Composite-Junction Circulators Using Ferrite Disks and Dielectric Rings

JOSEPH HELSZAJN, MEMBER, IEEE

Abstract—Since most junctions do not use the full available magnetic splitting of the ferrite material, it is possible to replace part of it by a dielectric. The theoretical and experimental development of such composite stripline circulators using ferrite disks surrounded by dielectric rings is given in this paper. Theoretical calculations and experimental results on the circulation frequency, gyrator admittance, and split frequencies of such circulators are included. The case of a partially magnetized ferrite disk on a ferrite substrate is treated separately. The susceptance slope parameter of this circulator geometry is also derived and measured. The results obtained in this paper show to what extent the ferrite disk behaves as a dielectric at the edge of the disk. The geometry leads to considerable saving in ferrite material, which is particularly important in UHF circulators. The experimental results are in good agreement with the theory.

INTRODUCTION

THE THEORY of the 3-port stripline circulator using a simple ferrite disk is well established [1]–[4]. This paper gives the theoretical and experimental development of composite stripline circulators using ferrite disks surrounded by dielectric rings. The geometry considered in this paper is shown in Fig. 1. It consists of a ferrite disk surrounded by a dielectric ring. A stripline circulator using a dielectric disk surrounded by a ferrite ring has been experimentally described previously [5]. A waveguide configuration has also been discussed in [9].

The construction considered in this paper relies on the fact that the frequency circulation condition is essentially determined by the dielectric properties of the junction, while, except in the case of the octave band circulator, the splitting between the frequencies of the two junction modes required to establish the gyrator circulation condition is usually obtained without fully magnetizing the junction. This means that some of the ferrite material can be replaced by a similar dielectric one without affecting either circulation conditions. The frequency splitting between the junction modes required to establish the gyrator impedance is determined by the susceptance slope parameter of the junction. This, in turn, defines the bandwidth of the device and the amount of ferrite that can be removed.

The theoretical results are developed in terms of the impedance matrix of the junction. This leads to two simple equations for the frequency and gyrator impedance of the circulator. The paper also gives the theoretical mode chart of such circulators and the split frequencies of the two counter-rotating modes of the junction. The case of the partially magnetized junction is treated separately. The susceptance slope parameter (and therefore the bandwidth) of the composite-junction circulator lies somewhere between that of a simple disk with the dielectric constant of the ferrite and that of a disk with the dielectric constant of the outer ring. Hence, the bandwidth of the device can to some extent be improved by loading the junction with low dielectric constant rings.

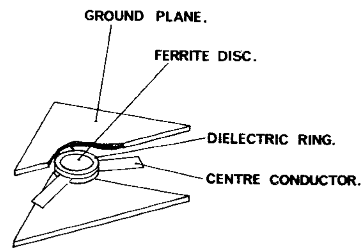

Fig. 1. Composite stripline circulator.

The geometry described leads to considerable saving in ferrite material. In one experimental example realized in this paper, a circulator was obtained with a bandwidth of 2 percent by removing 15/16 of the ferrite material. This is particularly important at UHF frequencies. It is also applicable to large average- and peak-power ferrite devices. This is because both low-level conventional magnetic losses and peak nonlinear losses are reduced with this configuration. The device has also the merit of increased thermal capacity because ferrite materials have inherent poor thermal conductivities compared to most ceramic materials.

FIELDS INSIDE JUNCTION

The schematic of the configuration considered in this paper is shown in Fig. 2. Solutions are sought with electric fields purely in the z direction and magnetic fields purely in the x–y plane. The fields are independent of z and are taken to have time dependence exp $(-j\omega t)$.

The electric field E_z and the magnetic field H_ϕ at $r = R_d$ are given in terms of the constants A_n, B_n, and C_n:

$$E_z = \sum_{n=-\infty}^{\infty} A_n[B_n J_n(k_d R_d) + C_n Y_n(k_d R_d)] \exp(jn\phi) \quad (1)$$

Manuscript received June 7, 1973; revised November 19, 1973.
The author is with the Department of Electrical and Electronic Engineering, Heriot-Watt University, Grassmarket, Edinburgh, Scotland.

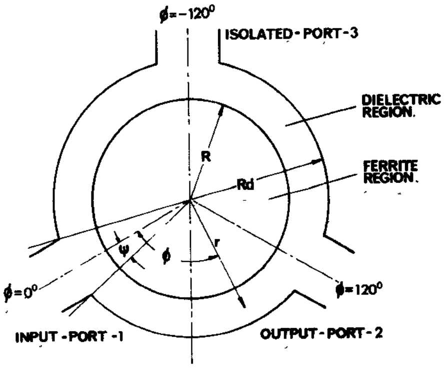

Fig. 2. Schematic of composite stripline circulator.

$$H_\phi = \sum_{n=-\infty}^{\infty} \frac{jA_n}{\eta_d}\left[B_n J_n'(k_d R_d) + C_n Y_n'(k_d R_d)\right] \exp(jn\phi). \tag{2}$$

The constants B_n and C_n are obtained by writing the fields in the two regions and applying continuity conditions on E_z and H_ϕ at $r = R$ in a similar way to the waveguide situation [6]:

$$B_n = \frac{(\eta_d/\eta_e)[Y_n(k_dR)]\{J_n'(kR) - (K/\mu)[nJ_n(kR)/kR]\} - J_n(kR)Y_n'(k_dR)}{J_n'(k_dR)Y_n(k_dR) - J_n(k_dR)Y_n'(k_dR)} \tag{3}$$

$$C_n = \frac{-(\eta_d/\eta_e)[J_n(k_dR)]\{J_n'(kR) - (K/\mu)[nJ_n(kR)/kR]\} + J_n(kR)J_n'(k_dR)}{J_n'(k_dR)Y_n(k_dR) - J_n(k_dR)Y_n'(k_dR)} \tag{4}$$

where

$$k_d = \omega(\mu_0\mu_d\epsilon_0\epsilon_d)^{1/2} \tag{5}$$

$$\eta_d = \left(\frac{\mu_0\mu_d}{\epsilon_0\epsilon_d}\right)^{1/2} \tag{6}$$

$$k = \omega(\epsilon_0\epsilon_r\mu_0\mu_e)^{1/2} \tag{7}$$

$$\eta_e = \left(\frac{\mu_0\mu_e}{\epsilon_0\epsilon_r}\right)^{1/2} \tag{8}$$

and μ_e and μ_d are the effective and demagnetized permeabilities. If $K/\mu = 0$ and $k = k_d$, then $B_n = 1$ and $C_n = 0$.

