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Millimeter-wave load-pull techniques

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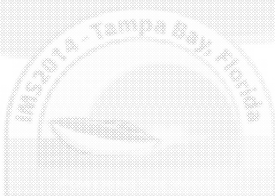


Millimeter-wave load-pull techniques

Valeria Teppati
ETH Zürich

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International Microwave Symposium
IEEE 1-6 June 2014, Tampa Bay, FL MTT-S



Outline

- ▶ Introduction
 - ▶ Basics of large signal characterization
 - ▶ Applications
- ▶ Large Signal Characterization at high frequency
 - ▶ Existing solution examples
 - ▶ Pros and cons
- ▶ A W-band on-wafer load-pull system
 - ▶ Block scheme
 - ▶ Calibration and accuracy verification
- ▶ Measurement examples
- ▶ Conclusions

Introduction

Large signal
characterization

A W-band on-wafer
load-pull system

Measurement
examples

International Microwave Symposium
IEEE 1-6 June 2014, Tampa Bay, FL MTT-S



Large signal Characterization

Basics	Applications
<ul style="list-style-type: none"> ▶ Linear characterization (small signal) provides full information as long as the device under test (DUT) can be considered linear <ul style="list-style-type: none"> ▶ e.g. passive components, transmission lines ▶ Active devices show nonlinear behavior when excited in realistic (large signal) conditions 	<ul style="list-style-type: none"> ▶ Many applications require measuring a few device performances in CW, while exciting its nonlinearities ▶ Examples: <ul style="list-style-type: none"> ▶ Performance/technology evaluation ▶ Circuit design ▶ Large signal models refinement
<ul style="list-style-type: none"> ▶ The extension of S-parameters to X-parameters might be too complicated ▶ What information do we really need? 	<ul style="list-style-type: none"> ▶ Reliability/failure tests ▶ Production tests

Introduction

Large signal characterization

A W-band on-wafer load-pull system

Measurement examples

Basics of Large signal Characterization

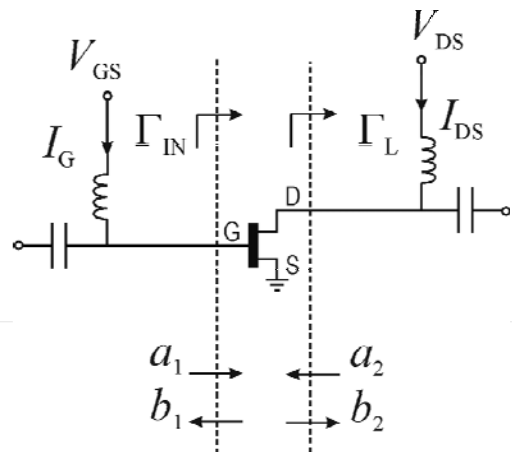
- ▶ We focus on the simplest example: a two port active device (a transistor in common source configuration) fed with a single CW tone @ f_0

- ▶ Interesting performances:

- ▶ DC power, $P_{DC} = V_{GS} I_G + V_{DS} I_D$
- ▶ Output power: $P_{OUT} = |b_2|^2 - |a_2|^2 @ f_0, 2f_0, \dots, nf_0$
- ▶ 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: $P_{IN} = |a_1|^2 - |b_1|^2$
- ▶ $\Gamma_L = a_2 / b_2 @ f_0, 2f_0, \dots, nf_0$

