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Two-Port Network Analyzer Calibration Using an Unknown "*Thru*"

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***Abstract*—A procedure performed by using a generic two port reciprocal network instead of a standard *thru* in a full two-port error correction of an automatic network analyzer is presented. Although it can be applied to any type of waveguide system the proposed technique is particularly useful with noninsertable coaxial or on-wafer devices. Experimental comparisons show that the suggested procedure provides a great degree of accuracy.**

I. Introduction

To the authors' knowledge, all the present known calibration procedures up today proposed [1]-[8] are based on the full knowledge of at least one two port network, usually called *thru* standard, used to connect the NWA ports.

Unfortunately in many applications this *thru* standard can not be completely known. As examples let us consider the case of a two port device with connectors of the same sex or on-wafer devices with not aligned ports.

The calibration technique here presented does not require any particular *thru* knowledge. The procedure is based on the classic "full two-port" technique, where any reciprocal two-port can be used as *thru* standard. The only requirements of this *undefined thru* are its reciprocity and a rough knowledge of its S_{21} phase shift.

As a consequence, if the device under test (DUT) is itself reciprocal, the reciprocal standard is unnecessary, and the DUT can, in effect, serve as its own calibration standard.

The following sections present the theory of the calibration, in the following called RSOL (reciprocal short open load), and some experimental results carried out to verify its effectiveness.

II. The Calibration Theory

It is well known that an actual two port S-parameter test set [3], can be seen as an ideal two-port reflectometer, which measures the raw scattering matrix $\boldsymbol{S}_m$, plus two error boxes E_A, E_B between the ideal measurement ports and the DUT reference planes as shown in Fig. 1.

The error boxes are characterized by the following scattering matrices:

$$\boldsymbol{E}_A = \begin{bmatrix} e_A^{00} & e_A^{01} \\ e_A^{10} & e_A^{11} \end{bmatrix} \qquad \boldsymbol{E}_B = \begin{bmatrix} e_B^{00} & e_B^{01} \\ e_B^{10} & e_B^{11} \end{bmatrix}.$$

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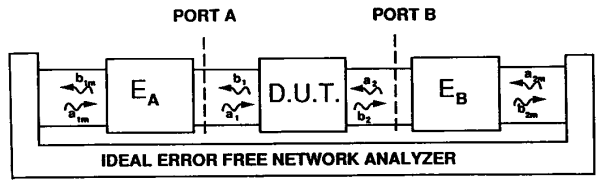

Fig. 1. Error box NWA model.

Let us define the matrices:

$$\boldsymbol{Y}_A = \begin{bmatrix} -\dfrac{\Delta_A}{t_{11}} & \dfrac{e_A^{00}}{t_{11}} \\ -\dfrac{e_A^{11}}{t_{11}} & \dfrac{1}{t_{11}} \end{bmatrix}, \tag{1}$$

$$\boldsymbol{Y}_B = \begin{bmatrix} \dfrac{1}{t_{22}} & -\dfrac{e_B^{11}}{t_{22}} \\ \dfrac{e_B^{00}}{t_{22}} & -\dfrac{\Delta_B}{t_{22}} \end{bmatrix}, \tag{2}$$

where $t_{11} = e_A^{01}e_A^{10}$, $t_{22} = e_B^{01}e_B^{10}$, $\Delta_A = (e_A^{00}e_A^{11} - e_A^{10}e_A^{01})$ and $\Delta_B = (e_B^{00}e_B^{11} - e_B^{10}e_B^{01})$.

The transmission matrix $\boldsymbol{T}_m$ computed by the measured scattering matrix $\boldsymbol{S}_m$ is:

$$\boldsymbol{T}_m = \begin{bmatrix} \dfrac{-\det \boldsymbol{S}_m}{S_{m21}} & \dfrac{S_{m11}}{S_{m21}} \\ -\dfrac{S_{m22}}{S_{m21}} & \dfrac{1}{S_{m21}} \end{bmatrix}. \tag{3}$$

It can be easily verified that among the defined matrices and the device under test transmission matrix ($\boldsymbol{T}_{\mathrm{DUT}}$) the following equation stands:

$$\boldsymbol{T}_m = \alpha \boldsymbol{Y}_A \boldsymbol{T}_{\mathrm{DUT}} \boldsymbol{Y}_B^{-1}, \tag{4}$$

where

$$\alpha = \frac{e_A^{01}}{e_B^{01}}. \tag{5}$$

From (4), it follows

$$\boldsymbol{T}_{\mathrm{DUT}} = \alpha^{-1} \boldsymbol{Y}_A^{-1} \boldsymbol{T}_m \boldsymbol{Y}_B. \tag{6}$$

The aim of the calibration procedure is to obtain $\boldsymbol{Y}_A$, $\boldsymbol{Y}_B$ and α from the measurements of a sufficient number of calibration standards.