The constant A_n may now be found by forming another equation for H_ϕ. A second solution for H_ϕ, which is determined by the boundary conditions at the edge of the junction, is [7]

$$H_\phi = \sum_{n=-\infty}^{\infty} b_n \exp(jn\phi) \tag{9}$$

where

$$b_n = \frac{\sin n\psi}{\pi n}\left[H_1 + H_2 \exp(j2\pi n/3) + H_3 \exp(-j2\pi n/3)\right] \tag{10}$$

where H_1, H_2, and H_3 are the fields at the three ports.

Comparing (9) and (10) gives

$$A_n = \frac{(\eta_d \sin n\psi/j\pi n)[H_1 + H_2 \exp(j2\pi n/3) + H_3 \exp(-j2\pi n/3)]}{[B_n J_n'(k_dR_d) + C_n Y_n'(k_dR_d)]}. \tag{11}$$

The constant A_n is determined by both the radii R and R_d. It reduces to that found for the simple disk when $R = R_d$.

The electric field E_z at $r = R_d$ is therefore given by

$$E_z = \sum_{n=-\infty}^{\infty} \frac{\eta_d \sin n\psi}{j\pi n} \cdot [H_1 + H_2 \exp(j2\pi n/3) + H_3 \exp(-j2\pi n/3)] \cdot \left[\frac{B_n J_n(k_dR_d) + C_n Y_n(k_dR_d)}{B_n J_n'(k_dR_d) + C_n' Y_n'(k_dR_d)}\right] \exp(jn\phi). \tag{12}$$

IMPEDANCE MATRIX OF COMPOSITE JUNCTION

The impedance matrix of the junction may now be obtained by taking the average values of E_z at $r = R$ at the three ports with the help of (12):

$$E_1 = (1/2\psi)\int_{-\psi}^{\psi} E_z\, d\phi = Z_{11}H_1 + Z_{12}H_2 + Z_{21}H_3 \tag{13}$$

$$E_2 = (1/2\psi)\int_{-2\pi/3-\psi}^{-2\pi/3+\psi} E_z\, d\phi = Z_{21}H_1 + Z_{11}H_2 + Z_{12}H_3 \tag{14}$$

$$E_3 = (1/2\psi)\int_{2\pi/3-\psi}^{2\pi/3+\psi} E_z\, d\phi = Z_{12}H_1 + Z_{21}H_2 + Z_{11}H_3. \tag{15}$$

Equations (13)–(15) define the wave impedance matrix of the junction. In order to obtain the characteristic impedance, it is necessary to obtain a relation between voltage and current instead of between electric and magnetic field. This can be done by using the following relations:

$$V = \int \bar{E}\cdot d\bar{l} \tag{16}$$

$$I = \oint \bar{H}\cdot d\bar{l}. \tag{17}$$

An approximate result for a stripline configuration having a center conductor width W and a groundplane spacing b which applies for $W \gg b$ is

$$V = \frac{Eb}{2} \tag{18}$$

$$I = H2W. \tag{19}$$

The characteristic impedance matrix is now obtained by rewriting (13)–(15) in terms of V and I with the help of (18) and (19):

$$\bar{R} = \begin{bmatrix} R_{11} & R_{12} & -R_{12}^* \\ -R_{12}^* & R_{11} & R_{12} \\ R_{12} & -R_{12}^* & R_{11} \end{bmatrix}. \tag{20}$$

The above impedance matrix makes use of the relation between R_{12} and R_{21}:

$$R_{21} = -R_{12}^* \tag{21}$$

where

$$R_{11} = \sum_{n=-\infty}^{\infty} \frac{r_n}{3} \tag{22}$$

$$R_{12} = \sum_{n=-\infty}^{\infty} \frac{r_n \exp(j2\pi n/3)}{3} \tag{23}$$

$$R_{21} = \sum_{n=-\infty}^{\infty} \frac{r_n \exp(-j2\pi n/3)}{3} \tag{24}$$

and

$$r_n = \frac{3Z_d \sin^2 n\psi}{j\pi n^2\psi} \left[\frac{B_nJ_n(k_dR_d) + C_nY_n(k_dR_d)}{B_nJ_n'(k_dR_d) + C_nY_n'(k_dR_d)}\right] \tag{25}$$

where

$$Z_d = \frac{\eta_d}{4}\left[\frac{b}{W}\right]. \tag{26}$$

Equation (26) is an approximate one for the characteristic impedance for a stripline transmission line when $W \gg b$. A more general one is [8], [11]

$$Z_d = \frac{\eta_d}{4} \ln\left[\frac{W + b}{W + t}\right]. \tag{27}$$

A similar equation applies to the characteristic impedance R_0. In what follows, the two circulation conditions will be obtained by comparing the impedance matrix obtained above with that obtained for an ideal circulator.

It is observed from (25) that the eigennetwork for r_0 is an open-circuited transmission line, while the eigennetworks for r_n are in every case short-circuited transmission lines.

SCATTERING MATRIX OF COMPOSITE-JUNCTION CIRCULATOR

Although the results of this paper are derived in terms of the impedance matrix of the junction, it is often useful to develop its scattering matrix also. This allows all of the reflection and transmission coefficients of the junction to be studied. This approach has been widely applied in the case of the composite waveguide circulator [6], [9].

The relation between the impedance and scattering eigenvalues are given in the usual way by

$$s_n = \frac{r_n - R_0}{r_n + R_0}. \tag{28}$$

Putting

$$\frac{r_n}{R_0} = -j \tan\frac{\theta n}{2}$$

gives

$$s_n = -\exp(j\theta_n). \tag{29}$$

In terms of the original variables the result is

$$\tan\frac{\theta n}{2} = \frac{3Z_d \sin^2 n\psi}{\pi R_0 n^2\psi} \cdot \left[\frac{B_nJ_n(k_dR_d) + C_nY_n(k_dR_d)}{B_nJ_n'(k_dR_d) + C_nY_n'(k_dR_d)}\right]. \tag{30}$$

The form of (30) is the same as for the waveguide case [6]. One also finds here that C_n/B_n is determined by the ferrite disk only, and the other constants are determined by the outer geometry, which in this case consists of the dielectric ring, and the boundary conditions at the three striplines. Equation (30) reduces to that of the simple stripline circulator when $R = R_d$ [2].

