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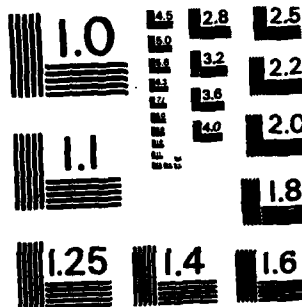
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# MEMORANDUM

No. 2986

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THE DESIGN OF MICROFORM CALCULATORS

Author: J. G. Gower

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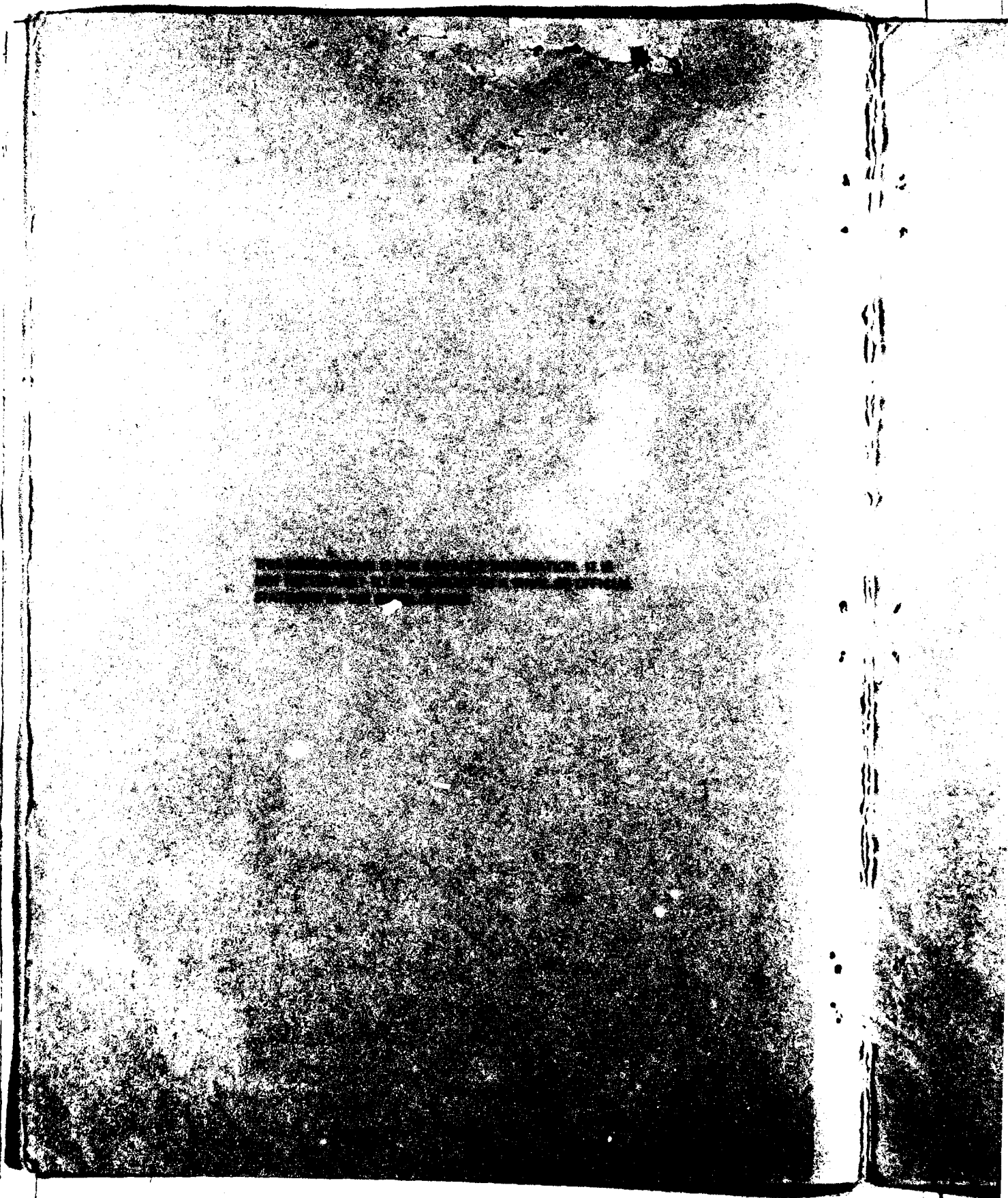
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THE DESIGN OF MICROFORM CALCULATORS

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RRE MEMORANDUM NO 2966

THE DESIGN OF MICROSTRIP CIRCULATORS

by R Genner

SUMMARY

This memorandum describes a theoretical procedure for the design of microstrip circulators on all ferrite substrates and substantiates its validity by using it to fabricate and measure a circulator for 9.3GHz; agreement between theory and practice was good. New information included in the theory consists of an extension of recent work by Wolff and Knoppik on microstrip disc capacitors to include the magnetic properties of the ferrite, leading to a much more accurate value for the disc radius of the circulator.

