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A HIGH POWER OCTAVE BANDWIDTH I/J BAND CIRCULATOR
RAYTHEON CO NORTHBOROUGH-MA SPECIAL MICROWAVE DEVICES
OPERATION 31 DEC 81 N00173-80-C-0434

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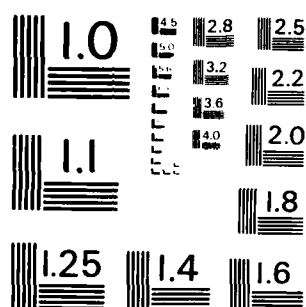
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TECHNICAL REPORT

FINAL REPORT

FOR

A HIGH POWER OCTAVE BANDWIDTH

I/J BAND CIRCULATOR

Contract Number N00173-80-C-0434

For Period September 2, 1980 to December 31, 1981

Prepared For

Naval Research Laboratory
Washington, D.C. 20375

Prepared By

Raytheon Company
Special Microwave Devices Operation
5 Bearfoot Road
Northborough, MA 01532

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1.0 INTRODUCTION

This report describes the results achieved for the development of a circulator under Contract N00173-80-C-0434. This program called for the development of an octave band circulator in 7.5 - 18 GHz, having the following specifications.

	<u>Design Objectives</u>	<u>Proposed</u>
Frequency Range	7.5 - 18	7.5 - 18
Instantaneous Bandwidth	1 Octave	1 Octave
Power Levels		
Peak Power	20 kW Min.	20 kW Min.
Average Power	1 kW Min.	1 kW Min.
Isolation	20 dB Min.	20 dB Min. (70% of band) 18 dB Min.
Insertion Loss	0.6 dB Max.	0.6 dB (70% of band) 0.7 dB Max.
VSWR		
VSWR Into Matched Load	1.15	1.25 (70% of band) 1.35 Max.
Max Load VSWR	2.0:1	2.0:1
Temperature Range	0 to 50°C	0 to 50°C
Waveguide Inputs	WRD750D24	WRD750D24
Number of Accessible Ports	4	4
Applied Field	Fixed Magnets	Fixed Magnets
Cooling	-	Liquid
Flow	-	1/4 gpm
Pressure Drop	-	10 psi

Initially, a four port differential phase shift circulator using nonreciprocal phase shifter in a rectangular waveguide structure was studied. Nonreciprocal phase shifter design with H-plane ferrite and E-plane dielectric in a rectangular waveguide displayed limitations in terms of broadband performance. With optimum phase shifter geometry, 90% of required bandwidth could be achieved. However matching section of phase shifter and transition from rectangular to ridge waveguide would further limit the bandwidth. Therefore, the phase shifter design using rectangular waveguide was abandoned and nonreciprocal phase shifters in double ridge waveguide structures were used in the circulator design.

During the course of the circulator development program analytical studies on dielectric and ferrite loaded double ridge waveguide were performed. Design effort was placed on the frequency range between 8 to 16 GHz. Raytheon circulator design uses two magic tees and two non-identical nonreciprocal phase shifters in standard WRD750D24 double ridge waveguide.

2.0 CIRCULATOR CONFIGURATIONS

Differential phase shift circulators can be built in several configurations. Four configurations are shown in Figure 1 (a), (b), (c), and (d). All four have the same principle of operations. Power entering Port 1 emerges from Port 2 only, and so on until power entering Port 4 emerges from Port 1 only.

The device in Figure 1(a) is the most common configuration. This option is probably the most favorable if a 3 dB quadrature hybrid operating over the required frequency range with acceptable unbalance is available. Unfortunately a 3 dB quadrature hybrid at the desired frequency range with suitable performance is not currently available. The design indicated in Figure 1(b) uses input and output magic tees, separated by a $0^\circ/180^\circ$ nonreciprocal phase shifter in parallel with a dielectrically loaded reciprocal tracking phase shifter. The design of $0^\circ/180^\circ$ nonreciprocal phase shifters requires longer ferrite slab, hence, causing higher insertion loss of the phase shifter. The circulator design using Figure 1(b) causes an amplitude unbalance because the insertion loss of the ferrite is higher than that of the dielectric. The design in Figure 1(c) uses two magic tees, two identical $0^\circ/90^\circ$ nonreciprocal phase shifters, and two dielectrically loaded reciprocal phase shifters which provide a fixed reciprocal phase difference of 90° between the two phase shifters over the operating frequency range. For wideband design, the reciprocal phase shifters imposes serious limitations on the

bandwidth because a phase shift of approximately 90° cannot be maintained across a wide range of frequencies. The approach using Figure 1(d) uses two magic tees and two non-identical nonreciprocal phase shifters. Phase tracking requirement over wide bandwidth can be met more easily using this technique. This approach was used in our design. Scattering matrix analysis for this configuration is shown in the next section.

2.1 Scattering Matrix Analysis of Circulator

Dynamic behavior of a four port differential phase shift circulator can be described using scattering matrix analysis. Employing scattering matrix, wave amplitude emerging from all four ports can be described as a function of input wave amplitude and scattering parameters of all the interconnected devices. Figure 2 shows four port differential phase shift circulator configuration used for analysis. Instead of using a conventional S-parameter notation such as S_{ij} , a slightly different notation is used in this analysis. They are defined as follows:

- X_i - indicates wave amplitude entering into Port i of the magic tee 1.
- x_i - indicates wave amplitude leaving from port i of the magic tee 1.
- a_{ij} - indicates scattering parameter of the magic tee 1.
- Y_i - indicates wave amplitude entering into Port i of the magic tee 2.
- y_i - indicates wave amplitude leaving from Port i of the magic tee 2.
- b_{ij} - indicates scattering parameter of the magic tee 2.

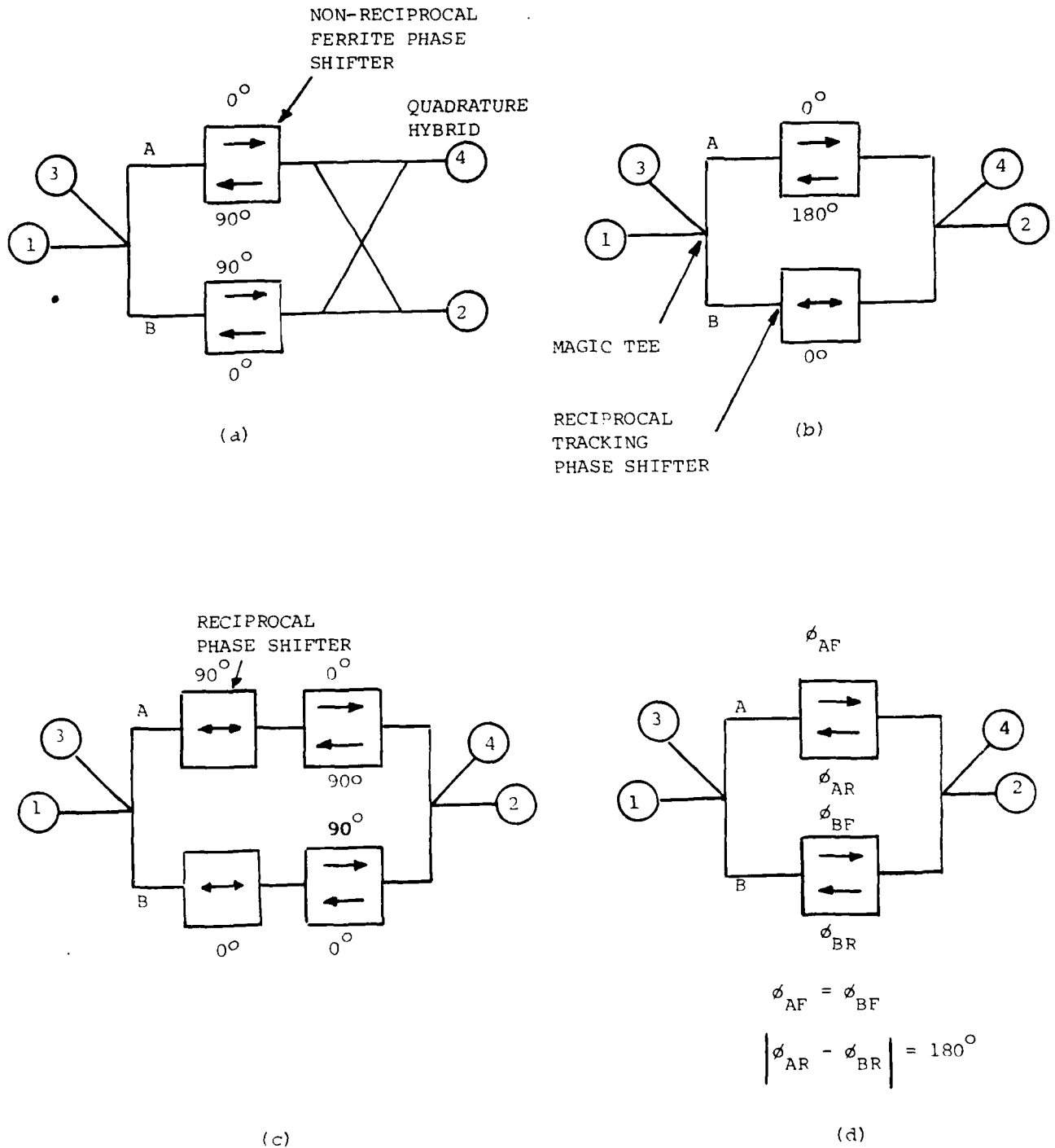


Figure 1. Circulator Configurations

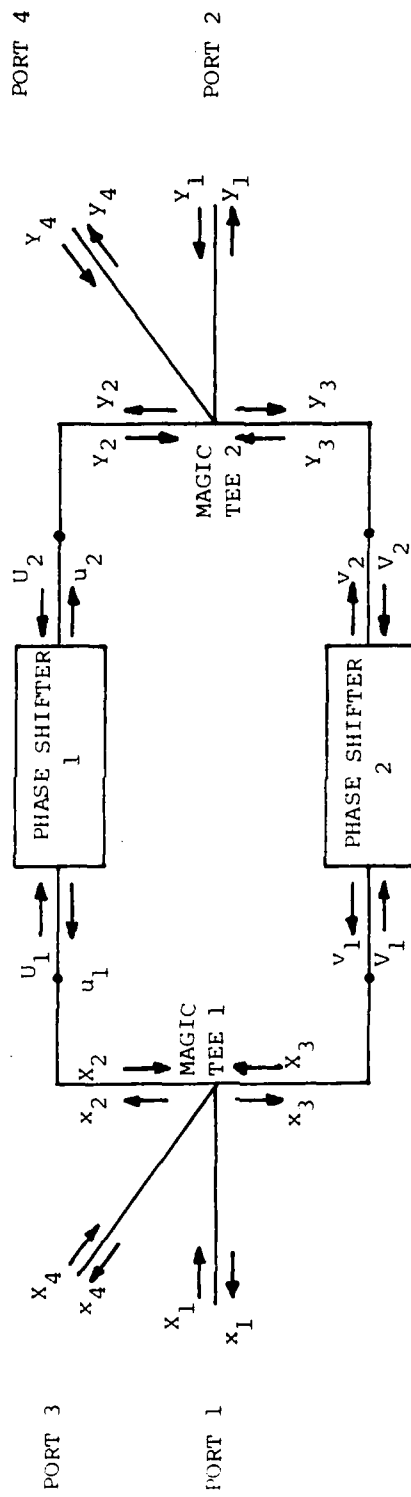


Figure 2. Circulator Configuration for Scattering Matrix Analysis

- U_i - indicates wave amplitude entering into Port i of the phase shifter 1.
 u_i - indicates wave amplitude leaving from Port i of the phase shifter 1.
 c_{ij} - indicates scattering parameter of the phase shifter 1.
 V_i - indicates wave amplitude entering into Port i of the phase shifter 2.
 v_i - indicates wave amplitude leaving from port i of the phase shifter 2.
 d_{ij} - indicates scattering parameter of the phase shifter 2.

All of the parameters defined above are complex quantities involving magnitude and phase. According to the notations given above, each device can be expressed as:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} \quad \text{For magic tee 1} \quad (1)$$

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \\ b_{31} & b_{32} & b_{33} & b_{34} \\ b_{41} & b_{42} & b_{43} & b_{44} \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \end{bmatrix} \quad \text{For magic tee 2} \quad (2)$$

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} \quad \text{For phase shifter 1} \quad (3)$$

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad \text{For phase shifter 2} \quad (4)$$

And we have the following relations:

$$\begin{aligned} X_2 &= u_1 \\ X_3 &= v_1 \\ Y_2 &= u_2 \\ Y_3 &= v_2 \end{aligned} \tag{5}$$

$$\begin{aligned} U_1 &= x_2 \\ U_2 &= y_2 \\ V_1 &= x_3 \\ V_2 &= y_3 \end{aligned} \tag{6}$$

We can identify X_1 , X_4 , Y_1 , and Y_4 as input wave amplitude of the circulator and x_1 , x_4 , y_1 , and y_4 as output wave amplitude of the circulator.

Using equations (1) through (6), any output wave amplitude can be expressed as a function of input wave amplitude and scattering parameters of all the interconnected devices.

For example, if we consider Port 1 as an input port then:

$$X_4 = Y_1 = Y_4 = 0 \tag{7}$$

and output wave amplitude can be written as:

$$\begin{aligned} x_1 &= a_{11}X_1 + a_{12} (c_{11}x_2 + c_{12}y_2) + a_{13} (d_{11}x_3 + d_{12}y_3) \\ x_4 &= a_{41}X_1 + a_{42} (c_{11}x_2 + c_{12}y_2) + a_{43} (d_{11}x_3 + d_{12}y_3) \\ y_1 &= b_{12} (c_{21}x_2 + c_{22}y_2) + b_{13} (d_{21}x_3 + d_{22}y_3) \\ y_4 &= b_{42} (c_{21}x_2 + c_{22}y_2) + b_{43} (d_{21}x_3 + d_{22}y_3) \end{aligned} \tag{8}$$

where x_2 , x_3 , y_2 , and y_3 can be obtained by solving the following simultaneous equations:

$$\begin{bmatrix} (1-a_{22}c_{11}) & -a_{23}d_{11} & -a_{22}c_{12} & -a_{23}d_{12} \\ -a_{32}c_{11} & (1-a_{33}d_{11}) & -a_{32}c_{12} & -a_{33}d_{12} \\ -b_{22}c_{21} & -b_{23}d_{21} & (1-b_{22}c_{22}) & -b_{23}d_{22} \\ -b_{32}c_{21} & -b_{33}d_{21} & -b_{32}c_{22} & (1-b_{33}d_{22}) \end{bmatrix} \begin{bmatrix} x_2 \\ x_3 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} a_{21}x_1 \\ a_{31}x_1 \\ 0 \\ 0 \end{bmatrix} \quad (9)$$

Similarly, we can obtain all the output wave amplitude involving with different input port.

If we assume ideal magic tee, scattering matrix of ideal magic tee can be written as:

$$\begin{bmatrix} 0 & 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 1/\sqrt{2} & 0 & 0 & 1/\sqrt{2} \\ 1/\sqrt{2} & 0 & 0 & -1/\sqrt{2} \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} & 0 \end{bmatrix} \quad (10)$$

and the equation (8) can be reduced to:

$$x_1 = \frac{x_1}{2} (c_{11} + d_{11})$$

$$x_4 = \frac{x_1}{2} (c_{11} - d_{11})$$

(11)

$$y_1 = \frac{x_1}{2} (c_{21} + d_{21})$$

$$y_4 = \frac{x_1}{2} (c_{21} - d_{21})$$

3.0 FERRITE MATERIAL

Choice of a ferrite material for our application involves the following considerations.

- (a) The material should be reproducible on a piece to piece basis - particularly free from density variations and $4\pi M_s$ variations.
- (b) The material should, when used in the device, have acceptably low rf magnetic loss at both low signal strength and high signal strength (i.e., not exhibit nonlinear loss mechanisms).
- (c) The material should have a low temperature coefficient of magnetization - this normally implies a Curie temperature in excess of 300°C .
- (d) The ratio $\gamma 4\pi M_s/W$ should be between 0.4 and 0.8. Below 0.4 the phase shift per unit length becomes too low, above 0.8 the ferrite exhibits low field loss.

Of the basic families of ferrite materials that are available (hybrid garnets, magnesium manganese, spinels, lithium ferrites and nickel ferrites) nickel ferrites are most useful at the frequency range and power level in consideration. They have high Curie temperature (greater than 450°C), suitable magnetization (1500 Gauss to 3100 Gauss) and acceptable magnetic loss. C-20 nickel ferrite material from Countis Industries was used for circulator design.

4.0 PHASE SHIFTER

4.1 Theoretical Analysis

Theoretical analysis was performed on dielectric and ferrite loaded ridge waveguide. The geometry under study is shown in Figure 3. Dielectric rib is fully extending across the ridge gap, and ferrite slabs are partially extending across the ridge gap. Exact solution to the given problem is very difficult to obtain, if not impossible. To approximate propagation constant of the dominant mode, transverse resonance equation was derived employing ABCD matrix method.¹

In ABCD matrix method, the electric field in the z direction and magnetic field in the y direction at $x = 0$ are related to the electric field in the z direction and the magnetic field in the y direction at $x = a$ by an ABCD matrix as

$$\begin{bmatrix} H_y (x = a) \\ E_z (x = a) \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} H_y (x = 0) \\ E_z (x = 0) \end{bmatrix} \quad (1)$$

Because the electric fields at the waveguide walls are zero, equation (1) can be written as:

$$\begin{bmatrix} H_y (x = a) \\ 0 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} H_y (x = 0) \\ 0 \end{bmatrix}$$

¹"TE-Mode Solutions for Partially Ferrite Filled Rectangular Waveguide Using ABCD Matrices", W.P. Clark, K.H. Hering, D.A. Charlton, MTT 1966.

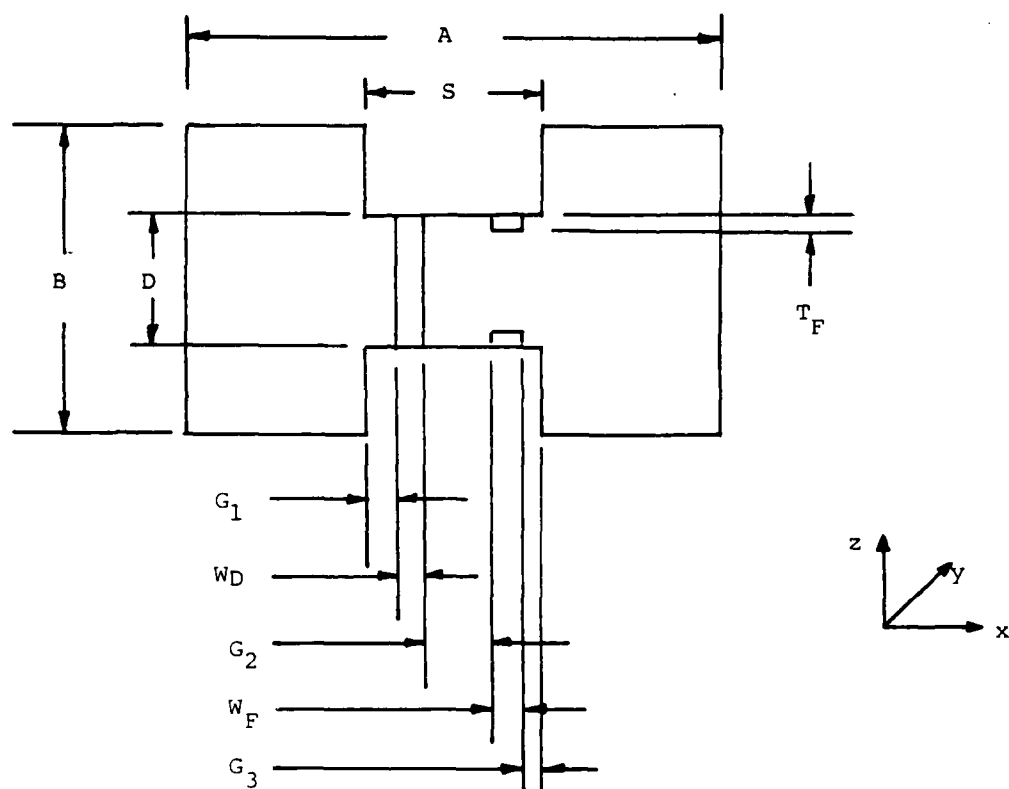


Figure 3. Dielectric and Ferrite Loaded Double Ridge Waveguide

or,

$$H_y (x = a) = A H_y (x = 0) \quad (2a)$$

$$0 = C H_y (x = 0) \quad (2b)$$

For nontrivial solution, the matrix term C must be zero.

Therefore, the transverse resonance equation requires

$$C = 0 \quad (3)$$

By applying the ABCD method to each region in Figure 3, the matrix quantity C can be calculated as follows:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \dots \begin{bmatrix} A_n & B_n \\ C_n & D_n \end{bmatrix} \quad (4)$$

ABCD matrix for each region can be represented as

i) Dielectric Region (including air)

$$A = \cos K_x \ell \quad (5a)$$

$$B = -j \frac{K_x}{\omega \mu_0} \sin K_x \ell \quad (5b)$$

$$C = -j \frac{\omega \mu_0}{K_x} \sin K_x \ell \quad (5c)$$

$$D = \cos K_x \ell \quad (5d)$$

$$\text{where } K_x^2 = K_0^2 \epsilon - \beta^2 \quad (6)$$

ℓ is the width of the region

ii) Ferrite region (H_0 and M_0 are in +z direction)

$$A = \cos K_{xf} \ell - \frac{j\beta}{K_{xf}\theta} \sin K_{xf} \ell \quad (7a)$$

$$B = \frac{j\rho}{\omega\mu K_{xf}} \left(\frac{\beta^2}{\theta^2} - K_{xf}^2 \right) \sin K_{xf} \ell \quad (7b)$$

$$C = \frac{-j\omega\mu}{\rho K_{xf}} \sin K_{xf} \ell \quad (7c)$$

$$D = \cos K_{xf} \ell + \frac{j\beta}{K_{xf}\theta} \sin K_{xf} \ell \quad (7d)$$

$$\text{where } K_{xf}^2 = \frac{\omega^2 \mu \epsilon_f}{\rho} - \beta^2 \quad (8)$$

$$\rho = \frac{1 + \chi_{xx}}{(1 + \chi_{xx})^2 + \chi_{xy}^2} \quad (9a)$$

$$\theta = \frac{1 + \chi_{xx}}{\chi_{xy}} \quad (9b)$$

$$\chi_{xx} = \frac{(\gamma 4\pi M_o) (\gamma H_o)}{(\gamma H_o)^2 - \omega^2} \quad (10a)$$

$$\chi_{xy} = \frac{-j(\gamma 4\pi M_o)\omega}{(\gamma H_o)^2 - \omega^2} \quad (10b)$$

γ is the electron gyromagnetic ratio

M_o is the ferrite magnetization

H_o is the internal DC magnetic field

ω is the angular frequency of the electromagnetic field.

If H_o and M_o are in $-z$ direction, χ_{xx} is unchanged and χ_{xy} changes sign.

In the region where the internal DC magnetic field is small compared to the angular frequency, equation (10) can be simplified as

$$X_{xx} \approx 0 \quad (11a)$$

$$X_{xy} \approx j \frac{\gamma 4 \pi M_0}{\omega} \quad (11b)$$

iii) Height change (See Figure 4)

When the height of the transmission line in the transverse plane changes from b to d , ABCD matrix can be written as

$$A = d/b \quad (12a)$$

$$B = 0 \quad (12b)$$

$$C = 0 \quad (12c)$$

$$D = 1 \quad (12d)$$

iv) Junction Capacitance (See Figure 4)

The ridge in the waveguide presents discontinuities to the electromagnetic waves and causes local fields. The effects of these local fields are capacitive in nature and included in the transmission line as discontinuity susceptance. ABCD matrix can be written as

$$A = 1 \quad (13a)$$

$$B = B_c \quad (13b)$$

$$C = 0 \quad (13c)$$

$$D = 1 \quad (13d)$$

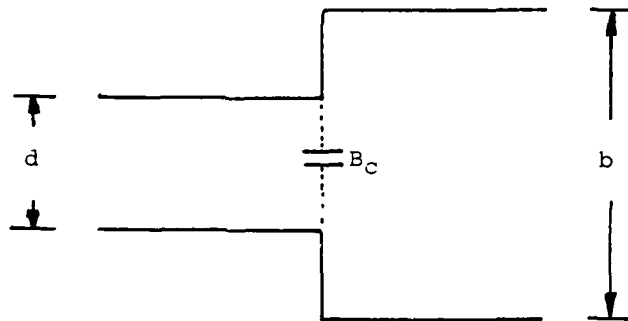


Figure 4. Transmission Line Model for Height Change and Junction Capacitance

Where jB_c is capacitive junction susceptance. The value of B_c can be obtained from the equation below.²

$$\frac{B_c}{Y_{01}} = \frac{2b}{\lambda_g} \left[\ln \left(\frac{1 - \alpha^2}{4\alpha} \right) \left(\frac{1 + \alpha}{1 - \alpha} \right)^{(\alpha + 1/\alpha)/2} + 2 \frac{(\lambda + A' + 2C)}{AA' - C^2} + \left(\frac{b}{4\lambda_g} \right)^2 \left(\frac{1 - \alpha}{1 + \alpha} \right)^{4\alpha} \left(\frac{5\alpha^2 - 1}{1 - \alpha^2} + \frac{4\alpha^2 C}{3A} \right)^2 \right] \quad (14)$$

$$\text{Where } A = \left(\frac{1 + \alpha}{1 - \alpha} \right)^{2\alpha} \frac{1 + \sqrt{1 - (b/\lambda_g)^2}}{1 - \sqrt{1 - (b/\lambda_g)^2}} - \frac{1 + 3\alpha^2}{1 - \alpha^2} \quad (15a)$$

$$A' = \left(\frac{1 + \alpha}{1 - \alpha} \right)^{2/\alpha} \frac{1 + \sqrt{1 - (d/\lambda_g)^2}}{1 - \sqrt{1 - (d/\lambda_g)^2}} + \frac{3 + \alpha^2}{1 - \alpha^2} \quad (15b)$$

$$C = \left(\frac{4\alpha}{1 - \alpha^2} \right)^2 \quad (15c)$$

$$\alpha = d/b \quad (15d)$$

$$\lambda_g = \frac{2\pi}{K_{x1}} \quad (15e)$$

$$Y_{01} = - \frac{K_{x1}}{\omega \mu_0} \quad (15f)$$

$$K_{x1} = \sqrt{K_0^2 \epsilon_0 - \beta^2} \quad (15g)$$

Note: The value of B_c obtained from equation (14) assumes homogeneous loading of dielectric in the ridge waveguide. In case of inhomogeneous loading of dielectric in the ridge waveguide, the value of B_c may be used as crude approximation.

