

Millimeter-wave load-pull techniques

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## Millimeter-wave load-pull techniques

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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

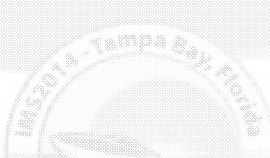
Measurement  
examples

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# Large signal Characterization

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



# Basics of Large signal Characterization

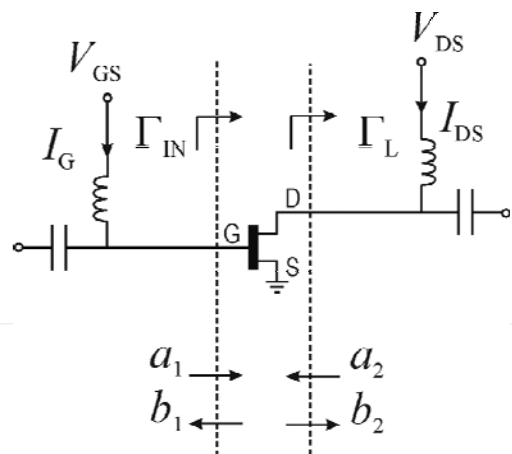
- ▶ We focus on the simplest example: a two port active device (a transistor in common source configuration) fed with a single CW tone @  $f_0$

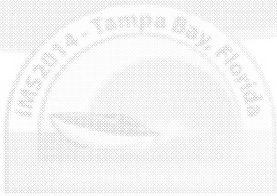
- ▶ Interesting performances:

- ▶ 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:

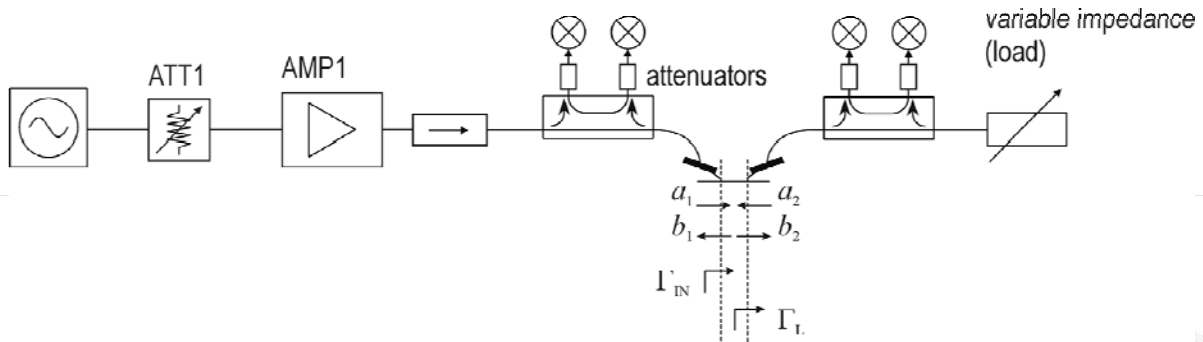
- ▶ Bias point (DC supply)
- ▶ Frequency  $f_0$
- ▶ Input power:  $P_{IN} = |a_1|^2 - |b_1|^2$
- ▶  $\Gamma_L = a_2 / b_2 @ f_0, 2f_0, \dots, nf_0$





## Load-pull measurements

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

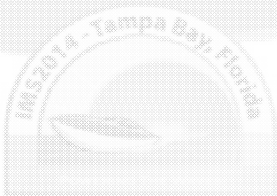


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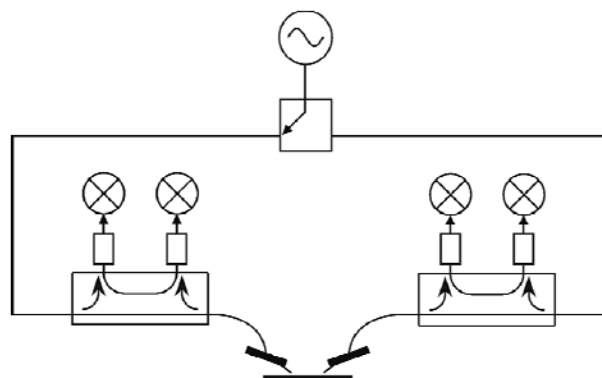
A W-band on-wafer  
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## Load-pull calibration – vector calibration