Use of the theory to calculate the resonant frequency of an alternative type of microstrip circulator in which a cylinder of ferrite is inserted in a hole in another dielectric also gives more accurate results than previously used theory.

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1 INTRODUCTION

The theory currently used in the design of microstrip circulators is that derived originally for stripline circulators in references (1), (2) and (3). In the last of these it is shown that the relation between the radius  $r_o$  of the metallized disc of the circulator and the wavelength  $\lambda_m$  of the  $TM_{110}$  mode in the ferrite material is

$$\frac{2\pi r_o}{\lambda_m} = 1.84$$

This can be re written in terms of frequency as

$$\frac{2\pi f_o}{c_o} \sqrt{\mu_m \epsilon_m} r_o = 1.84 \dots\dots\dots (1)$$

Where  $\mu_m$  and  $\epsilon_m$  are permeability and dielectric constant of the ferrite material.

The difficulty in using this formula to design a microstrip circulator arises from the spillover of the electromagnetic field into space outside the metallized disc and the additional complication that this fringing field exists in an inhomogeneous medium. These two factors necessitate the determination of effective values  $r_{eff}$ ,  $\mu_m^t$  and  $\epsilon_m^t$  with which to calculate the frequency  $f_o$  from

$$\frac{2\pi f_o}{c_o} \sqrt{\mu_m^t \epsilon_m^t} r_{eff} = 1.84 \dots\dots\dots (2)$$

Until the autumn of 1974 nothing had been published on circular as opposed to rectangular microstrip resonators and the design of circulators usually proceeded by scaling. In October 1974 however, Wolff and Knoppik published a paper on microstrip disc capacitors (4) describing a method of calculating the effective dielectric constant and quoting an effective radius due to Kirchoff. They showed that using these two effective values to calculate the resonant frequencies of microstrip discs gave answers in good agreement with practical results.

The present paper uses the results in (4) to derive a filling factor  $q$  from which the effective permeability  $\mu_m^t$  can be found. This together with the effective dielectric constant and the effective radius in (4) enable the resonant frequency  $f_o$  of a circulator to be calculated with much greater accuracy than heretofore. The results have been used to design a thick film circuit on an all ferrite substrate for the specific frequency of 9.3GHz. This has been fabricated in the microelectronics engineering unit at RRE and measurements of reflection coefficient, isolation and loss have been made using the HP automatic network analyser. Good agreement between theory and practice has been demonstrated.

It should be emphasized that no adjustment or scaling of the pattern on the microstrip were required and the only practical adjustment was a

slight movement of the magnet to adjust the external magnetic field to its design value. As the object of the work was to determine the resonant frequency of the circulator, no attempt was made at broadbanding and the metallic disc is joined to the three 50Ω input lines by simple quarter wave transformers.

Further confirmation of the proposed method of calculating the resonant frequency of circulators was then obtained by using it to find the resonant frequencies of four other microstrip circulators for which information was available. Two of these were on an all ferrite substrate and agreement between theory and practice was good. The other two were types in which the disc of ferrite was plugged into a hole in alumina. Agreement for these was not so good but still better than with extant theory.

## 2 PRINCIPLES OF DESIGN

In the introduction, the condition for resonance in the circulator disc is given by equation (2), viz;

$$\frac{2\pi f_o}{c_o} \sqrt{\mu'_m \epsilon'_m} r_{eff} = 1.84$$

For a given frequency  $f_o$ , calculation of the radius of the disc of the circulator becomes the problem of calculating the three quantities  $\mu'_m$ ,  $\epsilon'_m$  and  $r_{eff}$ .

Qualitatively the theoretical approach can be visualized as proceeding in two steps. In the first, the conductors of the circulator are envisaged completely surrounded by a homogeneous ferrite material and effective values  $\mu'_m$  and  $\epsilon'_m$  are calculated for it to account for the inhomogeneity of material in the real circulator; then an effective radius  $r_{eff}$  is calculated to correct for the bulging of the fields outside the metallization of the disc.

### 2.1 Effective radius ( $r_{eff}$ )

The effective radius  $r_{eff}$  used in the design is quoted in reference (4) and is

$$r_{eff} = r_o \left[ 1 + \frac{2h}{\pi r_o} \left[ \ln \left( \frac{\pi r_o}{2h} \right) + 1.7726 \right] \right]^{1/2} \dots\dots (3)$$

Where  $r_o$  is the radius of the disc and  $h$  is the substrate thickness.

In reference (4) Wolff and Knoppik have used the formula in conjunction with an effective dielectric constant to predict successfully the resonant frequency of microstrip disc capacitors.

