A Three-Port Vector Network Analyzer – Measurement System, Calibration and Results

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Abstract — **In this paper a practical three-port vector network analyzer (TVNA) measurement system with its calibration procedures, and results are presented. With this TVNA, the three-port device scattering matrix can be directly measured by using a test fixture or a probe station. It can then reduce the repeatability problem occurred in the use of conventional two-port vector network analyzer by connecting and disconnecting matched load at the different ports of a three-port device. The three-port TRL and LRM calibration procedures are developed and verified with the coaxial circuits. In addition, a three-port SOLR calibration procedure is developed for on-wafer measurement of a three-port MMIC with three orthogonal-oriented pads.**

I. INTRODUCTION

Two-port vector network analyzer is a well-known two-port scattering matrix measurement system and is commercially available, for example HP8510C. For multi-port scattering matrix measurement, one approach is to use a two-port network analyzer by terminating all other ports with matched loads. However, in the high frequency range the perfect load is not available. One may then use renormalization method [1,2], or port reduction method [3,4] to calculate the correct multi-port scattering matrix from the two-port network analyzer measurement with imperfect loads. The other approach for multi-port scattering matrix measurement is to directly use a multi-port vector analyzer as described by Ferrero [5].

In this paper, we modify Ferrero's multi-port network analyzer arrangement to be a practical three-port vector network analyzer and use all commercially available products. The associated three-port TRL (thru-reflect-line) and LRM (line-reflect-match) calibration procedures are described in Section III.A for coaxial or microstrip type DUT (device under test). However, for calibrating a three-port MMIC type DUT, two orthogonal-oriented wafer probes are used to contact a 90° "through" in the calibration. This 90° bent discontinuity may introduce undesired transmission line modes and give significant errors. A three-port SOLR (short-open-load-reciprocal) calibration procedure, which does not require a known "ideal through" standard, is then developed for the three-port MMIC measurement.

II. MEASUREMENT SYSTEM

The measurement system block diagram is shown in Fig.1. It mainly employs an HP8511A four-channel frequency down converter for the three-port scattering matrix measurement. The RF signal from an HP83615B synthesized sweeper is redirected through HP8511A to the selected input port of a DUT test fixture by a SP4T coaxial switch under the control of an HP34970 multiplexer. Each of the test fixture three ports is connected to a RHC OMH2-18 3 dB hybrid, which the operation frequency range is about from 2 to 18 GHz. The coupled port of each hybrid is then connected to the channel b_1, b_2 or b_3 of HP8511A. The channel a_1 is a reference channel for system phase locking. The IF signals from HP8511A are received by the HP85102 IF section for A/D conversion and the HP85101 for signal processing and display. The measurement system is linked with a Sun Ultra-1 workstation for automated instrument control, data acquisition and system calibration.

III. BASIC PRINCIPLE AND CALIBRATION PROCEDURES

Shown in Fig.2 is the error model of a three-port network analyzer. Under the assumption of no leakage between any port, there are three error matrices connected between an ideal three-port vector network analyzer and the DUT. Each matrix $\boldsymbol{E_i}$ with i = 1, 2, 3 contains the errors of switch, mismatch loss and frequency response… etc., and it is defined by

$$\boldsymbol{E_i} = \begin{bmatrix} e_i^{00} & e_i^{01} \\ e_i^{10} & e_i^{11} \end{bmatrix}. \quad (1)$$

The measured signals a_{mi}, b_{mi} and the actual signals a_i, b_i of DUT are then expressed as

$$\begin{bmatrix} b_{m1} \\ b_{m2} \\ b_{m3} \end{bmatrix} = \begin{bmatrix} e_1^{00} & 0 & 0 \\ 0 & e_2^{00} & 0 \\ 0 & 0 & e_3^{00} \end{bmatrix} \begin{bmatrix} a_{m1} \\ a_{m2} \\ a_{m3} \end{bmatrix} + \begin{bmatrix} e_1^{01} & 0 & 0 \\ 0 & e_2^{01} & 0 \\ 0 & 0 & e_3^{01} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \quad (2)$$

and

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} e_1^{10} & 0 & 0 \\ 0 & e_2^{10} & 0 \\ 0 & 0 & e_3^{10} \end{bmatrix} \begin{bmatrix} a_{m1} \\ a_{m2} \\ a_{m3} \end{bmatrix} + \begin{bmatrix} e_1^{11} & 0 & 0 \\ 0 & e_2^{11} & 0 \\ 0 & 0 & e_3^{11} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \quad (3)$$

