16-TERM ERROR MODEL AND CALIBRATION PROCEDURE FOR ON WAFER NETWORK ANALYSIS MEASUREMENTS

John V.Butler, Doug Rytting*, Magdy F. Iskander, Roger Pollard**, and Marc Vanden Bossche***

Electrical Engineering Department
University of Utah
Salt Lake City, Utah 84112

ABSTRACT

Vector network measurements are enhanced by calibrating the measurement system at the device under test interface. Many measurement systems such as MMIC wafer probes contain leakage and coupling error terms not modeled in current calibration systems. In this paper, all possible error terms are included in a new 16-term error model and calibration procedure. Corrected measurements using the new 16-term calibration procedure are compared with TRL calibration measurements and excellent agreement was observed.

INTRODUCTION

The accuracy and usefulness of the Vector Network Analyzer (VNA) is enhanced by calibrating the measurement system at the device under test (DUT) interface. The calibration should be capable of providing a repeatable representation of the measurement system and account for most of the system errors. A large number and variety of error models and calibration procedures have been proposed to date. These include the 12-term error model, TRL, TSD, and others [1-3]. Although these models are accurate for many measurement systems, they include only a portion of the possible errors in a measurement system and do not include many of the leakage and coupling terms often encountered in MMIC measurements.

In a MMIC wafer probing systems, the wafer probes utilize open air fixtures which contain leakage and coupling errors not modeled and accounted for in the 12-term or other models. Consequently, for accurate MMIC measurements, it is necessary to include these new leakage terms.

* Dr. Doug Rytting is with the Network Measurement Division, Hewlett Packard, Santa Rosa, California.

** Dr. Roger Pollard is with the University of Leeds, Leeds LS2 9JT, U.K.

*** Dr. Marc VanDen Bossche is with the Brussels Division, Hewlett Packard, Brussels, Belgium.

It is the purpose of this paper to present a new calibration procedure which includes all of the possible errors in an open air fixture such as a MMIC device. In the case of a two-port network, this extends to 16-terms. The 16-term model will allow fixtures that have poor grounding and numerous cross-talk paths to be accurately calibrated. This paper will investigate the theory, and methods used to solve the 16-term error model system, as well as results obtained from this model.

PROCEDURE

For a two-port measurement the 16-term S-parameter error model is shown in Fig. 1. As shown the dotted error terms represent the cross-talk paths of which six-terms are not accounted for in the 12-term error model. Using flowgraph analysis, the error adapter is depicted in matrix form as

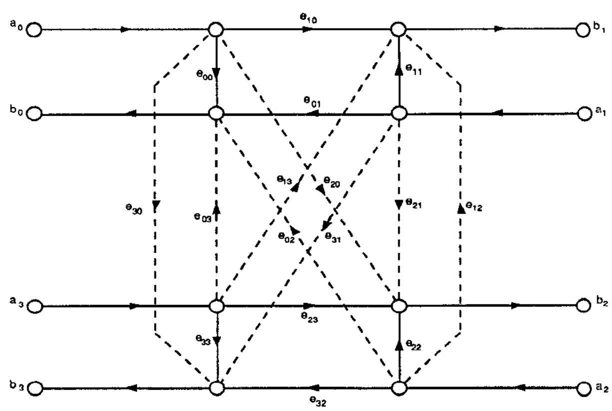


Figure 1 - 16 term error adapter

$$\begin{bmatrix} b_0 \\ b_3 \\ b_1 \\ b_2 \end{bmatrix} = [E] \begin{bmatrix} a_0 \\ a_3 \\ a_1 \\ a_2 \end{bmatrix}, \quad [E] \triangleq \begin{bmatrix} E_1 & E_2 \\ E_3 & E_4 \end{bmatrix} = \begin{bmatrix} e_{00} & e_{03} & e_{01} & e_{02} \\ e_{30} & e_{33} & e_{31} & e_{32} \\ e_{10} & e_{13} & e_{11} & e_{12} \\ e_{20} & e_{23} & e_{21} & e_{22} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} b_0 \\ b_3 \end{bmatrix} = [S_m] \begin{bmatrix} a_0 \\ a_3 \end{bmatrix}, \quad [S_m] = \begin{bmatrix} S_{11m} & S_{12m} \\ S_{21m} & S_{22m} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = [S_A] \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}, \qquad [S_A] = \begin{bmatrix} S_{11A} & S_{12A} \\ S_{21A} & S_{22A} \end{bmatrix} \tag{3}$$

By applying the definitions of the measured S-paramters $[S_m]$ and the actual S-paramters $[S_A]$ to (1) and applying linear algebra operations, a relationship between $[S_A]$, $[S_m]$, and the error matrix [E] is obtained as (4) and (5). Equation (5), however, is non-linear in the error terms thus making it difficult to solve for the error terms in terms of calibration standards.

$$[S_m] = [E_1] + [E_2][S_a]([I] - [E_4][S_a])^{-1}[E_3] \tag{4}$$

$$[S_a] = \{[E_3]([S_m] - [E_1])^{-1}[E_2] + [E_4]\}^{-1} \tag{5}$$

On the other hand, by using cascading T-parameters to represent the error terms, an easier solution may be obtained. The error system can be represented in terms of T-parameters as

$$\begin{bmatrix} b_0 \\ b_3 \\ a_0 \\ a_3 \end{bmatrix} = [T] \begin{bmatrix} a_1 \\ a_2 \\ b_1 \\ b_2 \end{bmatrix}, \quad [T] \triangleq \left[\begin{array}{c|c} T_1 & T_2 \\ \hline T_3 & T_4 \end{array}\right] = \left[\begin{array}{cc|cc} t_{00} & t_{01} & t_{04} & t_{05} \\ t_{02} & t_{03} & t_{06} & t_{07} \\ \hline t_{08} & t_{09} & t_{12} & t_{13} \\ t_{10} & t_{11} & t_{14} & t_{15} \end{array}\right] \tag{6}$$

