# Accurate On-Wafer Measurement Technique for *E*-Band MHMIC Communication Systems

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***Abstract*— The article has proposed a comprehensive analysis of on-wafer millimeter-wave measurements and addressed the challenges of calibration, measurements, and circuit characterization of *E*-band (60 to 90 GHz) circuits implemented on a thin ceramic substrate. The used thin ceramic substrate is suitable for miniaturized hybrid microwave integrated circuit fabrication at mm-wave frequencies. The proposed method is validated on a directional coupler, and a coupled-line bandpass filter in this frequency band. Simulation and experimental results are in great agreement at such high frequencies.**

## I. INTRODUCTION

The millimeter-wave (mm-wave) frequency range is nowadays the inescapable candidate to provide multi-gigabit per second data rates [1]–[3]. The monolithic microwave integrated circuit (MMIC) technology is often used in large-scale production and the miniaturized hybrid microwave integrated circuit (MHMIC) is ideal for prototyping and small- to medium-scale production [4]. The ceramic substrate, such as alumina, usually offers low dielectric loss and high dielectric constant, allowing the fabrication of compact mm-wave circuits [5]. The most significant identified challenges in present literature are related to grounding modelling and characterization, precision and characterization of the circuit design, and the calibration and measurement [6]. However, these issues are not simultaneously reported and analyzed, especially for thin ceramics at *E*-band (60 to 90 GHz) frequencies.

In this paper, we simultaneously addressed the challenges related to calibration, measurements and circuit design accuracy, and characterization of mm-wave circuits fabricated on a thin ceramic substrate. The on-wafer mm-wave calibration and measurements along with RF grounding are detailed in Section II. In Sec. III, For validation, S-parameters are measured for some passive component samples including a directional coupler, and a bandpass filter. The conclusion is presented at the end.

## II. ON-WAFER CALIBRATION AND MEASUREMENTS

A circuit that its passive components have been printed onto the surface of a substrate and the active elements are joined to the circuit individually by wire bonds, is called a miniature hybrid microwave integrated circuit (MHMIC). A thin ceramic substrate ($\varepsilon_r$ 9.9, thickness 5 mils) is selected for its very low dielectric loss tangent at such high frequencies and its great potential to be used as MHMIC technology. Also, this substrate is the most popular one for designing broadband on-wafer high-frequency resistors and terminations that are required in implementing couplers, Wilkinson power dividers, and loads [7]. The measurement error mostly depends on the accuracy of the calibration technique and its calibration kit. These errors are related to several factors, such as the non-ideal parameters of cables and probes, and the features of the used vector network analyzer (VNA). In order to simplify calibration procedures and to achieve more accurate and reliable measurements by introducing much minor systematic errors, the on-wafer calibration and measurement with pico-probes are provided..


Fig. 1. A photo of a circuit under test using GSG coplanar probes.

For the experimental validation, a customized probe station, a VNA (E8362 PNA) and a mm-wave head controller (N5260A) from Agilent Technologies, and two *E*-band extenders, from OML Inc., are used. Because of the high attenuation on coaxial cables at this frequency range, WR12 waveguide operation is utilized to connect the equipment to the circuit under test. Fig. 1 shows the circuit under test using the 150 µm ground–signal–ground (GSG) coplanar probes connected through WR12 waveguides to the VNA modules.

As mentioned, the TRL calibration kit is implemented on the same alumina substrate as the devices under test, using coplanar to microstrip line transitions to provide the connection to the GSG 150-µm Infinity probes. Instead of dc grounding via-hole, an RF short circuit using quarter-wavelength radial stub is used. The delay line is related to the operating frequency range. The delay line's physical length referring to the thru line is between $\lambda_g/4$ at the lower frequency (60 GHz) and $\lambda_g/2$ at the upper frequency (90 GHz), to cover the entire *E*-band without phase ambiguity. Fig. 2 shows a photo of the fabricated TRL calibration kit and the coplanar waveguide to microstrip line transition, captured by a high resolution microscope.

