Measurement Uncertainties in Millimeter Wave "On-Chip" Antenna Measurements

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Abstract—**As a result of recent technical and regulatory developments, the millimeter wave (mmw) frequency band (30GHz – 300 GHz) is being adopted for a wide range of applications. Based on array signal processing technologies used for 4G and MIMO, companies are developing small active array antennas operating throughout the millimeter-wave bands. These arrays may include radiating elements and feed structures that are a fraction of a millimeter in size and cannot be fed via a coaxial cable. Connection to the antenna is instead performed through a micro-probe, more commonly used in the chip industry. MVG-Orbit/FR has developed a compact antenna measurement system which integrates hardware and software necessary to provide antenna gain and radiation patterns of antennas fed with such a micro-probe.**

To evaluate uncertainties in the measurements of the Antenna Under Test (AUT) gain, directivity, efficiency, pattern, or VSWR, reference antennas are an invaluable tool. The authors have recently driven the development of a micro-probed chip reference antenna. This reference antenna was designed to be mechanically and electrically stable and with reduced sensitive to its mounting fixture and feeding method. Close agreement between measured and simulated characteristics has been achieved. With low losses, the antenna provides good dynamic range and confidence in the measured antenna efficiency and gain.

This paper will outline design requirements and present test results of 60 GHz Chip Reference antennas. Several dozen antennas have been tested. The related uncertainties in the micro-probed antenna measurements will be evaluated with particular emphasis on the gain calibration uncertainty. The paper will also describe the next steps towards developing a chip antenna gain standard, that should reduce gain uncertainties while also significantly simplifying the calibration process.

I. INTRODUCTION

The small features of mmw chip antennas (e.g. patch, and dipole elements printed on ceramic laminates) have led to industry adopting a coplanar micro-probe to interface the RF system to the AUT. The 1.85 mm and 1.0 mm coaxial connectors have significant interactions with the on-chip antenna and may have even greater impact on the measurement than a coplanar micro-probe. [1] An example of a chip antenna can be seen in **Error! Reference source not found.**.

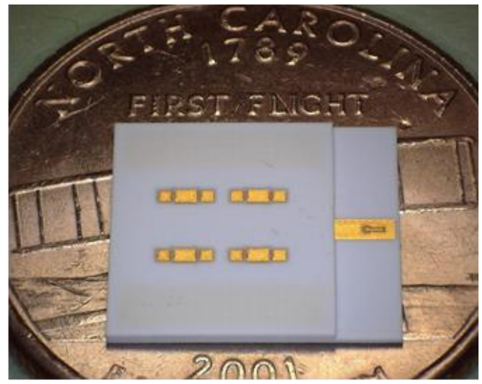

Figure 1: 60GHz 2x2 array chip antenna placed on a US Quarter

More details related to the design of this particular antenna intended to be used as a reference is given in [2]. A well characterized reference antenna can be an invaluable tool to characterize measurement uncertainties through the entire life cycle of an antenna measurement system. Situations where reference antennas are priceless include:

(1) Measurement System Initial Operational Validation (comparison to simulated gain and patterns)

(2) Showing repeatability between measurement systems (adding a new system to a lab or production floor or between an antenna manufacturer's test system and their customer's measurement system.)

(3) Characterizing new measurement systems

(4) Validating new antenna designs

(5) Monitoring product variations in production environments

(6) Measurement System Validation after repairs

(7) Vetting new processing algorithms

(8) Secondary calibration for drift characterization and evaluating required period between calibrations.

A. Reference Chip Antenna

The authors developed a set of reference antenna requirements to address system operators and technical support teams in validating the consistency of measured data. The following list highlights the key design goals for this reference antenna.