- ▶ Vector "VNA-like" calibration



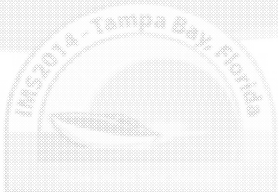
On-wafer or  
calibration substrate  
standards

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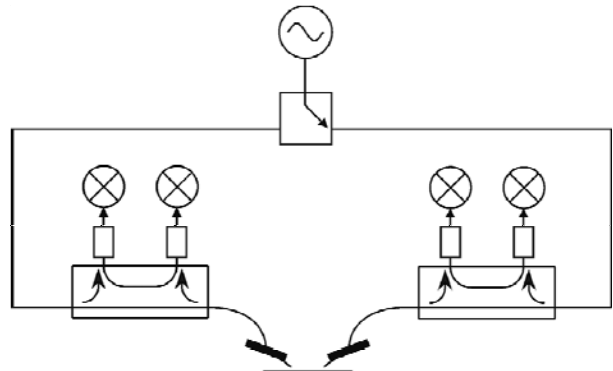
A W-band on-wafer  
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# Load-pull calibration – vector calibration

▶ Vector “VNA-like” calibration



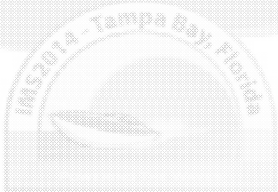
On-wafer or calibration substrate standards

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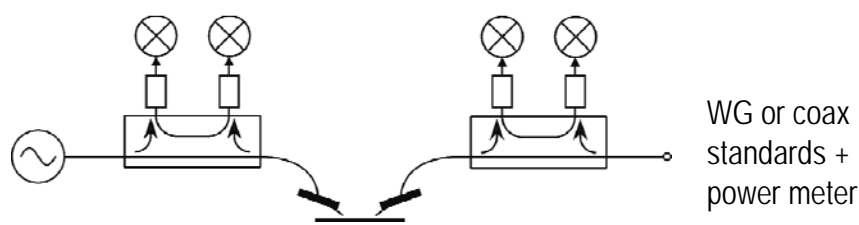
A W-band on-wafer load-pull system

Measurement examples



# Load-pull calibration – power calibration

▶ Power calibration



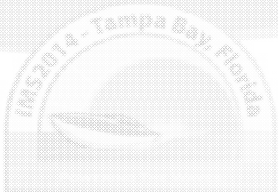
On-wafer or calibration substrate thru

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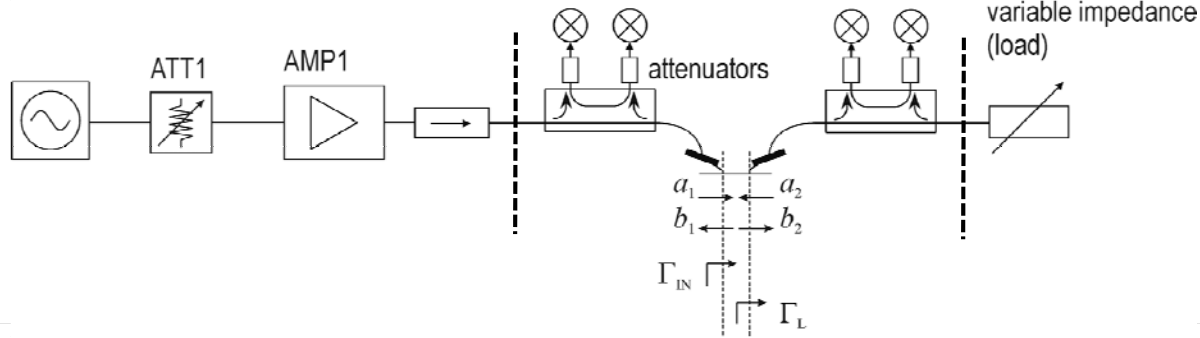
A W-band on-wafer load-pull system