²"Waveguide Handbook", N. Marcuvitz, McGraw-Hill, 1951.

The solution for the propagation constant of the geometry shown in Figure 3 was programmed for the Hewlett Packard 9845 desk top computer. A copy of that program is included as Appendix B of this report.

In the preceeding analysis it was assumed that the ferrite region was fully filled. In practice it will only be partially filled in a high power circulator. It was found that an averaging technique could be used to adequately represent the partially loaded ferrite structure. The approximate values were determined by a set of iterations comparing analysis with measured results.

4.2 Phase Tracking

To implement the design of a four port differential phase shift circulator using two magic tees and two non-identical nonreciprocal phase shifters as shown in Figure 1(d), the following conditions are imposed upon the phase shifters:

$$\phi_{AF} = \phi_{BF} \quad (16)$$

$$\phi_{AR} - \phi_{BR} = 180^\circ \quad (17)$$

where: ϕ_{AF} is insertion phase of Phase Shifter A in forward direction.
 ϕ_{BF} is insertion phase of Phase Shifter B in forward direction.
 ϕ_{AR} is insertion phase of Phase Shifter A in reverse direction.
 ϕ_{BR} is insertion phase of Phase Shifter B in reverse direction.

Due to the frequency dependence of phase characteristics, these requirements are difficult to meet over wideband.

There are many parameters which can effect insertion phase, such as width of the dielectric rib, dielectric constant, location of dielectric rib, dimension and location of ferrite slab, and biasing magnetic field strength. To meet the phase tracking requirement, the insertion phase differential of the two phase shifters at demagnetized state should be

reasonably uniform over frequency range, preferably about 90° . The choice of the dielectric constant and the width of the dielectric rib have the most significant effect in setting the proper amount of insertion phase differential. Typical insertion phase characteristics of dielectric and ferrite loaded phase shifter in WRD750D24 double ridge waveguide are shown in Figures 5 and 6. Two phase states due to oppositely directed biasing magnetic field are shown along with demagnetized phase state. Here we define longer phase state as β^- state and shorter phase state as β^+ state. The insertion phase characteristics of an empty WRD750D24 double ridge waveguide is also shown in the figures. In Figure 5, two phase shifters having the same dielectric constant are compared with respect to the variations in the width of the dielectric rib. In Figure 6, two phase shifters having the same width of dielectric rib are compared with respect to the variations in dielectric constant.

The phase tracking requirement given in equations (16) and (17) can be satisfied if we design the two phase shifters in such a way that:

- i) The insertion phase of one phase shifter, say phase shifter A, in β^+ state is equal to the insertion phase of another phase shifter, say phase shifter B, in β^- state over the operating frequency range.
- ii) The insertion phase of phase shifter A in β^- state is 180° degree longer than that of phase shifter B in β^+ state over the operating frequency range.

Dimensions:

Wide Rib: $G_1 = .014$, $W_D = .035$, $G_2 = .055$, $W_F = .050$

$G_3 = .019$, $T_F = .030$

Narrow Rib: $G_1 = .018$, $W_D = .027$, $G_2 = .059$, $W_F = .050$

$G_3 = .019$, $T_F = .030$

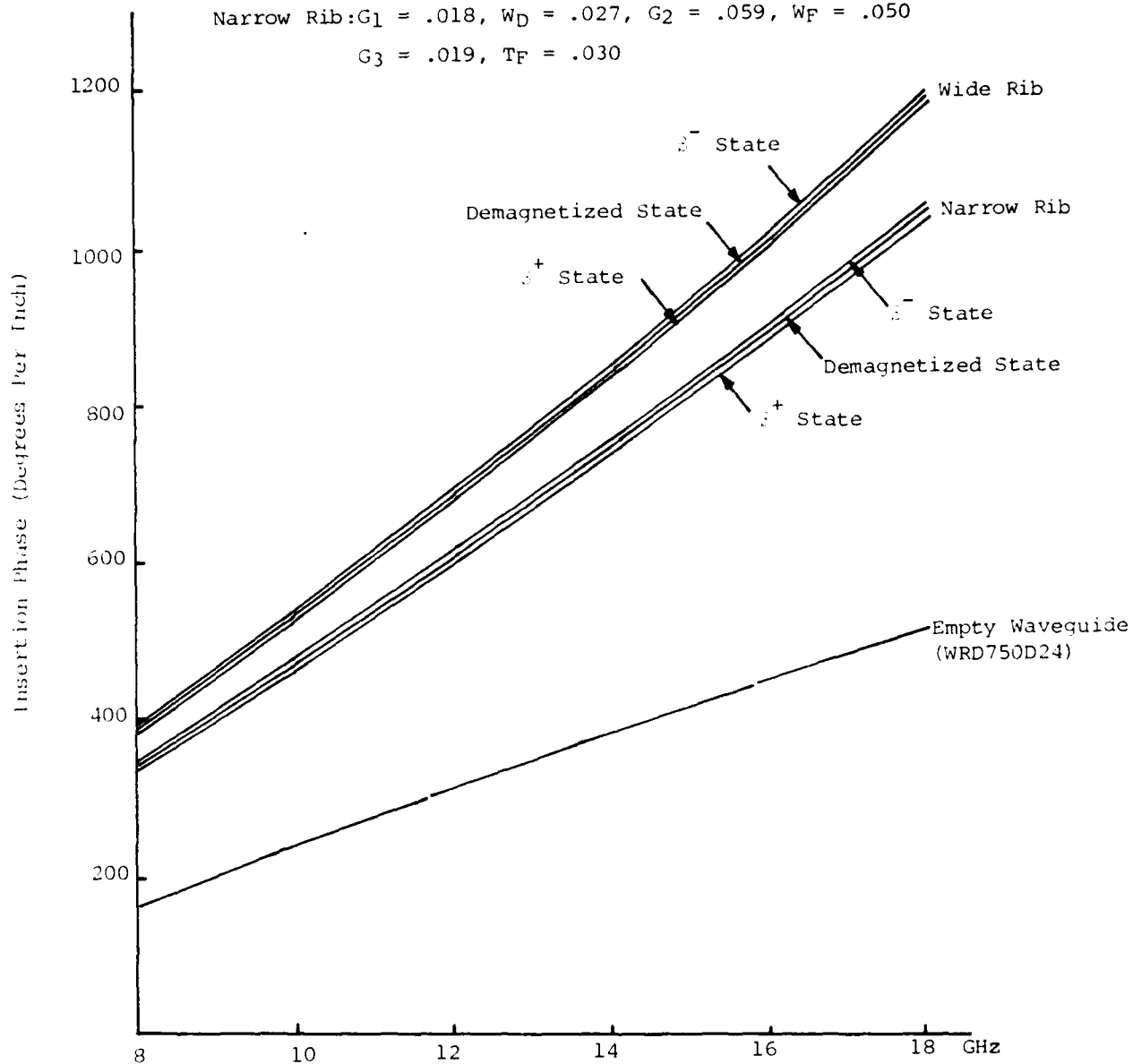


Figure 5. Phase Characteristics With Variations in the Width of Dielectric Rib (Dielectric Constant = 13)

Dimensions (Both Phase Shifters):

$G_1 = .018$, $W_D = .027$, $G_2 = .059$

$W_F = .050$, $G_3 = .019$, $T_F = .030$

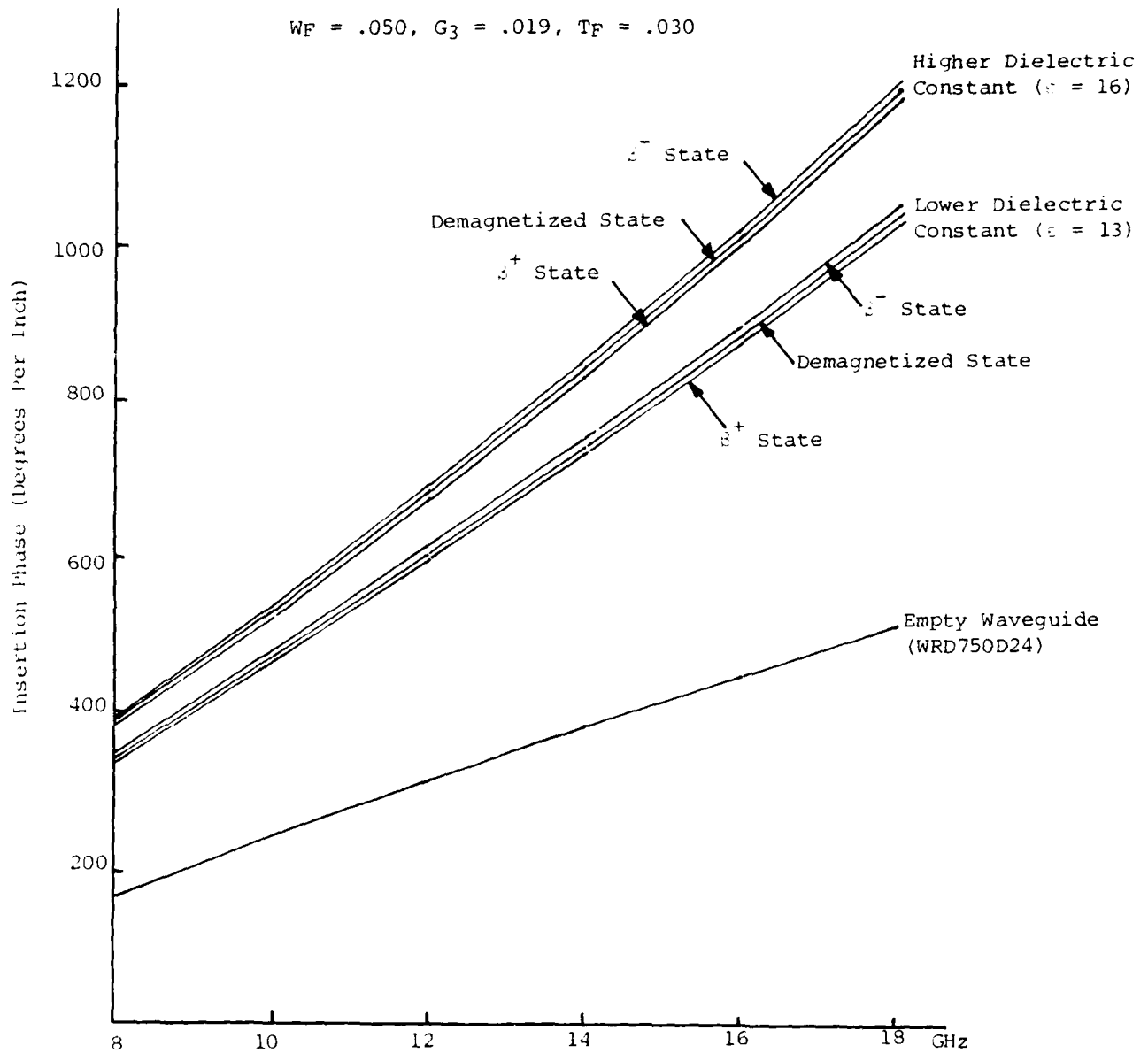


Figure 6. Phase Characteristics With Variations in the Dielectric Constant (Width of Dielectric Rib $W_D = .027$ ")

It can be accomplished by employing one phase shifter with shorter but wide dielectric rib (or higher dielectric constant) and another phase shifter with longer but narrow dielectric rib (or lower dielectric constant). The difference in length between these two sections is made up by length difference in the waveguide employed. The effect due to the insertion of matching transformers can be minimized by designing transformers having approximately the same insertion phase length for both phase shifters. Small insertion phase difference due to the matching transformer can be easily corrected by adjusting other parameter, such as location of dielectric rib and biasing magnetic field strength. Neglecting matching transformer, actual insertion phase differential of the two phase shifters at demagnetized state becomes:

$$\phi = \phi_N L_N - (\phi_W L_W + \phi_A L_A)$$

where ϕ_W is the phase length of wide phase shifter per inch at demagnetized state

ϕ_N is the phase length of narrow phase shifter per inch at demagnetized state

ϕ_A is the phase length of empty normal waveguide per inch

L_W is the physical length of wide phase shifter

L_N is the physical length of narrow phase shifter

L_A is the physical length of empty normal waveguide

$$L_N = L_W + L_A$$

By making adjustment of length, optimum result for uniform insertion phase differential can be obtained.

Once insertion phase differential is set within the acceptable range, fine adjustment can be made by adjusting location of dielectric rib and ferrite slab, and biasing H_{DC} field strength. Typical differential phase characteristics between S^- state and S^+ state with respect to the location of the dielectric rib is shown in Figure 7(a) and (b). When the dielectric rib is placed near the center of the ridge, it gives more differential phase at higher frequency. When the dielectric rib is moved toward the side, it gives more differential phase at lower frequency.

In practice, breadboard phase shifters were built based on computation, and absolute phase measurement was performed with variations in the width of dielectric rib, dielectric constant, location of dielectric and ferrite, and H_{DC} field strength. A simple computer program was written, and measured phase data were fed into the computer program to find optimum geometry. Introduction of matching sections introduced small deviation from optimum result, but compensation was done by adjusting the location of the dielectric rib.

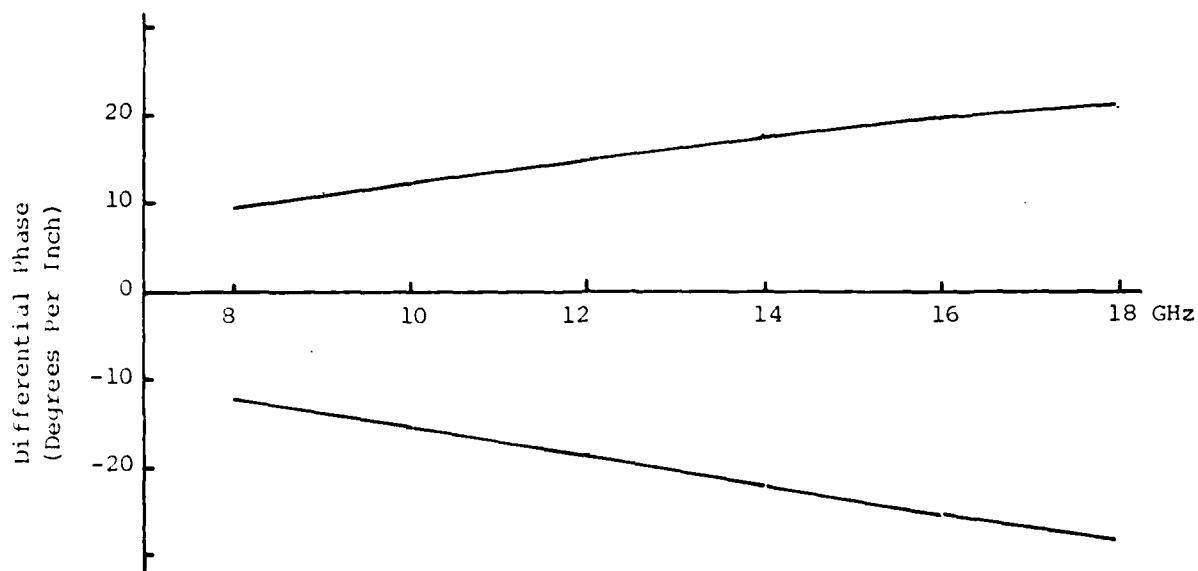


Figure 7(a). Differential Phase; Dielectric Rib is Loaded at the Center of the Ridge (WRD750D24)

$$G_1 = .069, W_D = .035, G_2 = 0, W_F = .050$$

$$G_3 = .019, T_F = .030, \epsilon = 13$$

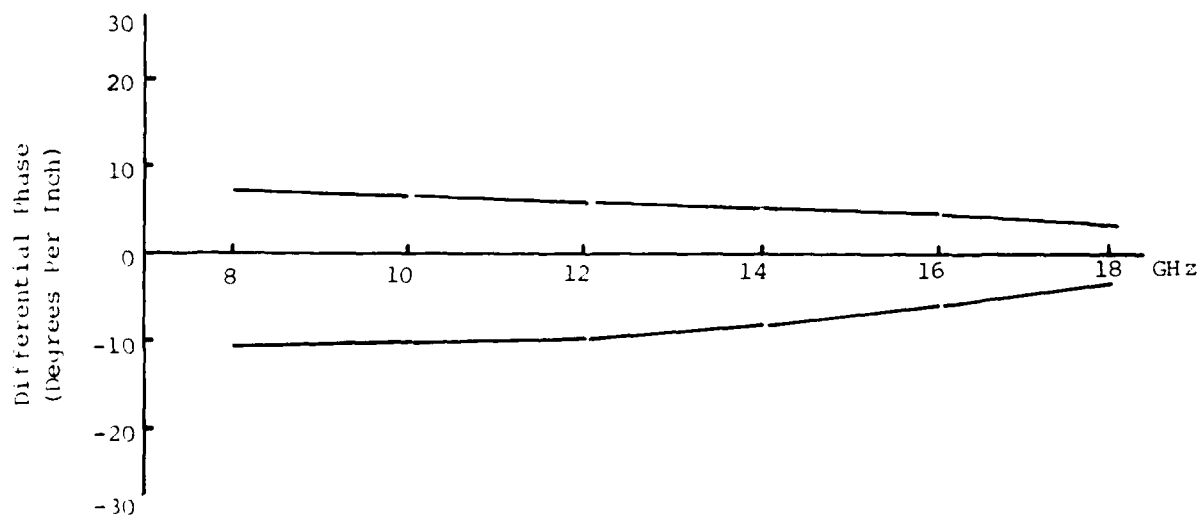


Figure 7(b). Differential Phase; Dielectric Rib is Loaded Near the Edge of the Ridge (WRD750D24)

$$G_1 = .014, W_D = .035, G_2 = .055, W_F = .050$$

$$G_3 = .019, T_F = .030, \epsilon = 13$$

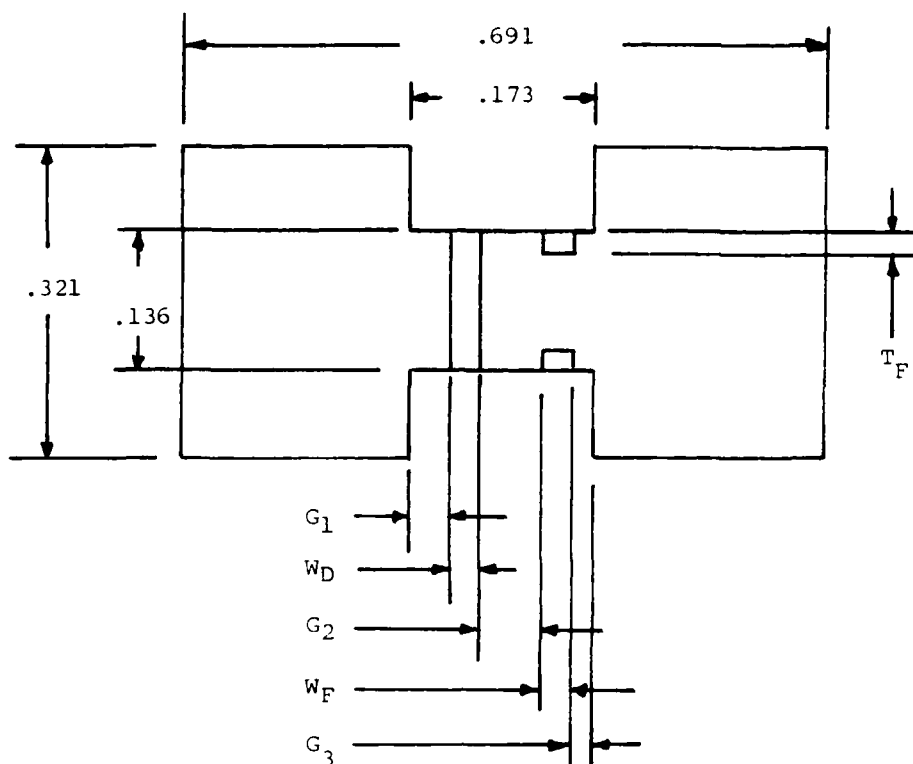
Figure 8 shows the actual dimension for phase shifters, and experimental results on phase are shown in Figure 9. (Note: Sign is inverted on phase scale, that is, bottom side has longer phase).

4.3 Matching

Chebyshev type 3 section dielectric loaded quarter wave transformers are utilized for both phase shifters. As mentioned above, the insertion of the matching transformers introduced small deviation from optimum result. By adjusting the location of the dielectric rib slightly, optimum result was obtained. Results on VSWR for both phase shifters are shown in Figures 10 and 11.

4.4 Insertion Loss

Figures 12 and 13 show total insertion loss for both phase shifters. These measurements include the line lengths of waveguide employed. Insertion loss can be reduced to some degree by improving VSWR and using low loss bonding material.



	<u>PHASE SHIFTER A</u>	<u>PHASE SHIFTER B</u>
G_1	.010"	.025"
W_D (Width of Dielectric Rib)	.035"	.0225"
G_2	.058"	.0455"
W_F (Width of Ferrite Slab)	.050"	.050"
G_3	.020"	.030"
T_F (Thickness of Ferrite Slab)	.030"	.030"
Length	3.890"	5.090"
Dielectric Constant	13	16

