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THESIS

FIN LINE FILTERS TECHNOLOGY
AND ELECTRONIC WARFARE

by

Stamatis Vitalis

December 1984

Thesis Advisor: J.B. Knorr

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Filters were fabricated and tested in X-band (8-12 GHz). Good agreement between the predicted response from a

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Some applications of fin line filter technology in Electronic Warfare are also shown.

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Fin Line Filters Technology and Electronic Warfare

by

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Filters were fabricated and tested in X-band (8-12 GHz). Good agreement between the predicted response from a MICRO-COMPACT (MPAC) program and the measured response from a network analyzer was obtained in the case of simple filters (two inductive strips).

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I. INTRODUCTION

During recent years, the attention of researchers has been focused on integrated fin-line filters, mainly in the millimeter wavelength (mmW) region.

The structure of the fin-line filter is very simple and consists of axial inductive metal strips, which are inserted in a rectangular waveguide such that, the strip surface is parallel to the narrow waveguide wall (i.e., parallel to the E-plane). For maximum dominant mode bandwidth the inductive metal strips are suspended in the center of the E-plane.

This method of construction, E-plane integrated-circuit, offers important advantages specifically in the mmWs region. Some of these are wide single mode bandwidth, low insertion loss, production economy, low equivalent dielectric constant, compatibility with hybrid IC devices, and simple transitions to waveguide instrumentation [Ref. 1].

The importance of millimeter wave (mmW) applications and technology has increased very quickly. This significance is probably more powerful in military applications than elsewhere, mainly in the current sophisticated warfare environment and weaponry. Applications include more precise tracking guidance systems for missiles in cluttered and smoke regions, and short range communications with link privacy, which the mmWs are capable of providing.

MICRO-COMPACT (MPAC) is a COMPACT software computer program that analyses and optimizes the performance of cascaded two-port microwave circuits. MPAC runs on the Hewlett-Packard 9845 B/T/C desktop computer with 186K of memory. There are a number of mnemonic codes for elements, connections and sub-circuits, which are used to operate the MPAC [Ref. 4]. In this program, the circuit description is entered into the computed by translating its schematic diagram into MPAC code.

In a previous thesis, a spectral domain program was developed to calculate scattering coefficients for inductive strips in a fin-line [Ref. 2]. Scattering coefficients of some inductive strips were measured directly using (a) a slotted line and (b) a vector microwave network analyzer. Good agreement between measured and computed scattering data was obtained.

Fin-line resonators can be constructed using two identical strips to form a half wave cavity. The resonator response (return loss, insertion loss, resonant frequency and Q) depends upon the scattering coefficients ($|S_{11}|$, θ_{11}, $|S_{21}|$, θ_{21}). These are the independent scattering quantities for a reciprocal, symmetric network (strip). Thus, measurement of the four filter parameters will, in principle, permit the computation of the scattering coefficients $S_{11} = S_{22}$ and $S_{21} = S_{12}$. The advantage over direct measurement is that a vector analyzer is not required since the filter parameters are scalar quantities.

The purpose of this thesis is to further investigate the accuracy of fin-line inductive strip scattering coefficients computed using the spectral domain method. This is done by comparing MPAC predicted filter response with measured filter response. For convenience, experiments were conducted in the 8-12 GHz frequency range.

II. FIN LINE FILTERS

A. FIN LINE STRUCTURE

1. Planar Filters

The main use of fin-line in the mmW band is for the E-plane circuit design. The axial inductive strips and dielectric layers are suspended in the E-plane of rectangular waveguide.

Many experts have published various papers about fin-line. The first approach of fin-line was for very special purposes of orthogonal-mode launching in circular waveguides [Ref. 6]. Meir purlished the first paper of the fin-line as a new transmission line for mmW integrated circuits (ICs) [Ref. 12].

The use of this approach to build bandpass filters provides a higher Q (quality factor) and the possibility for close integration of filters with semiconductor mounts (including printed bias networks). Multiport channel-dropping networks can be formed by combining filters and planar couplers. Typical unloaded Q values of 2500 at 12 GHz and 1600 at 32 GHz are provided by all metal resonator structures [Ref. 3].

2. Fin Line Characteristics

The main advantage of fin-line in relation with slot line is that it does not require a high-K substrate to prevent radiation. The avoidance of high-K substrate is very useful in mmWs where miniaturization problems appear [Ref. 6].

The effect of septum length was investigated by some researchers. Knorr calculated numerically the septum reactance for various values of distance from the leading edge of the septum to the end of the cavity [Ref. 8].

In Figure 2.1, it is obvious that the reactance increases rapidly as the length of the septum is increased and then saturates, for all frequencies. In the same figure it is shown that the septum length required to reach maximum reactance increases with frequency. Figure 2.2 shows the end and side views of a fin line cavity.

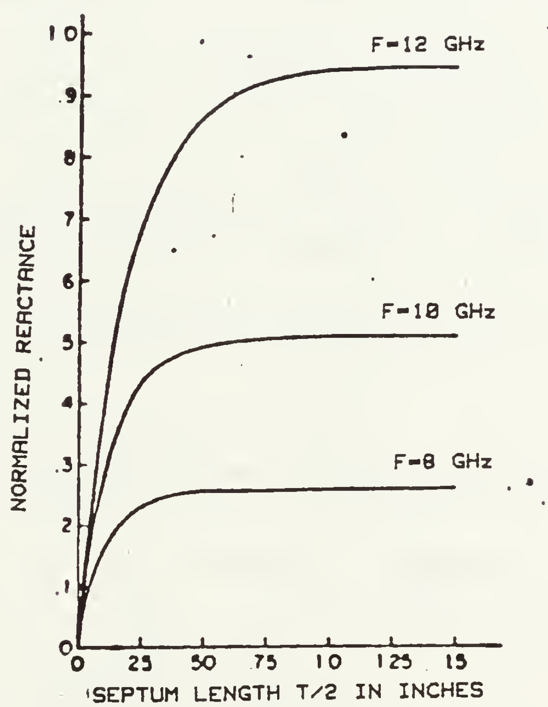


Figure 2.1 Normalized Reactance Versus Length [Ref. 8]

Some filters of narrow bandwidth were designed by a procedure which was based on the mode-watching technique

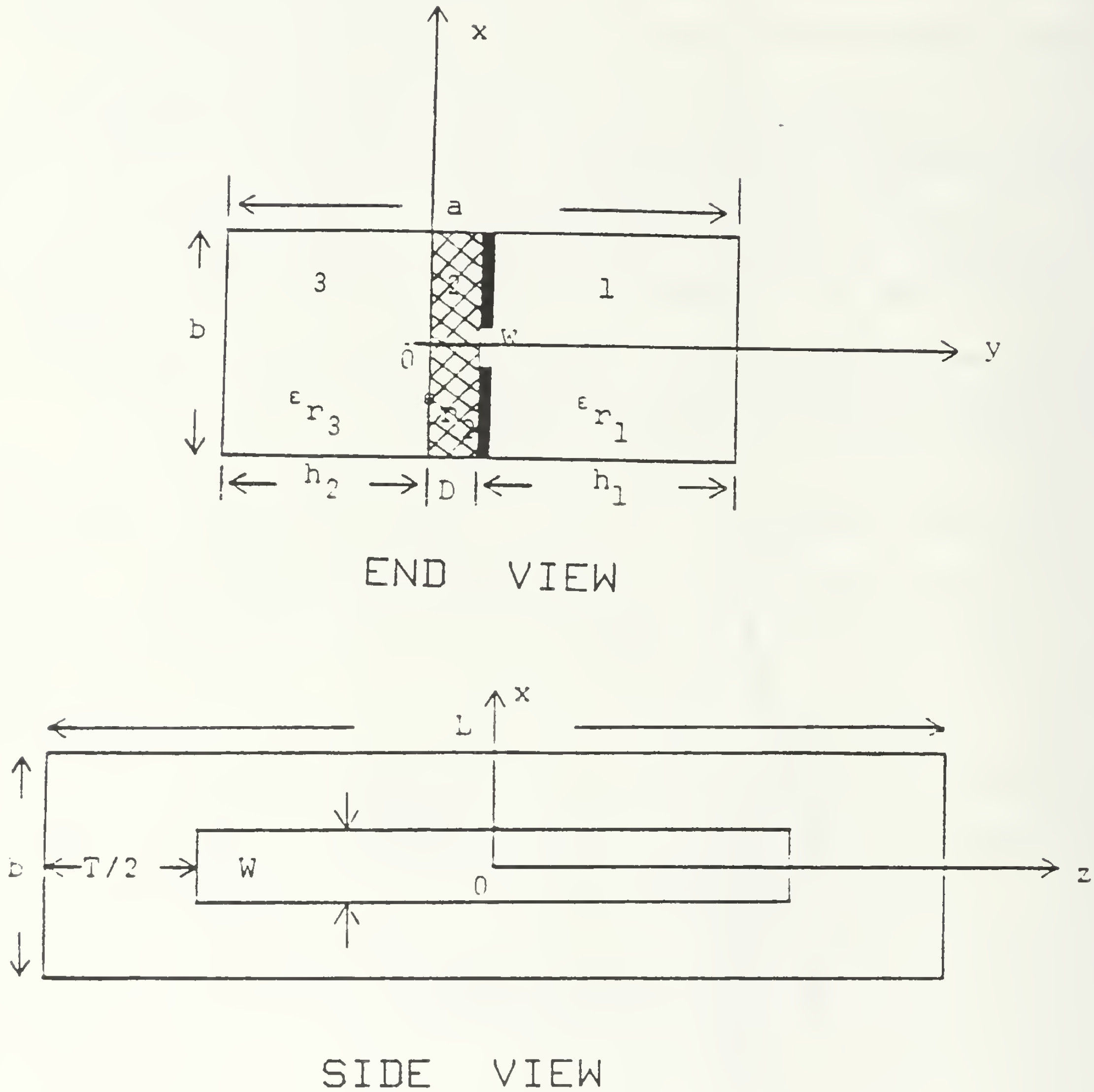


Figure 2.2 End and Side Views of Fin-Line Cavity [Ref. 2]

[Ref. 9]. It was proved that the thickness of metal strips effects a downward shift in the center frequency and a reduction in the passband bandwidth. Y.C. Shih suggested [Ref. 9], the use of a thick metal strip for narrow-band design at higher frequencies. The mode-matching technique is discussed in detail in the next section of this chapter.

3. E-Plane Printed Circuit Discontinuities

The problem of the fin-line shorting septum is related to the inductive strip. Konishi has published an approach using field-expansion, which applies if there is no dielectric in the structure [Ref. 21]. Hoefer and Pic have measured a large number of resonators in order to determine the equivalent circuit of a short-circuit end-element [Ref. 22].

During recent years, the two most common approaches to solving the discontinuity problem in fin-lines have been the spectral domain method and the mode-matching technique [Ref. 6].

a. Spectral Domain Method

In this method the propagation constant at a given frequency is provided by using algebraic equations. These algebraic equations are based on the Fourier transforms of the E field between the fins.

The use of algebraic equations in the numerical processing is an important advantage of this method. For practical applications the knowledge of higher order modes is essential to define the band for single mode operation.

Another important parameter for design purposes is the characteristic impedance of the dominant mode [Ref. 7].

Knorr has computed the eigenfrequencies of fin-line resonators and has described the equivalent short-circuit reactance by using this method in his calculations [Ref. 8].

b. Mode-Matching Technique

In this technique the fin-line structures in the waveguide are divided in two regions. The expansion of the unknown fields of each region is performed in terms of the normal modes. So, at the interfaces between regions, the field must satisfy the continuity requirements.

The solution of boundary value problem of the linear simultaneous equations, for the unknown model coeff-cients, is based on the orthogonality property. The derivation of an infinite set of equations leads to the scattering matrix for a discontinuity. In the case of the fin-line a cascading technique can be used to develop an equivalent scattering matrix [Ref. 1].

El Hennawy and Schunemann have described a single or a double step in the slot width, symmetrical or unsymmetrical using a mode-matching technique [Ref. 23].

4. E-Plane Printed Waveguides

During the last decade, the fin-line medium has been combined with other planar waveguiding structures like microstrip and coplanar line to form quite versatile mixed waveguide integrated circuits (IC).

The IC consists of a waveguide and an E-plane metal printed-circuit part. Several configurations of fin-lines may be used. These are shown in Figure 2.3 [Ref. 6].

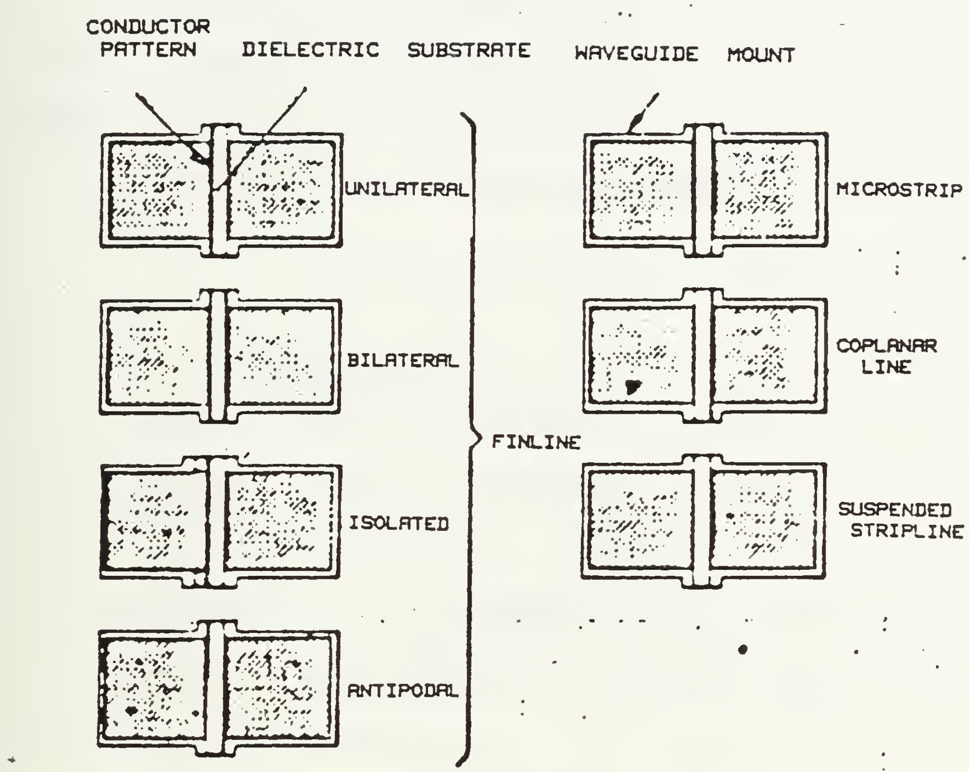


Figure 2.3 Several Types of Fin-line and Strip Transmission Line [Ref. 6]

Various other structures may also be mounted in a metal wave-guide housing split in the E-plane. There are a large number of combinations of these which may be used to realize special advantages in various applications.

Several researchers have measured the characteristics of sections of unilateral and bilateral fin-lines. Practical fin-lines on 17 μm copper clad RT/Duroid 5880 having relatively narrow slots of width around 0.1 mm--0.4 mm in the Ka band (26.5-40 GHz), exhibit attenuation of below 0.1 dB/wavelength (254 μm substrate thickness), while this figure tends to increase to 0.15 dB/wavelength in the E-band (60-90 GHz), (127 μm substrate) [Ref. 6].

B. MICRO-COMPACT (MPAC) PROGRAM

1. Scattering Matrix of the Inductive Strips

In the rectangular waveguide the dominant mode is the TE_{10} and the E-field is extended in the y-direction in the guide (Figure 2.4). However, in the fin-line guide as w/b goes to zero, the cut-off frequency (f_c) becomes lower. But once w/b becomes zero such as in the case of the septum or inductive strip (Figure 2.5), the dominant mode will not propagate at normal operating frequencies [Ref. 5].

The inductive strip (thin metal plate) in fin-line is reciprocal and symmetric and will be assumed lossless.

As a result, the scattering matrix of the network, (Figure 2.6), is:

- unitary
- $S_{11} = S_{22}$
- symmetric ($S_{21} = S_{12}$)

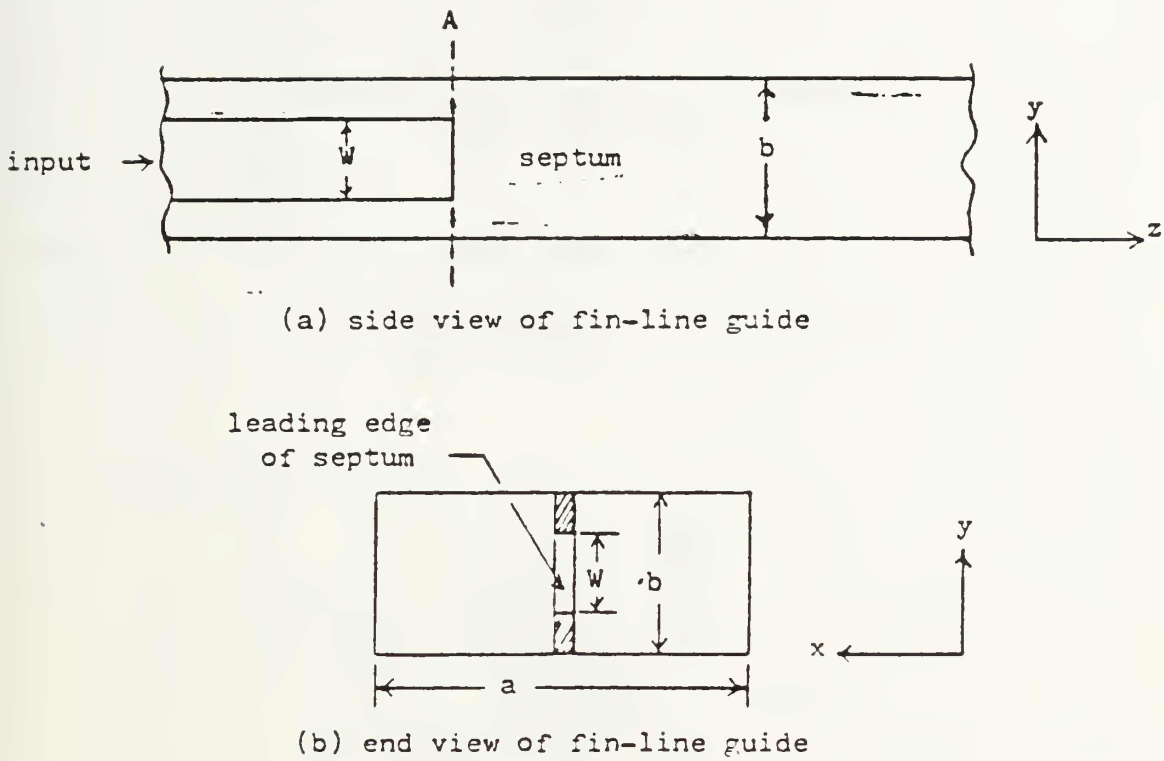
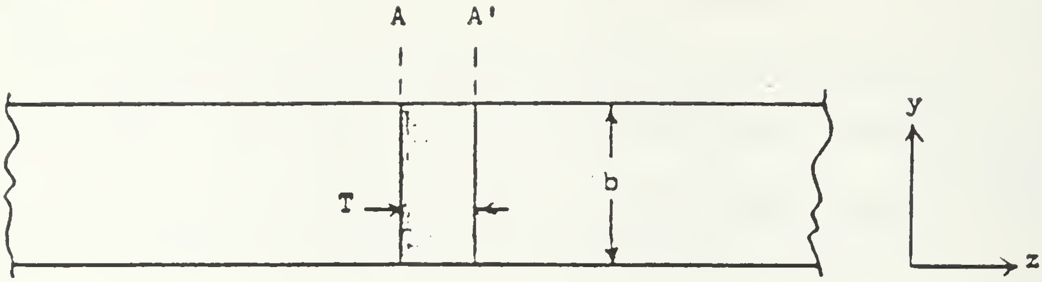
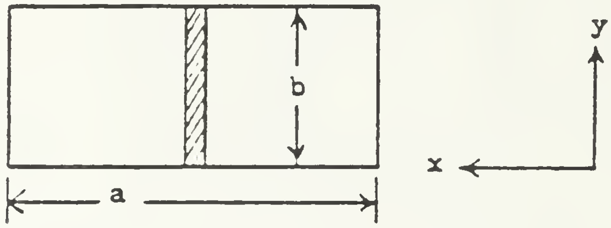


Figure 2.4 Fin-line Guide with Septum [Ref. 5]



(a) side view of inductive strip



(b) end view of inductive strip

Figure 2.5 Fin-line Guide with Inductive Strip [Ref. 5]

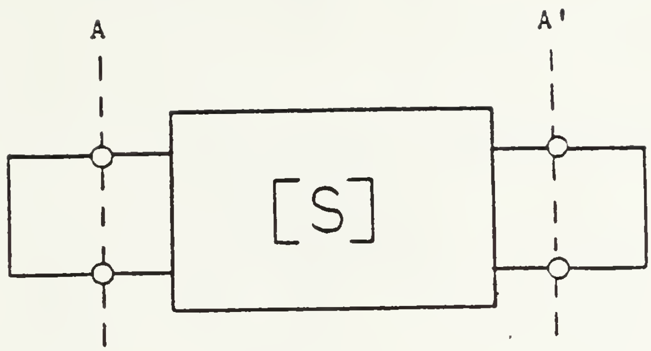


Figure 2.6 Scattering Matrix of the Network

Therefore,

$$[S] = \begin{bmatrix} S_{11} & S_{12} \\ S_{12} & S_{11} \end{bmatrix} \quad \text{and} \quad [\tilde{S}^*] = \begin{bmatrix} S_{11}^* & S_{12}^* \\ S_{12}^* & S_{11}^* \end{bmatrix}$$

where * denotes complex conjugate and ~ denotes the transpose. Using the unitary property of [S], $[S]\cdot[\tilde{S}^*] = [I]$, we obtain

$$S_{11} S_{11}^* + S_{12} S_{12}^* = 1 \qquad (2.1)$$

and

$$S_{11} S_{12}^* + S_{12} S_{11}^* = 0 . \qquad (2.2)$$

Thus, from (2.1) we obtain

$$|S_{11}| = \sqrt{1 - |S_{11}|^2} \qquad (2.3)$$

and from (2.2) we obtain

$$S_{11} S_{12}^* + (S_{12}^* S_{11})^* = 0 \; . \qquad (2.4)$$

Therefore,

$$2|S_{11}||S_{12}| \cos(\theta_{11} - \theta_{12}) = 0 \qquad (2.5)$$

or

$$\theta_{11} - \theta_{12} = \pm \pi/2 \; . \qquad (2.6)$$

For inductive strips, $\theta_{11} - \theta_{21} = +\pi/2$ or $\theta_{12} = \theta_{11} - \pi/2$.

2. Model of the Strips in MPAC

The flow diagram of the MPAC is shown in Figure 2.7. The operation of this program proceeds in a user interactive manner. The method of describing the circuit is shown in Figure 2.8.

One of the circuit elements in the MPAC library is the "black box." The maximum number of black boxes, which the program can use, is five.

Each inductive strip of the fin-line filter can be represented by a black box. The standard form of the black box in MPAC is shown in Figure 2.9.

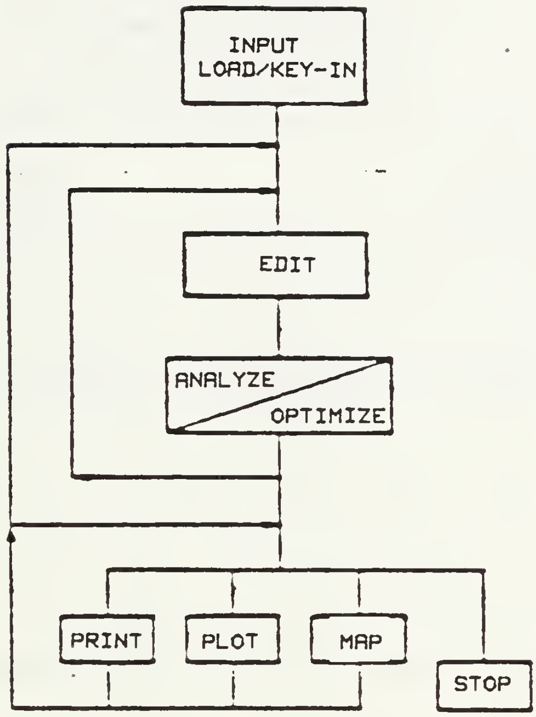


Figure 2.7 Block Diagram of MPAC Operation [Ref. 4]

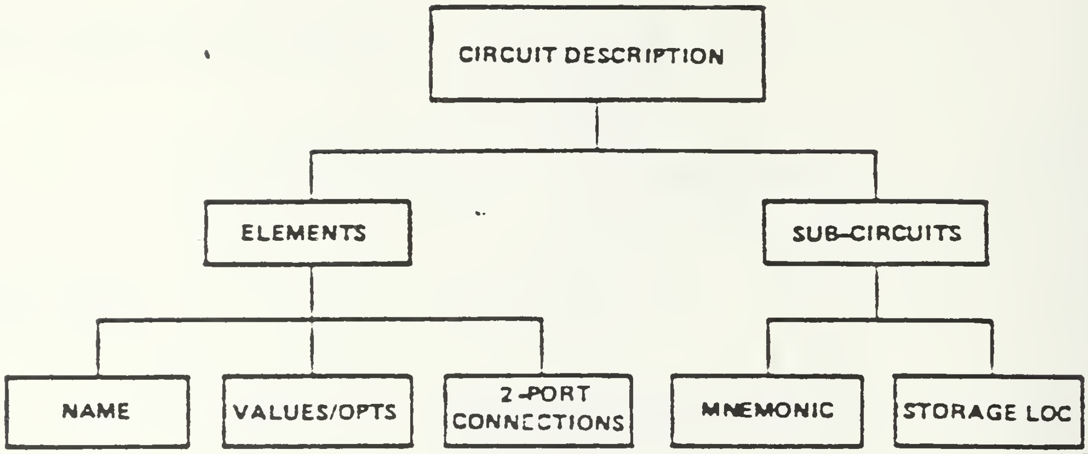


Figure 2.8 Description of the Entering Data [Ref. 4]

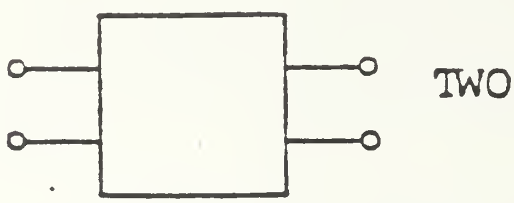


Figure 2.9 Form of the Black Box Element

The black box data are supplied from the keyboard by the user in the final step before program execution. The prompt that requests data is:

```
Enter data (F,11,12,21,22) for TWO ref. No(1-5)
/CONT terminates input
?
```

Each line of entered data must consist of a frequency value and four (4) sets of two numbers, which are the magnitude and angle values of the scattering parameters (S_{11},S_{12}, S_{21},S_{22}) of the inductive strip.

Appendix B contains the MPAC output for all filters studied in this thesis. The output includes both the circuit description (including strip scattering coefficients) and the analysis results.

