A 0.1 GHz to 1.1 THz Inverted Grounded-CPW mTRL Calibration Kit Characterization in an InP HBT Process

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***Abstract*——We report a novel design approach of on-wafer multiline thru-reflect-line (mTRL) calibration kit fabricated on a commercial semiconductor-based transistor process that we validate from 0.1 GHz to 1.1 THz. The on-wafer calibration standards are designed with an inverted grounded-coplanar waveguide (G-CPW) transmission line, where the calibration reference planes, buried under multiple layers of interconnects, provide direct access to the heterojunction-bipolar-transistor (HBT). We connect the different levels of ground-plane metallization with vias to avoid coupling with adjacent structures and limit the propagation of higher-order modes. We validate this approach with measurements of the complex characteristic impedance of the inverted G-CPW lines, the S-parameters of a 775 µm line, and a 600 GHz common-base amplifier.**

Keywords— grounded-coplanar waveguide line (G-CPW), multiline thru-reflect-line (mTRL), on-wafer calibration, terahertz (THz) frequencies, S-parameters.

I. Introduction

The recent development of semiconductor-based transistors with a terahertz of bandwidth [1-2] enables practical and emerging applications in millimeter-wave communications, imaging, and atmospheric sensing. However, substantial obstacles emerge as we perform on-wafer characterization above 100 GHz, preventing accurate estimates of measured RF performance of active devices and circuits. For instance, the presence of surface waves [3-4], higher order modes and radiation [5], crosstalk [6], and the influence of the RF probes [7] can degrade multiline thru-reflect-line (mTRL) calibration, resulting in erroneous measurements of devices-under-test (DUT) at millimeter-wave and terahertz frequencies.

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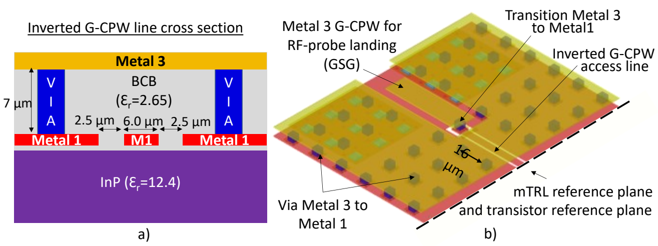

Fig. 1. Inverted G-CPW calibration standard design. a) cross section of the transmission line. b) detailed design of the launch RF-pad (half of the zero-length thru line standard).

In this paper, we propose a design approach for on-wafer mTRL calibration standards using grounded-coplanar waveguide (G-CPW). We speculate that G-CPWs is less sensitive design and more robust to higher-order modes of propagation, reducing measurement errors. The design of the calibration standards is described in section II. In section III, we characterize and validate the calibration kit from 0.1 GHz to 1.1 THz. We then present the measurement of a 6-stage common base amplifier at 600 GHz in section IV.

II. mTRL Inverted Grounded-CPW Calibration Kit Design.

General guidelines of on-wafer calibration design have been reported [8] to sub-terahertz frequencies. Although traditional coplanar waveguide (CPW) or microstrip lines are broadly used for mTRL calibration standards, they are not immune to surface wave propagation and the generation of higher-order modes in the millimeter-wave and terahertz frequency bands. Strip lines, substrate-integrated waveguides, and G-CPW transmission lines

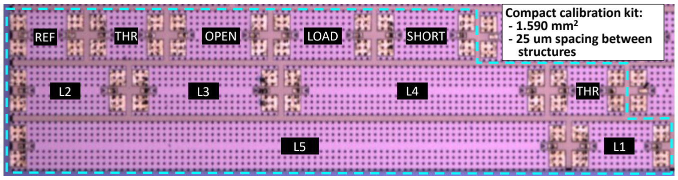

Fig. 2. Photograph of the inverted G-CPW mTRL calibration kit.

