ON-WAFER MILLIMETER-WAVE NETWORK ANALYSIS
FOR DEVICE AND CIRCUIT DESIGN

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ABSTRACT

A broadband, millimeter-wave on-wafer network analyzer system is necessary for the characterization and design of millimeter-wave devices and circuits. The HP 85109B, 45 MHz to 62.5 GHz network analyzer was used to determine the f_T and f_{max} of a 0.25μm MODFET. The S-Parameters were also used to model an equivalent circuit of the MODFET. A broadband 0.5 to 50 GHz travelling wave amplifier [1] was measured to determine the cutoff frequency and the potential for out-of-band oscillations. Finally, a criteria was established for the selection of a broadband millimeter-wave network analyzer.

INTRODUCTION

In recent years improvements in semiconductor processes have resulted in the ability to produce FETs with gate lengths as small as 0.1μm[2]. This, together with improved material systems, such as AlGaAs/InGaAs and AlInAs/InGaAs[3][4], has provided the capability to produce MODFETs with f_Ts as high as 250 GHz[5].

Until recently the only broadband network analyzer systems available to measure these devices and circuits were 26.5 or 40 GHz systems. Measurements were made on these systems and the data was extrapolated to predict performance at higher frequencies. Since these extrapolations were made over large frequency spans, large uncertainties resulted. In order to reduce these uncertainties, it is necessary to measure as high in frequency and reduce the extrapolation span. It is evident that as technology pushes devices and circuits to higher frequencies, the network analyzer systems must also evolve.

CRITICAL REQUIREMENTS OF A BROADBAND ON-WAFER NETWORK ANALYZER SYSTEM

The most important criteria of a broadband on-wafer network analyzer system is measurement bandwidth. For device measurements, it is desirable to have the widest bandwidth possible. For circuit measurements the bandwidth should not only be adequate to measure the device under test in its operating bandwidth, but should also extend higher in frequency for guardband measurements. Broadband on-wafer network analyzers are currently limited to 62.5 GHz and broadband wafer probes are limited to 65 GHz. V-Band network analyzer systems and wafer probes are available for measurements from 50 to 75 GHz [6], but are narrow banded.

In addition to measurement bandwidth, another very important characteristic to consider in selecting an on-wafer network analyzer system is accuracy. Since modelling accuracy is derived from measurement data, it is necessary to use measurement data of the highest accuracy. The accuracy of the measurement system will be determined by the raw performance of the system and the accuracy of the calibration. It is important to note that there is a trade-off between measurement bandwidth and accuracy. The best trade-off should be sought in the selection of a broadband network analyzer system.

For versatility, the network analyzer should support at least the three most common on-wafer calibration techniques: Open-Short-Load-Thru (OSLT), Thru-Reflect-Line (TRL) and Line-Reflect-Match (LRM). The selection of the appropriate technique will depend upon the availability of standards, the wafer probe configuration (fixed vs. moveable probes), and the measurement frequency range (see Figure 1).

CAL TYPE	FREQUENCY RANGE	# OF KNOWN STANDARDS	PROBE STATION	Zo REF
OSLT	PARASITICS LIMIT USE AT HIGHER FREQUENCIES	4 = OPEN SHORT LOAD THRU	FIXED & MOVABLE	FIXED LOADS
TRL	LINE STANDARDS TOO LONG < 2 GHz	2+N = THRU N LINES	MOVEABLE	TRANS. LINES
LRM	LIMITED ONLY BY SYSTEM FREQ. RANGE	2 = THRU MATCH	FIXED & MOVABLE	FIXED LOADS

Figure 1: A summary of the three most common on-wafer calibration techniques.

As can be seen in Figure 2, the OSLT technique provides good measurement results at low frequencies, but is limited at higher frequencies by the parasitics of the open and the short standards. On the other hand, the TRL technique is adequate at the upper frequencies, but is limited below 1 GHz because the line standards become longer than the maximum probe separation. The LRM calibration technique combines the advantages of TRL and OSLT without their disadvantages [7,8].