Figure 8. Dimensions for Phase Shifters

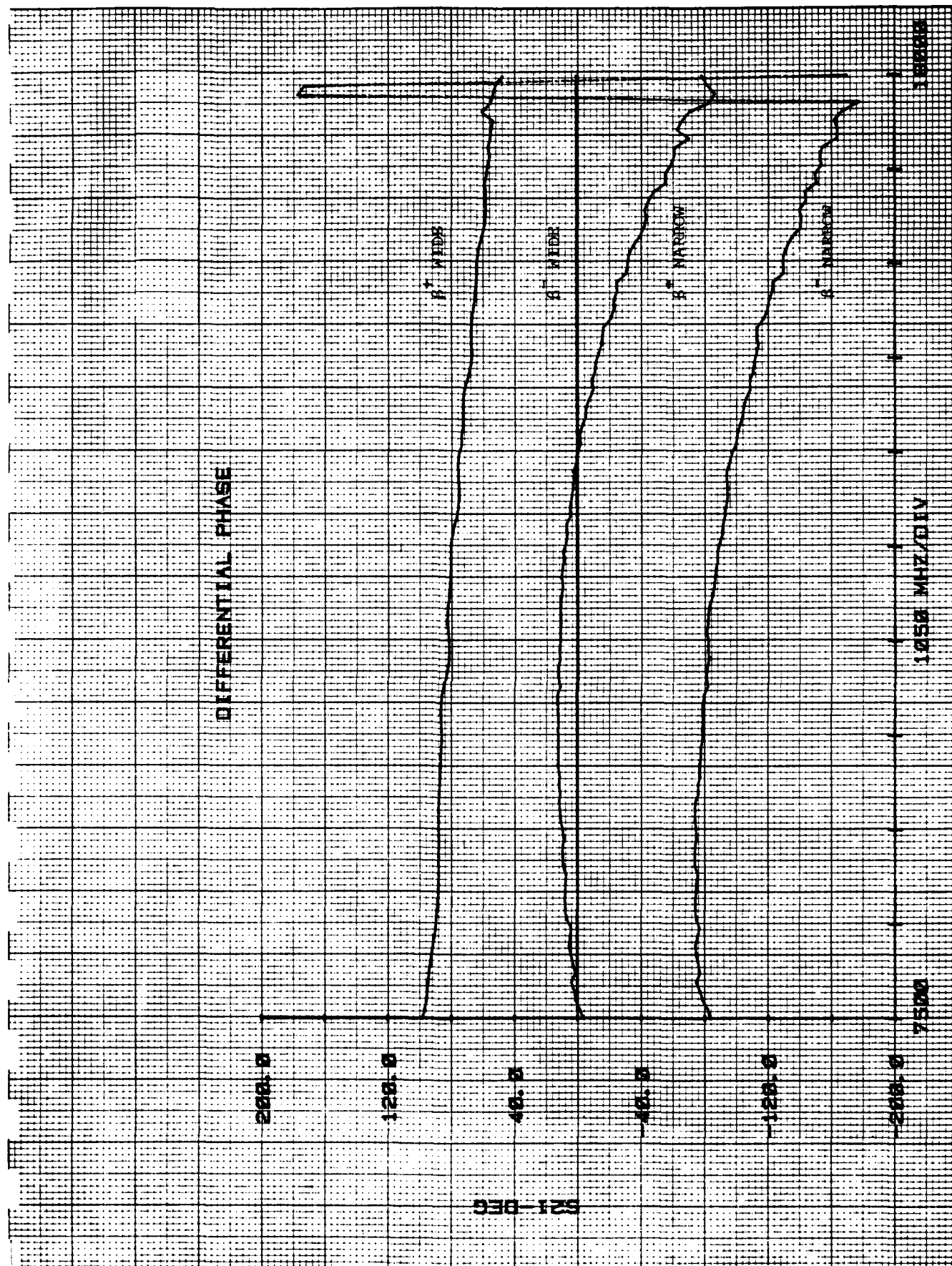


Figure 2. Differential Phase Shift

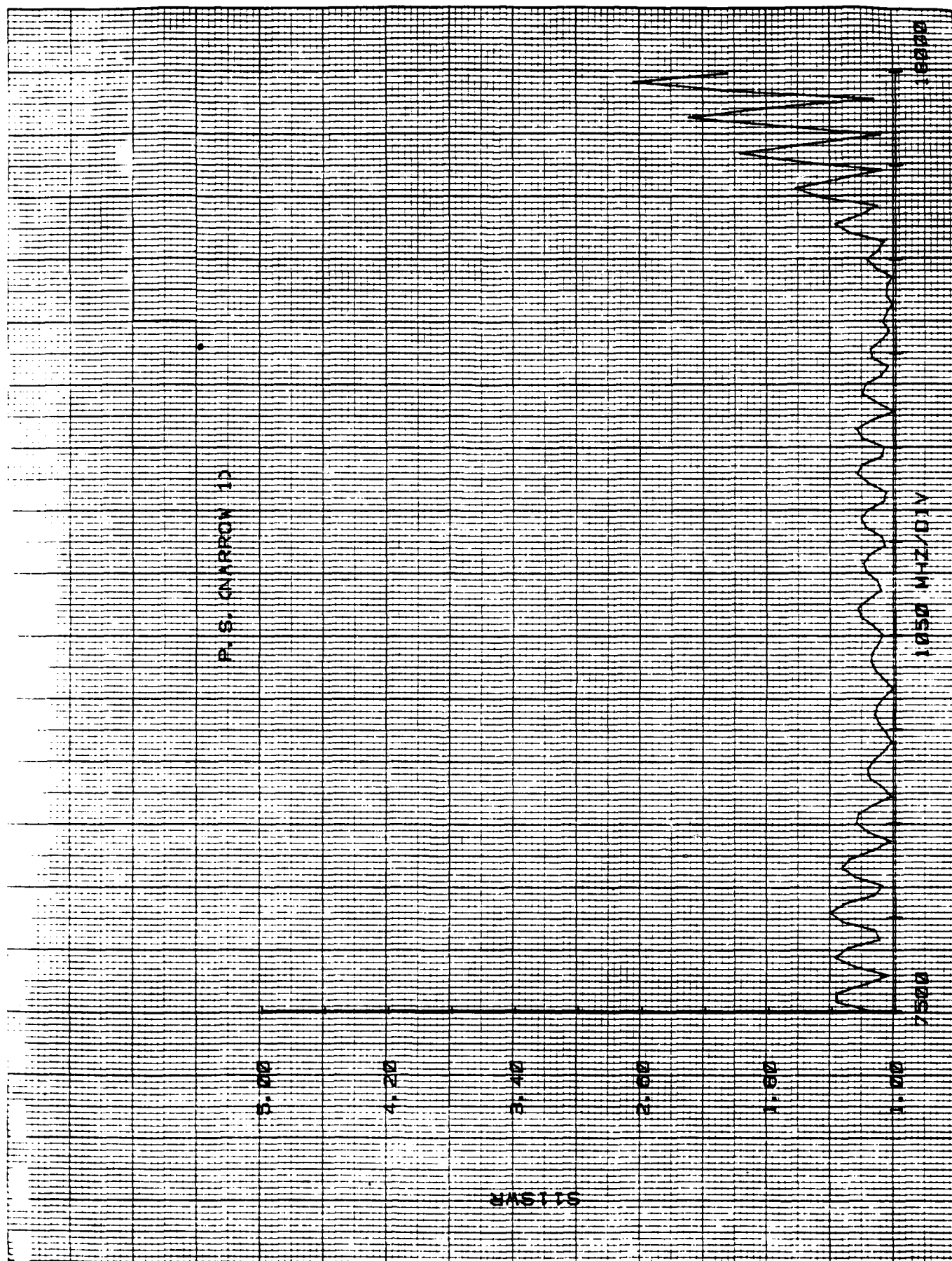


Figure 10. VSWR for Narrow Phase Shifter

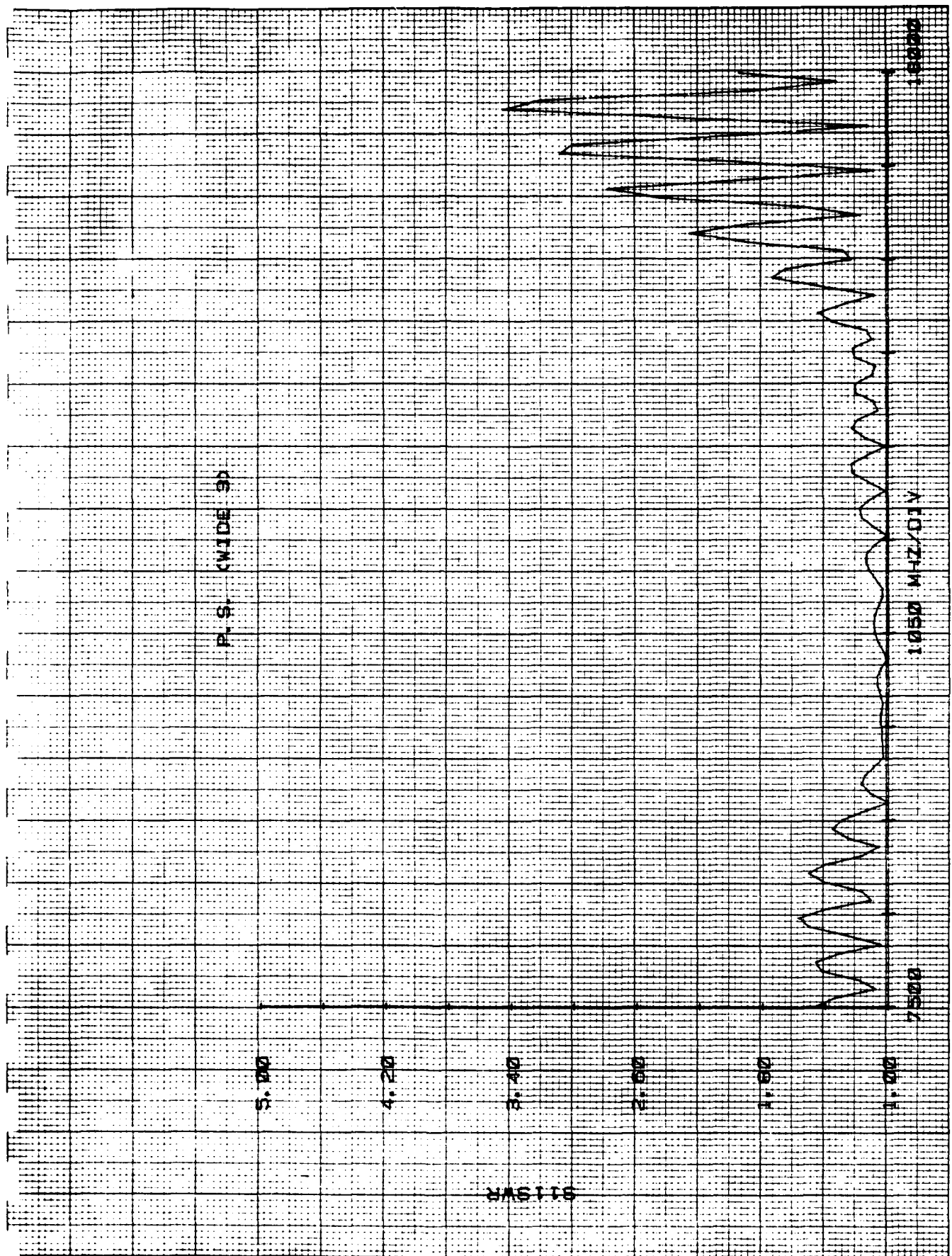


Figure 11. VSWR for wide phase shifter

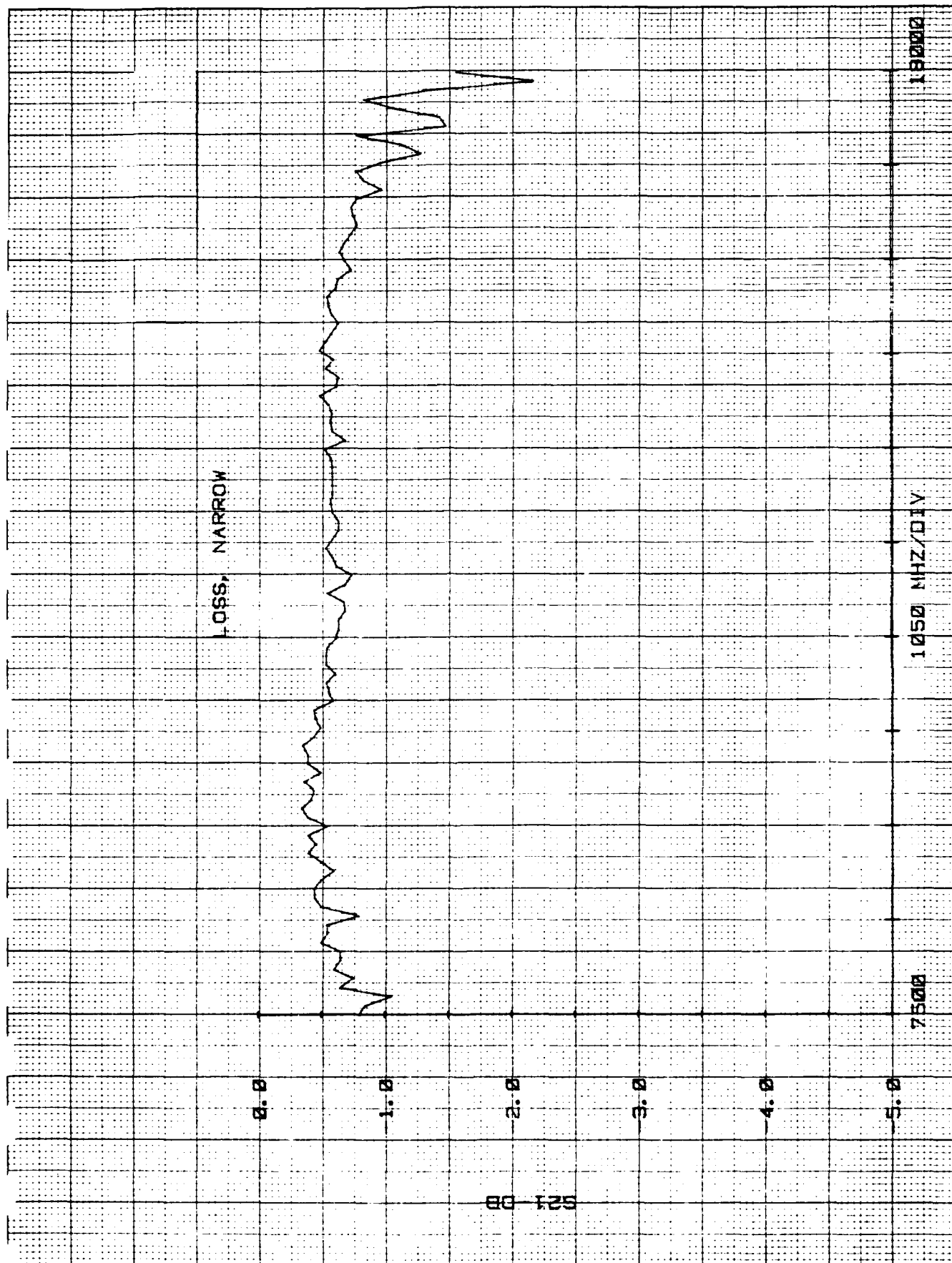


Figure 12. Insertion Loss for Narrow Phase Shifter

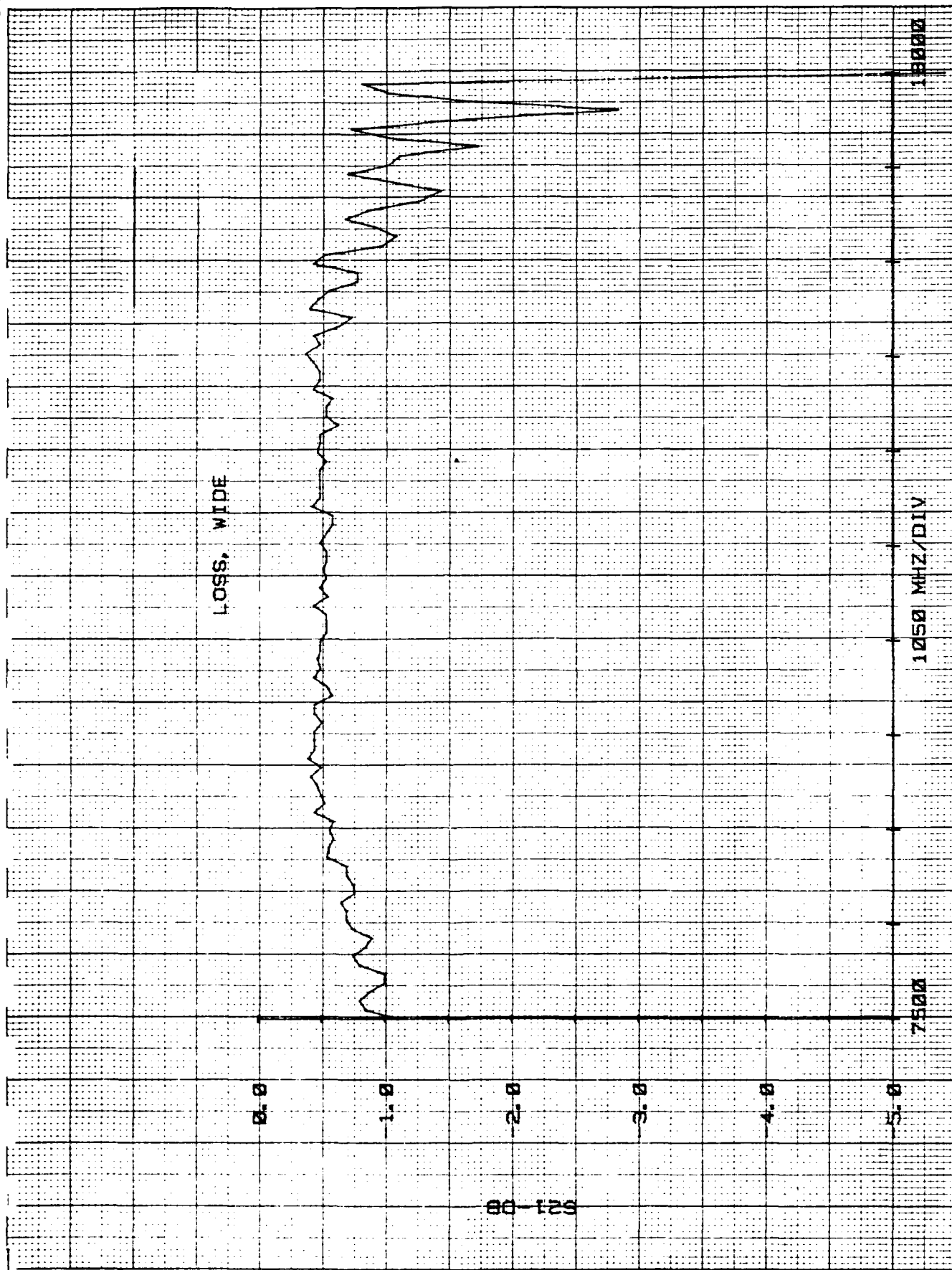


Figure 13. Insertion Loss for Wide Phase Shifter

5.0 MAGIC TEE

5.1 General Considerations

The major effort associated with the design of the hybrid magic tee is the impedance matching at the junction over the intended bandwidth. Methods of matching the junction include the use of reactive elements at the junction cavity, and transformers between the flanges of each arm and the actual junction at the cavity wall for each arm. In addition to matching problem, there are other considerations such as dissipated losses, phase balance, and power handling capacity. To minimize dissipated losses, it is desirable to avoid the use of dielectric materials, bonding agents or screws inside the waveguide cavity. Phase balance can be obtained as long as physical symmetry is maintained. In terms of power handling capacity, it is desirable to avoid sharp capacitive obstacles or low height construction in the waveguide.

5.2 Computer Analysis

In an attempt to study and design magic tee using double ridge waveguide, a computer program was written to find cutoff frequencies and characteristic impedance of double ridge waveguide. Cross-sectional shape of double ridge waveguide and its equivalent circuit representation is shown in Figure 14 and equations used for computation are summarized below without derivation.

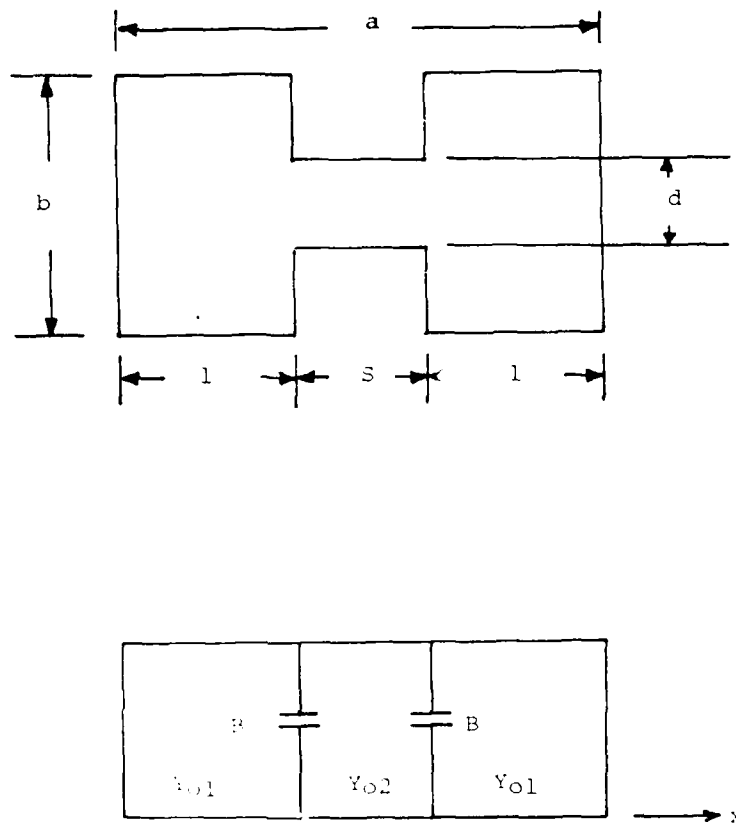


Figure 14. Double Ridge Waveguide Cross-Section and Its Equivalent Circuit Representation

(Original derivation of these equations can be found in Reference 3, 4, 5.)

The equations which govern the cutoff conditions of the TE_{no} type of modes are given by:

$$\cot k_x l - \frac{b}{d} \tan k_x s/2 - B/Y_{01} = 0 \quad (1)$$

$$\cot k_x l + \frac{b}{d} \cot k_x s/2 - B/Y_{01} = 0 \quad (2)$$

Equation (1) applies to the odd TE_{no} modes and (2) applies to the even TE_{no} modes. k_x is the propagation constant in the x direction at the cutoff and is given by $k_x = 2\pi/\lambda_c$. The characteristic admittances in the transverse direction (x-direction) Y_{01} and Y_{02} are defined as:

$$Y_{01} = \frac{k_x}{\omega \mu} \frac{1}{b} \quad Y_{02} = \frac{k_x}{\omega \mu} \frac{1}{d}$$

- (3) S.B. Cohn, "Properties of Ridge Waveguide", Proc. IRE, Vol. 35, pp. 783-788; August, 1947.
- (4) T.G. Mihran, "Closed and Open-Ridge Waveguide", Proc. IRE, Vol. 37, pp. 640-644; June, 1949.
- (5) S. Hopfer, "The Design of Ridge Waveguides", IRE. Trans., Vol. MTT-3, pp. 20-29; October, 1955

The value of the normalized susceptance term B/Y_{01} , which represents the effect of the step discontinuity, can be obtained from Waveguide Handbook².

Employing power-voltage impedance definition, the characteristic impedance at infinite frequency for the TE_{10} mode is given by:

$$Z_{pv}^{\infty} = \frac{2 * 120\pi^2}{2\pi \frac{c_d}{\epsilon_0} \cos^2 \theta_2 + \lambda_c \left[\frac{2}{d} + \frac{\sin^2 \theta_2}{2d} + \frac{2\cos^2 \theta_2}{b \sin^2 \theta_2} \left[\frac{1}{2} - \frac{\sin^2 \theta_1}{4} \right] \right]} \quad (3)$$

where λ_c is cutoff wavelength of ridge waveguide.

$$\theta_1 = \sin^{-1} \left(\frac{a-s}{\lambda_c} \right)$$

$$\theta_2 = \sin^{-1} \left(\frac{s}{\lambda_c} \right)$$

$$c_d = \frac{\epsilon_0}{\pi} \left[\frac{\left(\frac{d}{b} \right)^2 + 1}{\left(\frac{d}{b} \right)} \cosh^{-1} \left[\frac{1+(d/b)^2}{1-(d/b)^2} \right] - 2 \ln \frac{4(d/b)}{1-(d/b)^2} \right]$$

The characteristic impedance at any frequency f is obtained by:

$$Z_{pv}(f) = \frac{1}{\gamma} \times Z_{pv}^{\infty} = \frac{1}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} \quad (4)$$

5.3 Magic Tee Design

Initially, magic tee was designed based on intuitive reasoning. At the cavity junction impedance ratio of H-arm, colinear arm, and E-arm is assumed to be 1:2:4. Then Chebyshev type multisection quarterwave transformer between flanges of each arm (WRD750D24) and cavity junction of each arm were computed using equation (4). Cutoff frequencies of TE₁₀ and TE₂₀ mode at the junction were also computed. Based on the computed results, two sets of brassboard magic tees were made. Brassboard was chosen so that additional metal could be soldered in place whenever design modification is necessary. Figure 15 shows simplified sketch of the magic tee. For the purpose of evaluation of characteristic impedance of double ridge waveguide and verification of the theoretical result, each magic tee was made in three separate parts.

Part 1: H-Arm

Designed with four section step-down quarterwave transformer between WRD750D24 and H-arm junction.

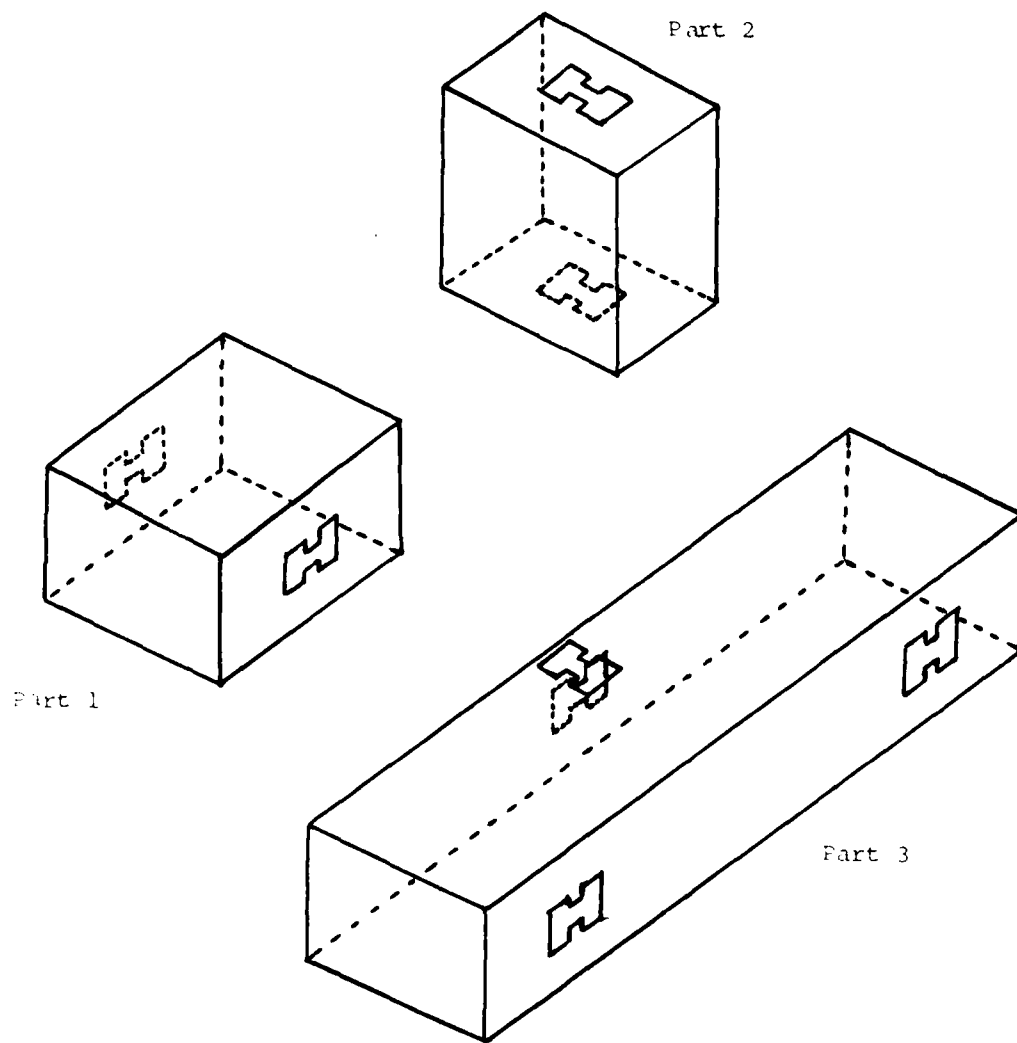


Figure 15. Brassboard Magic Tee

Part 2: E-Arm

Designed with 3 section step-up quarterwave transformer between WRD750D24 and E-arm junction.