- Compatible with Standard CPW Microprobes (150-250µm pitch)
- Minimal interaction with support structure and microprobe:
    - Directivity > 12dBi
    - Control surface waves and other spurious radiation
- 60 GHz Center Frequency >10% Bandwidth
- $|S_{11}| < -10$dB
- Sufficient durability to support numerous probe landings (connections)
- Stable performance over time.
- Hermetic and not degraded by temperature swings
- High performance similarity between individual antennas, even between manufactured lots.
- Ability to accurately model antenna performances.

Since the field of mmw chip reference antennas is new, many of the goals listed above were qualitative rather than quantitative.

B. 60 GHz Chip Reference Antenna

1) Design Description

A four element array of aperture coupled patches was designed and built with three different feeding configurations to support two polarization orientations and feeding from the opposite side of the radiating elements (for "nadir" pointing antennas), The design incorporates Electronic Band-Gap (EBG) structures to suppress surface waves. A photo of an antenna is shown in Figure 2. This reference antenna was fabricated from DuPont 9K7 GreenTape LTCC material using Au metallization to form a hermetic package that is stable with respect to changes in humidity and temperature [2].

Figure 2: Photo showing three feed orientations for the 60GHz reference antenna. From left to right: i) zenith radiating with feed orthogonal to H-Plane, ii) nadir radiating with feed orthogonal to E-Plane, and, iii) zenith Radiating with feed orthogonal to E-plane.

2) Measurement Results

The test campaign began with Design Validation Tests (DVT) of the antenna key component features – not reported in this paper.

The first production yielded almost 60 vetted reference antennas. A sample of the test results are reported on in this paper. Each antenna was first measured for its return-loss. The results of the first 14 units are presented in Figure 3. This plot is a good example of quality and repeatability of the lot and the production process.

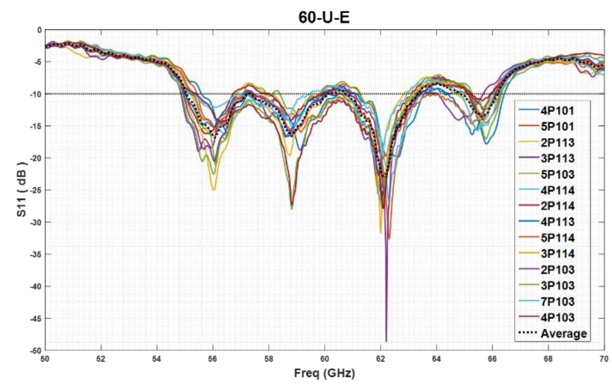

Figure 3: S11 First 14 units

The typical peak gain vs. frequency shows very good agreement with simulation and is plotted in Figure 4.

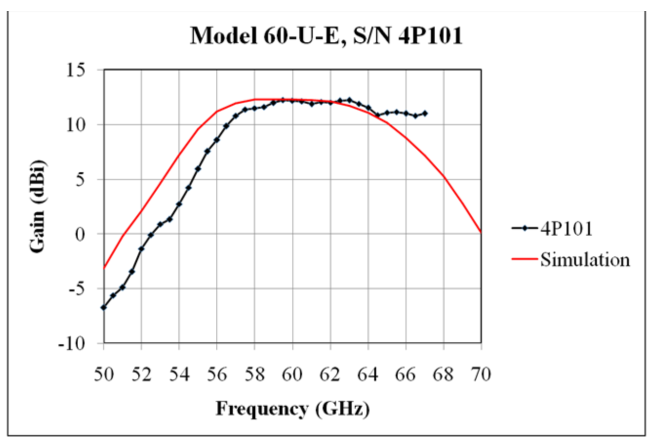

Figure 4: S/N 4P101 Peak Gain vs. Frequency

The E&H plan patterns are plotted against simulation and provided in Figure 5 & Figure 6 respectively.

