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Citation for the original published paper (version of record):
Blomberg, P., Cheron, J., Rodilla, H. et al (2025). Effects of ground-to-ground connections on coplanar waveguide calibration standards for
terahertz on-wafer measurements. International Conference on Infrared, Millimeter, and Terahertz Waves, IRMMW-THz, 2025. http://dx.doi.org/10.1109/IRMMW-THz61557.2025.11320108

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2025 50th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz) | 979-8-3503-7883-2/25/$31.00 ©2025 IEEE | DOI: 10.1109/IRMMW-THz61557.2025.11320108

Effects of ground-to-ground connections on coplanar waveguide calibration standards for terahertz on-wafer measurements

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***Abstract*—On-wafer measurements at terahertz frequencies remain challenging; discontinuities or asymmetries in coplanar waveguide (CPW) transmission lines can excite higher-order modes, leading to inaccurate calibration. In this work, we study the effects of two types of odd-mode suppression structures for CPW lines and compare them with a conventional design. The waveguides were fabricated on a semi-insulating InP substrate, and measurements were performed between 325 GHz to 1100 GHz. We show that by connecting the ground planes using air bridges, the accuracy of the calibration is improved. The probable reason is the suppression of the odd mode; however, secondary effects, such as crosstalk, require further investigation.**

I. Introduction

BEHIND the design of high-frequency electronics lies the necessity of accurate characterisation. A root cause of error stems from the uncertainties of the measurements, which are often propagated from inaccurate calibration. At terahertz frequencies, loads become increasingly difficult to characterise due to the reduced wavelengths and greater impact of parasitics, imposing specific requirements on the calibration methods used. One method which does not require an accurate load is the multiline-Thru-Reflect-Line (mTRL) [1].

Originating from the Thru-Reflect-Line, mTRL is an extension of this method, using several line standards to improve the calibration accuracy over a wider frequency range. However, the mTRL calibration builds upon the assumption of a single mode of propagation, which may result in multiple uncertainties. Probe radiation may generate crosstalk [2] and coupling with adjacent structures [3], forming several possible propagation paths. Misplacement of the probes leads to phase imbalance between the measurement reference planes and potentially asymmetric excitation. Additionally, the aforementioned coupling effects depend on both the chip design and the probe positioning, further amplifying the measurement errors.

Owing to its fabrication simplicity and low dispersion over a wide frequency range, CPW is a common choice for performing on-wafer characterisation. The conventional CPW consists of a centre conductor with a ground plane on each side, as seen in Fig. 1. The fields of the desired even mode are symmetric to the middle of the centre conductor. However, discontinuities and asymmetries can lead to the excitation of the unwanted odd mode, reducing the accuracy of the calibration. Moreover, as frequency increases, the propagation constants of parasitic substrate modes begin to exceed those of the CPW modes, leading to radiative losses and dispersion [4].

The design of the CPW lines plays a key role in the excitation and suppression of higher-order modes. It is recommended to minimize the coupling into these modes, requiring the design of the waveguides to have narrow gaps and widths, as well as thin substrates with low dielectric constants [5].

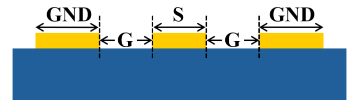

Fig. 1. Schematic cross-section of a conventional coplanar waveguide with finite ground and finite substrate.

In order to cancel the odd mode, the general consensus is to place a ground-to-ground connection after any discontinuities; however, to the best of the authors' knowledge, no comparative study on the impact of these connections has been conducted in the terahertz region. In this work, we compare the performance of two variations of ground-to-ground connected CPW mTRL calibration kits, one with a planar connection at the backside of the landing pad (Fig. 2(a)) and one with two air bridges located after the pad-to-line transition (Fig. 2(c) and (d)), to that of a conventional kit (Fig. 2(b)).

II. Method

The CPWs were designed using quasi-static conformal mapping techniques [6], and the resulting dimensions are seen in Tab. I. The design process was as follows. Initially, the desired characteristic impedance was set to 50 Ω and the substrate to 630 µm thick SI-InP. The substrate was chosen in accordance with our previous work [7]. Subsequently, a numerical analysis of possible geometrical combinations achieving the desired impedance was performed. To reduce radiation via substrate modes, the gap between the conductors and the total width, $\mathrm{W_{tot}} = \mathrm{S} + 2\mathrm{G} + 2\mathrm{GND}$, was kept small per the aforementioned design rules. However, the CPW had to accommodate the 25-µm and 50-µm-pitched probes available for measurements. This required a narrowing transition between the probe landing pad and the access line. The transition was designed to alter the dimensions over a 15 µm length while maintaining the characteristic impedance.

The CPW were fabricated using electron-beam lithography and evaporation of 10 nm/240 nm thick Ti/Au in a bilayer lift-off process. The air bridges were shaped by a resist reflow technique and consist of 10 nm/490 nm thick evaporated Ti/Au. Each type of CPW calibration kit was fabricated in three replicas on a single chip, where each set contains a thru, two reflect (short and open), and six line standards. The line lengths, presented in Tab. II, were optimised to provide significant delays between lines, enabling evaluation of calibrations using different combinations.