The matrices $\boldsymbol{Y}_A$ and $\boldsymbol{Y}_B$ are derived from one-port calibration procedures carried out at both ports. As well known,

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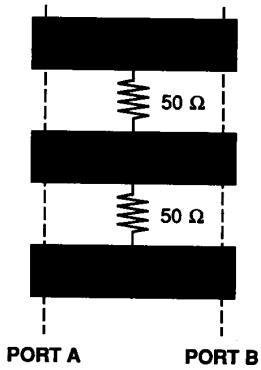

Fig. 2. CPW device used as reciprocal *unknown thru* for calibration.

the reflection coefficient measured at port A is

$$\Gamma_{mA} = e_A^{00} + \frac{e_A^{10} e_A^{01} \Gamma_A}{1 - e_A^{11} \Gamma_A}. \tag{7}$$

By measuring three standards (usually an open, a short and a load), connected at port A, three error coefficients, e_A^{00}, e_A^{11}, and $\Delta_A = e_A^{00} e_A^{11} - e_A^{10} e_A^{01}$, are evaluated by rearranging the (7); consequently the matrix $\boldsymbol{Y}_A$ is completely known.

The same procedure can be applied at port B, giving e_B^{00}, e_B^{11}, and $\Delta_B = e_B^{00} e_B^{11} - e_B^{10} e_B^{01}$, hence the matrix $\boldsymbol{Y}_B$ results. Any reciprocal unknown two port network, used as *thru*, can provide the information to obtain α. Because the reciprocity, the transmission matrix of the *unknown thru* has an unitary determinant. From (4), it follows

$$\det \boldsymbol{T}_m = \alpha^2 \det \boldsymbol{Y}_A (\det \boldsymbol{Y}_B)^{-1}, \tag{8}$$

therefore,

$$\alpha = \pm \sqrt{\frac{\det \boldsymbol{T}_m \det \boldsymbol{Y}_B}{\det \boldsymbol{Y}_A}}. \tag{9}$$

The α sign ambiguity can be solved as follows. Let

$$\boldsymbol{X} = \boldsymbol{Y}_A^{-1} \boldsymbol{T}_m \boldsymbol{Y}_B, \tag{10}$$

which is fully known from the one-port calibrations and the measured matrix $\boldsymbol{T}_m$ of the *unknown thru*, from (6) the scattering parameter $S_{21\,thru}$ becomes

$$S_{21\,thru} = \frac{\alpha}{X_{22}}. \tag{11}$$

A simple roughly knowledge of the *unknown thru* S_{21} phase shift ($\leq 180°$) allows to solve the α sign ambiguity.

III. Experimental Results

Several tests of measurement compatibility were carried out between RSOL and other well-known calibration techniques. Due to space limitations is presented only a comparison between LRM and RSOL. An on-wafer CPW 40-ps verification line built by CASCADE Microtech was measured.

The RSOL calibration uses as *unknown thru* the device shown in Fig. 2, while the LRM is carried out with the usual 1-ps standard thru line.

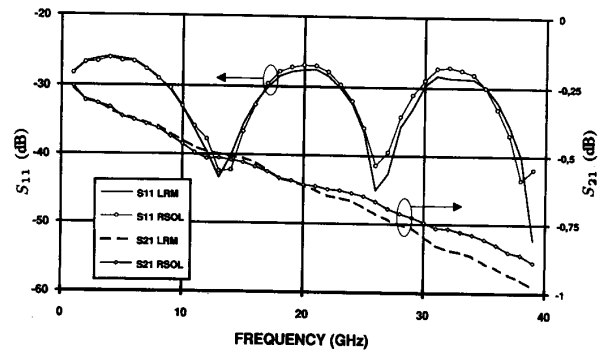

Fig. 3. Comparison between RSOL and LRM on a 40-ps CPW delay line.

The forward (S_{11} and S_{21}) scattering parameter amplitudes are shown in Fig. 3. The small difference in S_{21} at higher frequencies could be ascribed to the loss of accuracy in the standard line model used for LRM calibration.

The S_{12} matches S_{21} plot within ± 0.02 dB, while on S_{22} behavior both the techniques agree very well as in S_{11}.

All the phase plots in every parameters agree within ± 2 deg on the overall frequency band, obviously apart the reflectance resonance frequencies ($S_{ii} \leq -35$ dB).

A test of the RSOL calibration sensitivity to respect to different *unknown thru* (i.e., a 1-ps line, the device of Fig. 2 and a 10-dB CPW attenuator) was also done.

According to (8), since α, $\boldsymbol{Y}_A$ and $\boldsymbol{Y}_B$ are test set constants, all the determinants of $\boldsymbol{T}_m$ should be equal. The results prove the consistency of (8) with an agreement of less than 0.005 dB and 0.2 degree on the overall frequency band (1–40 GHz) and confirm that α is independent from the used *thru*.

IV. Conclusion

The procedure here presented solves the problem of the standard thru-line necessary to perform the conventional two-port calibration techniques of the NWA. The availability of a standard *thru* is often one of the main difficulties to deal with, when devices with non conventional physical ports have to be measured. By means of this technique, any reciprocal two-port can be used as *thru* without worrying about the knowledge of its electrical parameters.

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