III. ANALYSIS OF THE FIN LINE FILTERS

A. OVERVIEW

Fin-line filters have been designed and analyzed using several different computer programs. K.B. Alexander and S.R. Hamel designed and analyzed three types of E-plane fin-line filters [Ref. 1], in order to validate their computer aided design (CAD) program.

J.C. Deal analyzed the inductive discontinuity (strip) in a fin-line structure and developed two programs, FINCAV and FINSTRP. The FINCAV program calculates the resonant-length of a single resonant cavity and the corresponding equivalent reactance of the shorting septum (inductive discontinuity). The FINSTRP program calculates the odd and even mode resonant lengths of two coupled resonant cavities and the scattering (S) parameters of the inductive strip [Ref. 2].

Each strip of the fin-line filter can be considered as a "black box" element. The (MPAC) program can then be used to predict the response of the filter. The "black box" scattering coefficients required by the MPAC program were computed using Deal's program.

B. FILTER CONSTRUCTION AND TEST

All filters were designed to resonant within the 8 to 12 GHz band where measurements could be made more easily and accurately.

Figures 3.1-3.5 show pictures of the E-plane fin structure for all filters. The black color of the pictures represents the metal part (inductive strips) of the filter, while the empty part inside the waveguide (resonators). Filter #5 (ℓ = 1.40 cm) (Figure 3.4) has dielectric (ε_τ = 2.5) instead of air (ε_τ = 1), locking the inductive strips.

Table 1 contains the physical dimensions of strips and resonators. Filters #1 and #2 (Figures 3.1, 3.2), were constructed by Alexander and Hamel [Ref. 1]. All the other filters were built by Knorr. Appendix A describes the mathematical procedure for their design.

The filters were constructed of .002 in copper foil. The electrical performance was measured using a HP-8409 Vector Network Analyzer.

C. NUMERICAL RESULTS AND COMPARISON

Plots of insertion loss and return loss versus frequency for all filters are shown in Figures 3.8 through 3.23. The numerical curve is a plot of the MPAC predicted filter response, while the experimental curve is a plot of the response measured using the HP-8409.

Figures 3.9 and 3.11 show that the MPAC program does not work well for filters with a large number of inductive strips (Filter #2). One of the reasons is the limitation of frequency points for interpolation.

$$\text{(Max. number of points)} \times \text{(number of "black boxes")} \leq 128$$

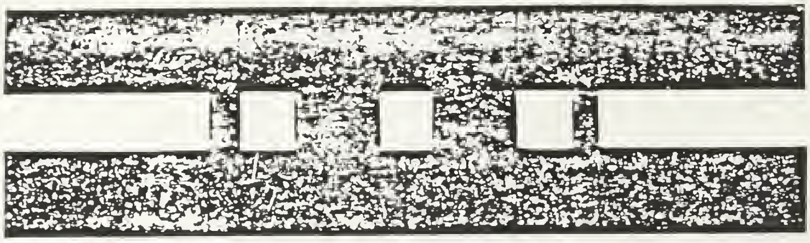


Figure 3.1 Filter #1, Four Strips

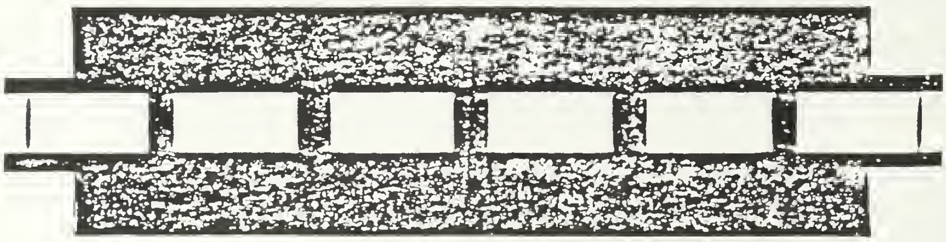


Figure 3.2 Filter #2, Seven Strips

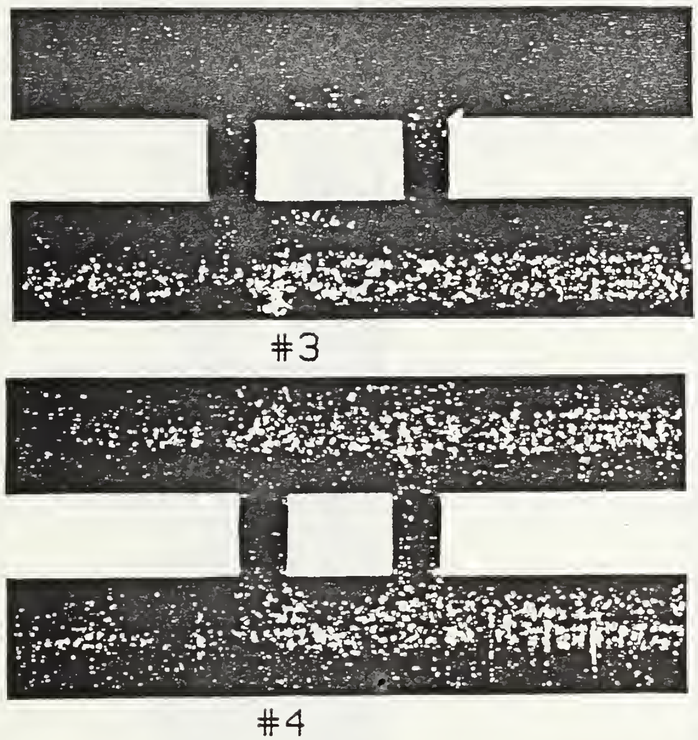


Figure 3.3 Filters #3, #4, Two Strips

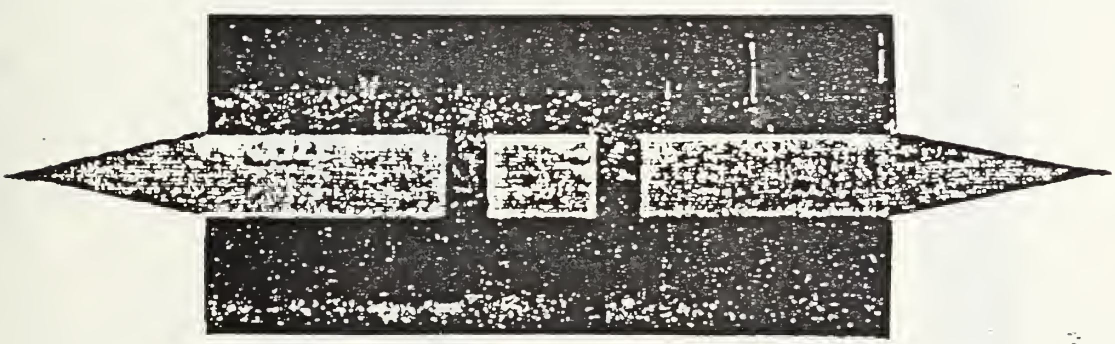


Figure 3.4 Filter #5 (ℓ = 1.40 cm), Two Strips, with Dielectric

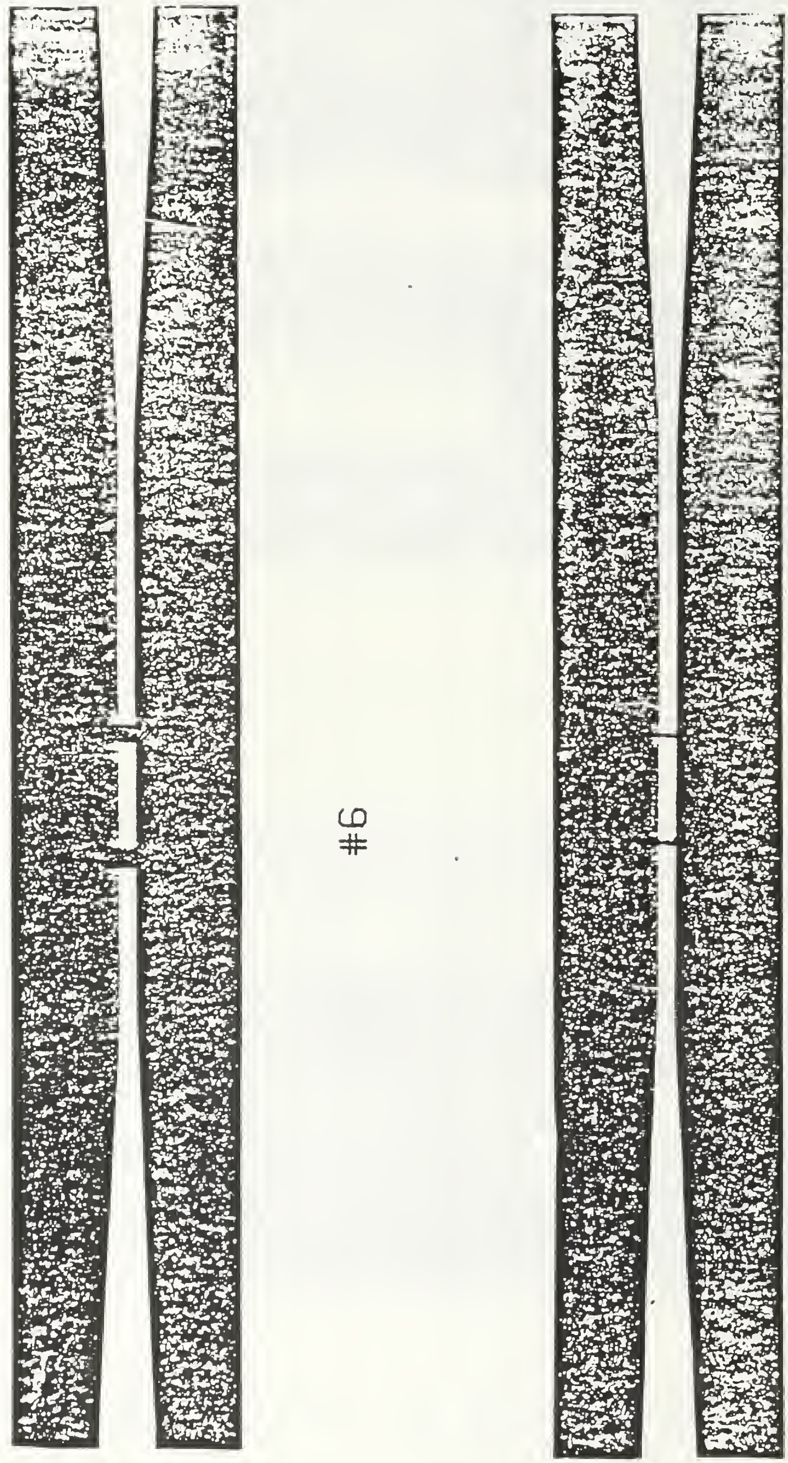
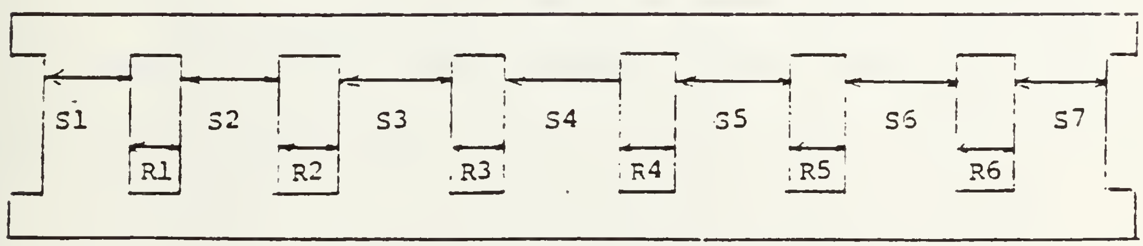


Figure 3.5 Filters #6, #7, Two Strips

TABLE 1

Physical Dimensions of Filters

Filter #	1	2	3	4	5	6	7
# Strips (S)	4	7	2	2	2	2	2
# Reson. (R)	3	6	1	1	1	1	1
w/b	1	1	1	1	1	.2612	.2638
S1 (cm)	.4995	.0906	.6197	.6223	.5588	.5285	.1695
S2 (cm)	1.4252	.4794	.6324	.6350	.5080	.4925	.1745
S3 (cm)	1.4252	.5961	-	-	-	-	-
S4 (cm)	.4995	.6134	-	-	-	-	-
S5 (cm)	-	.5961	-	-	-	-	-
S6 (cm)	-	.4794	-	-	-	-	-
S7 (cm)	-	.0906	-	-	-	-	-
R1 (cm)	.9420	2.0500	1.3335	1.8288	1.400	1.6873	1.7109
R2 (cm)	.9180	2.1160	-	-	-	-	-
R3 (cm)	-	2.1195	-	-	-	-	-
R4 (cm)	-	2.1195	-	-	-	-	-
R5 (cm)	-	2.1160	-	-	-	-	-
R6 (cm)	-	2.0500	-	-	-	-	-



The resonator length is another source of errors. It was found that the value of length (ℓ) is very critical. For example in Filter #5, with dielectric, for lower value ℓ, there is a shift of the predicted response to the left (e.g., decrease of ℓ by 0.03 cm results in 75 MHz shift, Figures 3.18 and 3.19).

The curves in Figures 3.6 and 3.7 show the experimental (circles) and the numerical (squares) values for θ_{11} vs. frequency for T = 0.2 inch and T = 0.05 inch inductive strips as determined by Deal [Ref. 2]. In this case the fins were centered with w/b = .25.

The experimental value of resonant frequency and the measured length of the resonators for filters #6 and #7 provided new experimental values of θ_{11} for the inductive strips used in these filters.

Good agreement between the new experimental values of θ_{11} and the experimental values from Deal's measurements is seen in Figures 3.6 and 3.7. It is satisfying that the two different experimental methods produce results which agree. Scalar analyzer measurements of resonant frequency for Filter #6 and Filter #7 were used to calculate θ_{11} for the inductive strips used in these filters.

Good agreement between predicted and actual response has been achieved for simple filters (see Figures 3.12-3.23).

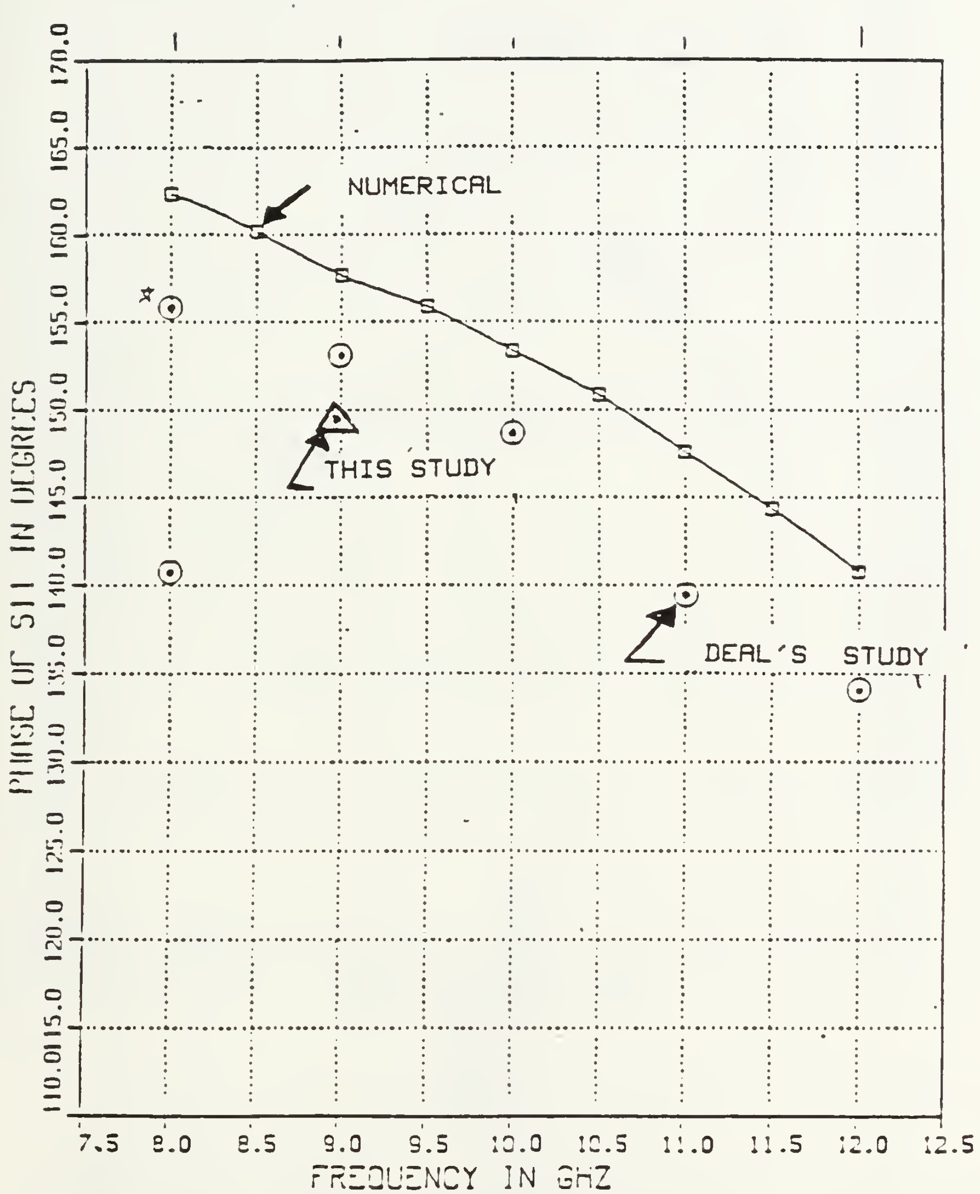


Figure 3.6 θ_{11} vs. Frequency for a T = 0.2 Inch Inductive Strip in a Fin-line Width w/b = 0.25. Fins are Centered and $\varepsilon_r = 1$. The Figure Compares Deal's Numerical and Experimental Results with the Experimental Point Obtained in this Study Using Filter #6.

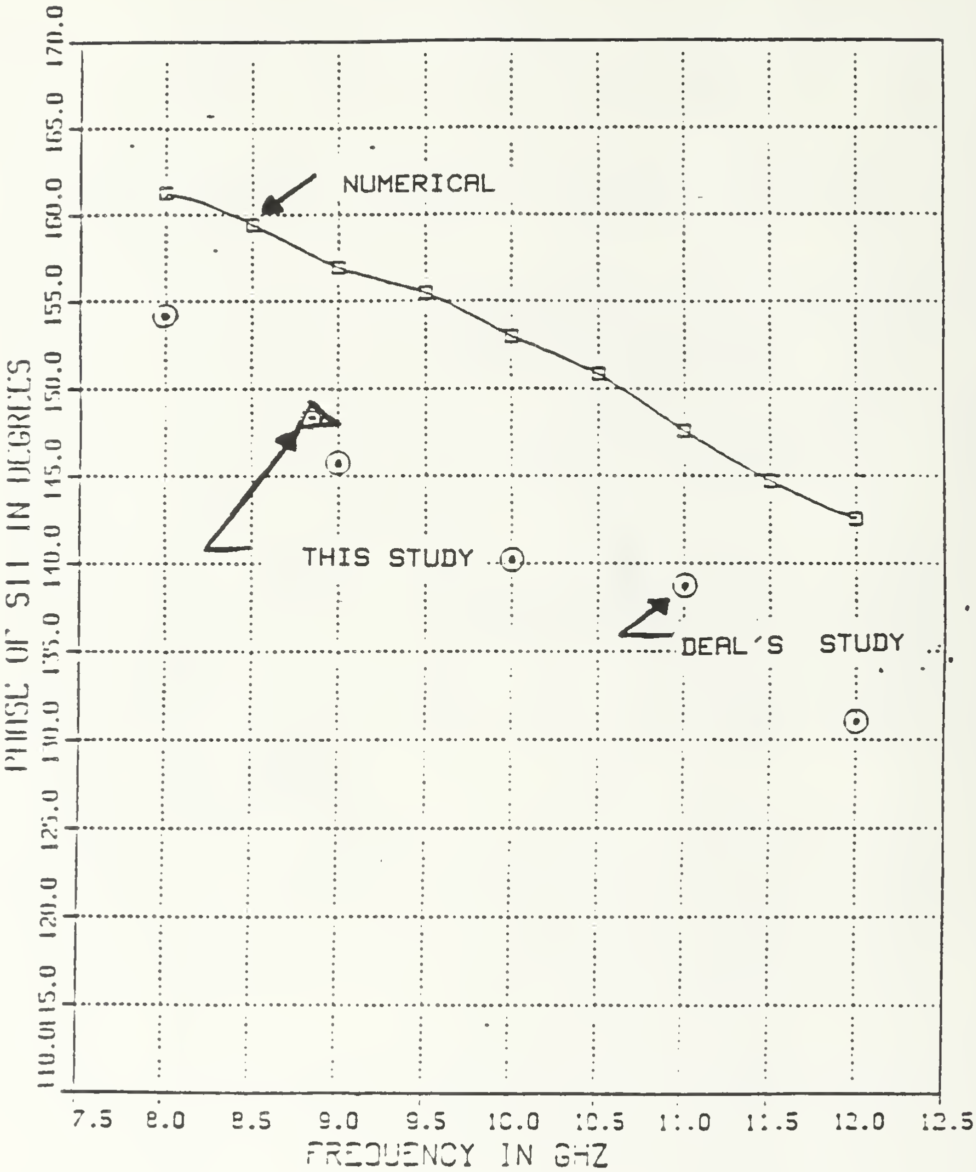


Figure 3.7 θ_{11} vs. Frequency for a T = 0.05 Inch Inductive Strip in a Fin-line Width w/b = 0.25. Fins are Centered and ε_{τ} = 1. The Figure Compares Deal's Numerical and Experimental Results with the Experimental Point Obtained in this Study Using Filter #7.