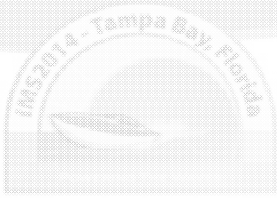


Introduction

Large signal characterization

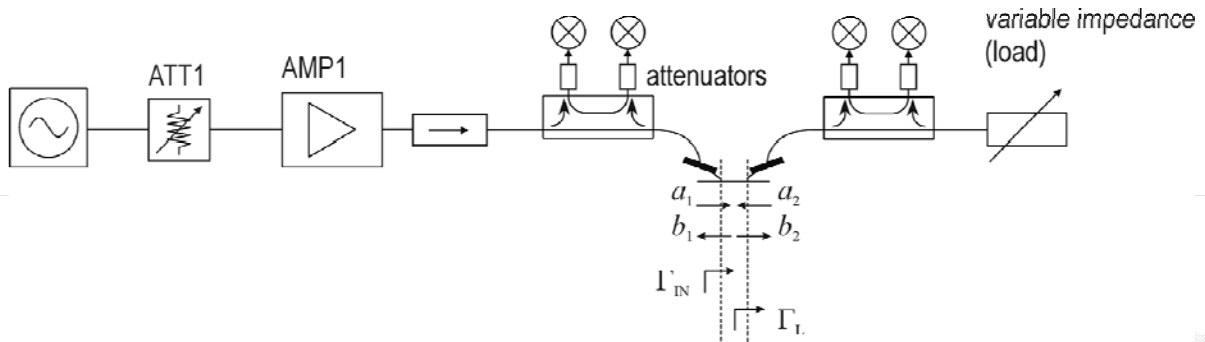
A W-band on-wafer load-pull system

Measurement examples



Load-pull measurements

- ▶ A simplified block scheme of an **on-wafer** load-pull measurement system
- ▶ On-wafer "environment" adds complications
 - ▶ calibration
 - ▶ additional losses

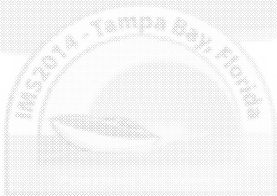


Introduction

Large signal
characterization

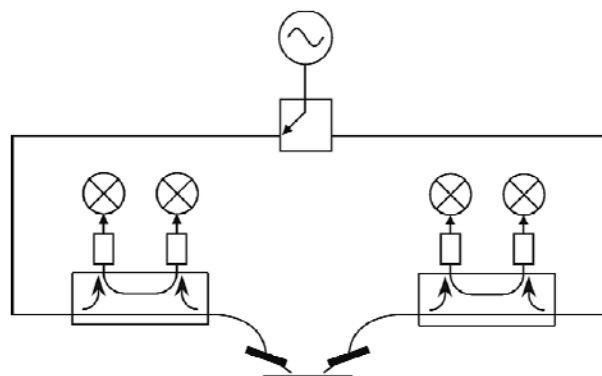
A W-band on-wafer
load-pull system

Measurement
examples



Load-pull calibration – vector calibration

- ▶ Vector "VNA-like" calibration



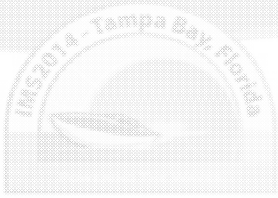
On-wafer or
calibration substrate
standards

Introduction

Large signal
characterization

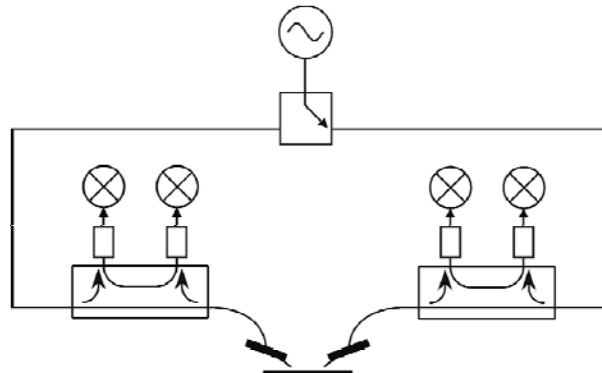
A W-band on-wafer
load-pull system

Measurement
examples



Load-pull calibration – vector calibration

- ▶ Vector “VNA-like” calibration



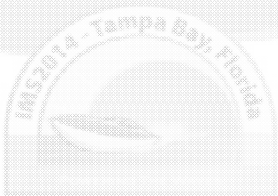
On-wafer or
calibration substrate
standards