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or $\boldsymbol{b_m} = \boldsymbol{\Gamma_{00}a_m} + \boldsymbol{\Gamma_{01}a}$, $\boldsymbol{b} = \boldsymbol{\Gamma_{10}a_m} + \boldsymbol{\Gamma_{11}a}$ in matrix form. After a proper matrix manipulation, the three-port scattering matrix $\boldsymbol{S}$ of DUT is given as

$$\boldsymbol{S} = \boldsymbol{A}(\boldsymbol{I} + \boldsymbol{\Gamma_{11}A})^{-1}, \tag{4}$$

where $\boldsymbol{I}$ is a unit matrix, and

$$\boldsymbol{A} = \boldsymbol{\Gamma_{01}^{-1}}(\boldsymbol{S_m} - \boldsymbol{\Gamma_{00}})\boldsymbol{\Gamma_{10}^{-1}} \tag{5}$$

or

$$\boldsymbol{A} = \begin{bmatrix} \frac{S_m^{11} - e_1^{00}}{e_1^{01}e_1^{10}} & \frac{S_m^{12}}{e_1^{01}e_2^{10}} & \frac{S_m^{13}}{e_1^{01}e_3^{10}} \\ \frac{S_m^{21}}{e_2^{01}e_1^{10}} & \frac{S_m^{22} - e_2^{00}}{e_2^{01}e_2^{10}} & \frac{S_m^{23}}{e_2^{01}e_3^{10}} \\ \frac{S_m^{31}}{e_3^{01}e_1^{10}} & \frac{S_m^{32}}{e_3^{01}e_2^{10}} & \frac{S_m^{33} - e_3^{00}}{e_3^{01}e_{31}^{10}} \end{bmatrix}. \tag{6}$$

(4) and (5) show that the corrected scattering matrix $\boldsymbol{S}$ of DUT can be directly calculated from the measured $\boldsymbol{S_m}$ and the error matrices $\boldsymbol{\Gamma_{ij}}$ with $i, j = 0, 1$. Note (6) has the same result as in [6] by reducing the n-port matrix to a three-port matrix. In the following, the conventional two-port TRL, LRM and SOLR calibration methods are extended for the three-port scattering matrix calibration.

A. Three-port TRL and LRM Calibration Procedures

The three-port TRL and LRM calibration procedures to acquire the error matrix $\boldsymbol{\Gamma_{ij}}$ are described as the following.

(a) Use two-port TRL or LRM calibration method for port 1 and port 2 to acquire the error coefficients of e_i^{00}, e_i^{11}, $e_i^{10}e_j^{01}$ $i, j = 1, 2$.

(b) Connect an ideal zero length "through" between port 1 and port 3 to measure the two-port scattering matrix $\boldsymbol{S^{m13}}$, then calculate the error coefficients e_3^{11}, e_3^{00}, $e_1^{10}e_3^{01}$, $e_1^{01}e_3^{10}$.

(c) Calculate the error coefficients $e_3^{10}e_2^{01}$, $e_3^{01}e_2^{10}$ from the error coefficients obtained from steps (a) and (b).

(d) Based on the results of steps (a) to (c), the error matrix $\boldsymbol{A}$ is determined. The corrected three-port device scattering matrix can then be calculated.

B. Three-port SOLR Calibration Procedure

The SOLR calibration method given in [7,8] uses a reciprocal standard with $S_{12R} = S_{21R}$ for calibration to relax the requirement of a known "through" standard. The following three-port SOLR calibration procedure can then eliminate the difficulty for probing a MMIC type DUT with three orthogonal-oriented pads. The calibration procedure to acquire the error matrix $\boldsymbol{\Gamma_{ij}}$ is described as the following.

(a) Use two-port SOL calibration method for ports 1, 2 and 3 to acquire the error coefficients of e_i^{00}, e_i^{11} and, $e_i^{10}e_i^{01}$, $i = 1, 2, 3$.

(b) Connect a reciprocal "through" between port 1 and port 2 to measure the two-port scattering matrix $\boldsymbol{S^{m12}}$, and its transmission elements are

$$S_{21}^{m12} = \frac{e_1^{10}S_{21R}e_2^{01}}{1 - e_1^{11}S_{11R} - e_2^{11}S_{22R} - e_1^{11}e_2^{11}(S_{11R}S_{22R} - S_{21R}S_{12R})}, \tag{7}$$

$$S_{12}^{m12} = \frac{e_1^{01}S_{12R}e_2^{10}}{1 - e_1^{11}S_{11R} - e_2^{11}S_{22R} - e_1^{11}e_2^{11}(S_{11R}S_{22R} - S_{21R}S_{12R})}. \tag{8}$$

Using $S_{12R} = S_{21R}$, the error coefficients $e_1^{01}e_2^{10}$, $e_1^{10}e_2^{01}$ can be solved as

$$e_1^{01}e_2^{10} = \pm\sqrt{\frac{(e_1^{10}e_1^{01})(e_2^{10}e_2^{01})}{S_{21}^{m12}/S_{12}^{m12}}}, \tag{9}$$

and

$$e_1^{10}e_2^{01} = \frac{S_{21}^{m12}}{S_{12}^{m12}}e_1^{01}e_2^{10}. \tag{10}$$

The sign ambiguity in (9) can be determined by measuring a given length of "through" with phase delay less than 180°

(c) Similarly as in step (b), connect a reciprocal "through" between port 1 and port 3 to measure the two-port scattering matrix $\boldsymbol{S^{m13}}$, then solve $e_1^{01}e_3^{10}$ and $e_1^{10}e_3^{01}$.