Part 3: Colinear Arm Including Junction Cavity

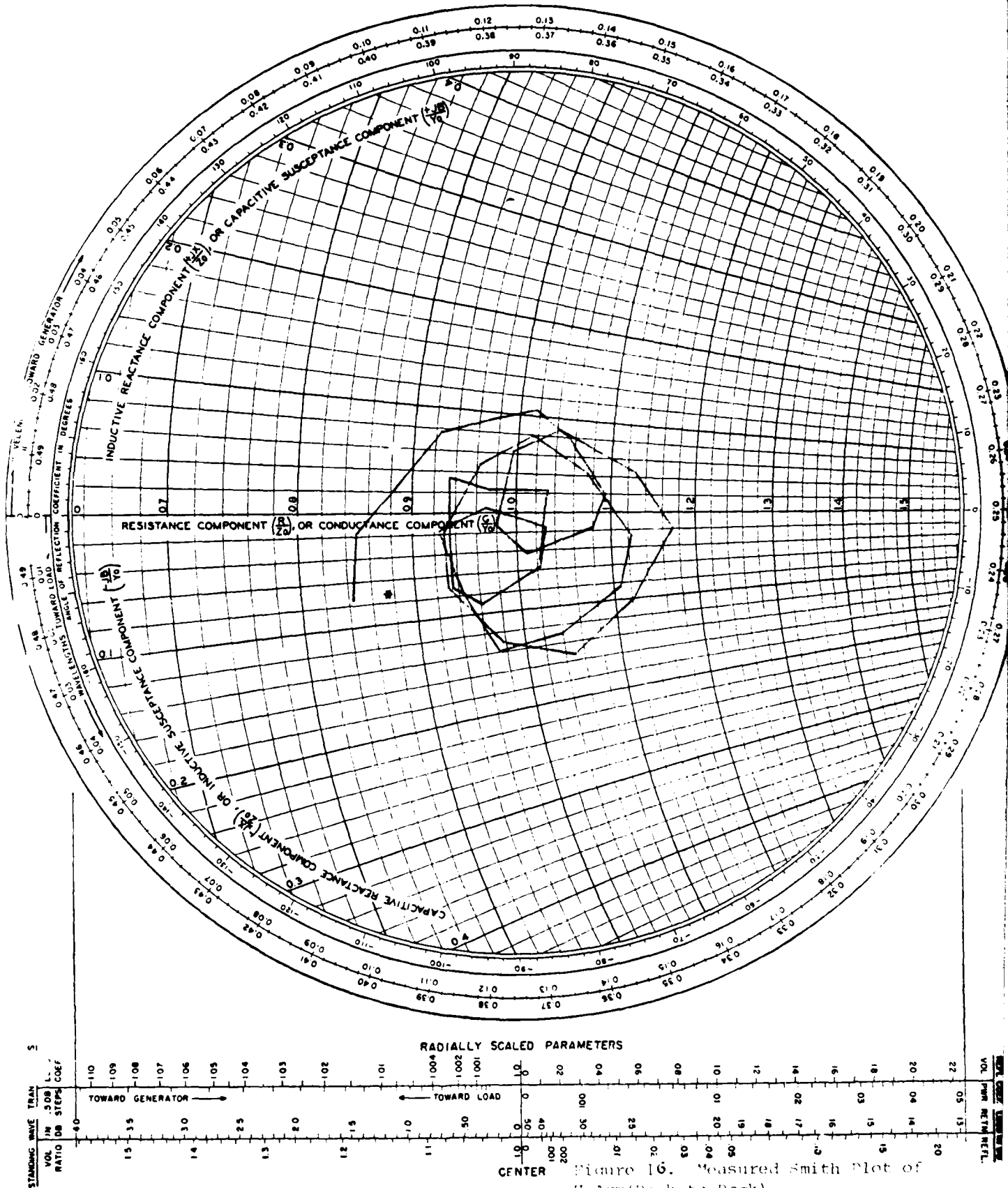
Designed with 4 section step-down quarterwave transformer between WRD750D24 and colinear arm junction.

Since Part 1 and Part 2 of the magic tee do not include junction cavity, these parts were used to verify computed characteristic impedance of the double ridge waveguide. VSWR of H-arm (two H-arm in back to back configuration) was measured and Smith Plot of the measured VSWR is shown in Figure 16. Smith Plot of VSWR for the same configuration was computed using transmission line equation employing characteristic impedance given by Equation (4). Computed results, shown in Figure 17, were in good agreement with experimental results.

Due to the difficulties of transmission line model including junction cavity, no attempt has been made to analyze magic tee as a whole theoretically. Instead, it was intended to find optimum matching structure experimentally by using reactive element at the junction cavity. The effect of reactive element can be measured at the flanges of each arm, and then these measured impedance can be transformed to cavity junction wall using transmission line equation. Based on these transformed impedance, necessary

NAME	TITLE	DWG. NO.
SMITH CHART FORM 82 SPR (2-49)	H-Arm BACK TO BACK KAY ELECTRIC COMPANY, PINE BROOK, N.J. ©1949 PRINTED IN U.S.A.	DATE

IMPEDANCE OR ADMITTANCE COORDINATES



NAME	TITLE	DWG. NO.
SMITH CHART FORM 82 SPR (2-49)	KAY ELECTRIC COMPANY, PINE BROOK, N.J. ©1949 PRINTED IN U.S.A.	DATE

IMPEDANCE OR ADMITTANCE COORDINATES

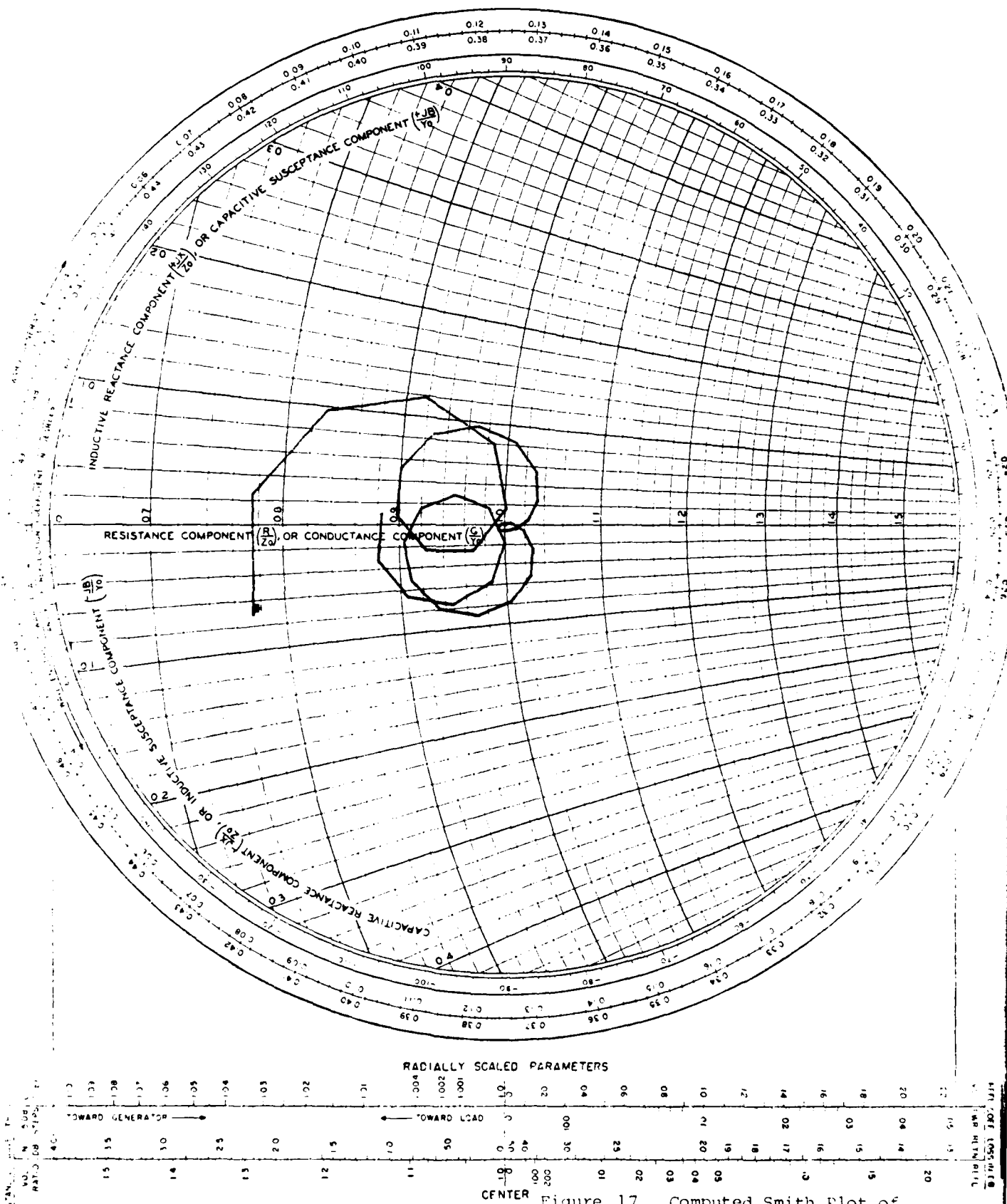


Figure 17. Computed Smith Plot of

modification can be made. This method requires iterative process of microwave measurement, engineering analysis, and modification. However, this method has not been pursued due to the time constraint. Therefore, magic tees designed by Raytheon for previous projects were used for final assembly of circulator. These magic tees were designed for frequency range between 8 to 18 GHz. Performance data of magic tees are shown in Figures 18 through 25.