### 2.2 Effective dielectric constant. ( $\epsilon'_m$ )

Before the effective values of dielectric constant  $\epsilon'_m$  can be calculated a filling factor  $\eta$  must be found for the microstrip configuration. The relationship between these two values and the bulk dielectric constant  $\epsilon_m$  is given by Wheeler (5) and is

$$\epsilon'_m = 1 + q \left( \epsilon_m - 1 \right) \dots\dots\dots (4)$$

Information on the effective dielectric constant of circular microstrip discs was first published in October 1974 (4). In this paper the effective dielectric constant is called  $\epsilon_{dyn}$  and a graph showing its variation with  $r_0/h$  for different modes and for  $\epsilon_m = 10.4$  is shown

Using it and equation (4) a graph of  $q$  versus  $r_0/h$  has been produced and this is shown in Fig 1. Since  $q$  is a function of  $\epsilon_m$  as well as  $r_0/h$  the graph applies strictly to  $\epsilon_m = 10.4$  but assuming the variation of  $q$  with  $\epsilon_m$  to be similar to that of  $\mu$ , a filling factor used in (4) and based on an electrostatic approximation, the error in using  $q$  corresponding to  $\epsilon_m = 10.4$  at  $\epsilon_m = 15.2$  is less than 1 part in 70. It should also be noted that although  $\mu$  is called a filling factor in (4) it is not defined in the same way as  $q$ .

### 2.3 Effective permeability. ( $\mu'_m$ )

The relation between the effective permeability  $\mu'_m$  and the bulk value  $\mu_m$  has been given by Pucel and Massè(6). It is

$$\frac{1}{\mu'_m} = 1 + q \left( \frac{1}{\mu_m} - 1 \right) \dots\dots\dots (5)$$

The authors of this reference show that once a T.E.M mode of propagation has been assumed, the electric field is the gradient of a scalar potential function which is independent of permeability and that the magnetic induction is the curl of a vector potential which is independent of dielectric constant. It is then deduced that the magnetic field distribution can be obtained from the solution of an electrostatic problem and that if

$$\epsilon'_m = f(g \epsilon_m) \text{ then } \frac{1}{\mu'_m} = f\left(g \frac{1}{\mu_m}\right) \dots\dots\dots (6)$$

where  $g$  is a geometrical factor.

Equations (4) and (5) are separate statements of the information in (6).

### 2.4 Bulk values of $\epsilon_m$ and $\mu_m$

The bulk value of dielectric constant  $\epsilon_m$  presents no difficulty since it is presented in the literature. To be exact, the value should be the dielectric constant at the microwave frequency and that in the literature is a low frequency value, and it has been assumed that these are equal.

The bulk value of permeability  $\mu_m$  is a function of the off diagonal elements  $\mu$  and  $K$  of the tensor permeability of the ferrite which in turn are functions of the magnetic field ( $H_s$ ) inside the ferrite, the field  $H_s$  at which magnetic resonance occurs in the ferrite and the value of saturation magnetization  $4\pi M_s$  of the ferrite. The exact relations given in (7) are:-



$$\mu_m = \frac{(\mu^2 - K^2)}{\mu} \dots\dots\dots (6)$$

where 
$$\mu = 1 + \frac{H_i 4\pi M_s}{(\mu_i^2 - H_o^2)} \dots\dots\dots (7)$$

and 
$$K = \frac{H_o 4\pi M_s}{(\mu_i^2 - H_o^2)} \dots\dots\dots (8)$$

In these equation  $H_o = f \omega / (2.8 \text{ MHz per oersted})$  and  $H_i = H$  applied  $-(N_x - N_z) 4\pi M_s$  where  $N_x$  and  $N_z$  are demagnetization factors and  $Z$  is the direction in which the external field is applied (7)

2.5 Choice of DC magnetic field

The choice of magnetic field is made to satisfy two conditions

2.5.1 It must be large enough to saturate the ferrite.

2.5.2 It must not be so large that the internal field is greater than that required to make  $\mu_m$  go negative. If this occurs no transmission of RF through the disc can occur because of the imaginary intrinsic impedance.

These conditions are dealt with in reference (2) where it is shown that the internal field  $H_i$  must exceed the anisotropy field in the ferrite to satisfy 2.5.1 but must be less than  $(H_o - 4\pi M_s)$  to satisfy 2.5.2. Information on anisotropy fields in particular ferrites is not very exact but from Lax and Button (9) they would appear to be of the order of tens of oersteds. In the practical design discussed in section 3 the internal field was chosen arbitrarily to be 300 oersteds.

2.6 Design of transformers

No effort was made to broadband the circulator and the resonator was treated as a parallel resonant circuit with a conductance  $G_L$  and a susceptance  $B_L$  (Figure 2). Several equivalent forms for  $G_L$  are given in the literature one of the most useful of which is

$$G_L = \frac{2}{3} \frac{\pi r_{eff}}{W} \frac{\sqrt{3} (K/\mu)}{(K_o r_{eff})} \sqrt{\frac{\mu_m}{\mu_o}} \sqrt{\frac{L}{W}} \dots\dots\dots (9)$$

This is a rearrangement of the formula given in (12)

In it  $W$  is the width of the transformer and  $(K_o r_{eff}) = 1.84$

Everything but  $W$  is known in this equation which can be rewritten as  $G_L = \frac{\eta}{W}$  where  $\eta$  is a numerical constant.

