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HIGH ACCURACY MICROWAVE S-PARAMETER MEASUREMENTS ON SOLID STATE--ETC(U)
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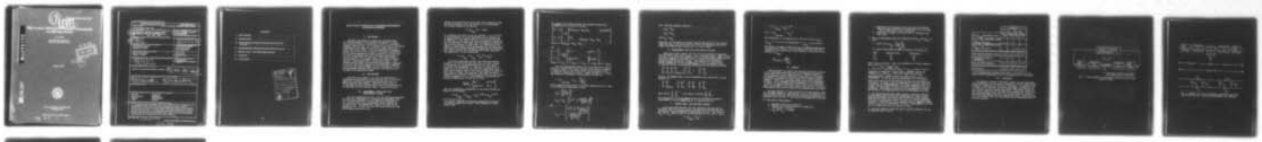

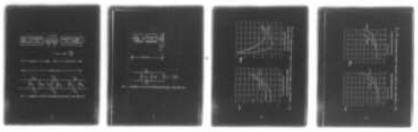

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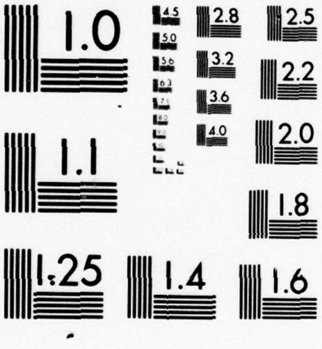

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High Accuracy Microwave S-Parameter Measurements on Solid State Devices

R. E. Neidert

Microwave Technology Branch
Electronics Technology Division

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NAVAL RESEARCH LABORATORY
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The absolute accuracy of automatic network analyzer measurement and de-imbedding of microwave S-parameters of solid state devices (diodes or transistors) is not easy to determine. A reasonable rule of thumb is that the fewer inaccurate measurements necessary to get at an answer, the more accurate the answer. The method outlined in this report, especially the low VSWR test equipment case (which uses only one measurement other than the one with the device in place), uses fewer measurements than any other method known. Because of this it is also possible that this measurement and de-imbedding method is the most accurate.

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CONTENTS

HIGH ACCURACY MICROWAVE S—PARAMETER MEASUREMENTS ON SOLID STATE DEVICES

I. THE PROBLEM

Typically the physical or electrical reference point for the measurement of the microwave S-parameters of solid state devices (diodes or transistors) is not at a convenient standard connector face. It is usually at the ends of microstrip transmission lines where the solid state device input and output bond wires connect. D.C. bias networks are invariably present but are not to be included in the device S-parameters. The following information is given to describe a new and more accurate de-imbedding method for S-parameter measurement of two port devices such as transistors. The method assumes the availability of a computer controlled, automatic network analyzer. The problem, then, is pictured in Fig. 1 - the network analyzer makes the S-parameter measurements referenced to Points 1 and 2 (for example, at precision APC-7 connector faces), but the desired answers are the S-parameters of only the unpackaged transistor and, possibly, its bond wire connections to the microstrip lines.

II. THE SOLUTION

Obviously the solution is to find the characteristic parameters of the networks to the right and left of the device under test, and then to analytically remove them from the Network Analyzer measurements. However, because there is no connector at all at the microstrip ends, the characteristics of the right and left networks cannot be measured directly.

III. MEASUREMENTS WITHOUT THE SOLID STATE DEVICE IN PLACE

Note the designations in Fig. 2 for the following discussion. Let the first measurement be a transmission measurement from the left side of Network A to the right side of Network B, or, in other words, an S_{21} measurement versus frequency on the Network AB. The Network AB is exactly the same as the network of Fig. 1 except that the solid state device has been

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Note: Manuscript submitted April 12, 1979.

