Millimeter-wave load-pull techniques

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Millimeter-wave load-pull techniques

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- Measurement examples
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**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  
- 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**

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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:
  - 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, $\text{PAE} = (P_{OUT} - P_{IN}) / P_{DC} @ f_0$

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

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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
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.

![Diagram of load-pull setup]

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 – open loop
  - Main issue: gamma varies with $P_{\text{OUT}}$
    - Compensated by iterations

![Diagram of mechanical tuner and active load]
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

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

#### References

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#### Load-pull measurements above 60 GHz

#### In Situ Tuners
- “In-situ” (integrated)
  - Still gamma limited
  - Integration required
  - no real-time

#### References

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### 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

Large signal characterization

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 (*)

![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
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

![Residual error comparison graph]

Measurement examples

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

**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