CIRCULATION CONDITIONS

The impedance matrix of an ideal circulator has the following form:

$$\bar{R} = \begin{bmatrix} 0 & -R_0 & R_0 \\ R_0 & 0 & -R_0 \\ -R_0 & R_0 & 0 \end{bmatrix}. \tag{31}$$

Comparing the impedance matrix equation for the stripline circulator defined by (20) to that for the ideal circulator given above gives the two circulation equations

$$R_{11} = 0 \tag{32}$$

$$R_{12} = -R_0. \tag{33}$$

Equation (32) determines the ferrite geometry for appropriate pairs of field patterns. Equation (33) can then be used to calculate the gyrator resistance.

For small magnetic splitting, one can apply a selection rule whereby circulation is taken to occur in the vicinity of a pair of degenerate impedance eigenvalues. In the vicinity of these eigenvalues it is assumed that the amplitude of the other eigenvalues are small and so can be neglected.

For small magnetic splitting, the approximate solutions for R_{11} and R_{12} are therefore

$$R_{11} \approx \frac{r_{+n} + r_{-n}}{3} \tag{34}$$

and

$$R_{12} \approx \frac{r_{+n} \exp(j2\pi n/3) + r_{-n} \exp(-j2\pi n/3)}{3}. \quad (35)$$

To obtain an analytical result, r_n is first put in the following form:

$$r_{\pm n} = \frac{3Z_d \sin n\psi}{j\pi n} \left\{ \frac{[B_n J_n(k_d R_d) + C_n Y_n(k_d R_d)] \mp (K/\mu)[nJ_n(kR)/kR](\eta_d/\eta_e)[J_n(k_d R_d) Y_n(k_d R) - J_n(k_d R) Y_n(k_d R_d)]}{[B_n J_n'(k_d R_d) + C_n Y_n'(k_d R_d)] \mp (K/\mu)[nJ_n(kR)/kR](\eta_d/\eta_e)[J_n'(k_d R_d) Y_n(k_d R) - J_n(k_d R) Y_n'(k_d R_d)]} \right\} \quad (36)$$

where B_n and C_n now refer to the isotropic parts of the numerators of (3) and (4).

The two circulation equations are now obtained by forming R_{11} and R_{12} in terms of $r_{\pm n}$. If it is assumed that the circulation frequency coincides with that of the isotropic disk one has

$$B_n J_n'(k_d R_d) + C_n Y_n'(k_d R_d) = 0 \quad (37)$$

and

$$Y_0 = \frac{1}{R_0} \approx \frac{[nJ_n(kR)/kR](\eta_d/\eta_e)[J_n'(k_d R_d) Y_n(k_d R) - J_n(k_d R) Y_n'(k_d R_d)]}{2 \sin(2\pi n/3)[(Z_d \sin n\psi)/n\pi][B_n J_n(k_d R_d) + C_n Y_n(k_d R_d)]} \cdot \frac{K}{\mu}. \quad (38)$$

PARTIALLY MAGNETIZED CIRCULATOR

This section considers the case in which the outer part of the ferrite disk is not magnetized. Such a situation directly applies to microstrip circulators built on ferrite substrates in which the magnetized area is not always well defined. This result is obtained by putting $k_d = k$ and $\eta_d = \eta_e$ for which $C_n = 0$ in (37) and (38).

The two circulation equations are now obtained by forming R_{11} and R_{12} in terms of r_n. The result for $n = \pm 1$ is

$$J_1'(kR_d) \approx 0 \quad (39)$$

$$Y_0 = \frac{\pi Y_d}{3^{1/2}(kR_d) \sin \psi} \left(\frac{kR_d J_1(kR)}{kR J_1(kR_d)} \right) \cdot \left[\frac{J_1(kR) Y_1'(kR_d)}{J_1(kR) Y_1'(kR) - J_1'(kR) Y_1(kR)} \right] \frac{K}{\mu}. \quad (40)$$

In obtaining (39) it has been assumed that the operating frequency coincides with the isotropic disk.

Equation (40) may also be written as

$$Y_0 = \frac{F(R/R_d) \pi Y_d}{3^{1/2}(kR_d) \sin \psi} \frac{K}{\mu}. \quad (41)$$

The gyrator equation differs from the standard one by the factor $F(R/R_d)$. For a circulator employing the $n = \pm 1$ modes, $F(R/R_d)$ is given by

$$F(R/R_d) = \frac{J_1^2(kR)}{kR J_1(1.84)} \left[\frac{1.84 Y_0(1.84) - Y_1(1.84)}{J_1(kR) Y_0(kR) - J_0(kR) Y_1(kR)} \right] \quad (42)$$

where kR_d has been replaced by 1.84. Equation (42) is obtained by using standard recurrence relations for $J_1'(kR)$ and $Y_1'(kR)$. The filling factor $F(R/R_d)$ is unity when $R/R_d = 1$. It is zero when $R/R_d = 0$. The variation of $F(R/R_d)$ with R/R_d is shown in Fig. 3.

The input admittance of a simple junction is shown in Fig. 4 as a function of ψ. This illustration is obtained directly from (23) by retaining the first six terms in the series.

MAGNETIC SPLITTING OF PARTIALLY MAGNETIZED JUNCTION

The two split frequencies of the junction are obtained from the two roots of the following equation for which $H_\phi = 0$ at $r = R_d$:

$$B_n J_n'(kR_d) + C_n Y_n'(kR_d) = 0. \quad (43)$$

The result in terms of the original variables for the $n = \pm 1$ modes is

$$J_1'(kR_d) \pm F(R/R_d) \frac{K}{\mu} \frac{J_1(kR_d)}{kR_d} = 0 \quad (44)$$

where $F(R/R_d)$ gives the reduction in magnetic splitting compared to that of a fully magnetized disk.

It can be shown that this result can also be put in the following form:

$$\frac{\omega_{+1} - \omega_{-1}}{\omega_0} = \frac{\Delta k R_d}{kR_d} = \frac{2F(R/R_d)}{(kR_d)^2 - 1} \cdot \frac{K}{\mu} \quad (45)$$

where $F(R/R_d)$ is the filling factor, defined in the last

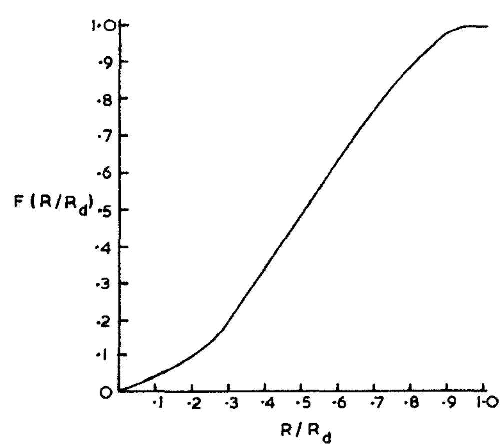

Fig. 3. Effective splitting factor.