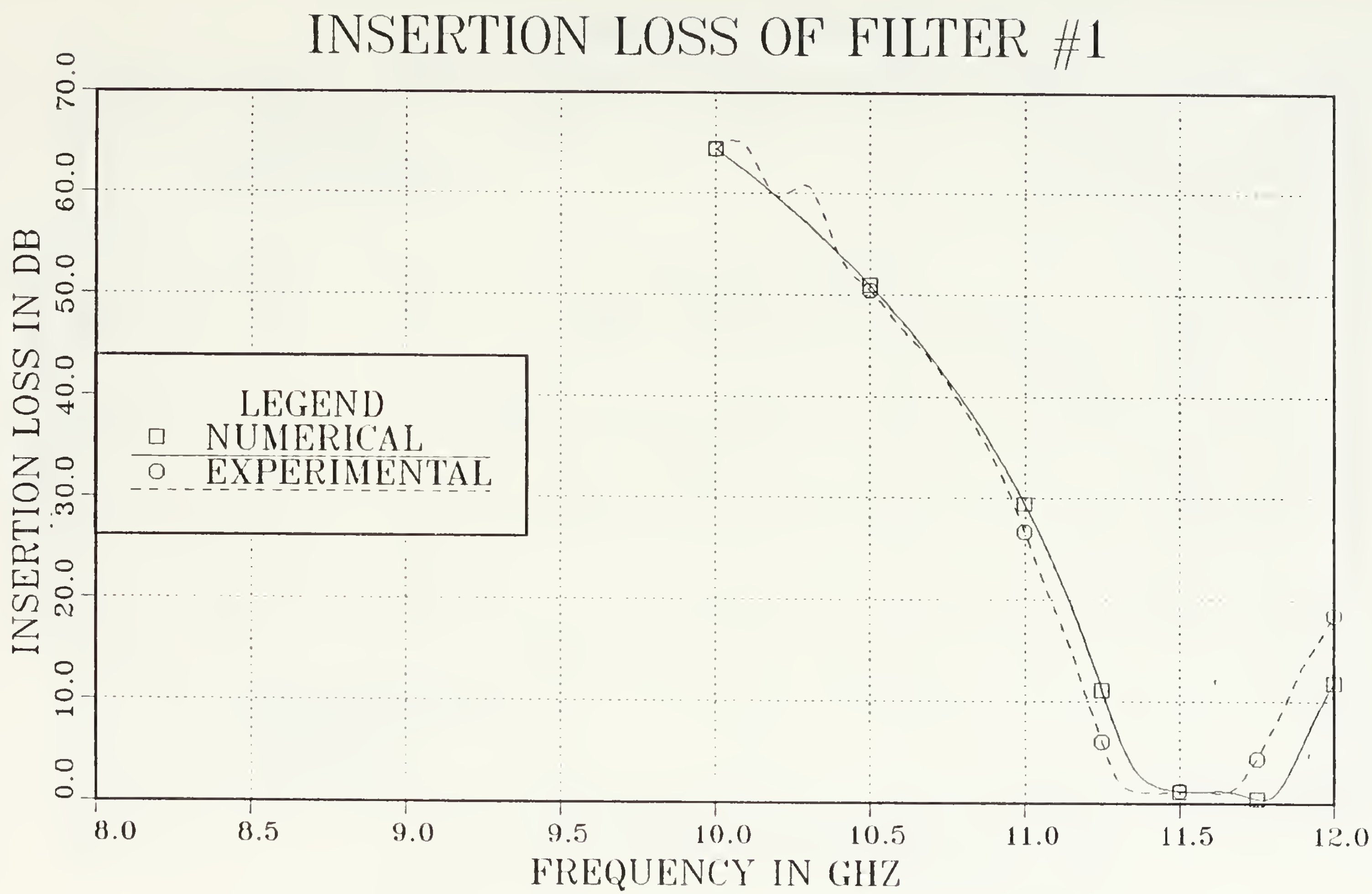


Figure 3.8 Predicted and Measured Insertion Loss vs. Frequency for Filter #1

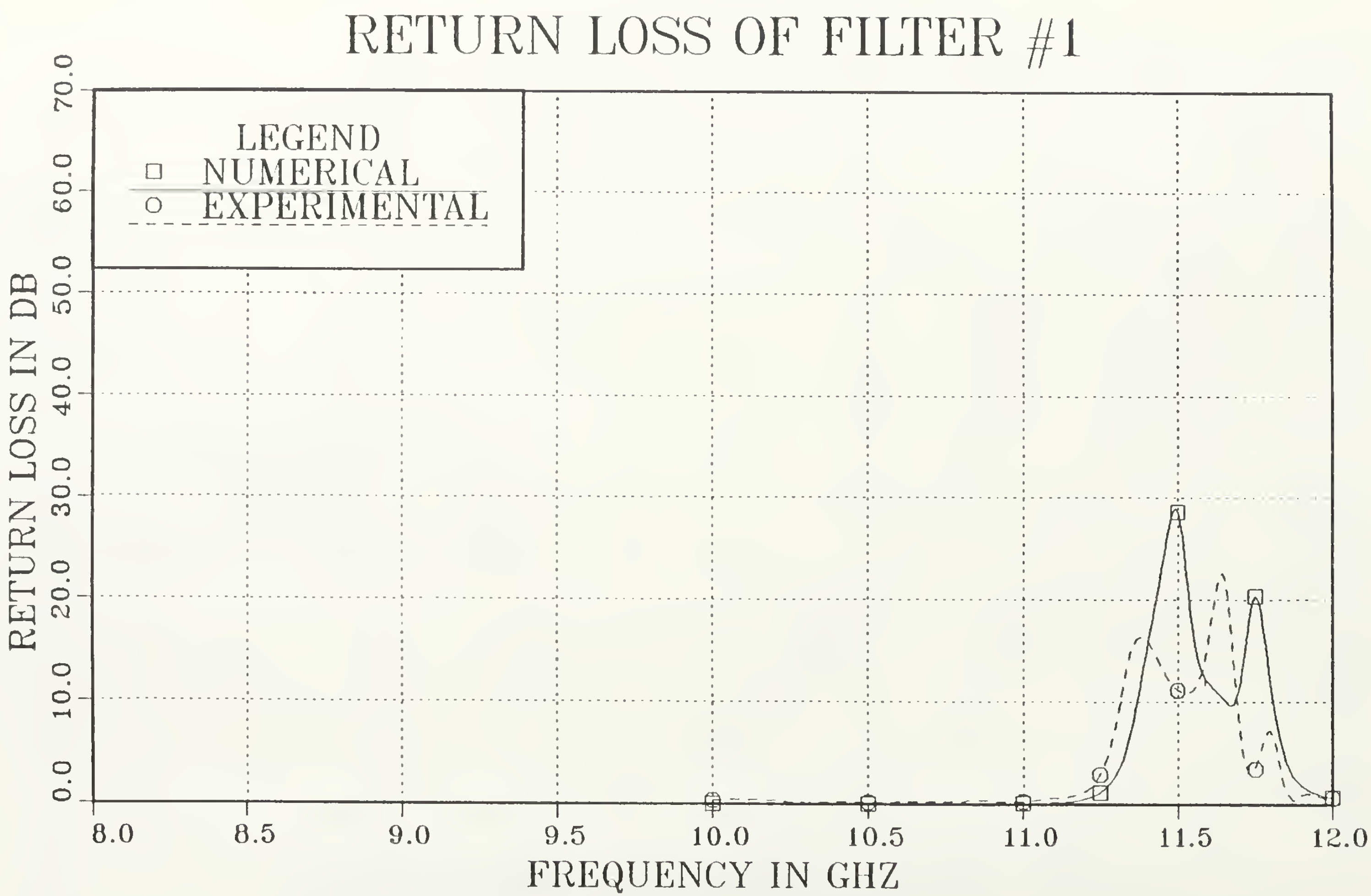


Figure 3.9 Predicted and Measured Return Loss vs. Frequency for Filter #1

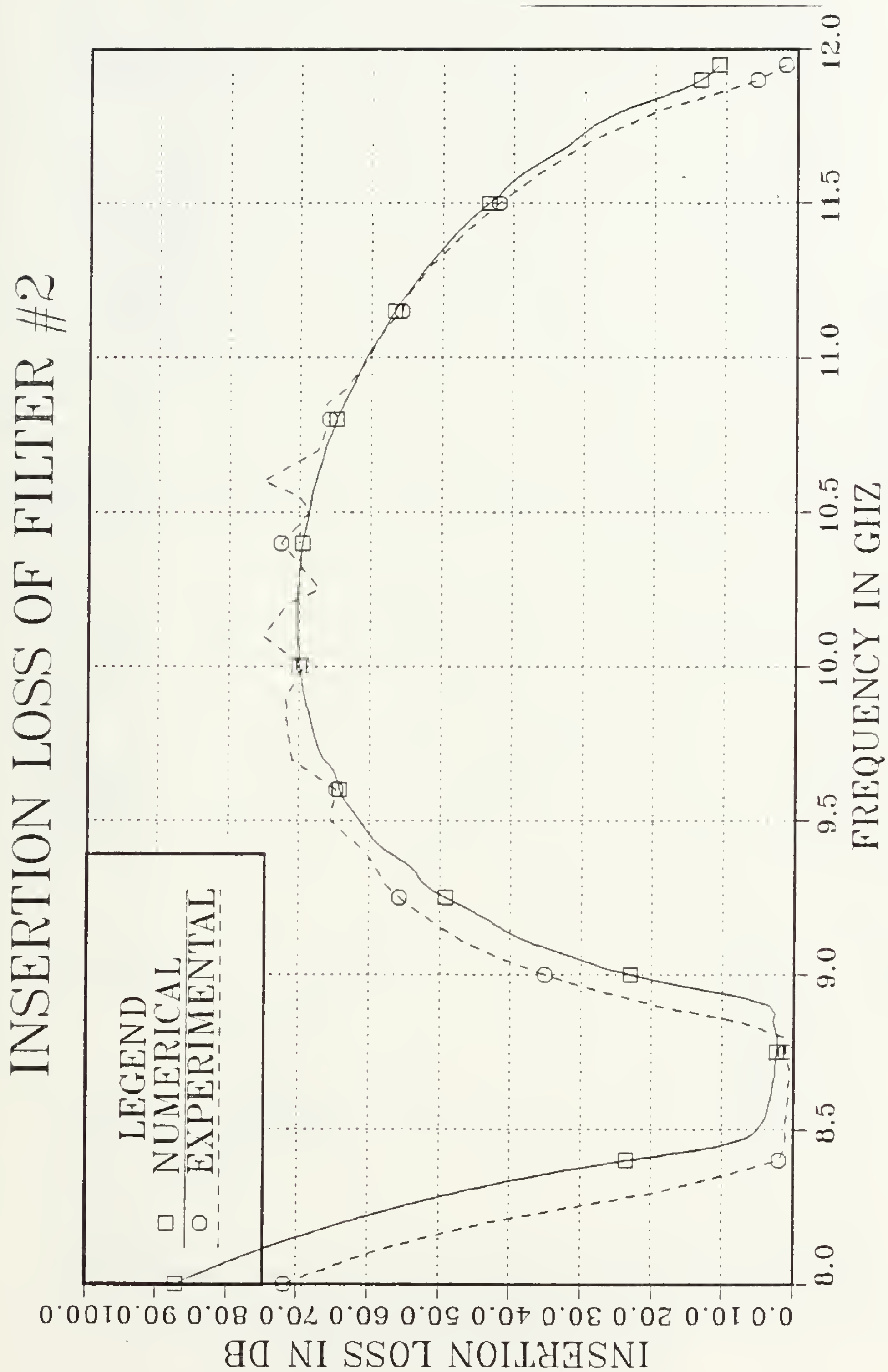


Figure 3.10 Predicted and Measured Insertion Loss vs. Frequency for Filter #2

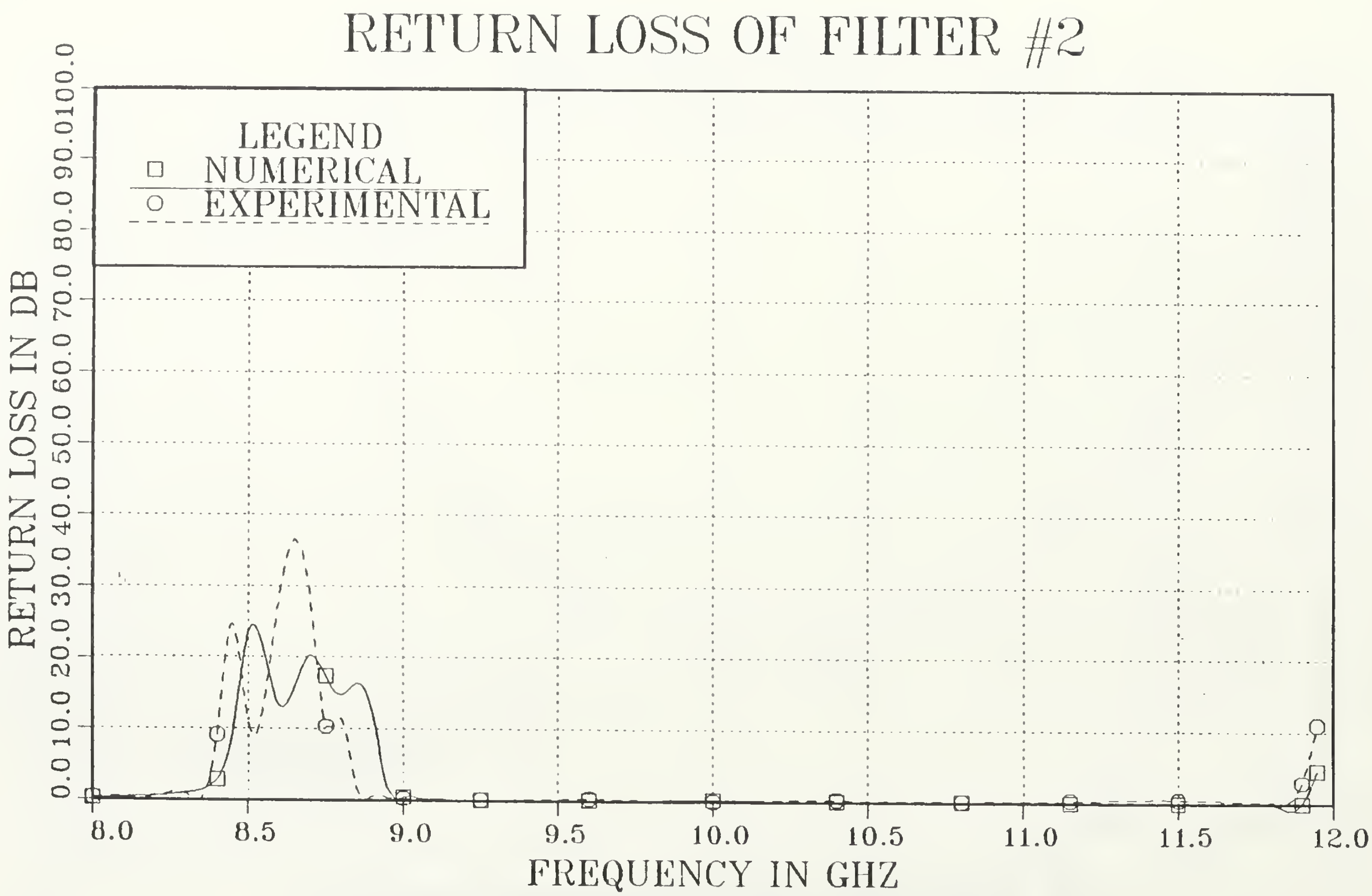


Figure 3.11 Predicted and Measured Return Loss vs. Frequency for Filter #2

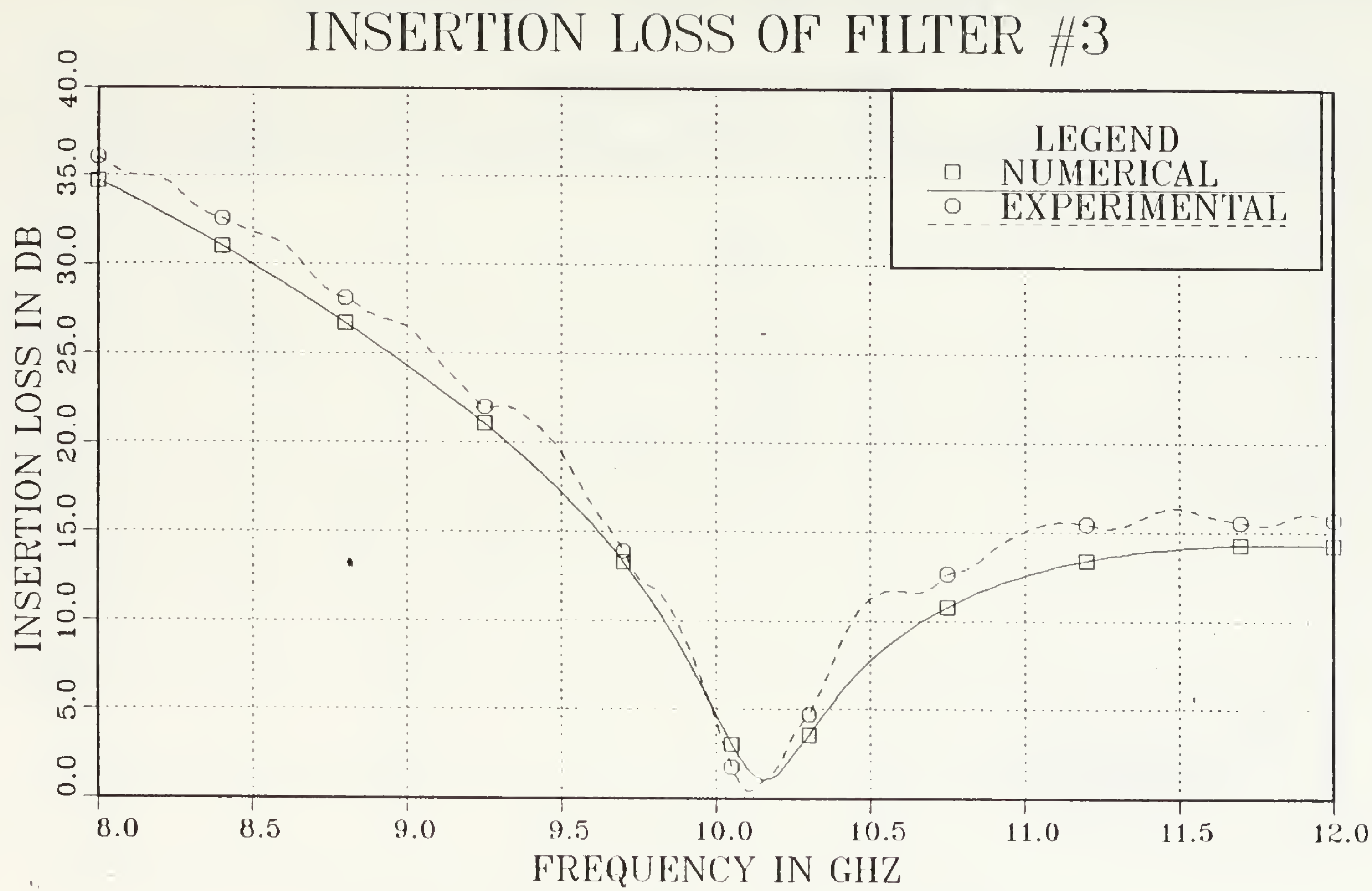


Figure 3.12 Predicted and Measured Insertion Loss vs. Frequency for Filter #3

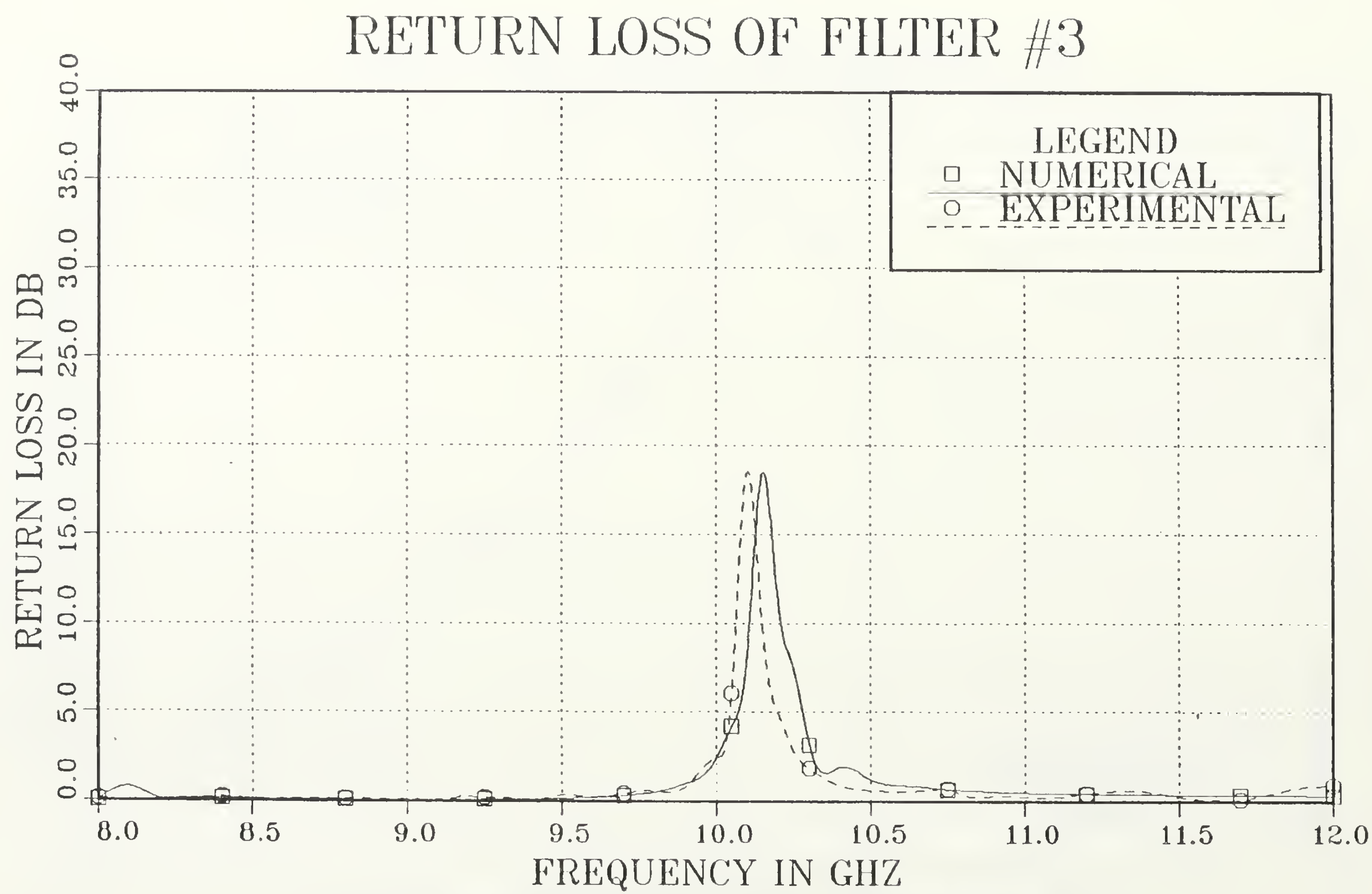


Figure 3.13 Predicted and Measured Return Loss vs. Frequency for Filter #3

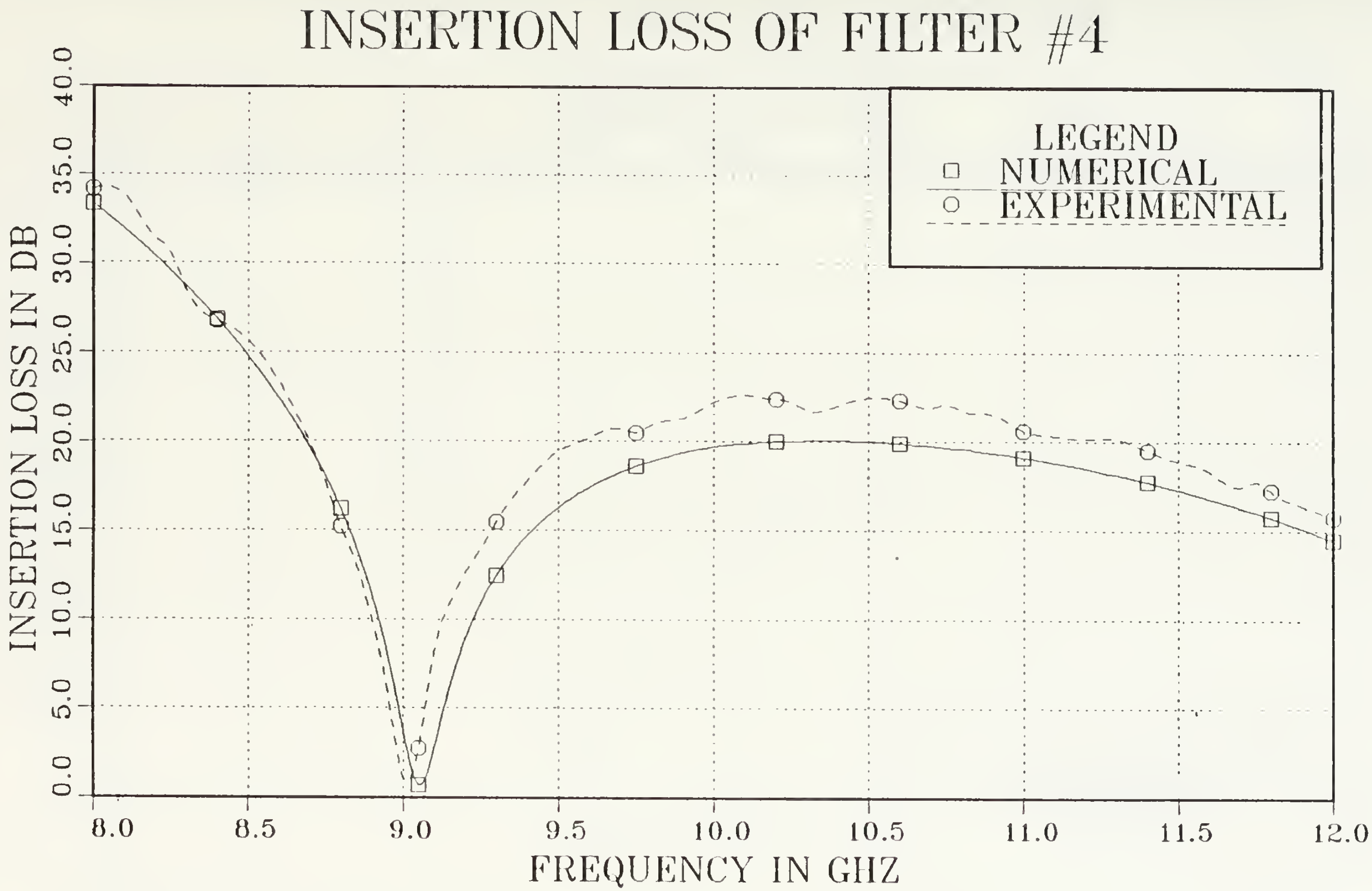


Figure 3.14 Predicted and Measured Insertion Loss vs. Frequency for Filter #4

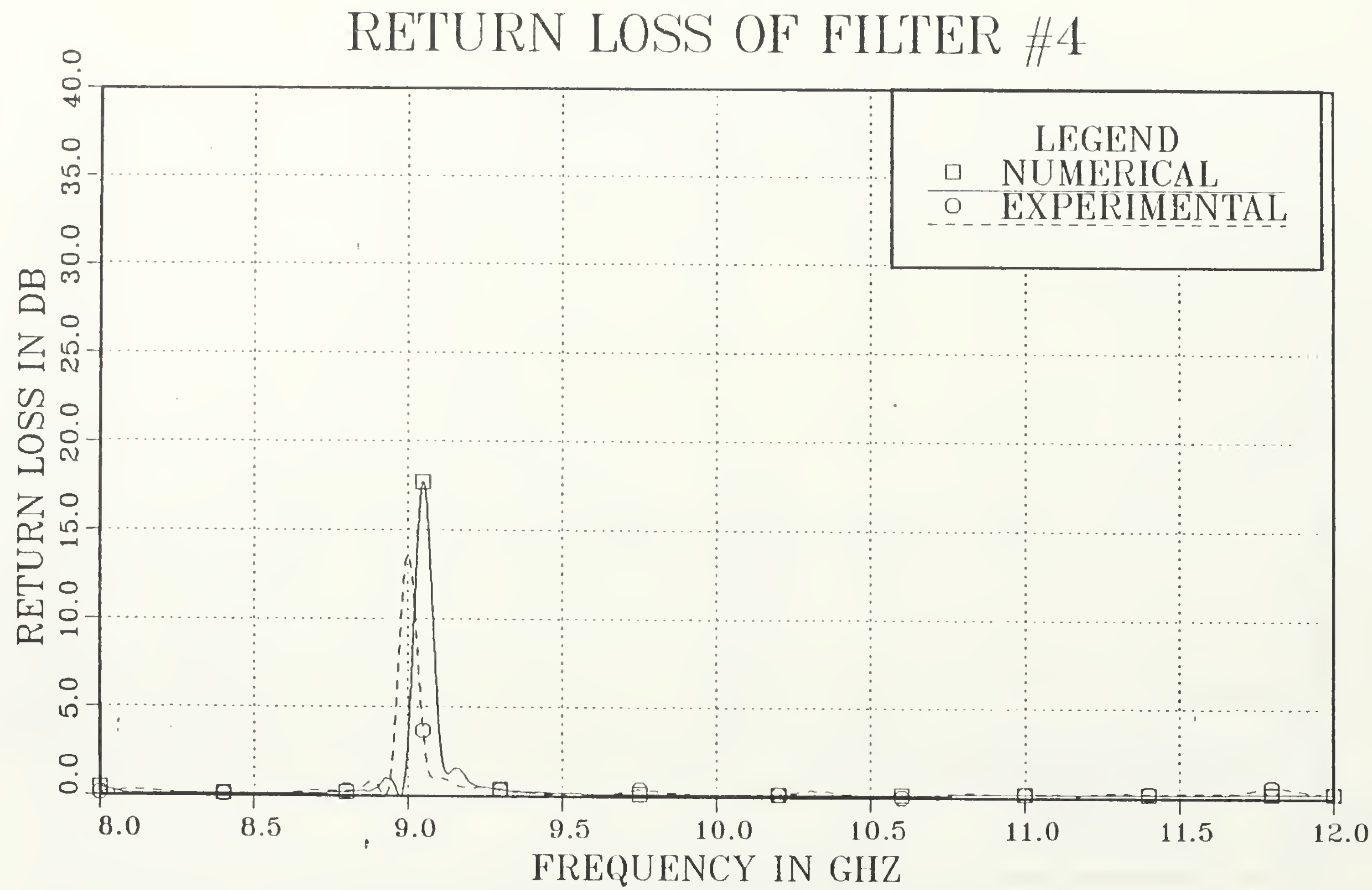


Figure 3.15 Predicted and Measured Return Loss vs. Frequency for Filter #4

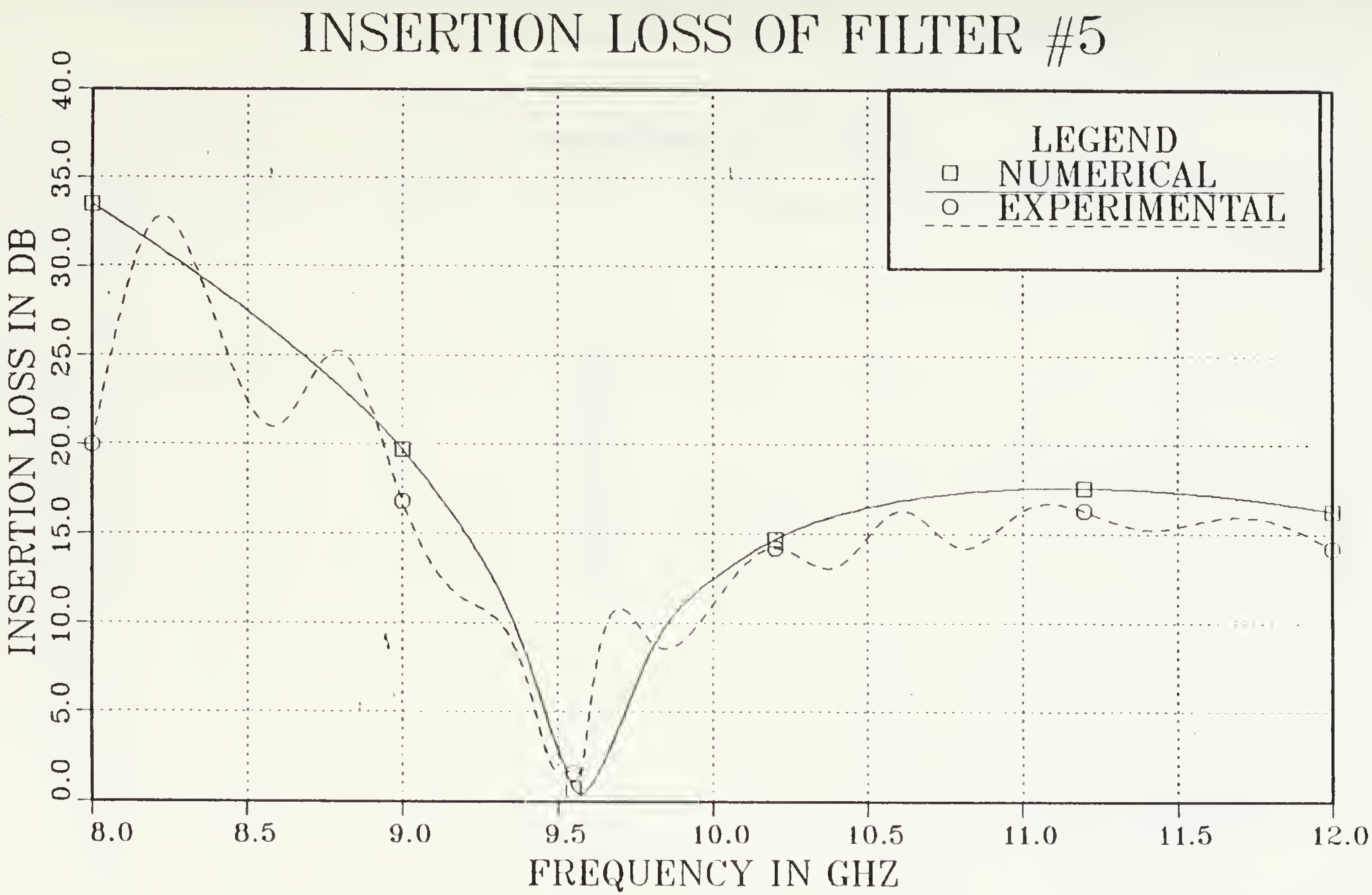


Figure 3.16 Predicted and Measured Insertion Loss vs. Frequency for Filter #5 (ℓ = 1.40 cm)