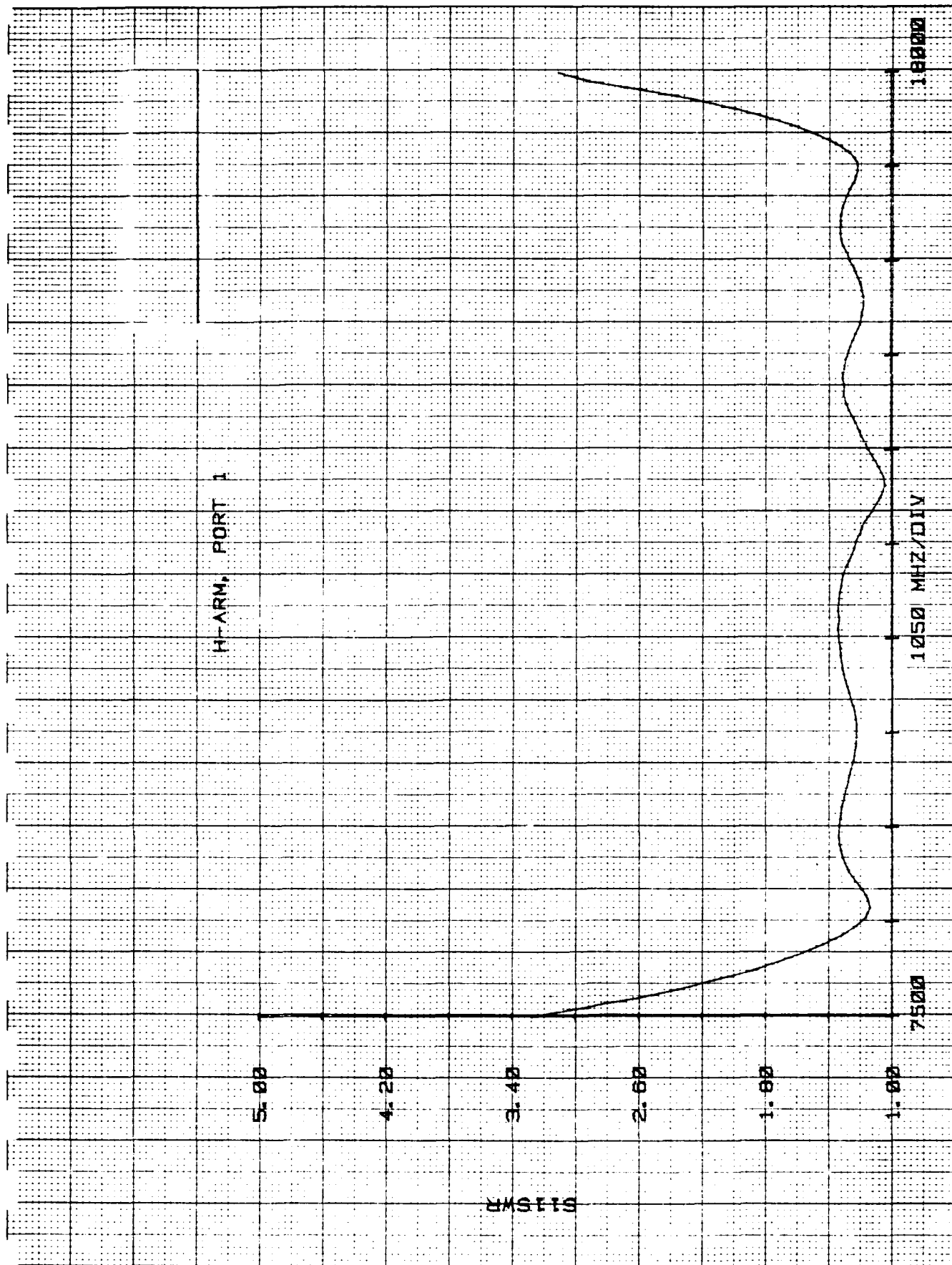


Figure 18. VSWR of H-Arm, Tee 1

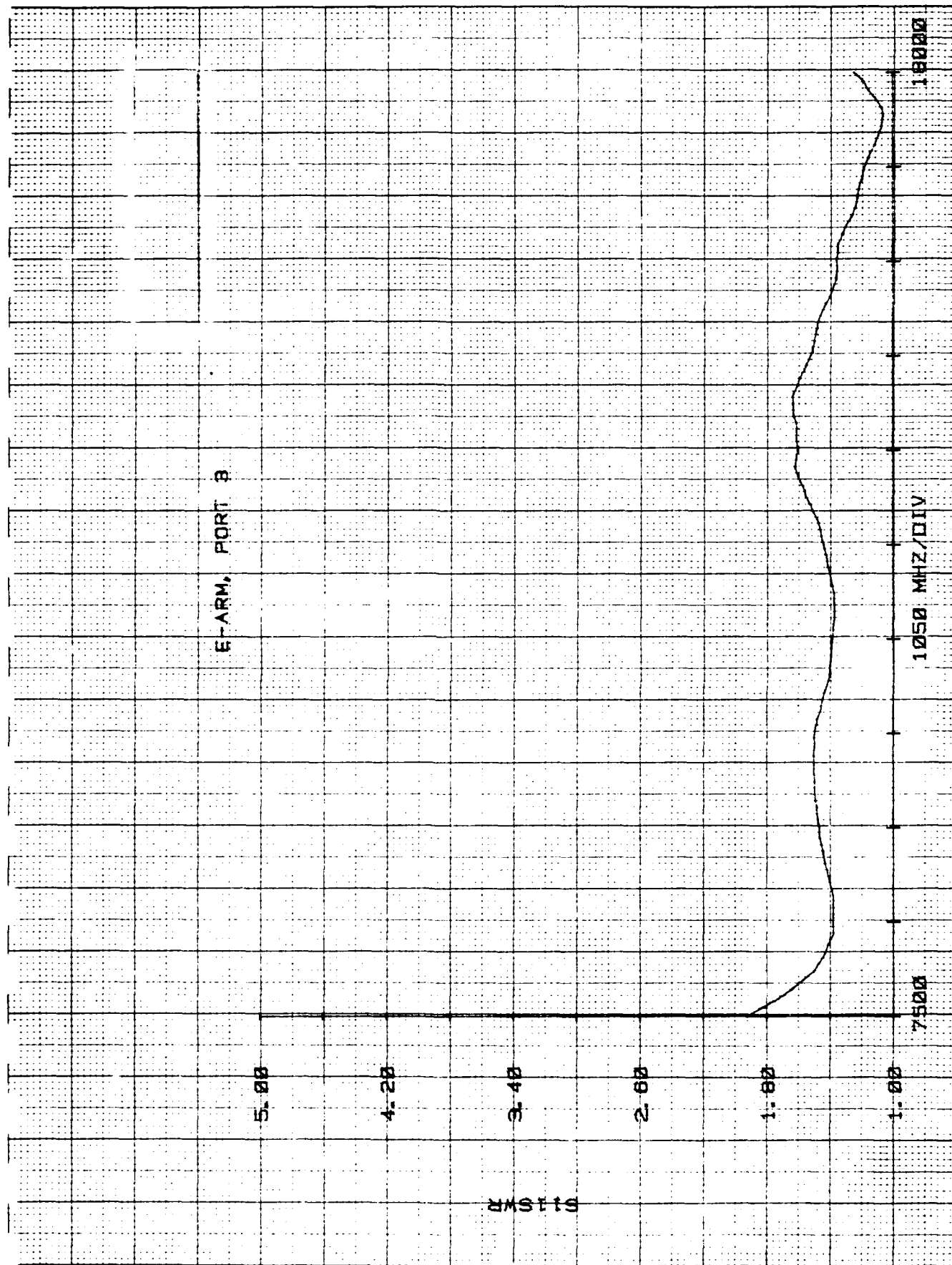


Figure 19. VSWR of E-Arm, Tee 1

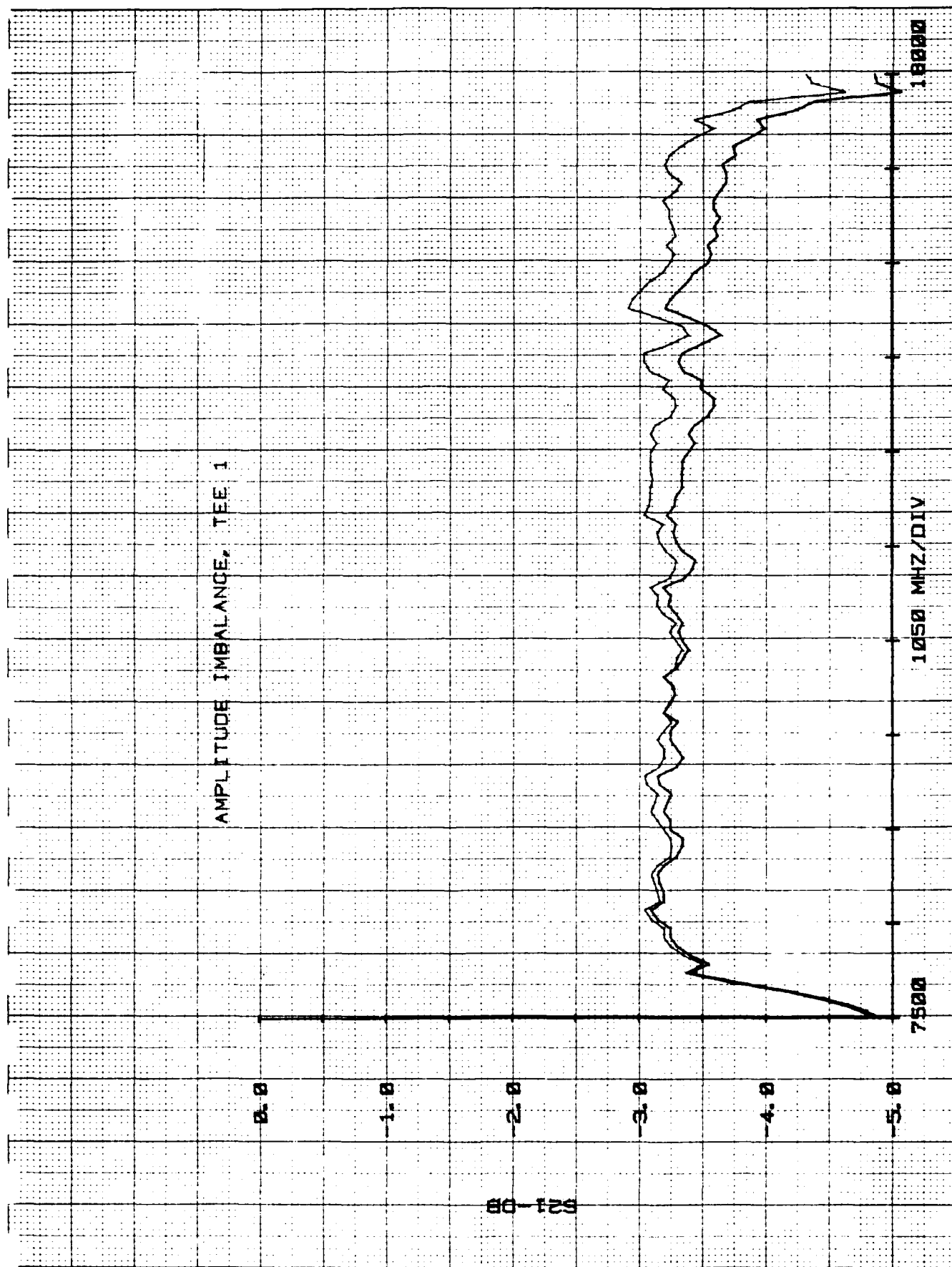


Figure 20. Amplitude Imbalance of Tee 1

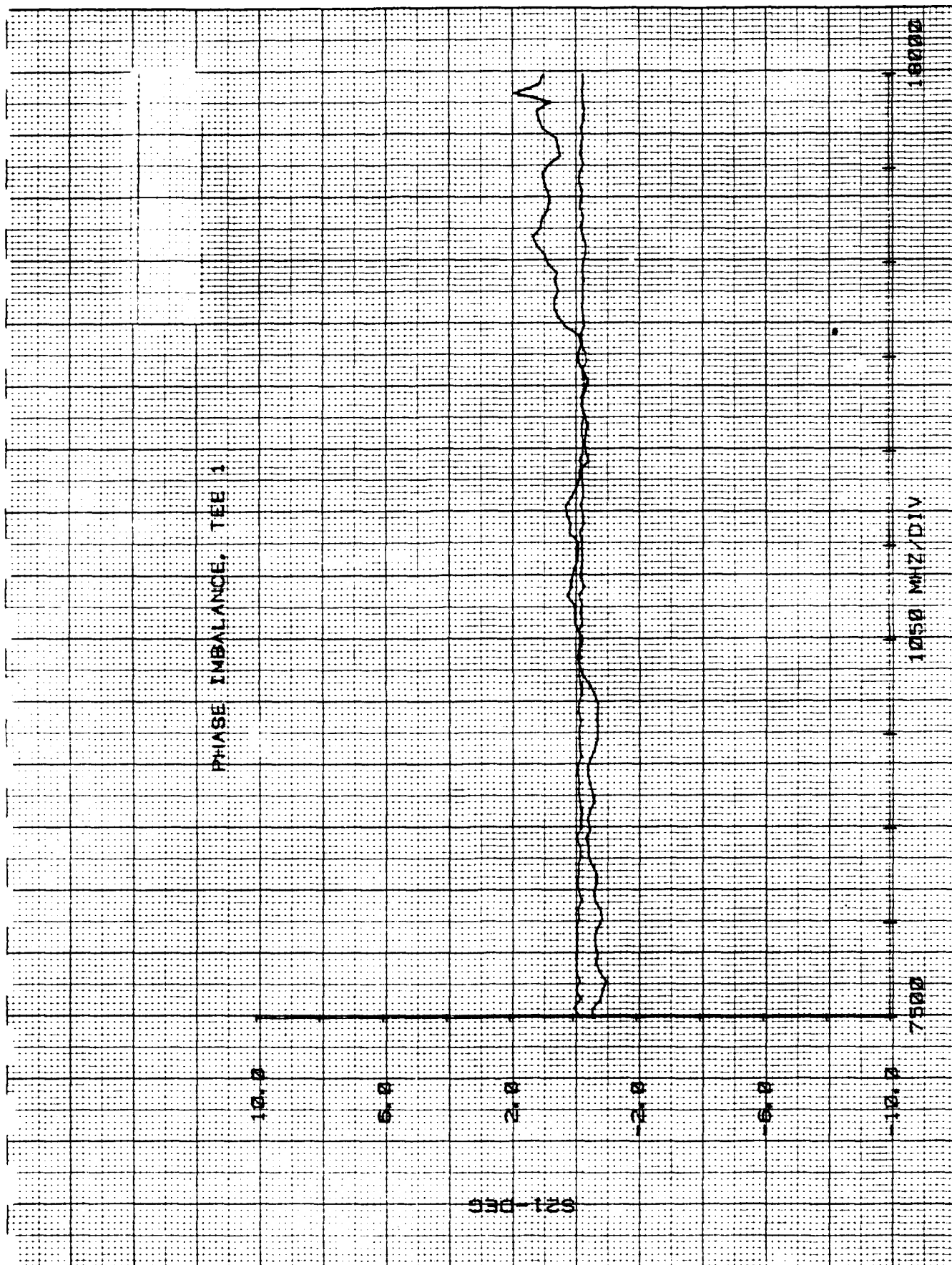


Figure 21. Phase Imbalance of Tee 1

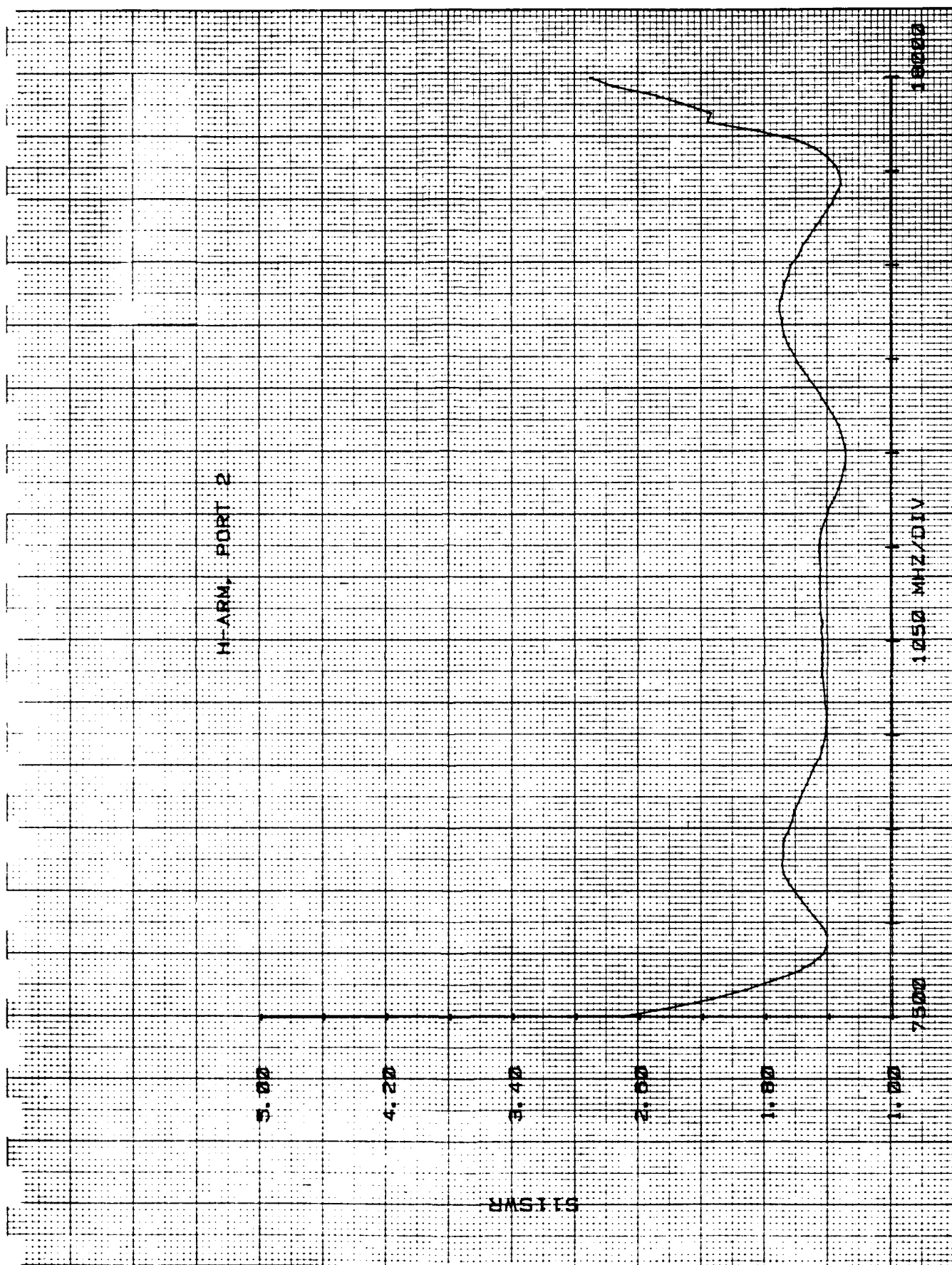


Figure 22. VSWR of H-Arm, Tee 2

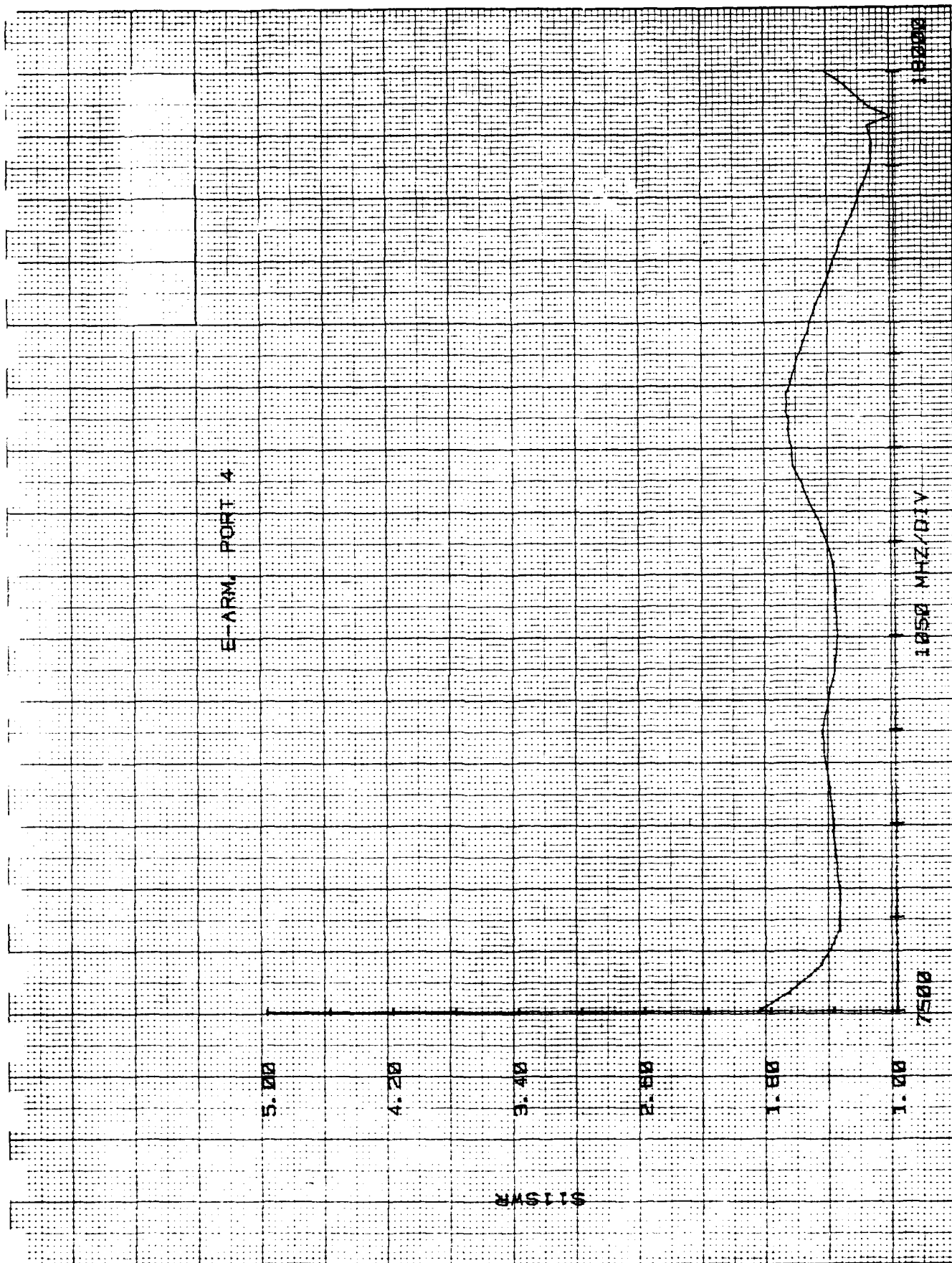


Figure 23. Graph of E-Arm, Tee 2

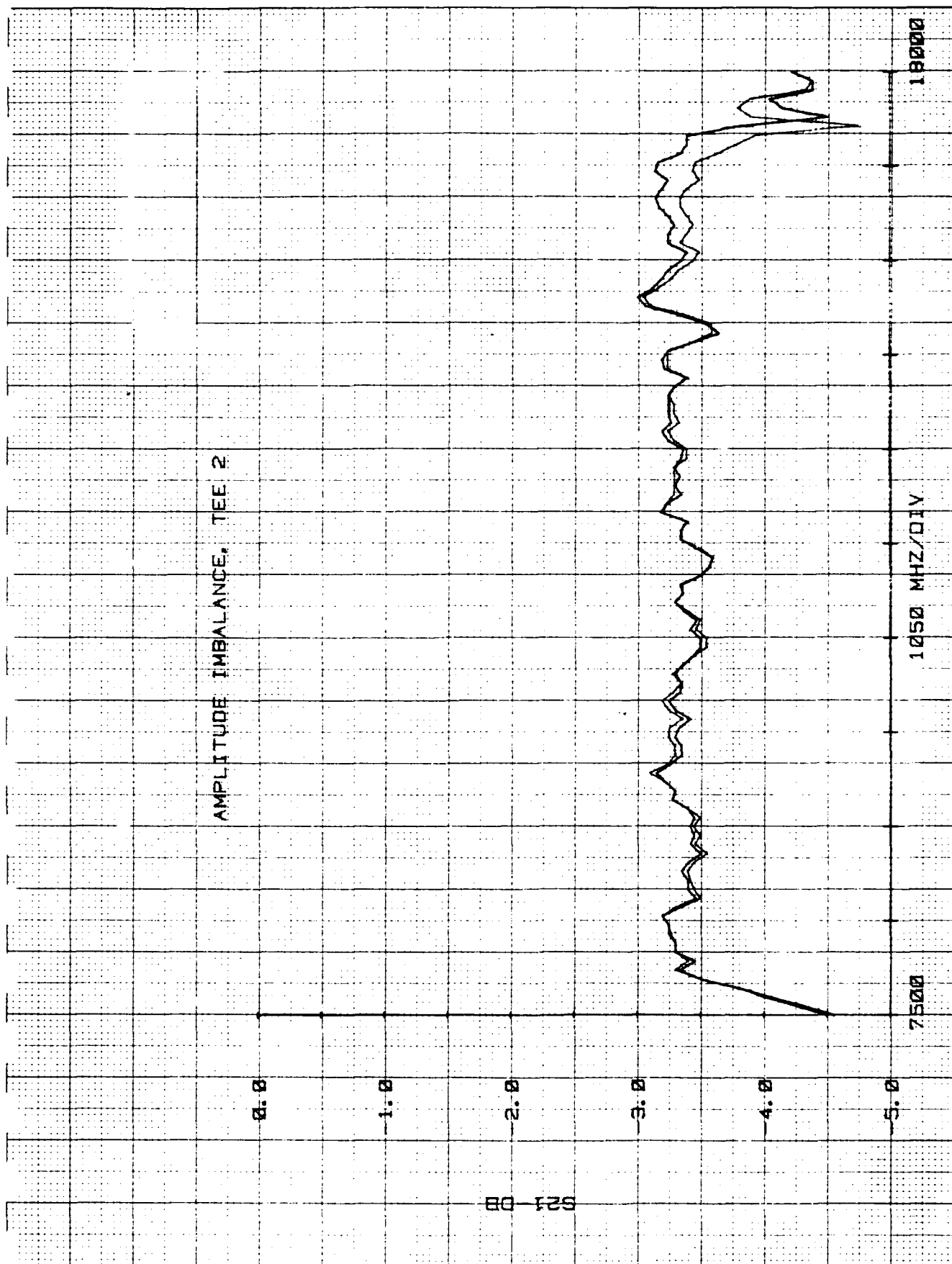


Figure 4. Amplitude Imbalance of Tee 2

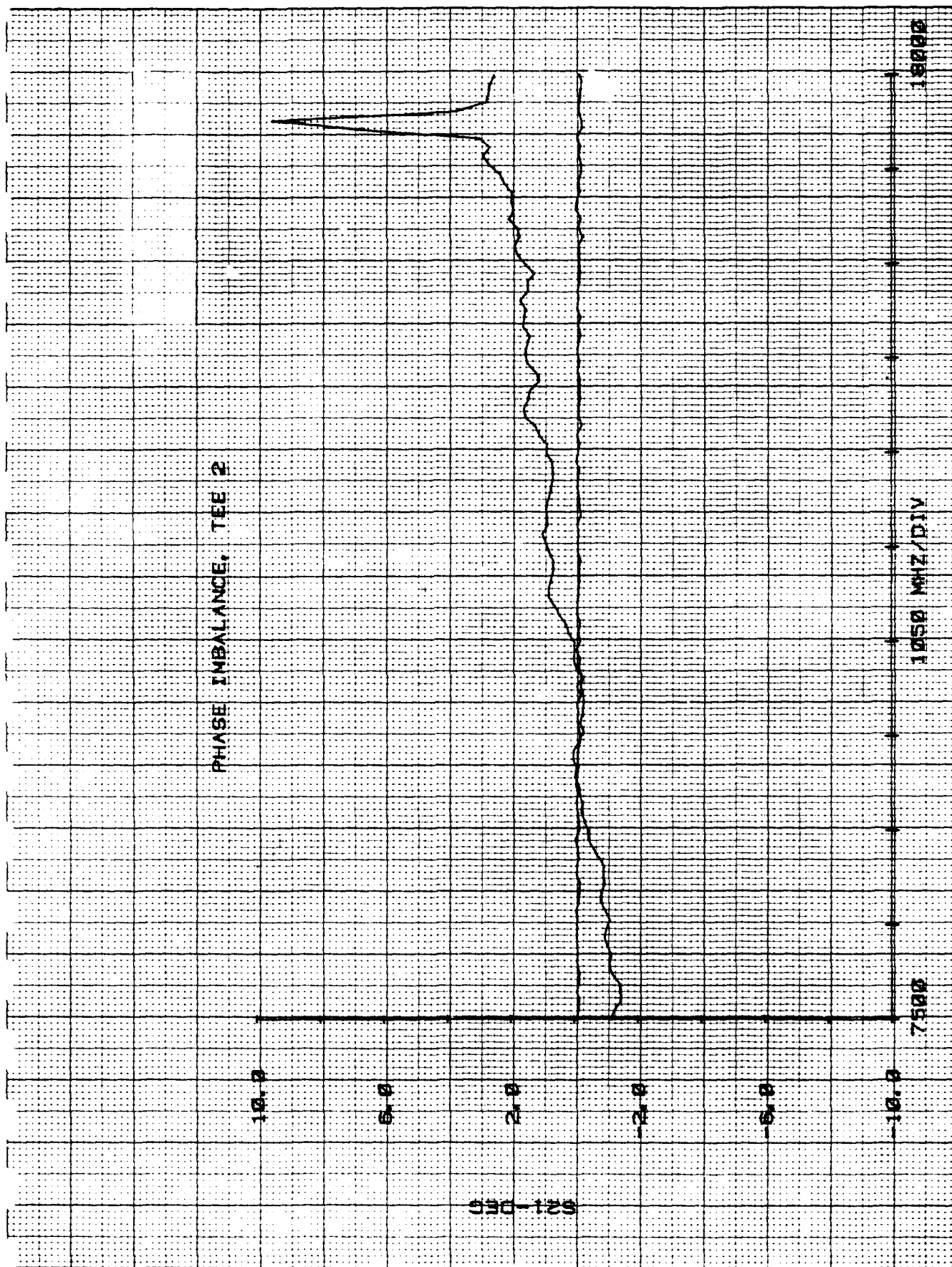


Figure 35. Phase Imbalance of Tee 2

6.0 HIGH POWER

High power measurement has not been performed for the circulator assembled. According to estimation based upon available informations, circulator would require pressurization and efficient cooling for safe operation at the specified high power level.

6.1 Peak Power

6.1.1 Magic Tee

Magic tee used for circulator assembly include capacitive obstacles for optimum matching. In order to guarantee safe operation at the specified power level, pressurization of waveguide would be necessary. Pressurization windows for the specified power level do not exist at this time. Microwave Research Corporation Model 270 is rated at 10 KW peak/600 watts average for a VSWR of $<1.1:1$ and loss of <0.1 dB. Microwave Development Labs have a unit under development. Further development will be necessary if the desired power levels of 20 KW peak/1 KW average are to be met.

6.1.2 Phase Shifter

There are two effects of concern in the phase shifter section, breakdown and nonlinearity. Nonlinearity is the increase in insertion loss above a certain peak power threshold. Ferrite material used for phase shifters design has been utilized previously for the similar frequency range with comparable geometry. To prevent peak power breakdown, air gap should be removed in bonding of dielectric rib.

6.2 Average Power

6.2.1 Magic Tee

The average power capability of the magic tees would be adequate if conduction cooling to liquid cooled phase shifters is used.

6.2.2 Phase Shifter

Since the phase tracking is essential for the operation of the circulator, efficient cooling of phase shifter is required to prevent phase change due to temperature variations. Liquid cooling with pressure drop of 10 psi would be adequate.

7.0 CIRCULATOR ASSEMBLY AND TEST DATA

Cross-sectional view of phase shifters for the circulator assembly is shown in Figure 26. Final data on circulator assembly are shown in Appendix A. WRD750D24 calibration standards were used in the calibration. The designation Port X-Y indicates that Port X was the input port while output signals were measured at Port Y.

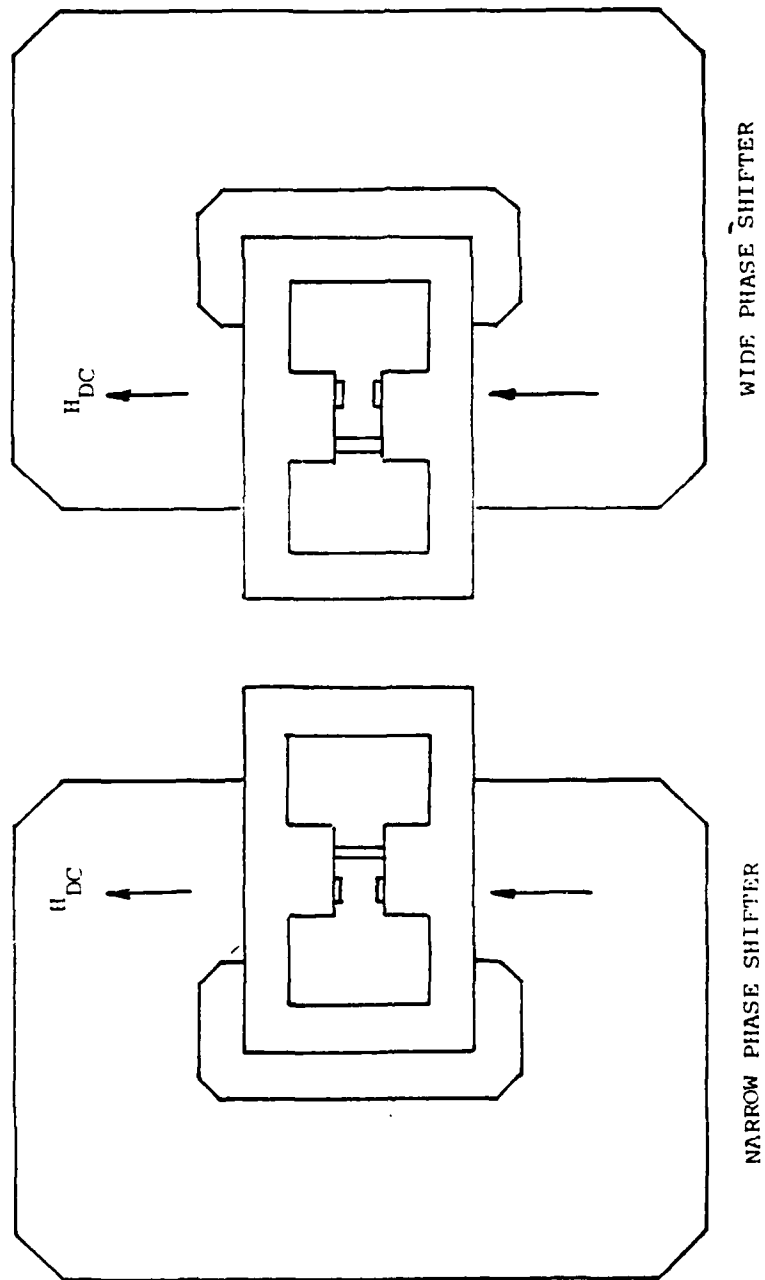


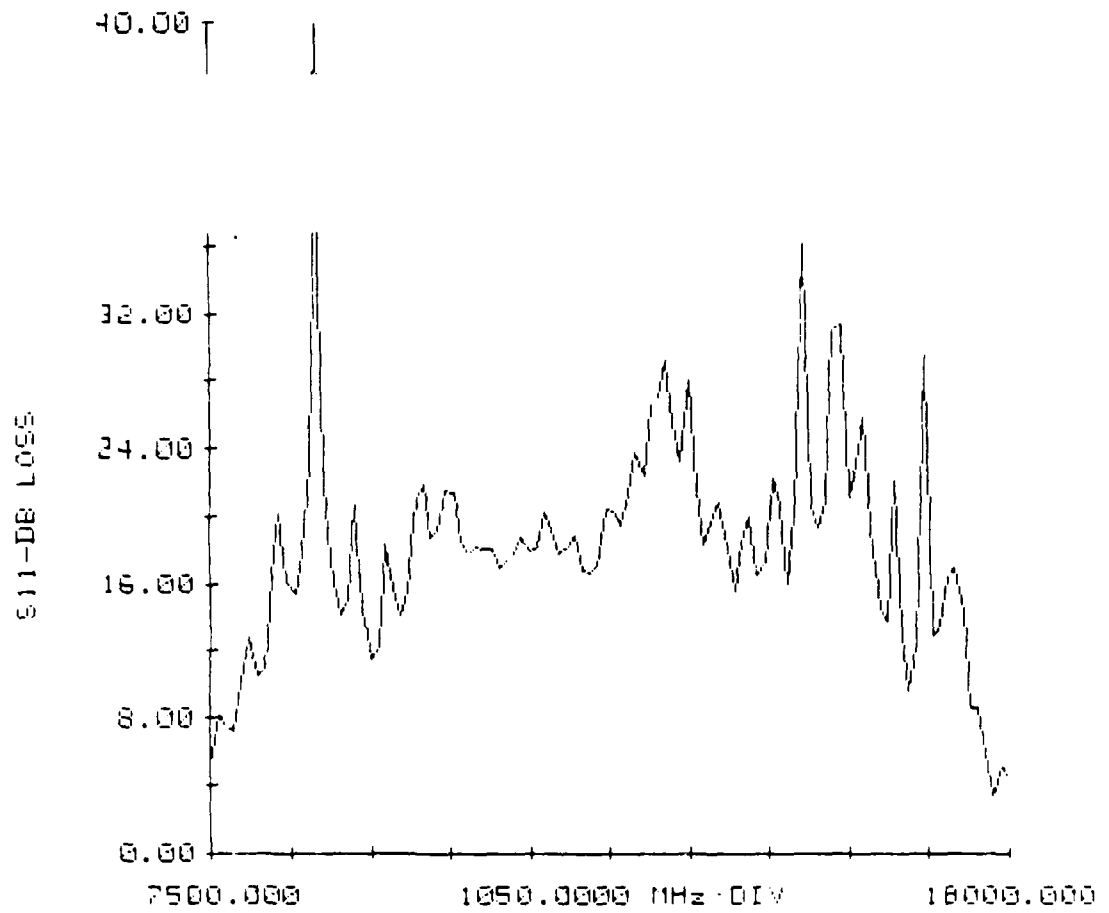
Figure 26. Cross-Sectional View of Phase Shifters for Circulator Assembly (Port 1 is Toward Viewer)

8.0 CONCLUDING REMARKS

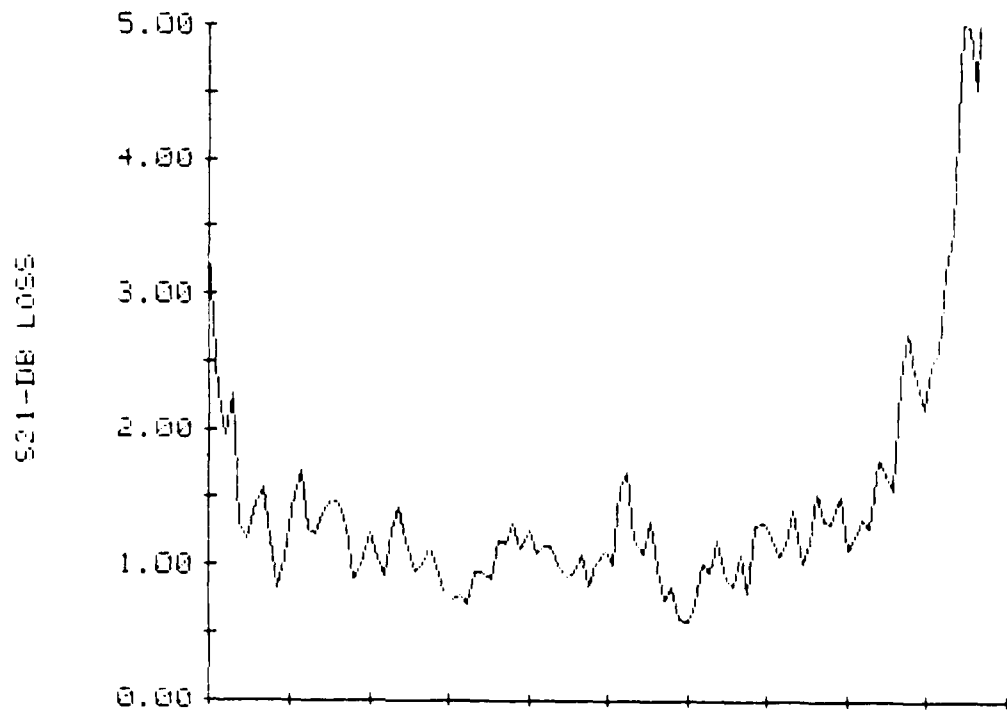
Four port differential phase shift circulator under Contract No. N00173-80-C-0434 for Naval Research Laboratory has been built. For frequency range between 8 to 16 GHz, 11 dB minimum isolation, 1.8 dB maximum insertion loss, and maximum VSWR of 2:1 were achieved. Even though the performance of the circulator designed did not meet the originally intended specification, it has demonstrated, at least, the feasibility of building the broadband four port differential phase shift circulator.

