On-Chip “Baluntennas” for Differential-Mode Non-Contact Characterization of mmW/THz Devices and ICs

Abstract—**We present a novel on-chip, lens-integrated differential-mode double-slot antenna structure to enable isolated, pure differential-mode signal injection and interrogation for on-wafer devices and integrated circuits. Testing of on-chip differential devices and circuits conventionally requires Marchand-type baluns integrated either with the device or with the dual-tip contact-probes. Nevertheless, these state-of-the-art balun-integrated probes can cover only up to 110 GHz. In this work, we demonstrate a 180°-hybrid “baluntenna” based on a novel on-chip antenna design that concurrently acts as a high isolation balun. The baluntenna is integrated with the device-under-test and a quasi-optical link is used to effectively couple test signals into and out of the on-wafer ports of the device under test. As such, this approach allows, for the first time, non-contact, pure differential-mode characterization of on-chip devices and integrated circuits at well beyond 100 GHz.**

I. Introduction

Differential-mode excitation of on-chip devices and circuits has long been a challenge, particularly in the higher millimeter- and sub-millimeter-wave bands. Pure-mode vector network analyzers (PMVNA) [1] used in conjunction with four-port, dual-source VNAs are inherently limited to microwave spectrum due to equipment and interconnect limitations. As an alternative, balun-integrated probes have been proposed [2], [3]. In such micro-machined probe architectures, a Marchand-type balun is constructed within the dual, coplanar contact probe tip structure. As such, the balun converts the conventional test signal injected from the VNA port into an on-wafer, pure-differential mode excitation while suppressing any common mode signals emerging from the discontinuities in the fixture, or the on-chip device. However, this approach is rather costly to fabricate and expensive to maintain due to fragility of probe tips. Moreover, most recent prototype reported in [2] covers only up to 110 GHz, leaving much of the sub-mmW spectrum out of reach.

In this paper, we present a new on-chip antenna design that concurrently functions as a 180°-hybrid balun, called a “baluntenna”. The antenna design is based on a dual-slot butterfly topology integrated onto the focal plane of an extended hemispherical lens. Two such antennas are fabricated at the input and output ports of the on-chip device under test and a probing technique free of physical contact to the wafer is used to inject and receive the test signals quasi-optically, as shown in Fig. 1.

A similar coupling scheme was previously demonstrated in [4] for on-chip characterization of single-ended devices and circuits. With the new baluntenna structure developed here, the same setup can be used to convert the VNA test signal to a pure-differential mode excitation without an additional balun structure. As such, the need for an on-chip or probe-integrated balun is eliminated. More importantly, non-contact probing of differential devices and ICs can now be carried out with great ease in higher mmW and THz bands for the first time.

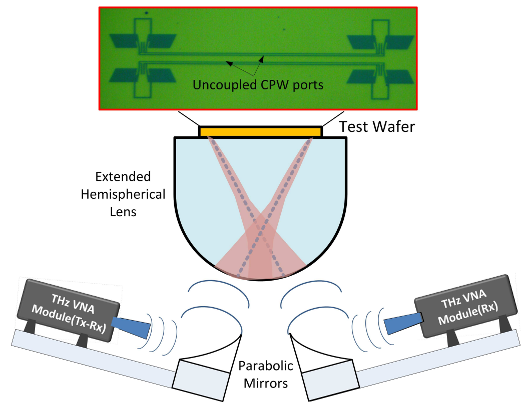

Fig. 1. Illustration of the differential non-contact probe setup for on-wafer characterization in the THz and mmW bands. The novel differential non-contact probe design is a quasi-optical 180°-hybrid, providing a pure differential-mode signal to the uncoupled twin coplanar lines to access device under test.

II. Differential-Mode Baluntennas as Non-Contact Probes

To create antenna structure that can launch purely differential signals to excite on-chip co-planar waveguide (CPW) pairs, the two slots of the antenna need to be fed by two symmetric CPW lines, parallel to the antenna slots, as shown in Fig. 1.In order to maximize isolation between on-wafer ports, the overall width of the 50Ω coplanar line was kept as small as possible and the CPW pair were designed far apart, without intruding the antenna slots. The lengths and distance between the slots were carefully designed to achieve a highly-directive radiation pattern over the entire operation bandwidth, which covers the *H*-band (220-325 GHz). This design exhibits highly-symmetric and directive (due to the hyper-hemispherical lens) radiation pattern as shown in Fig. 2. It is important to note that high directivity and pattern symmetry are essential for efficient coupling with the quasi-optical components in the non-contact test setup.