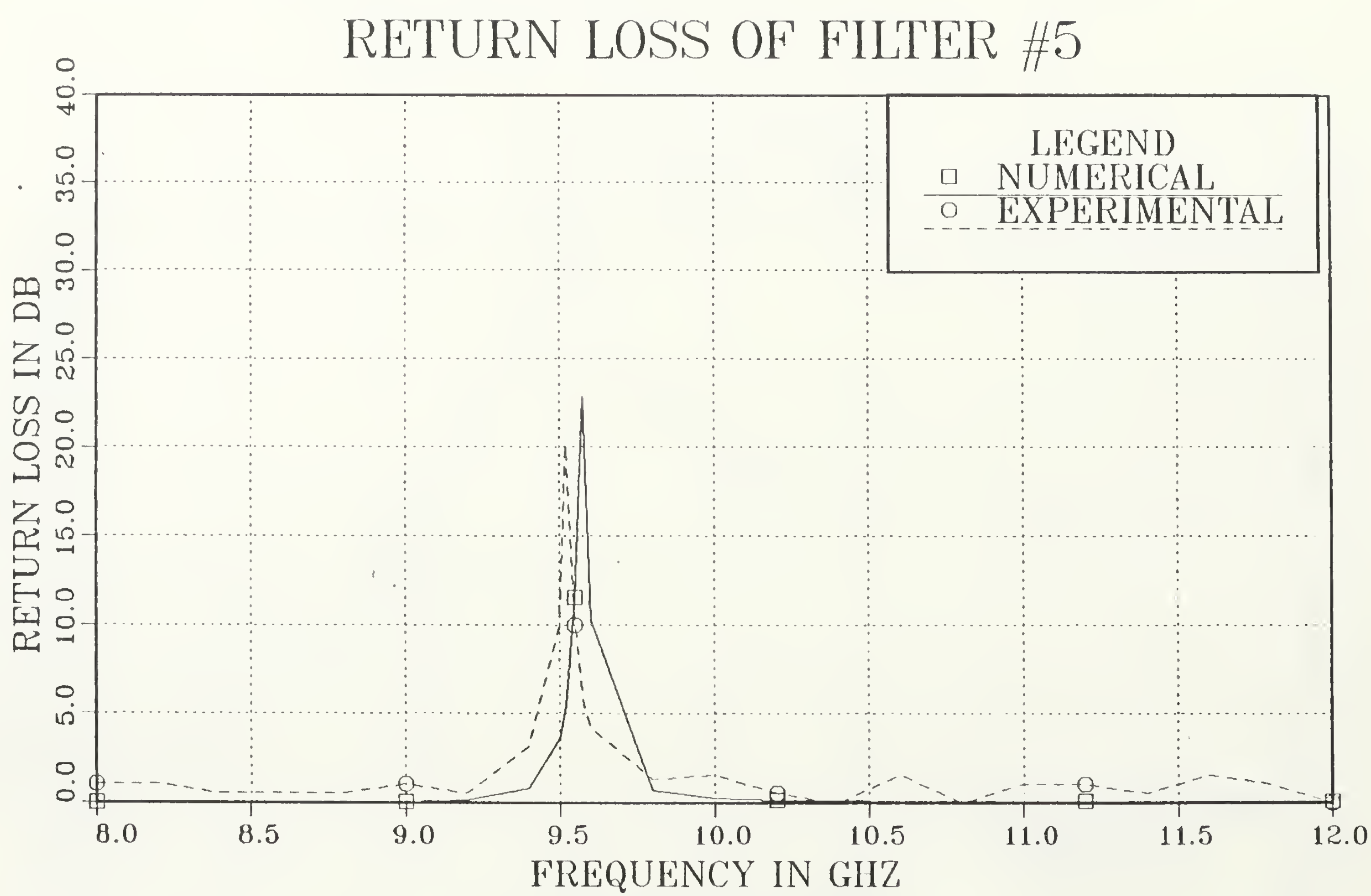


Figure 3.17 Predicted and Measured Return Loss vs. Frequency for Filter #5 (ℓ = 1.40 cm)

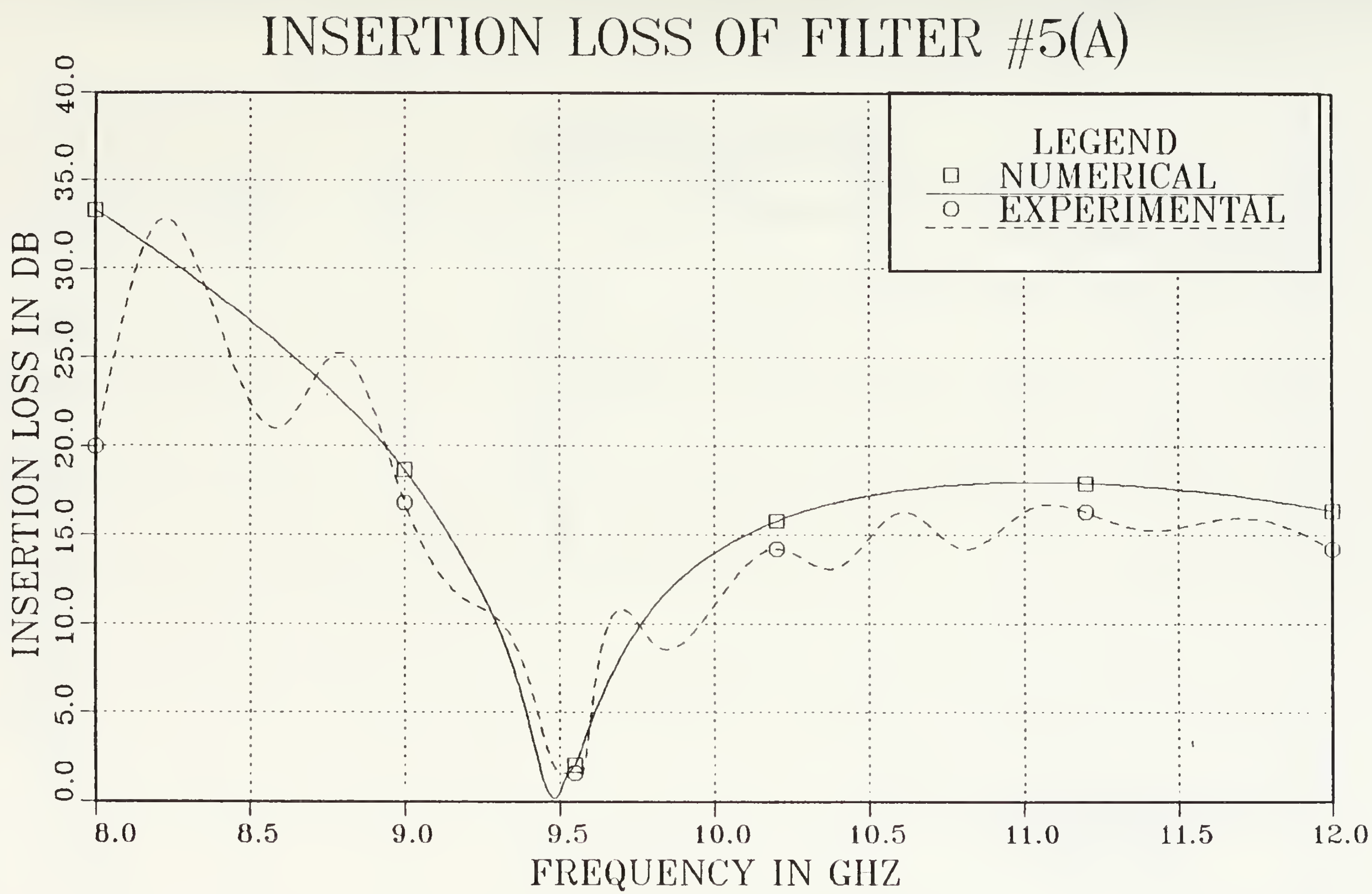


Figure 3.18 Predicted and Measured Insertion Loss vs. Frequency for Filter #5(a) (ℓ = 1.43 cm)

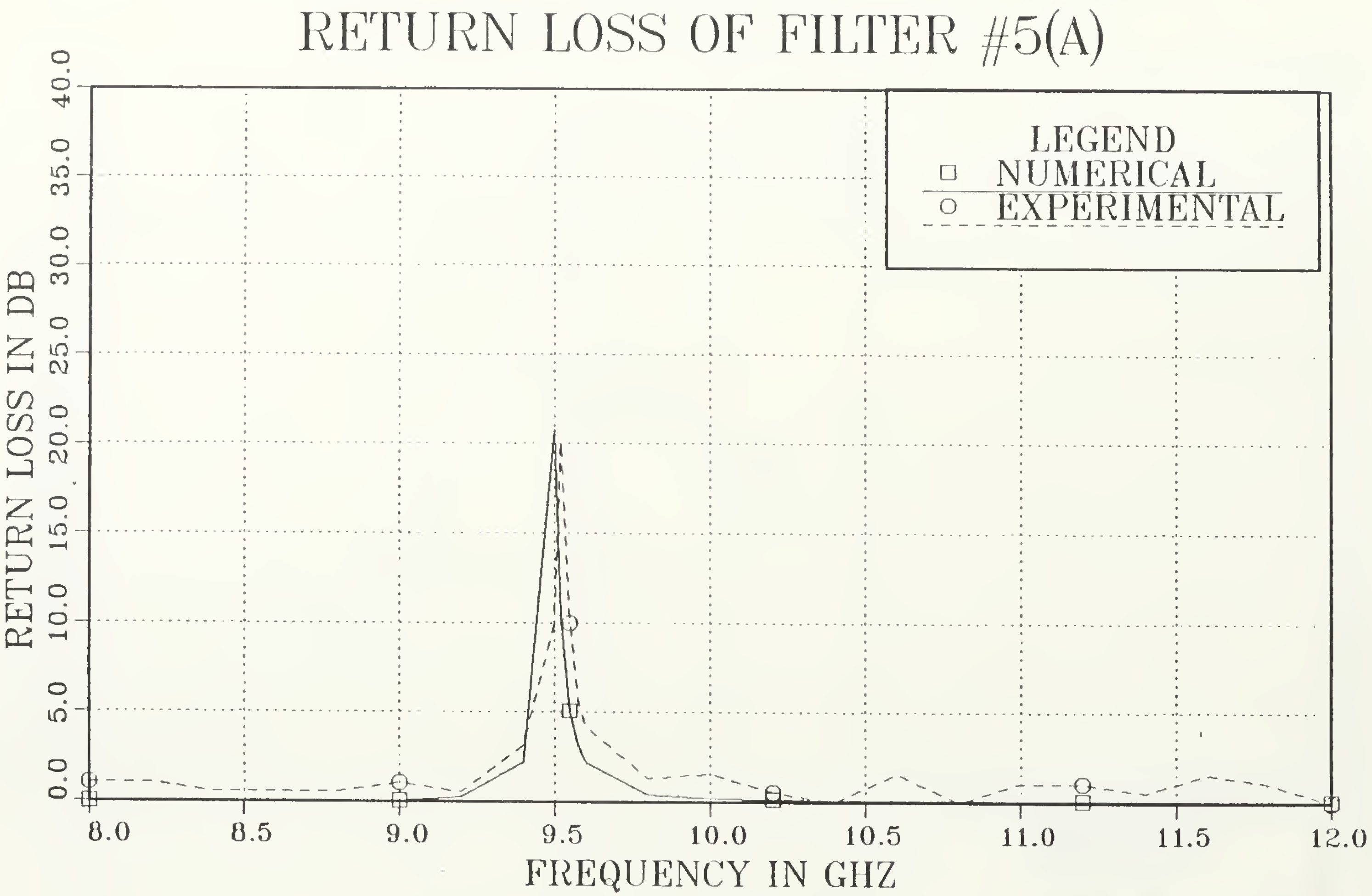


Figure 3.19 Predicted and Measured Return Loss vs. Frequency for Filter #5(a) (ℓ = 1.43 cm)

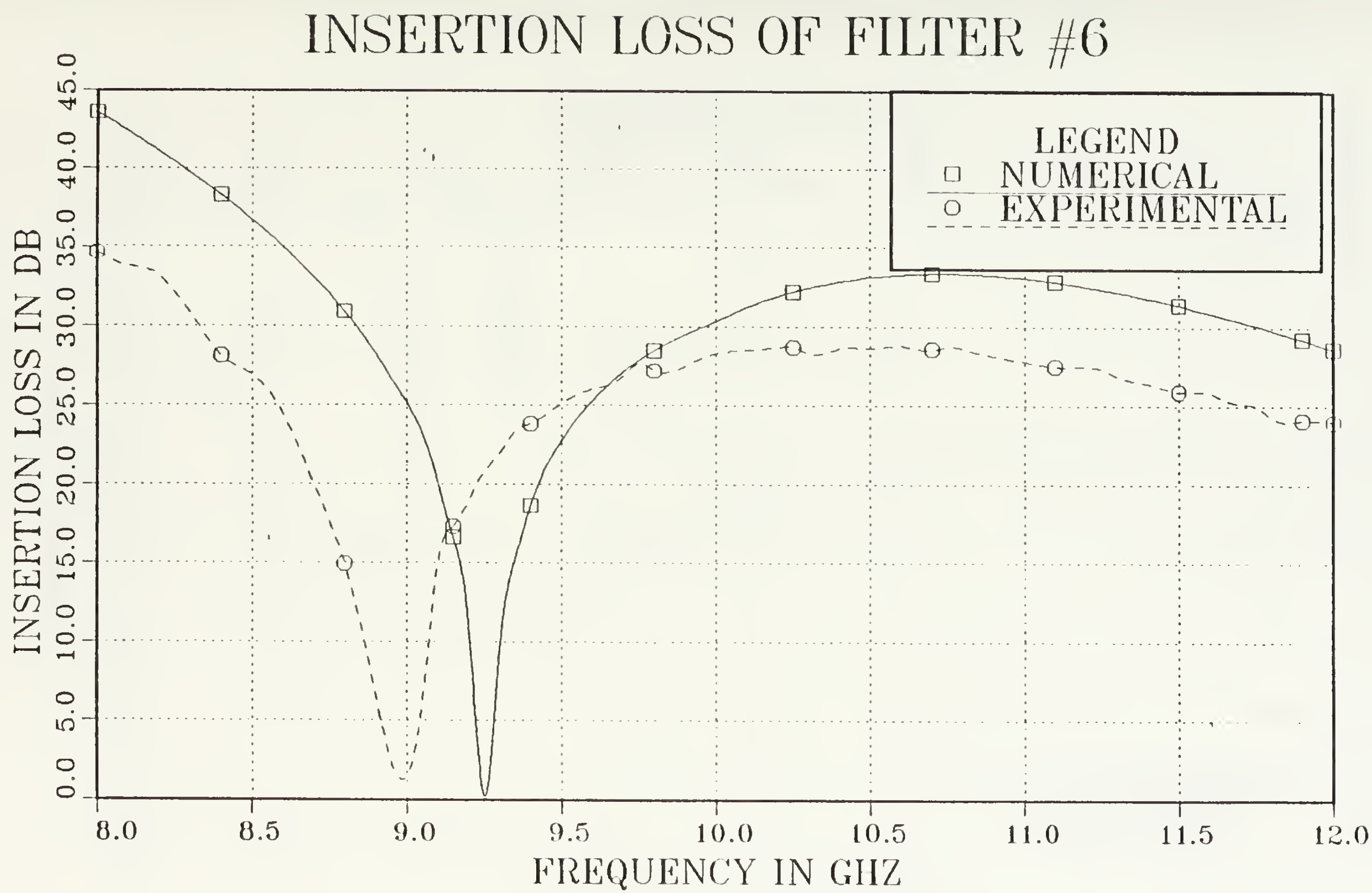


Figure 3.20 Predicted and Measured Insertion Loss vs. Frequency for Filter #6

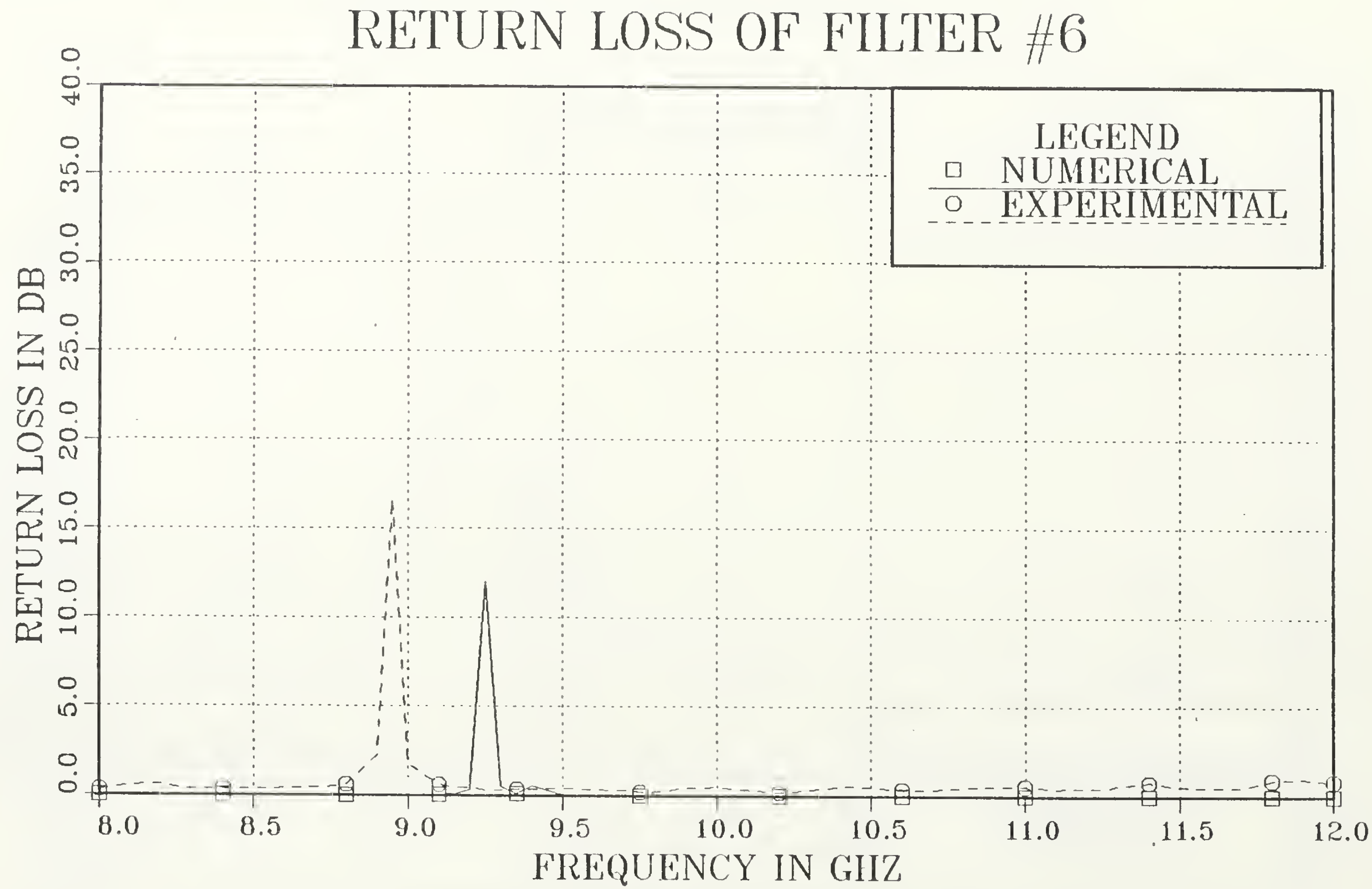


Figure 3.21 Predicted and Measured Return Loss vs. Frequency for Filter #6

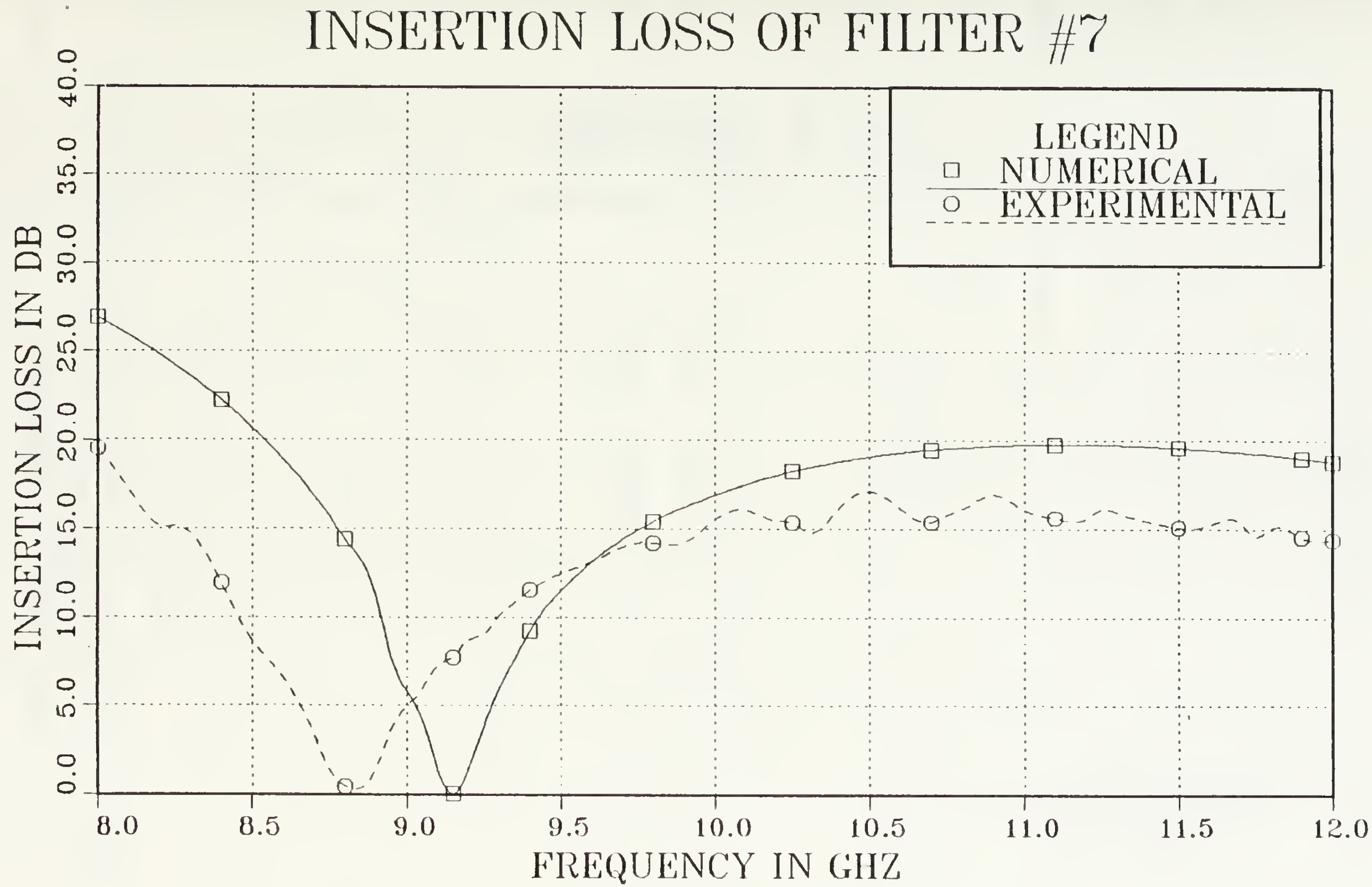


Figure 3.22 Predicted and Measured Insertion Loss vs. Frequency for Filter #7

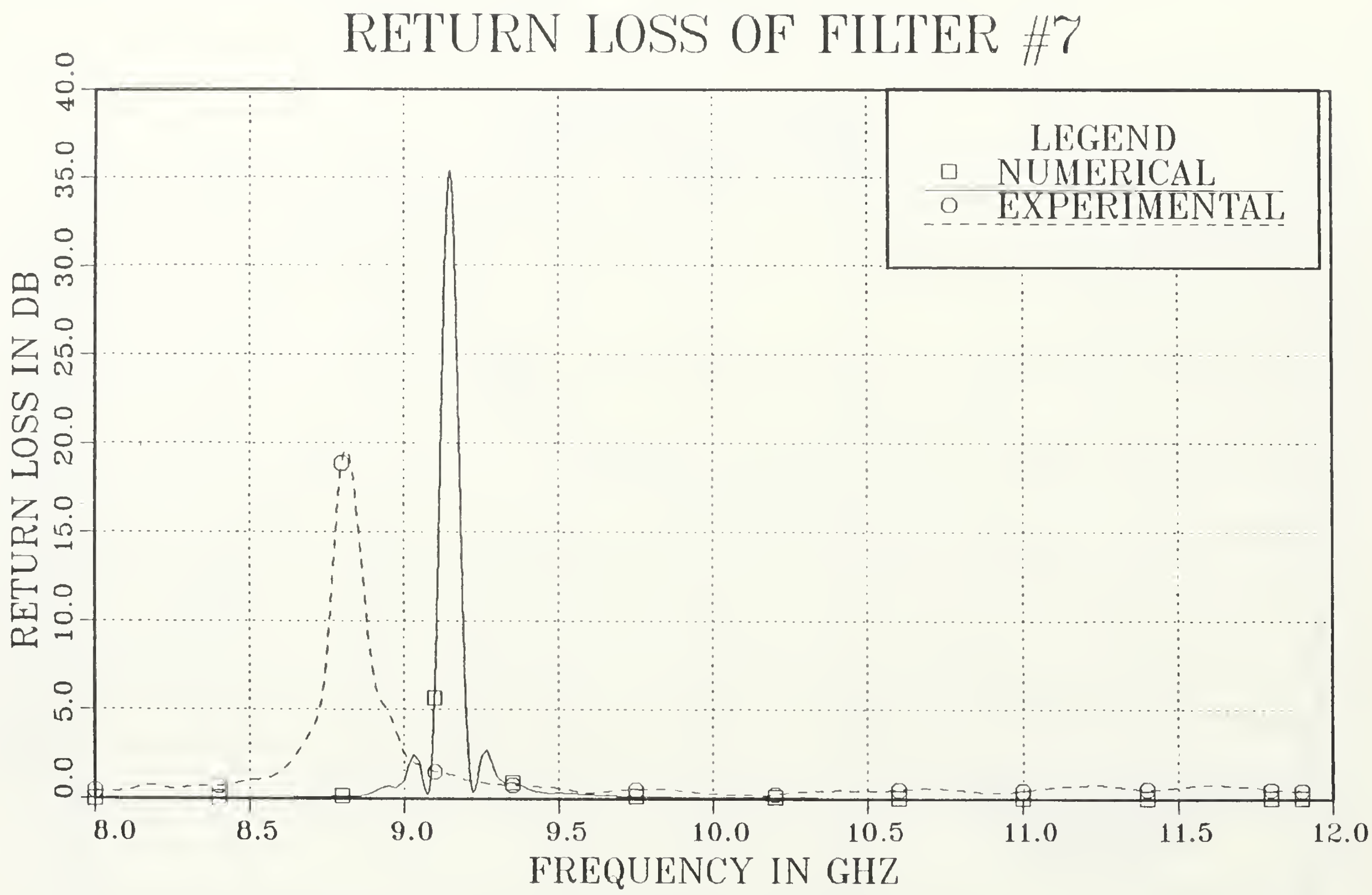


Figure 3.23 Predicted and Measured Return Loss vs. Frequency for Filter #7

IV. CONCLUSIONS

The whole work of this thesis covered two major parts. The first was a review of the mmW fin-line integrated circuits technology, especially printed E-plane, and its applications in Electronic Warfare. The second was the use of the MICRO-COMPACT (MPAC) program to verify the accuracy of computed scattering coefficients for inductive strips in fin-line.

