Non-Contact Differential-Mode On-Wafer Device Characterization in the mmW and THz Bands

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***Abstract*—We present a novel on-wafer metrology technique for characterization of differential Millimeter-wave and Terahertz Monolithic Integrated Circuits (MMIC and TMICs) using a contact-free setting that relies on quasi-optical coupling of test signals onto the device on chip. Due to their advantages over single-ended topologies, differential circuits are typically preferred, particularly for superior noise performance. However, lack of characterization equipment at sub-mmW frequencies severely inhibits the proliferation of differential MMIC and TMICs. Currently, balun-integrated wafer contacting probes are most commonly used for mixed mode *S*-parameter measurements. Nevertheless, these probes are commercially available only up to 110 GHz with prototypes proposed up to 140 GHz. In this paper, initial validation of novel, non-contact, differential-mode on-wafer probes is presented with validations for the 220-325 GHz.**

***Index Terms*—differential amplifiers, differential on-wafer measurements, balun-integrated probes, sub-millimeter waves, terahertz, millimeter waves.**

I. Introduction

Compared to single-fed circuits, differential circuits offer key advantages. Noise associated with the common-mode signals is rejected by differential circuits, significantly improving signal-to-noise ratios and amplifier noise figures. Furthermore, amplifier stability is increased and even-order harmonics are automatically suppressed in differential circuits, reducing the level of intermodulation products and harmonics. Differential circuits also allow for higher voltage swing and thus yielding higher speeds. However, on-wafer characterization of differential circuits has been a challenge, particularly so for higher mmW frequencies and THz band applications.

Several approaches have been proposed for differential on-wafer measurements, starting initially with pure-mode vector network analyzers (PMVNA) in [1] for 3-dB coupled measurements. Scaling of this approach and its variations [2] into the THz frequencies is not possible due to equipment and interconnect limitations. As an alternative, balun-integrated probes were more recently proposed [3], [4], [5].

Despite a pressing need for differential on-wafer testing in millimeter-wave and sub-millimeter wave bands, balun-integrated contact probes are commercially available only up to 110 GHz. Recently in [3], a prototype was shown for W-band. Furthermore, contact probes are known to have several key drawbacks such as fragility, wear&tear issues which can further complicate scaling of balun-integrated probes into higher frequencies. Alternatively, a balun can be fabricated along with the device under test as shown in [6]. However, the fabrication of on-wafer baluns is fairly complicated, adding to overall cost and introducing fabrication uncertainties such as yield, and implies the necessity of implementation of on-wafer baluns for every device under test.

