Millimeter-wave load-pull techniques

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Millimeter-wave load-pull techniques

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Outline

- Introduction
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  - Applications
- Large Signal Characterization at high frequency
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- A W-band on-wafer load-pull system
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  - Calibration and accuracy verification
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Large signal Characterization

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<td>• Linear characterization (small signal) provides full information as long as the device under test (DUT) can be considered linear&lt;br&gt;  • e.g. passive components, transmission lines&lt;br&gt; • Active devices show nonlinear behavior when excited in realistic (large signal) conditions</td>
<td>• Many applications require measuring a few device performances in CW, while exciting its nonlinearities&lt;br&gt; • Examples:&lt;br&gt;  • Performance/technology evaluation&lt;br&gt;  • Circuit design&lt;br&gt;  • Large signal models refinement&lt;br&gt; • Reliability/failure tests&lt;br&gt; • Production tests</td>
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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:<br>  • DC power, $P_{DC} = V_{GS}I_G + V_{DS}I_D$<br>  • Output power: $P_{OUT} = |b_2|^2 - |a_2|^2 @ f_0, 2f_0, \ldots, nf_0$<br>  • Gain = $P_{OUT}/P_{IN} @ f_0$
  • Power added efficiency, PAE = $(P_{OUT} - P_{IN})/P_{DC} @ f_0$

• Influence parameters:<br>  • Bias point (DC supply)<br>  • 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 on-wafer load-pull measurement system

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

Load-pull calibration – vector calibration

- Vector “VNA-like” calibration

On-wafer or calibration substrate standards
Load-pull calibration – vector calibration

- Vector “VNA-like” calibration

Load-pull calibration – power calibration

- Power calibration

On-wafer or calibration substrate standards

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 set up at the right of reflectometer 2 and at the left of reflectometer 1, without affecting calibration.

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 – open loop

- Main issue: gamma varies with $P_{OUT}$
  - Compensated by iterations
Solutions for tunable loads

Mechanical Tuners

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

Active Load – closed loop

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

References


Load-pull measurements above 60 GHz

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

### References

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### 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

Introduction A W-band on-wafer load-pull system
Measurement examples

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 set up (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

**Introduction**

A W-band on-wafer load-pull system

**Measurement examples**

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

- 0.3x8.4\,\mu\text{m}^2\,\text{InP/GaAsSb\ DHBT}
  - \( V_{CE}=1.6\,\text{V},\ V_{BE}=0.75\,\text{V}\) (class AB)

- \( V_{CE}=1.6\,\text{V},\ V_{BE}=0.75\,\text{V}\) (class AB)

Introduction
- A W-band on-wafer load-pull system

Large signal characterization
- 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