APPENDIX A
PERFORMANCE DATA

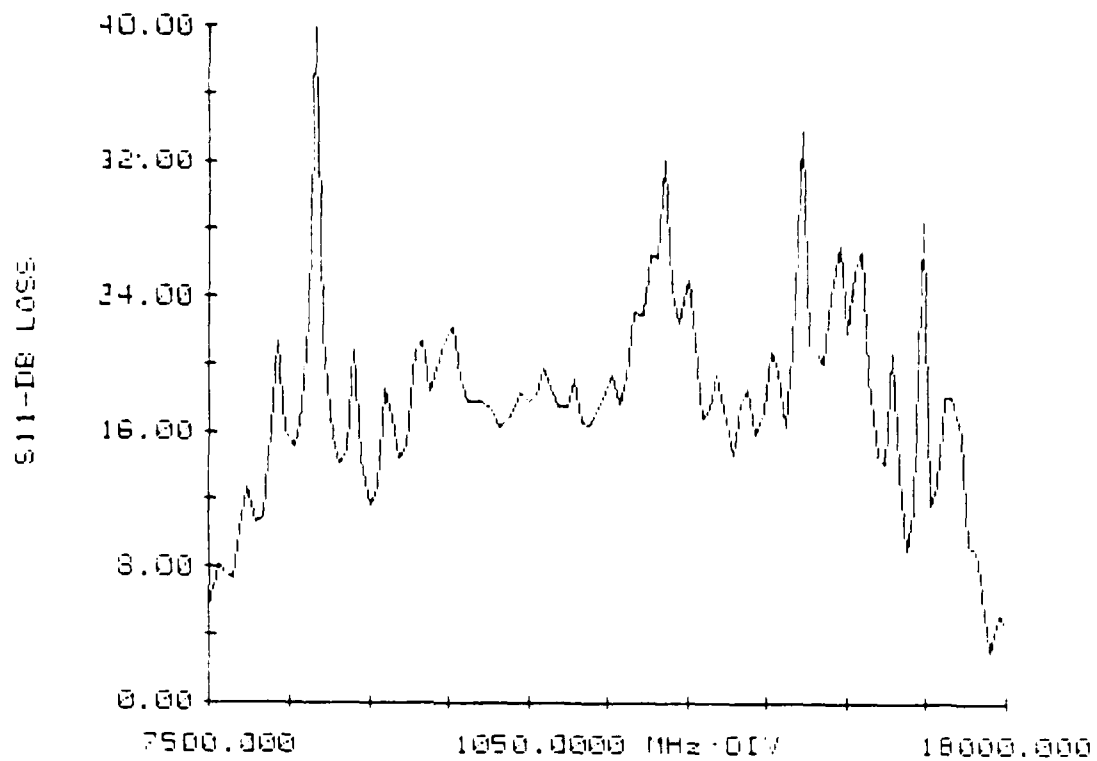
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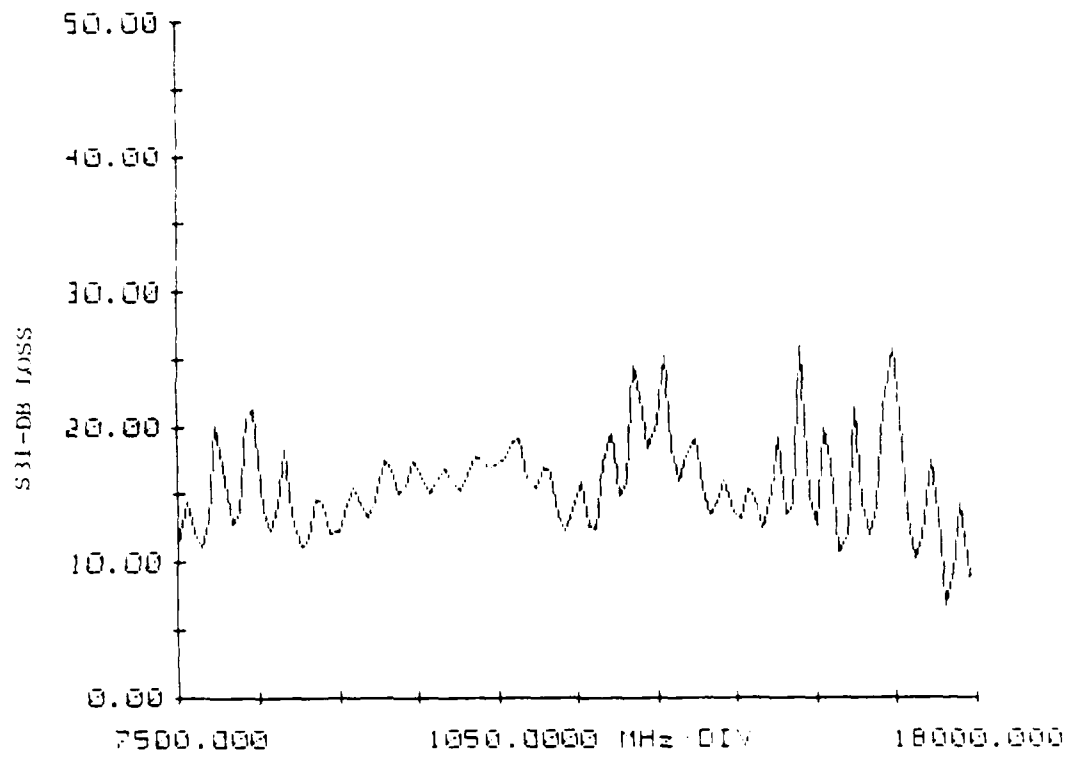
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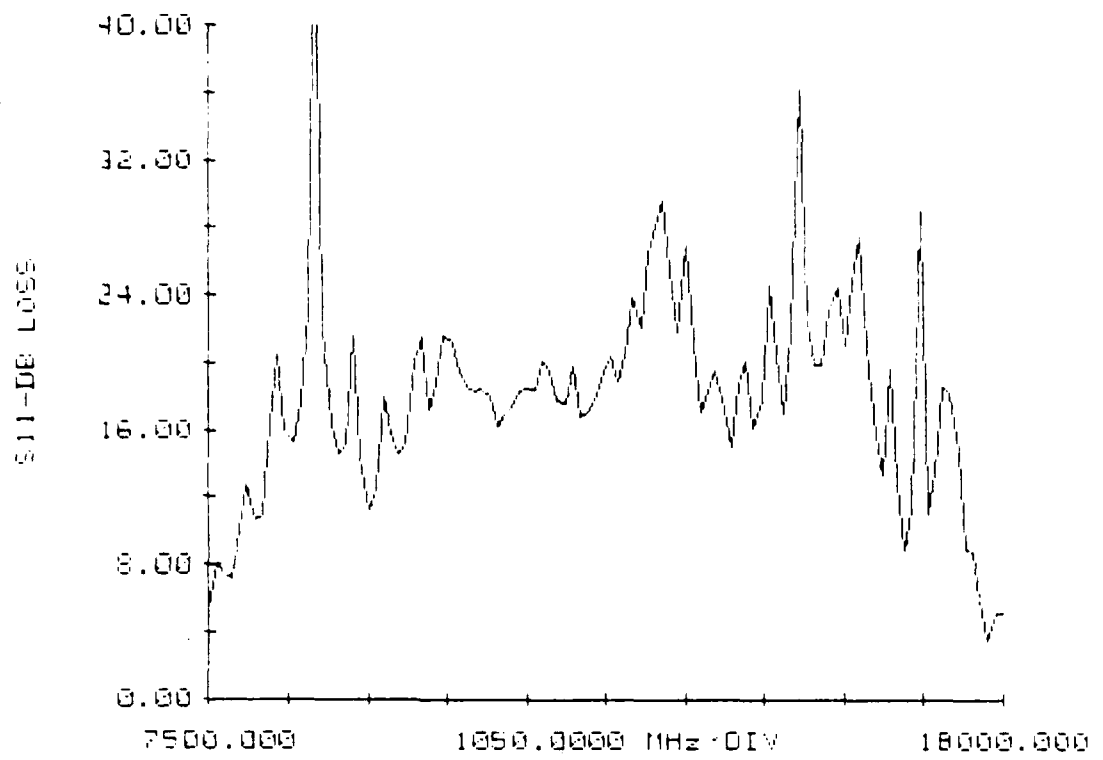
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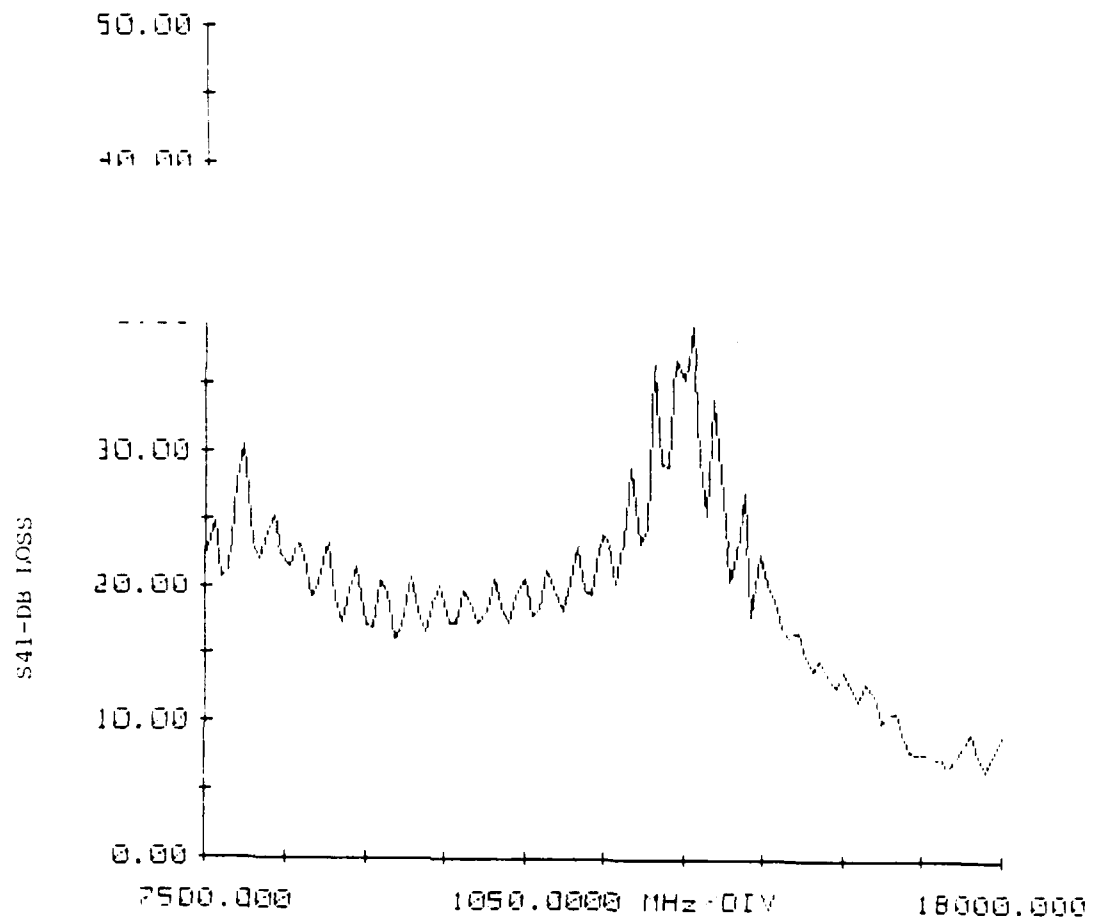
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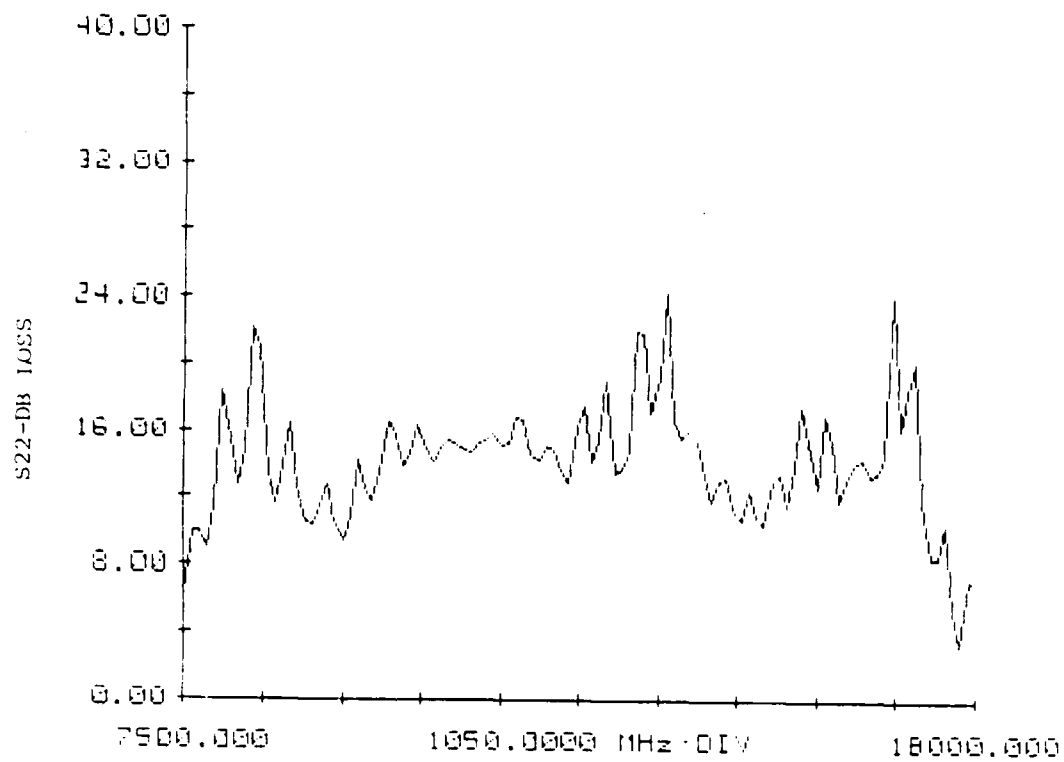
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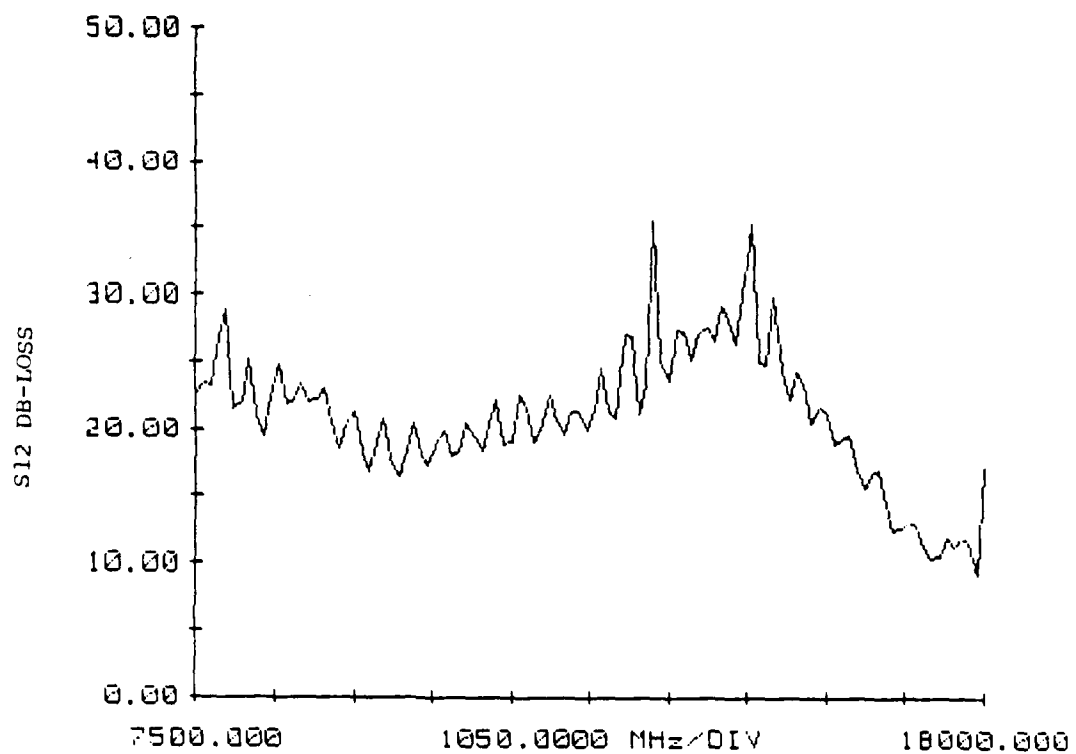
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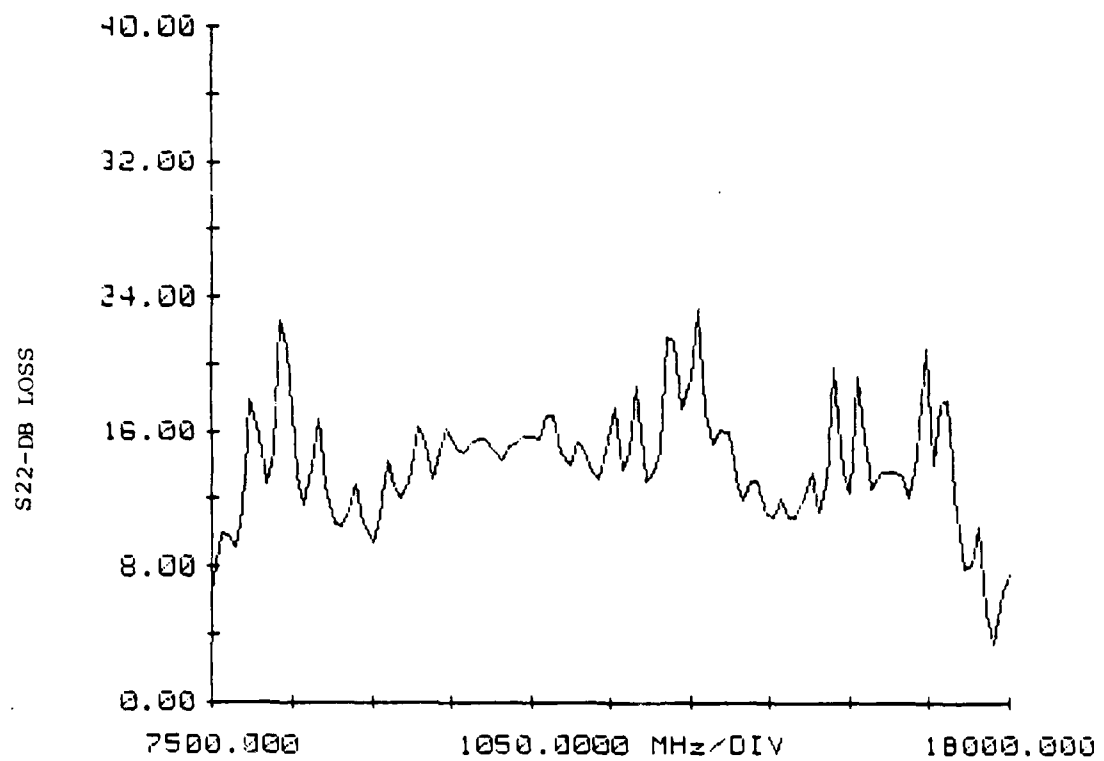
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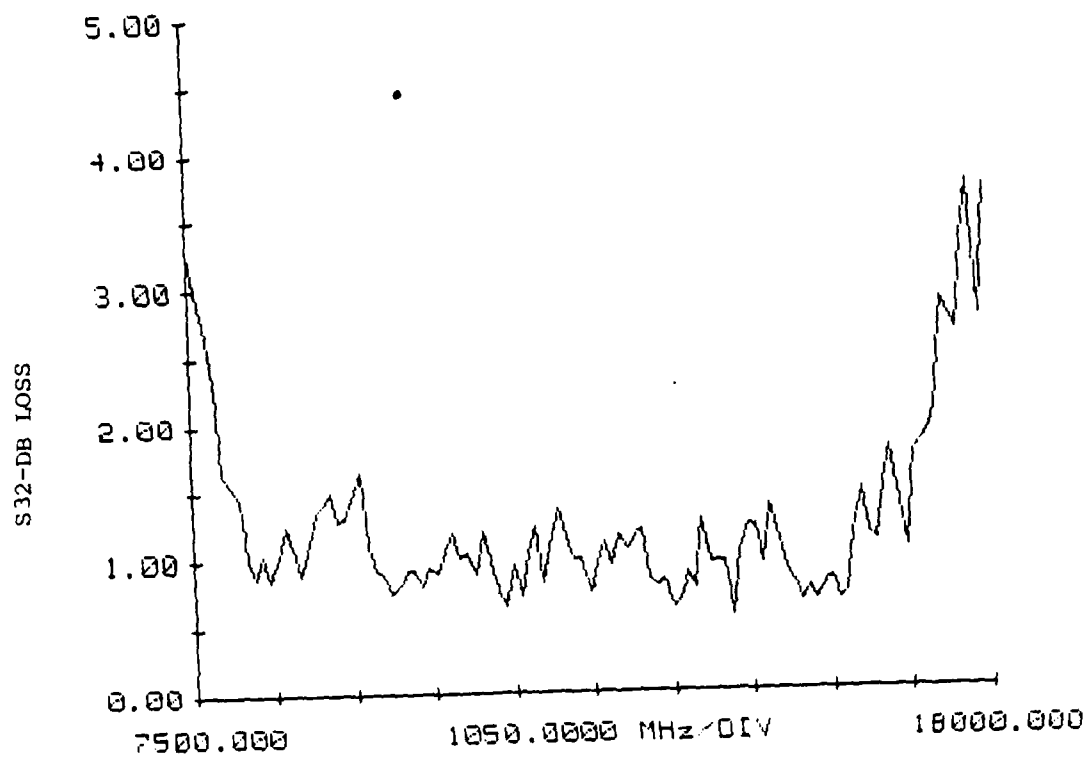
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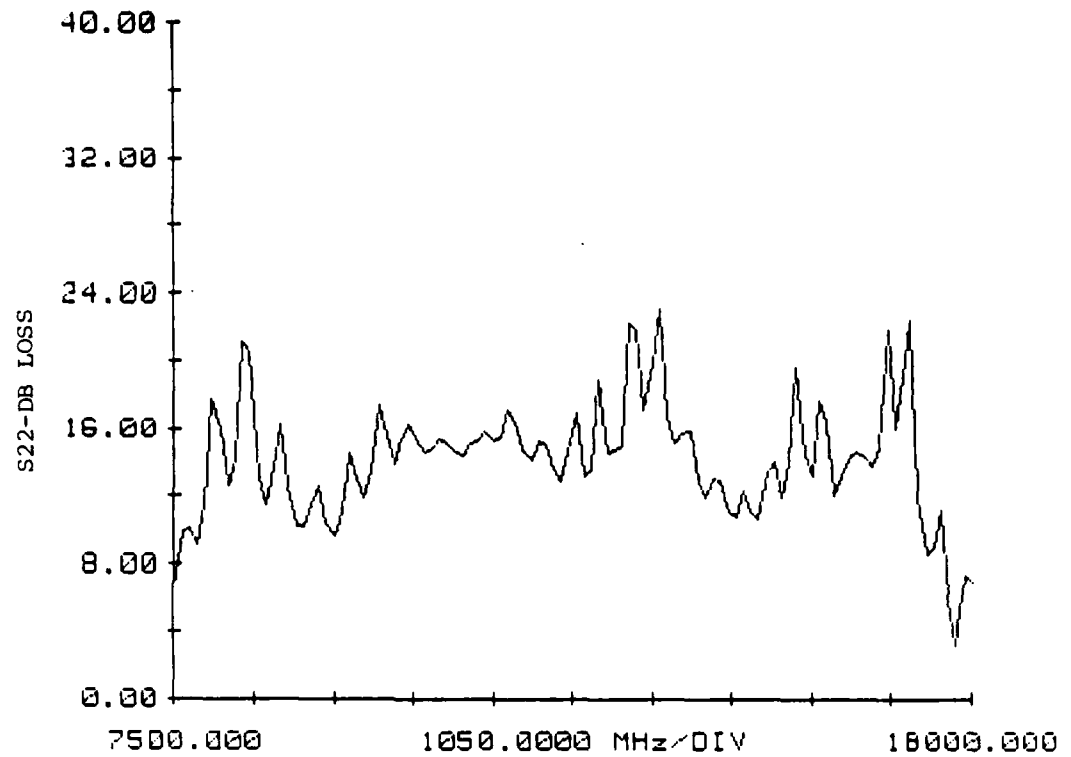
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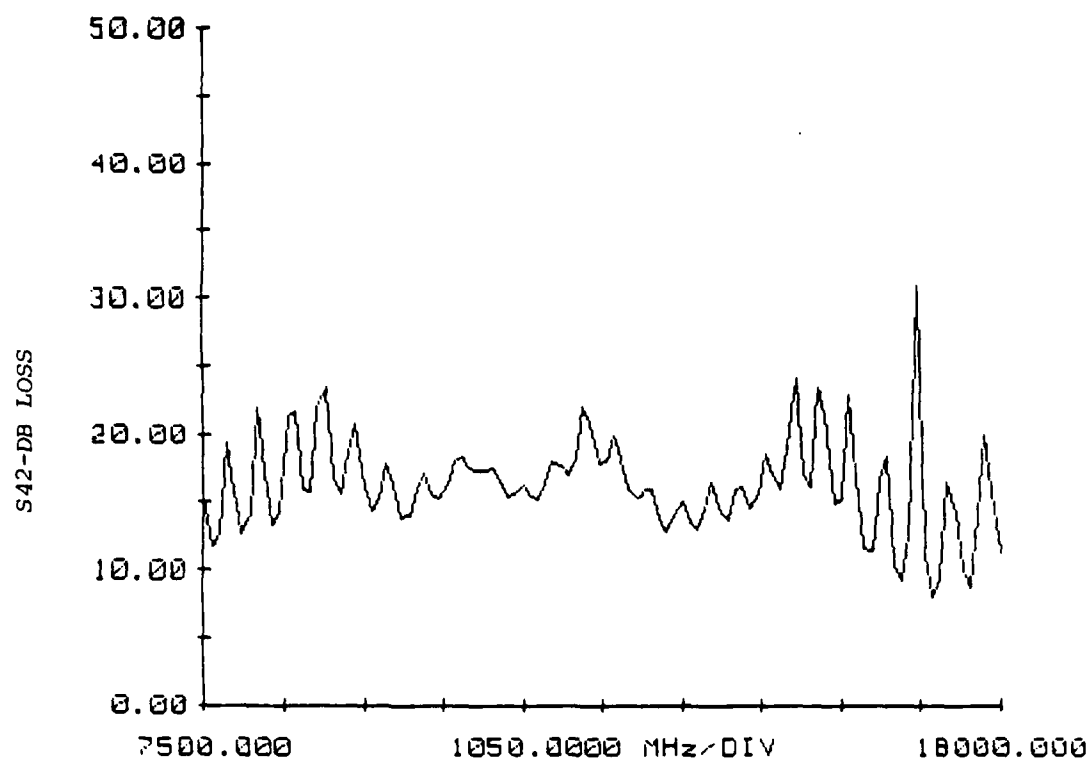
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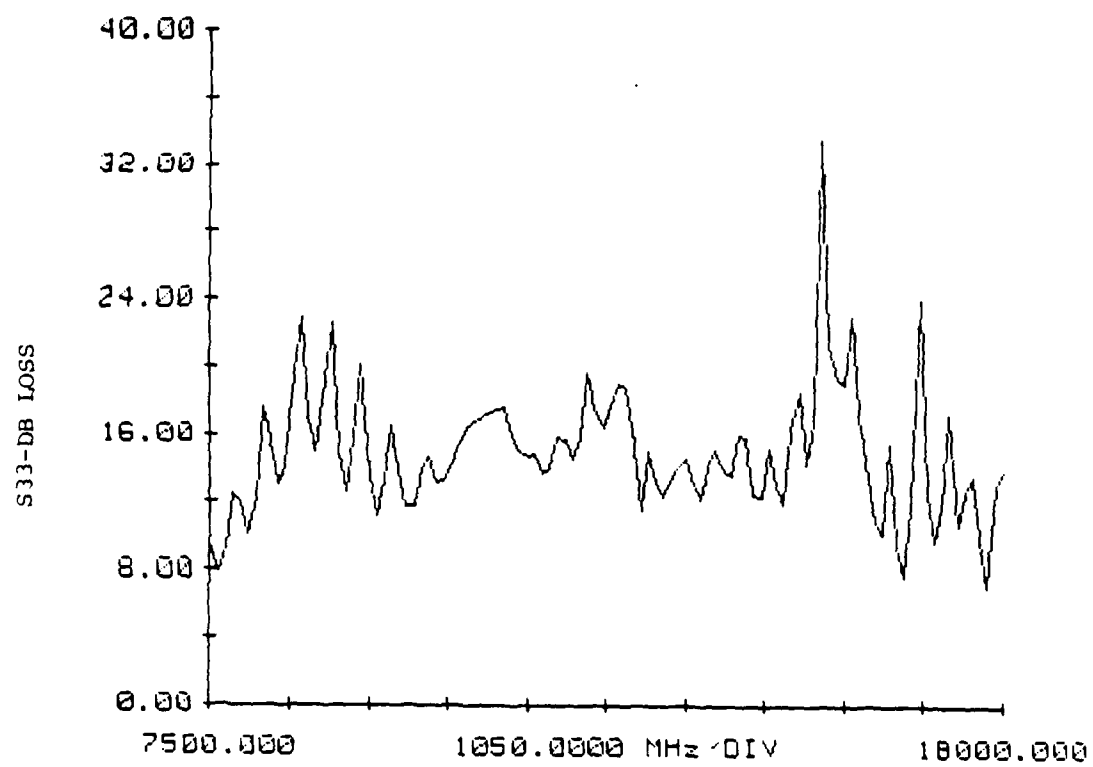