(d) Calculate error coefficients $e_3^{10}e_2^{01}$, $e_3^{01}e_2^{10}$ from the error coefficients obtained from steps (a) and (c).

(e) Based on the results of step (a) to (d), the error matrix $\boldsymbol{A}$ is determined.

IV. System Verification and Measurement Results

The first example is to measure a 16dB coaxial-type directional coupler (Omni Spectra 2026-6006-16) with three-port LRM calibration method. The results given in Fig.3 are shown in good agreement with the measured results in Fig.4 using HP8510C (two-port VNA) with SOLT calibration method. A dual-gate MESFET (DGMESFET) with 1um gate length and 300um gate width as shown in Fig.5 is then measured. Note its gate 1 (port 1) and gate 2 (port 2) are in the "east-west" orientation, while the drain (port 3) is in the "north" direction. In the calibration step (b) given in Sec. III.B, a Cascade ISS GSG straight "through" with length 200um is connected between port 1 and port 2. Then, a GSG right-angle bent "through" is used in the calibration step (c) for port 1 and port 3. The port 3 uses a right angle arm probe.

Fig.6 shows the measured DGMESFET three-port scattering matrix from 1.5 to 11.5GHz.

V. Conclusion

In this paper, the basic principle, measurement arrangement and calibration procedure of an automated three-port vector network analyzer are described. The measurement results show that the scattering matrix of a three-port device can be directly and accurately measured. This not only improves the repeatability problem encountered in using two-port network analyzer for the three-port scattering matrix measurement, but also gives more physical results as the test device is operated in a three-port mode such as a coplanar dual-gate MESFET.

Acknowledgement

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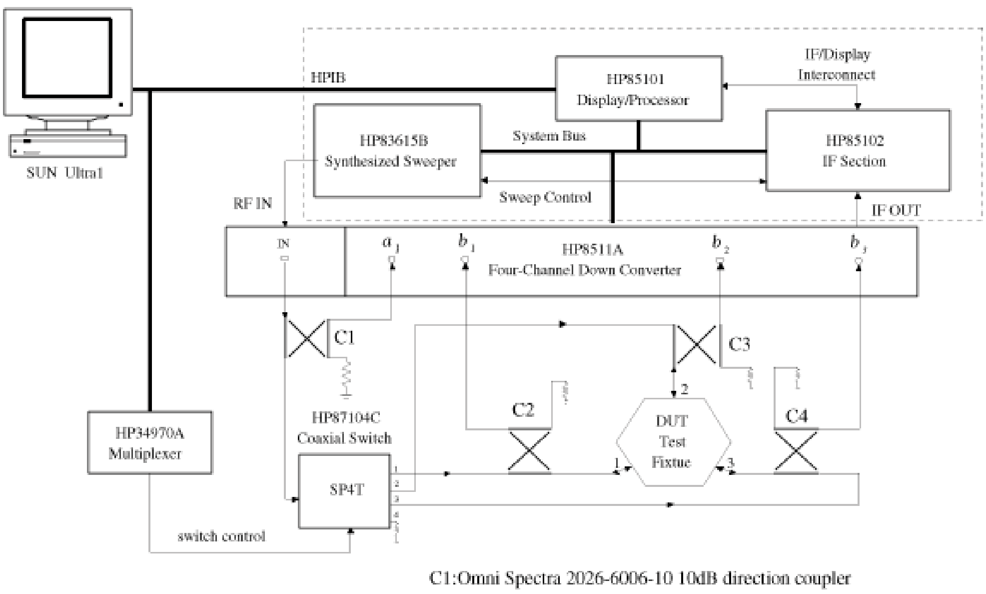

Fig.1 Block diagram of an automated three-port vector network analyzer (TVNA).

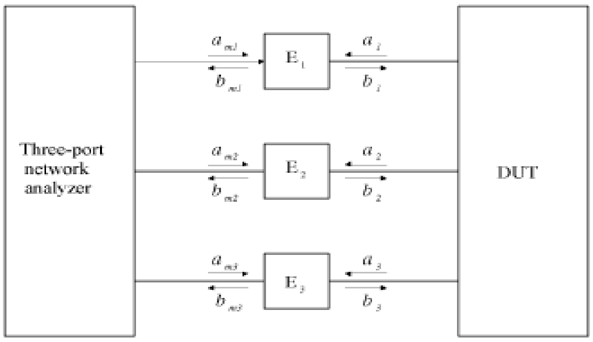

Fig.2 Error model of three-port network analyzer.

