Save the "THRU" in the A.N.A. calibration

SAVE THE "THRU" IN THE A.N.A. CALIBRATION

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Abstract

The conventional network analyzer (NWA) two-port calibration procedures require a standard *thru* line to be connected between the ports.

Unfortunately in many applications, for example when measuring MMIC or on-wafer devices with not aligned ports, a custom *thru* line must be used.

The procedure here applied overcomes the difficulty due to the poor knowledge of this *thru* element since it is based on a generic reciprocal unknown two port structure, provided that its S_{21} phase shift is roughly known.

Some experimental comparisons with other well sound calibration techniques will be here presented where different reciprocal two-port structures were used as *unknown thru.*

I. Introduction

The NWA accuracy is strictly connected to the standards and to the effectiveness of the calibration procedure used to remove the systemathic errors.

In the case of two-port measurements all the present known calibration procedures [1]-[8] are based on the full knowledge of at least one two-port standard network, usually called *thru*, used to connect together the NWA test ports.

Unfortunately in many applications this *thru* can not be completely known (e.g. the case of on-wafer devices with not aligned ports where a folded line shall be used as a *thru*).

The calibration technique here applied overcomes these problems since it doesn't require any particular *thru* knowledge, provided that the two-port used instead of the *thru* is reciprocal and its S_{21} phase shift is roughly known.

Although it can be applied to any type of wave guide system the technique is particularly useful with "*non-insertable*" coaxial or on-wafer devices; furthermore, 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.

Six complex independent error coefficients, of the seven required in a two-port calibration, are obtained with the usual measurements of one-port standards (open, short, load) carried out respectively at NWA test ports 1 and 2, following the classic "*full two-port*" technique.

The last one is provided by taking advantage of the reciprocity condition of the two-port network used as "thru", whose trasmission matrix has an unitary determinant.

That condition allows to calculate the amplitude of the last error coefficient while the roughly knowledge of the S_{21} phase of the two-port reciprocal network allows to decide the error coefficient phase shift.

Next paragraph briefly recall the theory of the RSOL (**R**eciprocal **S**hort **O**pen **L**oad) calibration, whose details are treated in [9]. Afterwards some experimental comparisons with other well sound calibration techniques will be presented where different reciprocal two-port structures were used as *unknown thru*.

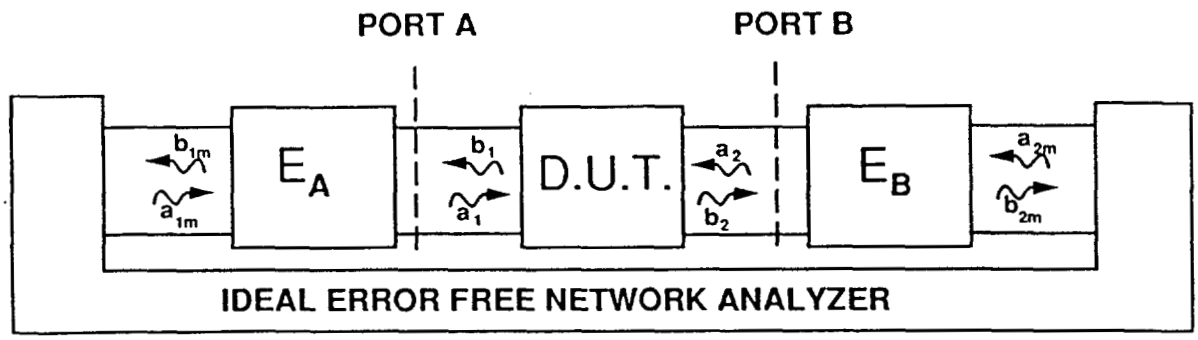

Figure 1: Error box NWA model

II. The calibration theory

An actual two port S-parameter test set can be seen as an ideal two-port reflectometer, which measures the device under test (**dut**) embedded between two error boxes, as shown in Fig. 1, which can be respectively characterized by the scattering matrices [3]:

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

If we call $\mathbf{T}_{dut}$ and $\mathbf{T}_m$ respectively the actual and the measured raw transmission matrices of the embedded dut, the following equation stands:

$$\mathbf{T}_m = \alpha \mathbf{Y}_A \mathbf{T}_{dut} \mathbf{Y}_B^{-1} \tag{1}$$

where

$$\alpha = \frac{e_A^{01}}{e_B^{01}},$$

$$\mathbf{Y}_A = \begin{bmatrix} -\frac{\Delta_A}{t_{11}} & \frac{e_A^{00}}{t_{11}} \\ -\frac{e_A^{11}}{t_{11}} & \frac{1}{t_{11}} \end{bmatrix} \tag{2}$$

$$\mathbf{Y}_{\mathrm{B}} = \begin{bmatrix} \frac{1}{t_{22}} & -\frac{e_{\mathrm{B}}^{11}}{t_{22}} \\ \frac{e_{\mathrm{B}}^{00}}{t_{22}} & -\frac{\Delta_{\mathrm{B}}}{t_{22}} \end{bmatrix} \tag{3}$$

$t_{11} = e_{\mathrm{A}}^{01} e_{\mathrm{A}}^{10}$, $t_{22} = e_{\mathrm{B}}^{01} e_{\mathrm{B}}^{10}$, $\Delta_{\mathrm{A}} = (e_{\mathrm{A}}^{00} e_{\mathrm{A}}^{11} - e_{\mathrm{A}}^{10} e_{\mathrm{A}}^{01})$, $\Delta_{\mathrm{B}} = (e_{\mathrm{B}}^{00} e_{\mathrm{B}}^{11} - e_{\mathrm{B}}^{10} e_{\mathrm{B}}^{01})$

The matrices $\mathbf{Y}_{\mathrm{A}}$ and $\mathbf{Y}_{\mathrm{B}}$ are completely known from one-port calibration procedures carried out by measuring three standards (usually an open, a short and a load) respectively connected at both the network analyzer test ports, but α cannot be directly derived from these one-port measurements. For a reciprocal network connected between the test ports, the equation (1) can be rewritten as:

$$\mathbf{T}_{\mathrm{mrec}} = \alpha \mathbf{Y}_{\mathrm{A}} \mathbf{T}_{\mathrm{rec}} \mathbf{Y}_{\mathrm{B}}^{-1} \tag{4}$$

where $\mathbf{T}_{\mathrm{rec}}$ and $\mathbf{T}_{\mathrm{mrec}}$ are respectively the actual and the measured raw transmission matrix of the reciprocal network. Because the reciprocity, the matrix $\mathbf{T}_{\mathrm{rec}}$ has an unitary determinant, so from the equation (4) it follows:

$$\det \mathbf{T}_{\mathrm{mrec}} = \alpha^2 \det \mathbf{Y}_{\mathrm{A}} (\det \mathbf{Y}_{\mathrm{B}})^{-1} \tag{5}$$

therefore

$$\alpha = \pm \sqrt{\frac{\det \mathbf{T}_{\mathrm{mrec}} \det \mathbf{Y}_{\mathrm{B}}}{\det \mathbf{Y}_{\mathrm{A}}}} \tag{6}$$

A sign ambiguity results for α, but it can be solved considering that from the equation (4) it results:

$$\mathbf{T}_{\mathrm{rec}} = \alpha^{-1} \mathbf{Y}_{\mathrm{A}}^{-1} \mathbf{T}_{\mathrm{mrec}} \mathbf{Y}_{\mathrm{B}} \tag{7}$$

let

$$\mathbf{X} = \mathbf{Y}_{\mathrm{A}}^{-1} \mathbf{T}_{\mathrm{mrec}} \mathbf{Y}_{\mathrm{B}} \tag{8}$$

it shall be noted that $\mathbf{X}$ is fully known from the one-port calibrations and the measured matrix $\mathbf{T}_{\mathrm{mrec}}$. From equation (7) the scattering parameter $S_{21\mathrm{rec}}$ can be calculated as:

$$S_{21\mathrm{rec}} = \frac{\alpha}{X_{22}} \tag{9}$$

So a simple roughly knowledge of the reciprocal network $S_{21\mathrm{rec}}$ phase shift ($\leq 180°$) allows to solve the α sign ambiguity.

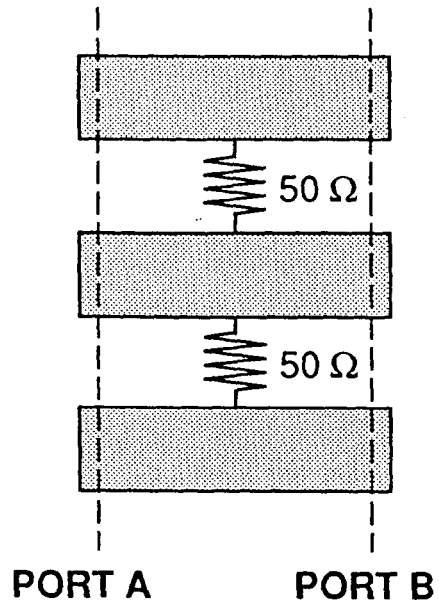

Figure 2: Layout of the CPW resistor used as reciprocal network (*unknown thru*) for RSOL calibration

III. Experimental results

Several on wafer devices were measured and their raw data were corrected by LRM and RSOL techniques, so probe repositioning errors are avoided and only the calibration process influence are highlight.