may be preferred to ensure a single mode of propagation in the on-wafer standards. We chose an inverted G-CPW line configuration designed in an indium phosphide (InP) heterojunction-bipolar-transistor (HBT) process. Three layers of metallization interconnects in a benzocyclobutene (BCB) film are deposited on top of the InP substrate to construct complex monolithic microwave integrated circuits (MMICs) with interconnects useable to 1 THz. More information regarding this technology can be found in [1]. The cross section of the inverted G-CPW transmission line and the launch RF pad are illustrated in Fig. 1. While most calibration kits use the top-level metallization layer, we designed our calibration standards in the first level of metallization (Metal 1) in the thin-film BCB, just above the InP substrate. This configuration allows us to set the mTRL calibration reference planes very close to the HBT reference planes and enables accurate characterizations of active circuits designed in Metal 1. We limited radiation by designing a narrow 6.0 µm signal conductor width and a 2.5 µm gap. A transition from the Metal 3 G-CPW launch RF pad to the Metal 1 transmission line is carefully designed to limit impedance mismatch up to 1 THz. We also added a bridge in Metal 2 right after the transition to ensure the proper mode of propagation in the inverted G-CPW. The third (top-level) of metallization Metal 3 serves as a finite ground plane and is connected to the electrically large Metal 1 ground plane with vias, using a 16 µm edge-to-edge spacing. This configuration suppresses surface wave propagation and avoids coupling with adjacent structures. Since the Metal 3 ground plane is on the top of the circuits, we can directly place the on-wafer standards and circuits in the shadow of the probes (right underneath the probe, without applying a Y-offset) and avoid direct coupling from the probe to the adjacent lines [7]. These two arrangements allow a compact placement of the inverted G-CPW standards (25 µm spacing between the Metal 3 of each structure) as shown in Fig. 2. The total area of the inverted G-CPW mTRL calibration kit is only 1.590 mm^2, which is at least 3 to 4 times smaller than a classical CPW or microstrip calibration kit with adequate spacing between the structures. The calibration kit includes two identical zero-length thru lines, two reflects (a short and an open), a load, and five additional lines of varying lengths. We carefully designed five line lengths such that the electrical delays of all pairs of lines provide acceptable coverage [9] from 0.1 GHz to 1.1 THz.

III. Characterization Of the mTRL Inverted G-CPW Calibration Kit

A. Calibration Approach and Instrumentation

We performed S-parameter measurements of the calibration kit standards from 0.1 GHz to 220 GHz with a broadband vector network analyzer (VNA). We then used 4 sets of waveguide extenders from 220 GHz to 1.1 THz (WR3.4, WR2.2, WR1.5, and WR1.0). Different frequency bands required different makes and models of RF probes and VNAs. We also used different kits across the wafer to create the aggregated dataset to mitigate pad wear during the measurements in each band. For each mTRL calibration, we verified the complex effective relative dielectric constant resulting from the measured complex propagation constant (γ). The complex characteristic impedance of the transmission lines (Z_0) was used to calibrate the DUTs in a real 50 Ω impedance system and was calculated based on the approach of Marks [10]. Assuming a conductance per unit length of the transmission line being negligeable ($G << C\omega$), and a constant capacitance per unit length (C) of the transmission line, Z_0 is obtained as follows:

$$Z_0 = \frac{\gamma}{G + jC\omega} \approx \frac{\gamma}{jC\omega} \quad (1)$$

As demonstrated in [11], errors in C may lead to substantial measurement errors in the calibrated DUTs. We extracted a value of $C = (1.599 \pm 0.039)$ pF/cm using a 2D finite element method simulation of the cross section of the inverted G-CPW transmission line, as reported in [11]. We varied the 2D simulation geometry guided by the process variation to estimate the uncertainty in C. This uncertainty bound accounts for the process variation in the calibration standards, which may affect our characterizations as the calibration kits have been measured on different sites of the wafer across different frequency bands. The resulting 2.4 % variation of the extracted C was smaller for the inverted G-CPW than a microstrip (6.6 %) with comparable Z_0 [11]

