ABSTRACT

Calibrating network analyzer is still an issue for bended access port devices (devices with accesslines at an angle to conventional transmission lines). Bended accesses can give additional errors which are taken into account by using a new design standards of Vector Network Analyzer (VNA) calibration. This Thru-Reflect-Line calibration technique is computed from ABCD parameters that easily allow to remove the bended port effects. This approach is based on the assumption that the Vector Network Analyzer error boxes can be considered as passive system. Furthermore, the method can be applied for de-embedding devices with bended accessses. This calibration and de-embedding technique could be applied, for example, to a coplanar circulator or a power divider measurement which have access lines at 120° from each other.

Keywords: VNA Measurement; Bended Access Ports; Calibration Technique; 120° Calibration Standards

*Corresponding author: E-mail: arafat.ousman@yahoo.fr;
1. INTRODUCTION

From the 1950’s, the need of reliable components measurement at RF and microwave frequencies began to emerge and first fully automated VNA providing high-precision measurement capabilities were introduced [1,2]. Later, in the 1990’s, national measurement standards laboratories began turning their attention to demonstrating the reliability of VNA measurements made on planar circuits (such as on-wafer measurements) [3,4]. The VNA measurements are reflection and transmission parameters (S-parameters) of a device under test (DST) [5]. To achieve effective and reliable measurements, VNA calibration procedures are crucial [6,7,8].

The Thru-Reflect-Line (TRL) is one of these procedures and has been developed and widely used for accurate microwave measurements on planar devices [9,10]. TRL calibration procedure is based on the measurement of three standards: Thru (short transmission line), Line (longer transmission line), and Reflect usually from a open or a short circuit. The characteristic impedance of Thru and Line standards and their lengths (or the gap length) must be known. Furthermore, the standards can be added on wafers for calibrating VNA and the technique can be applied in dispersive transmission media. Many developments on the same calibration principle were made in the last years. For example, multi-Line Thru-Reflect-Line algorithms were proposed to reduce the calibration errors [11,12]. Moreover, The TRL technique was extended to multi-port devices where the cross-talk among the ports can be taken into account [13,14]. A generalization of the TRL calibration technique for differential device, is the multimode TRL calibration technique [15,16].

In order to apply this calibration procedure on special devices, some other calibration kits have to be fabricated. The characterization of coplanar circulator or power divider with bended access ports (120° bended accesses) requires a specific kit for accurate calibration and measurement. Usually, conventional TRL procedure with commercial calibration standards is used. These standards do not permit to work with bended ports. So, additional manipulations of probes are needed to realign the microwave wafer probing at 120° after the calibration process. These manipulations, although performed with the utmost care, involve a change of measurement conditions and additional errors. To avoid a new orientation of probes after calibration procedure, new calibration standards with bended accesses has been designed [17,18]. Later, other authors have looked at this subject and have shown the difference between calibration standards using conventional lines and bended CPW lines [19,20]. However, although the probes are at 120° and the bended access effect had been taken into account during the calibration procedure, this effect does not exist for some devices under test. Consequently, the bended access effect must be removed after the calibration. The use of transmission (ABCD) matrices is convenient to remove this effect.

2. TRL METHOD WITH BENDED ACCESSES

The new calibration standards are shown in Fig. 1. The reference planes are defined in this figure in order to take into account the bended access effect in the calibration procedure.

So, the bended access effect can be include in the error boxes. TRL procedure and error boxes are indicated in Fig. 2.

![Fig. 1. Calibration standards and reference planes](image-url)
2.1 TRL Theory with ABCD Matrices

The calculation is based on ABCD parameters [21]. Following the same approach, the matrices "Thru" (T) and "Line" (L) are defined as:

\[
T = T_0 \lambda_T T_0^{-1} \\
L = T_0 \lambda_L T_0^{-1}
\]  

(2.1)

t and I being respectively the length of the Thru and the Line standards and \(Z_0\) the characteristic impedance. Then, including the error matrices (E1 and E2), the measurement matrices can be written as:

\[
M_T = E_1 T_0 \lambda_T T_0^{-1} E_2 \\
M_L = E_1 T_0 \lambda_L T_0^{-1} E_2
\]  

(2.2)
\( T_X = E_1T_0, \quad T_Y = T_0^{-1}E_2 \)

(2.2) can be expressed as:

\[
\begin{align*}
M_T &= T_X\lambda_T T_Y \\
M_L &= T_X\lambda_L T_Y
\end{align*}
\] (2.3)

From the measurement of Thru and Line standards, it is possible to calculate:

\[
M_LM_T^{-1} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}
\] (2.4)

\[
\gamma = \frac{1}{2(1-\theta)} \ln \frac{m_{11} + m_{12} - b_c (m_{21} + m_{22})}{m_{22} - m_{12} - b_c (m_{21} - m_{11})}
\] (2.5)

By assuming that error boxes can be passive, we can deduce following relations:

\[
\begin{align*}
a_1d_1 - b_1c_1 &= 1 \\
A_XD_X - B_XC_X &= 2
\end{align*}
\]

**2.2 Reflection Measurement**

An additional step is required to complete the calibration procedure. A reflection measurement allows to determine the last parameter: \(c_x\) (Fig. 2). Taking into account the offset length \(p\) and the load \(Y_m\) (open or short circuit) of the Reflect standard, it is easy to show from

\[
T_X\lambda_p T_0^{-1}Y_m
\]