Introduction

Large signal
characterization

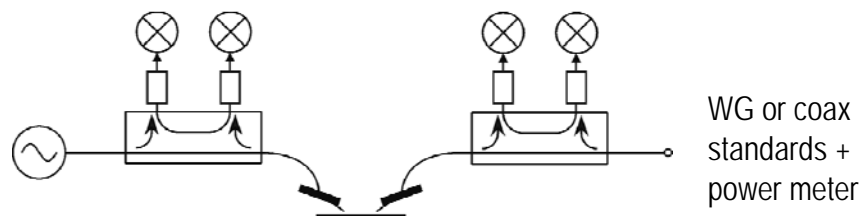
A W-band on-wafer
load-pull system

Measurement
examples



Load-pull calibration – power calibration

- ▶ Power calibration



On-wafer or
calibration substrate
thru

Introduction

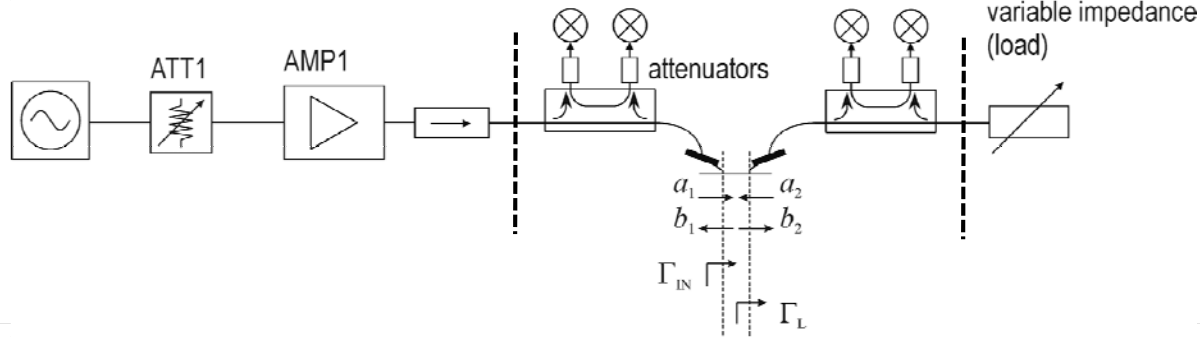
Large signal
characterization

A W-band on-wafer
load-pull system

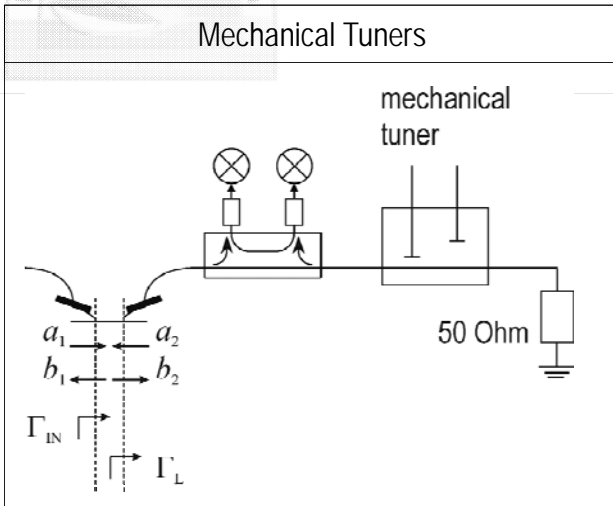
Measurement
examples

Load-pull calibration

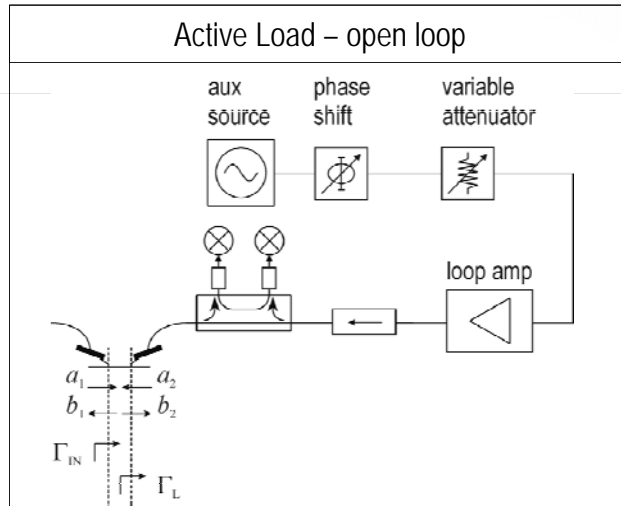
- ▶ After calibration it is possible to modify the set up at the right of reflectometer 2 and at the left of reflectometer 1, without affecting calibration