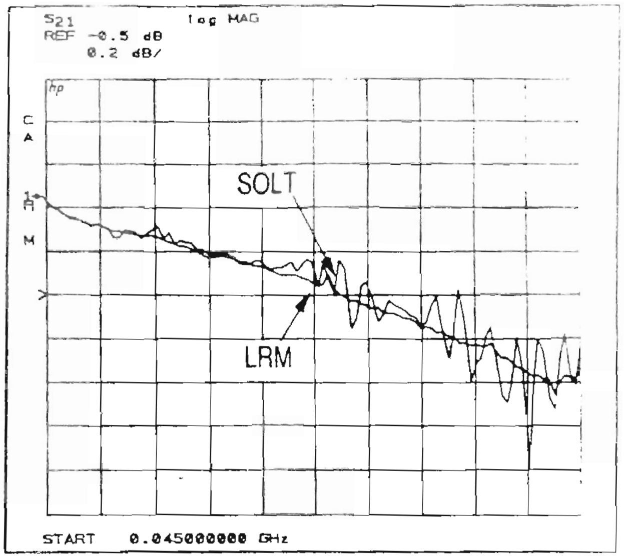
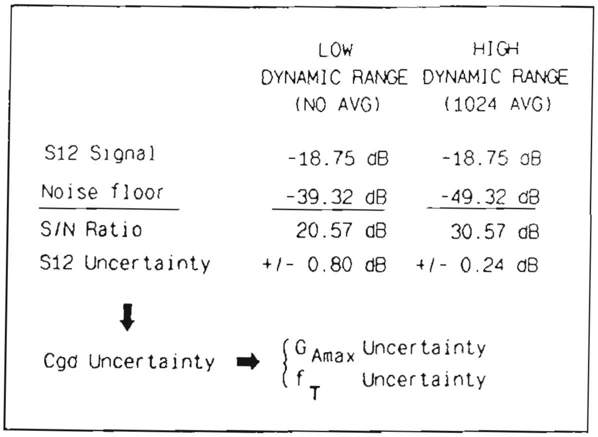


Figure 2: Measurements of a 15 ps coplanar transmission line using the OSLT and LRM calibration techniques reveals large uncertainties at high frequencies when using the OSLT technique.

Another very important characteristic to consider is calibration stability. The accuracy of the measurements depends not only on the accuracy of the calibration, but on the amount of system drift between calibration and measurements. It is important, therefore, to choose a dependable system that minimizes the effects of drift.

A third important characteristic of a broadband network analyzer is high dynamic range. It is often thought that if high gain devices are to be measured, high dynamic range is unimportant. This is not true, however, because accurate device modelling also requires accurate measurements of the high loss, reverse isolation S_{12} term. The S_{12} term is used to determine C_{gd}, which is then used for calculating the f_{max} and gain of the FET.

$$C_{gd} = -\mathrm{Im}\ \frac{-2S_{12}}{(1-S_{11})(1+S_{22})+S_{12}S_{21}}$$



	LOW DYNAMIC RANGE (NO AVG)	HIGH DYNAMIC RANGE (1024 AVG)
S12 Signal	-18.75 dB	-18.75 dB
Noise floor	-39.32 dB	-49.32 dB
S/N Ratio	20.57 dB	30.57 dB
S12 Uncertainty	+/- 0.80 dB	+/- 0.24 dB

Cgd Uncertainty ➡ $\left\{\begin{array}{l} G_{Amax} \text{ Uncertainty} \\ f_T \text{ Uncertainty} \end{array}\right.$

Figure 3: A comparison of S_{12} uncertainty with low and high dynamic range.

The effect of dynamic range on the accuracy of the S12 term can be simulated by using measurement averaging. As can be seen in Figure 3, increasing the averaging increases the dynamic range, which yields almost a four-fold decrease in uncertainty.

