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On-Wafer TRL Calibration Design for Microwave Nanoscale and High Impedance Measurement

Daouda Seck^{#§1}, Djamel Allal^{#2}, Kamel Haddadi^{§3}

[#]Laboratoire national de métrologie et d'essais (LNE), 29 Avenue Roger Hennequin, 78197, Trappes Cedex, France

[§]Univ. Lille, CNRS, Univ. Polytechnique Hauts-de-France, UMR 8520 - IEMN - Institut d'Electronique de Microélectronique et de Nanotechnologie, USR 3380 IRCICA - Lille, France

{¹daouda.seck, ²djamel.allal}@lne.fr, ³kamel.haddadi@univ-lille.fr

Abstract — Miniaturization of microwave devices at the nanoscale induces high impedance, posing significant challenges in accurate measurement techniques. In response, this work introduces novel calibration kits tailored specifically for nanoscale applications. We present the design of an on-wafer Thru Reflect Line (TRL) calibration kit, optimized for precise measurements at frequencies up to 110 GHz. The kit accommodates 100- μm pitch ground signal ground (GSG) on-wafer probes. The proposed calibration structures offer enhanced accuracy, addressing the demands of high impedance measurement in miniaturized microwave devices. This work contributes to advancing measurement capabilities in nanoscale microwave engineering, facilitating the development of next-generation high-frequency devices.

Keywords — On-wafer calibration, coplanar waveguide (CPW), thru reflect line (TRL), nanotechnology.

I. INTRODUCTION

Microwave devices play a pivotal role in modern technology, ranging from telecommunications systems to radar applications and beyond. The validation of these devices is crucial to ensure their performance meets desired specifications. One of the primary methods for evaluating microwave devices is through on-wafer S -parameter measurements. Achieving accurate and reliable S -parameter measurements requires meticulous calibration of the measuring system, typically a vector network analyzer (VNA) connected to signal ground signal (GSG) probes through coaxial cables. Different calibration techniques have been introduced including Thru-Reflect-Line (TRL) [1], Short-Open-Load-Thru (SOLT) [2], Short-Open-Load-Reflect (SOLR) [3], Load-Reflect-Match (LRM) [5], Load-Reflect-Reflect-Match (LRRM) [5], multiline Thru-Reflect-Line (TRL) [6], and others. These techniques encompass a diverse array of methodologies designed to address specific challenges in calibration, such as mitigating impedance discrepancies, reducing systematic errors, and accommodating complex measurement setups. Each technique offers unique advantages and trade-offs, making them suitable for different applications and scenarios in microwave device characterization and validation.

In this study, we explore the design of coplanar calibration kits in GSG configuration within the unique context of nanoscale dimensions. The reduction of these structures to the nanometer scale introduces significant challenges, particularly concerning limitations of coplanar waveguide (CPW) transmission line theory [7]. Conventional CPW line theory

relies on geometric parameters to define line characteristics, setting limitations on line dimensions. Nevertheless, when scaled down to the nanoscale, metal thickness close to width signal line undermines coplanarity, prompting a reassessment of traditional methodologies. To address these challenges, we employ the TRL calibration method alongside 3D electromagnetic simulations conducted using CST Microwave Studio. Our study focuses on the design of calibration and verification kits based on TRL methodology, tailored to accommodate nanoscale dimensions. We analyze the performance of these structures and validate their suitability for accurate calibration in GSG configurations at the nanoscale.

II. TRL ALGORITHM

Introduced by Engen and Hoer in 1974 [1], TRL is a self-calibration algorithm that operates without requiring precise knowledge of the standards. Utilizing a short line, a second line, and a reflective component—either open or short—TRL method does not mandate knowledge of all components, although the lengths of the lines must differ, creating a phase-shift between 20° and 160° . Additionally, the reflector must exhibit minimal loss, with consistent reflection coefficients across each port. Through this approach, TRL facilitates the determination of key electrical properties of a line, including its propagation constant and characteristic impedance.