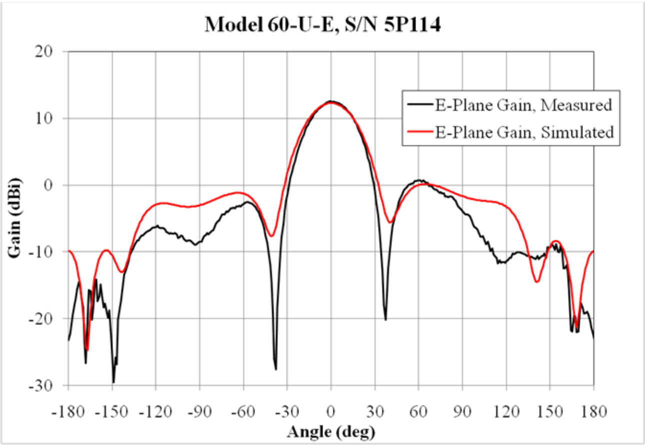

Figure 5: S/N 5P114 E-Plane Gain vs. Angle

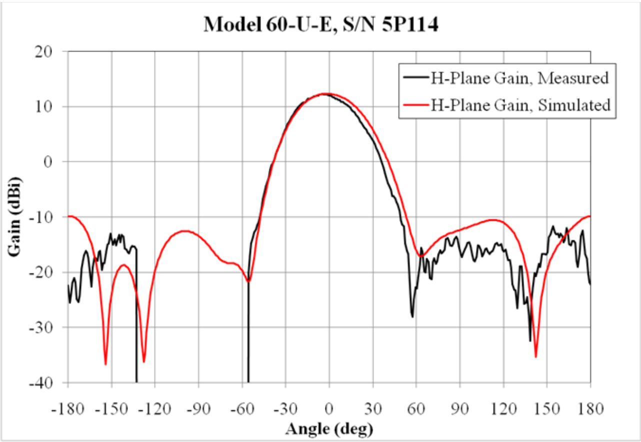

Figure 6: S/N 5P114 H-Plane Gain vs. Angle

C. Overview of an on-chip antenna measurement system

The authors have designed and developed a spherical mmw measurement lab. This system was configured for chip antenna measurements and used to characterize the chip reference antennas. This spherical near/far-field measurement system **(μ-Lab)** accommodates all necessary hardware and software for characterizing the chip antenna performances over nearly a full sphere [3].

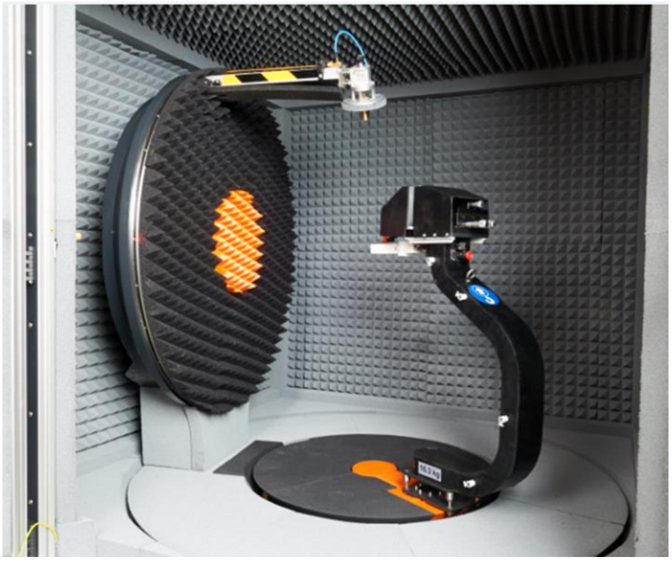

Figure 7: Photo of interior of the μ-lab test system configured micro-probing

Figure 7 shows the positioning system which allows a probe antenna to rotate in θ and ϕ over the sphere surrounding a stationary microprobe assembly with a low density foam "chuck" supporting the Antenna Under Test (AUT).