There are some questions about the limits of the printed E-plane circuits. It is not sure that they can be practically used above 100 GHz.

Although Meir [Ref. 24], Meinel and Schmidt [Ref. 25] have successfully produced fin-line circuits up to 120 GHz and 170 GHz, some serious problems still remain. The printing accuracy of the circuit is very critical and the limits of fin-line structures in high power transmission have not been investigated thoroughly [Ref. 6].

This is the reason why the fin-line is used for receiving (low power) purposes only. Most of the communication, radar, EW systems use receivers up to 90 GHz today. The 140 GHz band is attractive for high-volume applications, military terminal guidance and small size radars.

The MPAC program provides the capability to predict the response of simple fin-line filters easily and quickly.

It is necessary to know the S-parameters for each element (inductive strip) of the circuit. Deal's program [Ref. 2] can be used for the calculation of S-parameters. For the simple resonant cavity Deal found 2% agreement between numerical and experimental results.

Good agreement between MPAC predictions and experimental results has been achieved for the single resonant cavity filters. In addition, for Filters #6 and #7, it has been shown that there is agreement between Deal's experimental results and scalar analyzer results (Figures 3.5 and 3.6) obtained in this study.

The number of interpolating points in MPAC analysis depends on the number of inductive strips (black boxes) of the fin-line filter. As the number of inductive strips increases, the number of interpolating points decreases.

The distance between inductive strips is more critical than the strip length in determining the resonant frequency of a fin-line cavity.

APPENDIX A

CALCULATION OF FILTER DESIGN DATA

All test filters (except #1, #2) are built with two inductive strips and one resonator between them. WR(90) waveguide is used as the shield (cutoff frequency, f = 6.569).

Figure A.1 shows the equivalent circuit of a fin-line filter with two inductive strips and a length of fin-line between them.

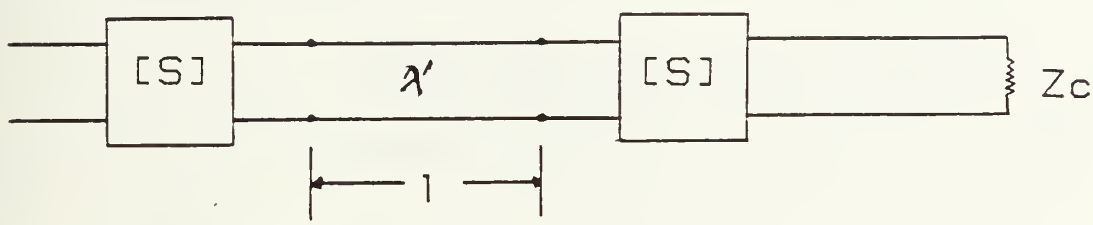


Figure A.1 Equivalent Circuit of Fin Line Filter

1. Calculation of the Resonator Length:

At resonance,

$$-\beta\ell + \theta_{11} - \beta\ell + \theta_{22} = n2\pi \ . \qquad \text{(A.1)}$$

Since $\theta_{11} = \theta_{22}$, then

$$\theta_{11} - \beta\ell = n\pi \qquad (A.2)$$

and for first resonance, n = 0. Thus

$$\theta_{11} - \beta\ell = 0 \quad \text{or} \quad \ell = \frac{\theta_{11}}{\beta} \qquad (A.3)$$

where:

β: phase-shift constant;

ℓ: length of resonator;

θ_{11}, θ_{21}: angles of scattering coefficients.

2. Calculation of the Phase Constant:

For any fin-line the phase constant is

$$\beta = \frac{2\pi}{\lambda'} = \frac{2\pi}{\lambda}(\lambda/\lambda') \qquad (A.4)$$

where:

f_c: cutoff frequency;

f: resonant frequency;

λ': waveguide wavelength;

λ" free space wavelength.

The value (λ/λ') is obtained by Deal's (FINSTRP) program. By using equations (A.3) and (A.4), the results of Table 2 are obtained.

TABLE 2

Values of Resonator Lengths

FILTERS #	3	4	6	7
LENGTHS (cm)	1.38	1.86	1.6936	1.688

In the case of Filters #5 (ℓ = 1.40 cm) and #5(a) (ℓ = 1.43 cm) the resonator between two inductive strips is modeled as a two port "black box" with the following S-parameters:

$$S_{11} = S_{22} = 0 \angle 0$$

$$S_{21} = S_{12} = 1 \angle \theta_{12}$$

and

$$\theta_{12} = -\beta\ell$$

The value of ℓ is calculated by using equations (A.3) and (A.4) and ℓ is the real resonant length. All values of ($\beta\ell$) are summarized in Table 3.

TABLE 3

Angle $\theta_{12} = -\beta\ell$ in Degrees

FREQUENCY (in GHz)	θ_{12} for Filter #5 (ℓ = 1.40 cm)	θ_{12} for Filter #5(a (ℓ = 1.43 cm)
8	- 88.6	- 90.5
9	-115	-117.4
10	-138.3	-141.23
11	-160.85	-164.3
12	-181.62	-185.5

APPENDIX B

ANALYSIS IN MPAC

TABLE 4

Analysis of Filter #1

```
WRITE
<INITIALIZING ARRAYS>
KEY-IN or LOAD circuit? (<K> or L)
?
K
Key-in ckt description: then enter frequencies
?
TWO 1 WG 6.569 .9435 TWO 2 HOLD 1 USE 1 WG 6.569 .918 USE -1
?
STEP 8 12 .1 STEP 11 12 .05
Sorting frequencies
EDIT, RUN, STORE, STOP? (E, <R>, STORE or STOP)
?
E
<Editor> CONT exits to <Analysis>
?
LIS 0
Select print/list device (<CPT> or PRINTER)
?
P
GHZ OH  NH  PF  CM  ZR= 50
SDB
 10 TWO   1 CAS
 20 WG   CAS    6.569  .9435
 30 TWO   2 CAS
 40 HOLD  1 CAS
 50 USE   1 CAS
 60 WG   CAS    6.569  .918
 70 USE  -1 CAS
Frequencies: 8  8.1  8.2  8.3  8.4  8.5  8.6  8.7  8.8  8.9  9  9.1  9.2  9.3
 9.4  9.5  9.6  9.7  9.8  9.9  10  10.1  10.2  10.3  10.4  10.5  10.6  10.7
 10.8  10.9  11  11.05  11.1  11.15  11.2  11.25  11.3  11.35  11.4  11.45  11.5
 11.55  11.6  11.65  11.7  11.75  11.8  11.85  11.9  11.95  12

<Editor> CONT exits to <Analysis>
?
P
Enter data (F,11,12,21,22) for TWO 1
</ CONT> terminates input
?
8 .939,156 .2,69 .2,69 .939,156
?
9 .95,137 .31,48 .31,48 .95,137
?
10 .91,126 .4,37.5 .4,37.5 .91,126
?
11 .868,115 .49,25.5 .49.25.5 .868,115
?
12 .81,102.9 .58,14 .58,14 .81,102.9
?
/
<S>,G,H,Y,OR Z
?
```

TABLE 5

Analysis of Filter #1 (Cont.)

```
S
RI,<MP>,OP DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
Enter data (F,11,12,21,22) for TWO 2
</ CONT> terminates input
?
8 .999,152 .032,62.5 .032,62.5 .999,152
?
9 .997,138.8 .055,48 .055,48 .997,138.8
?
10 .991,124 .085,38.3 .085,38.3 .991,124
?
11 .99,113.9 .13,21.5 .13,21.5 .99,113.9
?
12 .975,97.3 .22,7.0 .22,7.0 .975,97.3
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OP DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
<Analysis>
Select print/list device (<CRT> or PRINTER)
?
P
```

TABLE 6

Analysis of Filter #1 (Cont.)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	DB	ANG	DB	ANG	MAG	ANG
8.000	.959	156.4	-104.68	73.8	-104.68	73.8	.959	156.4
8.100	.961	154.0	-103.00	68.5	-103.00	68.5	.961	154.0
8.200	.965	151.6	-101.28	64.1	-101.28	64.1	.965	151.6
8.300	.969	149.4	-99.52	60.3	-99.52	60.3	.969	149.4
8.400	.973	147.2	-97.74	57.1	-97.74	57.1	.973	147.2
8.500	.977	145.2	-95.94	54.4	-95.94	54.4	.977	145.2
8.600	.982	143.2	-94.11	52.1	-94.11	52.1	.982	143.2
8.700	.987	141.3	-92.26	50.2	-92.26	50.2	.987	141.3
8.800	.992	139.4	-90.38	48.6	-90.38	48.6	.992	139.4
8.900	.996	137.7	-88.48	47.3	-88.48	47.3	.996	137.7
9.000	1.000	135.9	-86.54	46.2	-86.54	46.2	1.000	135.9
9.100	.999	134.6	-84.52	48.1	-84.52	48.1	.999	134.6
9.200	.999	133.2	-82.48	49.3	-82.48	49.3	.999	133.2
9.300	.998	131.8	-80.41	49.8	-80.41	49.8	.998	131.8
9.400	.998	130.3	-78.31	49.8	-78.31	49.8	.998	130.3
9.500	.998	128.8	-76.16	49.3	-76.16	49.3	.998	128.8
9.600	.997	127.2	-73.95	48.3	-73.95	48.3	.997	127.2
9.700	.997	125.6	-71.68	46.9	-71.68	46.9	.997	125.6
9.800	.997	123.8	-69.34	45.1	-69.34	45.1	.997	123.8
9.900	.998	122.1	-66.92	42.9	-66.92	42.9	.998	122.1
10.00	.998	120.2	-64.40	40.3	-64.40	40.3	.998	120.2
10.10	.999	118.2	-62.10	37.3	-62.10	37.3	.999	118.2
10.20	1.000	116.0	-59.62	33.9	-59.62	33.9	1.000	116.0
10.30	1.000	113.7	-56.96	30.1	-56.96	30.1	1.000	113.7
10.40	1.001	111.2	-54.07	26.0	-54.07	26.0	1.001	111.2
10.50	1.001	108.3	-50.94	21.5	-50.94	21.5	1.001	108.3
10.60	1.002	105.1	-47.52	16.6	-47.52	16.6	1.002	105.1
10.70	1.002	101.4	-43.76	11.1	-43.76	11.1	1.002	101.4
10.80	1.001	96.8	-39.58	4.8	-39.58	4.8	1.001	96.8
10.90	1.000	91.2	-34.87	-2.8	-34.87	-2.8	1.000	91.2
11.00	.995	83.6	-29.48	-12.3	-29.48	-12.3	.995	83.6
11.05	.991	78.6	-26.45	-18.4	-26.45	-18.4	.991	78.6
11.10	.984	72.5	-23.14	-25.8	-23.14	-25.8	.984	72.5
11.15	.970	64.6	-19.51	-35.3	-19.51	-35.3	.970	64.6
11.20	.941	54.0	-15.50	-47.9	-15.50	-47.9	.941	54.0
11.25	.876	38.9	-11.16	-66.0	-11.16	-66.0	.876	38.9
11.30	.723	17.3	-6.85	-92.4	-6.85	-92.4	.723	17.3
11.35	.443	-8.4	-3.57	-127.7	-3.57	-127.7	.443	-8.4
11.40	.177	-21.1	-2.01	-164.4	-2.01	-164.4	.177	-21.1
11.45	.068	-12.0	-1.43	163.5	-1.43	163.5	.068	-12.0
11.50	.037	-109.7	-1.16	135.2	-1.16	135.2	.037	-109.7
11.55	.145	-166.4	-1.10	109.0	-1.10	109.0	.145	-166.4
11.60	.254	168.9	-1.17	85.0	-1.17	85.0	.254	168.9
11.65	.308	147.0	-1.15	62.8	-1.15	62.8	.308	147.0
11.70	.271	123.8	-.86	40.3	-.86	40.3	.271	123.8
11.75	.096	66.8	-.41	14.0	-.41	14.0	.096	66.8
11.80	.256	-104.0	-.64	-18.9	-.64	-18.9	.256	-104.0
11.85	.613	-141.3	-2.65	-52.3	-2.65	-52.3	.613	-141.3
11.90	.808	-167.0	-5.82	-77.0	-5.82	-77.0	.808	-167.0
11.95	.891	176.3	-9.02	-93.0	-9.02	-93.0	.891	176.3
12.00	.927	165.0	-11.87	-103.8	-11.87	-103.8	.927	165.0

TABLE 7

Analysis of Filter #2

```
WRITE
<INITIALIZING ARRAYS>
KEY-IN or LOAD circuit? (<K> or L)
?
K
Key-in ckt description: then enter frequencies
?
TWO 1 WG 6.569 2.05 TWO 2 WG 6.569 2.116 TWO 3 HOLD 1 USE 1 WG 6.569 2.103
?
TWO 4 WG 6.569 2.136 USE -1
?
STEP 8 12 .2 STEP 8.5 8.720 .02
Sorting frequencies
EDIT, RUN, STORE, STOP? (E, <R>, STORE or STOP)
?
E
<Editor> CONT exits to <Analysis>
?
LIS 0
Select print/list device (<CPT> or PRINTER)
?
P
GHZ OH  NH  PF  CM  ZR= 50
SDB
 10 TWO   1 CAS
 20 WG   CAS    6.569  2.05
 30 TWO   2 CAS
 40 WG   CAS    6.569  2.116
 50 TWO   3 CAS
 60 HOLD  1 CAS
 70 USE   1 CAS
 80 WG   CAS    6.569  2.103
 90 TWO   4 CAS
 100 WG   CAS    6.569  2.136
 110 USE  -1 CAS
Frequencies: 8  8.2  8.4  8.5  8.52  8.54  8.56  8.58  8.6  8.62  8.64  8.66
 8.68  8.7  8.72  8.8  9  9.2  9.4  9.6  9.8  10  10.2  10.4  10.6  10.8  11
 11.2  11.4  11.6  11.8  12

<Editor> CONT exits to <Analysis>
?
R
Enter data (F,11,12,21,22) for TWO 1
</ CONT> terminates input
?
8 .8,142.75 .5685,53.95 .5685,53.95 .8,142.75
?
9 .674,129.6 .7225,38.95 .7225,38.95 .674,129.6
?
10 .595,120.7 .7895,31.85 .7895,31.85 .595,120.7
?
11 .5331,114.4 .8460,24.6 .8460,24.6 .5331,114.4
?
12 .48,108.75 .8735,19.55 .8735,19.55 .48,108.75
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
```

TABLE 8

Analysis of Filter #2 (Cont.)

```
N
<Interpolating>
Enter data (F,11,12,21,22) for TWO 2
</ CONT> terminates input
?
8 .9375,156.75 .251,66.75 .251,66.75 .9375,156.75
?
9 .9345,136.75 .349,47.25 .349,47.25 .9345,136.75
?
10 .8845,125.55 .445,35.65 .445,35.65 .8845,125.55
?
11 .8285,115.05 .5335,25.85 .5335,25.85 .8285,115.05
?
12 .7755,103.7 .6195,14.9 .6195,14.9 .7755,103.7
?
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
Enter data (F,11,12,21,22) for TWO 3
</ CONT> terminates input
?
8 .977,158.77 .1892,68.02 .1892,68.02 .977,158.77
?
9 .9597,137.47 .2718,48 .2718,48 .9597,137.47
?
10 .9278,125.62 .3518,35.87 .3518,35.87 .9278,125.62
?
11 .884,114.65 .4395,25.45 .4395,25.45 .884,114.65
?
12 .8362,102.03 .532,13.37 .532,13.37 .8362,102.03
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
Enter data (F,11,12,21,22) for TWO 4
</ CONT> terminates input
?
8 .9485,158.65 .1885,67.95 .1885,67.95 .9485,158.65
?
9 .9605,137.65 .2695,48 .2695,48 .9605,137.65
?
10 .9285,125.45 .3495,35.95 .3495,35.95 .9285,125.45
?
11 .887,114.5 .4375,25.4 .4375,25.4 .887,114.5
?
12 .8385,101.95 .5295,12.95 .5295,12.95 .8385,101.95
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
<Analysis>
Select print/list device (<CRT> or PRINTER)
?
P
```

TABLE 9

Analysis of Filter #2 (Cont.)

S-MATRIX IN MAGNITUDE AND PHASE

FREQ	11		12		21		22	
	MAG	ANG	DB	ANG	DB	ANG	MAG	ANG
8.000	.976	127.5	-87.15	28.6	-87.15	28.6	.976	127.5
8.200	.937	108.5	-63.22	-1.1	-63.22	-1.1	.937	108.5
8.400	.721	46.5	-23.47	-85.0	-23.47	-85.0	.707	45.2
8.500	.078	-138.1	-5.14	83.9	-5.14	83.9	.126	108.9
8.520	.142	177.5	-4.55	48.6	-4.55	48.6	.147	98.3
8.540	.185	156.0	-4.14	16.6	-4.14	16.6	.132	83.4
8.560	.194	145.2	-3.81	-13.2	-3.81	-13.2	.075	61.8
8.580	.195	143.8	-3.54	-41.6	-3.54	-41.6	.021	-96.9
8.600	.215	144.6	-3.36	-68.8	-3.36	-68.8	.121	-144.4
8.620	.246	139.0	-3.26	-94.8	-3.26	-94.8	.208	-166.0
8.640	.259	126.9	-3.17	-119.6	-3.17	-119.6	.261	175.6
8.660	.239	110.6	-3.03	-143.6	-3.03	-143.6	.275	160.2
8.680	.181	90.5	-2.85	-167.3	-2.85	-167.3	.255	148.8
8.700	.097	61.9	-2.67	168.8	-2.67	168.8	.219	143.7
8.720	.037	-37.3	-2.52	144.7	-2.52	144.7	.192	145.2
8.800	.183	-148.7	-2.29	47.0	-2.29	47.0	.077	87.1
9.000	.940	-143.5	-23.01	134.7	-23.01	134.7	.943	-144.8
9.200	.967	178.0	-44.89	93.9	-44.89	93.9	.967	177.9
9.400	.968	162.2	-56.56	77.1	-56.56	77.1	.968	162.2
9.600	.969	152.0	-63.59	66.5	-63.59	66.5	.969	152.0
9.800	.971	144.2	-67.80	58.4	-67.80	58.4	.971	144.2
10.00	.975	137.5	-69.99	51.5	-69.99	51.5	.975	137.4
10.20	.982	131.2	-70.43	45.1	-70.43	45.1	.982	131.2
10.40	.987	125.1	-69.68	38.8	-69.68	38.8	.987	125.1
10.60	.991	119.1	-67.83	32.4	-67.83	32.4	.991	119.0
10.80	.993	112.7	-64.87	25.7	-64.87	25.7	.993	112.7
11.00	.995	105.9	-60.75	18.4	-60.75	18.4	.995	105.9
11.20	.997	98.2	-55.28	10.2	-55.28	10.2	.997	98.2
11.40	.998	89.2	-48.14	.6	-48.14	.6	.998	89.1
11.60	.999	77.5	-38.61	-11.7	-38.61	-11.7	.999	77.3
11.80	.999	59.0	-24.68	-31.1	-24.68	-31.1	.999	58.2
12.00	.188	68.7	-.35	-155.3	-.35	-155.3	.154	144.1

TABLE 10

Analysis of Filter #3

```
WRITE
<INITIALIZING ARRAYS>
KEY-IN or LOAD circuit? (<K> or L)
?
K
Key-in ckt description: then enter frequencies
?
TWO 1 HOLD 1 USE 1 WG 6.569 1.3335 USE -1
?
STEP 8 12 .05 STEP 9.9 10.9 .025
Sorting frequencies
EDIT, RUN, STORE, STOP? (E, <R>, STORE or STOP)
?
E
<Editor> CONT exits to <Analysis>
?
LIS 0
Select print/list device (<CRT> or PRINTER)
?
P
GHZ OH  NH  FF  CM  ZR= 50
SDB
 10 TWO    1 CAS
 20 HOLD   1 CAS
 30 USE    1 CAS
 40 WG   CAS     6.569  1.3335
 50 USE   -1 CAS
Frequencies: 8  8.05  8.1  8.15  8.2  8.25  8.3  8.35  8.4  8.45  8.5  8.55  8.6
 8.65  8.7  8.75  8.8  8.85  8.9  8.95  9  9.05  9.1  9.15  9.2  9.25  9.3  9.35
 9.4  9.45  9.5  9.55  9.6  9.65  9.7  9.75  9.8  9.85  9.9  9.925  9.95  9.975
 10  10.025  10.05  10.075  10.1  10.125  10.15  10.175  10.2  10.225  10.25
 10.275  10.3  10.325  10.35  10.375  10.4  10.425  10.45  10.475  10.5  10.525
 10.55  10.575  10.6  10.625  10.65  10.675  10.7  10.725  10.75  10.775  10.8
 10.825  10.85  10.875  10.9  10.95  11  11.05  11.1  11.15  11.2  11.25  11.3
 11.35  11.4  11.45  11.5  11.55  11.6  11.65  11.7  11.75  11.8  11.85  11.9
 11.95  12

<Editor> CONT exits to <Analysis>
?
R
Enter data (F,11,12,21,22) for TWO 1
</ CONT> terminates input
?
8 .977,158.77 .1892,68.02 .1892,68.02 .977,158.77
?
9 .9597,137.47 .2718.48 .2718.48 .9597,137.47
?
10 .9278,125.62 .3518,35.87 .3518,35.87 .9278,125.62
?
11 .884,114.65 .4395,25.45 .4395,25.45 .884,114.65
?
12 .8362,102.03 .532,13.37 .532.13.37 .8362.102.03
?
/
<S>,G,H,Y,OR Z
?
S
R1,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
<Analysis>
Select print/list device (<CRT> or PRINTER)
?
P
```

TABLE 11

Analysis of Filter #3 (Cont.)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	DB	ANG	DB	ANG	MAG	ANG
8.000	.995	158.7	-34.72	67.2	-34.72	67.2	.995	158.7
8.050	.992	157.3	-34.30	65.6	-34.30	65.6	.992	157.3
8.100	.991	156.0	-33.86	64.2	-33.86	64.2	.991	156.0
8.150	.989	154.7	-33.41	62.8	-33.41	62.8	.989	154.7
8.200	.988	153.4	-32.96	61.4	-32.96	61.4	.988	153.4
8.250	.987	152.1	-32.49	60.2	-32.49	60.2	.987	152.1
8.300	.986	150.8	-32.01	59.0	-32.01	59.0	.986	150.8
8.350	.986	149.6	-31.53	57.8	-31.53	57.8	.986	149.6
8.400	.986	148.3	-31.03	56.7	-31.03	56.7	.986	148.3
8.450	.986	147.1	-30.52	55.6	-30.52	55.6	.986	147.1
8.500	.986	145.9	-30.01	54.6	-30.01	54.6	.986	145.9
8.550	.987	144.8	-29.49	53.6	-29.49	53.6	.987	144.8
8.600	.988	143.6	-28.96	52.6	-28.96	52.6	.988	143.6
8.650	.989	142.5	-28.41	51.7	-28.41	51.7	.989	142.5
8.700	.989	141.3	-27.86	50.8	-27.86	50.8	.989	141.3
8.750	.991	140.2	-27.30	49.9	-27.30	49.9	.991	140.2
8.800	.992	139.1	-26.72	49.0	-26.72	49.0	.992	139.1
8.850	.993	138.0	-26.13	48.2	-26.13	48.2	.993	138.0
8.900	.994	136.9	-25.53	47.3	-25.53	47.3	.994	136.9
8.950	.995	135.9	-24.92	46.5	-24.92	46.5	.995	135.9
9.000	.996	134.8	-24.29	45.6	-24.29	45.6	.996	134.8
9.050	.995	133.9	-23.69	44.6	-23.69	44.6	.995	133.9
9.100	.995	133.0	-23.07	43.6	-23.07	43.6	.995	133.0
9.150	.994	132.0	-22.43	42.5	-22.43	42.5	.994	132.0
9.200	.993	131.0	-21.77	41.4	-21.77	41.4	.993	131.0
9.250	.992	130.0	-21.09	40.3	-21.09	40.3	.992	130.0
9.300	.991	129.0	-20.38	39.1	-20.38	39.1	.991	129.0
9.350	.989	127.8	-19.64	37.9	-19.64	37.9	.989	127.8
9.400	.988	126.7	-18.87	36.6	-18.87	36.6	.988	126.7
9.450	.986	125.4	-18.07	35.2	-18.07	35.2	.986	125.4
9.500	.984	124.0	-17.22	33.7	-17.22	33.7	.984	124.0
9.550	.981	122.5	-16.33	32.1	-16.33	32.1	.981	122.5
9.600	.977	120.9	-15.39	30.3	-15.39	30.3	.977	120.9
9.650	.972	119.0	-14.38	28.3	-14.38	28.3	.972	119.0
9.700	.966	116.9	-13.31	26.0	-13.31	26.0	.966	116.9
9.750	.957	114.5	-12.15	23.3	-12.15	23.3	.957	114.5
9.800	.943	111.6	-10.90	20.1	-10.90	20.1	.943	111.6
9.850	.924	108.0	-9.53	16.1	-9.53	16.1	.924	108.0
9.900	.893	103.5	-8.04	11.1	-8.04	11.1	.893	103.5
9.925	.871	100.8	-7.25	8.0	-7.25	8.0	.871	100.8
9.950	.843	97.7	-6.42	4.4	-6.42	4.4	.843	97.7
9.975	.806	94.1	-5.57	.3	-5.57	.3	.806	94.1
10.00	.758	90.0	-4.70	-4.6	-4.70	-4.6	.758	90.0
10.03	.696	85.4	-3.85	-10.2	-3.85	-10.2	.696	85.4
10.05	.616	80.3	-3.03	-16.7	-3.03	-16.7	.616	80.3
10.08	.513	75.0	-2.28	-24.3	-2.28	-24.3	.513	75.0
10.10	.388	70.6	-1.66	-33.0	-1.66	-33.0	.388	70.6
10.13	.246	71.0	-1.23	-42.5	-1.23	-42.5	.246	71.0
10.15	.119	96.8	-1.04	-52.4	-1.04	-52.4	.119	96.8
10.18	.147	162.7	-1.09	-62.2	-1.09	-62.2	.147	162.7
10.20	.275	176.6	-1.37	-71.4	-1.37	-71.4	.275	176.6
10.23	.398	175.7	-1.80	-79.6	-1.80	-79.6	.398	175.7
10.25	.502	172.0	-2.35	-86.9	-2.35	-86.9	.502	172.0
10.28	.586	167.8	-2.95	-93.1	-2.95	-93.1	.586	167.8
10.30	.652	163.9	-3.57	-98.3	-3.57	-98.3	.652	163.9

TABLE 12

Analysis of Filter #3 (Cont.)

