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Development of gallium-arsenide-based GCPW calibration kits for on-wafer measurements in the W-band

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Abstract

We present details of on-wafer-level 16-term error model calibration kits used for the characterization of W-band circuits based on a grounded coplanar waveguide (GCPW). These circuits were fabricated on a thin gallium arsenide (GaAs) substrate, and via holes, were utilized to ensure single mode propagation (i.e., eliminating the parallel-plate mode or surface mode). To ensure the accuracy of the definition for the calibration kits, multi-line thru-reflect-line (MTRL) assistant standards were also fabricated on the same wafer and measured. The same wafer also contained passive and active devices, which were measured subject to both 16-term and conventional line-reflect-reflect-match calibrations. Measurement results show that 16-term calibration kits are capable of determining the cross-talk more accurately. Other typical calibration techniques were also implemented using the standards on the GCPW calibration kits, and were compared with the MTRL calibration using a passive device under test. This revealed that the proposed GCPW GaAs calibration substrate could be a feasible alternative to conventional CPW impedance standard substrates, for on-wafer measurements at W-band and above.

Introduction

A transistor is the fundamental element of complex monolithic microwave integrated active circuits and can be characterized using on-wafer measurements. There are commercial impedance standard substrates (ISSs), which allow different types of on-wafer calibrations, such as short-open-load-thru (SOLT) [1], line-reflect-match (LRM) [2], line-reflect-reflect-match (LRRM) [3], multi-line thru-reflect-line (MTRL) [4], *etc*. Commercial calibration standard substrates have appealing advantages of relatively low cost and good durability. These ISSs are usually based on thick ceramic substrates, with a thickness ranging from 250 to 600 µm, and are designed to have coplanar waveguide (CPW) structures. These ISSs provide off-wafer calibrations, when the devices are fabricated on gallium arsenide (GaAs), gallium nitride (GaN), or indium phosphide (InP). Off-wafer measurement impairs the accuracy of calibration, as reported in [5] and [6]. The deviation in *S*-parameter (scattering parameters) measurement, due to off-wafer effects, will become more significant as the frequency rises.

In recent years, on-wafer-level calibration, i.e., the Device Under Test (DUT) and the calibration kits have identical substrates, boundaries, and parasitical influences, and have been investigated extensively. A prescription for terahertz (THz) calibration kits was introduced in [7], and calibration-kit design guidelines for millimeter-wave use were described in [8] and [9] (these demonstrate an improved performance over off-wafer calibrations). Similar to ISSs, the 625-µm thick ceramic substrate calibration kits in [9] and the complicated calibration kits in [8] are not ideal choices for measurement of transistors fabricated on thin GaAs substrates. As the frequency rises, the substrate thickness could be reduced to 70 µm or less, to minimize parasitical resistance and inductance. Additionally, cross-talk between the probes may need to be taken into account at W-band frequencies and above [7], to achieve the desired measurement accuracy and results. To the best of the authors' knowledge, on-wafer-level calibration standards based on the thin substrate and operating at the W-band have not yet been reported in open literature. TFMSL (thin film microstrip lines) [10] have the appealing advantage of easing single-mode propagation and are therefore another promising type of transmission line for use at millimeter-wave and THz frequencies. Compared to the CPW type of structure, TFMSL is more difficult to access in a ground state: this may prevent its wider application in the design of active circuits.

We report on W-band on-wafer-level calibration kits, based on a grounded coplanar waveguide (GCPW) structure, and fabricated on a thin (70 µm) GaAs substrate.

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Thin substrates with a conductor on the back are undesirable, as they can easily excite parallel-plate modes which could degrade calibration accuracy [11, 12]. In this work, holes were utilized to suppress the excitation of parallel-plate modes. Sixteen-term calibration standards were designed for better predictions of cross-talk at these high frequencies. A comparison between 16-term and other on-wafer and off-wafer calibration methods was performed on both passive and active devices. The new GCPW calibration substrate was also employed to realize four conventional calibration methods. Investigation into their corresponding performance, with respect to MTRL, was conducted. The paper is organized as follows: Section "design of calibration kits" introduces the design of calibration kits, and Section "definition of the 16-term calibration" describes the definition of the calibration standards. Experimental results are presented in Section "experiment", which is followed by the conclusion in Section "conclusion".