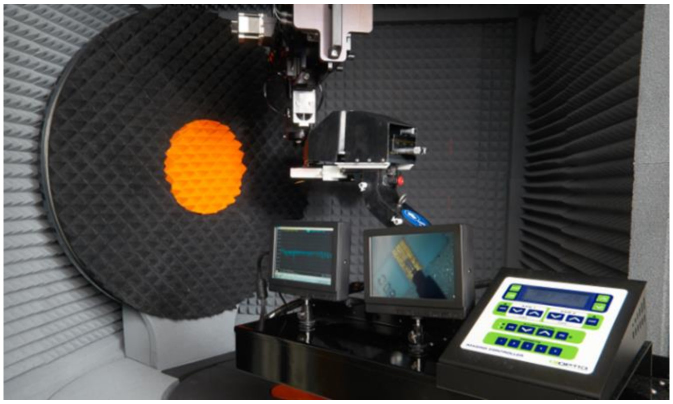

Figure 8: Photo of the chamber interior with the vision system and real-time S11 feedback to assist probe landing.

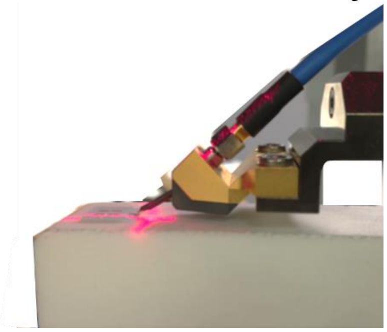

Figure 9: Picture of microprobe landing on the 60GHz reference antenna that has been placed on a low density chuck.

Red laser cross-hairs indicate the center of the measurement sphere.

1) *Simplified RF Block Diagram*

Although there are several manufacturers that promote single box network analyzers that function in mmw, the preferred solution for antenna measurements is to use remote mixing to compensate for the high cable losses at mmw frequencies. A simplified schematic of such a measurement system with micro-probed AUT is shown in Figure 10.

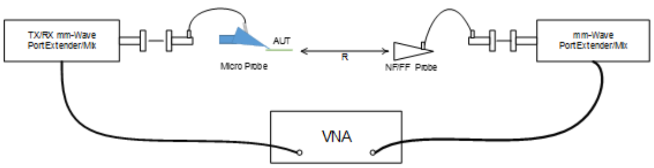

Figure 10: Simplified block diagram for a micro-probed antenna measurement using Port Extender Modules and Vector Network Analyzer

2) *Test Challenges*

On-Chip antenna measurement provide unique challenges and methods for mitigation of measurement error. These include: positioning system accuracy, unintended probe and DUT radiation [3][4]. While these are all important considerations calibration errors can often be the largest single uncertainty in an antenna measurement.

One unique calibration challenge to On-Chip measurements is compensation for the micro-probe. Therefore, good accuracy in micro-probe measurements require the measurement and compensation for both the mismatches and losses of the micro-probe. Techniques have been developed to derive the full scattering matrix of the micro-probe based on short-open-load calibrations at both the tip and at the coaxial connection point of the microprobe [5].

II. CALIBRATION METHODS

Achieving calibrated antenna gain is generally achieved through one of two methods: 1) Insertion Loss Measurement, or 2) Gain Transfer Method [6]. Each of these are described in more detail below and expanded for the case where measurements are made with a microprobe. Figure 11a shows the system schematics as used for AUT measurement and the two calibration techniques. If a good antenna gain standard would be available, it is quite obvious from the diagrams that when comparing the AUT measurement and the two calibration measurements, that the gain transfer method involves much less manipulations to the test setup.

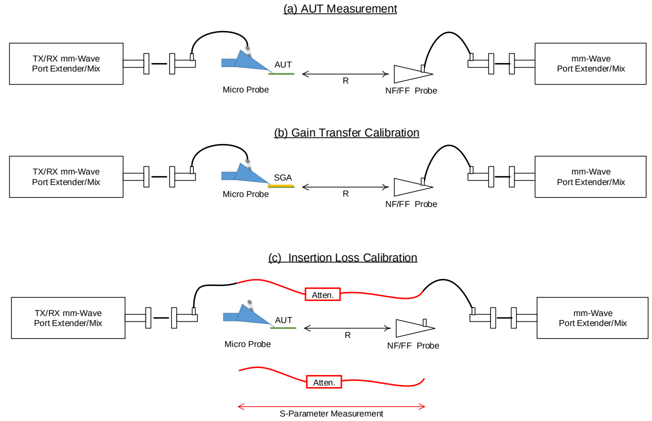

Figure 11: Simplified System Diagram for (a) AUT (Chip) Measurements, (b) Gain Transfer Method using on-chip gain standard, and (c.) Insertion Loss Method Calibration including the direct cable/attenuator S21 measurement.