The TRL method is an advantageous technique for properly performing calibration and having good traceability using primary standards such as air lines [8]. However, it may suffer from a frequency band limitation because the choice between thru and line must satisfy an adequate length difference relative to the frequency of interest. TRL calibration consists of evaluating systematic measurement errors with a VNA using three standards: a Thru T, an open or closed Reflect R circuit and a second Line L. There are 8 error terms to determine, including four on either side of the component under test: directivity e_{00} , source adaptation e_{11} , frequency responses in transmission $e_{10}e_{32}$ and reflection $e_{10}e_{01}$ (Fig. 1).

These errors are represented by fictitious networks embedding the device under test (DUT) modeled by a network of S or T parameters between the two ports of the VNA. As can be seen, the error boxes contain different calibration terms or coefficients. The measurement results obtained at the level of the VNA measurement reference planes are a result of cascaded

networks including these error boxes and the DUT given by the relation

$$M = X \cdot T_{DUT} \cdot Y. \quad (1)$$

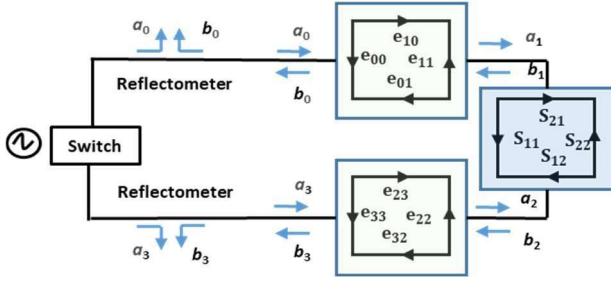


Fig. 1. VNA and 2-port error model representation.

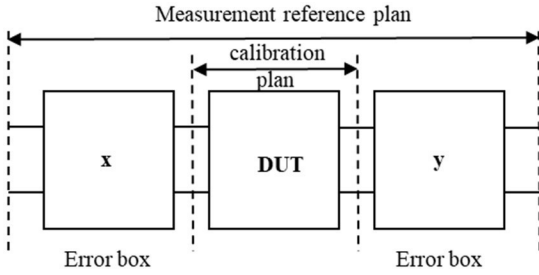


Fig. 2. 2-port measurement model.

Symbols M and T_{DUT} are respectively the transfer matrix measured at the VNA measurement plane and the transfer matrix of the DUT. The transfer matrices X and Y represent overall the systematic error terms. The two lines (TL) make it possible to determine part of the errors. The last standard reflect (R) is used to complete the determination of the error terms. In the TRL process, a transfer matrix T of the theoretical and measured responses of thru and line standards is used.

$$T_{thru} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}; M_{thru} = \begin{pmatrix} M_{11thru} & M_{12thru} \\ M_{21thru} & M_{22thru} \end{pmatrix} \quad (2)$$

$$T_{line} = \begin{pmatrix} e^{-\gamma l} & 0 \\ 0 & e^{\gamma l} \end{pmatrix}; M_{line} = \begin{pmatrix} M_{11line} & M_{12line} \\ M_{21line} & M_{22line} \end{pmatrix} \quad (3)$$

The reflect standard is specified by its S -parameter matrix.

$$S_{Reflect} = \begin{pmatrix} \Gamma_r & 0 \\ 0 & \Gamma_r \end{pmatrix} \quad (4)$$

T -matrix error boxes can be represented as

$$X = \begin{pmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \end{pmatrix} = \frac{1}{e_{10}} \begin{pmatrix} -\Delta_{e1} & e_{00} \\ -e_{11} & 1 \end{pmatrix} \quad (5)$$

$$Y = \begin{pmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{pmatrix} = \frac{1}{e_{32}} \begin{pmatrix} -\Delta_{e1} & e_{22} \\ -e_{33} & 1 \end{pmatrix} \quad (6)$$

Equation (1) forms the foundation of the TRL algorithm, allowing for the determination of initial unknowns through redundancy by applying principles of matrix algebra.