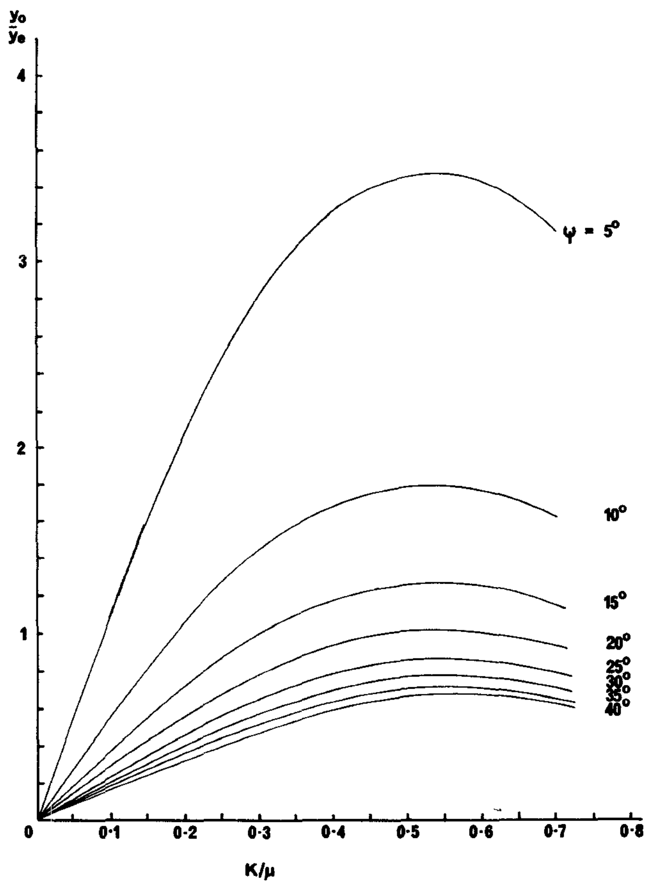

Fig. 4. Gyrator admittance of simple circulator.

section, and $\omega_{\pm 1}$ are the two split frequencies of the magnetized junction.

SUSCEPTANCE SLOPE PARAMETER OF PARTIALLY MAGNETIZED JUNCTION

The susceptance slope parameter of the junction determines its bandwidth. Once this is specified, the difference between the two split frequencies of the magnetized junction is determined by the universal gyrator equation given below. This allows the filling factor to be determined and thereafter R/Rd, which determines the amount of ferrite that can be removed. The universal admittance equation is

$$g = 3^{1/2} b' \left(\frac{\omega_{+1} - \omega_{-1}}{\omega_0} \right). \tag{46}$$

Combining (45) and (46) gives

$$F(R/R_d) = \frac{1}{3^{1/2}} \frac{g}{b'} \left[\frac{(kR_d)^2 - 1}{2} \right] \frac{\mu}{K}. \tag{47}$$

For a directly coupled circulator the normalized susceptance slope parameter is

$$b' \simeq \frac{(r-1)}{2\delta_0 r^{1/2}} \tag{48}$$

and the normalized gyrater conductance is

$$g = 1 \tag{49}$$

where r is the VSWR and $2\delta_0$ is the full normalized bandwidth $(\omega_2 - \omega_1)/\omega_0$.

The minimum filling factor is now given in terms of junction specification by

$$F(R/R_d) = \frac{1}{3^{1/2}} \cdot \frac{2\delta_0 r^{1/2}}{(r-1)} \left[\frac{(kR_d)^2 - 1}{2} \right] \frac{\mu}{K}. \tag{50}$$

Equation (50) may be used to determine the minimum amount of ferrite that must be used to establish a gyrator conductance of unity once the specification of the junction is known.

Equation (46) may also be used to obtain the susceptance slope parameter given by (48) in terms of the physical variables by combining it with (41) and (45). The result is

$$b' = \frac{\pi Y_d}{3 Y_0 \sin \psi} \left[\frac{(kR_d)^2 - 1}{2(kR_d)} \right]. \tag{51}$$

This result is the same as for the simple ferrite disk [8]. It is independent of R/R_d because the magnetized and demagnetized parts of the ferrite disk have been assigned identical permeabilities. However, this will not be the case in the more general case of the composite junction, as will be demonstrated experimentally later in this paper.

Fig. 5 gives the susceptance slope parameter for this configuration as a function of $\sin \psi$.

EXPERIMENTAL RESULTS WITH $\epsilon_d = 16$

This section gives the experimental results obtained on a composite junction consisting of a ferrite disk surrounded by a dielectric ring with $\epsilon_d = 16$. The material used was a

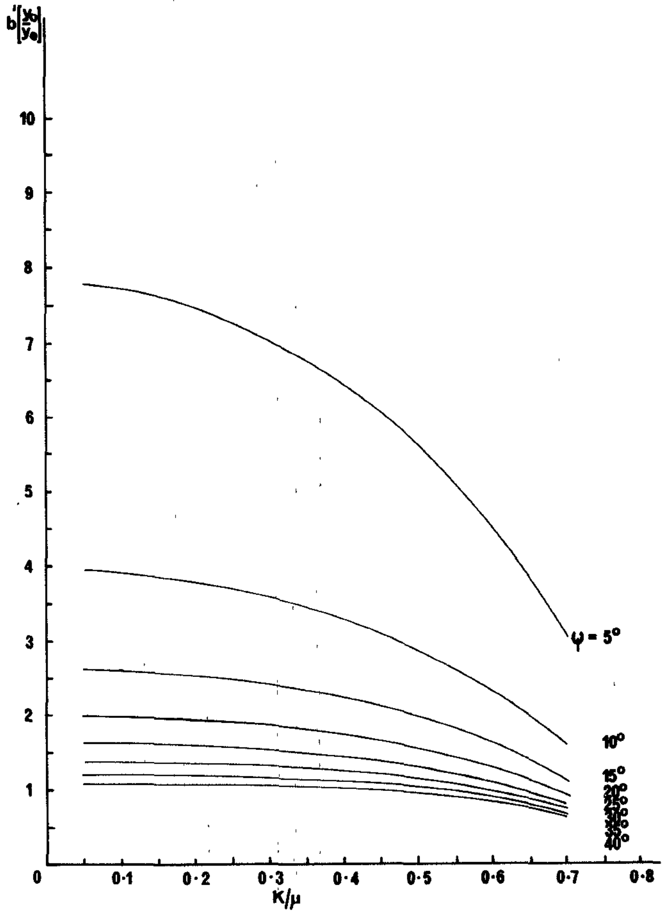

Fig. 5. Susceptance slope parameter of simple circulator.