removed and the microstrip ground plane and transmission line are made continuous. Call the results of this measurement (at as many frequencies as desired)

$$a = S_{21_{AB_I}}(\omega) \quad \text{, where}$$

"a" represents the value at any one frequency. At this point in the discussion, let it be stipulated that the Network AB be symmetrical--this implies that the two bias networks must be identical to each other, the coax to microstrip transitions must be identical to each other, and the lengths of microstrip line must be identical to each other. An evaluation of the degree of identicalness which is necessary will be given later. From Signal Flow Analysis Methods,[1] recognizing that Networks A and B are reciprocal and that Network AB is both reciprocal and symmetrical, it can be shown that

$$a = S_{21_{AB_I}} = S_{12_{AB_I}} = S_{21_A}{}^2/(1-S_{22_A}{}^2) .$$

The second measurement without the solid-state device in place is on mostly the same circuitry, but with a length of microstrip, ℓ_2, inserted between the prior two pieces, which were each designated ℓ_1. See Fig. 3, noting that the length, ℓ_2, is not critical but should be significant (say more than 30 degrees long) at the lowest frequency of interest while being no longer than necessary. The added microstrip length must be accurately known and should have the same characteristic impedance as ℓ_1 to avoid impedance discontinuities. Taking the ABCD matrix of the line ℓ_2 to be

$$\left[ABCD\right]_{\ell_2} = \begin{bmatrix} \cos\theta & jZo\sin\theta \\ j\dfrac{1}{Zo}\sin\theta & \cos\theta \end{bmatrix} ,$$

then the transmission S-parameters of the second network are given by the following:

$$b = S_{21_{AB_{II}}} = S_{12_{AB_{II}}} = S_{21_A}{}^2 e^{-j\theta}/(1-S_{22_A}{}^2 e^{-j2\theta}) .$$

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[1] J.K. Hunton, "Analysis of Microwave Measurement Techniques by Means of Signal Flow Graphs," IRE Transactions on MTT, March, 1960.

The general relationship between an S-parameter matrix and an [ABCD] matrix is given as follows:

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \frac{1}{H} \begin{bmatrix} B-CZ_{01}Z_{02} + AZ_{02}-DZ_{01} & 2Z_{01}(AD-BC) \\ 2Z_{02} & B-CZ_{01}Z_{02} - AZ_{02} + DZ_{01} \end{bmatrix}$$

where $H = B+CZ_{01}Z_{02} + AZ_{02} + DZ_{01}$,

and

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \frac{1}{2S_{21}} \begin{bmatrix} mn + t & Z_{02}(mq - t) \\ \frac{1}{Z_{01}}(pn-t) & \frac{Z_{02}}{Z_{01}}(pq+t) \end{bmatrix}$$

where $m = 1+S_{11}$, $n = 1-S_{22}$, $p = 1-S_{11}$, $q = 1+S_{22}$, and $t = S_{12}S_{21}$.

The third measurement without the solid state device yet in place may be made with a short circuit at the center of symmetry as shown in Fig. 4. The short circuit can be represented as a reflection coefficient of unity at angle 180 degrees, as shown. The reflection S-parameter of this circuit is given as:

$$c = S_{11_{A_{\text{shorted}}}} = S_{11_A} - \frac{S_{21_A}^{\;2}}{1+S_{22_A}} .$$

After algebraic manipulation of the above equations for a, b, and c, the following relationships result:

$$S_{22_A} = \left[\frac{be^{j\theta} - a}{be^{-j\theta} - a}\right]^{\frac{1}{2}} ,$$

$$S_{21_A} = S_{12_A} = \left[be^{j\theta} - be^{-j\theta}\left(\frac{be^{j\theta} - a}{be^{-j\theta} - a}\right)\right]^{\frac{1}{2}} ,$$

and

$$S_{11_A} = c + \left[\frac{be^{j\theta} - be^{-j\theta}\left(\dfrac{be^{j\theta} - a}{be^{-j\theta} - a}\right)}{1 + \left(\dfrac{be^{j\theta} - a}{be^{-j\theta} - a}\right)^{\frac{1}{2}}}\right] .$$

Also, from the symmetry condition,

$$S_{22_B} = S_{11_A}$$

$$S_{21_B} = S_{21_A}$$

and $S_{11_B} = S_{22_A}$.

Therefore, all 16 terms of the eight complex S-parameters of the networks right and left of the device under test have been determined from three simple measurements whose values are a, b, and c, above.

IV. MEASUREMENTS WITH SOLID STATE DEVICE IN PLACE

Referring to Fig. 1 again, the full set of S-parameters is measured with the device under test in place. This S-parameter matrix, $[S]_M$, is then converted to its equivalent [ABCD] matrix by the relationship given earlier, and called $[ABCD]_M$, to indicate that it is derived from "Measured" S-parameters with the device in place. The mathematical relationship between $[ABCD]_M$ and the desired [ABCD] matrix of the de-imbedded device is shown as follows, using ordinary [ABCD] matrix multiplication methods:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_A \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Device} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_B = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_M$$

Finally, the [ABCD] matrix of the de-imbedded device under test is given directly as:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Device} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_A^{-1} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_M \begin{bmatrix} A & B \\ C & D \end{bmatrix}_B^{-1} ,$$

where matrix $\begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1}$ = the Inverse of matrix $\begin{bmatrix} A & B \\ C & D \end{bmatrix}$.