A. *Insertion Loss Method*

The insertion loss method requires a S21 measurement between the transmission line connecting to the AUT and the line connecting to the measurement antenna (e.g. NF probe). To accomplish this, it is typically necessary to add cable(s) to overcome physical spacing and/or attenuator(s) to avoid saturation of the receivers. The Cable/Attenuator assembly has to be accurately characterized such that their losses and mismatch can be taken into account in the calibration (reference Figure 11 c).

When using a microprobe, an additional set of calibrations need to be performed [7]. A Short-Open-Load calibration is performed at the port connecting to the microprobe. A second Short-Open-Load calibration is performed using on-chip impedance standards. Based on these measurements the full two-port S-parameters are obtained for the micro-probe [5]. Great care needs to be taken by the operator when performing the port calibrations to ensure accurate results. The complete process is time consuming and can be difficult for a naivest operator.

Although complex source and receiver reflection coefficients at the output of the mmw modules may also be measured, this is often not a simple process in a chamber. While most antenna ranges do account for mismatch at probe and AUT ports, it is less common to rely on stability in the phase of the reflections coefficients. More commonly, mismatches are mitigated to acceptable levels through attenuators or isolators. However, for the de-embedding the microprobe (as mentioned above) full complex S-parameters are required. When properly performed, this calibration will remove any mismatch uncertainties at the input to the microprobe and at the feed point of the chip antenna.

A list of primary uncertainty terms related to gain calibration for the Insertion loss measurement is given below.

1. *NF Probe Gain Uncertainty*
2. *Attenuator/ Cable Assembly Loss/S-Parameter Measurement*
3. *Mismatch Uncertainty at AUT Feed Cable to Attenuator/Cable*
4. *Mismatch Uncertainty NF Probe Cable to Attenuator/Cable*
5. *Mismatch Uncertainty NF Probe Cable to NF Probe*
6. *Range length, or equivalently, the location of the phase center of the NF Probe as a function of frequency.*
7. *S-parameters of the micro-probe*

B. Gain Transfer Method(Substitution)

The gain transfer method involves the use of a known gain standard. The only change in the setup is the replacement of the antenna gain standard by the AUT as illustrated in Figure 11b.

Comparing the uncertainty terms from the Insertion Loss Method, we see the that the first item in the list "Probe Gain" is replaced with "Chip SGA Gain" uncertainty, and all other term fall-out. Hence, the primary uncertainty terms related to calibration are reduced from 7 to 1.

1. *Chip SGA Gain Uncertainty (assumed to include S11)*

When calibrating the first chip SGA, the only method available is the Insertion Loss measurement including all its error terms. Practically, however, the time and effort to calibrate a chip SGA, may be afforded a lot more time than the typical regular and frequent periodic calibrations required in a typical measurement lab.

III. CONCLUSION

Uncertainties in the measurements of the Chip Antenna Under Test (AUT) gain, directivity, efficiency, pattern, or VSWR, can be evaluated with the use of reference antennas. These devices can be invaluable tools for every measurement system. A Chip Based Reference antenna has been successfully developed and vetted for operation centered at 60 GHz.

A high level treatment of key calibration uncertainty terms along with a practical look at the standard calibration methods shows the need for a Chip SGA.

Development of a Chip SGA is a significantly and challenging undertaking. The authors have set in motion efforts in this direction.

IV. REFERENCES

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