A Technique for Improving the Accuracy of Wafer Probe Measurements

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ABSTRACT

A technique has been developed to increase the accuracy of wafer probe measurements by identifying the calibration standards as "imperfect." Parasitic effects associated with each standard change their expected characteristics and can cause errors in the calibration data. A computer program is used with a network analyzer to determine the parasitic terms and minimize the measurement error.

INTRODUCTION

Microwave wafer probes have been shown to be an accurate and convenient tool for detailed vector network analysis of monolithic microwave elements and circuits. This accuracy results from the wafer probe system design, network analyzer interface, and the calibration correction and verification of the standards. This paper focuses on the effects of calibration standard specifications on the measurement system.

As with any measurement standard, the verification of its accuracy is related to mathematical modeling of non-ideal characteristics with respect to its physical structure and fundamental properties. Since the microwave wafer probe standards are very small physically, it has been assumed that their non-ideal characteristics are correspondingly small. This assumption is not completely true, and if the standards are not properly verified the system is not calibrated to the probe tips producing measurement errors. The presented method identifies and corrects these errors, verifies the measurement capability, and will demonstrate an improved measurement accuracy for a one port system.

PARASITIC TERM DESCRIPTIONS

For a one port calibration the short, open, and 50 ohm wafer standards (coplanar ground - signal - ground configuration) are used to correct the network analyzer measurement errors. These standards are selected for their ease of fabrication and their ability to calibrate over a very large frequency range. The "imperfect" standards are caused by parasitic effects due to the standards themselves and to the standards when probed. Simple lumped element models are used to describe these effects since the physical size of the standards is much smaller than the signal wavelength. An inductance term is included for the short, a capacitance for the open, and a resistance term and series inductance for the 50 ohm load. A single capacitive term is used to describe the open circuit effects of the standard, and there is no evidence of significant nonlinear capacitance because of the small probe tip size. The inductance terms for the short and load standards dominate the parasitic shunt capacitance from the pads and probes. The load termination is a thin film resistor trimmed at DC to nearly 50 ohms and shows minimal skin effects to 26Ghz. However, if the load used during calibration is not trimmed or done improperly, then the "unknown" resistance term is required. Also, the resistance term of the load significantly effects the convergence properties of the iterative routine (see next section). These four parasitic terms are the variables of the system.

CALIBRATION METHOD

With the standard definitions of the previous section, it is not possible to accurately calibrate the network analyzer since the standards have only a lumped model form with some initial estimated values. The use of an additional standard will provide the solution of the variables and measurement errors. An open circuit stub transmission line is used as the extra standard since its characteristics are assumed known [1]. The line loss should theoretically increase monotonically with frequency and its phase should increase linearly with frequency (first order effects assumed) due to skin effects losses.

For a one port measurement system a three term model is required to describe the measurement errors. The model consists of a directivity error (ED), a frequency response error (ER), and a source match error (ES). These errors are associated with the assumed known reflection characteristics of the standards (open=1 short=-1 load=0). Additional error terms to the error model will represent the discrepancy between the known and actual coefficients as shown in figure 1.

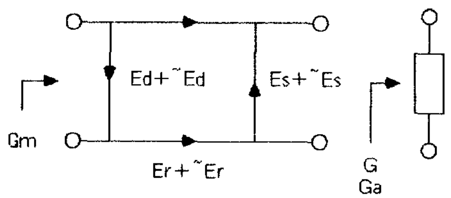

Figure 1 Complete one port error model

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From the figure Gm is the measured reflection coefficient, Ga is the assumed calibration standard, and G represents the actual coefficient. The error terms are related through the following transform:

$$Ga = \frac{Gm-(Ed+\sim Ed)}{(Es+\sim Es)*(Gm-(Ed+\sim Ed))+(Er+\sim Er)} \quad (1)$$

This expression can be applied to each calibration standard and open stub and then factored to produce

$$Gstub = \frac{G1*G2*A + G2*G3*B + G1*G3*C}{G1*(-B) + G2*(-C) + G3*(-A)} \quad (2)$$

where $A=(Gm-Gm3)*(Gm1-Gm2)$
$B=(Gm-Gm1)*(Gm2-Gm3)$
$C=(Gm-Gm2)*(Gm3-Gm1)$

and Gm1,Gm2,Gm3,Gm represent the measured uncorrected responses of the open, short, load, and stub and G1,G2,G3 are the actual coefficients of the calibration standards. Gstub is the calculated response of the stub (all responses are functions of frequency).