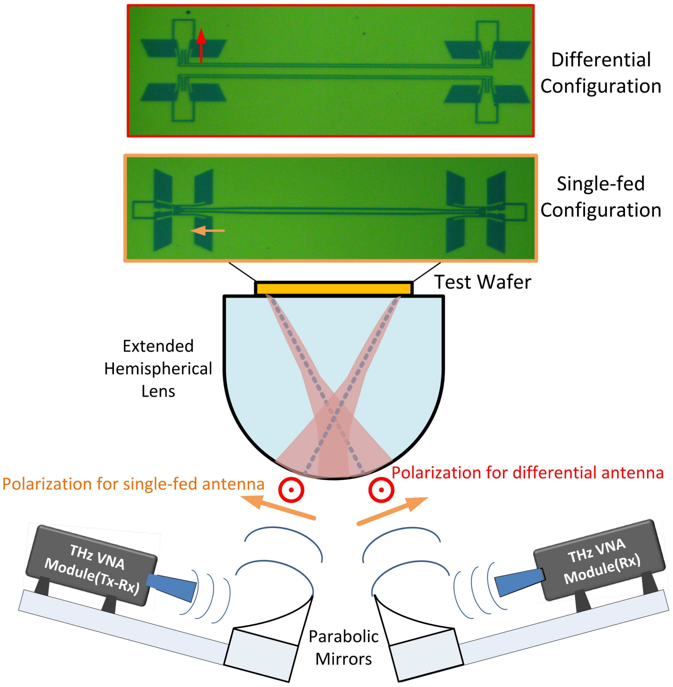
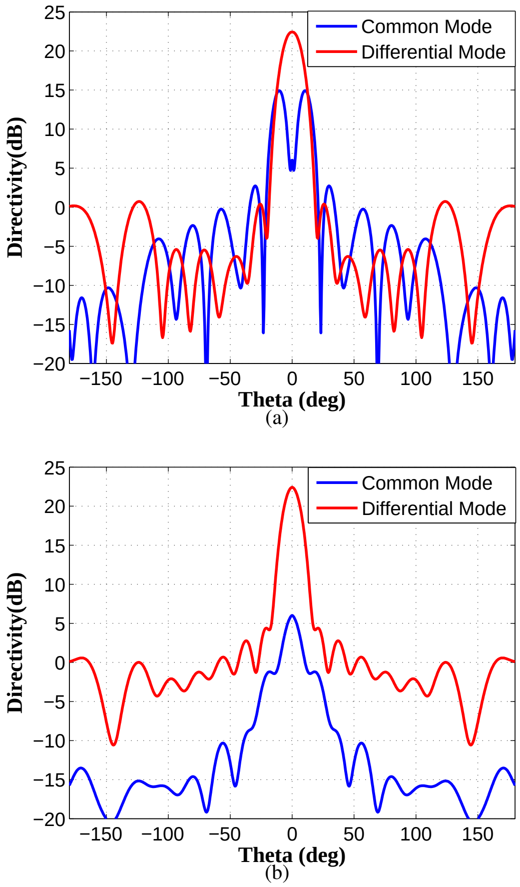


Fig. 1. Illustration of the differential non-contact probe setup for on-wafer characterization in the THz and mmW bands. Polarization for the differential on-chip antennas is adjusted using waveguide twists attached to the VNA extension module. As shown, the novel differential on-chip antenna's polarization is perpendicular to the previously demonstrated non-contact probe antenna for single-fed circuits.

In this paper, a novel, non-contact method for on-wafer characterization of differential circuits is presented based on the previously demonstrated non-contact metrology in [7] and [8]. Non-contact on-wafer metrology allows wear&tear free characterization of integrated devices and circuits by eliminating the need for physical contact with the wafer under test. As shown in Fig. 1, test signals are effectively coupled in and out of the on-wafer coplanar environment of the devices using butterfly-shaped dual-slot antennas that are impedance matched to standard 50Ω coplanar transmission lines. For differential-mode non-contact testing, the original butterfly-shaped on-wafer antenna is modified to interface with the



(a)

(b)

Fig. 2. Common-mode pattern of the differential non-contact probe antenna exhibits a null in the broadside direction, thus, any common-more return signal is radiated away from the test-port leading to excellent isolation of the common and differential modes: (a) E-plane cut showing the null in the broadside direction (b) H-plane cut showing the difference in directivity levels

dual feeding lines of the differential twin-CPW topology. The difference between the single-fed and differential-fed non-contact antenna is also shown in Fig. 1. Here, we demonstrate for the first time, differential-mode 1-port calibration and illustrate the common-mode rejection by the differential-mode antenna using the measurements conducted on mixed-mode calibration standard as detailed below.

II. Differential Non-Contact Probes

As mentioned above, most popular technique for differential on-wafer characterization are dual-tip probes with an integrated balun to suppress propagation of common-mode [3], [4], [5]. In the current work, the common-mode suppresion for non-contact metrology is achieved by a modified, the butterfly-shaped on-chip antenna. To do so, the antenna design and the feed structure, as well as the DC signal feed pads have been modified to interface with dual coplanar feed lines for differential testing. Perhaps most important aspect of this new design is the rejection of the common-mode signals due to the pattern null of the on-chip antennas. For a common-mode signal induced on the lines, the antenna pattern has a null in the broadside direction that prevents common-mode signal reaching to the VNA ports as illustrated in Fig. 2. Furthermore, the Gaussicity of the beam resulting from common-mode is orthogonal to the differential-mode beam. This provides excellent suppresion of the common-mode on the coplanar lines. The antenna design and pattern simulations were carried out using ANSYS HFSS v.15.