Solutions for tunable loads



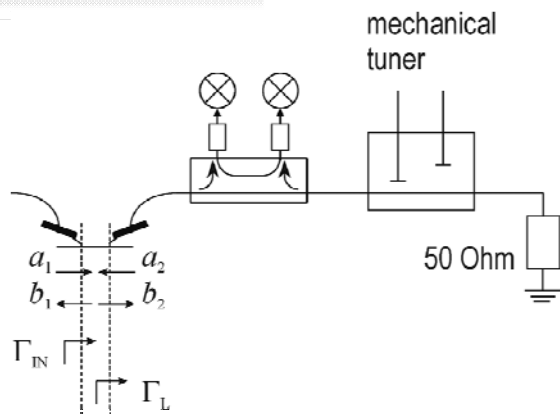
- ▶ Main issue: gamma limitation
 - ▶ Losses cannot be compensated
 - ▶ 2.5 dB losses reduce $|\Gamma|=1$ to $|\Gamma|=0.56$
 - ▶ 0.2 dB losses reduce $|\Gamma|=1$ to $|\Gamma|=0.95$



- ▶ Main issue: gamma varies with P_{OUT}
 - ▶ Compensated by iterations

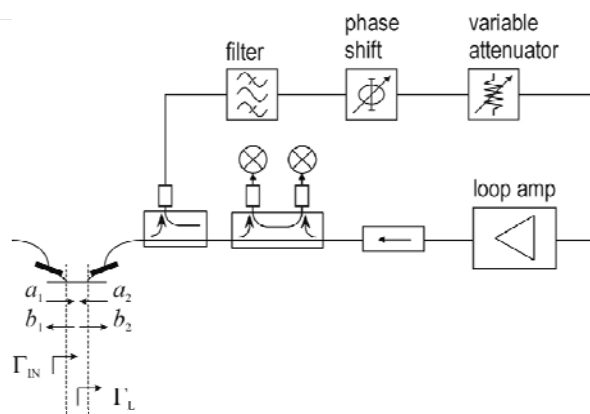
Solutions for tunable loads

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

Large signal
characterization

A W-band on-wafer
load-pull system

Measurement
examples

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

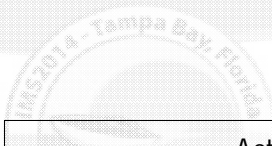
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Introduction

Large signal
characterization

A W-band on-wafer
load-pull system

Measurement
examples



Load-pull measurements above 60 GHz

Active Loads

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

References

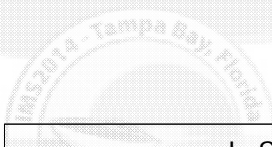
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Introduction

Large signal
characterization

A W-band on-wafer
load-pull system

Measurement
examples



Load-pull measurements above 60 GHz

In Situ Tuners

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

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Introduction

Large signal
characterization

A W-band on-wafer
load-pull system

Measurement
examples



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

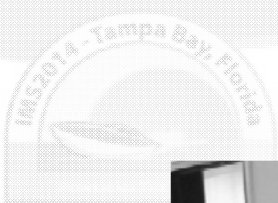
- ▶ Mechanical tuners with pre-calibration: less accurate than real-time
 - ▶ Mechanical tuners with real-time measurements: reduced gamma (0.5 maximum is typical)
 - ▶ In situ tuners: integration with the device / highly developed fabrication capabilities
- ↓
- ▶ Active loads with real-time measurements are a good solution, not yet widely diffused