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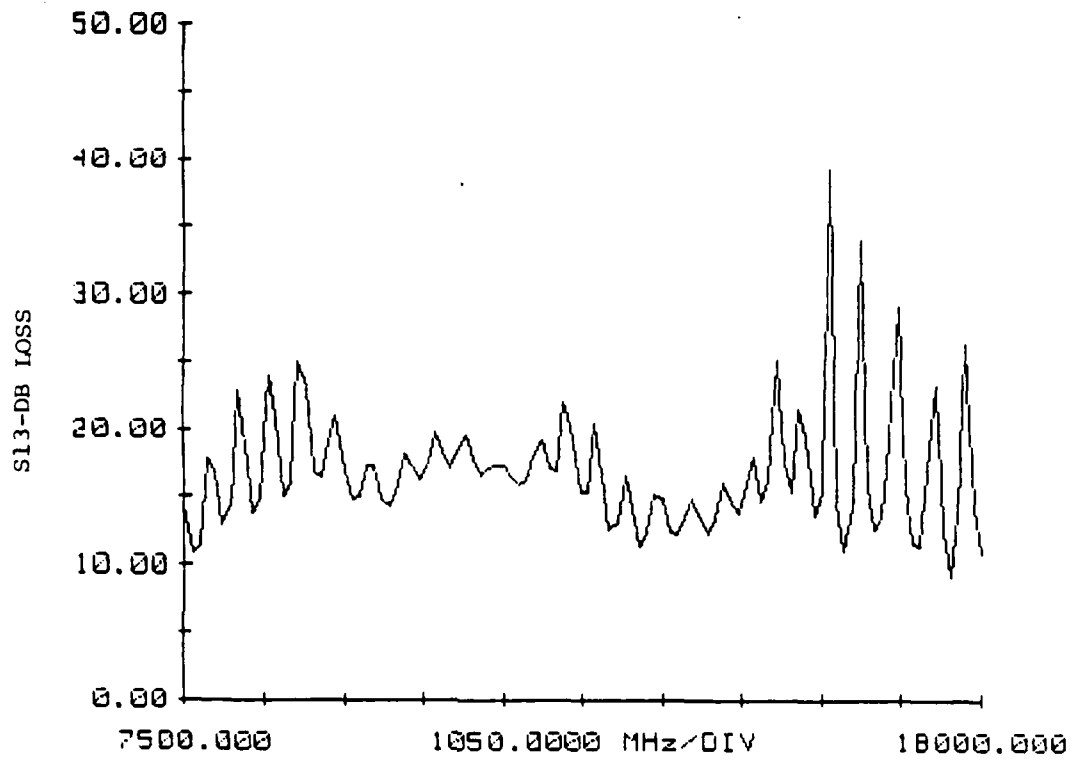
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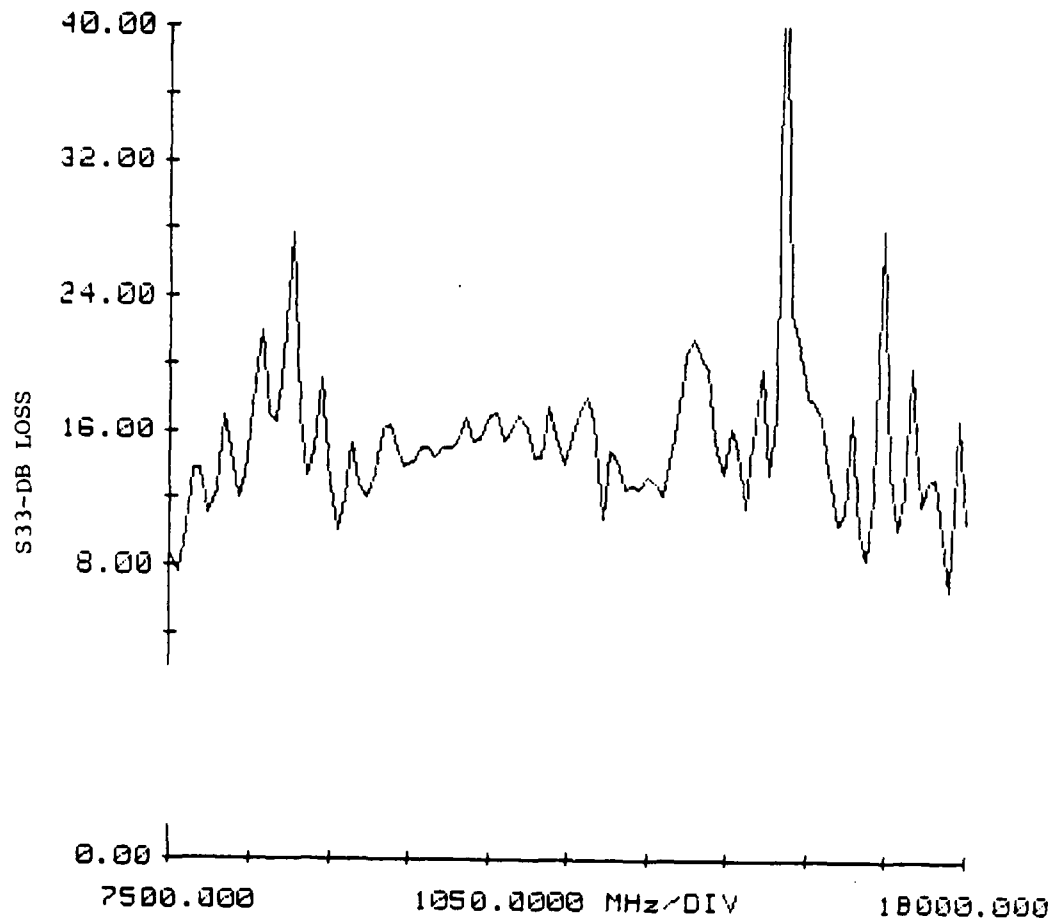
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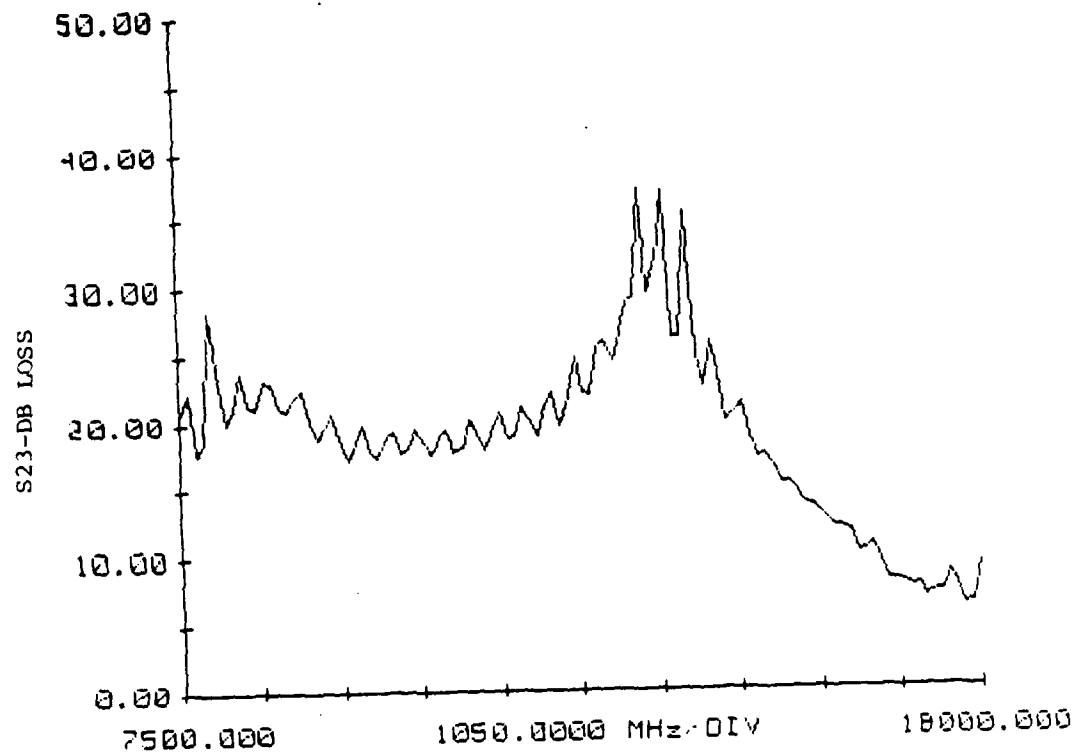
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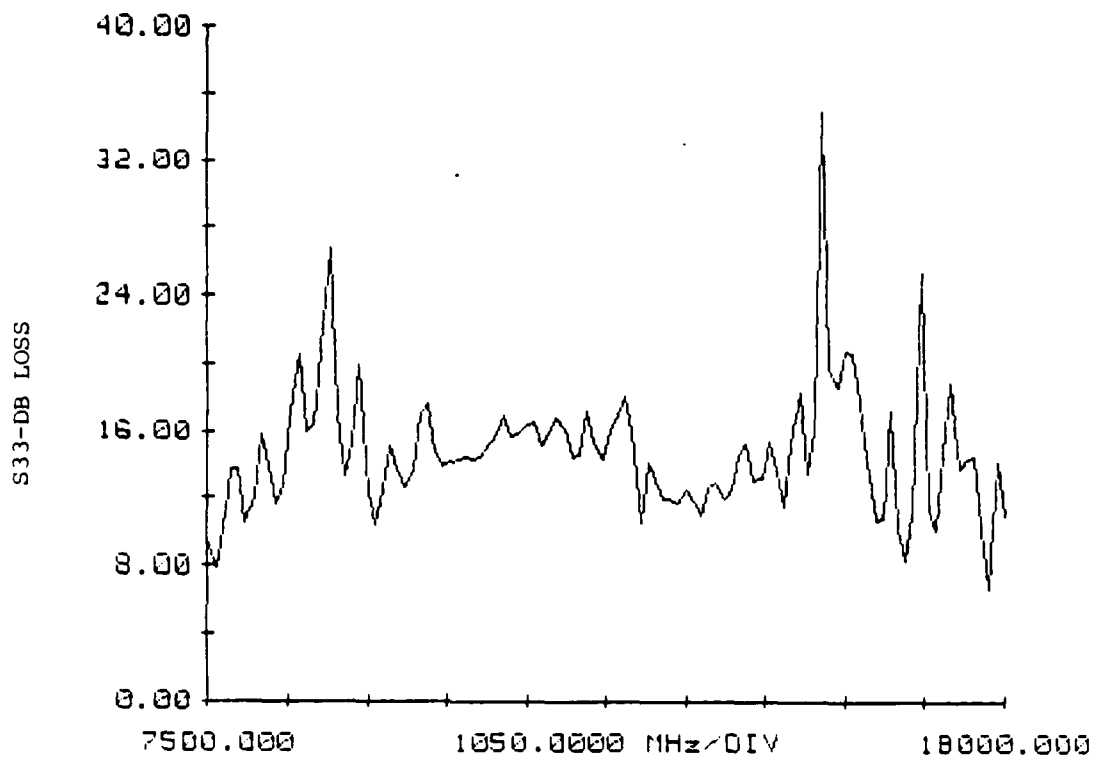
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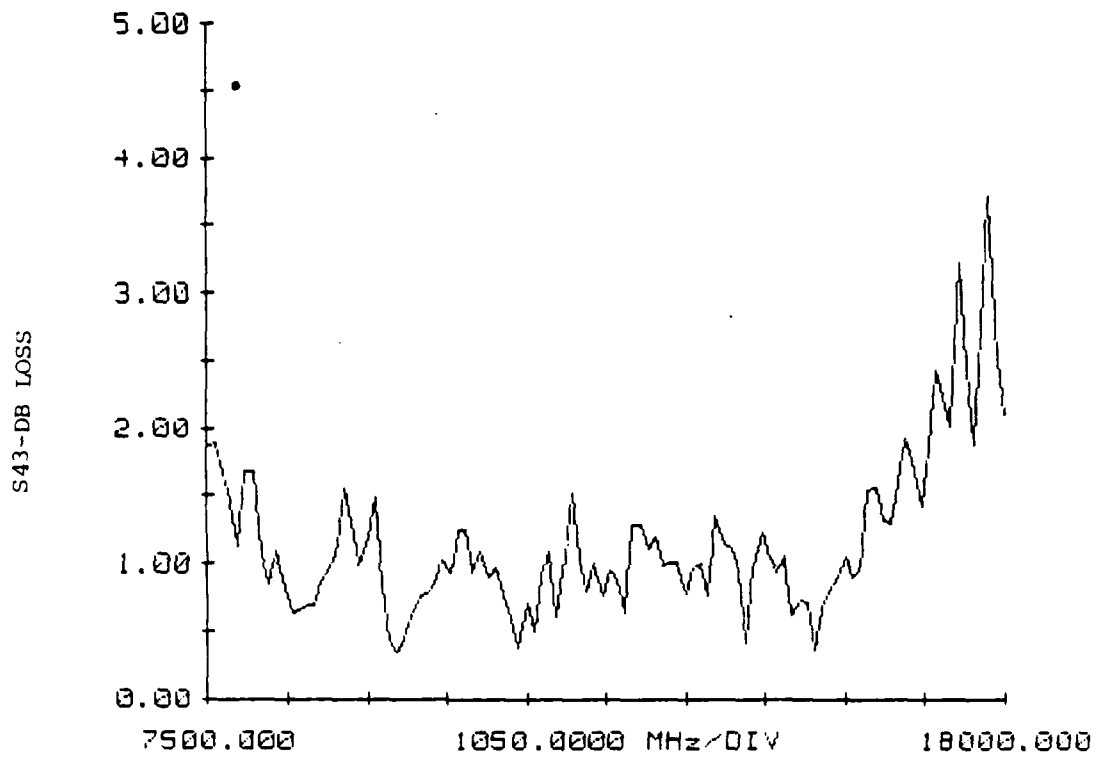
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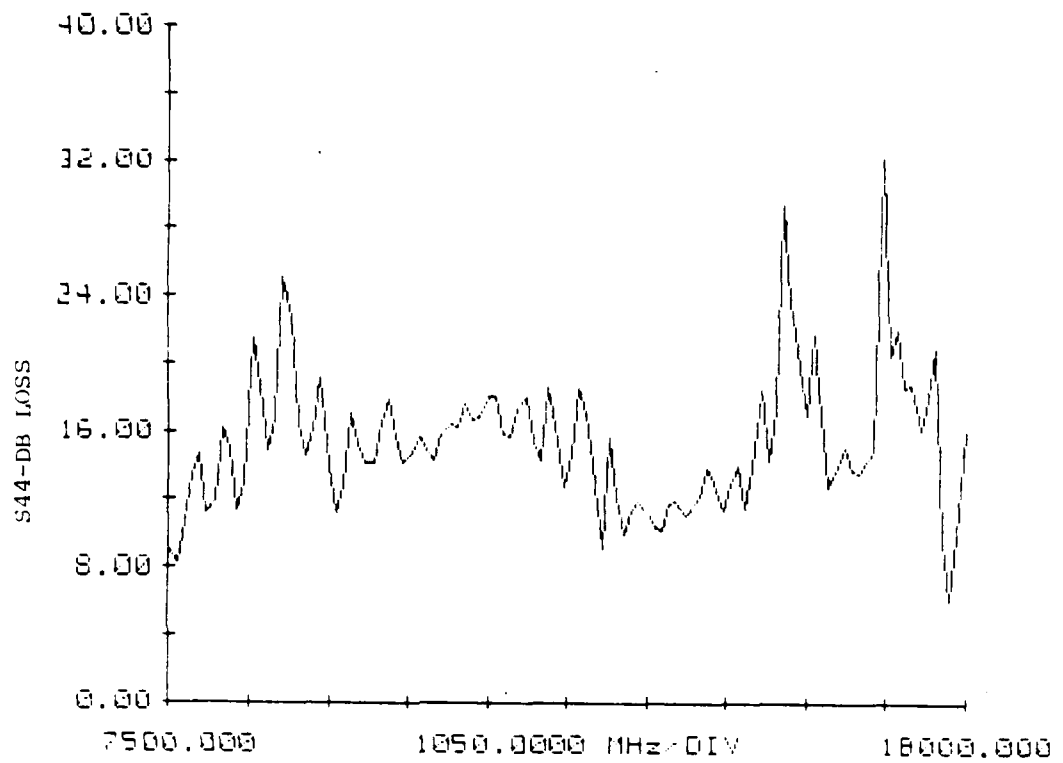
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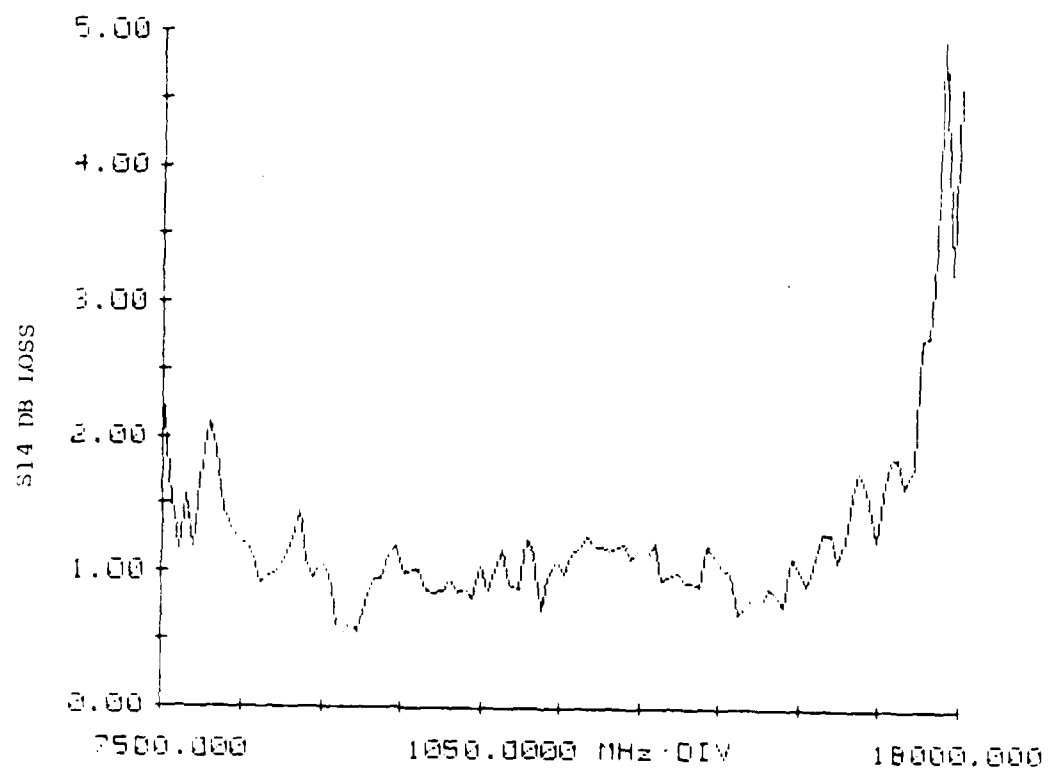
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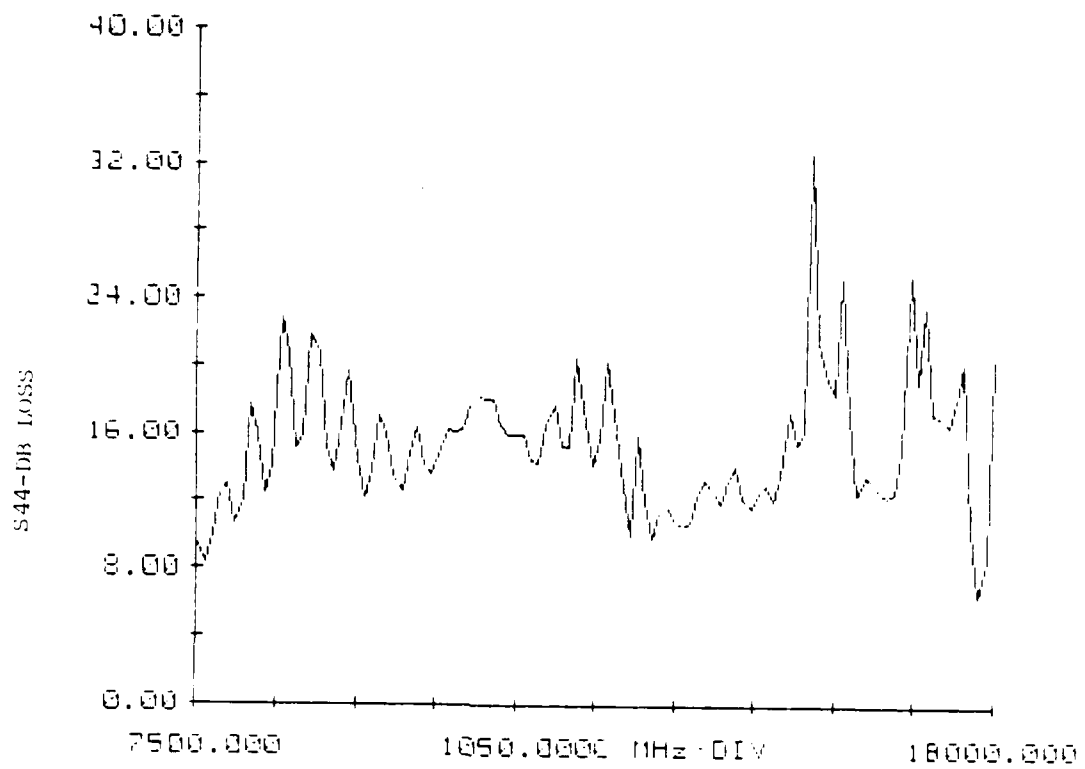
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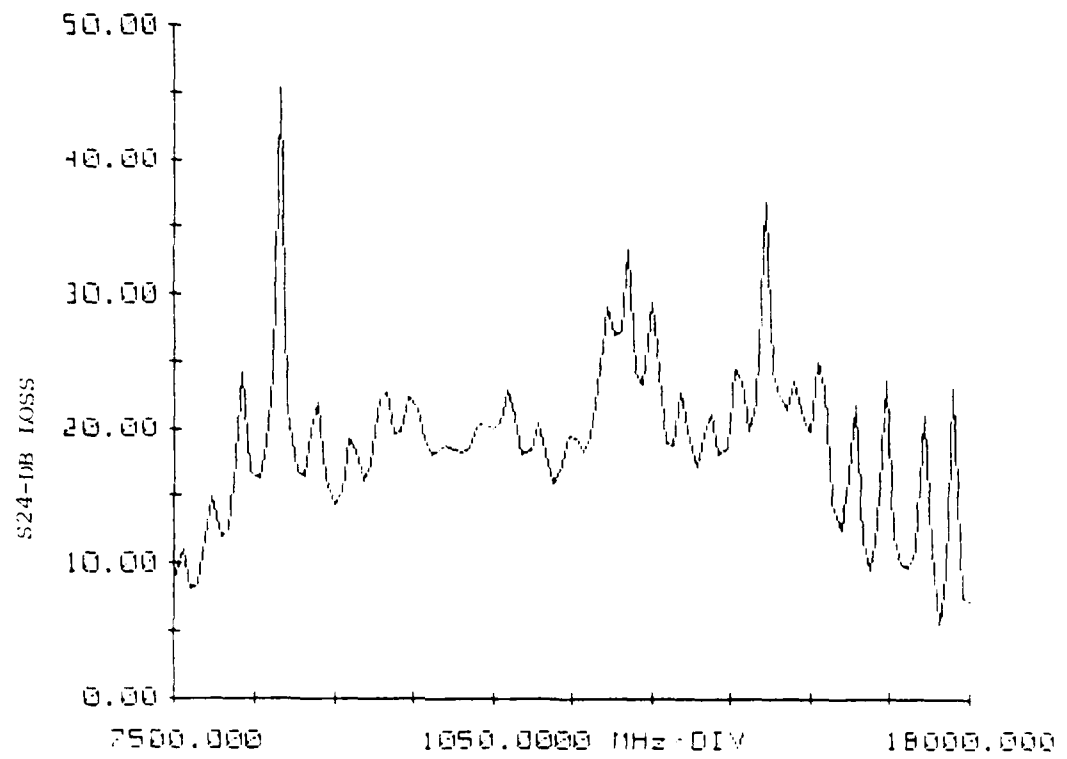
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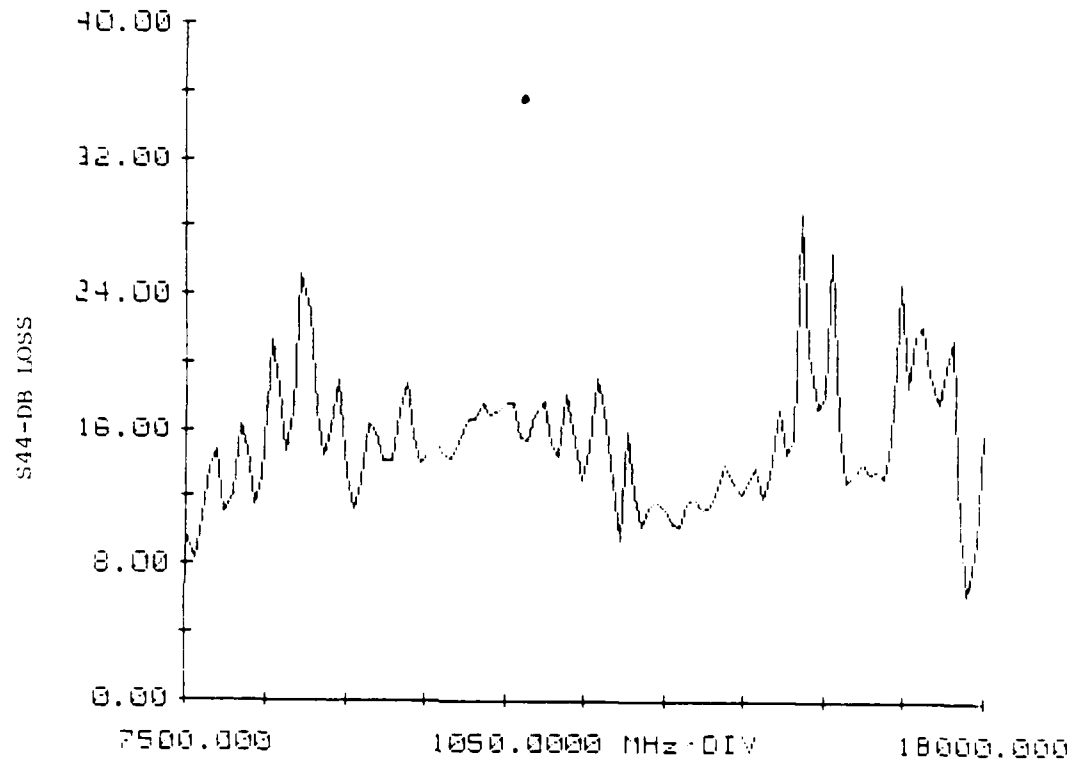
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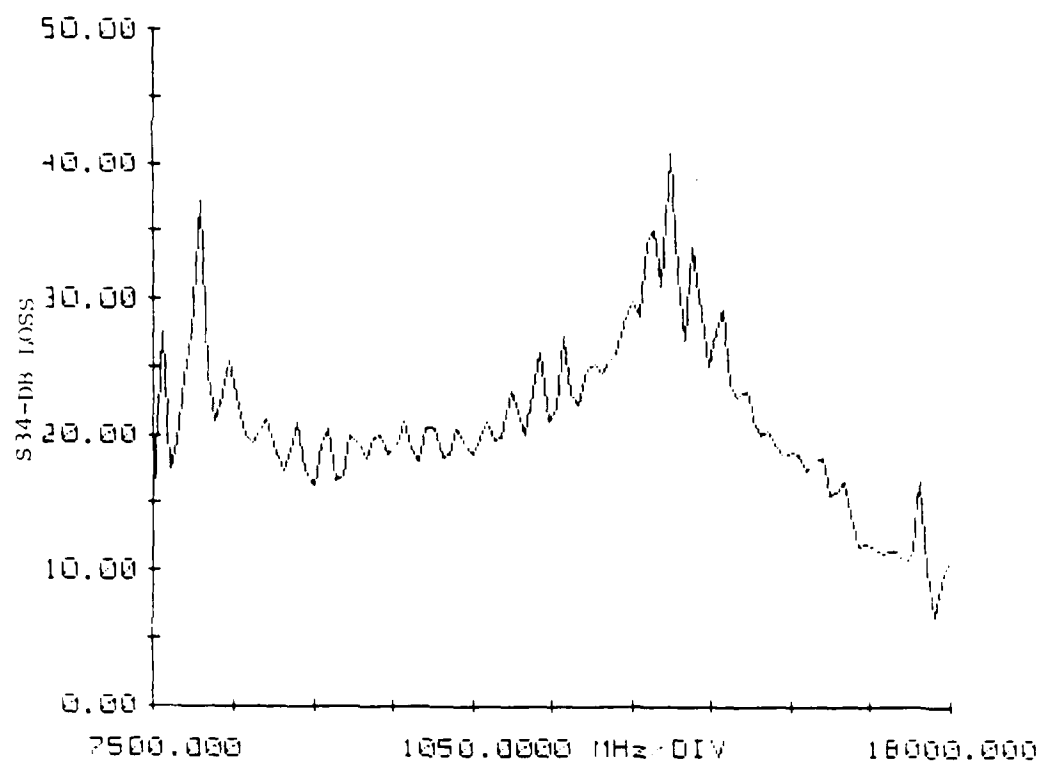
RAYTHEON CKuH40 PORT 4-2