10.33	.704	160.3	-4.19	-102.8	-4.19	-102.8	.704	160.3
10.35	.745	157.1	-4.79	-106.7	-4.79	-106.7	.745	157.1
10.38	.778	154.3	-5.36	-110.0	-5.36	-110.0	.778	154.3
10.40	.804	151.8	-5.90	-112.9	-5.90	-112.9	.804	151.8
10.43	.826	149.6	-6.41	-115.4	-6.41	-115.4	.826	149.6
10.45	.844	147.7	-6.88	-117.6	-6.88	-117.6	.844	147.7
10.48	.858	145.9	-7.33	-119.6	-7.33	-119.6	.858	145.9
10.50	.870	144.3	-7.76	-121.4	-7.76	-121.4	.870	144.3
10.53	.881	142.8	-8.15	-123.0	-8.15	-123.0	.881	142.8
10.55	.889	141.5	-8.52	-124.5	-8.52	-124.5	.889	141.5
10.58	.897	140.3	-8.87	-125.8	-8.87	-125.8	.897	140.3
10.60	.903	139.1	-9.20	-127.1	-9.20	-127.1	.903	139.1
10.63	.909	138.1	-9.51	-128.2	-9.51	-128.2	.909	138.1
10.65	.914	137.1	-9.80	-129.3	-9.80	-129.3	.914	137.1
10.68	.918	136.2	-10.08	-130.3	-10.08	-130.3	.918	136.2
10.70	.922	135.3	-10.34	-131.3	-10.34	-131.3	.922	135.3
10.73	.926	134.4	-10.58	-132.2	-10.58	-132.2	.926	134.4
10.75	.929	133.6	-10.81	-133.0	-10.81	-133.0	.929	133.6
10.78	.931	132.9	-11.03	-133.8	-11.03	-133.8	.931	132.9
10.80	.934	132.1	-11.24	-134.6	-11.24	-134.6	.934	132.1
10.83	.936	131.4	-11.44	-135.4	-11.44	-135.4	.936	131.4
10.85	.938	130.8	-11.62	-136.1	-11.62	-136.1	.938	130.8
10.88	.940	130.1	-11.80	-136.8	-11.80	-136.8	.940	130.1
10.90	.941	129.5	-11.97	-137.4	-11.97	-137.4	.941	129.5
10.95	.944	128.3	-12.28	-138.7	-12.28	-138.7	.944	128.3
11.00	.947	127.1	-12.55	-139.9	-12.55	-139.9	.947	127.1
11.05	.949	126.0	-12.80	-141.1	-12.80	-141.1	.949	126.0
11.10	.950	125.0	-13.03	-142.2	-13.03	-142.2	.950	125.0
11.15	.952	123.9	-13.23	-143.3	-13.23	-143.3	.952	123.9
11.20	.953	122.9	-13.41	-144.4	-13.41	-144.4	.953	122.9
11.25	.954	122.0	-13.57	-145.4	-13.57	-145.4	.954	122.0
11.30	.955	121.0	-13.71	-146.4	-13.71	-146.4	.955	121.0
11.35	.956	120.1	-13.83	-147.3	-13.83	-147.3	.956	120.1
11.40	.957	119.1	-13.94	-148.3	-13.94	-148.3	.957	119.1
11.45	.958	118.2	-14.03	-149.3	-14.03	-149.3	.958	118.2
11.50	.959	117.3	-14.11	-150.2	-14.11	-150.2	.959	117.3
11.55	.959	116.4	-14.18	-151.1	-14.18	-151.1	.959	116.4
11.60	.960	115.5	-14.23	-152.0	-14.23	-152.0	.960	115.5
11.65	.961	114.6	-14.27	-152.9	-14.27	-152.9	.961	114.6
11.70	.961	113.7	-14.30	-153.8	-14.30	-153.8	.961	113.7
11.75	.962	112.8	-14.32	-154.7	-14.32	-154.7	.962	112.8
11.80	.963	111.9	-14.32	-155.6	-14.32	-155.6	.963	111.9
11.85	.963	111.0	-14.32	-156.5	-14.32	-156.5	.963	111.0
11.90	.964	110.1	-14.31	-157.4	-14.31	-157.4	.964	110.1
11.95	.965	109.2	-14.28	-158.3	-14.28	-158.3	.965	109.2
12.00	.966	108.2	-14.25	-159.1	-14.25	-159.1	.966	108.2

TABLE 13

Analysis of Filter #4

```
WRITE
<INITIALIZING ARRAYS>
KEY-IN or LOAD circuit? (<K> or L)
?
K
key-in ckt description: then enter frequencies
?
TWO 1 HOLD 1 USE 1 WG 6.569 1.8288 USE -1
?
STEP 8 12 .05 STEP 8.5 9.5 .025
Sorting frequencies
EDIT, RUN, STORE, STOP? (E, <R>, STORE or STOP)
?
E
<Editor> CONT exits to <Analysis>
?
LIS 0
Select print/list device : CRT> or PRINTER>
?
P
GHZ OH  NH  PF  CM  ZR= 50
SDB
 10 TWO    1 CAS
 20 HOLD   1 CAS
 30 USE    1 CAS
 40 WG   CAS    6.569  1.8288
 50 USE   -1 CAS
Frequencies: 8  8.05  8.1  8.15  8.2  8.25  8.3  8.35  8.4  8.45  8.5  8.525
 8.55  8.575  8.6  8.625  8.65  8.675  8.7  8.725  8.75  8.775  8.8  8.825  8.85
 8.875  8.9  8.925  8.95  8.975  9  9.025  9.05  9.075  9.1  9.125  9.15  9.175
 9.2  9.225  9.25  9.275  9.3  9.325  9.35  9.375  9.4  9.425  9.45  9.475  9.5
 9.55  9.6  9.65  9.7  9.75  9.8  9.85  9.9  9.95  10  10.05  10.1  10.15  10.2
 10.25  10.3  10.35  10.4  10.45  10.5  10.55  10.6  10.65  10.7  10.75  10.8
 10.85  10.9  10.95  11  11.05  11.1  11.15  11.2  11.25  11.3  11.35  11.4
 11.45  11.5  11.55  11.6  11.65  11.7  11.75  11.8  11.85  11.9  11.95  12

<Editor> CONT exits to <Analysis>
?
R
Enter data (F,11,12,21,22) for TWO 1
</ CONT> terminates input
?
8 .977,158.77 .1892,98.02 .1892,98.02 .977,158.77
?
9 .9597,137.47 .2718,48 .2718,48 .9597,137.47
?
10 .9278,125.62 .3518,35.87 .3518,35.87 .9278,125.62
?
11 .884,114.65 .4395,25.45 .4395,25.45 .884,114.65
?
12 .8362,102.03 .532,13.37 .532,13.37 .8362,102.03
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
<Analysis>
Select print/list device (<CRT> or PRINTER)
?
P
```

TABLE 14

Analysis of Filter #4 (Cont.)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	DB	ANG	DB	ANG	MAG	ANG
8.000	.996	159.3	-33.37	126.5	-33.37	126.5	.996	159.3
8.050	.995	157.9	-33.06	119.7	-33.06	119.7	.995	157.9
8.100	.994	156.4	-32.64	113.0	-32.64	113.0	.994	156.4
8.150	.993	155.0	-32.12	106.5	-32.12	106.5	.993	155.0
8.200	.992	153.5	-31.50	100.3	-31.50	100.3	.992	153.5
8.250	.992	152.1	-30.78	94.3	-30.78	94.3	.992	152.1
8.300	.992	150.7	-29.97	88.7	-29.97	88.7	.992	150.7
8.350	.992	149.2	-29.07	83.3	-29.07	83.3	.992	149.2
8.400	.992	147.8	-28.09	78.3	-28.09	78.3	.992	147.8
8.450	.993	146.3	-27.03	73.6	-27.03	73.6	.993	146.3
8.500	.993	144.7	-25.89	69.1	-25.89	69.1	.993	144.7
8.525	.993	144.0	-25.29	67.0	-25.29	67.0	.993	144.0
8.550	.993	143.2	-24.66	64.9	-24.66	64.9	.993	143.2
8.575	.993	142.3	-24.01	62.9	-24.01	62.9	.993	142.3
8.600	.993	141.5	-23.34	60.9	-23.34	60.9	.993	141.5
8.625	.993	140.6	-22.63	59.0	-22.63	59.0	.993	140.6
8.650	.993	139.7	-21.90	57.1	-21.90	57.1	.993	139.7
8.675	.993	138.7	-21.13	55.2	-21.13	55.2	.993	138.7
8.700	.992	137.7	-20.32	53.2	-20.32	53.2	.992	137.7
8.725	.991	136.6	-19.48	51.3	-19.48	51.3	.991	136.6
8.750	.990	135.5	-18.58	49.4	-18.58	49.4	.990	135.5
8.775	.989	134.2	-17.63	47.4	-17.63	47.4	.989	134.2
8.800	.986	132.7	-16.62	45.2	-16.62	45.2	.986	132.7
8.825	.983	131.1	-15.53	42.9	-15.53	42.9	.983	131.1
8.850	.978	129.2	-14.34	40.4	-14.34	40.4	.978	129.2
8.875	.971	126.9	-13.05	37.6	-13.05	37.6	.971	126.9
8.900	.960	124.1	-11.61	34.2	-11.61	34.2	.960	124.1
8.925	.941	120.4	-10.01	30.0	-10.01	30.0	.941	120.4
8.950	.910	115.4	-8.18	24.5	-8.18	24.5	.910	115.4
8.975	.852	108.2	-6.10	16.7	-6.10	16.7	.852	108.2
9.000	.733	97.1	-3.78	4.8	-3.78	4.8	.733	97.1
9.025	.504	83.0	-1.80	-12.6	-1.80	-12.6	.504	83.0
9.050	.130	84.5	-.69	-36.7	-.69	-36.7	.130	84.5
9.075	.323	-165.0	-1.19	-61.8	-1.19	-61.8	.323	-165.0
9.100	.604	-177.3	-2.77	-80.8	-2.77	-80.8	.604	-177.3
9.125	.756	172.1	-4.57	-93.2	-4.57	-93.2	.756	172.1
9.150	.837	164.9	-6.22	-101.4	-6.22	-101.4	.837	164.9
9.175	.883	159.8	-7.66	-107.0	-7.66	-107.0	.883	159.8
9.200	.911	156.0	-8.89	-111.1	-8.89	-111.1	.911	156.0
9.225	.930	153.1	-9.96	-114.3	-9.96	-114.3	.930	153.1
9.250	.942	150.9	-10.90	-116.8	-10.90	-116.8	.942	150.9
9.275	.951	149.0	-11.72	-118.8	-11.72	-118.8	.951	149.0
9.300	.958	147.4	-12.46	-120.5	-12.46	-120.5	.958	147.4
9.325	.963	146.1	-13.11	-122.0	-13.11	-122.0	.963	146.1
9.350	.967	144.9	-13.70	-123.3	-13.70	-123.3	.967	144.9
9.375	.970	143.8	-14.24	-124.4	-14.24	-124.4	.970	143.8
9.400	.972	142.9	-14.72	-125.4	-14.72	-125.4	.972	142.9
9.425	.974	142.0	-15.16	-126.4	-15.16	-126.4	.974	142.0
9.450	.976	141.2	-15.57	-127.2	-15.57	-127.2	.976	141.2

TABLE 15

Analysis of Filter #4 (Cont.)

9.475	.977	140.5	-15.94	-128.0	-15.94	-128.0	.977	140.5
9.500	.978	139.8	-16.29	-128.8	-16.29	-128.8	.978	139.8
9.550	.980	138.5	-16.90	-130.1	-16.90	-130.1	.980	138.5
9.600	.982	137.4	-17.42	-131.3	-17.42	-131.3	.982	137.4
9.650	.983	136.3	-17.88	-132.5	-17.88	-132.5	.983	136.3
9.700	.983	135.3	-18.27	-133.5	-18.27	-133.5	.983	135.3
9.750	.984	134.4	-18.61	-134.5	-18.61	-134.5	.984	134.4
9.800	.984	133.5	-18.90	-135.4	-18.90	-135.4	.984	133.5
9.850	.985	132.6	-19.15	-136.3	-19.15	-136.3	.985	132.6
9.900	.985	131.8	-19.37	-137.1	-19.37	-137.1	.985	131.8
9.950	.985	131.0	-19.55	-138.0	-19.55	-138.0	.985	131.0
10.00	.985	130.2	-19.71	-138.8	-19.71	-138.8	.985	130.2
10.05	.985	129.5	-19.81	-139.4	-19.81	-139.4	.985	129.5
10.10	.985	128.8	-19.90	-140.0	-19.90	-140.0	.985	128.8
10.15	.984	128.1	-19.97	-140.6	-19.97	-140.6	.984	128.1
10.20	.984	127.5	-20.02	-141.3	-20.02	-141.3	.984	127.5
10.25	.984	126.8	-20.05	-141.9	-20.05	-141.9	.984	126.8
10.30	.984	126.1	-20.07	-142.5	-20.07	-142.5	.984	126.1
10.35	.983	125.4	-20.08	-143.2	-20.08	-143.2	.983	125.4
10.40	.983	124.7	-20.07	-143.8	-20.07	-143.8	.983	124.7
10.45	.983	124.0	-20.05	-144.5	-20.05	-144.5	.983	124.0
10.50	.982	123.3	-20.02	-145.2	-20.02	-145.2	.982	123.3
10.55	.982	122.6	-19.98	-145.8	-19.98	-145.8	.982	122.6
10.60	.982	121.9	-19.92	-146.5	-19.92	-146.5	.982	121.9
10.65	.981	121.2	-19.86	-147.2	-19.86	-147.2	.981	121.2
10.70	.981	120.5	-19.78	-147.9	-19.78	-147.9	.981	120.5
10.75	.981	119.8	-19.70	-148.6	-19.70	-148.6	.981	119.8
10.80	.980	119.0	-19.61	-149.4	-19.61	-149.4	.980	119.0
10.85	.980	118.3	-19.50	-150.1	-19.50	-150.1	.980	118.3
10.90	.980	117.6	-19.39	-150.9	-19.39	-150.9	.980	117.6
10.95	.979	116.8	-19.27	-151.6	-19.27	-151.6	.979	116.8
11.00	.979	116.0	-19.14	-152.4	-19.14	-152.4	.979	116.0
11.05	.979	115.3	-19.00	-153.2	-19.00	-153.2	.979	115.3
11.10	.978	114.5	-18.85	-154.0	-18.85	-154.0	.978	114.5
11.15	.978	113.7	-18.69	-154.8	-18.69	-154.8	.978	113.7
11.20	.978	112.9	-18.52	-155.6	-18.52	-155.6	.978	112.9
11.25	.977	112.0	-18.34	-156.4	-18.34	-156.4	.977	112.0
11.30	.977	111.2	-18.16	-157.3	-18.16	-157.3	.977	111.2
11.35	.977	110.3	-17.96	-158.1	-17.96	-158.1	.977	110.3
11.40	.977	109.5	-17.76	-159.0	-17.76	-159.0	.977	109.5
11.45	.976	108.6	-17.54	-159.9	-17.54	-159.9	.976	108.6
11.50	.976	107.7	-17.32	-160.8	-17.32	-160.8	.976	107.7
11.55	.976	106.7	-17.09	-161.7	-17.09	-161.7	.976	106.7
11.60	.976	105.8	-16.84	-162.6	-16.84	-162.6	.976	105.8
11.65	.975	104.8	-16.59	-163.6	-16.59	-163.6	.975	104.8
11.70	.975	103.8	-16.32	-164.5	-16.32	-164.5	.975	103.8
11.75	.975	102.8	-16.05	-165.5	-16.05	-165.5	.975	102.8
11.80	.975	101.7	-15.76	-166.5	-15.76	-166.5	.975	101.7
11.85	.975	100.7	-15.46	-167.5	-15.46	-167.5	.975	100.7
11.90	.975	99.6	-15.15	-168.6	-15.15	-168.6	.975	99.6
11.95	.975	98.4	-14.83	-169.7	-14.83	-169.7	.975	98.4
12.00	.974	97.2	-14.50	-170.7	-14.50	-170.7	.974	97.2

TABLE 16

Analysis of Filter #5 (ℓ = 1.40 cm)

```
WRITE
<INITIALIZING ARRAYS>
KEY-IN or LOAD circuit? (<K> or L)
?
K
Key-in ckt description: then enter frequencies
?
TWO 1 TWO 2 TWO 3
?
STEP 8 12 .2 STEP 9.5 9.6 .005
Sorting frequencies
EDIT, RUN, STORE, STOP? (E, <R>, STORE or STOP)
?
E
<Editor> CONT exits to <Analysis>
?
P
<Editor> CONT exits to <Analysis>
?
LIS 0
Select print/list device (<CRT> or PRINTER)
?
P
GHZ OH  NH  PF  CM  ZR= 50
SDB
 10 TWO   1 CAS
 20 TWO   2 CAS
 30 TWO   3 CAS
Frequencies: 8  8.2  8.4  8.6  8.8  9  9.2  9.4  9.5  9.505  9.51  9.515  9.52
 9.525  9.53  9.535  9.54  9.545  9.55  9.555  9.56  9.565  9.57  9.575  9.58
 9.585  9.59  9.595  9.6  9.8  10  10.2  10.4  10.6  10.8  11  11.2  11.4  11.6
 11.8  12

<Editor> CONT exits to <Analysis>
?
R
Enter data (F,11,12.21,22) for TWO 1
</ CONT> terminates input
?
8 .979,146.461 .2,56.461 .2.56.461 .979,146.461
?
9 .960,135.070 .279,45.070 .279,45.070 .960,135.070
?
10 .935,123.961 .354,33.961 .354,33.961 .935,123.961
?
11 .897,113.625 .440,23.625 .440,23.625 .897,113.625
?
12 .849,101.742 .529,11.742 .529,11.742 .849,101.742
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
```

TABLE 17

Analysis of Filter #5 (Cont.)

```
<Interpolating>
Enter data (F,11,12,21,22) for TWO 2
</ CONT> terminates input
?
8 .0,0.0 1.0,-88.60 1.0,-88.60 .0,0.0
?
9 .0,0.0 1.0,-115.00 1.0,-115.00 .0,0.0
?
10 .0,0.0 1.0,-138.30 1.0,-138.30 .0,0.0
?
11 .0,0.0 1.0,-160.85 1.0,-160.85 .0,0.0
?
12 .0,0.0 1.0,-181.62 1.0,-181.62 .0,0.0
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
Enter data (F,11,12,21,22) for TWO 3
</ CONT> terminates input
?
8 .984,146.742 .176,56.742 .176,56.742 .984,146.742
?
9 .969,135.211 .247,45.211 .247,45.211 .969,135.211
?
10 .946,124.031 .322,34.031 .322,34.031 .946,124.031
?
11 .914,113.414 .405,23.414 .405,23.414 .914,113.414
?
12 .868,100.969 .496,10.969 .496,10.969 .868,100.969
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
<Analysis>
Select print/list device (<CPT> or PRINTER)
?
P
```

TABLE 18

Analysis of Filter #5 (Cont.)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	DB	ANG	DB	ANG	MAG	ANG
8.000	.999	145.7	-33.50	55.9	-33.50	55.9	.999	146.2
8.200	.998	143.0	-31.22	52.9	-31.22	52.9	.999	143.5
8.400	.998	140.1	-28.80	50.0	-28.80	50.0	.999	140.7
8.600	.999	136.9	-26.18	46.9	-26.18	46.9	.998	137.7
8.800	.997	133.3	-23.23	43.5	-23.23	43.5	.997	134.4
9.000	.994	128.8	-19.73	39.5	-19.73	39.5	.995	130.3
9.200	.983	121.6	-15.12	32.5	-15.12	32.5	.985	124.2
9.400	.910	104.6	-8.12	16.2	-8.12	16.2	.912	110.3
9.500	.661	76.6	-2.91	-9.2	-2.91	-9.2	.668	90.4
9.505	.633	74.2	-2.64	-11.4	-2.64	-11.4	.641	88.9
9.510	.603	71.5	-2.38	-13.6	-2.38	-13.6	.612	87.5
9.515	.571	68.7	-2.12	-16.0	-2.12	-16.0	.580	86.0
9.520	.535	65.7	-1.87	-18.5	-1.87	-18.5	.546	84.6
9.525	.497	62.4	-1.64	-21.2	-1.64	-21.2	.509	83.3
9.530	.456	58.8	-1.42	-24.0	-1.42	-24.0	.470	82.1
9.535	.412	55.0	-1.21	-26.8	-1.21	-26.8	.428	81.2
9.540	.365	50.7	-1.02	-29.8	-1.02	-29.8	.384	80.8
9.545	.316	45.9	-.85	-32.9	-.85	-32.9	.339	81.0
9.550	.265	40.2	-.71	-36.1	-.71	-36.1	.293	82.3
9.555	.213	33.2	-.59	-39.4	-.59	-39.4	.247	85.4
9.560	.160	23.6	-.50	-42.8	-.50	-42.8	.204	91.3
9.565	.110	7.9	-.44	-46.1	-.44	-46.1	.168	101.9
9.570	.072	-23.9	-.40	-49.5	-.40	-49.5	.146	118.2
9.575	.071	-75.2	-.40	-52.9	-.40	-52.9	.145	137.9
9.580	.107	-108.6	-.42	-56.3	-.42	-56.3	.165	154.7
9.585	.155	-124.8	-.48	-59.6	-.48	-59.6	.199	165.7
9.590	.206	-134.6	-.56	-62.9	-.56	-62.9	.240	172.0
9.595	.257	-141.6	-.66	-66.0	-.66	-66.0	.283	175.4
9.600	.306	-147.1	-.79	-69.1	-.79	-69.1	.328	176.9
9.800	.921	150.7	-8.43	-121.1	-8.43	-121.1	.922	146.0
10.00	.971	138.7	-12.47	-132.5	-12.47	-132.5	.970	136.1
10.20	.982	132.9	-14.72	-137.6	-14.72	-137.6	.982	130.9
10.40	.986	128.8	-16.05	-141.5	-16.05	-141.5	.987	127.2
10.60	.989	125.4	-16.85	-144.9	-16.85	-144.9	.989	124.0
10.80	.990	122.3	-17.32	-148.1	-17.32	-148.1	.991	121.0
11.00	.990	119.3	-17.55	-151.3	-17.55	-151.3	.991	118.1
11.20	.990	116.3	-17.58	-154.4	-17.58	-154.4	.990	115.2
11.40	.989	113.3	-17.46	-157.5	-17.46	-157.5	.990	112.2
11.60	.989	110.1	-17.20	-160.7	-17.20	-160.7	.989	109.1
11.80	.989	106.8	-16.81	-163.9	-16.81	-163.9	.988	105.8
12.00	.989	103.3	-16.29	-167.2	-16.29	-167.2	.988	102.3

TABLE 19

Analysis of Filter #5(a)(ℓ = 1.43 cm)

```
WRITE
<INITIALIZING ARRAYS>
KEY-IN or LOAD circuit? (<k> or L)
?
K
Key-in ckt description: then enter frequencies
?
TWO 1 TWO 2 TWO 3
?
STEP 8 12 .2 STEP 9.45 9.55 .005
Sorting frequencies
EDIT, RUN, STORE, STOP? (E, <R>, STORE or STOP)
?
E
<Editor> CONT exits to <Analysis>
?
LIS 0
Select print list device (<CRT> or PRINTER)
?
P
GHZ OH  NH  PF  CM  ZR= 50
SDB
 10 TWO   1 CAS
 20 TWO   2 CAS
 30 TWO   3 CAS
Frequencies: 8  8.2  8.4  8.6  8.8  9  9.2  9.4  9.45  9.455  9.46  9.465  9.47
 9.475  9.48  9.485  9.49  9.495  9.5  9.505  9.51  9.515  9.52  9.525  9.53
 9.535  9.54  9.545  9.55  9.6  9.8  10  10.2  10.4  10.6  10.8  11  11.2  11.4
 11.6  11.8  12

<Editor> CONT exits to <Analysis>
?
P
Enter data (F,11,12,21,22) for TWO 1
</ CONT> terminates input
?
8 .979,146.461 .2,56.461 .2,56.461 .979,146.461
?
9 .960,135.070 .279,45.070 .279,45.070 .960,135.070
?
10 .935,123.961 .354,33.961 .354,33.961 .935,123.961
?
11 .897,113.625 .440,23.625 .440,23.625 .897,113.625
?
12 .849,101.742 .529,11.742 .529,11.742 .849,101.742
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (Y, N)
N
<Interpolating>
Enter data (F,11,12,21,22) for TWO 2
</ CONT> terminates input
?
8 .0,0.0 1.0,-90.50 1.0,-90.50 .0,0.0
?
9 .0,0.0 1.0,-117.40 1.0,-117.40 .0,0.0
?
10 .0,0.0 1.0,-141.23 1.0,-141.23 .0,0.0
?
11 .0,0.0 1.0,-164.30 1.0,-164.30 .0,0.0
?
12 .0,0.0 1.0,-185.50 1.0,-185.50 .0,0.0
?
/
```