Since the transformer is a straightforward quarter wave device, the condition for match at  $f_o$  is  $Z_1^2 G_L = 50\Omega$ , where  $Z_1$  is a function of  $W$ .

It is now necessary to find a value of  $W$  which results in values of  $G_L$  and  $Z_1$  which satisfy the condition for match.

### 2.7 Bandwidth

To find the bandwidth of the circulator to a given VSWR the quality factor  $Q_L$  of the circulator must be known. This is in the literature (12) as

$$\frac{1}{Q_L} = \sqrt{3} \left[ \frac{2}{(k_e r_{eff})^2 - 1} \right] \frac{K}{\mu}$$

and all the information to calculate it has been found.

For a parallel resonant circuit

$$\left. \frac{\delta R_L}{\delta \omega} \right|_{\omega_0} = \frac{2Q_L G_L}{\omega_0}$$

and assuming  $R_L$  to vary linearly over small bandwidths about  $f_0$  leads to  $\delta R_L = \left( \frac{2Q_L G_L}{\omega_0} \right) \frac{\delta \omega}{\omega_0}$ . This enables the susceptive part of the parallel

resonant circuit to be calculated at fractional intervals of  $f_0$ .

Assuming that  $G_L$  is constant, means that the admittance of the circulator disc is known for frequencies near to  $f_0$ .

To calculate the reflection coefficient  $\rho$  looking into the circulator it is then only necessary to transform  $Y_L$  at each frequency through the length  $l$  (Fig 2) of admittance  $Y_1$  by standard transmission line theory.

### 3 Application of design principles to a specific case.

Some representative data to illustrate the application of the method described is:-

$$f_0 = 9.3 \text{ GHz}$$

Ferrite material Trans Tek C 1001 with

$$4\pi M_0 = 1200 \pm 5\%$$

$$\epsilon_m = 15.2 \pm 5\%$$

Choose  $N_{int}$  arbitrarily as 300 turns and calculate  $\mu$  and  $k$  from equation (7) and (8) to give a value of  $\mu_m$  from (6) via

$N_{int}$	300
$\mu$	0.967
$K$	0.364
$\frac{k}{\mu}$	0.376

$\mu_m = 0.830$

Then using equation (2) figure 1 and then equations (4) and (5) the value of  $r_o = 0.237$  cms will be found to satisfy the condition

$$\frac{2\pi f_o}{c_o} \sqrt{\mu_m' \epsilon_m'} r_{\text{eff}} = 1.84$$

This was the radius used to design the circulator.

Also, when  $\frac{2\pi f_o}{c_o} \sqrt{\mu_m' \epsilon_m'} r_{\text{eff}} = 1.84$ ,  $\epsilon_m' = 11.41$  and  $\mu_m' = 0.869$ .

and  $r_{\text{eff}} = 0.300$  cms and  $\frac{K}{\mu} = 0.376$

Substitution in equation (9) now gives  $G_L = \frac{0.00214}{W}$  where  $W$  is in cms

This has to be solved graphically to find the value of  $W$  giving values of  $G_L$  and  $Z_1$  which satisfy  $Z_1^2 G_L = 50$

These came out as

$$\begin{aligned} W &= 0.0665 \text{ cms} \\ \text{giving } Z_1 &= 39.41 \Omega \\ \text{and } R_L &= 31.06 \Omega \\ \text{and } Q_L &= 1.835 \end{aligned}$$

Bandwidth to VSWR of 1.2 = 1.17 GHz

#### 4 Practical Results

To test the validity of the procedure outlined in section 3, it was used to design a circulator for 9.3 GHz on an all ferrite substrate of dimensions  $1'' \times 1'' \times 0.025''$ . The material used was Trans Tech G 1001 with  $\epsilon_m = 15.2$  and  $4\pi M_s = 1200$  gauss. The information in section 3 refers to this design and the dimensions are shown in figure 3. In this report this circulator is called RRE I.

The circulator was fabricated in the microelectronic engineering unit at RRE using thick film techniques and mounted on a brass block for ease in attaching coax to microstrip transitions. The magnet used was a small cylindrical one under the ground plane and to maintain homogeneity of the DC magnetic field a small disc of low loss microwave ferrite was placed on top of the metallic disc of the circulator. A photograph of the circulator (Fig 6) mounted on the brass block and of the assembly in a jig for accurate adjustment of the magnet is included.

Measurements of reflection coefficient, isolation and loss were made on an HP automatic network analyser. The performance of the circulator was optimized by moving the magnet back from the ground plane of the microstrip until the design value of magnetic field was obtained. The micrometers on the jig enabled the position of the magnet to be determined accurately, and its position was 0.58 mm away from the ground

plane.

With the magnet in the correct position, measurements of reflection coefficient, isolation and loss were made from 6 to 12GHz and these are shown in figure 4.