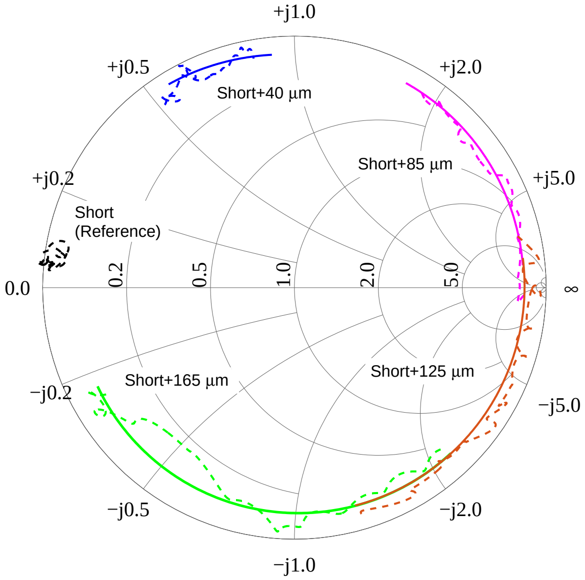
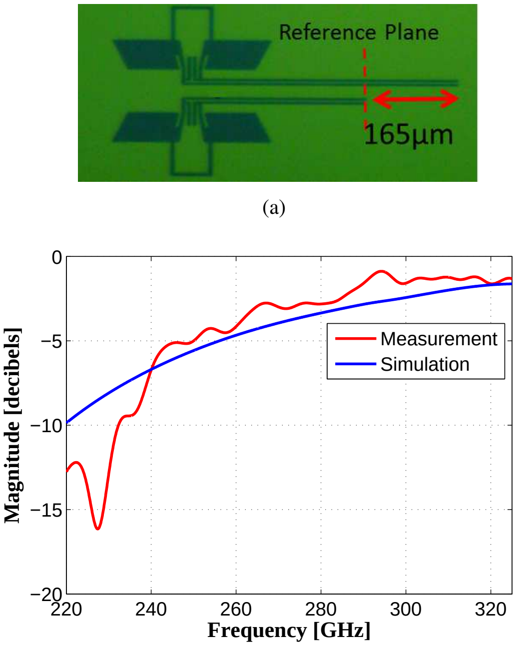


Fig. 3. Single-port, differential mode on-wafer calibration using 5 differential offset-short standards. After calibration, standards were re-measured and compared to simulations as described in [9]. Dashed lines are re-measured standards and solid lines are simulated results for the standards.

The 1-port calibration performance of the differential non-contact probes is shown in Fig. 3. First, the VNA is calibrated to waveguide flanges using a SOLT (Short-Open-Load-Thru) routine with waveguide standards. To this reference plane, a 90-degree waveguide twist and a diagonal horn antenna were attached. The 90-degree waveguide twist was included in order to adjust the polarization of the VNA test signal and the orientation of the differential antenna. Subsequently, an on-wafer calibration kit, comprised of symmetric offset-shorts (i.e. same offset for each port for each standard) is used for 1-port, on-wafer differential-mode calibration. This calibration inherently assumes only differential mode is propagated on both on-wafer ports.

Following this calibration, the standards used in the calibration were re-measured. Since redundant number of standards are used, the error terms are calculated with a least-squares fitting (non-linear) method. Thus, re-measurement of these standards can be regarded as a way to validate the calibration as outlined in [9]. In Fig. 3, re-measured standards are compared to the simulated responses in HFSS (v.15). As seen, there is excellent agreement between simulated and measured values, demonstrating the effectiveness of the calibration.