Equation (2) describes a transformation of the measured reflection coefficient of the open stub to the actual corrected reflection coefficient including possible errors when incorrect standards are specified. Equation (2) has four unknowns from the standards and requires an iterative minimization routine to solve. The error in the system is the deviations from linear magnitude and phase. A discrete min-max line is "drawn" through the magnitude and phase data to obtain the deviation errors and represents the linear components of the open stub. The objective function is defined as:

$$E=\sum_{i=1}^{N} \{(GMstub-(Gmm*freq(i)+Gcm))/A + (GPstub-(Gpp*freq(i)+Gcp))/B\} \quad (3)$$

where N is the number of points, freq(i) the frequency, Gmm,Gcm,Gpp,Gcp are the slope intercept points of the stub magnitude and phase respectively, E the total error, A and B are scale/weighting factors, and GMstub and GPstub are the magnitude and phase of the stub from equation (2).

The iterative method used to solve equation (3) is a global quasi-Newton model trust region scheme [2]. A global strategy is needed since the algorithm would get "stuck" at some initial starting points. Exact gradient information is calculated and the Hessian (4 x 4 system) is approximated by Broyden's method [2] which is a very efficient procedure. The stopping criterion is based on the relative change in successive values of the variables be less than a step tolerance figure.

After the system has been solved, the actual reflection coefficient information determines the complete error terms at each frequency in Equation(1). The error terms are transferred to the network analyzer, and can be stored for retrieval. The one port measurement is now calibrated and can accurately measure devices under test.

CALCULATED RESULTS

An example of this wafer probe standard method is presented using a Cascade Microtech model 42 wafer probe station with 150 micron wide probes, an HP8510 network analyzer, and an HP310 computer acting as the controller. The program code is written in HP BASIC. A frequency range between 45Mhz and 26.5Ghz with 51 data points is selected. The results of the program iterations are stated in table 1 with the magnitude and phase errors and maximum deviations (DB and degrees).

ITER	M ERR	P ERR	M DEV(DB)	P DEV(DEG)
1	12.663	13.356	.517	12.180
2	3.074	7.041	.297	8.766
3	1.614	4.668	.204	7.753
4	1.129	3.018	.151	5.431
5	1.058	2.992	.160	4.879
6	1.050	2.885	.165	4.696
7	1.079	2.469	.175	4.530
8	1.124	1.680	.182	4.018
9	1.054	.927	.173	3.187
10	1.017	.594	.163	2.174
11	1.037	.341	.158	1.530
12	1.067	.188	.151	1.250
13	1.083	.148	.154	1.140
14	1.082	.149	.153	1.145

Table 1 Results of the Iteration Program

The first iteration corresponds to the assumed reflection coefficients (open=1 short=-1 load=0). The large phase deviation is attributed to the variation from linear characteristics of the stub at higher frequencies. The final values of the variables are shown in table 2 as

Copen = -19.245fF
Lshort = 13.801pH
Rload = 47.425ohm
Lload = 28.817pH

Table 2 Corrected calibration standards

The values in table 2 may have some uncertainty due to linear assumptions about the open stub. Radiative losses and frequency dispersion of the stub exist and add nonlinear effects to the response. These nonlinear effects are being investigated and will be included in the future. The negative COPEN value indicates that the open standard is electrically shorter than the short standard due to different dielectric media of the standards.

Figures 2 and 3 show the stub responses with and with out the correction scheme, respectively. The corrected stub demonstrates a linear change with frequency in magnitude and phase, as predicted.

Figures 4 and 5 describe the deviations from linear magnitude and phase of the stub correction scheme(CWPS) in comparison with a similar, but shorter coplanar line using the line-thru-line (LRL) calibration technique [3]. The LRL required different line lengths to calibrate over the entire frequency band for this example. The figures show that both methods result in accurate wafer probe measurements.

Wafer probe measurements exhibit an additional calibration standard variable due to nonrepeatable probe positioning. Probe placement upon the short reference plane can have a phase variation of approximately +/-8 degrees at 26.5Ghz [4]. This limitation requires the iterative program be used at each network analyzer calibration setting.

The measurement accuracy of the wafer probe network analyzer system can be determined for this example. The uncertainty of the wafer probe calibration method for the one port system is the maximum deviations from linear magnitude and phase over the frequency range. The one port measurement resolution of the HP8510 network analyzer is obtained from reference [5]. The maximum uncertainty of the measurement system is assumed to be the sum of the uncertainties. For the example, this corresponds to an approximate accuracy of 0.41dB in magnitude and 2.7 degrees in phase (for low to high reflective devices under test) to 26.5 Ghz. This is an improvement from 0.75dB in magnitude and 13.7 degrees in phase from the initial assumed reflection of the standards.

CONCLUSION

The correction scheme for the wafer probe measurement system provides a superior increase in the accuracy capability. This improvement results from a better understanding and characterization of the calibration standards. A procedure is developed to minimize deviations from linear magnitude and phase of the one port measurement system using a fourth standard whose characteristics are assumed known. After the iterative program converges, values for the standards are calculated. The stub response can then be determined and demonstrates a linear variation with frequency. This result verifies the method, calibration standards, and measurement accuracy of the system.

ACKNOWLEDGEMENT

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REFERENCES

(1) Cascade Microtech Model 42 Probe Station Operating Manual, 1987.