Design of calibration kits

The 16-term error model calibration method, as described in [13 14], was utilized in this work. The 16-term calibration kits include a 400-μm-long thru line and six pairs of lumped elements: resistor–resistor, short–short, open–open, resistor–open, resistor–short, and open–short, all with 200 μm offset from the beginning of the line. To ensure the accuracy of the definition for 16-term calibration kits, the TRL calibration algorithm, as reported in [4, 15], has been utilized, with a calibration reference at the probe tips.

For the 16-term or MTRL to work, three requirements need to be fulfilled: (i) the transmission line should operate in quasi-transverse electromagnetic mode; (ii) resonances need to be eliminated within the frequency band of interest; and (iii) the characteristic impedance Z_0 of the transmission line should be uniform. In this work, the GCPW type transmission line, which is effectively a CPW with a finite metal boundary [16], has been adopted and the thickness of the GaAs substrate is 70 μm. Such a thick substrate with a conductor on the back can easily excite unwanted multi-modes, e.g. the parallel-plate waveguide mode and surface wave mode [17]. The ground-to-ground spacing (center conductor width w plus twice the gap g between the center conductor and the ground plane on each side) has been designed to help to maintain single mode propagation [18] and to achieve the desired Z_0. Parallel-plate waveguide modes between the topside ground plane and the conductor on the back can be suppressed by introducing holes connecting the top and bottom grounds. Parts of the calibration kits are shown in Fig. 1.

The Linecalc tool in the Advanced Design System was employed to determine GCPW ground-to-ground spacing. To achieve a 50 Ω characteristic impedance, w and g were calculated to be 26 and 22 μm, respectively. These calculations utilized a substrate dielectric constant of 12.9, a substrate thickness of 70 μm, a metal conductivity of 5.7×10^6 S/m and a metal thickness of 0.5 μm. Holes with a diameter of 30 μm were added between the topside ground and the rear conductor, and these holes are uniformly distributed along the GCPW line with the separation c, as shown in Fig. 1(b). The distance d, shown in Fig. 1(b), between the center of the holes to the edge of the ground plane was set to 45 μm. The optimum hole separation c was obtained from full-wave simulations in CST Microwave Studio [19]. The simulation results indicate that a separation c of 100 μm is desired, in terms of the ease of fabrication and a wide spurious free band.

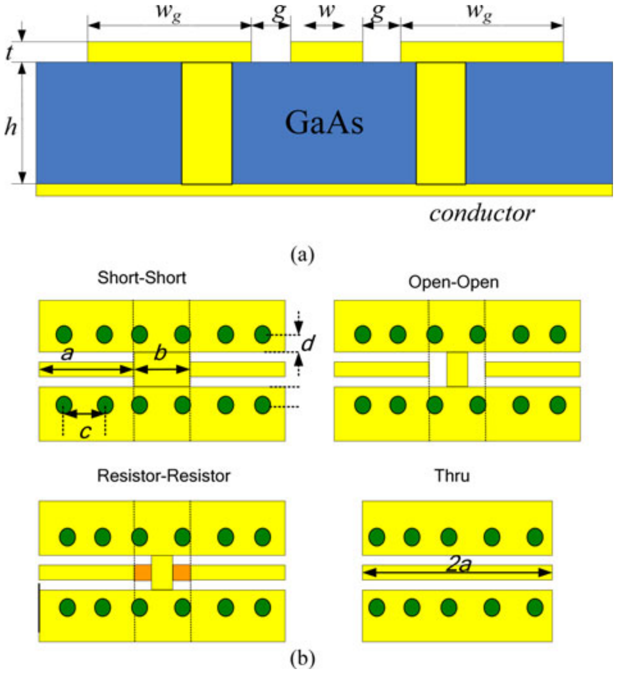


Fig. 1. Calibration standards. (a) Side view of CPW transmission line conductor on the back. (b) Short–short, open–open, resistor–resistor, and Thru elements.