Introduction

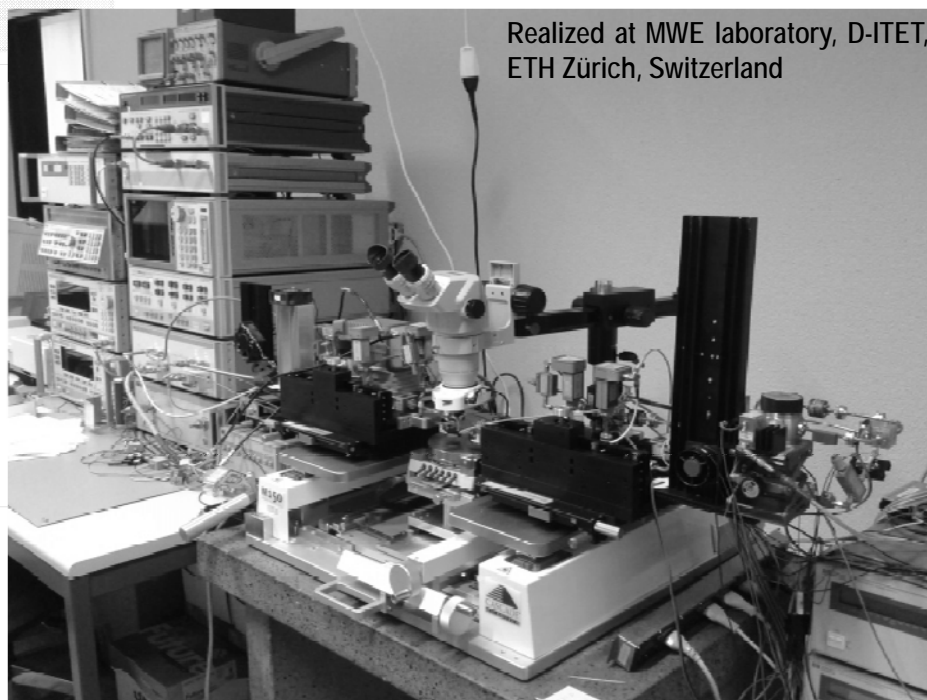
Large signal
characterization

A W-band on-wafer
load-pull system

Measurement
examples



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



Introduction

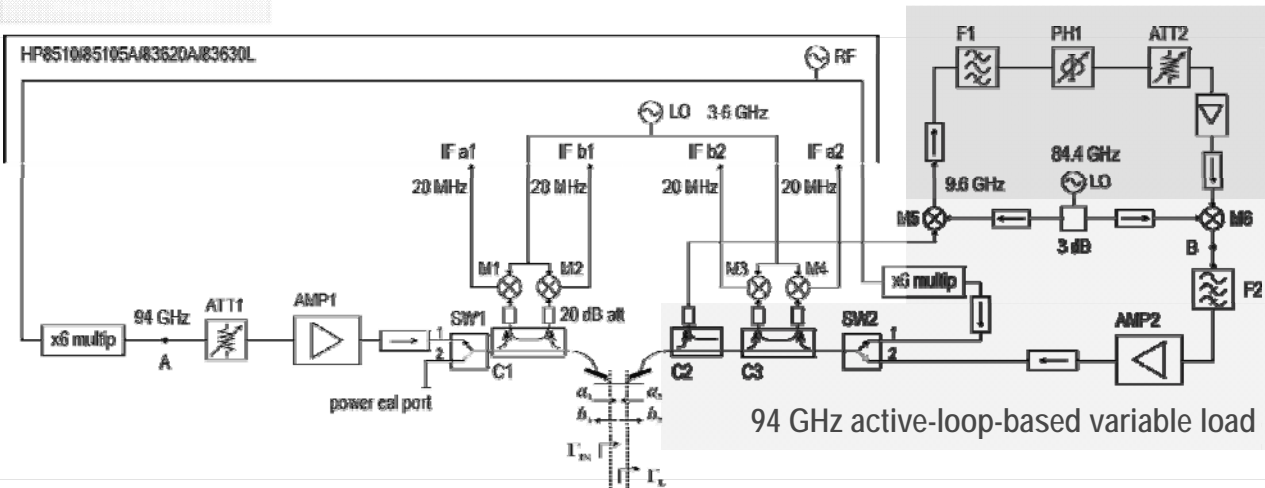
Large signal
characterization

A W-band on-wafer
load-pull system

Measurement
examples

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

(*) V. Teppati, H.-R. Benedikter, et al., "A W-Band On-Wafer Active Load-Pull System based on Down-Conversion Techniques", IEEE Transactions on Microwave Theory and Techniques, Vo. 64, is.1, Jan. 2014, pp. 148-153.