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 provided by Cascade.

A first test was carried out on the same device shown in Fig. 2, Fig. 3 reports the corrected four scattering parameters up to 40 GHz.

A second test was done on a 40 ps CPW line, whose corrected scattering parameters are shown in Fig. 4.

Up to 20 GHz all the results agree very well. A small difference in all the parameters appear beyond this frequency, but it can be noted, especially on S_{22} plots of Fig. 3, that the RSOL results agree better than the LRM ones with the S_{11} plot, as required by the geometrical simmetry of the device.

A significant test to hightlight the RSOL calibration effectivness can be carried out by comparing the measured value of $\det\mathbf{T}_m$ for several reciprocal networks. Following the equation 5 all these should be equal, since α, $\mathbf{Y}_A$, and $\mathbf{Y}_B$ are test set constants.

Fig. 5 shows the plots of $\det\mathbf{T}_m$ for three cases of reciprocal networks (e.g. a 10 dB attenuator, a 1 ps line and the 25 Ω resistor). To evidence the small differences founded, these plots were normalized to the determinant of the CPW (40 ps) line.

These plots clearly testify the independence of the technique from the reciprocal network used.

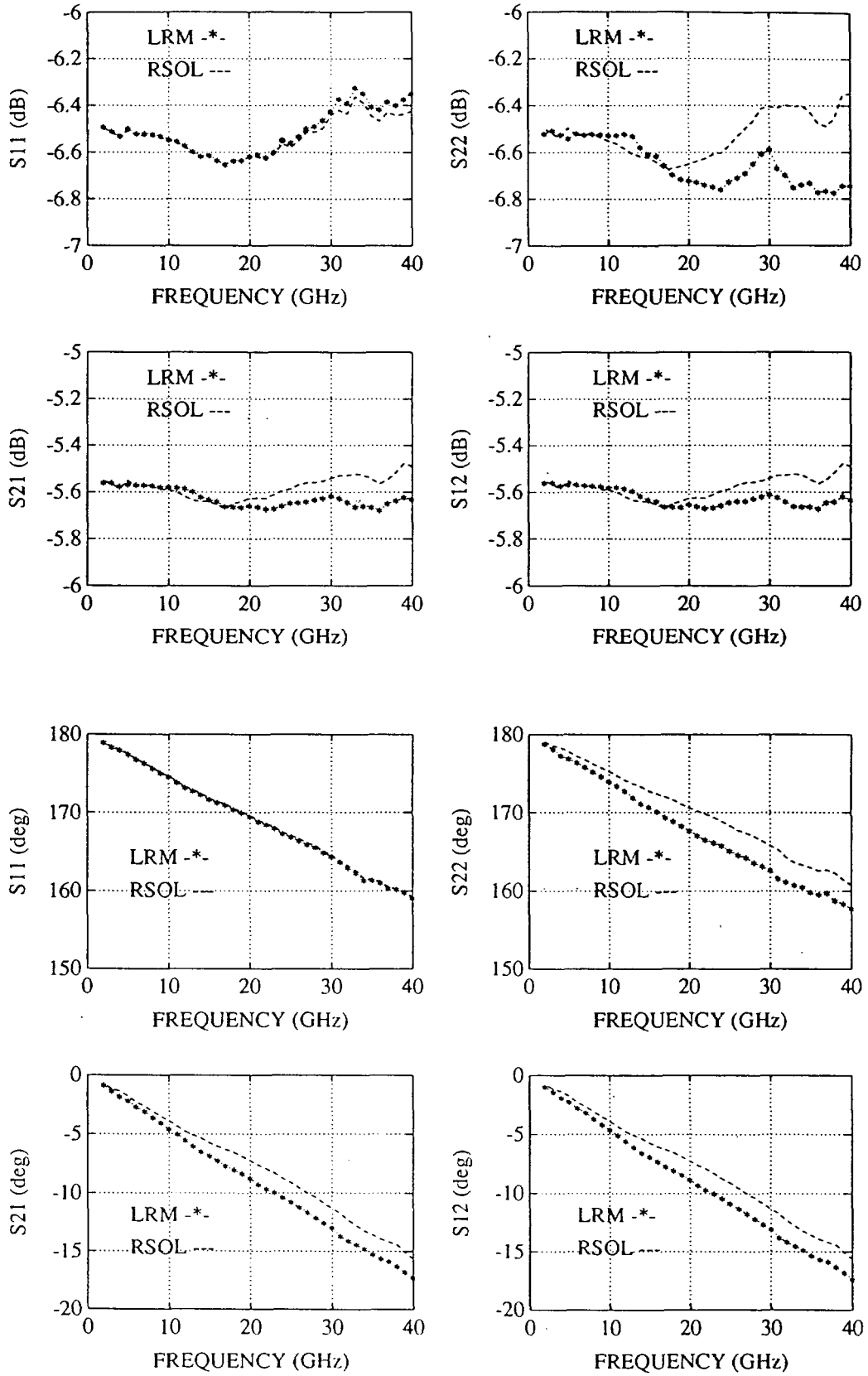

Figure 3: Comparison between the scattering parameters of the CPW resistor corrected with RSOL and LRM