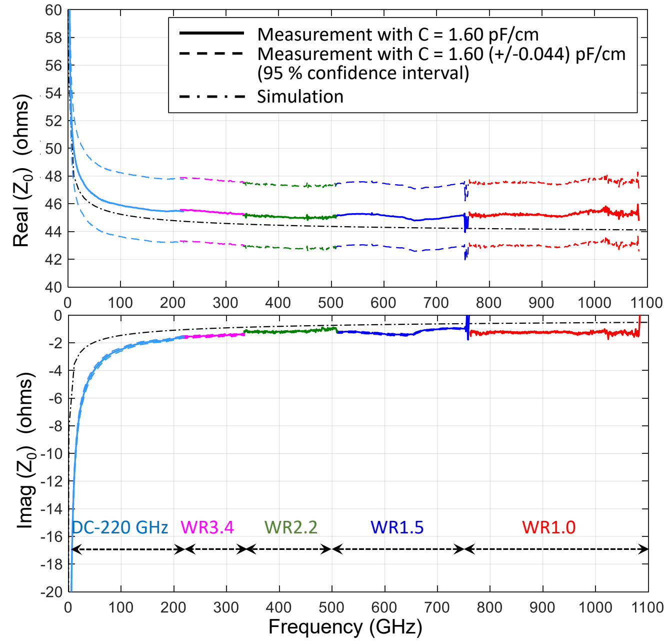

Fig. 3. Measurement and simulation of the complex characteristic impedance of the inverted G-CPW line from 0.1 GHz to 1.1 THz. Each color represents a band-limited measurement.

B. Measurement of the Charactistic Impedance of the Line.

Figure 3 shows the measured and simulated complex characteristic impedance of the inverted G-CPW line using (1) from 0.1 GHz to 1.1 THz. There are a few features that

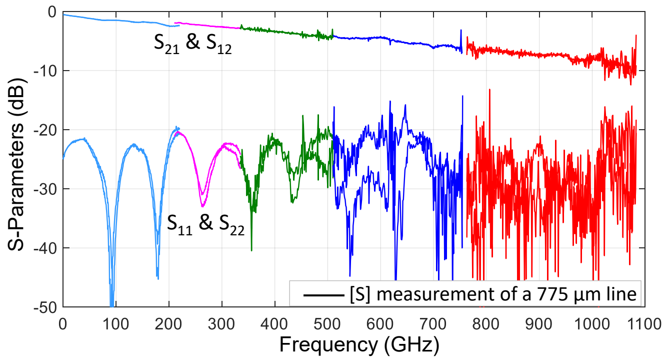

Fig. 4. S-parameter measurement of a 775 μm inverted G-CPW line length from 0.1 GHz to 1.1 THz. Each color represents a band-limited measurement.

merit some discussion in Fig. 3. First, the agreement between the predicted impedance and the measured value is with the 95 % confidence interval over the entire bandwidth. Second, the band-to-band continuity of the measured Z_0 supports the hypothesis that G-CPW topology has a single mode of propagation. Furthermore, the band-to-band continuity may indicate that the G-CPW topology suppresses higher-order modes and resonances with adjacent structures. Finally, the band-to-band continuity also indicates that we are not sensitive to the different models of RF probes used in the separate waveguide bands.

While our results are encouraging, we also noticed some discrepancies between the model and measurement that warrant some further investigation. For example, there is a discrepancy between the measured and simulated imaginary part of Z_0 below 100 GHz. Other discrepancies include features near 750 GHz and 1080 GHz. Isolated in small bands around these frequencies, the impedance shows some significant variations versus frequencies. We attribute these variations to the extender heads operated near edge of their operating bandwidths. Looking even closer at the data, we noticed what could be increased noise within the bands from 325 GHz to 500 GHz and from 750 GHz to 1100 GHz. We attribute this noise to the repeatable RF probing contacts in these two specific waveguide bands. This noise is directly observable in the measured S-parameters of a DUT (Fig. 4), but not outside these bands. Finally, the non-constant value of Z_0 observed above 500 GHz is attributed to the high insertion loss of the longest line that is used in the mTRL calibration.