With

\[
\lambda_p = \begin{pmatrix} e^{\gamma p} & 0 \\ 0 & e^{-\gamma p} \end{pmatrix}; \quad Y_m = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}
\]

that the input impedance (input of the \(E_1\) error box) is:

\[
Z_{in} = \frac{a_x e^{\gamma p} \frac{1}{z_0} y_m + b_x e^{-\gamma p} (Z_0 y_m - 1)}{c_x e^{\gamma p} \frac{1}{z_0} \frac{1}{y_m} + b_x e^{-\gamma p} (Z_0 y_m - 1)}
\] (2.7)

Following the calculations steps, the error box is:

\[
E_1 = \begin{pmatrix} A_X - B_X Z_0 \\ C_X \end{pmatrix} \begin{pmatrix} A_X - B_X Z_0 \\ C_X \end{pmatrix}
\]

(2.8)

The second error box \(E_2\) can be calculated from relations (2.2), (2.3) and (2.8):

\[
\begin{align*}
T_Y &= \lambda_T^{-1}T_X^{-1}M_T \\
E_2 &= T_0 T_Y
\end{align*}
\] (2.9a, 2.9b)

**2.3 Bended Access Model**

Recently, a simple lumped element model (Fig. 3) has been developed taking into account the bended access effect on the thru standard. Referring to the de-embedded method described in [22] and [18], it is possible to determine the elements of a \(\pi\) - type equivalent circuit model for the THRU standard.

This model is valid for designed TRL standards. In actual fact, a parasite mode (slot-line mode) is generated in the bended access [20]. However, simulations and measurements have been shown small impact of this parasite mode up to 60 GHz. In our first approach, this effect is neglected.

It is now possible to perform calibration with the bended access standards, and then, if necessary, to add or to remove this bended access effect (as we now know determine its \(ABCD\) matrix depending on frequency) according to the requirement of the device under test measurement.

**3. RESULTS**

We have fabricated test samples to verify the procedure described in this paper. These samples are CPW transmission lines with different sizes than standards but having a characteristic impedance close to 50 Ω (Fig. 4) and power dividers with an operating frequency band between 30 GHz and 40 GHz. The characteristic impedance of these sample lines are chosen close to 50 Ω to study the most unfavorable case for reflection measurements.

Measurements were performed in the frequency band of 20 GHz-50 GHz in two steps.

The first step is to calibrate the VNA with the ISS Commercial calibration kit Cascade Microtech 101-109 C and then redirect carefully the probes at 120° to perform sample \(S\)-parameter measurements. We called this method of measurement “VNA correction”.

The second step consists in measuring, without prior calibration of the VNA, fabricated standards and the test samples. Then we use the algorithm previously described for the correction. We called this method “\(ABCD\) correction”.

In the measurement of CPW lines, the 120° bended access effects is taken into account in
the calibration process, because these access lines are the same as those of the standards. Therefore, the DUT corrected parameters are given by:

$$M_{\text{cor}} = E_1^{-1} M_{\text{meas}} E_2^{-1}$$  \hspace{1cm} (3.1)

Power dividers characterization were performed by "2-ports" measurements. The third port is terminated with a matched load. The bended access effects should not be taken into account because the probes are aligned with the access ports without bends. These effects can be easily removed using ABCD matrices ($MC_1$, $MC_2$) obtained from the equivalent circuit of the bended access effects.

So, the calibration box errors $E_1$ and $E_2$ can be re-written as: $E_1 = MC_1 E_1$, $E_2 = MC_2 E_2$. So,

$$E_1 \circ = MC_1^{-1} E_1 \circ$$  \hspace{1cm} (3.2)

$E_2 \circ = MC_2^{-1} E_2 \circ$

($MC_1$ et $MC_2$ are ABCD matrices evaluating only the bended access effects). Then, the corrected parameters are given by:

$$M_{\text{cor}} = E_1 \circ^{-1} M_{\text{meas}} E_2 \circ^{-1}$$  \hspace{1cm} (3.3)

Fig. 4. Fabricated samples

Fig. 5. S12 parameter of 120° bended accesses CPW line (L = 10 mm)
Figs. 5-7 allow to compare the measurements performed with VNA correction and external bended access ABCD correction. The results show that the measured transmission parameters after conventional calibration (in black) and external correction (in red) are close up to 50 GHz.

The measured reflection should be low because the DUT characteristic impedance (considered CPW line) is close to 50 Ω. However, as shown in Fig. 6, the reflection coefficient $S_{11}$ obtained by the VNA correction (black) reaches −10 dB. So, as expected, redirecting probes after calibration generate additional errors, especially in reflection measurements. The external calibration with the new standards using the correction calculations by ABCD matrices shows a significant improvement. The corrected reflections are globally below −20 dB (the characteristic impedance of the lines are evaluated to 49 Ω).

The power divider measurements (Figs. 8-9) also confirm that these new standards and this calculation method offer better performance for the characterization of “3-ports” planar devices with accesses placed at 120°.
4. CONCLUSION

A new method of external TRL calibration by ABCD matrices has been presented. It was used to correct S-parameters measurements of planar devices that accesses are at 120° from each other. A great advantage is the determination of all error terms independently using ABCD error matrices. This makes it possible to take into account (or not) the 120° effects when the DUT accesses are the same (or not) as those of the calibration standards.

Measurements of two samples (120° access CPW line and power divider) were performed in two different ways: measurements with calibrated VNA and measurements without calibrated VNA and then corrected by the algorithm.

For such components, these measurements confirm that the “120° calibration” of the VNA with our standards gives better results, especially in reflection measurement. Thus, in any calibration process, the probes should not be moved to keep the measurement conditions unchanged. This technique could be generalized, including a specific calibration kit in designs, for any planar devices with any bended access ports.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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