HP 85109B NETWORK ANALYZER SYSTEM OVERVIEW

The HP 85109B is a network analyzer system specifically designed for on-wafer measurements of devices and circuits from 45 MHz to 62.5 GHz. This system satisfies all of the above criteria for successful high frequency measurements. Because the HP 85109B system measures higher in frequency than previous systems, it reduces uncertainties resulting from extrapolations of lower frequency data.

The system is based on the high performance HP 8510C and family of test sets and sources (see Figure 4). The system uses an HP 8517A test set for measurements from 45 MHz to 50 GHz and an HP U85104A K09 U-Band test set for measurements from 40 GHz to 62.5 GHz.

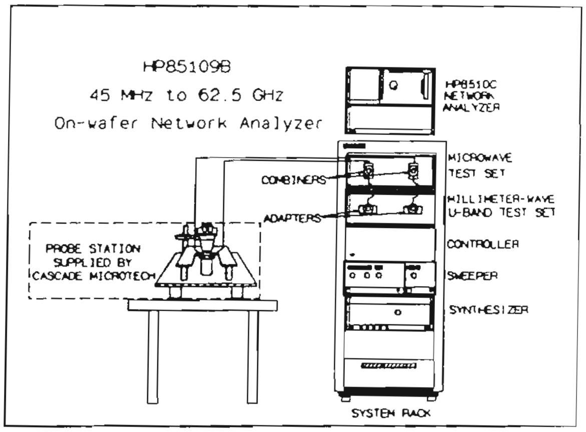


Figure 4: HP 85109B system diagram.

The key to the HP 85109B system is a component that combines the ports of the two test sets. This test port combiner takes the microwave and millimeter wave inputs, sends these signals through a frequency selective coupling structure and provides a single broadband output port. Each output port is then connected to a Cascade Microtech WPH-405 (DC-65GHz) probe through a 1.85mm connector cable.

Control software is provided with the HP 85109B system to change frequency bands, guide the user through a calibration sequence, control one of several possible bias supplies and display a single broadband trace to the HP 8510C.

Calibrations are performed on-wafer by using either the Open-Short-Load-Thru (OSLT), Thru-Reflect-Line (TRL) or Line-Reflect-Match (LRM) calibration techniques. Hewlett-Packard and Cascade Microtech have co-developed the LRM technique and have concentrated on making the on-wafer impedance standard substrates compatible with the HP 8510.

To verify the calibration stability of the HP 85109B system, an LRM calibration was performed and measurements were made on a 0.25μm HEMT FET 15 minutes, 6 hours and 22 hours after calibration. Figure 5 shows minimal variation throughout the 22 hour period. Temperature during the evaluation period was maintained to within approximately +-2 degree Celsius.

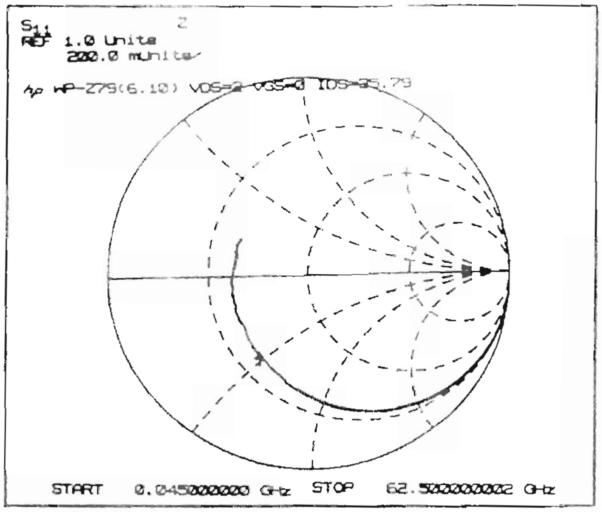


Figure 5: S_{11} measurements of a HEMT FET made 15 minutes, 6 hours and 22 hours after calibration.

APPLICATIONS IN THE MODELLING OF A 0.25μm MODFET

One very important application of broadband millimeter test data is for the characterization and modelling of discrete FETs. In this example, the S-Parameters of a 0.25μm gate length by 122μm gate width MODFET were measured from 45 MHz to 62.5 GHz. The unmatched MODFET showed S_{21} gain of 8.9 dB at 45 MHz, with greater than 0dB up to 61 GHz, as shown in figure 9 on the following page.