The S-parameters of the de-imbedded device are obtained by numerical transformation from its [ABCD] matrix, as described earlier.

V. SPECIAL CASE - LOW VSWR TEST CIRCUITS

In the much used case when the test circuitry right and left of the device under test is all close to 50 ohms with no significant discontinuities, great mathematical simplification results. The values of S_{22_A} and S_{11_A} approach zero in the expressions for a, b, and c. Then,

$$a = S_{21_{AB_I}} = S_{21_A}^{\;2} ,$$

$$b = S_{21_{AB_{II}}} = S_{21_A}^{\;2} e^{-j\theta} \;,$$

$$\text{and } c = S_{11_{A_{\text{shorted}}}} = - S_{21_A}^{\;2} \;.$$

The information to be gained here is that the value of $S_{21_A} = (S_{21_{AB_I}})^{\frac{1}{2}}$, and that the measurement of $S_{21_{AB_I}}$ is the only one which has to be made to obtain the full de-imbedding information. The mathematics evolves, for this simple case, such that the S-parameters of the device equal those measured in the test circuit divided by $S_{21_{AB_I}}$,

$$\left[S\right]_{\text{Device}} = \frac{\left[S\right]_M}{S_{21_{AB_I}}}$$

VI. ACCURACY

There persists, of course, the question of absolute accuracy of the measurements made with the full de-imbedding procedure versus those with the Low-VSWR procedure. Figures 5 and 6 give the approximate computer controlled, automatic network analyzer uncertainty (supplied as tentative data by the Hewlett Packard Company). Notice the large phase angle error in the measurement of any S_{11} or S_{22} parameter when the magnitude of the reflection is small. It is this observation which leads to the conclusion that, if the VSWR's of the test circuitry are kept low, the overall measurement accuracy may be improved by assuming them to be unity.

An error analysis has been carried out for measurements using the low VSWR assumption. Incorporated in this error analysis are the allowable values for VSWR, and the allowable dissimilarity, of Networks A and B of Fig. 2. The results are summarized as follows:

A. Test Circuit Requirements :

1. Networks A and B are reciprocal
2. Network AB is both reciprocal and symmetrical (see #4 and 5, below)
3. S_{22_A} and S_{11_B} <1.3 VSWR

4. Magnitudes twice through A and B less than 2% different from each other (measured as though measuring S_{11} with ℄ point either open or short circuited).
5. Phase twice through A and B less than 3^o different from each other.

B. Error in measurements from the assumption that S_{11_B} and S_{22_A} are zero :

1. Recall that $S_{21_{AB}} = \dfrac{S_{21_A} S_{21_B}}{1-S_{11_B} S_{22_A}}$

2. Error versus VSWR (if VSWR is assumed to be unity) is:

VSWR	Magnitude Error	Phase Error
1.3	2%	1.1^o
1.2	1%	$.6^o$
1.15	.5%	$.3^o$

These errors carry over to all four parameters of a device measurement, since $S_{ij_D} = S_{ij_{MEAS}} / S_{21_{AB}}$.

C. The error in assuming that $(S_{21_A})^2 = S_{21_{AB}}$ is equal to the % difference in magnitudes (Δ% Mag) and to the phase difference (ΔφDeg) of S_{21_A} and S_{21_B}. This error affects S_{11} and S_{22} measurements on a device but does not affect the S_{21} or S_{12} measurements. In the S_{11} and S_{22} measurements on a solid state device, the error can be "Δ% Mag" and "Δφ Deg" plus the VSWR error from above. In the S_{21} and S_{12} measurements on a device, the error is only from the VSWR assumption. The values suggested above for Δ% Mag = 2% and Δφ Deg = 3^o are fairly easily achievable over wide bandwidths. The absolute accuracy of the measurements of Δ% Mag and Δφ Deg are not important since only the differences are used.