A check on the magnetic field was also made using a Hall probe. This was placed on top of the ferrite disc of the circulator and readings of 1.3 Kiloersted and 0.94 Kiloersted were measured depending on which face of the probe was adjacent to the disc. The different readings indicated that the sensor in the instrument was not centrally situated in the encapsulation around it. The thickness of this encapsulation was 0.096 cms and a mean value of 1120 oersted was assumed to be the field at a distance of 0.048 cms above the circulator disc. Assuming a linear decrease in field with distance from the face of the magnet, a simple calculation shows that the field at the centre of the ferrite would be 1200 oersted. This is also in good agreement with the theoretical value of 1260 oersted.

#### 5 Comparison of Theory and Practice.

The table below indicates good agreement between theory and practice.

	Theoretical	Practical
Frequency of Min VSWR	9.3 GHz	9.1 GHz
Frequency of Max Isolation	9.3 GHz	9.4 GHz
Bandwidth to VSWR = 1.2	1.17GHz	0.96 GHz
Bandwidth to isolation of 20 dB	1.17GHz	1.28 GHz
DC Magnetic Field	1260 oersted	1200 oersted
Loss in circulator + input lines + transformers	0.63 dB	0.8 dB

The slight discrepancy between the frequency of minimum VSWR and the theoretical result probably means that the transformer length is too long by 2 parts in 91. The difference between the measured peak of isolation and the theoretical one means that the radius of the disc is too small by 1 part in 94. This sort of error would be within the spread expected because of the tolerances for dimensions made by thick film circuitry and on the accuracy placed on material constants like  $\mu_m$  and  $\epsilon_m$ .

The resonant frequency is also very much better than that predicted using Fay and Constock with bulk values for  $\mu_m$  and  $\epsilon_m$  and the true radius of metallization. This results in 10.43 GHz as the centre of resonance. It should also be noticed that using effective values for permeability and dielectric constant without realizing that for the radius would result in an even higher resonant frequency since

$$\sqrt{\mu_m \epsilon_m} < \sqrt{\mu_m \epsilon_m} \quad \text{and} \quad f_0 = \frac{1}{2\pi} \sqrt{\frac{1}{\mu_m \epsilon_m}}$$

Referring to the two loss curves in the upper part of fig 4, the larger value is the loss due to the ferrite disc and the smaller value is the loss due to the input and output lines and in the

transformers between them and the circulator disc. Since they are on ferrite, the input lines are much narrower than they would be on alumina (0.039 cms c/f .064 cms). The only practical measurements of losses on ferrite lines is published in (10). These were made using thin film technology and indicate a loss of 0.21 dB per cm at 9 GHz in lines of 0.039 cms width. Since the 50Ω input lines to the circulator were 1.425 cms long the loss in them would be at least 0.30 dB in thin film and 0.45 dB in thick film. The corresponding losses in the transformers would be 0.12 dB giving a total loss in the circuitry outside the disc of the circulator as 0.57 dB. This leaves 0.23 dB to be accounted for in the disc. Magnetic and Dielectric losses account for 0.06 dB and the remaining 0.17 dB must be conductor loss in the disc. The curve labelled "Loss in circulator" in fig 4 represents the true loss in the disc of the circulator.

- 6 Comparison of the modified theory with former theory in calculating the resonant frequency of circulators.

Microstrip circulators which are described in the literature (11) (12) and (13) are of two kinds; plug in types in which the ferrite is a cylindrical disc fitted into a hole in a ceramic substrate and a more advanced type in which the metallization is deposited onto a ferrite substrate. Only the latter type would be expected to conform accurately to the modified theory but if there is merit in it one could reasonably expect it to give more accurate results than existing theory for the plug in types. Since the ceramic in these has a lower dielectric constant than the ferrite puck one would expect the fringing fields to be more widespread, leading to a larger value of radius and hence a lower resonant frequency than that predicted by even the modified theory. The results are shown below:-

Circulator	Practical Result	Modified Theory	Former Theory
RRE I	9.25 GHz	9.30 GHz	10.43 GHz
RCA (12)	8.51 GHz	8.44 GHz	10.10 GHz
<u>Plug in Types</u>			
RRE II	7.48 GHz	7.75 GHz	8.45 GHz
Raytheon (13)	2.75 GHz	2.96 GHz	3.25 GHz
Raytheon (13)	10.75 GHz	11.17 GHz	12.09 GHz

Where the frequencies for maximum isolation and minimum VSWR differ, a mean value has been taken as the resonant frequency. In reference (12) two different frequencies for maximum isolation occur and a mean value has been quoted.

