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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  - Calibration and accuracy verification
- Measurement examples
- Conclusions
### Large signal Characterization

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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 |
| - Many applications require measuring a few device performances in CW, while exciting its nonlinearities |
| - Examples:  
  - Performance/technology evaluation  
  - Circuit design  
  - Large signal models refinement  
- The extension of S-parameters to X-parameters might be too complicated |
| - Reliability/failure tests  
- Production tests |
| - What information do we really need? |

### 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: \( P_{OUT} = |b_2|^2 - |a_2|^2 \) @ \( f_0, 2f_0, \ldots, nf_0 \)  
  - 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 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

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
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

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**Introduction**

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

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

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### References


### In Situ Tuners

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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

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

- **Simplified block diagram (*)**

![Block Diagram](image)

- **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**

![Diagram of Load-pull system calibration](image)
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

![Graph showing residual error comparison](image)

Measurement examples

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

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

Graph showing performance characteristics.

Introduction

A W-band on-wafer load-pull system

Large signal characterization

Measurement examples

Basic 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

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