III. DESIGN OF TRL KITS

CPW technology offers flexibility and feasibility in electronic circuit design and fabrication. CPW supports quasi-TEM mode, integrates passive or active components on its surface, and easily accommodates shunt or series elements. It eliminates the need for via holes, reduces losses, and its electrical characteristics are defined by cross-sectional dimensions.

We have chosen coplanar technology with a GSG configuration. On a substrate with thickness H_s , two metallic ground planes of width Wg are deposited, separated by a central metallic ribbon of width W with an equidistant gap g . The metal has a thickness t (Fig. 3).

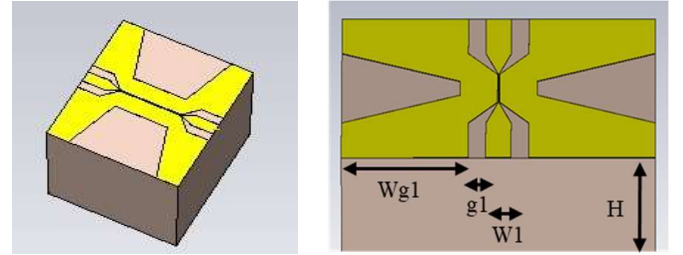


Fig. 3. Coplanar structure in GSG configuration.

This structure comprises two distinct sections: a *normal* section and a *tapered* section. Dimensional choices are determined by both analytical calculations of coplanar line impedance and material constraints.

Table 1. Cross section dimensions.

Length	W1	W2	g1	g2	Wg1	Wg2	Hs	t
(μm)	27	0.5	14.5	0.727	140	30	350	0.5

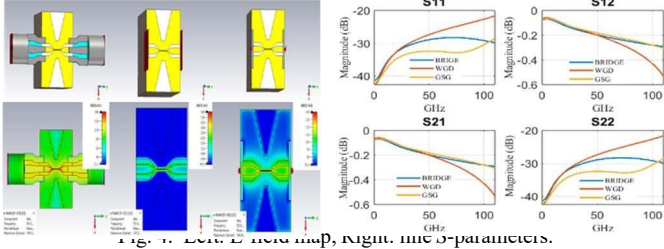
The materials under consideration are alumina (with a dielectric constant $\epsilon_r = 9.9$ and loss factor $\tan\delta = 0.0001$) for the substrate, and gold (with a conductivity $\sigma = 4.561 \times 10^7$ S/m) for the metallic lines. Additionally, a 25 nm-thick layer of Titanium (with a conductivity $\sigma = 6.61 \times 10^5$ S/m) serves as a bonding and resistance layer. We have designed and simulated several structures: reflective components (Short and Open), lines and verification devices.

First we use CST microwave studio analytic model to adjust line characteristic impedance at 50Ω by choosing different values of cross section dimensions. With this in mind, we have tried to keep the shape ratio between the trace width W and the gap g as close as possible. As one can see in Table 2, there is a limit to the ratio below which the line is not only unsuitable for exactly 50 ohms, but also the analytical CPW model becomes invalid. We then used this data to extrapolate the impedance of

the line when the trace width is of the order of a few nanometers. Consequently, a trace width of 500nm corresponds

roughly to a gap of 727nm and a characteristic impedance of 51 Ω .

This preliminary study enabled us to define our tapered structures dimensions. Two distinct parts can be noticed: nanometric section and micrometric section. We have simulated a 200 μm line differently according to three types of excitation, in particular with a GSG probe, a bridge and a waveguide port.



IV. ELECTRICAL CHARACTERISTICS OF THE LINE

Coplanar transmission lines have a certain peculiarity among known waveguides. Their electrical characteristics, in particular the characteristic impedance and the effective permittivity, depend on the one hand on the dimensions of the cross section such as the width of the signal, the slots, the thickness of the metal and the height of the substrate [7]. It is important to note that these characteristics also depend on the properties of the materials used (Table 2.) whether the metallic part or the dielectric part. During our simulations, we carried out the analytical calculation of this impedance in CST Microwave Studio. Taking into account the parameters just mentioned, the impedance was adjusted to 50 Ω .