The results on circulator RRE II are shown in Fig 5. The design of this circulator prompted a closer investigation of the theory of circulators which has resulted in the modified theory described in this report. The object was to produce a circulator at 9.3 GHz; using the theory described in (1) (2) and (3) this was designed and the circulator fabricated in the microelectronic engineering unit at RRE. It showed no sign of resonance at 9.3 GHz in the magnetic field for which it had been designed but after prolonged experimental investigation in different magnetic fields it was made to give an excellent result at 7.48 GHz Fig 5. The magnetic field in which this result was obtained was very much lower than that for which the

circulator had originally been designed and in this lower field the theory in (1) (2) and (3) indicated a resonant frequency of 8.45 GHz. Replacing  $\mu_m$  and  $\epsilon_m$  by effective values  $\mu_m^e$  and  $\epsilon_m^e$  made matters worse by indicating a higher resonant frequency and only when  $\mu_m^e$  and  $\epsilon_m^e$  were used with an effective radius  $r_{eff}$  could reasonable agreement be reached between theory and practice.

#### 7 Conclusions

A method of designing microstrip circulators on ferrite substrates has been described which in addition to effective values for permeability and dielectric constant includes an effective radius. A graph of filling factor is included which can be used for values of dielectric constant from 9 to 16 and for values of the ratio radius/height of substrate up to 8:1.

The method has been verified by using it to fabricate a circulator at 9.3 GHz. This required no trimming of the conductors on the substrate and was the subject of a controlled experiment in which the magnetic field at the centre of the ferrite was accurately measured. Agreement between theory and practice was good.

The method has also been shown to give more accurate predictions of the resonant frequencies for plug in type circulators but in this case further work is required to take into account the change in dielectric round the periphery of the circulator disc.

#### 8 Acknowledgements

Thanks are due to Mr N Pearce, Mr B C Davis and Mr J W Sandell of the microelectronic engineering unit at RRE for the fabrication of all the circuits described in this report.

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Date : 8 January 1976

$r_0$  = RADIUS OF METALLIZATION

$h$  = HEIGHT OF SUBSTRATE

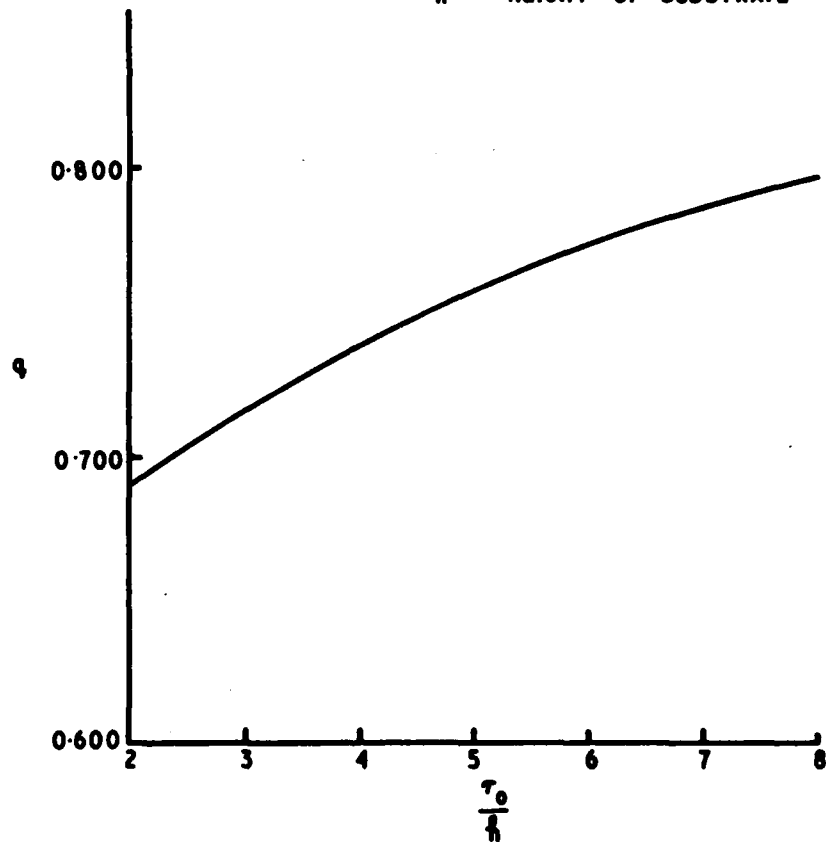
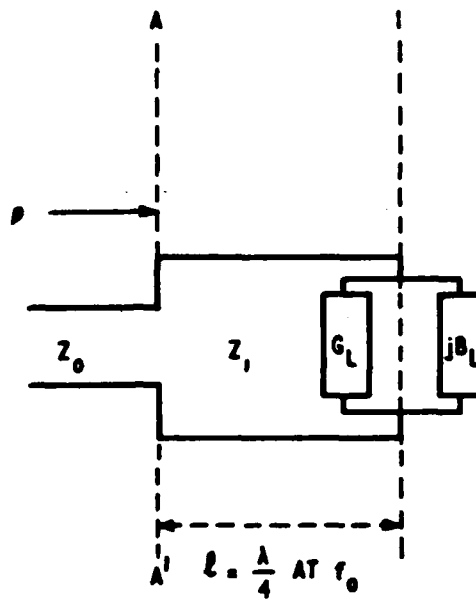


FIG. 1.