garnet with $M_0 = 0.0550$ Wb/m² and $\epsilon_r = 13.8$, for which K/μ is 0.77 at saturation at 2000 MHz. The geometry used had $\psi = 15°$. Fig. 6 shows the gyrator conductance of such a circulator at the three ports as a function of magnetic field for various geometries. Fig. 7 gives the two split frequencies as a function of magnetic field. It is observed from these two figures that the gyrator conductance is proportional to the difference in the two split frequencies, as is the usual case. The susceptance slope parameter of the junction is determined by the ratio of the gyrator conductance and the differences between the split frequencies. This result is given in Fig. 8. It is essentially independent of the center frequency and of R/R_d. The susceptance slope parameter obtained here is $b' = 10.3$. This is exactly the value obtained theoretically using (51) with $\epsilon_d = 16$.

Fig. 6 indicates that it is possible to realize a directly coupled circulator with $R/R_d = 0.27$ with a susceptance slope parameter of 10.3 which coincides with a bandwidth of 2 percent at the 20-dB points. Indeed, (50) in conjunction with Fig. 3 predicts that the minimum value of R/R_d for this bandwidth is 0.20 for $K/\mu = 0.77$, which corresponds to $M_0 = 0.0550$ Wb/m² at 2000 MHz.

EXPERIMENTAL RESULTS WITH $\epsilon_d = 5$

This section describes the experimental results obtained on a composite junction consisting of a ferrite disk surrounded by a dielectric ring with $\epsilon_d = 5$. The garnet

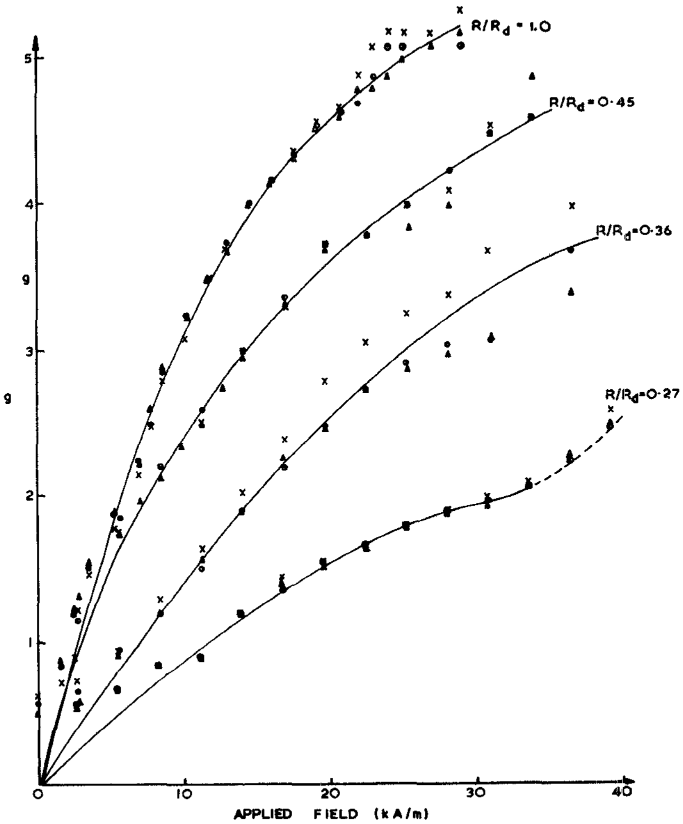

Fig. 6. Experimental gyrator admittance for $\epsilon_d = 16$, $\epsilon_r = 13.8$, $\mu_e = 0.65$.