Secondly, a mixed-mode calibration standard is measured after this calibration to demonstrate the common-mode suppression by the antenna. For this purpose, the 1-port calibration



(a)

(b)

Fig. 4. A mixed-mode 1-port standard is measured after differential-mode calibration that assumes port symmetry. The feed arms have a 165μm difference, creating a phase difference close to 180 degrees towards the 220 GHz: (a) Micrograph of 1-port mixed-mode standard measured (b) Measured reflection signal after on-wafer differential-mode calibration

standard shown in Fig. 4(a) is chosen since there is a 165μm offset between on-wafer shorted ports of the two CPW lines. As illustrated in Smith Chart in Fig. 3, 165μm offset line yields a phase difference close to 180 degrees towards the 220 GHz. Thus, the return signal (S_{11}) is expected to drop significantly at the low end of the measurement band when this mixed-mode standard is measured. Indeed, as seen in Fig. 4(b), the measured reflection agrees with this expectation, showing a significant drop near the low frequency end.

III. CONCLUSION

Initial demonstration of non-contact, differential-mode on-wafer probes in 220-325 GHz band is presented for the first time. The advantages of non-contact technique include straight-forward scaling into THz band without the need of sophisticated fabrication procedures, unlimited testing cycles without degradation of testing equipment or the wafer under test and system modularity that requires only swapping of frequency extension modules while keeping the rest of the setup intact for measurements in different sub-bands. 2-port calibration and measurements are under way and will be presented at the conference.

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REFERENCES

[1] D. Bockelman and W. Eisenstadt, “Pure-mode network analyzer for on-wafer measurements of mixed-mode S-parameters of differential circuits,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 45, no. 7, pp. 1071–1077, Jul 1997.

[2] T. Zwick and U. Pfeiffer, “Pure-mode network analyzer concept for on-wafer measurements of differential circuits at millimeter-wave frequencies,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 3, pp. 934–937, March 2005.

[3] C. Zhang, M. Bauwens, N. Barker, R. Weikle, and A. Lichtenberger, “A W-band balun integrated probe with common mode matching network,” *2014 IEEE MTT-S International Microwave Symposium (IMS)*, pp. 1–4, June 2014.

[4] K. Jung, R. Campbell, P. Hanaway, M. Andrews, C. McCuen, W. Eisenstadt, and R. Fox, “Marchand balun embedded probe,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 56, no. 5, pp. 1207–1214, May 2008.

[5] J. S. Kim, W. Eisenstadt, M. Andrew, and P. Hanaway, “Analysis and design of impedance transformed balun integrated microwave probe for differential circuit measurement,” *2008 IEEE MTT-S International Microwave Symposium Digest*, pp. 56–61, June 2008.

[6] E. Ojefors, B. Heinemann, and U. Pfeiffer, “Subharmonic 220- and 320-GHz SiGe HBT receiver front-ends,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 5, pp. 1397–1404, May 2012.

[7] C. Caglayan, G. Trichopoulos, and K. Sertel, “Non-contact probes for on-wafer characterization of sub-millimeter-wave devices and integrated circuits,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 11, pp. 2791–2801, September 2014.

[8] C. Caglayan, G. C. Trichopoulos, and K. Sertel, “Non-contact probes for device and integrated circuit characterization in the THz and mmW bands,” *2014 IEEE MTT-S International Microwave Symposium (IMS)*, pp. 1–3, June 2014.

[9] L. Chen, C. Zhang, T. Reck, A. Arsenovic, M. Bauwens, C. Groppi, A. Lichtenberger, R. Weikle, and N. Barker, “Terahertz micromachined on-wafer probes: Repeatability and reliability,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 9, pp. 2894–2902, July 2012.