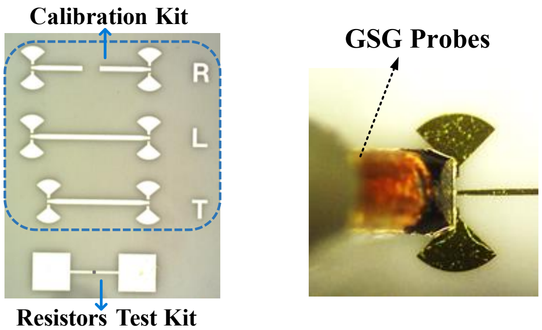


Fig. 2. A photo of the fabricated TRL calibration kit and the coplanar waveguide to microstrip line transition.

## III. RESULTS AND DISCUSSION

In this section, several widely used passive components, including directional couplers, and a coupled-line bandpass filter are designed and built on the selected substrate. The S-parameters are measured using the suggested measurement technique and compared to the ADS software simulation results. Figure 3 shows a microphotograph of a fabricated directional coupler with a 25 dB coupling value. Note that for measuring all S-parameters of this coupler, three similar couplers with different exciting ports should be printed on the board. For example, for measuring the coupling value, ports 1 and 3 of the desired coupler should be connected to the probes, and ports 2 and 4, are terminated to loads (Fig. 3).

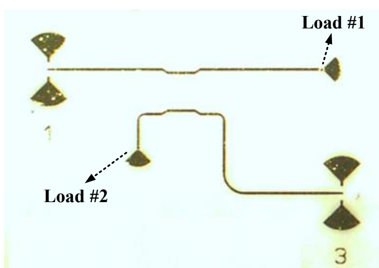


Fig. 3. A microphotograph sample of the fabricated directional coupler for measuring the coupling ($S_{13}$) value.

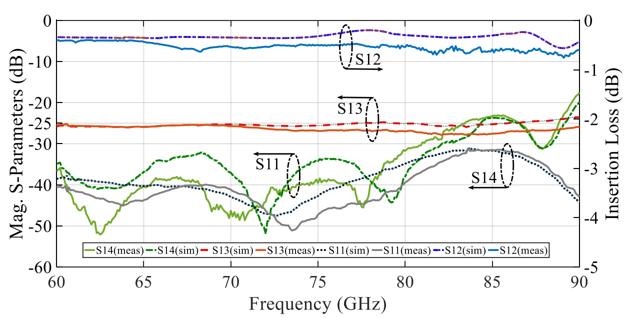


Fig. 4. The simulation and measurement results of S-parameters for the directional coupler with 25 dB coupling value.

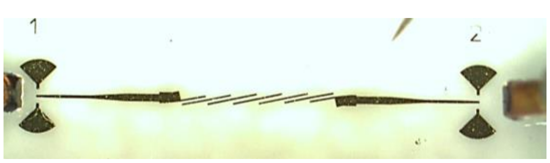


Fig. 5. A photograph of the fabricated *E*-band bandpass filter.

Figure 4 shows the simulation and measurement results of the return loss ($S_{11}$), insertion loss ($S_{12}$), coupling ($S_{13}$), and directivity ($S_{14}$) parameters for the designed directional coupler. A microphotograph of a coupled-line bandpass filter in this frequency band is presented in Figure 5, while Fig. 6 illustrates the simulation and measurement results of its S-parameters. It can be noticed that by employing this method, simulation, and experimental results are in perfect agreement at such high frequencies.

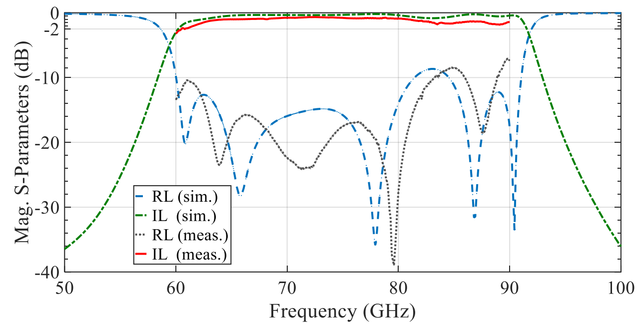


Fig. 6. The simulation and experimental results of S-parameters for the bandpass filter (RL: Return Loss, and IL: Insertion Loss).

## IV. CONCLUSION

An accurate on-wafer mm-wave characterization technique is presented in this paper. A thin ceramic substrate is used for miniaturized hybrid microwave integrated circuit fabrication. Two passive components are designed and measured using this technique to evaluate the accuracy of the method and validate the results. By comparing the simulation to the experimental results, it can be concluded that the suggested technique is a reliable measurement method for mm-wave MHMIC applications.

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