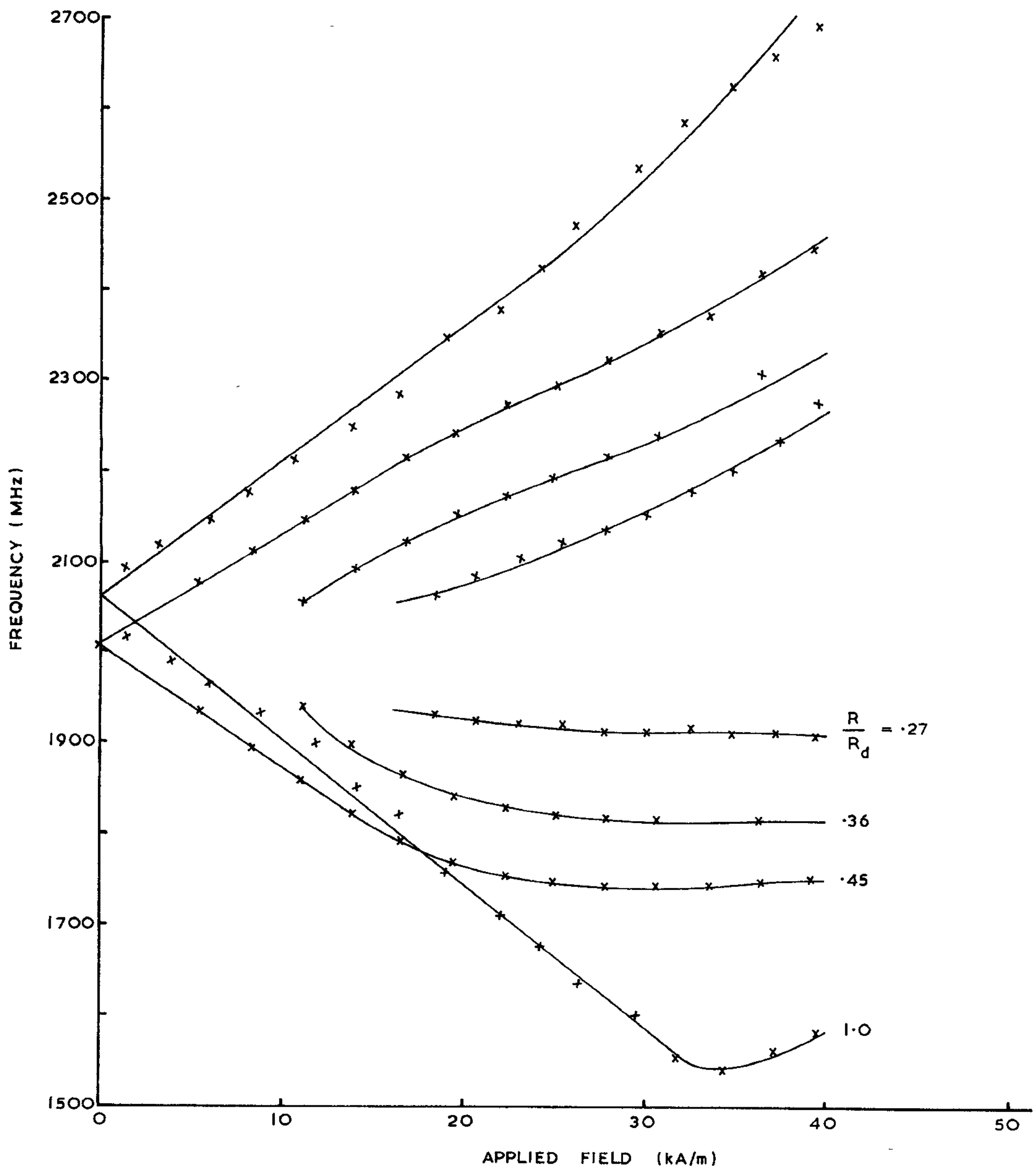

Fig. 7. Experimental split frequencies for $\epsilon_d = 16$, $\epsilon_r = 13.8$, $\mu_e = 0.65$.

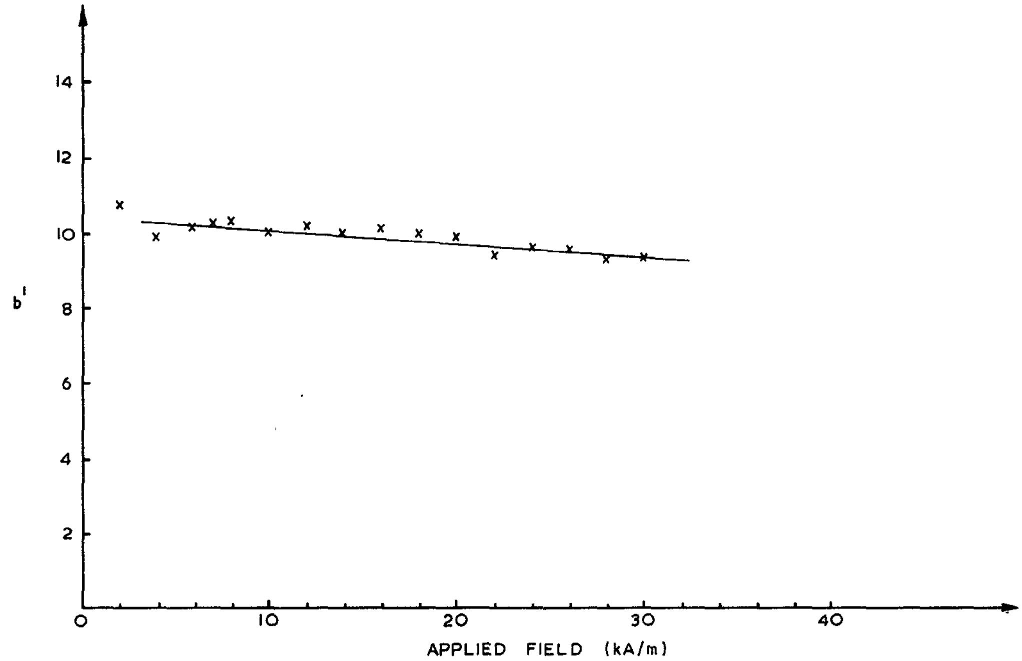

Fig. 8. Experimental susceptance slope parameter for $\epsilon_d = 16$, $\epsilon_r = 13.8$, $\mu_e = 0.65$.

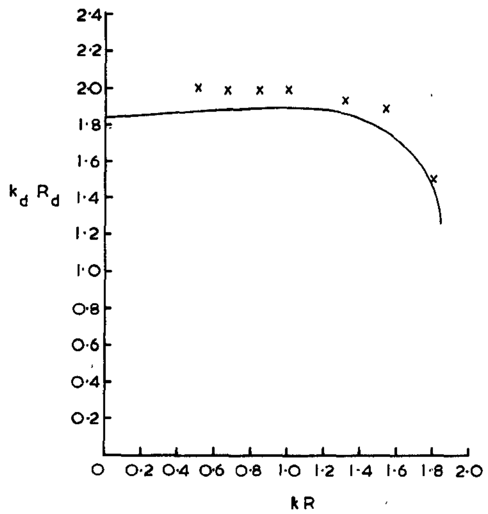

Fig. 9. k_dR_d versus kR for $\epsilon_d = 5$, $\epsilon_r = 13.8$, $\mu_e = 0.65$.

material used was the same as in the previous section. The theoretical relation between k_dR_d and kR for this material is shown in Fig. 9. The experimental results on such a circulator are superimposed on Fig. 9.

The experimental gyrator admittance at the three ports, split frequencies, and susceptance slope parameter are shown in Figs. 10–12 as a function of direct magnetic field for parametric values of the ferrite radius. Fig. 12 shows that the susceptance slope parameter is a function of R when ϵ_d is different from ϵ_r. It appears to lie between the limits imposed by a simple disk with the dielectric constant of the ferrite material and by a simple disk with the dielectric constant of the dielectric ring. One effect of dielectric loading is therefore to broadband the junction when ϵ_d is less than ϵ_r, but this is not the main advantage of this geometry.

Fig. 13 gives the effective splitting factors for composite junctions with $\epsilon_d = 5$ and 16. It is seen that the latter one is in excellent agreement with the theoretical one shown in Fig. 3. It experimentally appears that $F(R/R_d)$ does not have a strong dependence on ϵ_d.

CONCLUSIONS

This paper has given the general theory of stripline circulators consisting of ferrite disks and dielectric rings in terms of the impedance matrix of the junction. In the case of the partially magnetized junction, an expression is derived that relates the amount of ferrite that can be demagnetized to the bandwidth of the device. The experimental results are in good agreement with the theory. The main application of the geometry described is likely to be in the area of large average-power junctions.