TRL calibration transfers the measurement plans to the ports of the DUT using line properties, then all its interest lies in knowing the propagation constant of the line and its characteristic impedance which becomes the reference impedance for the component under test. The characteristics of coplanar lines that we have designed can be obtained from the simulation software or calculated. In the last case, we use both values from simulated S -parameters of the line and mathematical relationships. Another way to determine the characteristics of the line is to make real measurements with at least two lines of different lengths. Indeed, the line propagation constant is evaluated using the data from these two lines. The line impedance is then defined after measuring the line capacitance [9].

In Fig.5, the characteristics of two lines with same length 200 μm (tapered nano-scale line and normal line) are represented, in particular the propagation constant and the impedance in real and imaginary parts. For the propagation constant, the imaginary part or attenuation constant shows how the signal is attenuated along the line. It increases with frequency, and is much more important for the tapered line. Its real part or phase constant is specific to the phase change of the signal. At the same time, the real part of the characteristic impedance is close to 50 Ohms, while the imaginary part results from losses due to the conductor.

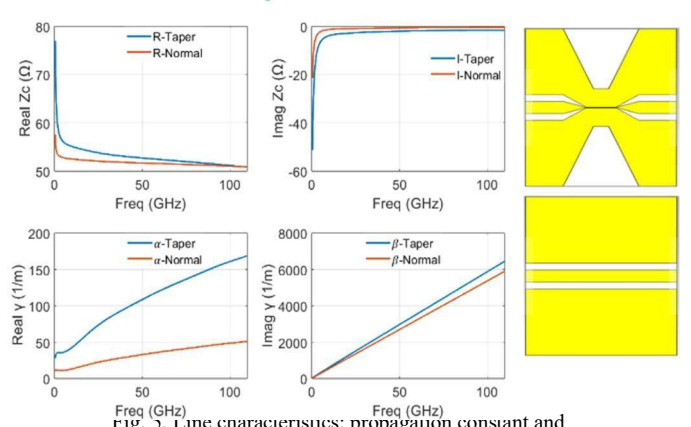


Fig. 5. Line characteristics: propagation constant and characteristic impedance.

V. RESULTS

The results of the 3D electromagnetic simulations of the different structures were used to implement the TRL calibration algorithm under MATLAB software. Thus, we considered these results as raw and uncorrected measurements, and therefore subject to errors. By performing a TRL calibration, these errors were quantified. This allowed us to obtain the true values of our simulated components. In this paper, we focused the study on two components: a 340 μm line and a 10 dB attenuator.

The TRL structures are two lines of length 200 μm and 250 μm and a reflective component (open). Figures 6 and 7 respectively give comparisons of the results of corrected and uncorrected (simulated) S -parameters of a line and a 10 dB attenuator.

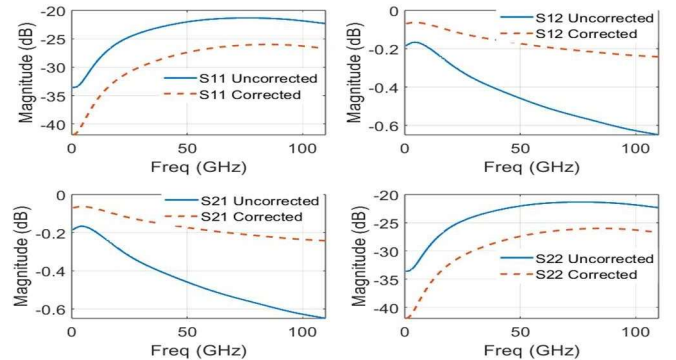


Fig. 6. Line - S -parameters before and after TRL calibration.