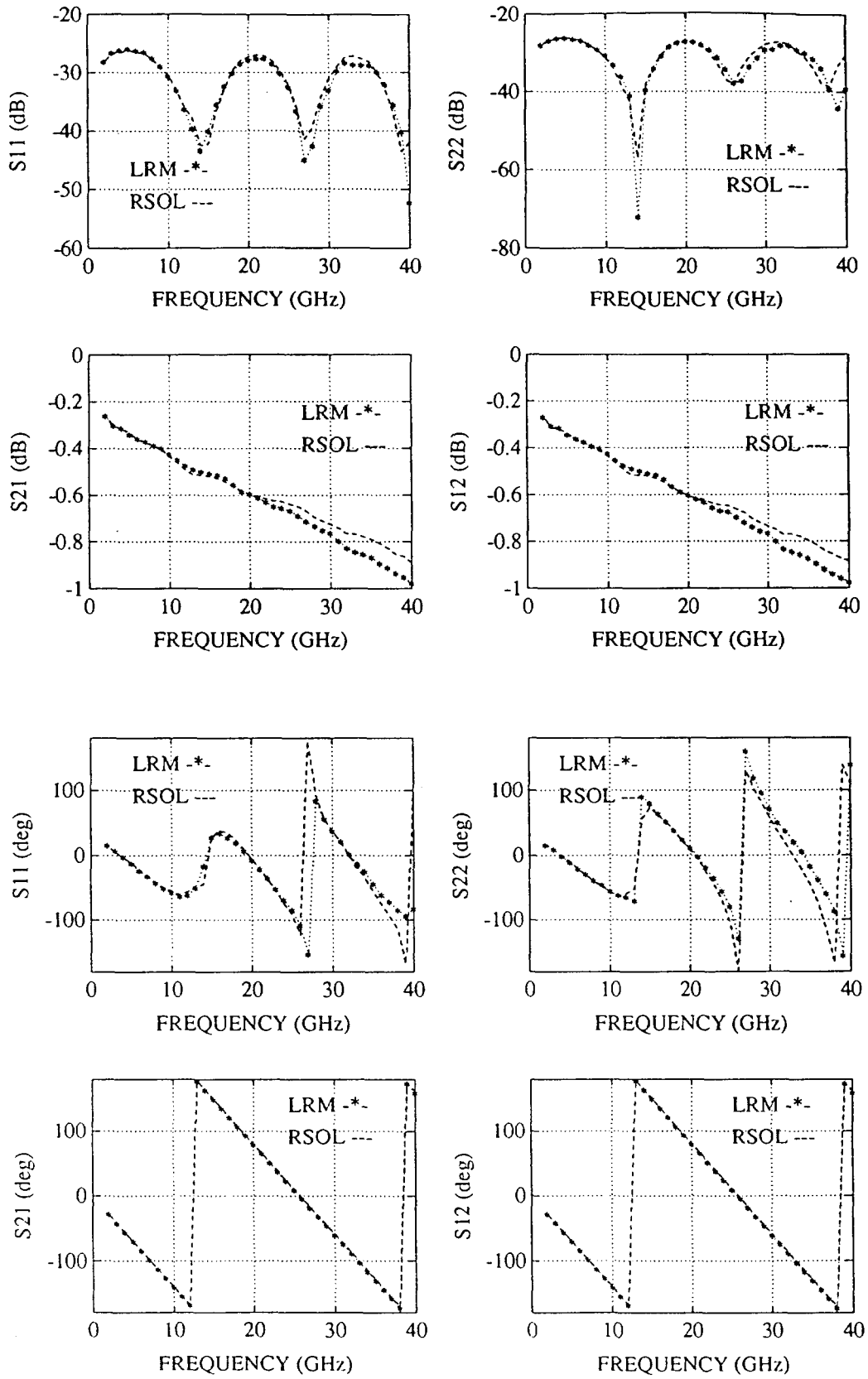

Figure 4: Comparison between the scattering parameters of a 40ps CPW delay line cor-reted with RSOL and LRM

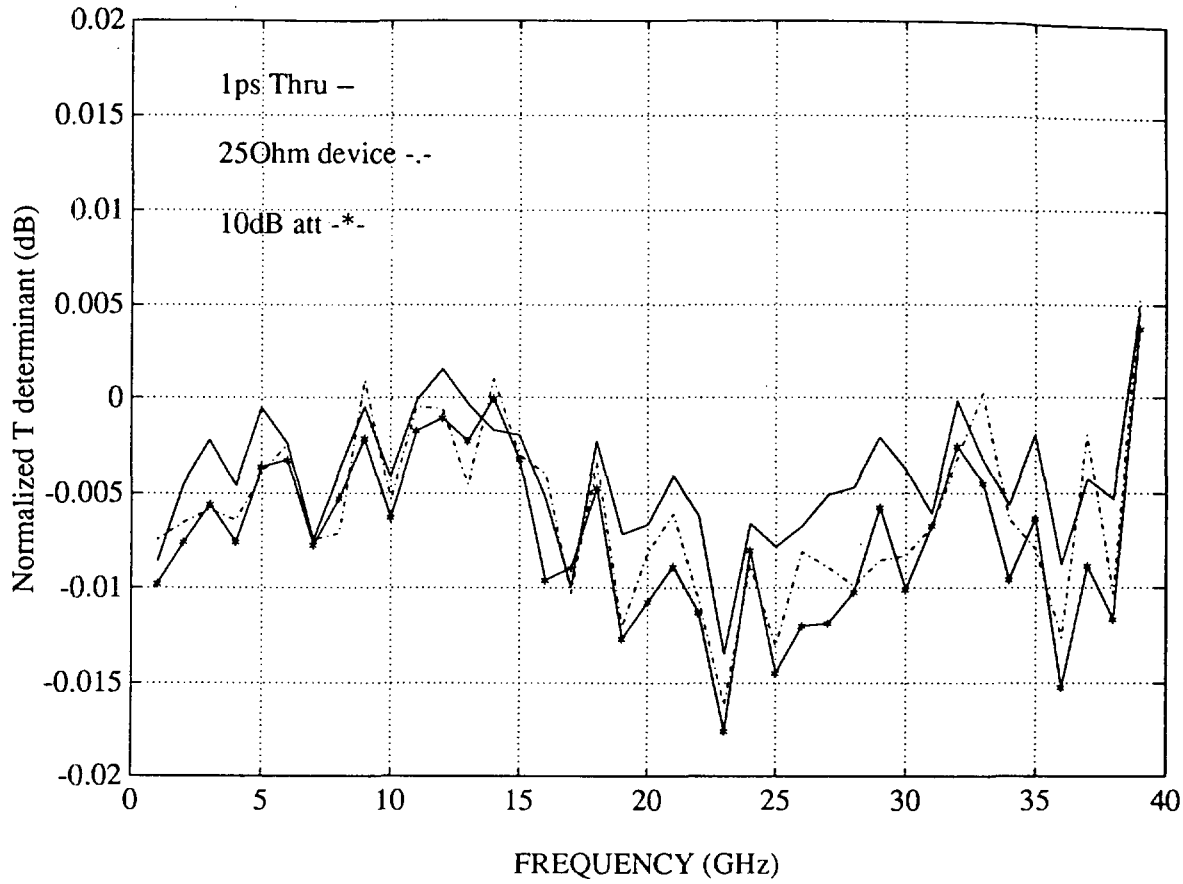

Figure 5: Comparison between the det$\mathbf{T}_m$ measured on three reciprocal networks, normalized to the determinant of the CPW (40 ps) line

IV. Conclusion

The procedure here presented overcomes 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.

V. Acknowledgements

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