C. S-parameters Measurement of a 775 μm Inverted G-CPW Transmission Line.

Figure 4 shows the calibrated S-parameter measurements of a 775 μm inverted G-CPW transmission line from 0.1 GHz to 1.1 THz that was used in the mTRL calibration. The transmission coefficients (S_{21} and S_{12}) are continuous and linear and expected to be around -10 dB at 1.1 THz. The reflection coefficients (S_{11} and S_{22}) do not exceed -20 dB across all five frequency bands. The good agreement and continuity demonstrate that we can accurately characterize the gain/attenuation of DUTs as well as reflection coefficients with -20 dB of accuracy over 1 THz of bandwidth. The noise observed above 325 GHz could be improved by performing repeatable RF contacts between the mTRL standards.

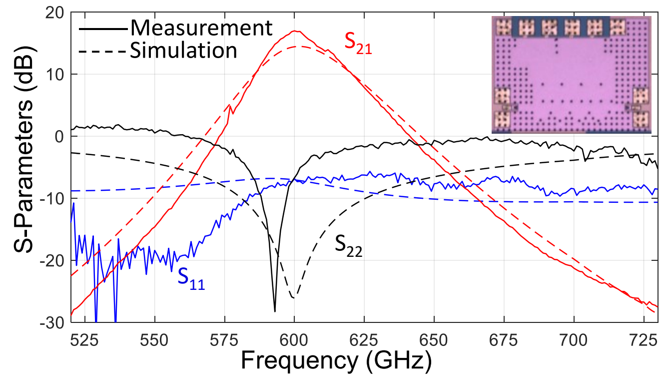

Fig. 5. S-parameter measurement and simulation of a 6-stage common-base amplifier from 500 GHz to 750 GHz using the inverted G-CPW calibration kit.

IV. 600 GHz Power Amplifier Characterization

Several active devices and circuits designed in the 130 nm HBT process have been characterized using the inverted G-CPW mTRL calibration kit. A tunable electrical comb generator based on an ultrabroadband mixer [12] has been reported from 140 GHz to 220 GHz. Diverse common-emitter and common-base HBTs were characterized in [11] from 220 GHz to 325 GHz. A state-of-the-art MMIC amplifier that exhibits over 19 dB of small-signal gain from 325 GHz to 477 GHz has been demonstrated in [13] and large-signal characterizations of MMIC common-base amplifiers were also reported in [14] at 498 GHz and 520 GHz.

Using a nonlinear HBT model provided by the foundry we designed and simulated a 6-stage common-base MMIC amplifier in the WR1.5 band (500 GHz to 750 GHz). The design approach follows the architecture of the amplifier reported in [14] that uses shunt lines. Each stage of the amplifier was biased with J_E=21.8 mA/μm^2 and V_{CB} = 0.78 V. The S-parameter measurement and simulation of this amplifier is presented Fig. 5 where we see that the MMIC exhibits over 10 dB of small-signal gain from 587 GHz to 621 GHz with a measured 17 dB peak at 600 GHz. Although some differences can be observed, we obtain very good agreement between the measured and simulated results. This comparison also demonstrates the effectiveness of the inverted G-CPW transmission line in suppressing higher-order modes to improve the S-parameter calibrations and measurement of active circuits in the THz frequency bands.

V. Conclusion

We demonstrated an inverted G-CPW mTRL calibration kit. The G-CPW topology 1) did not show evidence of coupling with adjacent structures and propagation of higher order modes, 2) limits radiation at the highest frequencies, 3) is compact, 4) is fabricated on a commercial semiconductor-based transistor process, and 5) permits active device characterization with well-defined reference planes under multiple layers of interconnects, improving the accuracy of the device and circuit models. Although continuous mTRL calibrations have recently been reported in the literature from 110 GHz to 1.1 THz [15], this work constitutes the first report in the literature of a novel approach to mTRL calibration kit designed on a commercial semiconductor-based transistor process with continuous measurements from 0.1 GHz to 1.1 THz. However, some perturbations, such as crosstalk, must still be considered to improve the accuracy of device characterization in the THz frequency bands.

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