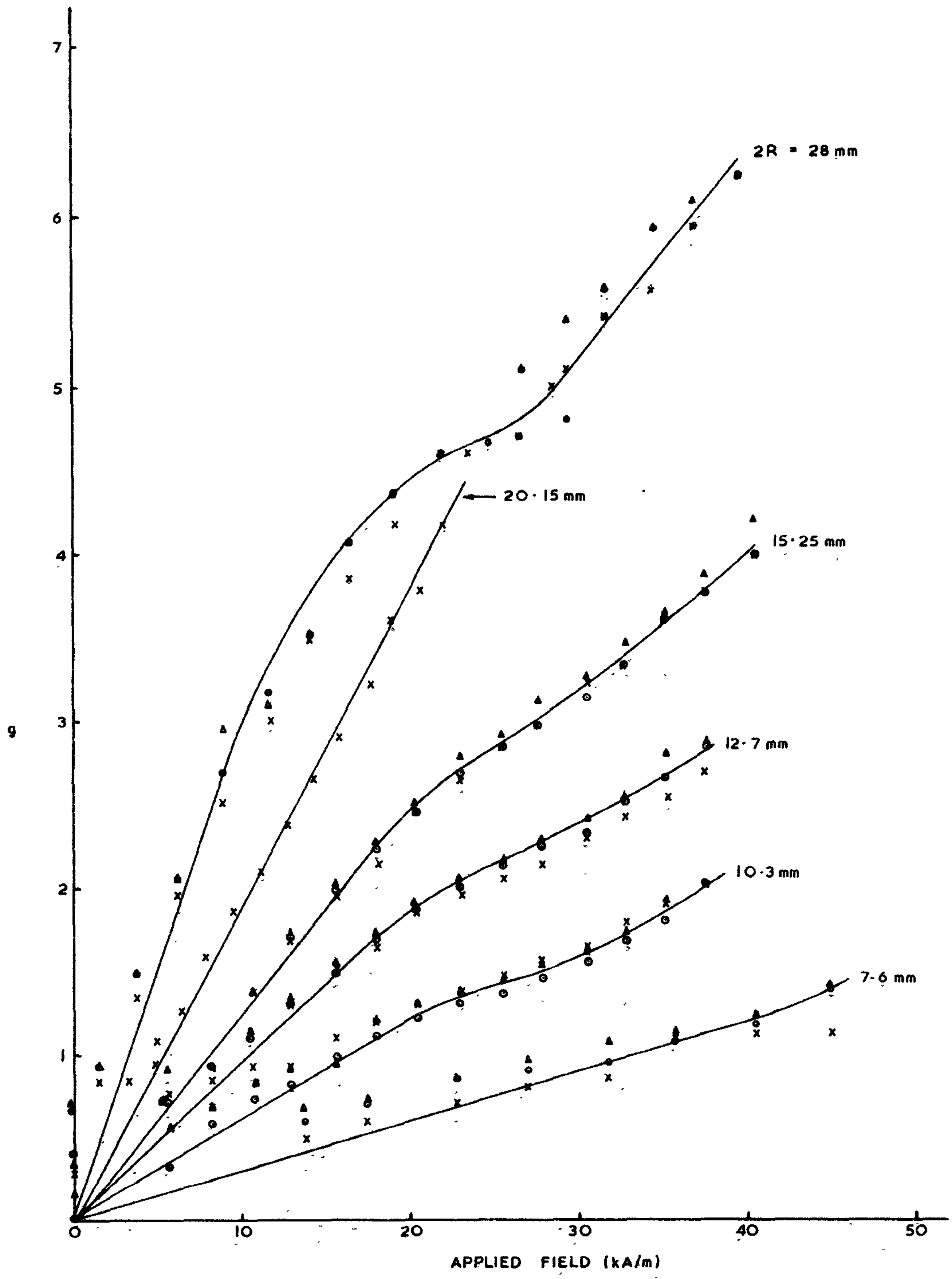

Fig. 10. Experimental gyrator admittance for $\epsilon_d = 5$, $\epsilon_r = 13.8$, $\mu_e = 0.65$.