FILLING FACTOR  $q$  FOR  $TM_{110}$  MODE IN CIRCULAR DISCS FROM WOLFF AND KNOPPIK (4) FOR  $\epsilon_m$  FROM 9 TO 16.

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- $Z_0$  = CHARACTERISTIC IMPEDANCE OF INPUT LINE.
- $Z_1$  = CHARACTERISTIC IMPEDANCE OF THE TRANSFORMER.
- $G_L$  = CONDUCTANCE OF CIRCULATOR
- $B_L$  = SUSCEPTANCE OF CIRCULATOR
- $\rho$  = REFLECTION COEFFICIENT AT PLANE  $AA'$

**FIG. 2.**  
EQUIVALENT CIRCUIT OF TRANSFORMER COUPLED  
CIRCULATOR.

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MATERIAL TRANS TEK FERRITE 61001  
MAGNETIC FIELD AT CENTRE OF  
FERRITE = 1200 OERSTEDS.

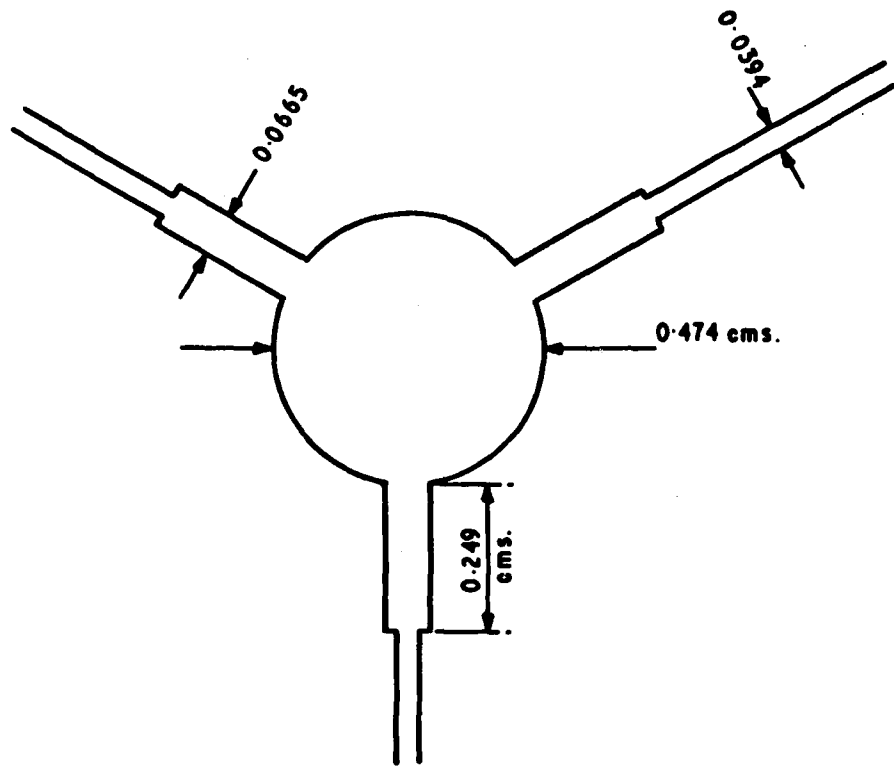


FIG. 3.  
DIMENSIONS OF THE CIRCULATOR.

