Calibration of a Measurement System for High Frequency Nonlinear Devices

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Calibration of a Measurement System for High Frequency Nonlinear Devices

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Overview

- Introduction
- Vectorial “Nonlinear Network” Analyzer Hardware
- Accuracy of Broadband Sampling Oscilloscopes
- The “Nose-to-Nose” Calibration Procedure
- Absolute Calibration of a VNNA
- Consistency Check: Model versus Measurements
- Conclusions
• **Introduction**
  - Vectorial “Nonlinear Network” Analyzer Hardware
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  - Conclusions
The High-Tech World
Engineering Tools
Vectorial “Nonlinear Network” Analyzer

Amplitude & Phase

DUT

input output

a₁

b₁

a₂

b₂
• Introduction

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VNNA Hardware

Preexistent Prototypes

- Couplers
- Broadband Oscilloscopes
- Linear Network Analyzer Test Sets
- Synthesizers
- RF Switches

Measurements
- Amplitude & Phase
- Incident & Reflected
- Port 1 & Port 2

Amplitude Cal

Phase Cal

RF Power Meter

Ideal RF signal samplers
“Golden diode”
HP-NMDG Prototype

- Precision analog-to-digital converter
- 4 channel broadband downconvertor
- DUT (on wafer)
- Spec Sheet:
  - Bandw.: 18 GHz
  - Dyn. Range: 60 dB
Traceability Of Calibration

Amplitude Cal

Standards Lab
RF Power Meter

Phase Cal

“Nose-to-Nose” Calibration

Broadband Sampling Oscilloscope

Reference Waveform Generator
13

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Sampling Oscilloscope Basics

Trigger Level → DAC → TRIGGER → DELAY → CH1, CH2, CH3, CH4 → Screen

Delay Setting
Timebase Errors

Drift

HLog estimator
Log Spectral Averaging

Jitter

Noise rms
$= F(\text{signal derivative})$

Distortion

Phase Demodulation
## Vertical Errors

<table>
<thead>
<tr>
<th>Gain Offset</th>
<th>DC measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distortion</td>
<td>Limit Signal Amplitude</td>
</tr>
<tr>
<td>Dynamical Charact.</td>
<td>“Nose-to-Nose”</td>
</tr>
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</table>
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Impulse Response = Kick-Out

Dirac Delta

Precharged

Kick-Out
“Nose-to-Nose” Measurement

Measured Kick-Out
Systematic Measurement Error

Fourier transform of sampling aperture waveform

measured freq. response function

\[ M(\omega) = H(\omega) e^{j\phi(P(\omega))} \]

physical freq. response function

measured freq. response function

physical freq. response function

MEASUREMENT ERROR
Upperbound For Phase Error

Sampling Aperture:

- Positive
- 1 Local Max
- Finite In Time

Finite In Time Positive

Max. Error (degrees)

Frequency (GHz)
Comparison With Power Measurements

![Graph showing frequency response with labels for Low BW and High BW]
Repeatability and Noise

Amplitude

Phase

Frequency (GHz) vs. Amplitude Diff. (dB)

Frequency (GHz) vs. Phase Diff. (deg)
Sampler Linearity

![Graph showing amplitude differences (dB) vs. frequency (GHz)]
Frequency Response Function

**Amplitude**

![Graph showing amplitude in dB vs frequency (GHz)]

**Phase**

![Graph showing phase in degrees vs frequency (GHz)]
“Nose-To-Nose” Errors

(Frequency = 20GHz)

<table>
<thead>
<tr>
<th></th>
<th>Amplitude</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Distortion</td>
<td>8 mdB</td>
<td>0.02 deg</td>
</tr>
<tr>
<td>Timing Jitter</td>
<td>150 mdB</td>
<td>/</td>
</tr>
<tr>
<td>Time Drift</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Repeatab., Noise</td>
<td>20 mdB</td>
<td>0.15 deg</td>
</tr>
<tr>
<td>Nonlinearity</td>
<td>&lt; 20 mdB</td>
<td>&lt; 0.15 deg</td>
</tr>
<tr>
<td>Unknown Phase</td>
<td>/</td>
<td>0.72 deg</td>
</tr>
</tbody>
</table>
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Error Model

Definition of Variables
Calibration

\[ |K^i| e^{j\phi(K^i)} \]

\[
\begin{bmatrix}
1 & \beta_1^i & 0 & 0 \\
\gamma_1^i & \delta_1^i & 0 & 0 \\
0 & 0 & \alpha_2^i & \beta_2^i \\
0 & 0 & \gamma_2^i & \delta_2^i \\
\end{bmatrix}
\begin{bmatrix}
a_{i m1} \\
b_{i m1} \\
a_{i m2} \\
b_{i m2} \\
\end{bmatrix}
= 
\begin{bmatrix}
a_{i d1} \\
b_{i d1} \\
a_{i d2} \\
b_{i d2} \\
\end{bmatrix}
\]

classical calibration (LOS, LRM)
Absolute Calibration

Amplitude

Phase

reference gen.

power sensor
On Wafer: Reciprocity

- Power sensor
- Reference gen.

Data Acquisition

Line

APC-3.5

Reciprocity

Probe tip
The Reference Generator

trigger signal
1.5 m SMA cable
differentiator
20dB att.

1 GHz amplifier (0.5 W)

SRD module

APC-3.5 conn. (m)

Amplitude (mV)

Time (ps)
Absolute Calibration Factor

Amplitude

Phase

Frequency (GHz)

Amplitude (dB)

Phase (deg)
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Model vs. Measurements

- Large Signal Model (Root or Jansen et al.)
- s-parameters as a function of DC bias
- Simulation
- VNNA Data
Early Results

MESFET transistor (INTEC-UG, IMEC): HDA, fundamental 3GHz

- : Root-model
● : VNNA measurements
More Advanced Results

HEMT transistor (ESAT-KUL, IMEC): HDA, fundamental 3GHz

- : Jansen et al. model
- : VNNA measurements
Time Domain

- : VNNA measurement
- : Jansen et al. model
• : incident voltage wave
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Conclusions

• The Instrumentation And Calibration Procedure Developed Allows the Accurate Measurement of Phase and Amplitude of the Spectral Components of Incident and Scattered Voltage Waves at the Signal Ports of a Nonlinear Microwave Device.

• The Relative Calibration And Amplitude Calibration Are Traceable To National Standards, The Phase Calibration Is Traceable To The “Nose-To-Nose” Calibration Procedure.
Future Research

• Phase Calibration Traceable To National Standards
• More Theoretical Work Concerning “Nose-To-Nose”
• Implementing The “Nose-To-Nose” For Photo-Conductive Samplers
• Putting Error Flags On VNNA Measurements
• Towards Commercial Use Of VNNA