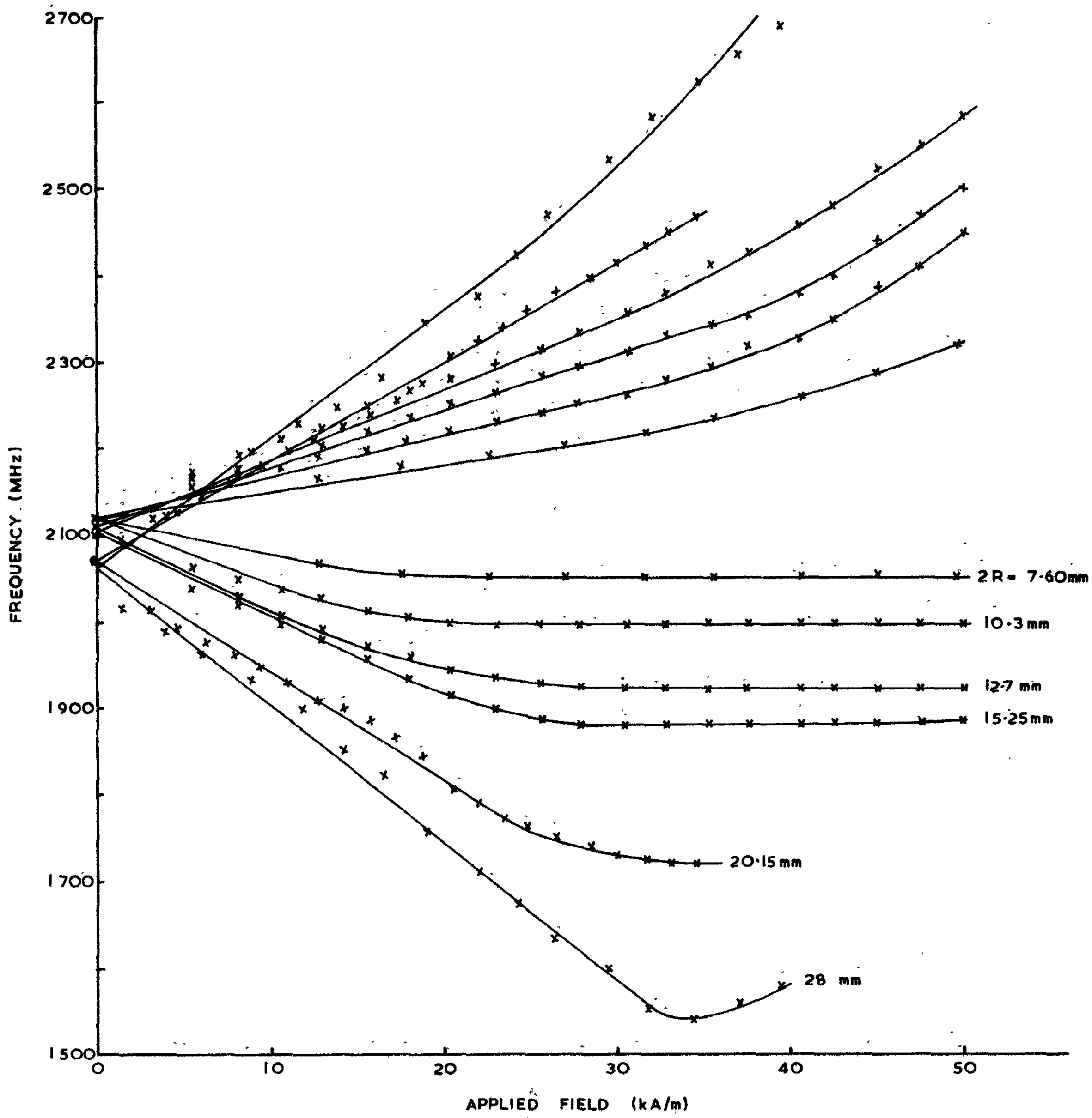

Fig. 11. Experimental split frequencies for $\epsilon_d = 5$, $\epsilon_r = 13.8$, $\mu_e = 0.65$.

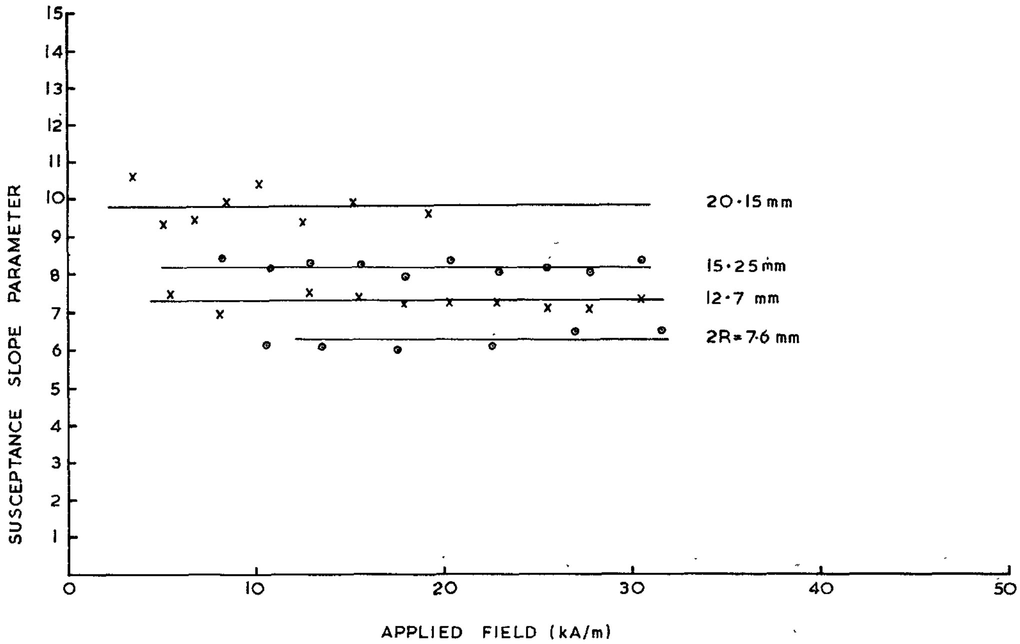

Fig. 12. Experimental susceptance slope parameter for $\epsilon_d = 5$, $\epsilon_r = 13.8$, $\mu_e = 0.65$.

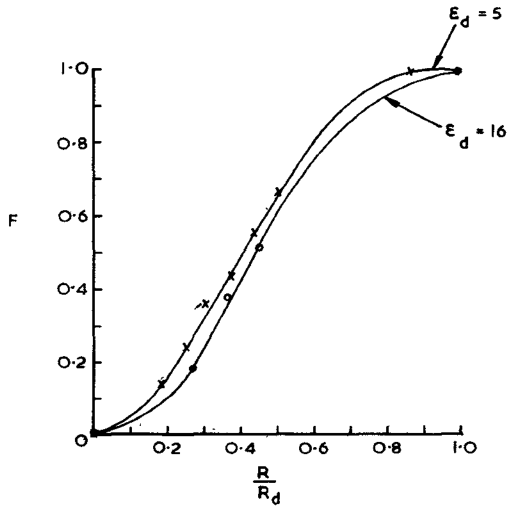

Fig. 13. Effective experimental splitting factors for $\epsilon_d = 5$ and 16.

ACKNOWLEDGMENT

The author wishes to thank K. L. Flett for the experimental work, and MESL for providing the experimental facilities.

REFERENCES

[1] U. Milano, J. H. Saunders, and L. Davis, Jr., "A Y-junction strip-line circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-8, pp. 346–351, May 1960.
[2] J. B. Davies and P. Cohen, "Theoretical design of symmetrical junction stripline circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-11, pp. 506–512, Nov. 1963.
[3] H. Bosma, "On stripline Y-circulation at UHF," *IEEE Trans. Microwave Theory Tech.* (*1963 Symposium Issue*), vol. MTT-12, pp. 61–62, Jan. 1964.
[4] C. E. Fay and R. L. Comstock, "Operation of the ferrite junction circulator," *IEEE Trans. Microwave Theory Tech.* (*1964 Symposium Issue*), vol. MTT-13, pp. 15–27, Jan. 1965.
[5] J. Helszajn, "A ring stripline junction circulator," *Radio Electron. Eng.*, vol. 32, pp. 55–60, July 1966.
[6] J. B. Davies, "An analysis of the m-port symmetrical H-plane waveguide junction with central ferrite post," *IEEE Trans. Microwave Theory Tech.* (*1962 Symposium Issue*), vol. MTT-10, pp. 596–604, Nov. 1962.
[7] V. G. Feoktistov, "Design of a strip Y-circulator," *Radio Eng. Electron. Phys.*, vol. 14, pp. 1111–1115, 1968.
[8] H. Bosma, "A general model for junction circulators; choice of magnetization and bias field," *IEEE Trans. Magn.* (*1968 Intermagn. Conference*), vol. MAG-4, pp. 587–596, Sept. 1968.
[9] J. B. Castillo, Jr., and L. E. Davis, "Computer-aided design of three-port waveguide junction circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-11, pp. 25–34, Jan. 1970.
[10] J. Helszajn, "Microwave measurement techniques for below-resonance junction circulators," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-21, pp. 347–351, May 1973.
[11] J. K. Richardson, "An approximate formula for calculating Z_0 of a symmetrical strip line," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-15, pp. 130–131, Feb. 1967.