TABLE 20

Analysis of Filter #5(a) (Cont.)

```
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
Enter data (F,11,12,21,22) for TWO 3
</ CONT> terminates input
?
8 .984,146.742 .176,56.742 .176,56.742 .984,146.742
?
9 .969,135.211 .247,45.211 .247,45.211 .969,135.211
?
10 .946,124.031 .322,34.031 .322,34.031 .946,124.031
?
11 .914,113.414 .405,23.414 .405,23.414 .914,113.414
?
12 .868,100.969 .496,10.969 .496,10.969 868,100.969
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
<Analysis>
Select print/list device (<CRT> or PRINTER)
?
P
```

TABLE 21

Analysis of Filter #5(a) (Cont.)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	DB	ANG	DB	ANG	MAG	ANG
8.000	.999	145.7	-33.31	55.9	-33.31	55.9	.999	146.1
8.200	.998	142.9	-30.95	52.8	-30.95	52.8	.999	143.4
8.400	.998	139.9	-28.44	49.8	-28.44	49.8	.999	140.6
8.600	.997	136.7	-25.67	46.6	-25.67	46.6	.998	137.5
8.800	.996	132.9	-22.52	43.1	-22.52	43.1	.997	134.1
9.000	.993	127.8	-18.68	38.7	-18.68	38.7	.993	129.6
9.200	.974	119.0	-13.35	29.9	-13.35	29.9	.974	122.1
9.400	.774	88.5	-4.46	1.3	-4.46	1.3	.779	98.7
9.450	.490	63.2	-1.66	-20.8	-1.66	-20.8	.505	84.7
9.455	.446	59.5	-1.43	-23.7	-1.43	-23.7	.463	83.6
9.460	.399	55.4	-1.22	-26.8	-1.22	-26.8	.419	82.8
9.465	.348	50.9	-1.03	-30.0	-1.03	-30.0	.372	82.7
9.470	.295	45.7	-.86	-33.3	-.86	-33.3	.324	83.4
9.475	.240	39.5	-.72	-36.8	-.72	-36.8	.276	85.7
9.480	.184	31.4	-.61	-40.3	-.61	-40.3	.229	90.4
9.485	.129	19.1	-.53	-43.8	-.53	-43.8	.189	99.0
9.490	.079	-5.3	-.48	-47.4	-.48	-47.4	.160	113.3
9.495	.060	-59.0	-.47	-51.0	-.47	-51.0	.151	132.4
9.500	.091	-104.1	-.48	-54.5	-.48	-54.5	.165	150.5
9.505	.142	-123.6	-.53	-58.1	-.53	-58.1	.197	163.1
9.510	.197	-134.2	-.61	-61.5	-.61	-61.5	.239	170.6
9.515	.251	-141.6	-.72	-64.9	-.72	-64.9	.284	174.6
9.520	.303	-147.3	-.86	-69.1	-.86	-68.1	.330	176.5
9.525	.352	-152.1	-1.01	-71.2	-1.01	-71.2	.375	177.1
9.530	.399	-156.3	-1.19	-74.2	-1.19	-74.2	.418	176.9
9.535	.443	-160.1	-1.38	-77.1	-1.38	-77.1	.459	176.2
9.540	.484	-163.5	-1.58	-79.8	-1.58	-79.8	.498	175.3
9.545	.521	-166.7	-1.80	-82.4	-1.80	-82.4	.534	174.1
9.550	.556	-169.6	-2.03	-84.8	-2.03	-84.8	.567	172.9
9.600	.777	170.2	-4.41	-102.7	-4.41	-102.7	.781	160.8
9.800	.955	144.4	-10.83	-126.9	-10.83	-126.9	.955	141.0
10.00	.979	136.2	-13.97	-134.8	-13.97	-134.8	.979	134.0
10.20	.986	131.4	-15.79	-139.0	-15.79	-139.0	68.508	-79.4
10.40	.989	127.8	-16.88	-142.5	-16.88	-142.5	103.163	-79.3
10.60	.990	124.6	-17.52	-145.7	-17.52	-145.7	103.140	-79.2
10.80	.991	121.6	-17.87	-148.8	-17.87	-148.8	68.436	-79.3
11.00	.991	118.6	-17.99	-151.9	-17.99	-151.9	.992	117.6
11.20	.991	115.7	-17.94	-154.9	-17.94	-154.9	105.019	101.1
11.40	.990	112.7	-17.74	-158.0	-17.74	-158.0	243.770	101.0
11.60	.989	109.5	-17.41	-161.2	-17.41	-161.2	417.204	101.0
11.80	.989	106.2	-16.96	-164.4	-16.96	-164.4	625.321	101.0
12.00	.989	102.7	-16.37	-167.8	-16.37	-167.8	868.120	101.0

TABLE 22

Analysis of Filter #6

```
WRITE
<INITIALIZING ARRAYS>
KEY-IN or LOAD circuit? (<K> or L)
?
K
Key-in ckt description: then enter frequencies
?
TWO 1 HOLD 1 USE 1 WG 5.08 1.68735 USE -1
?
STEP 8 12 .05 STEP 9 9.4 .01
Sorting frequencies
EDIT, RUN, STORE, STOP? (E, <R>, STORE or STOP)
?
E
<Editor> CONT exits to <Analysis>
?
LIS 0
Select print/list device (<CRT> or PRINTER)
?
P
GHZ OH  NH  PF  CM  ZR= 50
SDB
 10 TWO    1 CAS
 20 HOLD   1 CAS
 30 USE    1 CAS
 40 WG   CAS     5.08  1.68735
 50 USE   -1 CAS
Frequencies: 8  8.05  8.1  8.15  8.2  8.25  8.3  8.35  8.4  8.45  8.5  8.55  8.6
 8.65  8.7  8.75  8.8  8.85  8.9  8.95  9  9.01  9.02  9.03  9.04  9.05  9.06
 9.07  9.08  9.09  9.1  9.11  9.12  9.13  9:14  9.15  9.16  9.17  9.18  9.19
 9.2  9.21  9.22  9.23  9.24  9.25  9.26  9.27  9.28  9.29  9.3  9.31  9.32
 9.33  9.34  9.35  9.36  9.37  9.38  9.39  9.4  9.45  9.5  9.55  9.6  9.65  9.7
 9.75  9.8  9.85  9.9  9.95  10  10.05  10.1  10.15  10.2  10.25  10.3  10.35
 10.4  10.45  10.5  10.55  10.6  10.65  10.7  10.75  10.8  10.85  10.9  10.95
 11  11.05  11.1  11.15  11.2  11.25  11.3  11.35  11.4  11.45  11.5  11.55
 11.6  11.65  11.7  11.75  11.8  11.85  11.9  11.95  12

<Editor> CONT exits to <Analysis>
?
R
Enter data (F,11,12,21,22) for TWO 1
</ CONT> terminates input
?
8 .996,162.083 .089,72.083 .089,72.083 .996,162.083
?
9 .993,157.5 .118,67.5 .118,67.5 .993,157.5
?
10 .989,153.333 .147,63.333 .147,63.333 .989,153.333
?
11 .983,147.291 .183,57.291 .183,57.291 .983,147.291
?
12 .964,140.791 .265,50.791 .265,50.791 .964,140.791
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OP DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
<Analysis>
Select print/list device (<CRT> or PRINTER)
?
P
```

TABLE 23

Analysis of Filter #6 (Cont.)

S-MATRIX IN MAGNITUDE AND PHASE

FREQ	11 MAG	11 ANG	12 DB	12 ANG	21 DB	21 ANG	22 MAG	22 ANG
8.000	.996	159.3	-33.37	126.5	-33.37	126.5	.996	159.3
8.050	.995	157.9	-33.06	119.7	-33.06	119.7	.995	157.9
8.100	.994	156.4	-32.64	113.0	-32.64	113.0	.994	156.4
8.150	.993	155.0	-32.12	106.5	-32.12	106.5	.993	155.0
8.200	.992	153.5	-31.50	100.3	-31.50	100.3	.992	153.5
8.250	.992	152.1	-30.78	94.3	-30.78	94.3	.992	152.1
8.300	.992	150.7	-29.97	88.7	-29.97	88.7	.992	150.7
8.350	.992	149.2	-29.07	83.3	-29.07	83.3	.992	149.2
9.400	.992	147.8	-28.09	78.3	-28.09	78.3	.992	147.8
9.450	.993	146.3	-27.03	73.6	-27.03	73.6	.993	146.3
8.500	.993	144.7	-25.89	69.1	-25.89	69.1	.993	144.7
8.550	1.000	158.6	-35.92	68.6	-35.92	68.6	1.000	158.6
8.600	1.000	158.3	-35.04	68.3	-35.04	68.3	1.000	158.3
8.650	1.000	158.0	-34.12	67.9	-34.12	67.9	1.000	158.0
8.700	1.000	157.6	-33.13	67.6	-33.13	67.6	1.000	157.6
8.750	1.000	157.2	-32.08	67.2	-32.08	67.2	1.000	157.2
8.800	1.000	156.8	-30.93	66.8	-30.93	66.8	1.000	156.8
8.850	.999	156.3	-29.68	66.3	-29.68	66.3	.999	156.3
8.900	.999	155.8	-28.29	65.7	-28.29	65.7	.999	155.8
8.950	.999	155.1	-26.72	65.1	-26.72	65.1	.999	155.1
9.000	.998	154.3	-24.90	64.3	-24.90	64.3	.998	154.3
9.010	.998	154.1	-24.52	64.1	-24.52	64.1	.998	154.1
9.020	.998	153.9	-24.12	63.9	-24.12	63.9	.998	153.9
9.030	.998	153.7	-23.71	63.8	-23.71	63.8	.998	153.7
9.040	.998	153.5	-23.28	63.6	-23.28	63.6	.998	153.5
9.050	.998	153.2	-22.83	63.3	-22.83	63.3	.998	153.2
9.060	.997	152.9	-22.35	63.1	-22.35	63.1	.997	152.9
9.070	.997	152.7	-21.86	62.8	-21.86	62.8	.997	152.7
9.080	.997	152.3	-21.34	62.6	-21.34	62.6	.997	152.3
9.090	.996	152.0	-20.79	62.2	-20.79	62.2	.996	152.0
9.100	.996	151.6	-20.21	61.9	-20.21	61.9	.996	151.6
9.110	.995	151.1	-19.60	61.5	-19.60	61.5	.995	151.1
9.120	.995	150.6	-18.94	61.0	-18.94	61.0	.995	150.6
9.130	.994	150.0	-18.24	60.5	-18.24	60.5	.994	150.0
9.140	.992	149.4	-17.48	59.8	-17.48	59.8	.992	149.4
9.150	.991	148.6	-16.66	59.1	-16.66	59.1	.991	148.6
9.160	.989	147.6	-15.77	58.2	-15.77	58.2	.989	147.6
9.170	.986	146.4	-14.78	57.1	-14.78	57.1	.986	146.4
9.180	.981	144.9	-13.67	55.7	-13.67	55.7	.981	144.9
9.190	.975	143.0	-12.43	53.9	-12.43	53.9	.975	143.0

TABLE 24

Analysis of Filter #6 (Cont.)

9.200	.965	140.5	-11.00	51.5	-11.00	51.5	.965	140.5
9.210	.948	136.8	-9.34	48.1	-9.34	48.1	.948	136.8
9.220	.916	131.4	-7.35	42.9	-7.35	42.9	.916	131.4
9.230	.847	122.3	-4.95	34.5	-4.95	34.5	.847	122.3
9.240	.677	105.4	-2.14	19.2	-2.14	19.2	.677	105.4
9.250	.251	67.9	.22	-9.2	.22	-9.2	.251	67.9
9.260	.378	-127.5	-.18	-45.4	-.18	-45.4	.378	-127.5
9.270	.726	-157.0	-2.78	-69.9	-2.78	-69.9	.726	-157.0
9.280	.862	-171.2	-5.43	-82.9	-5.43	-82.9	.862	-171.2
9.290	.919	-179.0	-7.64	-90.2	-7.64	-90.2	.919	-179.0
9.300	.947	176.1	-9.46	-94.8	-9.46	-94.8	.947	176.1
9.310	.963	172.8	-10.98	-97.9	-10.98	-97.9	.963	172.8
9.320	.973	170.4	-12.28	-100.1	-12.28	-100.1	.973	170.4
9.330	.979	168.7	-13.40	-101.8	-13.40	-101.8	.979	168.7
9.340	.983	167.3	-14.40	-103.1	-14.40	-103.1	.983	167.3
9.350	.987	166.1	-15.29	-104.2	-15.29	-104.2	.987	166.1
9.360	.989	165.2	-16.09	-105.0	-16.09	-105.0	.989	165.2
9.370	.991	164.4	-16.82	-105.8	-16.82	-105.8	.991	164.4
9.380	.992	163.8	-17.48	-106.4	-17.48	-106.4	.992	163.8
9.390	.993	163.2	-18.10	-106.9	-18.10	-106.9	.993	163.2
9.400	.994	162.7	-18.67	-107.4	-18.67	-107.4	.994	162.7
9.450	.997	160.9	-21.01	-109.1	-21.01	-109.1	.997	160.9
9.500	.998	159.8	-22.77	-110.2	-22.77	-110.2	.998	159.8
9.550	.998	158.9	-24.18	-111.0	-24.18	-111.0	.998	158.9
9.600	.999	158.3	-25.33	-111.6	-25.33	-111.6	.999	158.3
9.650	.999	157.7	-26.30	-112.2	-26.30	-112.2	.999	157.7
9.700	.999	157.2	-27.13	-112.7	-27.13	-112.7	.999	157.2
9.750	.999	156.8	-27.85	-113.1	-27.85	-113.1	.999	156.8
9.800	.999	156.4	-28.48	-113.5	-28.48	-113.5	.999	156.4
9.850	.999	156.0	-29.03	-113.9	-29.03	-113.9	.999	156.0
9.900	.999	155.7	-29.52	-114.3	-29.52	-114.3	.999	155.7
9.950	.999	155.3	-29.96	-114.7	-29.96	-114.7	.999	155.3
10.00	.999	155.0	-30.35	-115.0	-30.35	-115.0	.999	155.0
10.05	1.000	154.6	-30.82	-115.2	-30.82	-115.2	1.000	154.6
10.10	1.000	154.2	-31.24	-115.5	-31.24	-115.5	1.000	154.2
10.15	1.000	153.8	-31.60	-115.7	-31.60	-115.7	1.000	153.8
10.20	1.000	153.4	-31.93	-116.0	-31.93	-116.0	1.000	153.4
10.25	1.000	153.1	-32.22	-116.3	-32.22	-116.3	1.000	153.1
10.30	1.000	152.7	-32.47	-116.6	-32.47	-116.6	1.000	152.7
10.35	1.000	152.4	-32.68	-116.9	-32.68	-116.9	1.000	152.4
10.40	1.000	152.1	-32.86	-117.2	-32.86	-117.2	1.000	152.1
10.45	1.000	151.7	-33.01	-117.6	-33.01	-117.6	1.000	151.7
10.50	1.000	151.4	-33.14	-117.9	-33.14	-117.9	1.000	151.4
10.55	1.000	151.1	-33.23	-118.3	-33.23	-118.3	1.000	151.1
10.60	1.000	150.7	-33.30	-118.7	-33.30	-118.7	1.000	150.7
10.65	1.000	150.4	-33.35	-119.0	-33.35	-119.0	1.000	150.4
10.70	1.000	150.1	-33.37	-119.4	-33.37	-119.4	1.000	150.1
10.75	1.000	149.7	-33.38	-119.8	-33.38	-119.8	1.000	149.7
10.80	1.000	149.4	-33.36	-120.2	-33.36	-120.2	1.000	149.4
10.85	1.000	149.1	-33.32	-120.7	-33.32	-120.7	1.000	149.1
10.90	1.000	148.8	-33.26	-121.1	-33.26	-121.1	1.000	148.8
10.95	1.000	148.4	-33.19	-121.5	-33.19	-121.5	1.000	148.4
11.00	1.000	148.1	-33.09	-121.9	-33.09	-121.9	1.000	148.1
11.05	1.000	147.8	-32.99	-122.3	-32.99	-122.3	1.000	147.8
11.10	.999	147.4	-32.86	-122.7	-32.86	-122.7	.999	147.4
11.15	.999	147.1	-32.72	-123.1	-32.72	-123.1	.999	147.1
11.20	.999	146.8	-32.57	-123.5	-32.57	-123.5	.999	146.8
11.25	.999	146.5	-32.40	-123.9	-32.40	-123.9	.999	146.5
11.30	.999	146.1	-32.22	-124.3	-32.22	-124.3	.999	146.1
11.35	.999	145.8	-32.03	-124.7	-32.03	-124.7	.999	145.8
11.40	.999	145.4	-31.83	-125.1	-31.83	-125.1	.999	145.4
11.45	.999	145.1	-31.61	-125.4	-31.61	-125.4	.999	145.1
11.50	.999	144.8	-31.39	-125.8	-31.39	-125.8	.999	144.8
11.55	.999	144.4	-31.15	-126.1	-31.15	-126.1	.999	144.4
11.60	.999	144.1	-30.90	-126.5	-30.90	-126.5	.999	144.1
11.65	.999	143.7	-30.65	-126.8	-30.65	-126.8	.999	143.7
11.70	.999	143.4	-30.38	-127.1	-30.38	-127.1	.999	143.4
11.75	.999	143.0	-30.11	-127.4	-30.11	-127.4	.999	143.0
11.80	.999	142.7	-29.83	-127.7	-29.83	-127.7	.999	142.7
11.85	.999	142.3	-29.54	-128.0	-29.54	-128.0	.999	142.3
11.90	.999	141.9	-29.24	-128.3	-29.24	-128.3	.999	141.9
11.95	.999	141.6	-28.94	-128.6	-28.94	-128.6	.999	141.6
12.00	.999	141.2	-28.63	-128.8	-28.63	-128.8	.999	141.2

TABLE 25

Analysis of Filter #7

```
WRITE
<INITIALIZING ARRAYS>
KEY-IN or LOAD circuit? (<K> or L)
?
K
key-in ckt description: then enter frequencies
?
TWO 1 HOLD 1 USE 1 WG 5.08 1.7109 USE -1
?
STEP 8 12 .05 STEP 8.8 10.2 .01
Limit of 128 freqs -- first 128 accepted
Sorting frequencies
EDIT, RUN, STORE, STOP? (E, <R>, STORE or STOP)
?
E
<Editor> CONT exits to <Analysis>
?
LIS 0
Select print/list device (<CRT> or PRINTER)
?
P
GHZ OH  NH  PF  CM  ZR= 50
SDB
 10 TWO    1 CAS
 20 HOLD   1 CAS
 30 USE    1 CAS
 40 WG    CAS     5.08  1.7109
 50 USE   -1 CAS
Frequencies: 8  8.05  8.1  8.15  8.2  8.25  8.3  8.35  8.4  8.45  8.5  8.55  8.6
 8.65  8.7  8.75  8.8  8.81  8.82  8.83  8.84  8.85  8.86  8.87  8.88  8.89  8.9
 8.91  8.92  8.93  8.94  8.95  8.96  8.97  8.98  8.99  9  9.01  9.02  9.03  9.04
 9.05  9.06  9.07  9.08  9.09  9.1  9.11  9.12  9.13  9.14  9.15  9.16  9.17
 9.18  9.19  9.2  9.21  9.22  9.23  9.24  9.25  9.26  9.3  9.35  9.4  9.45  9.5
 9.55  9.6  9.65  9.7  9.75  9.8  9.85  9.9  9.95  10  10.05  10.1  10.15  10.2
 10.25  10.3  10.35  10.4  10.45  10.5  10.55  10.6  10.65  10.7  10.75  10.8
 10.85  10.9  10.95  11  11.05  11.1  11.15  11.2  11.25  11.3  11.35  11.4
 11.45  11.5  11.55  11.6  11.65  11.7  11.75  11.8  11.85  11.9  11.95  12

<Editor> CONT exits to <Analysis>
?
R
Enter data (F,11,12,21,22) for TWO 1
</ CONT> terminates input
?
8 .975,160.833 .222,70.833 .222,70.833 .975,160.833
?
9 .964,156.666 .265,66.666 .265,66.666 .964,156.666
?
10 .943,152.916 .332,62.916 .332,62.916 .943,152.916
?
11 .921,147.50 .389,57.50 .389,57.50 .921,147.50
?
12 .893,142.50 .450,52.50 .450,52.50 .893,142.50
?
/
<S>,G,H,Y,OR Z
?
S
RI,<MP>,OR DB
?
MP
Do you want to store this data in a device file ? (<Y>, N)
N
<Interpolating>
<Analysis>
Select print/list device (<CRT> or PRINTER)
?
P
```

TABLE 26

Analysis of Filter #7 (Cont.)

S-MATRIX IN MAGNITUDE AND PHASE

	11		12		21		22	
FREQ	MAG	ANG	DB	ANG	DB	ANG	MAG	ANG
8.000	.999	158.7	-26.90	68.7	-26.90	68.7	.999	158.7
8.050	.999	158.3	-26.41	68.3	-26.41	68.3	.999	158.3
8.100	.999	157.9	-25.90	68.0	-25.90	68.0	.999	157.9
8.150	.999	157.5	-25.37	67.6	-25.37	67.6	.999	157.5
8.200	.998	157.0	-24.81	67.2	-24.81	67.2	.998	157.0
8.250	.998	156.6	-24.22	66.7	-24.22	66.7	.998	156.6
8.300	.998	156.1	-23.59	66.2	-23.59	66.2	.998	156.1
8.350	.998	155.6	-22.93	65.7	-22.93	65.7	.998	155.6
8.400	.997	155.0	-22.24	65.1	-22.24	65.1	.997	155.0
8.450	.997	154.4	-21.49	64.5	-21.49	64.5	.997	154.4
8.500	.996	153.7	-20.70	63.8	-20.70	63.8	.996	153.7
8.550	.995	152.9	-19.86	63.0	-19.86	63.0	.995	152.9
8.600	.994	152.0	-18.95	62.1	-18.95	62.1	.994	152.0
8.650	.992	151.0	-17.96	61.1	-17.96	61.1	.992	151.0
8.700	.990	149.9	-16.89	59.9	-16.89	59.9	.990	149.9
8.750	.987	148.4	-15.71	58.5	-15.71	58.5	.987	148.4
8.800	.982	146.6	-14.40	56.7	-14.40	56.7	.982	146.6
8.810	.980	146.2	-14.12	56.2	-14.12	56.2	.980	146.2
8.820	.979	145.8	-13.83	55.8	-13.83	55.8	.979	145.8
8.830	.977	145.3	-13.54	55.3	-13.54	55.3	.977	145.3
8.840	.976	144.9	-13.24	54.9	-13.24	54.9	.976	144.9
8.850	.974	144.4	-12.93	54.3	-12.93	54.3	.974	144.4
8.860	.972	143.8	-12.61	53.8	-12.61	53.8	.972	143.8
8.870	.970	143.2	-12.28	53.2	-12.28	53.2	.970	143.2
8.880	.967	142.6	-11.94	52.6	-11.94	52.6	.967	142.6
8.890	.964	142.0	-11.59	51.9	-11.59	51.9	.964	142.0
8.900	.961	141.3	-11.24	51.2	-11.24	51.2	.961	141.3
8.910	.958	140.5	-10.87	50.4	-10.87	50.4	.958	140.5
8.920	.954	139.7	-10.49	49.6	-10.49	49.6	.954	139.7
8.930	.949	138.8	-10.10	48.7	-10.10	48.7	.949	138.8
8.940	.944	137.9	-9.69	47.8	-9.69	47.8	.944	137.9
8.950	.938	136.8	-9.27	46.7	-9.27	46.7	.938	136.8
8.960	.931	135.7	-8.83	45.6	-8.83	45.6	.931	135.7
8.970	.923	134.5	-8.39	44.3	-8.39	44.3	.923	134.5
8.980	.914	133.1	-7.92	43.0	-7.92	43.0	.914	133.1
8.990	.904	131.6	-7.44	41.5	-7.44	41.5	.904	131.6
9.000	.891	130.0	-6.94	39.8	-6.94	39.8	.891	130.0
9.010	.877	128.2	-6.42	38.0	-6.42	38.0	.877	128.2
9.020	.860	126.2	-5.90	36.0	-5.90	36.0	.860	126.2
9.030	.840	123.9	-5.35	33.8	-5.35	33.8	.840	123.9
9.040	.815	121.4	-4.79	31.2	-4.79	31.2	.815	121.4
9.050	.786	118.6	-4.22	28.4	-4.22	28.4	.786	118.6
9.060	.751	115.4	-3.64	25.2	-3.64	25.2	.751	115.4
9.070	.709	111.8	-3.06	21.6	-3.06	21.6	.709	111.8
9.080	.657	107.8	-2.49	17.6	-2.49	17.6	.657	107.8
9.090	.596	103.2	-1.93	13.0	-1.93	13.0	.596	103.2
9.100	.522	98.1	-1.40	7.8	-1.40	7.8	.522	98.1
9.110	.435	92.4	-.93	2.2	-.93	2.2	.435	92.4
9.120	.336	86.3	-.54	-4.1	-.54	-4.1	.336	86.3
9.130	.225	79.8	-.24	-10.7	-.24	-10.7	.225	79.8
9.140	.105	73.4	-.07	-17.7	-.07	-17.7	.105	73.4
9.150	.017	-121.0	-.02	-24.8	-.02	-24.8	.017	-121.0
9.160	.138	-122.5	-.10	-31.8	-.10	-31.8	.138	-122.5
9.170	.251	-128.8	-.30	-38.4	-.30	-38.4	.251	-128.8
9.180	.355	-134.9	-.60	-44.7	-.60	-44.7	.355	-134.9
9.190	.445	-140.6	-.97	-50.4	-.97	-50.4	.445	-140.6
9.200	.523	-145.7	-1.41	-55.6	-1.41	-55.6	.523	-145.7
9.210	.590	-150.3	-1.87	-60.2	-1.87	-60.2	.590	-150.3
9.220	.645	-154.4	-2.35	-64.2	-2.35	-64.2	.645	-154.4
9.230	.692	-158.0	-2.84	-67.9	-2.84	-67.9	.692	-158.0
9.240	.731	-161.2	-3.33	-71.1	-3.33	-71.1	.731	-161.2
9.250	.763	-164.0	-3.81	-73.9	-3.81	-73.9	.763	-164.0
9.260	.790	-166.5	-4.27	-76.4	-4.27	-76.4	.790	-166.5
9.300	.864	-174.2	-5.99	-84.2	-5.99	-84.2	.864	-174.2
9.350	.912	179.5	-7.78	-90.4	-7.78	-90.4	.912	179.5
9.400	.938	175.4	-9.24	-94.5	-9.24	-94.5	.938	175.4
9.450	.954	172.4	-10.46	-97.5	-10.46	-97.5	.954	172.4
9.500	.964	170.2	-11.49	-99.7	-11.49	-99.7	.964	170.2
9.550	.970	168.5	-12.37	-101.5	-12.37	-101.5	.970	168.5

TABLE 27

Analysis of Filter #7 (Cont.)