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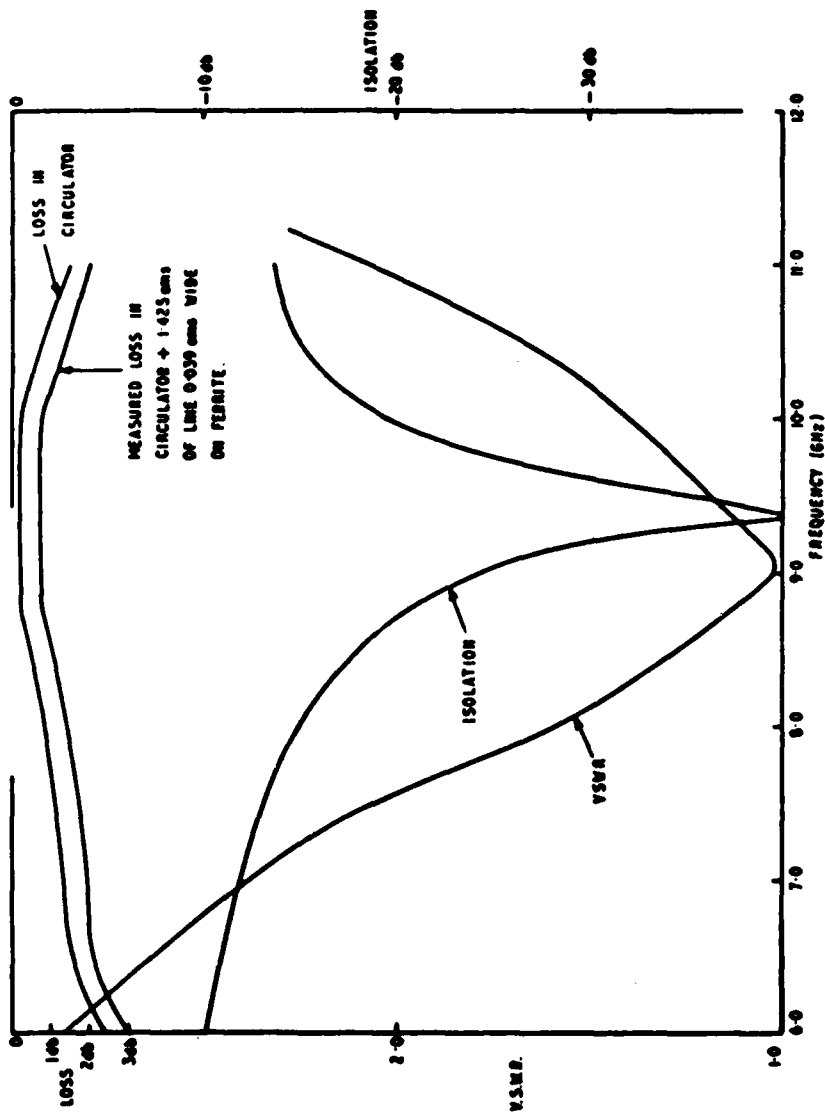
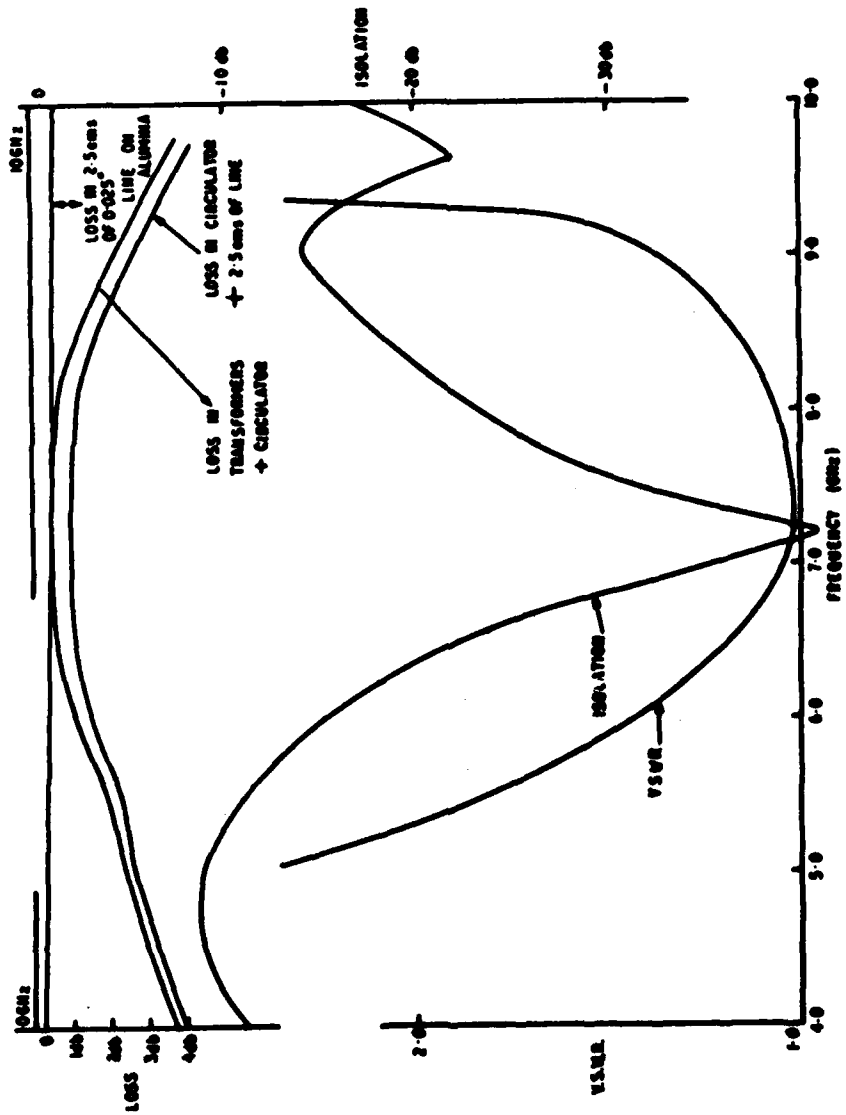


FIG. 4  
MEASUREMENTS ON CIRCULATOR RREI

RR/R 31/7150



**FIG. 5**  
**MEASUREMENTS ON CIRCULATOR RRE II.**

RR/R 31/7157



FIG. 6

END

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