

Fig. 16. Frequency response at ports 1, 2, and 3 of quarter-wave coupled E-plane junction circulator.

appropriate choice, and this was indeed experimentally found to be the case. Fig. 16 gives the result. The use of a ferrite material with a somewhat larger value of magnetization may have something to be said for it in this connection. It is also of note that the bandwidth of conventional H-plane junction circulators using turnstile E-plane resonators is often limited by the onset of the first $TE_{01\frac{1}{2}}$ resonance in this type of structure. This mode is also a fact present in the arrangement described here. The use of resonators with somewhat smaller values of radial wavenumber may have something to recommend it in this connection.

VII. Conclusions

A classic E-plane circulator is one consisting of three waveguides coupled to an evanescent-mode E-plane junction loaded with one or two H-plane turnstile resonators. The main endeavor of the paper has been to experimentally deduce the eigenvalue diagram and complex gyrator circuit of this type of device. The frequencies of the degenerate counterrotating modes of the classic H-plane junction using coupled E-plane turnstile resonators coincide with the odd-mode solution of two coupled resonators as is generally understood; the dual problem of the E-plane junction employing H-plane coupled turnstile resonators described here corresponds to the even one. The junction is cut off for the in-phase eigenvector and the frequency variation of this eigennetwork can be neglected compared to that of the degenerate counterrotating ones. The secondary task has been to quarter-wave couple it using quarter-wave-long partial-height waveguide sections in the manner outlined in some prior art.

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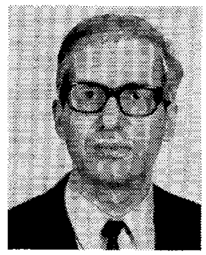

Joseph Helszajn (M'64) was born in Brussels, Belgium, in 1934. He received the Full Technological Certificate of the City and Guilds of London Institute from Northern Polytechnic, London, England (1955), the M.S.E.E. degree from the University of Santa Clara, CA (1964), the Ph.D. degree from the University of Leeds, Leeds, England (1969), and the D.Sc. degree from Heriot-Watt University, Edinburgh, Scotland (1976).

He has held a number of positions in the microwave industry. From 1964 to 1966, he was Product Line Manager at Microwave Associates, Inc., Burlington, MA. He is now Professor of Microwave Engineering at Heriot-Watt University. He is the author of the books *Principles of Microwave Ferrite Engineering* (New York: Wiley, 1969), *Nonreciprocal Microwave Junctions and Circulators* (New York: Wiley, 1975), *Passive and Active Microwave Circuits* (New York: Wiley, 1978), *YIG Resonators and Filters* (New York: Wiley, 1985), and *Ferrite Phase Shifters and Control Devices* (London, McGraw-Hill, 1987).

Dr. Helszajn is a Fellow of the Institution of Electronic and Radio Engineers (England) and a Fellow of the Institute of Electrical Engineers. In 1968, he was awarded the Insignia Award of the City and Guilds of London Institute. He is an Honorary Editor of *Microwaves, Antennas and Propagation* (IEE Proceedings).