Introduction

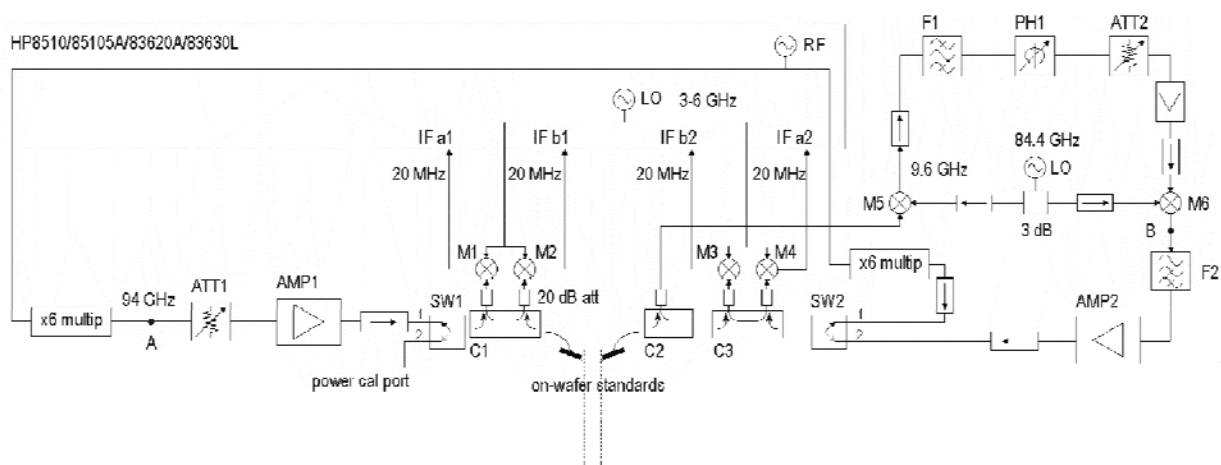
Large signal characterization

A W-band on-wafer load-pull system

Measurement examples

Load-pull system calibration – step 1

- ▶ SW1 and SW2 in position 1
- ▶ On-wafer (or calibration substrate) standards are connected and measured