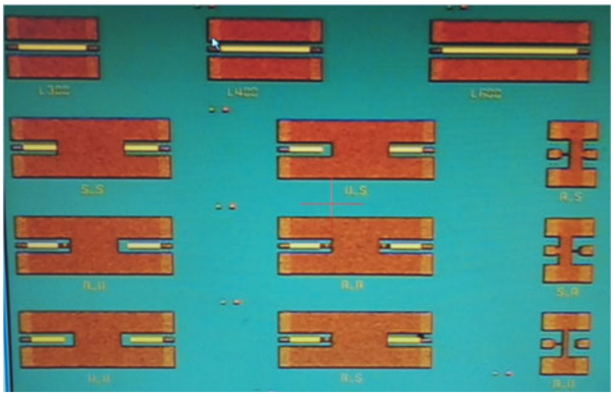
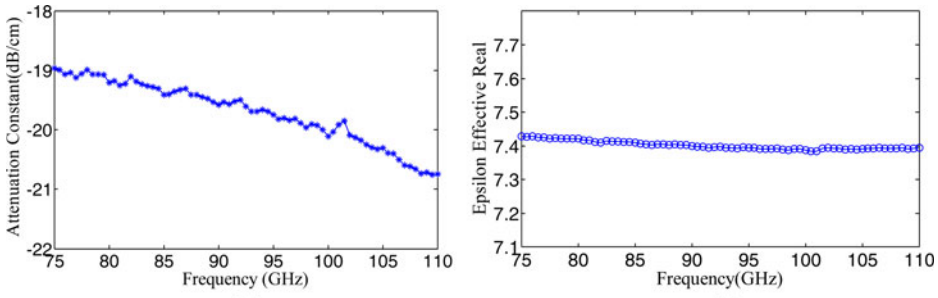


Fig. 2. Optical image showing parts of the fabricated standards.

Therefore, c was chosen as 100 μm in this work. Note that CST simulations assumed that the holes are perfect cylinders, however in practice these holes were fabricated to have sloping side walls owing to the etching process used. The influence of this is believed to be negligible. Figure 2 shows the layout of the final calibration kits.

Definition of the 16-term calibration

The MTRL calibration determines S-parameters directly in printed transmission lines and avoids many of the systemic errors associated with lumped calibrations. Here, the TRL calibration standards were fabricated with a 400-μm-long GCPW thru line (the identical Thru for 16-term), four lines with additional lengths of 100, 300, 500, and 2600 μm, and identical shorts with 16-term short–short elements. GaAs is a low-loss substrate material, and therefore it is feasible to calculate the transmission



(a) (b)

Fig. 3. Propagation constant and effective permittivity real part of the transmission line. (a) Attenuation constant and (b) effective permittivity (real part).

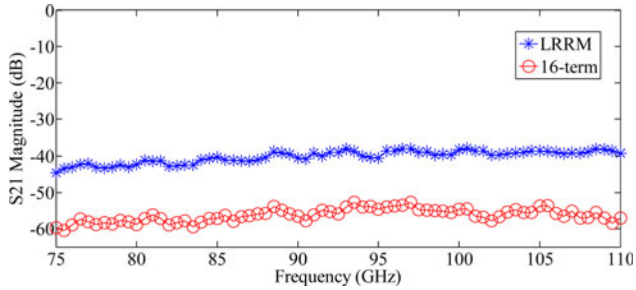


Fig. 4. Comparison of S_{21} responses between two calibration kits for resistor–resistor, as shown in Fig. 1(b).