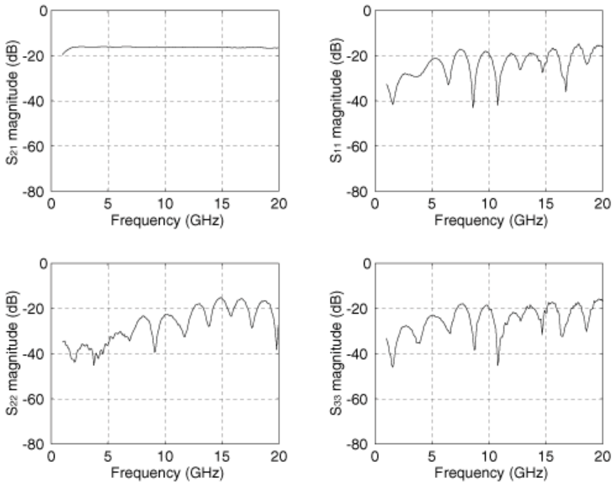

Fig.3 Measured results of a 16 dB directional coupler using TVNA with three-port LRM calibration method from 1 to 20 GHz.

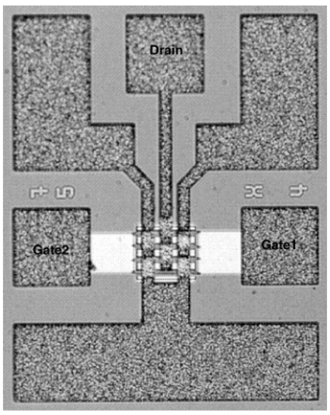

Fig.5 Photograph of a dual-gate MESFET.

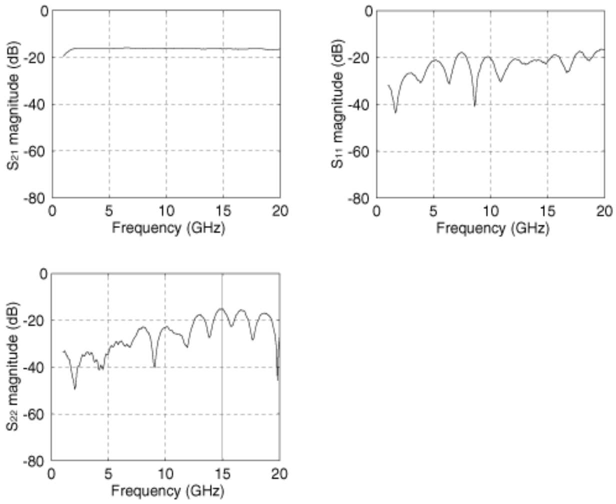

Fig.4 Measured results of a 16 dB directional coupler using HP-8510C with two-port SOLT calibration method from 1 to 20 GHz. (Note the scattering parameters related to port 3 are not shown, because a 50Ω load is connected at port 3 in the measurement.)

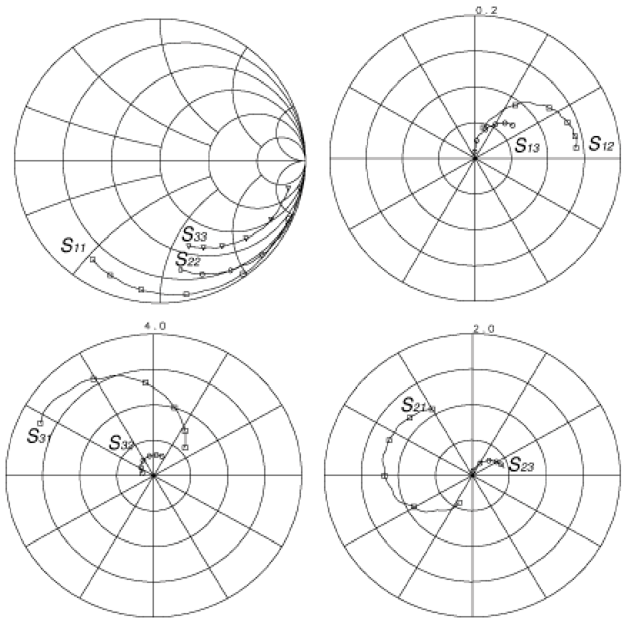

Fig.6 Measured results of the three-port scattering matrix of a dual-gate MESFET with V_{DS} = 3V, V_{G1S} = -0.4 V, V_{G2S}=2 V and I_{DS}=15.1 mA.

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