Introduction

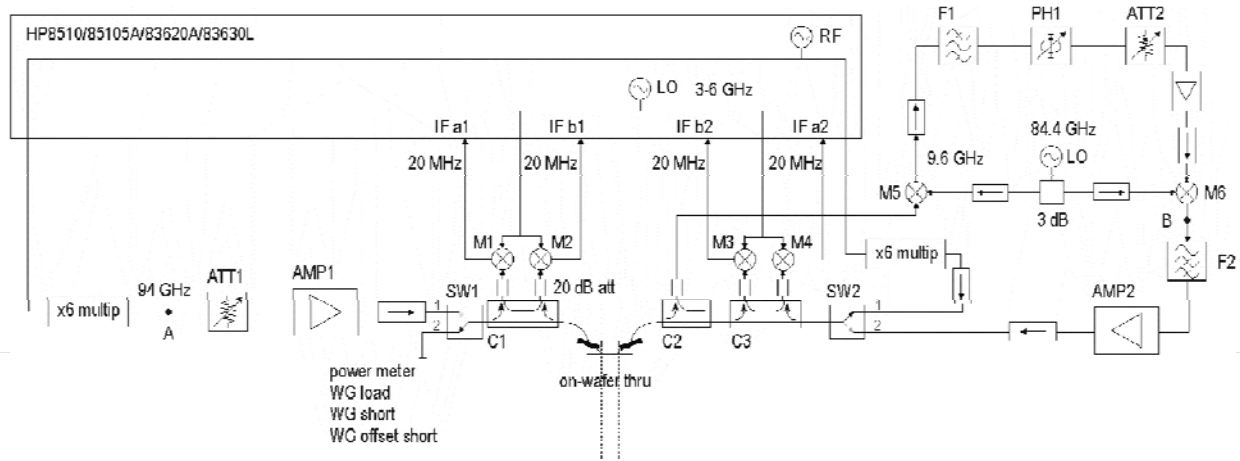
Large signal characterization

A W-band on-wafer load-pull system

Measurement examples

Load-pull system calibration – step 2

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



Introduction

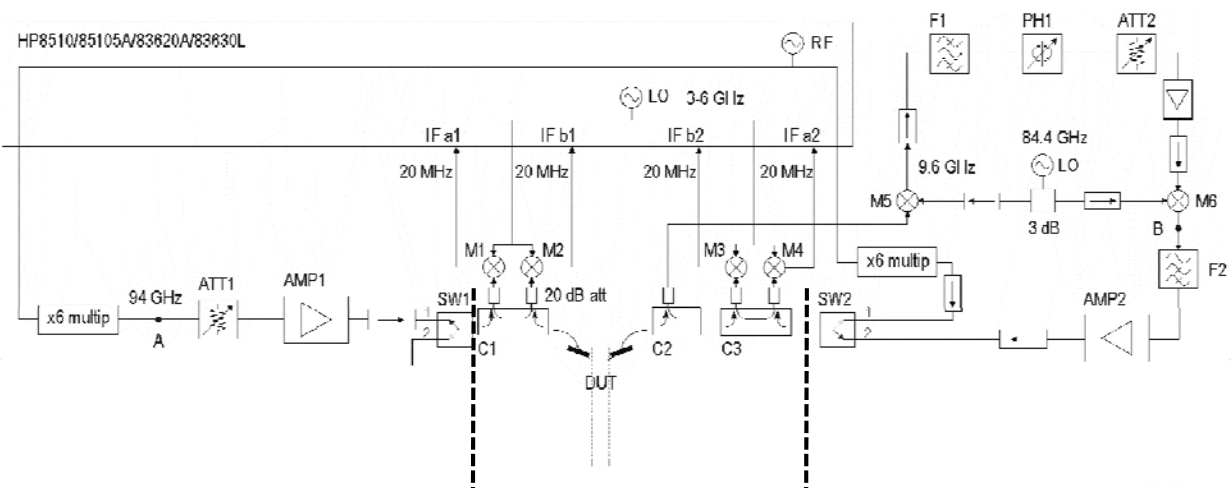
Large signal characterization

A W-band on-wafer load-pull system

Measurement examples

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



Introduction

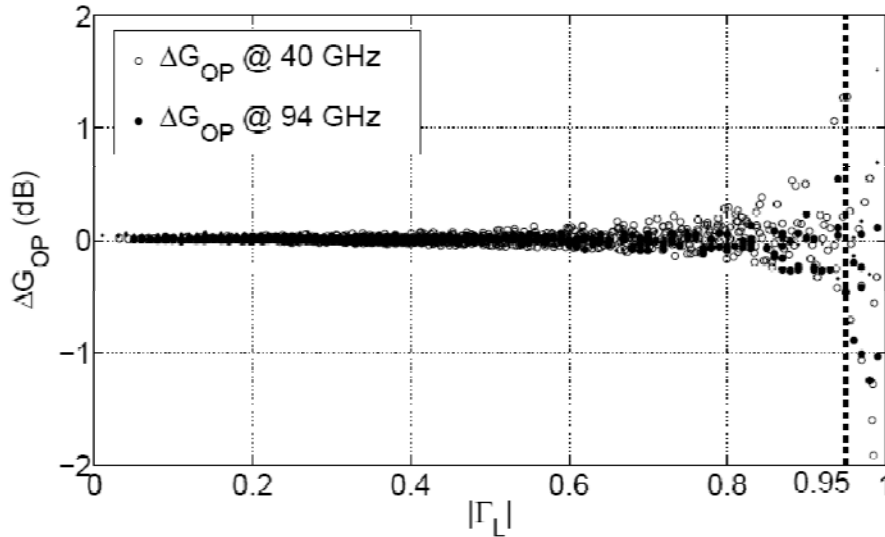
Large signal characterization

A W-band on-wafer load-pull system

Measurement examples

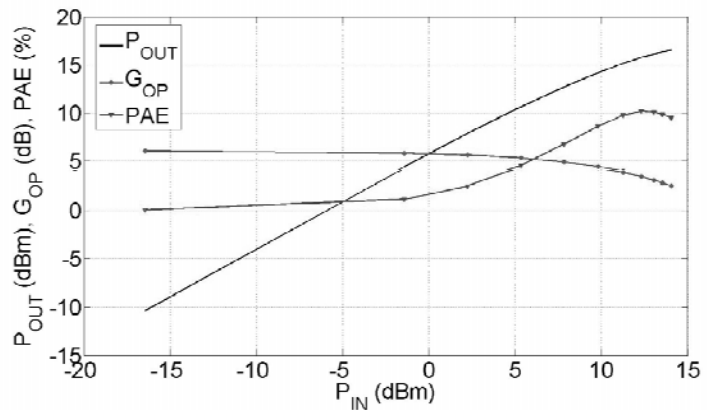
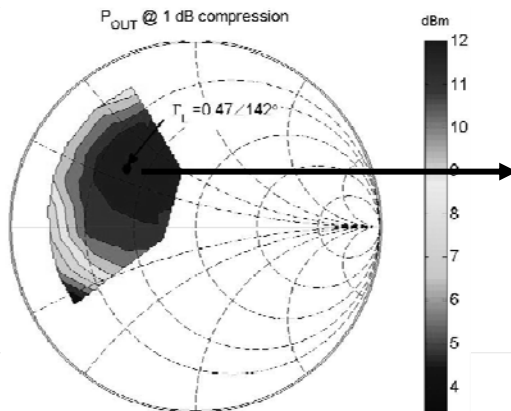
Residual error comparison

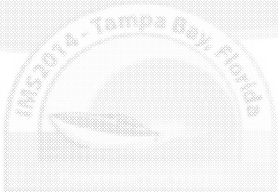