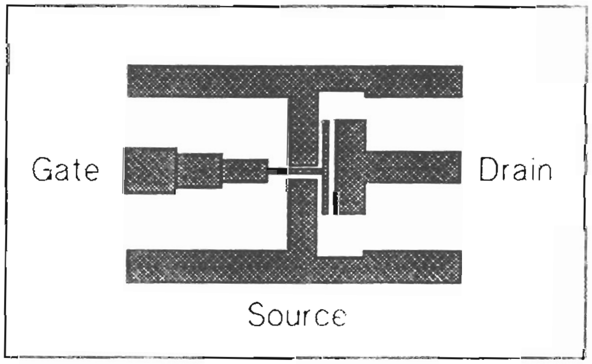


Figure 6: Layout of a 0.25μm T-gate MODFET

The four S-Parameters were then used to calculate the stability factor K, the H_{21} current gain, and the maximum available gain $G_{A\max}$ versus log frequency, using the equations shown below [9].

$$K = \frac{1+|D|^2-|S_{11}|^2-|S_{22}|^2}{2|S_{12}S_{21}|},$$

where $|D|=|S_{11}S_{22}-S_{12}S_{21}|<1$

$$H_{21} = \frac{2S_{12}}{(1-S_{11})(1+S_{22})+S_{12}S_{21}}, \text{ and}$$

$$G_{A\max} = \frac{|S_{21}|}{|S_{12}|}\left(K-\sqrt{K^2-1}\right),$$

for $K > 1$.

The H_{21} plot can be extrapolated to determine that the f_T is approximately 58 GHz. It can also be seen that the FET is not unconditionally stable until about 33 GHz, where the K-factor equals unity. At this point the maximum available power gain can now begin to be calculated. When the $G_{A\max}$ curve has a slope of -20 dB/decade the curve can be extrapolated to determine $f_{\max}$, which is 98 GHz for this FET. The curve, in this case, approaches a slope of -20dB/decade only at frequencies above 40 GHz. It can be clearly seen that measurements from a 62.5 GHz network analyzer system are critical for fitting the $G_{A\max}$ curve accurately.

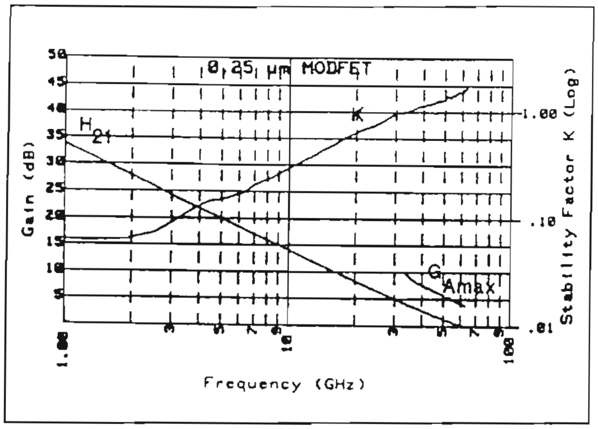
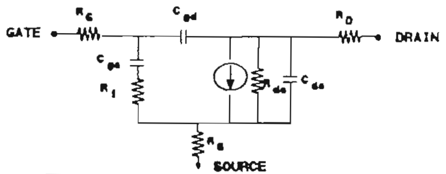


Figure 7: Figures of merit - H21, K-factor and Gma of a 0.25μm MODFET.

The S-Parameter data was also used to extract the small signal model parameters of the MODFET. Results of the parameter extraction are shown below.



Cgs/Wg pF/mm	Cgd/Wg pF/mm	Cds/Wg pF/mm	RiWg Ω-mm	RgdWg Ω-mm	gds/Wg mS/mm	gm/Wg mS/mm	Tau pS
0.98	0.11	0.20	1.30	1.30	24.4	370	0.8

Where Wg = MODFET gate width

Figure 8: Extracted small signal model parameters.