10.00	.989	160.4	-16.92	-109.6	-16.92	-109.6	.989	160.4
10.05	.990	159.8	-17.24	-110.2	-17.24	-110.2	.990	159.8
10.10	.991	159.2	-17.54	-110.8	-17.54	-110.8	.991	159.2
10.15	.991	158.6	-17.81	-111.4	-17.81	-111.4	.991	158.6
10.20	.992	158.0	-18.05	-111.9	-18.05	-111.9	.992	158.0
10.25	.992	157.5	-18.27	-112.5	-18.27	-112.5	.992	157.5
10.30	.992	157.0	-18.47	-113.0	-18.47	-113.0	.992	157.0
10.35	.993	156.5	-18.66	-113.5	-18.66	-113.5	.993	156.5
10.40	.993	156.0	-18.82	-113.9	-18.82	-113.9	.993	156.0
10.45	.993	155.6	-18.97	-114.4	-18.97	-114.4	.993	155.6
10.50	.993	155.1	-19.10	-114.8	-19.10	-114.8	.993	155.1
10.55	.994	154.7	-19.22	-115.3	-19.22	-115.3	.994	154.7
10.60	.994	154.3	-19.32	-115.7	-19.32	-115.7	.994	154.3
10.65	.994	153.8	-19.42	-116.1	-19.42	-116.1	.994	153.8
10.70	.994	153.4	-19.50	-116.6	-19.50	-116.6	.994	153.4
10.75	.994	153.0	-19.57	-117.0	-19.57	-117.0	.994	153.0
10.80	.994	152.6	-19.63	-117.4	-19.63	-117.4	.994	152.6
10.85	.994	152.2	-19.68	-117.8	-19.68	-117.8	.994	152.2
10.90	.994	151.8	-19.72	-118.2	-19.72	-118.2	.994	151.8
10.95	.994	151.4	-19.76	-118.5	-19.76	-118.5	.994	151.4
11.00	.994	151.1	-19.78	-118.9	-19.78	-118.9	.994	151.1
11.05	.995	150.7	-19.80	-119.3	-19.80	-119.3	.995	150.7
11.10	.995	150.3	-19.80	-119.7	-19.80	-119.7	.995	150.3
11.15	.995	149.9	-19.80	-120.1	-19.80	-120.1	.995	149.9
11.20	.995	149.5	-19.80	-120.5	-19.80	-120.5	.995	149.5
11.25	.995	149.2	-19.78	-120.8	-19.78	-120.8	.995	149.2
11.30	.995	148.8	-19.76	-121.2	-19.76	-121.2	.995	148.8
11.35	.995	148.4	-19.73	-121.6	-19.73	-121.6	.995	148.4
11.40	.994	148.1	-19.70	-122.0	-19.70	-122.0	.994	148.1
11.45	.994	147.7	-19.66	-122.3	-19.66	-122.3	.994	147.7
11.50	.994	147.3	-19.61	-122.7	-19.61	-122.7	.994	147.3
11.55	.994	146.9	-19.56	-123.1	-19.56	-123.1	.994	146.9
11.60	.994	146.6	-19.50	-123.4	-19.50	-123.4	.994	146.6
11.65	.994	146.2	-19.44	-123.8	-19.44	-123.8	.994	146.2
11.70	.994	145.8	-19.37	-124.2	-19.37	-124.2	.994	145.8
11.75	.994	145.4	-19.30	-124.6	-19.30	-124.6	.994	145.4
11.80	.994	145.1	-19.22	-124.9	-19.22	-124.9	.994	145.1
11.85	.994	144.7	-19.14	-125.3	-19.14	-125.3	.994	144.7
11.90	.994	144.3	-19.05	-125.7	-19.05	-125.7	.994	144.3
11.95	.994	143.9	-18.95	-126.1	-18.95	-126.1	.994	143.9
12.00	.993	143.6	-18.85	-126.4	-18.85	-126.4	.993	143.6

APPENDIX C

FIN LINE--MMWS AND ELECTRONIC WARFARE

A. BACKGROUND

The recent increase of sophistication in weapon systems and the experience from previous combat systems showed the need for effective equipments that would increase the capability to detect the location of the enemy.

This capability requires very effective countermeasure systems to minimize the hostile threats and to maximize the effectiveness of one's own weapons.

In radar applications, the need for compact, low-cost sensors for missiles and smart munitions pushed developers to the mmW region. Table 28 shows a comparison of mmW operations with microwave (μmW) and electro-optics techniques [Ref. 20].

The integrated circuits (ICs) of mmWs appear very attractive because of reduction of their size and weight, lower transmission losses and higher overall bandwidths.

The combination of small size, high accuracy and high reliability in adverse environment conditions offsets the current cost disadvantage. In addition, new fin-line manufacturing techniques minimize the cost of mmW hardware.

Figure C.1 shows the electromagnetic spectrum with radar band designations. The main advantages and limitations for mmWs radar are tabulated into Table 29 [Ref. 13].

TABLE 28

Comparison mmWs-Microwaves-Electro/Optical Techniques

mm-Wave CHARACTERISTIC	FREQUENCY MICROWAVE	mm-WAVE	ELECTRO-OPTIC
- Range in fog	Excellent	Good	Poor
- Components	Large, rugged	Small, rugged	Smaller
- Aperture	Large antenna	Small antenna	Very small aperture
- Mode	Active only (radar)	Active or passive	Mostly passive
- Imaging	Impractical	Possible	Excellent
- Atmosphere	Atmosphere transparent	Good spectral responses	Fog and clouds opaque

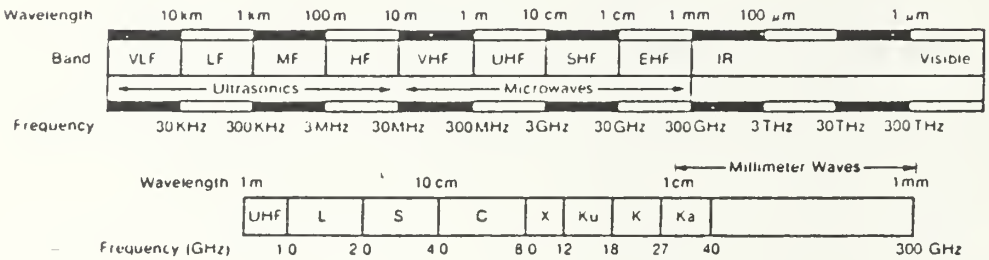


Figure C.1 Electromagnetic Spectrum

TABLE 29

mmW Radar System Tradeoff Considerations

ADVANTAGES

- Physically Small Equipment
- Low Atmospheric Loss[1]
- High Resolution

  Angular
  Doppler
  Imaging Quality
  Classification

- Small Beamwidths

  High Accuracy
  Reduced ECM Vulnerability
  Low Multipath/Clatter
  High Antenna Gain

- Large Bandwidth

  High Range Resolution
  Spread Spectrum ECCM
  Doppler Processing
  ECM

LIMITATIONS

- Component Cost High
- Component Reliability/Availability Low
- Short Range 10-20 km
- Weather Propagation[2]

Notes:

[1]Compared to IR and visual wavelengths

[2]Compared to microwave frequencies

The emergence of radars with high performance seekers requires an equal modernization of ECM systems. Due to the high cost of modern aircraft and ships, ECM is no longer just an added feature, but rather an operational necessity.

Table 30 shows some useful characteristics of air defense systems, which operate in the mmW region [Ref. 14].

TABLE 30

Characteristics of mmW for Air Defense Systems

- The mmW spectrum is now crowded
- High antenna directivity with small aperture can be achieved
- The RF components are small and light
- There are a number of low attenuation "atmospheric windows"
- mmW can penetrate high density plasmas

The high directivity and low attenuation due to atmospheric windows of the mmWs can be used for highly secure operations. The penetration of the mmWs into high density plasmas provides the capability propagation into a nuclear explosion [Ref. 14].

B. APPLICATIONS

This section discussed mmW-planar IC components and system applications. In the first part, the performance of various components are briefly described and in the second, examples of the state-of-the-art applications in radars, communications and missiles are shown.

1. Integrated Circuits Components

TRW Electronic Systems Group has developed many ICs components including mixers, Gun-VSOs, frequency multipliers, switches, attenuators, filters and couplers. These elements are available for applications in advanced sensors, radar, electronic warfare, radiometer, surveillance and communications systems.

The characteristics of the performance of the components are shown in Table 31 [Ref. 15].

The suspended stripline and fin-line techniques have higher Q (quality factor) and thus lower circuit loss compared with microstrip.

The fin-line balanced mixer [Ref. 15] is very useful for extremely wideband operation. A bandwidth of over 30% has been achieved with less than 7.5 dB conversion loss at W-band (75-110 GHz).

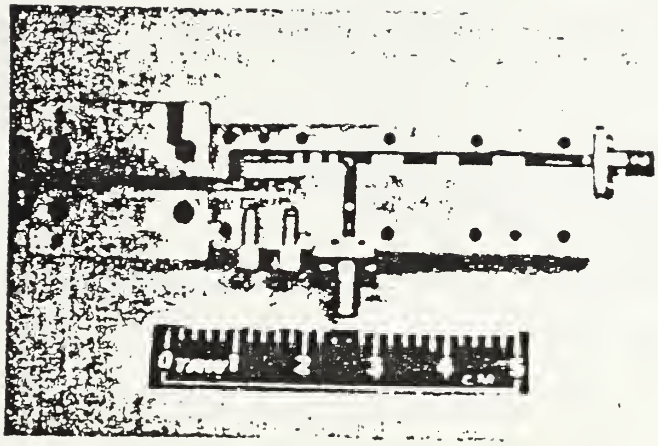
Various types of receivers have been developed at Ka (26.5-40 GHz), V (50-75 GHz) and W (75-110 GHz) bands by using the components mentioned above. The Ka-band receiver was scaled up to V-band for purposes of satellite communications. Figure C.2 shows two RF modules for V-band and W-band, respectively [Ref. 15].

So far experience has shown that fin-line technology is a proper tool to build mmW components and subsystems above 90 GHz. In Figure C.3, a mount of a balanced radiometer

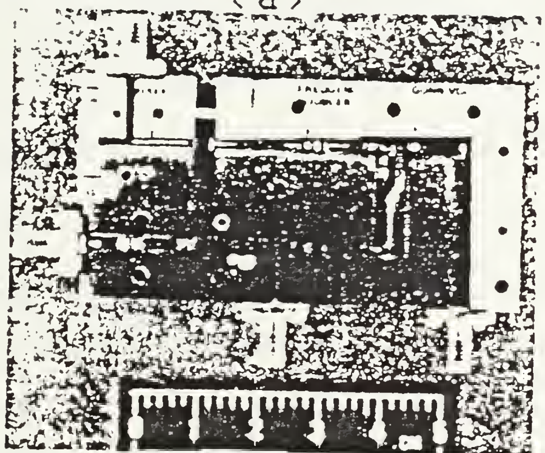
TABLE 31

Summary of Integrated Circuit Components of Receivers

FREQUENCY	COMPONENT	PERFORMANCE
44 GHz	CIRCULATOR	• 0.6 dB INSERTION LOSS • 2 GHz BANDWIDTH • OVER 20 dB ISOLATION
	MIXER	• 5.5 dB CONVERSION LOSS • 3 GHz INSTANTANEOUS BANDWIDTH
	PIN SWITCH	• 1.2 dB INSERTION LOSS; OVER 20 dB ISOLATION
	GUNN VCO	• 80 MW POWER OUTPUT • 1 GHz VARACTOR TUNING
60 GHz	MIXER	• 6 dB CONVERSION LOSS • 6 GHz BANDWIDTH
	GUNN OSCILLATOR	• 37 MW POWER OUTPUT
	GUNN VCO	• 10 MW OUTPUT WITH 1.1 GHz VARACTOR TUNING
94 GHz	MIXER	• CONVERSION LOSS 5.5 dB FOR 1 GHz IF BANDWIDTH • CONVERSION LOSS 7.0 dB FOR 15 GHz INSTANTANEOUS IF BANDWIDTH • CONVERSION LOSS 7.5 dB FOR 28 GHz INSTANTANEOUS IF BANDWIDTH
	DOUBLER	• 40 TO 80 GHz • 6.5 dB CONVERSION LOSS
	PIN SWITCH	• 2 dB INSERTION LOSS • 20 dB ISOLATION • 10 GHz BANDWIDTH
	GUNN OSCILLATOR	• 7 MW POWER OUTPUT



(a)



(b)

Figure C.2 RF Modules (a) V-band Receiver, (b) W-band Receiver [Ref. 15]

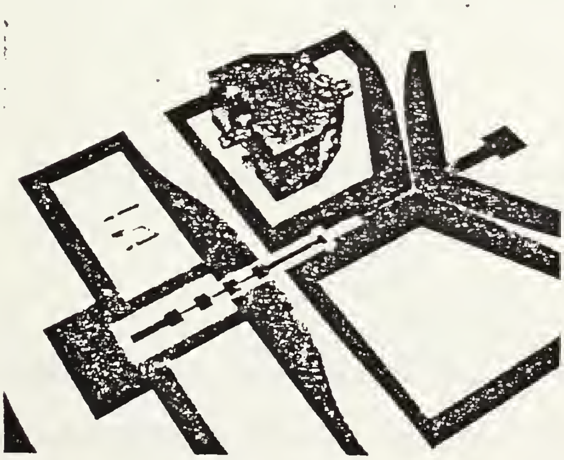


Figure C.3 Balanced Radiometer Mixer [Ref. 16] mixer with SRDT-switch in front of the Signal Port is shown [Ref. 16]. The design of that component was based on the combination of fin-line and coplanar line [Ref. 16].

2. Some Applications in Systems

a. Doppler Radar Sensor

The block diagram of the experimental 35 GHz FSK-CW radar sensor is shown in Figure C.4 [Ref. 17]. The main features of this device are low cost and small size due to integrated fin-line components. It also has a minimum number of elements for a minimum range of 70 m with 1 m^2 effective radar cross section targets.

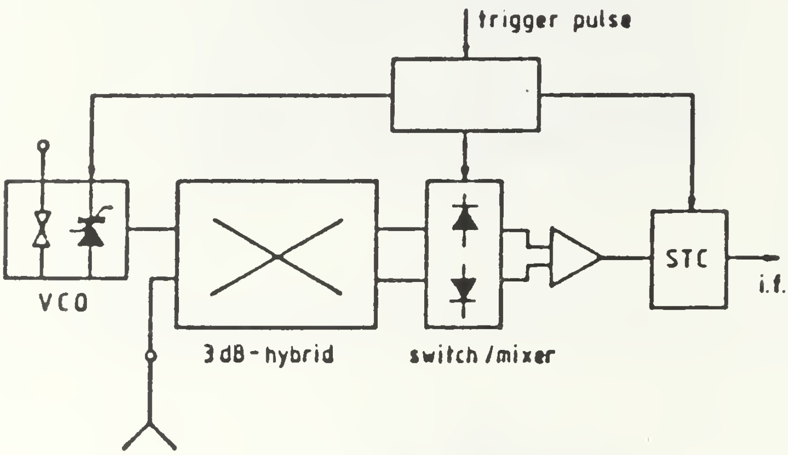


Figure C.4 Block Diagram of the Doppler Sensor [Ref. 17]

The system uses the Frequency Shift Keyed Continuous Wave Radar (FSK-CW) technique, which presents a lost of advantages. Some of them are summarized in Table 32 [Ref. 17].

TABLE 32

Main Advantages of FSK-CW Radar Techniques

- One antenna
- No need for non-reciprocal components
- Only one oscillator
- Minimization of semiconductor elements in mmW region
- Integration using FIN-LINE circuits
- Low cost, minimum size approach

The fin-line switch mixer is the most important part of the radar sensor in the mmW region. It works as a transmit-receive selector and down-converter. The slot pattern of the switch-mixer mount for one arm and the integrated-fronted structure are shown in Figures C.5 and C.6, respectively. Table 33 contains the parameters of the system [Ref. 17].

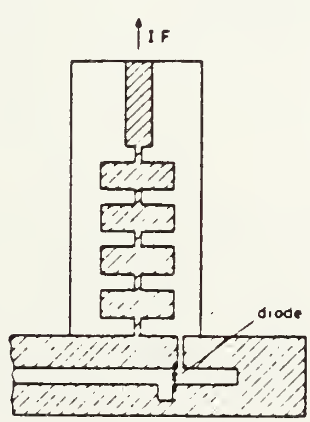


Figure C.5 Slot Pattern of the Mixer/Modulator [Ref. 17]

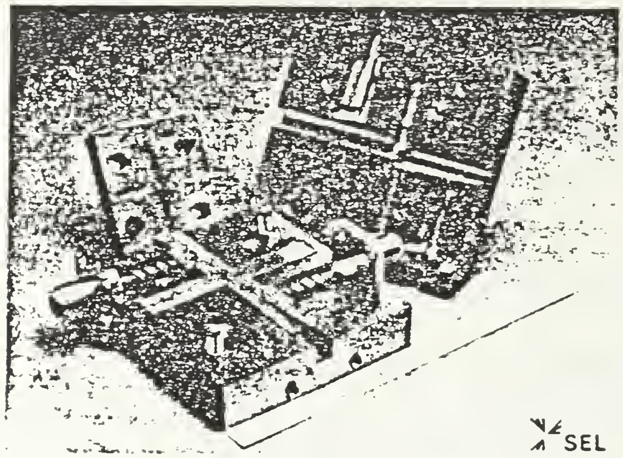


Figure C.6 Integrated Fronted Structure [Ref. 17]

TABLE 33

FSK-CW Doppler Sensor Main Parameters

Transmit Frequency	$f = 36.0$ GHz
Receive-LO-Frequency	$f_{LO} = 35.85$ GHz
Pulse Length	$\tau = 20$ ns
Transmit Power	$P_T = 30$ mW
Pulse Repetition Frequency	$f_p = 150$ kHz
Antenna Gain	$G_A = 28$ dB
Range Gates	24
Noise Figure	$F < 8$ dB
Reaction Time	< 200 ms
Range (for $\sigma = 1\ m^2$)	> 70 m
Volume (Front end)	$4 \times 5.5 \times 1.8\ cm^3$

b. Development of Terrestrial mmW Communications

Recently, a large number of developments in the area of mmWs communications have been seen. Terrestrial and satellite communication systems have been built [Ref. 18].

Point-to-point links, including ship-to-ship or air-to-air systems is one part of terrestrial communications. The point-to-point link further is divided into two different cases. The carrier frequency is chosen to be either in a range of low atmospheric attenuation (e.g., 30-40 GHz) to minimize losses or in a high attenuation area (e.g., 50-60 GHz) for privacy or security reasons.

There are a lot of documents which describe approaches to mmW electronic intelligence (ELINT). Paul G. Steffers andRonald A. Meck [Ref. 19] describe a 60 GHz simplex (one-way) communication link, that is capable of transmitting data television or voice to a distance of nearly 2 Km, when set for operation at 60 GHz.

Figure C.7 shows the link between two stations A and B and the intercept receiver C. It is obvious that the direct-line intercept is more difficult to operate at 60 GHz than even at 40 GHz [Ref. 19].

c. mmW Sensors for Missile Guidance

Several types of guidance have been developed in the mmW area. Applications are found in air-to-surface and surface-to-surface missiles as well as freefall and parachute-suspended munitions.

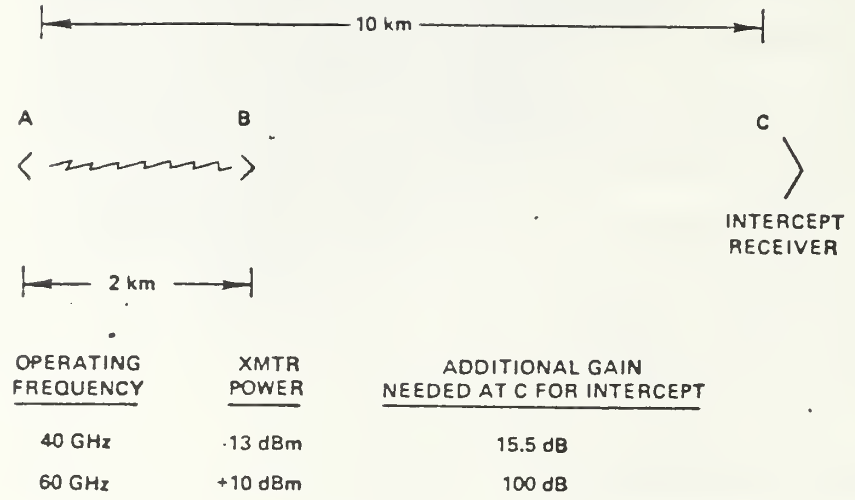


Figure C.7 Direct-line Interception [Ref. 19]

There are three operating modes for autonomous, lock-on-after launch mmW seekers:

- passive acquisition and track-to-target encounter;
- active acquisition and track-to-target encounter;
- active acquisition and early track with passive final track to target encounter.

Table 34 summarizes the parameter for operation at 35, 94, and 140 GHz [Ref. 20].

The threat of countermeasures against mmW active and passive guidance sensors is being taken more seriously during the design of the system. Table 35 [Ref. 20] contains the anticipated countermeasure threats and the passive countermeasure techniques.

TABLE 34

Summary of Sensor Parameters at 35, 94 and 140 GHz

DESIGN PARAMETER	OPERATING FREQUENCY 35 GHz	94 GHz	140 GHz
Wavelength	8.6 MM	3.2 MM	2.2 MM
Clear air attenuator	0.12 dB/KM	0.4 dB/KM	1.6 dB/KM
Rain attenuator			
— 0.25 mm/hr	0.07 dB/KM	0.17 dB/KM	0.2 dB/KM
— 1.0 mm/hr	0.25	0.6	0.7
— 4.0 mm/hr	1.0	3.0	3.2
— 16.0 mm/hr	4.0	8.0	9.0
Fog attenuator			
— light 0.01 g/M³	0.006 dB/KM	0.035 dB/KM	0.07 dB/KM
— thick 0.1 g/M³	0.06	0.35	0.7
— dense 1.0 g/M³	0.6	3.5	7.0
Apparent sky temperature			
— clear	23°K	50°K	81°K
— moderate overcast	65	120	200
— rain	110	220	250
Receiver noise figure	4.5 dB	6.5 dB	7.0 dB
IMPATT transmitter Peak pulse power	15 W	10 W	3 W
Antenna beamwidth D = 15.24 CM	4°	1.4°	0.98°

TABLE 35

Active/Passive Countermeasures

(a) Active Countermeasures Threats

- On target low power jammer
- Deception jammer
- Barrage jammer
- Low power on target/off axis CW of noise jammer
- High power CW or pulse jammer

(b) Passive Countermeasures Techniques

- Smokes
- Aerosols
- Chaff
- Metalized particles
- Corner reflectors
- Target shape decoys

LIST OF REFERENCES

1. Alexander, K.B., and Hamel, S.R., Design and Analysis of Generated Class of Fin-Line Filters, M.S. Thesis, Naval Postgraduate School, Monterey, California, 1983.

2. Deal, J.C., Numerical Computation of The Scattering Coefficients of an Inductive Strip in a Fin-Line, M.S. Thesis, Naval Postgraduate School, Monterey, California, 1984.

3. Meir, P.J, "Millimeter Integrated Circuits Suspended in the E-Plane of Rectangular Waveguide," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-26, No. 10, pp. 726-732, October 1978.

4. Micro-Compact, Circuit Analysis and Optimization, Compact Engineering, Version 1.0, December 1980.

5. Miller, G.S., An Experimental Investigation of Several Fin-Line Discontinuities, M.S. Thesis, Naval Postgraduate School, Monterey, California, 1980.

6. Solbach, K., "The Status of Printed Millimeter-Wave E-Plane Circuits," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-31, No. 2, pp. 107-121, February 1983.

7. Schmidt, L.P., and Itoh, T., "Spectral Domain Analysis of Dominant and Higher Order Modes in Fin-Lines," IEEE Transactions on Microwaves Theory and Technqiues, Vol. MTT-28, No. 9, pp. 981-675, September 1980.

8. Knorr, J.B., "Equivalent Reactance of a Shorting Septum in a Fin-Line: Theory and Experiment," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-29, No. 11, pp. 1196-1202, November 1981.

9. Shih, Y.C., "Design of Waveguide E-Plane Filters with All-Metal Inserts," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-32, No. 7, pp. 695-704, July 1984.

10. Morgan, G.B., "Dielectric Filters for Short Millimeter-Wave Integrated Circuits," IEEE Infrared and Millimeter Waves Symposium, 1983.

11. Brown, R.G., and others, Lines, Waves, and Antennas, Ronald, 1973.

12. Meir, P.J., "Integrated Fin-Line Millimeter Components," IEEE Transaction on Microwave Theory and Techniques, Vo. MTT-22, No. 12, pp. 1209-1216, December 1974.

13. Reedy, E.K., "Millimeter Radar-Fundamentals and Applications (Part One)," Military Electronics/Countermeasures, pp. 62-65, August 1980.

14. Cooper, H.M., and Littlpage, R.S., "ECM at Millimeter Wavelengths," Microwave Journal, p. 22, September 1982.

15. Chang, K., and Sun, C., "Integrated Circuit Components and Receivers for Millimeter-Wave Applications," IEEE International Conference on Infrared and Millimeter Waves, 8th, 1983.

16. Rembold, B., Fin-Line Components and Subsystems for Use Above 90 GHz, IEEE International Conference on Infrared and Millimeter Waves, 8th, 1983.

17. Szabo, L., and Jensen, E., Doppler Radar Sensor in Integrated Fin-Line Technique, IEEE International Microwave Symposium, pp. 472-474, 1983.

18. Witse, J.C., Development of Terrestrial Millimeter-Wave Communications, IEEE International Conference on Infrared and Millimeter Waves, 8th, 1983.

19. Steffer, P.G., and Meck, R.A., "Prototype Tests Secure Millimeter Communications," Microwave Systems News, Vol. 10, pp. 59-68, October 1980.

20. Seashore, C.R., "mm-Wave Sensors for Missile Guidance," Microwave Journal, pp. 133-144, September 1983.

21. Konishi, Y., and Uenakada, K., "Short End Effect of Ridge Guide with Planar Circuit Mounted in a Waveguide," IEEE Transaction on Microwave Theory and Techniques, Vol. MTT-27, pp. 168-170, February 1979.

22. Hoefer, W.J.R., and Pic, E., "Experimental Characterization of Fin-Line Discontinuities Using Resonant Techniques," IEEE MTT-S Int. Microwave Symp. Dig., pp. 108-110, 1981.

23. El Hennaway, H., and Schunemann, K., "Computer-aided Design of Semiconductor Mounts in Fin-Line Technology," IEEE MTT-S Int. Microwave Symp. Dig., pp. 307-309, 1980.

24. Meir, P.J., private communication, 1982.

25. Meinel, H., and Schmidt, L.-P., High Sensitivity Millimeter-Wave Detectors Using Fin-Line Technology, 5th Int. Conf. Infrared and Millimeter-Waves Dig., (Freiburg Germany), pp. 133-135, 1980.

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