- ▶ A "thru" (on-wafer direct connection) should have 0 dB gain
- ▶ Its gain variation vs. Γ_L is taken as an estimation of the accuracy of the measurement



Measurement examples

- ▶ 0.1x100 μm^2 GaN HEMT
- ▶ $V_{DS}=5\text{ V}$, $V_{GS}=-3\text{ V}$ (class A)

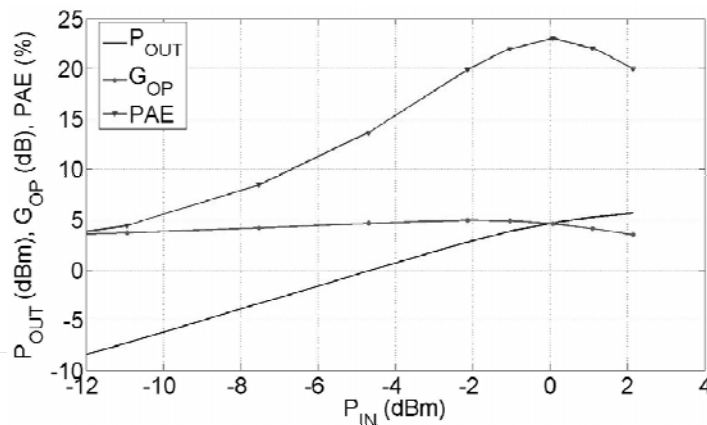
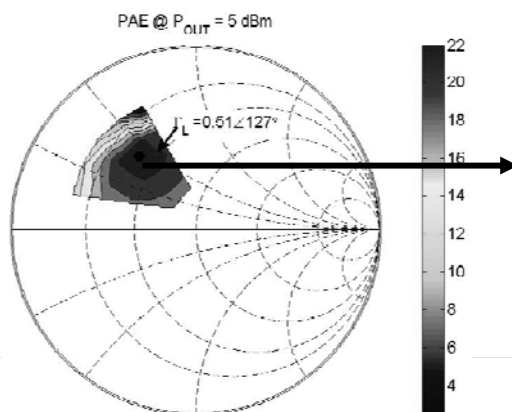




Measurement examples

- ▶ 0.3x8.4 μm^2 InP/GaAsSb DHBT

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



Introduction

Large signal
characterization

A W-band on-wafer
load-pull system

Measurement
examples

- ▶ 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

Introduction

Large signal
characterization

A W-band on-wafer
load-pull system

Measurement
examples