After determining the model parameters, the four S-Parameters were simulated to verify that the model parameters were accurate. Figure 9 shows the very close agreement between measured and modeled S-Parameters.

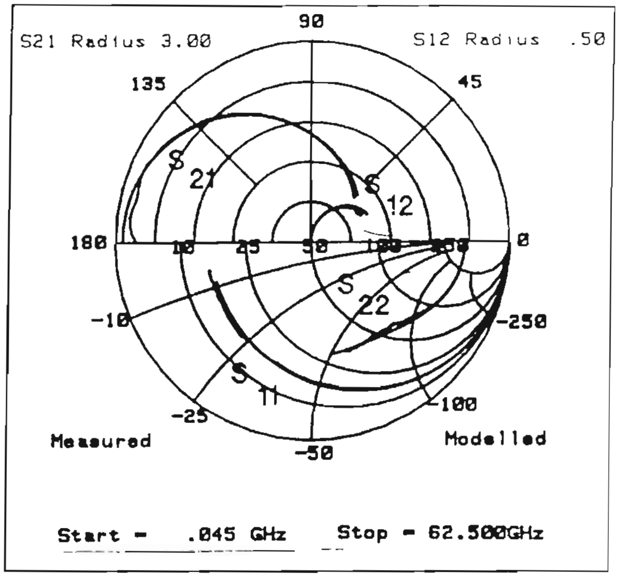


Figure 9: A comparison of measured versus modelled S-parameters.

TRAVELLING WAVE AMPLIFIER CHARACTERIZATION

A second example of the need for a broadband network analyzer system like the HP 85109B system is in the characterization of a broadband MMIC amplifier. In this case, the performance of a 0.5 to 50 GHz GaAs distributed amplifier was measured. This amplifier uses six cascoded 0.25μm gate length by 44μm gate width MODFETs.

The HP 85109B system was used to measure the in- and out-of-band characteristics of the MMIC amplifier. As shown in Figure 10, the amplifier has flat gain (+/-1dB) throughout the design bandwidth. It was also important to measure the out-of-band gain to determine the amount of margin between the upper end of the designed bandwidth and the actual cutoff frequency. This difference provided a feel for how sensitive the performance was to process variations.

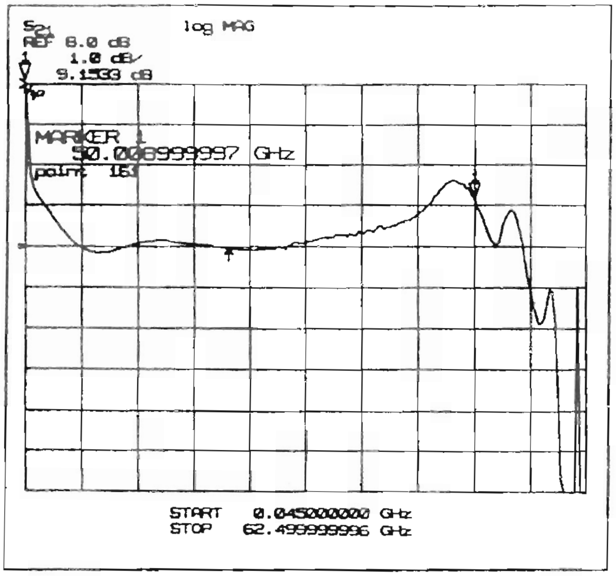


Figure 10: S_{21} gain measurement of the 0.5 to 50 GHz travelling wave amplifier.

Next, the amplifier was measured to determine its sensitivity to gate bias changes. The gate bias was first set to Vgs=-0.6v to achieve maximum gain. The bias was then changed to Vgs=-0.85v. Figure 11 shows that the amplifier maintained the same general S21 shape up to approximately 55 GHz, changing by only approximately 2 dB. Above 55 GHz the amplifier is very sensitive to changes in bias, changing S21 by more than 7 dB. This measurement has determined that the amplifier is insensitive to bias variations within the design bandwidth. However, if the amplifier is to be used above 55 GHz, care should be used to maintain an accurate gate voltage.