Again, by applying the definitions of [Sm] and [Sa] to (6), and applying linear operations, The following relationships between [Sm], [Sa], and [T] are obtained.

$$[S_m] = ([T_1][S_a] + [T_2])([T_3][S_a] + [T_4])^{-1} \tag{7}$$

$$[T_1][S_a] + [T_2] - [S_m][T_3][S_a] - [S_m][T_4] = [0] \tag{8}$$

$$[S_a] = ([T_1] - [S_m][T_3])^{-1}([S_m][T_4] - [T_2]) \tag{9}$$

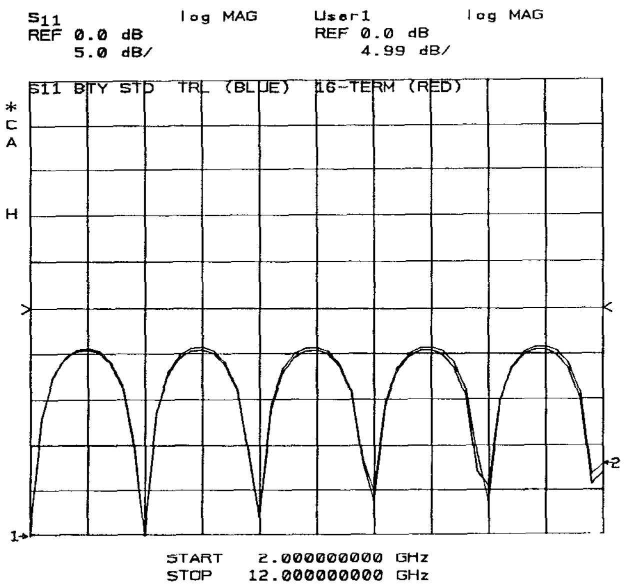
We note that (8) is set of four homogeneous equations that are linear in the entries of the T-error matrix. By using "**four**" different two-port standards, enough equations are generated to solve the "sixteen" T-error terms.

The homogeneous system of equations can be solved by normalizing the equations to one of the T-terms or effectively dividing each T-term by one of the T-terms, preferably one whose magnitude is close to one. This will effectively reduce the number of unknowns by one and leave a constant column which can then be used as a B vector on the right side. Thus, the homogeneous system **AT = 0** is transformed to a non-homogeneous system **A'T' = B'** leaving a system of 16 equations and 15 unknowns which can now be solved in a least squares sense. Once [T] is solved, equation (9) can then be used to determine an unknown device under test (DUT) from its measured S-parameters $[S_m]$.

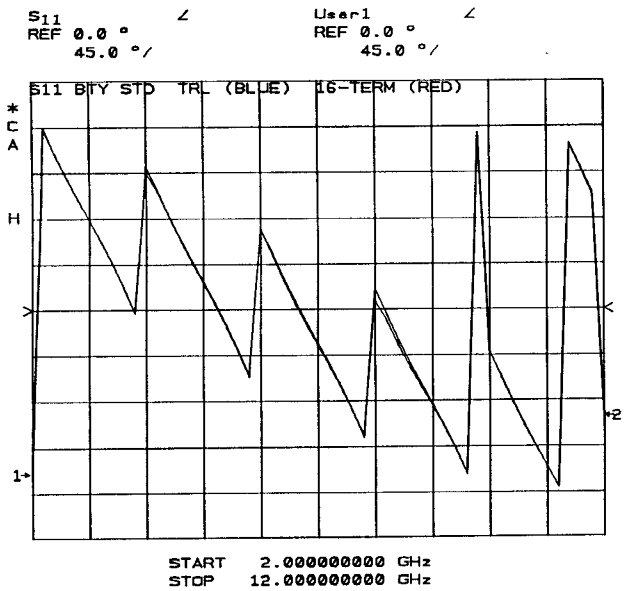
SIMULATION AND MEASUREMENT RESULTS

For verification of the 16-term model theory and calibration procedure, the 16-term calibration procedure was first simulated and then implemented on the HP 8510B via HP-IB communication to an external controller. First extensive simulations were performed to verify the accuracy of the new procedure. Then a 51-point calibration was performed on HP8510B from 2 to 12 GHz on a 7 mm coaxial measurement system. Two different verification standards, a 20 dB attenuator and a dual impedance airline, were used. These corrected measurement obtained from the 16-term calibration were then compared to measurements made using a TRL calibration of the same measurement system.

The 16-term measurements corresponded very well to the TRL measurements as shown in Fig. 2. The phase measurements can be hardly distinguished in Fig. 2b. It thus confirms the validity of the 16-term error model system and calibration procedure developed in this paper. There was, however, a slight difference in the measurements. This difference could be due to the fact that in this coaxial measurement system, many of the leakage terms in the system are below the noise and systematic errors in the system. By including these terms in our calculations, another source of systematic error is introduced causing errors in the resulting measurements.



(a) Magnitude



(b) Phase

Fig. 2. Comparison of results from the new 16-term calibration procedure vs. TRL measurements. The DUT is a dual-impedance air line.

CONCLUSIONS

The 16-term error model and calibration procedure were successfully developed, simulated, and implemented on the HP 8510B. It provides a very "general" model and method for characterizing all of the possible errors in the error adapter. Good results were obtained in both simulation and measurements showing the validity of the 16-term error model. Efforts are under way to test the results using a wafer probe measurement system. Results of these recent efforts will also be presented. The new calibration procedure provides an accurate network analysis of MMIC devices taking into account the leakage terms.

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