The reflection terms are much more important before than after the TRL correction, which highlights the errors altering the propagation of the electromagnetic signal; for example at 110 GHz, the coefficient S_{11} (S_{22}) increased from -18.5 dB to -25.4 dB after TRL calibration. For transmission, the correction made it possible to improve the terms by extracting the errors. We can see that at 110 GHz, the coefficient S_{21} (S_{12}) goes from -1.3 dB to -0.6 dB.

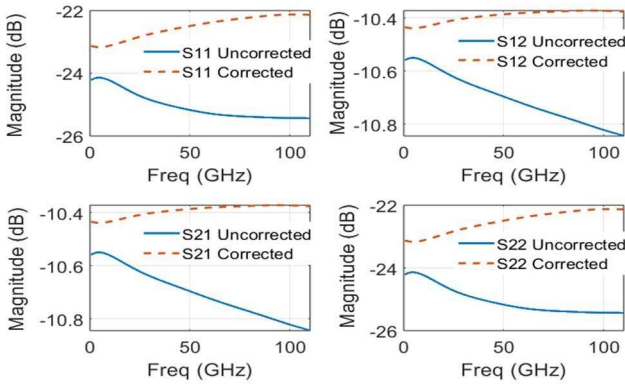


Fig. 7. 10 dB attenuator – S -parameters before and after TRL calibration

Likewise, the correction increases the transmission coefficient from -10.8 dB to -10.2 dB at 110 GHz.

The TRL calibration method also allows us to have access to the error terms that are responsible for the differences in the corrected and uncorrected S -parameters. These terms embedded in fictitious boxes to form two-port networks, as shown in Fig. 8, are considered in both directions.

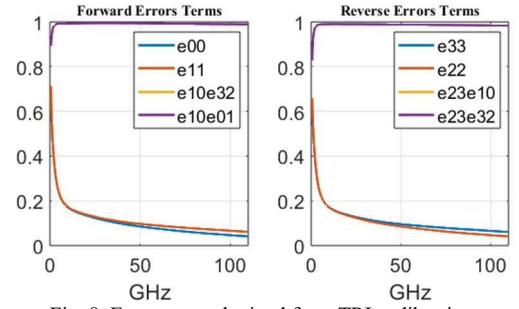


Fig. 8. Error terms obtained from TRL calibration.

In Fig. 8, we observe that the frequency responses in transmission and reflection exhibit module values close to 1, despite an increasing gap with frequency due to losses. This trend is logical, as in an ideal scenario, total transmission or reflection would be expected. However, directivity and source adaptation, which ideally should approach 0 in module, display a noticeable shift. Particularly at low frequencies, the error terms deviate considerably from these expected values. This discrepancy highlights the challenges faced by the TRL method at low frequencies. These results reaffirm the effectiveness of the TRL algorithm when coupled with simulated components, further validating its utility in practical applications.

Table 2. Shape ratio line cross-section dimensions and characteristic impedance.

Impedance : Zc (Ohm)	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.68	~51.00
Trace width : W (μm)	10,5	10	9.5	9	8.5	8	7.5	7	6.5	6.5	0.5
Ratio (W/g)	1.5461	1.527	1.506	1.484	1.4609	1.435	1.408	1.378	1.2999	1.2999	0.6874

VI. CONCLUSION

This work aimed to establish traceable S -parameter standards using CPW technology at the nanometer scale for the characterization of high-frequency nanodevices. The traceability was achieved through the application of the TRL calibration method, utilizing the characteristic impedance of the transmission line as the reference impedance. Specifically, the conductor thickness of these standards matched the central strip width, with the characteristic impedance calculated based on the constrained thickness/width ratio. Through extrapolation, the obtained characteristic impedance value, close to 50Ω , was validated via electromagnetic simulations. Application of the TRL method yielded consistent results on two verification components. This work facilitated the selection of various components to constitute a calibration and verification kit, which will undergo production and subsequently demonstrate the traceability of S -parameter measurements at the nanometer scale.

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