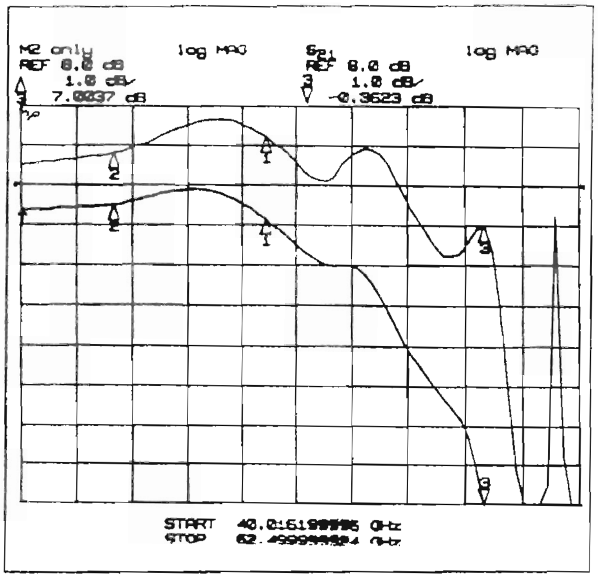


Figure 11: Sensitivity of gain due to a change in gate bias.

The final measurement was made to determine areas of potential oscillation. Oscillations can occur if the output of the amplifier is not well matched to its load. For example, in a typical application, a low pass filter is connected to the output of the amplifier to reduce harmonics. However, since the filter has poor match in its reject band, oscillations can occur due to the re-reflections off of the output of the amplifier. The condition for oscillation to occur is as follows:

$$S_{22amp} \times S_{11filter} > 1$$

Figure 12 shows that the output reflection, S_{22amp} was less than 8.3 dB in the design bandwidth, up to 50 GHz. However, at higher frequencies S_{22amp} approaches 0 dB and there is a potential for oscillation to occur. These oscillations could appear in the operating band as a result of mixing with the intended signal.

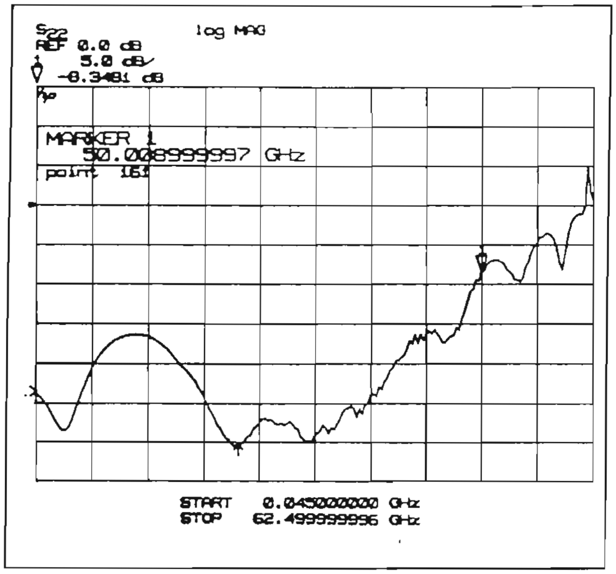


Figure 12: Output reflections reveal potential oscillation problems.

With this useful information, the designer eliminated this problem on the next design iteration. Measurements outside the design band of this amplifier has provided useful feedback of the accuracy of the circuit model and highlighted potential problems with the design.

CONCLUSIONS

As technology has pushed the device and circuit capabilities to higher frequencies, it has become necessary for network analyzer systems to evolve to be able to fully characterize these components. This paper has presented a selection criteria for broadband on-wafer network analyzer systems, namely the need for broad bandwidth, calibration accuracy and versatility, measurement stability, and high dynamic range. The HP 85109B network analyzer system has been applied to characterize a 0.25μm MODFET and a 0.5 to 50 GHz travelling wave amplifier.

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