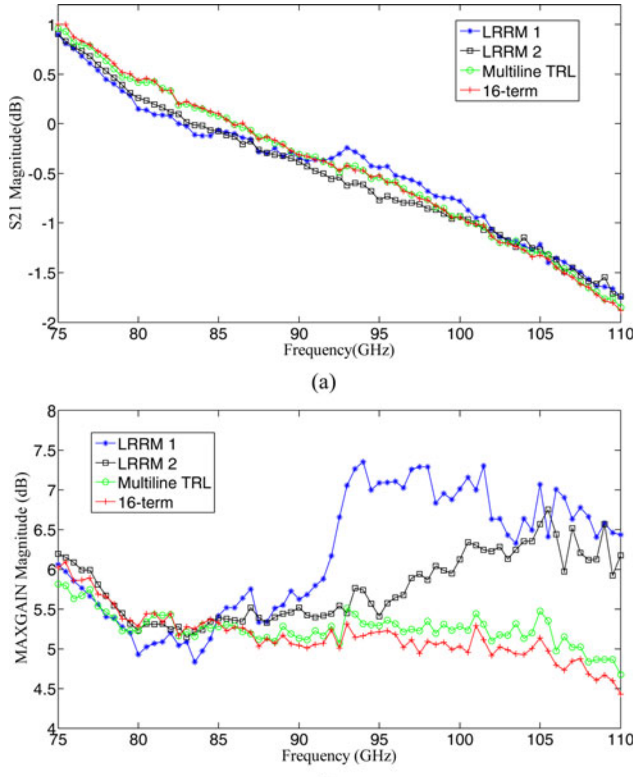
line capacitance [20], and to correct the reference impedance of the system to 50 Ω by following the method outlined in [21]. The transmission line was found, by measurement, to have a smooth attenuation constant and a flat effective permittivity (Fig. 3). This indicates that the transmission line operates mostly in single-mode propagation with little dispersion. Finally, 16-term calibration kits are defined by the MTRL corrected vector network analyzer (VNA) mentioned below, including a thru-line and the reflection coefficient of six pairs of lumped elements.

Experiment

The experimental set-up comprised: a Keysight N5245A, a Cascade 12 000 probe station, two OML W-band V10VNA2 extension modules, and two Cascade Infinity i110-T-GSG-100-BT probes. The pitch size of these probes is 100 µm. The DUTs are resistor–resistor and active high-electron-mobility-transistor (HEMT), both of which were fabricated on the same 70-µm-thick GaAs substrate with a conductor on the back. A single measurement of the raw (i.e., uncorrected) measurement data was acquired for each of these DUTs: a different calibration was then applied to the raw measurement data to obtain the corrected measurement data.

Measurement results: resistor–resistor

The GCPW calibration substrate includes two sets of resistor–resistor configurations with the same design. One of these was used as a standard for the 16-term calibration. Measurement was conducted on the other device, subject to two different types of calibrations, i.e., LRRM using ISS 104-783A and 16-term using the calibration kit developed here. In this work, Wincal XE 4.6 [22] was adopted to define and manage different calibrations. Figure 4 shows S_{21} responses (i.e., isolation) of the resistor–resistor. It can be observed that the 16-term calibration improves the isolation by around 10 to 15 dB, compared with the LRRM technique. This demonstrates that 16-term calibration kits are capable of factoring in the effects of cross-talk.



(a)

(b)

Fig. 5. Measurement results: (a) S_{21} magnitude and (b) Maxgain, associated with four calibration techniques. LRRM 1 corresponds to ISS on metal, LRRM 2 represents ISS on the absorbing material, MTRL and 16-term configurations were tested by using a GCPW calibration substrate placed on metal.

Measurement results: high electron mobility transistor

The pHEMT transistor with a gate width of 25 µm × 4 was measured without correction. Four different types of calibrations were then applied to the raw data, to get the corrected results. These four calibrations are: LRRM using ISS placed on metal, LRRM using ISS placed on the absorbing material, 16-term using the fabricated kit placed on metal, and MTRL using the fabricated kit placed on metal. Figure 5 illustrates the results of the transistor