D. The Hewlett-Packard Model 8545A computer controlled automatic network analyzer has errors given approximately by Figs. 5 and 6. Assuming that VSWR's will not be small during the actual measurements with the solid state device in place, S_{11} and S_{22} measurement accuracy is approximately ± 3% on magnitude and ± 2 degrees on phase. Similarly S_{21} and S_{12} measurement accuracy is approximately ± 0.14 db (±1.6% on magnitude) and ±1.8 degrees on phase.

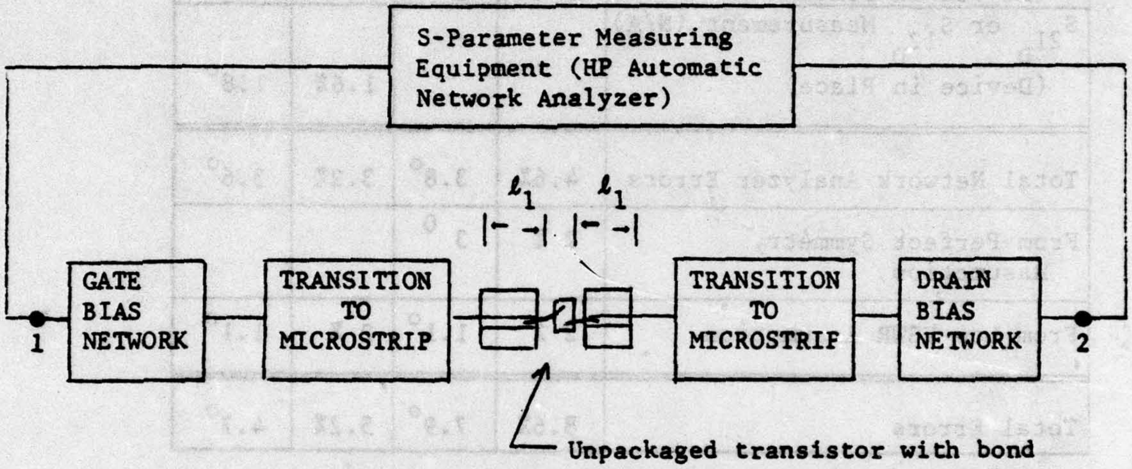
E. The total amount of absolute error is given as follows, for the de-imbedded device results:

	Error in			
	S_{11}, S_{22}		S_{21}, S_{12}	
	Mag.	Phase	Mag.	Phase
From $S_{21_{AB}}$ Measurement (N/A)	1.6%	1.8°	1.6%	1.8°
S_{11_D} or S_{22_D} Measurement (N/A) (Device in Place)	3 %	2 °		
S_{21_D} or S_{12_D} Measurement (N/A) (Device in Place)			1.6%	1.8°
Total Network Analyzer Errors	4.6%	3.8°	3.2%	3.6°
From Perfect Symmetry Assumption	2 %	3 °		
From Low VSWR Assumption	2 %	1.1°	2 %	1.1°
Total Errors	8.6%	7.9°	5.2%	4.7°

It is discomforting to realize that there is this much error in high precision measurements, but to be unaware of it is even worse.

VII. CONCLUSION

The absolute accuracy of automatic network analyzer measurement and de-imbedding of the microwave S-parameters of solid state devices (diodes or transistors) is not easy to determine. A reasonable rule of thumb is that the fewer inaccurate measurements necessary to get at an answer, the more accurate the answer. The method outlined in this report, especially the low VSWR test equipment case (which uses only one measurement other than the one with the device in place), uses fewer measurements than any other method known. Because of this it is also possible that this measurement and de-imbedding method is the most accurate.



Unpackaged transistor with bond wire connections to microstrip.