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# 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



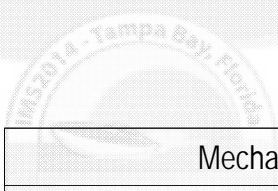
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Large signal characterization

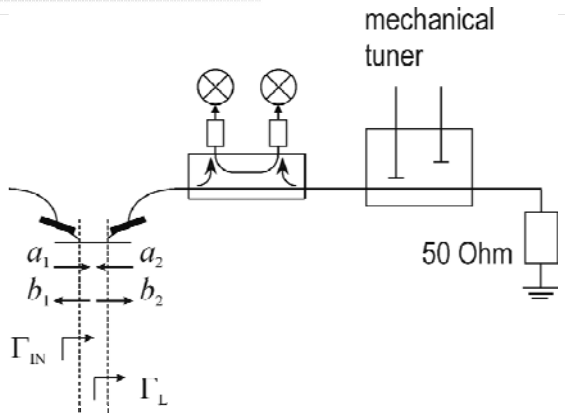
A W-band on-wafer load-pull system

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# Solutions for tunable loads

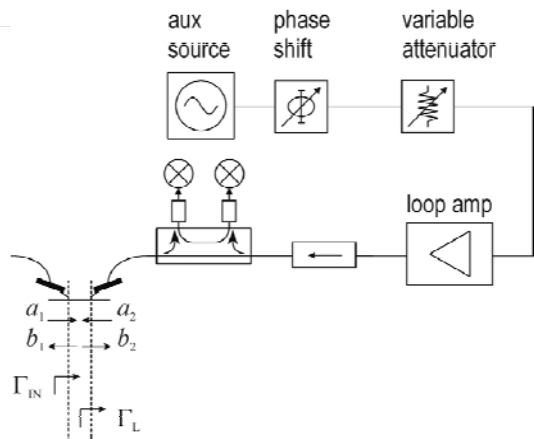


## Mechanical Tuners



- ▶ 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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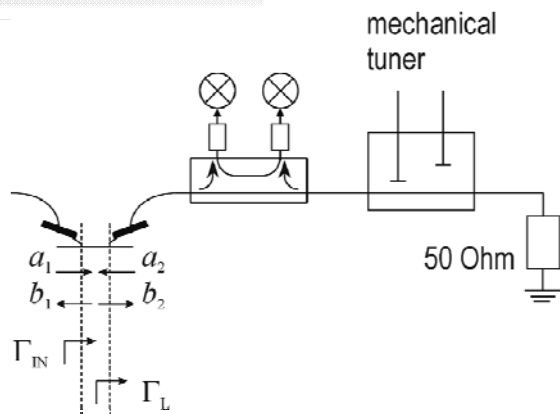
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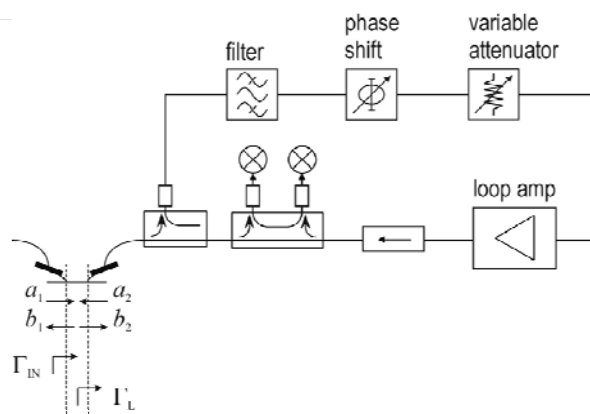
## Solutions for tunable loads

### 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

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## 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