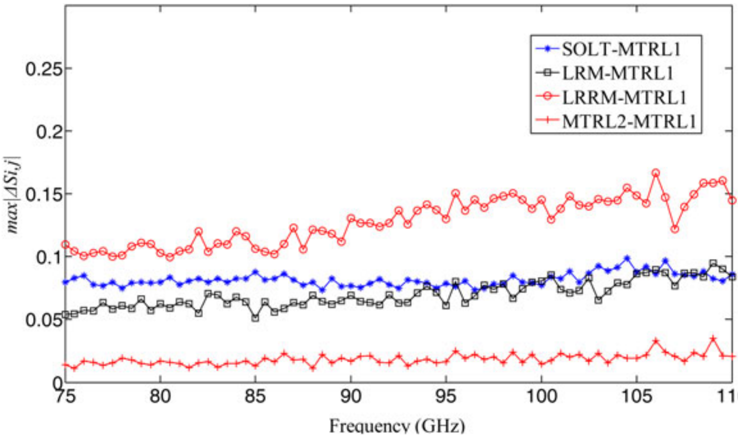


Fig. 6. Calibration comparison results between MTRL and SOLT (star), LRM (square), LRRM (circle), and another MTRL (plus).

subject to these four calibrations. It can be observed from Fig. 5 that the testing environment affects the ISS, with the absorbing material yielding the better result. There is good agreement between the results from MTRL and 16-term calibrations. This indicates that cross-talk is not a dominant factor in the measurement of transistors. Note that other transistors fabricated on the same batch were also found to produce similar results.

Comparison of different calibrations using standards on GCPW substrate

The fabricated GCPW calibration substrate was also used to implement different calibrations, i.e., SOLT, LRM, LRRM, and MTRL. A calibration comparison [5] was carried out to qualify the differences between these calibrations with respect to the MTRL (a well-known, and precise, technique). Figure 6 shows the maximum difference between the results obtained from MTRL and the other three techniques. LRRM returns the worst difference of 0.17, this may be attributed to LRRM's assumption of an intrinsic shunt-load [23]. SOLT and LRM demonstrate a promising result and exhibit a difference of less than 0.1 across the whole W-band. The small difference between the two MTRL results demonstrates the good measurement repeatability. As shown in Fig. 6, the difference between a MTRL and an LRM or LRRM calibration using standards pre-characterized with MTRL is higher than the system drift (i.e., MTRL2–MTRL1). It is believed that this is attributed to errors in fabrication, resulting in a characteristic impedance of the transmission line of 48.6 Ω and a match resistance of 51.8 Ω, instead of the designed nominal value of 50 Ω. This deviation can be addressed when the process becomes more developed.

Conclusion

Thin GaAs calibration kits based on GCPW structures have been presented. This new type of calibration kit enables accurate on-wafer-level measurements, at W-band frequencies and beyond. Sixteen-term calibration was conducted and was compared with off-wafer LRRM and on-wafer MTRL calibrations. The comparison, on both passive and active devices, demonstrates that 16-term is capable of better determining isolation: however, the difference between 16-term and MTRL is insignificant, and therefore the latter might be sufficient when cross-talk or isolation is not critical. Different calibration techniques were investigated using standards set by the new calibration kits. Generally, SOLT and LRM offered better results over LRRM, assuming MTRL gives an accurate and reliable result. This investigation was carried out at W-band frequencies, and all measurements were the on-wafer-level (i.e., the DUT and the calibration standards were fabricated on the same substrate). Overall, the work presented in this paper demonstrates the promising potential for the utilization of thin GaAs calibration kits, with GCPW structures, for high-frequency on-wafer-level probing.

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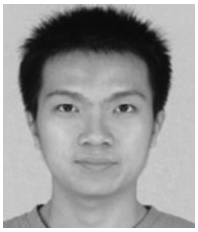

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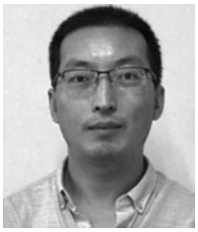

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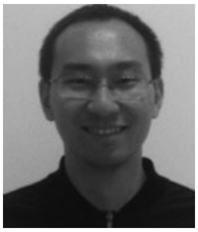

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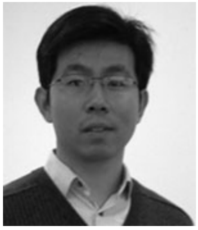

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