Millimeter-wave load-pull techniques

Original

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- Large Signal Characterization at high frequency
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- A W-band on-wafer load-pull system
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Large signal Characterization

<table>
<thead>
<tr>
<th>Basics</th>
<th>Applications</th>
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</thead>
<tbody>
<tr>
<td>▶ Linear characterization (small signal) provides full information as long as the device under test (DUT) can be considered linear</td>
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<td>▶ e.g. passive components, transmission lines</td>
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<td>▶ Active devices show nonlinear behavior when excited in realistic (large signal) conditions</td>
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<tr>
<td>▶ The extension of S-parameters to X-parameters might be too complicated</td>
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<tr>
<td>▶ What information do we really need?</td>
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Many applications require measuring a few device performances in CW, while exciting its nonlinearities

Examples:

▶ Performance/technology evaluation
▶ Circuit design
▶ Large signal models refinement
▶ Reliability/failure tests
▶ Production tests

Introduction

Basics of Large signal Characterization

We focus on the simplest example: a two port active device (a transistor in common source configuration) fed with a single CW tone @ \( f_0 \)

Interesting performances:

▶ DC power, \( P_{DC} = V_G S I_G + V_D S I_D \)
▶ Output power: \( P_{OUT} = |b_2|^2 - |a_2|^2 @ f_0, 2f_0, \ldots, nf_0 \)
▶ Gain = \( P_{OUT}/P_{IN} @ f_0 \)
▶ Power added efficiency, \( PAE = (P_{OUT} - P_{IN})/P_{DC} @ f_0 \)

Influence parameters:

▶ Bias point (DC supply)
▶ Frequency \( f_0 \)
▶ Input power: \( P_{IN} = |a_1|^2 - |b_1|^2 \)
▶ \( \Gamma_L = a_2/b_2 @ f_0, 2f_0, \ldots, nf_0 \)
Load-pull measurements

- A simplified block scheme of an \textit{on-wafer} load-pull measurement system

- On-wafer “environment” adds complications
  - calibration
  - additional losses

\[
\begin{align*}
\text{ATT1} & \quad \text{AMP1} \\
& \quad \text{attenuators} \\
\Gamma_{\text{in}} & \quad \Gamma_{\text{L}} \\
\end{align*}
\]

Load-pull calibration – vector calibration

- Vector “VNA-like” calibration

\[
\begin{align*}
\text{On-wafer or} \\
\text{calibration substrate} \\
\text{standards}
\end{align*}
\]
Load-pull calibration – vector calibration

- Vector “VNA-like” calibration

On-wafer or calibration substrate standards

Load-pull calibration – power calibration

- Power calibration

On-wafer or calibration substrate thru

WG or coax standards + power meter

Introduction Large signal characterization A W-band on-wafer load-pull system Measurement examples
Load-pull calibration

- After calibration it is possible to modify the setup at the right of reflectometer 2 and at the left of reflectometer 1, without affecting calibration.

### Solutions for tunable loads

**Mechanical Tuners**
- Main issue: gamma limitation
- Losses cannot be compensated
- 2.5 dB losses reduce $|\Gamma| = 1$ to $|\Gamma| = 0.56$
- 0.2 dB losses reduce $|\Gamma| = 1$ to $|\Gamma| = 0.95$

**Active Load – open loop**
- Main issue: gamma varies with $P_{OUT}$
- Compensated by iterations

### Introduction
- Large signal characterization
- A W-band on-wafer load-pull system
- Measurement examples
Solutions for tunable loads

Mechanical Tuners

- Main issue: gamma limitation
  - Losses cannot be compensated
  - 2.5 dB losses reduce $|\Gamma|=1$ to $|\Gamma|=0.56$
  - 0.2 dB losses reduce $|\Gamma|=1$ to $|\Gamma|=0.95$

Active Load – closed loop

- Main issue: possible oscillations
  - Reduced risk when losses are reduced

Introduction

A W-band on-wafer load-pull system

Measurement examples

Large signal characterization

Load-pull measurements above 60 GHz

Mechanical Tuners

- Mechanical tuners exist (sold by main vendors) in the millimeter-wave range, up to 110 GHz
  - require pre-calibration
  - Including probe and set-up losses, 0.5-0.6 gamma is reachable on-wafer

References

# Load-pull measurements above 60 GHz

## Active Loads

- Open loop active loads combined with
  - 6-port measurements
  - Mixed signal measurement technique

## References


## In Situ Tuners

- "In-situ" (integrated)
  - Still gamma limited
  - Integration required
  - no real-time

## References

94 GHz on-wafer active-loop load-pull system

- Mechanical tuners with pre-calibration: less accurate than real-time

- Mechanical tuners with real-time measurements: reduced gamma (0.5 maximum is typical)

- In situ tuners: integration with the device / highly developed fabrication capabilities

- Active loads with real-time measurements are a good solution, not yet widely diffused

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Realized at MWE laboratory, D-ITET, ETH Zürich, Switzerland
94 GHz on-wafer active-loop load-pull system

- Simplified block diagram (*)

Novelty – the down-conversion-based active loop

- Similar techniques exist to realize IF loads, at a few hundreds of MHz


Load-pull system calibration – step 1

- SW1 and SW2 in position 1
- On-wafer (or calibration substrate) standards are connected and measured
Load-pull system calibration – step 2

- SW1 in position 2 and SW2 in position 1, thru connection

Measurement Phase

- SW1 in position 1 and SW2 in position 2
- It is possible to modify the setup (add a circulator, or a spectrum analyzer) at the right of reflectometer 2 and at the left of reflectometer 1, without affecting calibration
Residual error comparison

- A “thru” (on-wafer direct connection) should have 0 dB gain
- Its gain variation vs. $\Gamma_L$ is taken as an estimation of the accuracy of the measurement

Measurement examples

- 0.1x100µm² GaN HEMT
  - $V_{DS}=5$ V, $V_{GS}=-3$V (class A)
Measurement examples

- 0.3x8.4µm² InP/GaAsSb DHBT
  - \(V_{CE}=1.6\,V\), \(V_{BE}=0.75\,V\) (class AB)

![Graph showing power and efficiency characteristics]

Introduction

Large signal characterization

A W-band on-wafer load-pull system

Measurement examples

Conclusions

- Basics of large signal characterization
  - Mechanical tuners vs. active loads

- Existing solutions for large signal characterization at high frequencies

- W-band, down-conversion active loop, on-wafer load-pull system

- accuracy
- measurement examples