- ▶ E. Alekseev, D. Pavlidis, and C. Tsironis, "W-band on-wafer load-pull measurement system and its application to HEMT characterization," in IEEE MTT-S, Baltimore, MD, USA, Jun. 1998, pp. 1479–1482.
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## Load-pull measurements above 60 GHz

### Active Loads

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

### References

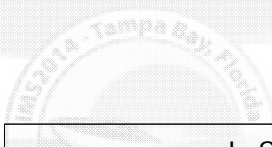
- ▶ S. A. Chahine, B. Huyart, E. Bergeault, and L. P. Jallet, "An active millimeter load-pull measurement system using two six-port reflectometers operating in the W-frequency band," IEEE Trans. Instrum. Meas., vol. IM-51, pp. 408–412, Jun. 2002.
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## Load-pull measurements above 60 GHz

### In Situ Tuners

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

### References

- ▶ T. V. Heikkil, J. Varis, J. Tuovinen, and G. M. Rebeiz, "W-band RF MEMS double and triple-stub impedance tuners," in IEEE MTT-S Intl. Microwave Symp. Dig., Long Beach, CA, USA, Jun. 2005, pp. 923–926.
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- ▶ T. Quemerai, D. Gloria, S. Jan, N. Derrier, P. Chevalier, "Millimeter-wave characterization of Si/SiGe HBTs noise parameters featuring  $f_T/f_{MAX}$  of 310/400 GHz," Radio Frequency Integrated Circuits Symposium (RFIC), 2012 IEEE , vol., no., pp.351,354, 17-19 June 2012

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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

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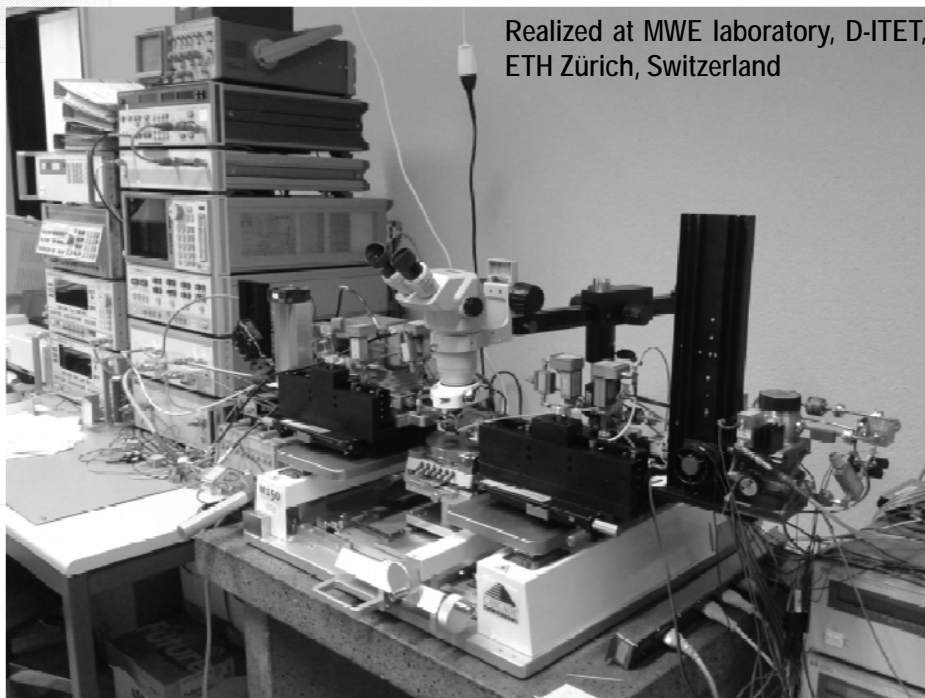
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## 94 GHz on-wafer active-loop load-pull system