Measurements were conducted in the frequency bands WR2.2, WR1.5, and WR1.0 using a vector network analyser with frequency extender modules and micromachined

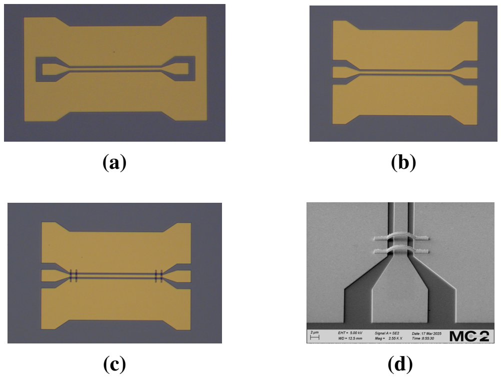

Fig. 2. Example micrographs of fabricated mTRL calibration kits. (a)-(c) Photomicrograph of thru-lines for the backshort, conventional and air-bridged kit, respectively. (d) Electron micrograph of an air-bridged line.

probes [8]. During measurements, commercial calibration software was used to perform preliminary calibrations and verify proper contact of the probes. Raw data were then collected from five consecutive sweeps with an IF bandwidth of 100 Hz. After averaging, calibrations were post-processed and analysed using the NIST Microwave Uncertainty Framework.

Tab. I. Dimensions of the launch pads

	S (µm)	G (µm)	GND (µm)	W_{tot} (µm)	Length (µm)
Pad	13	6.8	44	114.6	15
Line	3	1.5	44	94.4	50

Tab. II. Calibration line standards lengths

Thru	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6
0 µm	22 µm	31 µm	46 µm	70 µm	210 µm	500 µm

III. Results and Conclusion

For the three proposed types of calibration kits, we compare the results of mTRL calibrations performed with two optimised sets of lines; the first set contains only the shorter lines (1, 2 and 3), while the second one includes all six lines. In Fig. 3, we plot the attenuation (α) and phase (β) constants resulting from the measured complex propagation constant. Analysis of the first set of lines shows that the calibration fails to consistently predict α for all calibration kits. At the same time, β reveals that all kits succeed in WR2.2 and WR1.5 yet fail in the WR1.0 band. However, the air-bridged kit allows β to be estimated accurately everywhere except at the region around 950 GHz. Upon evaluating the second set, it becomes apparent that when longer lines are included, both α and β achieve much better performance for all three calibration kits. Additionally, the air-bridged version displays an overall flatter response of α compared to the others, indicating that higher-order propagation modes are suppressed. Nevertheless, anomalies remain for all calibration kits, especially in WR1.0. Fig. 4 reveals that the measured S_{21} for the reflect standards of all kits exceed -30 dB around 1 THz, implying significant crosstalk. Further investigation into the cause and effects of the parasitic coupling is required.

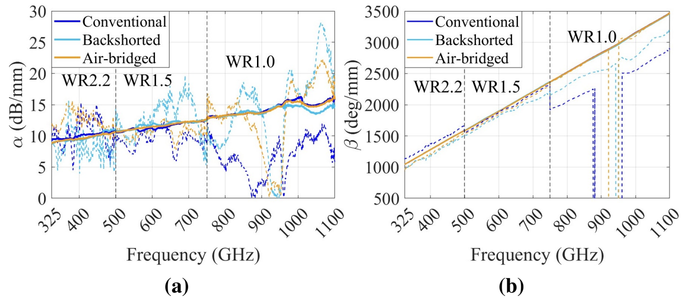

Fig. 3. Attenuation and phase constants extracted from the measured complex propagation constants of the calibration kits. Solid lines represent results using all six lines; dashed lines represent results using lines one, two, and three.

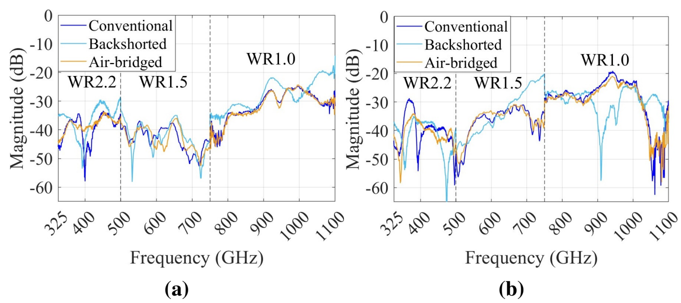

Fig. 4. Measured and calibrated S_{21} transmission parameters for the reflect standards of each calibration kit, obtained using the six-line calibration set. (a) Results for the short standards. (b) Results for the open standards.

IV. Acknowledgments

This work was supported in part by the WiTECH Centre CRYTER+ and the Swedish Foundation for Strategic Research, project number CHI19-0027. Measurements were performed in the Kollberg Laboratory, and fabrication was carried out at MyFab Chalmers.

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