Fig. 1 - Block diagram of measurement system with solid state device in place

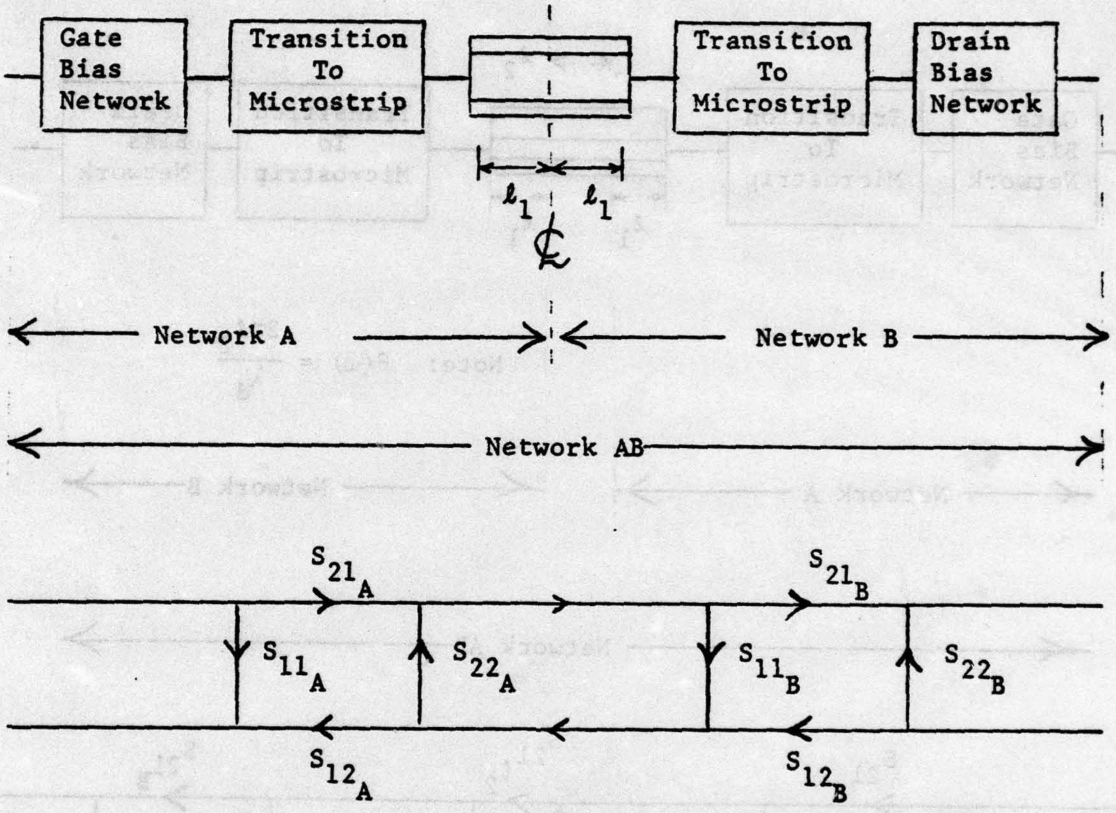
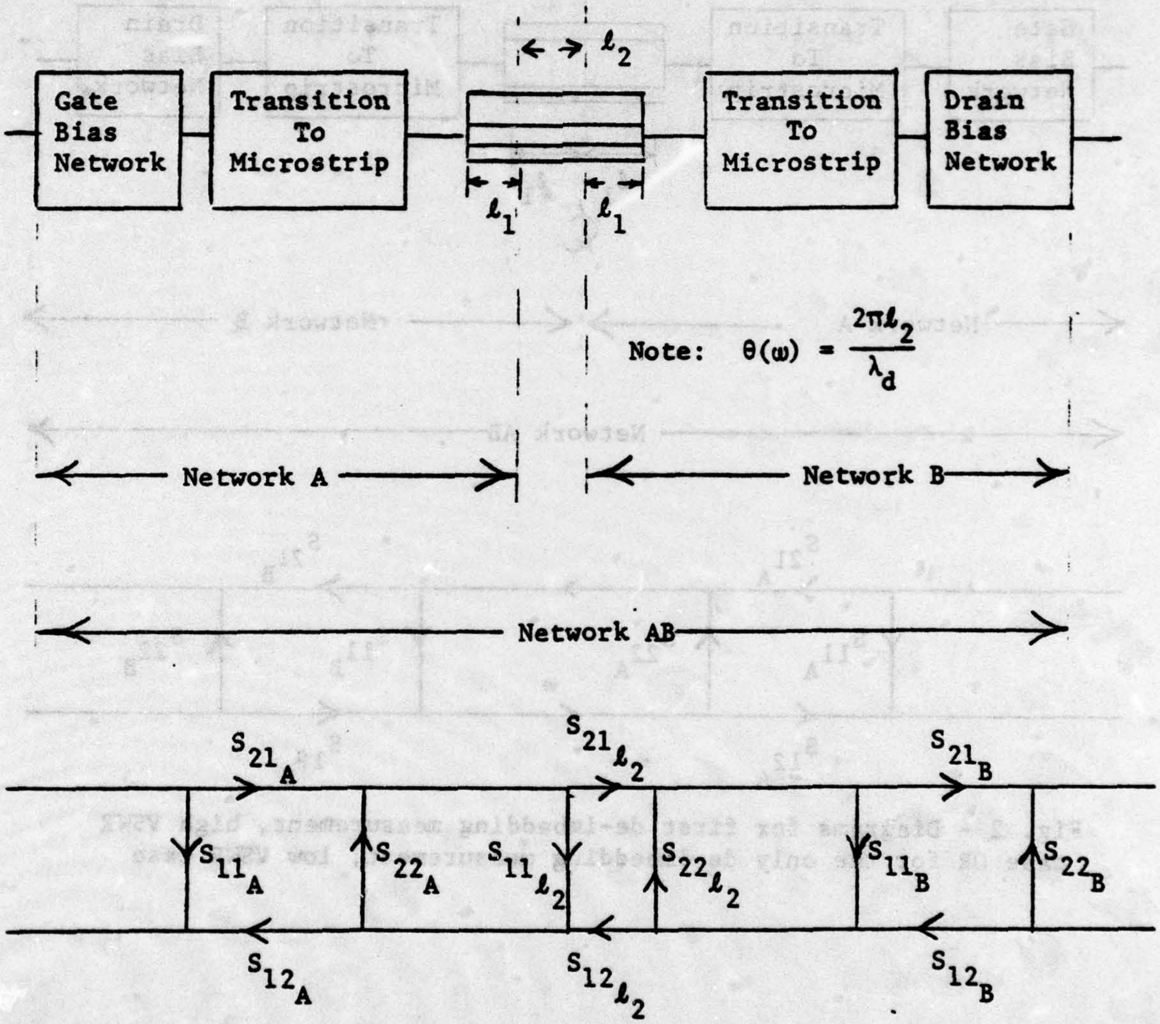


