Millimeter-wave load-pull techniques

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Millimeter-wave load-pull techniques

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Outline

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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
- Measurement examples
- Conclusions
Large signal Characterization

<table>
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<th>Basics</th>
<th>Applications</th>
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| • Linear characterization (small signal) provides full information as long as the device under test (DUT) can be considered linear  
  e.g. passive components, transmission lines  
  • Active devices show nonlinear behavior when excited in realistic (large signal) conditions  
  • The extension of S-parameters to X-parameters might be too complicated  
  • What information do we really need? | • 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 | Large signal characterization | A W-band on-wafer load-pull system | Measurement examples

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, \( P_{DC} = V_{GS} I_G + V_{DS} I_D \)
  • Output power: \( P_{OUT} = |b_2|^2 - |a_2|^2 \) @ \( f_0, 2f_0, \ldots, n\ell \)
  • 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: \( P_{IN} = |a_1|^2 - |b_1|^2 \)
  • \( \Gamma_L = a_2/b_2 \) @ \( f_0, 2f_0, \ldots, n\ell \)
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

![Diagram of vector calibration setup]

On-wafer or calibration substrate standards

Load-pull calibration – power calibration

- Power calibration

![Diagram of power calibration setup]

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

- 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 $|\Gamma|=0.95$

- Main issue: gamma varies with $P_{\text{out}}$
  - Compensated by iterations
## 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

### Large signal characterization

- 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

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

### Measurement examples

### Load-pull measurements above 60 GHz

**References**

### Load-pull measurements above 60 GHz

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

#### References

### Load-pull measurements above 60 GHz

#### 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
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


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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

![Graph showing residual error comparison.](image)

Measurement examples

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

![Measurement example graph.](image)
Measurement examples

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

Introduction

A W-band on-wafer load-pull system

Large signal characterization

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