(2) Numerical Methods for Unconstrained Optimization and Nonlinear Equations, J. E. Dennis and R. B. Schnabel, Prentice-Hall,Inc., 1983.

(3) G. F. Engen and C. A. Hoer, "Thru-Reflect-Line: An Improved Technique for Calibrating the Dual Six-Port ANA.", IEEE Trans. MTT, vol. MTT-27, pp.987-993, Dec. 1979.

(4) E. W. Strid, "26 Ghz Wafer Probing for MMIC Development and Manufacture.", Microwave Journal, August 1986.

(5) Bruce Donecker, "Determining the Measurement Accuracy of the HP8510 Microwave Network Analyzer.", HP RF and Microwave Symposium and Exhibition.

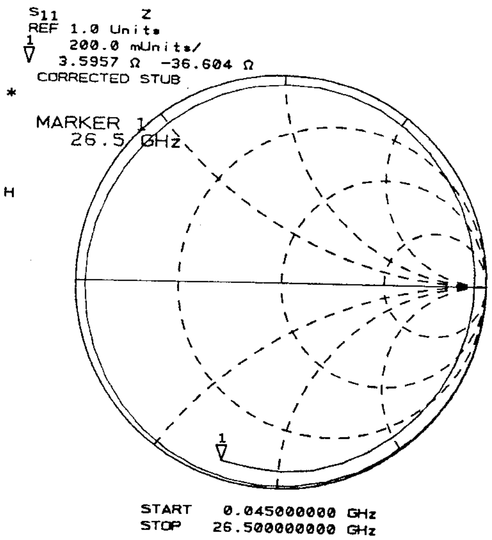

Figure 2 Stub response with the correction scheme.

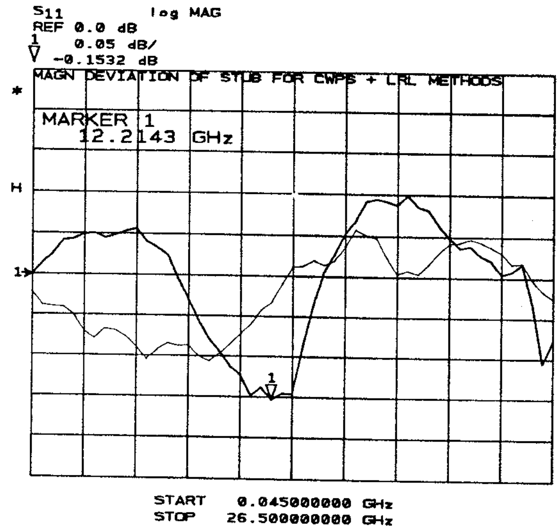

Figure 4 Deviation from linear magnitude of the CPWS and the LRL (lighter trace) methods.

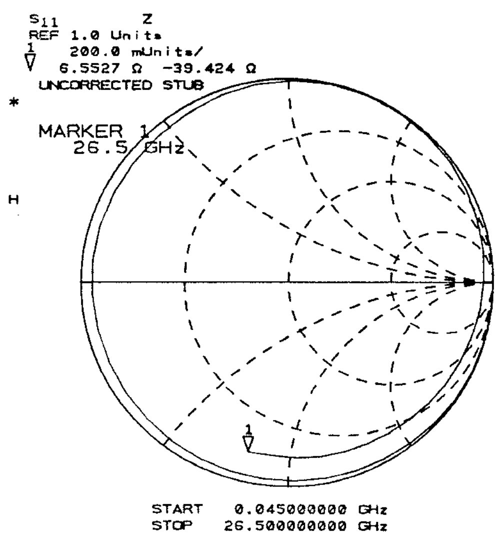

Figure 3 Stub response without the correction scheme.

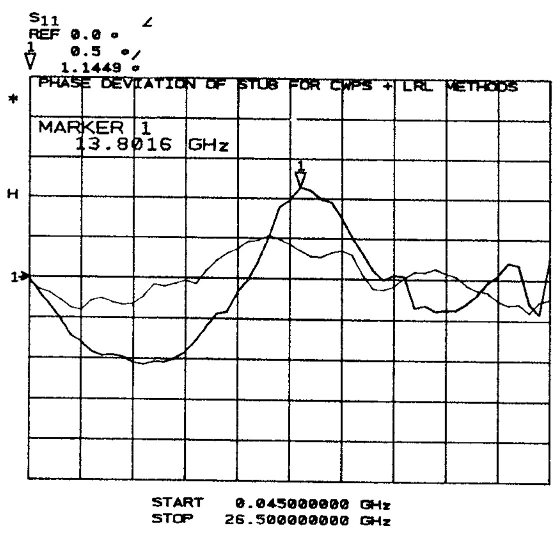

Figure 5 Deviation from linear phase of the CPWS and the LRL (lighter trace) methods.