Fig. 2 - Diagrams for first de-imbedding measurement, high VSWR case OR for the only de-imbedding measurement, low VSWR case



Note: $\theta(\omega) = \frac{2\pi\ell_2}{\lambda_d}$

Fig. 3 - Diagrams for second de-imbedding measurement, high VSWR case

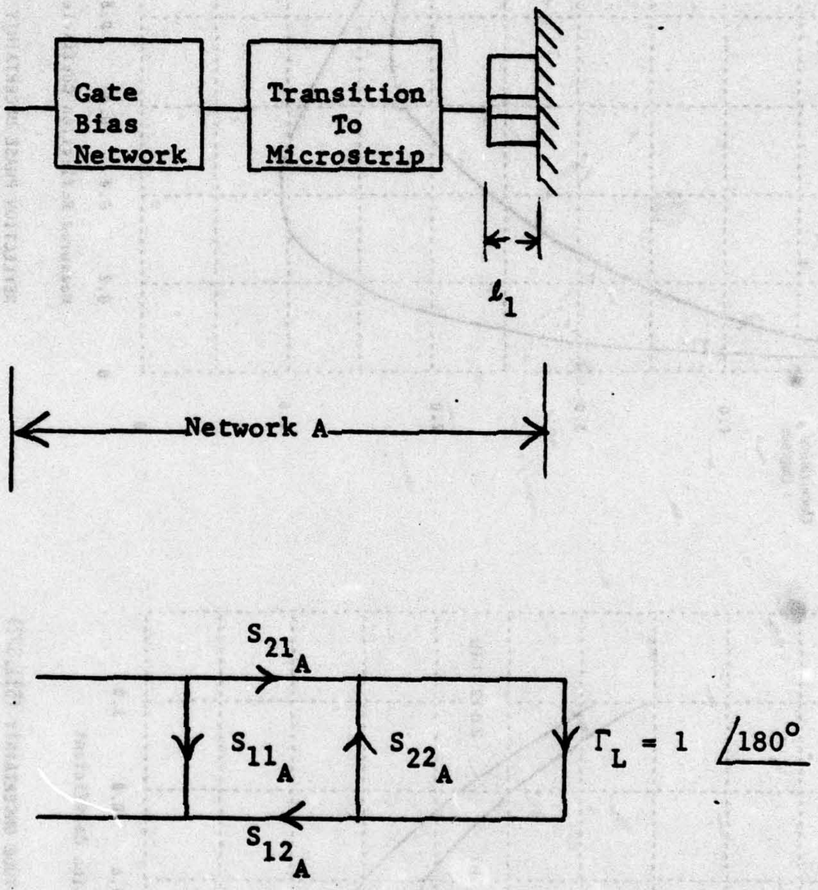
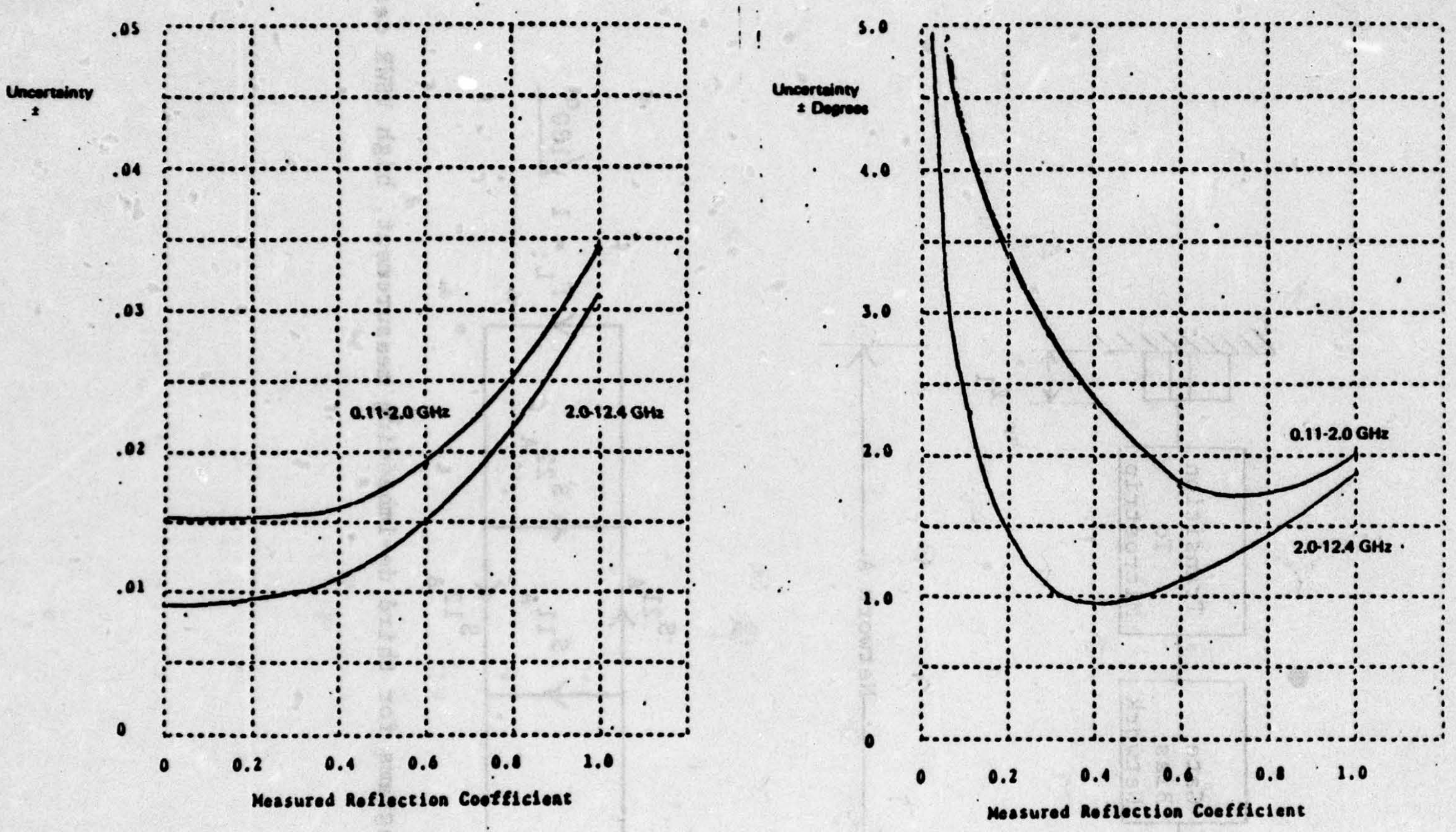