RAYTHEON CKuH40 PORT 4-3



RAYTHEON CKuH40 PORT 4-3



APPENDIX B
COMPUTER PROGRAM

```

10  REM Program "RIDGE" :
20  OPTION BASE 1
30  DIM Nbr(20),Pbr(20),Obt(20),Rbo(20)
40  COM A(7),E(7),F,K,kk,Gama,Sat,Rem,B,D
50  Cnit=.0001
60  Eps=.0001
70  Ea=1
80  M=0
90  N=0
100 A1=.259
110 A2=.014
120 A3=.035
130 A5=.050
140 A6=.020
150 A4=.173-(A2+A3+A5+A6)
160 A7=.259
170 B=.321
180 D=.1375
190 B1=.030
200 B2=D-2*B1
210 Ef=11.4
220 E1=1
230 E2=1
240 E3=13+.78
250 E4=1
260 E5=(2+B1+B2)/(2+B1*Ef+B2-Ea)
270 E6=1
280 E7=1
290 Upm=0
300 Gama=3.5
310 Sat=1820
320 Remp=1820
330 Remn=-Remp
340 Fi=8
350 Ff=16
360 Delf=1
370 A(1)=A1
380 A(2)=A2
390 A(3)=A3
400 A(4)=A4
410 A(5)=A5
420 A(6)=A6
430 A(7)=A7
440 E(1)=E1
450 E(2)=E2
460 E(3)=E3
470 E(4)=E4
480 E(5)=E5
490 E(6)=E6
500 E(7)=E7
510 IMAGE 4X,"A1",7X,"A2",7X,"A3",7X,"A4",7X,"A5",7X,"A6",7X,"A7"
520 PRINT USING 510
530 IMAGE 2X,7(DD.DDDD,2X)
540 PRINT USING 530;A1,A2,A3,A4,A5,A6,A7
550 IMAGE 4X,"E1",7X,"E2",7X,"E3",7X,"E4",7X,"E5",7X,"E6",7X,"E7"
560 PRINT USING 550
570 PRINT USING 530;E1,E2,E3,E4,E5,E6,E7
580 IMAGE 4X,"B",8X,"D",8X,"B1",7X,"Ef",6X,"Gama",6X,"Sat",6X,"Rem+"
590 PRINT USING 580
600 IMAGE 2X,5(DD.DDDD,2X),X,2(DDDD.D,3X),-
610 PRINT USING 600;B,D,B1,Ef,Gama,Sat,Remp

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620 F=F1
630 Rem=0
640 Lb1: Rbt=6.8
650 Ibt=0
660 IF Sat=0 THEN GOTO Lb2
670 IMAGE /, "Rem=", MDDDD, 5X, "*****", /
680 PRINT USING 670; Rem
690 Rem=Rem*.5*(1+B2/(B2+2*B1))
700 Lb2: K=2*PI*F/11.8
710 Kk=K*K
720 CALL Newton(Rbt, Ibt, Cnit, Eps)
730 M=M+1
740 IF Rem=0 THEN Lb3
750 GOTO Lb4
760 Lb3: Rbo(M)=Rbt
770 Beta=Rbt
780 GOTO Lb5
790 Lb4: Dbt=(Rbt-Rbo(M))*2*B1/D
800 Beta=Rbo(M)+Dbt
810 Lb5: Phase=Beta*180/PI
820 IMAGE DD.DD, " GHz", 5X, "KY= ", D.DDDDE, " /INCH", 5X, "PHASE= ", D.DDDDE, " DEG-I
NCH"
830 PRINT USING 820; F, Beta, Phase
840 IF Rem=0 THEN Lb7
850 IF Rem<0 THEN Lb6
860 Pbt(M)=Phase
870 GOTO Lb8
880 Lb6: Nbt(M)=Phase
890 GOTO Lb8
900 Lb7: Obt(M)=Phase
910 Lb8: IF F=Ff THEN Lb9
920 F=F+Delf
930 GOTO Lb2
940 Lb9: IF Rem<0 THEN Lb10
950 Lg=720*(Obt(1)+Obt(M))/4
960 IMAGE "Quarter Wave Length=", D.DDDDE, " INCH"
970 PRINT USING 960; Lg
980 Lb10: IF Sat=0 THEN Lb99
990 N=N+1
1000 ON N GOTO Lb11, Lb12, Lb14
1010 Lb11: Rem=Remn
1020 GOTO Lb13
1030 Lb12: Rem=Remp
1040 Lb13: F=F1
1050 M=0
1060 GOTO Lb1
1070 Lb14: M=1
1080 F=F1
1090 PRINT LIN+1, "DIFFERENTIAL PHASE(DEG INCH)"
1100 PRINT "FREQ(GHz)      B- - Bo      B+ - Bo      B- - B+"
1110 Lb15: Dnp=Nbt(M)-Pbt(M)
1120 Dno=Nbt(M)-Obt(M)
1130 Dpo=Pbt(M)-Obt(M)
1140 IMAGE X, DD.DD, 7X, MDDDD, DD, 5X, MDDDD, DD, 5X, MDDDD, DD
1150 PRINT USING 1140; F, Dno, Dpo, Dnp
1160 M=M+1
1170 F=F+Delf
1180 IF F<=Ff THEN Lb15
1190 Lb99: STOP
1200 END
1210 SUB Juncd(Bc, Kx1, B, D)
1220 An=D/B
1230 Lc=2*PI/Kx1
1240 Cb=(4*An*(1-An/2))/2
1250 App=(1+(D/Lc)/2)/.5
1260 App=(1+App)/(1-App)

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1270 App=App*((1+An)/(1-An))^(2/An)
1280 App=App*(3+An^2)/(1-An^2)
1290 Ab=(1-(B/Lc)^2)^.5
1300 Ab=(1+Ab)/(1-Ab)
1310 Ab=Ab*((1+An)/(1-An))^(2*An)
1320 Ab=Ab-(1+3*An^2)/(1-An^2)
1330 B1=(1-An^2)/(4*An)
1340 B1=B1*((1+An)/(1-An))^(An+1/An)/2)
1350 B1=LOG(B1)
1360 B2=2*(Ab+App+2*Cb)/(Ab*App-Cb^2)
1370 B3=C/(4*Lc)^2
1380 B3=F*((1-An)/(1+An))^(4*An)
1390 B3=3*((5*An^2-1)/(1-An^2)+4*Cb*An^2/(3*Ab))^2
1400 Bc= *B/Lc*(B1+B2+B3)
1410 SUB END
1420 SUB Newton(Rbt,Ibt,Crit,Eps)
1430 I=1
1440 Id=1
1450 Ln1: Rs=Rbt
1460 Is=Ibt
1470 IF Ibt=0 THEN Ln2
1480 Is=-Ibt
1490 Ln2: Ro=Rs
1500 Io=Is
1510 Ln3: ON Id GOTO Ln4,Ln5
1520 Ln4: Rdel=Eps
1530 Idel=0
1540 GOTO Ln6
1550 Ln5: Rdel=0
1560 Idel=Eps
1570 Id=1
1580 Ln6: Rm=Ro-Rdel
1590 Im=Io-Idel
1600 Rp=Ro+Rdel
1610 Ip=Io+Idel
1620 Rbt=Ro
1630 Ibt=Io
1640 CALL Fund(Rbt,Ibt,Rn,In)
1650 CALL Cabs(Rn,In,Cn)
1660 IMAGE MD,DDDE,4N,MD,DDDE,6N,D,DDDE
1680 IF Cn>Crit THEN Ret_main
1690 Rfo=Rn
1700 Ifo=In
1710 Rbt=Rm
1720 Ibt=Im
1730 CALL Fund(Rbt,Ibt,Rn,In)
1740 Rfm=Rn
1750 Ifm=In
1760 Rbt=Rp
1770 Ibt=Ip
1780 CALL Fund(Rbt,Ibt,Rn,In)
1790 Rfp=Rn
1800 Ifp=In
1810 Rfd=Rfo-Rfm
1820 Ifd=Ifo-Ifm
1830 CALL Cdiv(Rfd,Ifd,Rdel,Idel,Rfd,Ifd)
1840 Rfs=Rfm+Rfp-2*Rfo
1850 Ifs=Ifm+Ifp-2*Ifo
1860 CALL Cmult(Rdel,Idel,Rdel,Idel,Rdels,Idels)
1870 CALL Cdiv(Rfs,Ifs,Rdels,Idels,Rfs,Ifs)
1880 CALL Cabs(Rfs,Ifs,Cfs)
1890 IF Cfs<.0000001 THEN Ln9
1900 ON Id GOTO Ln7,Ln8
1910 Ln7: Id=2
1920 IF I>10 THEN Ln11
1930 I=I+1

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1940 GOTO Ln3
1950 Ln8: GOTO Ln10
1960 Ln9: CALL Cmult(Rfo,Ifo,Rfs,Ifs,Ros,Ios)
1970 CALL Cmult(Rfd,Ifd,Rfd,Ifd,Rdd,Idd)
1980 CALL Cdiv(Ros,Ios,Rdd,Idd,Rosd,Iosd)
1990 Rosd=1-2*Rosd
2000 Iosd=-2*Iosd
2010 CALL Csqrt(Rosd,Iosd,Rcosd,Icosd)
2020 Rcosd=1-Rcosd
2030 Icosd=-Icosd
2040 CALL Cmult(Rfd,Ifd,Rcosd,Icosd,Rdz,Idz)
2050 CALL Cdiv(Rdz,Idz,Rfs,Ifs,Rdzz,Idzz)
2060 Rdz=-Rdzz
2070 Idz=-Idzz
2080 CALL Cabs(Rdz,Idz,Odz)
2090 IF Odz<.0000001 THEN Ln11
2100 Rbt=Rs+Rdz
2110 Ibt=Is+Idz
2120 IF I>10 THEN Ln11
2130 I=I+1
2140 GOTO Ln1
2150 Ln10: PRINT "ZERO DERIVATIVE"
2160 GOTO Ret_main
2170 Ln11: IMAGE "DIVERGENCE OF ITERATION PROCESS: f(x)=",D,DDDE
2180 PRINT USING 2170;Ch
2190 Ret_main: SUBEXIT
2200 SUBEND
2210 SUB Cmult(X1,Y1,X2,Y2,X3,Y3)
2220 X3=X1*X2-Y1*Y2
2230 Y3=X1*Y2+Y1*X2
2240 SUBEND
2250 SUB Cdiv(X1,Y1,X2,Y2,X3,Y3)
2260 Denom=X2*X2+Y2*Y2
2270 X3=(X1*X2+Y1*Y2)/Denom
2280 Y3=(Y1*X2-X1*Y2)/Denom
2290 SUBEND
2300 SUB Cabs(X,Y,Rm)
2310 Rm=(X*X+Y*Y)>.5
2320 SUBEND
2330 SUB Csin(X1,Y1,X2,Y2)
2340 X2=SIN(X1)+(EXP(Y1)+EXP(-Y1))/2
2350 Y2=COS(X1)+(EXP(Y1)-EXP(-Y1))/2
2360 SUBEND
2370 SUB Ccos(X1,Y1,X2,Y2)
2380 X2=COS(X1)+(EXP(Y1)+EXP(-Y1))/2
2390 Y2=-SIN(X1)+(EXP(Y1)-EXP(-Y1))/2
2400 SUBEND
2410 SUB Csqrt(X1,Y1,X2,Y2)
2420 Mag=(X1*X1+Y1*Y1)>.25
2430 IF X1#0 THEN Lba1
2440 IF Y1#0 THEN Lba2
2450 Ang=ATN(Y1/X1)/2
2460 GOTO Lcsq
2470 Lba1: Ang=(PI+ATN(Y1/X1))/2
2480 GOTO Lcsq
2490 Lba2: IF Y1#0 THEN Lba3
2500 Ang=PI/4
2510 GOTO Lcsq
2520 Lba3: Ang=-PI/4
2530 Lcsq: X2=Mag*COS(Ang)
2540 Y2=Mag*SIN(Ang)
2550 SUBEND
2560 SUB Fund(Rbt,Ibt,Rr,Ir)
2570 DIM Rk(7),Ik(7),Rm(7),Im(7),Rcm(7),Icm(7)
2580 DIM Rma(11),Ima(11),Rmb(11),Imb(11),Rmc(11),Imc(11),Rmd(11),Imd(11)
2590 COM A(+),E(+),F,K,Kk,Gama,Sat,Rem,B,D

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2600 R0=0
2610 I1=1
2620 CALL Cmult(R0,I1,R0,I1,R0,I1,R0,I1)
2630 FOR I=1 TO 7
2640 Rkx=Kk+E(I)-Rbts
2650 Ikx=-Ibts
2660 CALL Csqnt(Rkx,Ikx,Rkx(I),Ikx(I))
2670 IF Ikx(I)>0 THEN CALL Neg(Rkx(I),Ikx(I),Rkx(I),Ikx(I))
2680 NEXT I
2690 U=1
2700 Rxy=0
2710 Ixy=0
2720 IF Sat=0 THEN Lbb1
2730 U=1/3+2*(1-(Gama*Sat/(F+1000))2)/3
2740 U=U+(1-U)*ABS(Rem/Sat)/1.5
2750 U=1
2760 Ixy=Gama*Rem/(F+1000)
2770 Lbb1: Rho=U/(U+U-Ixy/2)
2780 Iteta=Ixy/U
2790 Rkx=Kk+E(5)/Rho-Rbts
2800 CALL Csqnt(Rkx,Ikx,Rkx(5),Ikx(5))
2810 IF Ikx(5)>0 THEN CALL Neg(Rkx(5),Ikx(5),Rkx(5),Ikx(5))
2820 Kx1=Rkx(1)
2830 Bc=0
2840 IF Kx1<=0 THEN Lbb2
2850 IF D=B THEN Lbb2
2860 CALL Junct(Bc,Kx1,B,D)
2870 Bc=-Bc+Kx1/K
2880 Lbb2: FOR I=1 TO 7
2890 Rkxa=Rkx(I)+A(I)
2900 Ikxa=Ikx(I)+A(I)
2910 CALL Csin(Rkxa,Ikxa,Rsn,Isn)
2920 Rsn(I)=Rsn
2930 Isn(I)=Isn
2940 CALL Ccos(Rkxa,Ikxa,Rcn,Icn)
2950 Rcn(I)=Rcn
2960 Icn(I)=Icn
2970 Rma(I)=Rcn
2980 Ima(I)=Icn
2990 CALL Cmult(Rkx(I),Ikx(I),Rsn,Isn,Rkxsn,Ikxsn)
3000 CALL Cmult(R0,I1,Rkxsn,Ikxsn,Rmb,Imb)
3010 Rmb(I)=-Rmb(I)
3020 Imb(I)=-Imb(I)
3030 CALL Cdiv(Rsn,Isn,Rkx(I),Ikx(I),Rsnk,Isnk)
3040 CALL Cmult(R0,I1,Rsnk,Isnk,Rmc,Imc)
3050 Rmc(I)=-K*Rmc
3060 Imc(I)=-K*Imc
3070 Rmd(I)=Rma(I)
3080 Imd(I)=Ima(I)
3090 NEXT I
3100 Rma(11)=Rma(7)
3110 Ima(11)=Ima(7)
3120 Rmb(11)=Rmb(7)
3130 Imb(11)=Imb(7)
3140 Rmc(11)=Rmc(7)
3150 Imc(11)=Imc(7)
3160 Rmd(11)=Rmd(7)
3170 Imd(11)=Imd(7)
3180 Rma(10)=1
3190 Ima(10)=0
3200 Rmb(10)=0
3210 Imb(10)=Bc
3220 Rmc(10)=0
3230 Imc(10)=0
3240 Rmd(10)=1
3250 Imd(10)=0

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3260 Rma(9)=D
3270 Ima(9)=0
3280 Rmb(9)=0
3290 Imb(9)=0
3300 Rmc(9)=0
3310 Imc(9)=0
3320 Rmd(9)=B
3330 Imd(9)=0
3340 Rma(8)=Rma(6)
3350 Ima(8)=Ima(6)
3360 Rmb(8)=Rmb(6)
3370 Imb(8)=Imb(6)
3380 Rmc(8)=Rmc(6)
3390 Imc(8)=Imc(6)
3400 Rmd(8)=Rmd(6)
3410 Imd(8)=Imd(6)
3420 CALL Cdnv(Ran(5),Ian(5),Rkx(5),Ikx(5),Rank5,Iank5)
3430 CALL Cmult(P0,I1,Rank5,Iank5,Rak5,Iak5)
3440 CALL Cmult(P0,Ibt,Rak5,Iak5,Rak,Iak)
3450 CALL Cmult(P0,Ieta,Rak,Iak,Rakk,Iakk)
3460 CALL Cmult(Rkx(5),Ikx(5),Rkx(5),Ikx(5),Rkx5s,Ikx5s)
3470 Rxtk=-Rbtak*Ieta+2-Rkx5s
3480 Ixtk=-Ibtak*Ieta+2-Ikx5s
3490 CALL Cmult(Rxtk,Ixtk,Rak5,Iak5,Rtk,Itk)
3500 Rma(7)=Rcn(5)+Rakk
3510 Ima(7)=Icn(5)+Iakk
3520 Rmb(7)=Rho+Rtk+K
3530 Imb(7)=Rho+Itk+K
3540 Rmc(7)=-K+Rak5/Rho
3550 Imc(7)=-K+Iak5/Rho
3560 Rmd(7)=Rcn(5)+Rakk
3570 Imd(7)=Icn(5)+Iakk
3580 Rma(6)=Rma(4)
3590 Ima(6)=Ima(4)
3600 Rmb(6)=Rmb(4)
3610 Imb(6)=Imb(4)
3620 Rmc(6)=Rmc(4)
3630 Imc(6)=Imc(4)
3640 Rmd(6)=Rmd(4)
3650 Imd(6)=Imd(4)
3660 Rma(5)=Rma(3)
3670 Ima(5)=Ima(3)
3680 Rmb(5)=Rmb(3)
3690 Imb(5)=Imb(3)
3700 Rmc(5)=Rmc(3)
3710 Imc(5)=Imc(3)
3720 Rmd(5)=Rmd(3)
3730 Imd(5)=Imd(3)
3740 Rma(4)=Rma(2)
3750 Ima(4)=Ima(2)
3760 Rmb(4)=Rmb(2)
3770 Imb(4)=Imb(2)
3780 Rmc(4)=Rmc(2)
3790 Imc(4)=Imc(2)
3800 Rmd(4)=Rmd(2)
3810 Imd(4)=Imd(2)
3820 Rma(3)=B
3830 Ima(3)=0
3840 Rmb(3)=0
3850 Imb(3)=0
3860 Rmc(3)=0
3870 Imc(3)=0
3880 Rmd(3)=D
3890 Imd(3)=0
3900 Rma(2)=1
3910 Ima(2)=0

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3920 Rmb(2)=0
3930 Imb(2)=Bc
3940 Rmc(2)=0
3950 Imc(2)=0
3960 Rmd(2)=1
3970 Imd(2)=0
3980 Rxa=Rma(1)
3990 Ixa=Ima(1)
4000 Rxb=Rmb(1)
4010 Ixb=Imb(1)
4020 Rxc=Rmc(1)
4030 Ixc=Imc(1)
4040 Rxd=Rmd(1)
4050 Ixd=Imd(1)
4060 FOR I=2 TO 11
4070 CALL Cmult(Rxa,Ixa,Rma(I),Ima(I),Raa,Iaa)
4080 CALL Cmult(Rxb,Ixb,Rmb(I),Imb(I),Rba,Iba)
4090 Rta=Raa+Rba
4100 Ita=Iaa+Iba
4110 CALL Cmult(Rxc,Ixc,Rmc(I),Imc(I),Rab,Iab)
4120 CALL Cmult(Rxb,Ixb,Rmd(I),Imd(I),Rbd,Ibd)
4130 Rtb=Rab+Rbd
4140 Itb=Iab+Ibd
4150 CALL Cmult(Rxc,Ixc,Rma(I),Ima(I),Rca,Ica)
4160 CALL Cmult(Rxd,Ixd,Rmc(I),Imc(I),Rdc,Idc)
4170 Rtc=Rca+Rdc
4180 Itc=Ica+Idc
4190 CALL Cmult(Rxc,Ixc,Rmb(I),Imb(I),Rcb,Icb)
4200 CALL Cmult(Rxd,Ixd,Rmd(I),Imd(I),Rdd,Idd)
4210 Rtd=Rcb+Rdd
4220 Itd=Icb+Idd
4230 Rxa=Rta
4240 Ixa=Ita
4250 Rxb=Rtb
4260 Ixb=Itb
4270 Rxc=Rtc
4280 Ixc=Itc
4290 Rxd=Rtd
4300 Ixd=Itd
4310 NEXT I
4320 Rn=Rxc
4330 In=Ixc
4340 SUBEND
4350 SUB Neg(X1,Y1,X2,Y2)
4360 X2=-X1
4370 Y2=-Y1
4380 SUBEND

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END

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