As seen in both 3D polar plots in Fig. 2(a) and 2(b) and *E*-plane patterns in Fig. 2(c), in-phase currents fed into antenna ports yields a null in the broadside direction as opposed to the single-lobed beam radiated when the ports are excited 180° out-of-phase. Moreover, the change in the overall directivity of the resulting beam in *H*-plane is shown in Fig. 2(d), indicating 25dB isolation between the two modes. Thus, the

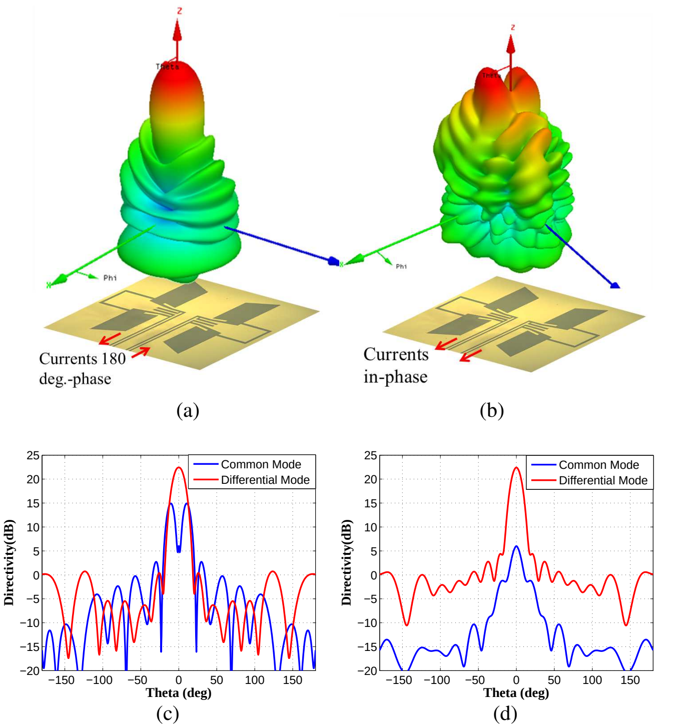

Fig. 2. Simulated radiation properties (at the midband) of the baluntenna: (a) Single lobe, Gaussian beam pattern when antenna ports are 180°out-of-phase (b) Two lobes with a null in the broadside direction when antenna ports are in-phase (c) *E*-plane patterns showing the null in the broadside direction. (d) *H*-plane patterns illustrating the difference in directivity levels.

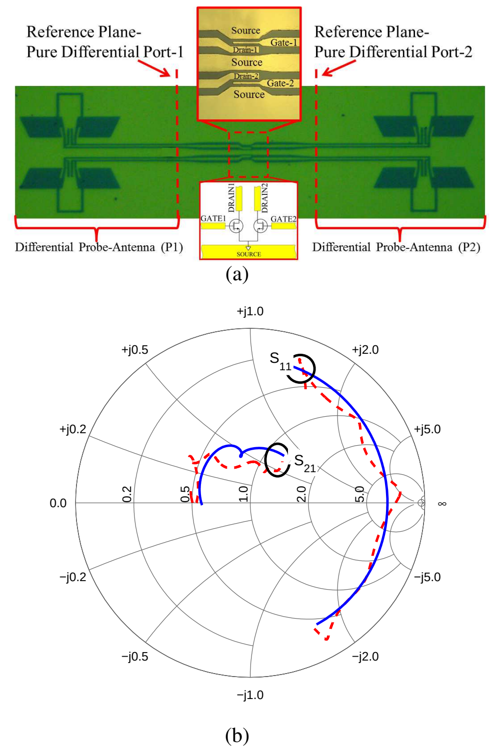

Fig. 3. Characterization of a HEMT structure (cold-no bias assumption): (a) Device under test integrated together with the differential-mode non-contact probes (b) Smith chart showing both measured (dashed) reflected and transmitted *S*-parameters compared to simulated (solid) responses.

combination of the quasi-optical link and the baluntenna behaves as a quasi-optical/THz-frequency 180°-hybrid. As such, the baluntenna provides pure differential-mode signals to the on-wafer CPW ports, while suppressing the any common mode propagation, thanks to the orthogonal radiation properties of the two modes.

The input impedance of the baluntenna is adjusted using the stubs around the feed area and the reactive part of the differential antenna impedance was kept as small as possible to maximize probe-to-probe power transfer. In addition, two probe landing pads are included for independent DC power injection into the two signal lines of the differential CPW.

III. Differential On-Wafer Measurements

By employing the aforementioned on-chip baluntenna in the context of non-contact probing, we provide here an example measurement of a differential high electron mobility transistor (HEMT), structure as shown in the inset of Fig. 3(a). The calibration and measurements were performed under pure-differential mode assumption and quick-offset-short procedure [4] was employed for the two-port calibration. Figure 3 also shows the micrograph of the on-chip fixture. As illustrated in Fig. 3(b) there is excellent correlation between the simulated and measured differential *S*-parameters, first-time in 220-325 GHz, validating the utility of the baluntenna.

IV. Conclusion

We demonstrated a novel differential-mode on-chip baluntenna design for non-contact probes and illustrated their utility for first-ever device characterization in the *H*-band (220-325 GHz) via full two-port, on-wafer measurements of a HEMT structure. In addition to circumventing major drawbacks associated with the reliability and cost of contact probes, as well as the complexity of an integrated balun, the new on-chip baluntenna provides an effective solution for differential-mode device and IC characterization. Moreover, differential non-contact probes can be easily scaled into the THz band due to theur quasi-optical nature.

References

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