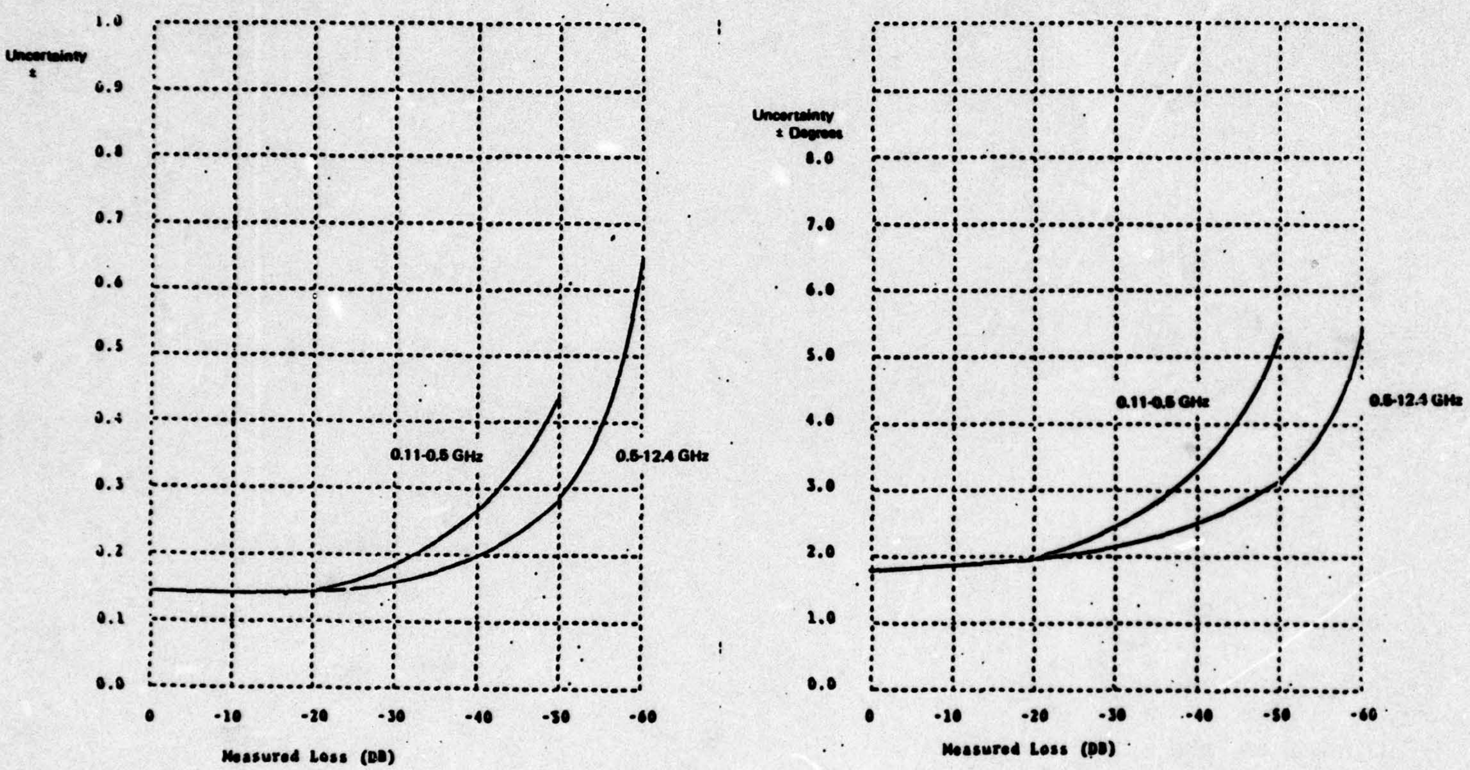
Fig. 4 - Diagrams for third de-imbedding measurement, high VSWR case



REFLECTION MAGNITUDE UNCERTAINTY (S11,S22)

REFLECTION PHASE UNCERTAINTY (S11,S22)

Fig. 5 - Approximate error of computer controlled, automatic network analyzer, S_{11} or S_{22}



TRANSMISSION MAGNITUDE UNCERTAINTY (S21,S12)

TRANSMISSION PHASE UNCERTAINTY (S21,S12)

Fig. 6 - Approximate error of computer controlled, automatic network analyzer, S_{21} or S_{12}