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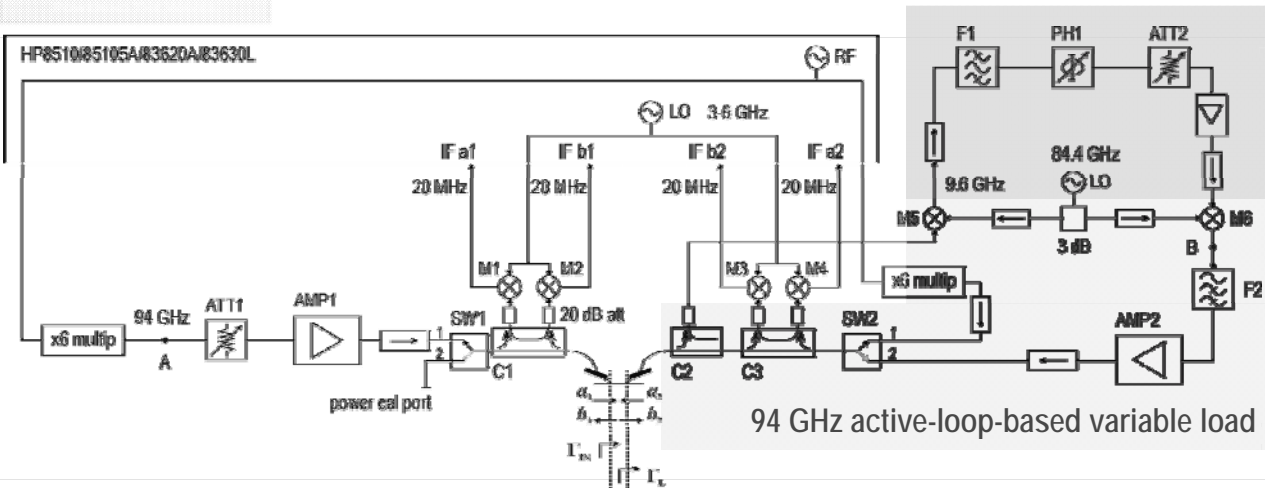
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# 94 GHz on-wafer active-loop load-pull system

- ▶ 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.

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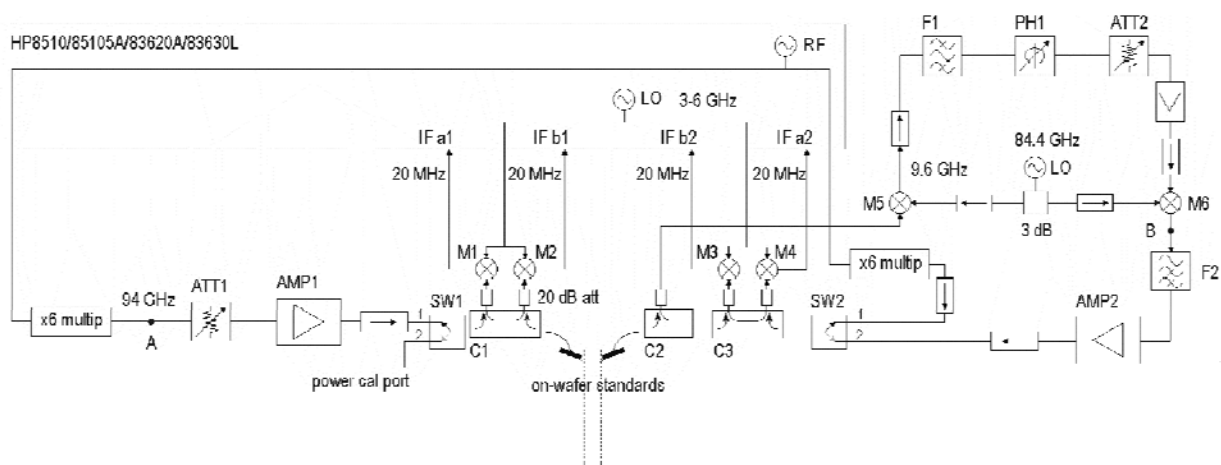
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## Load-pull system calibration – step 1

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



Introduction

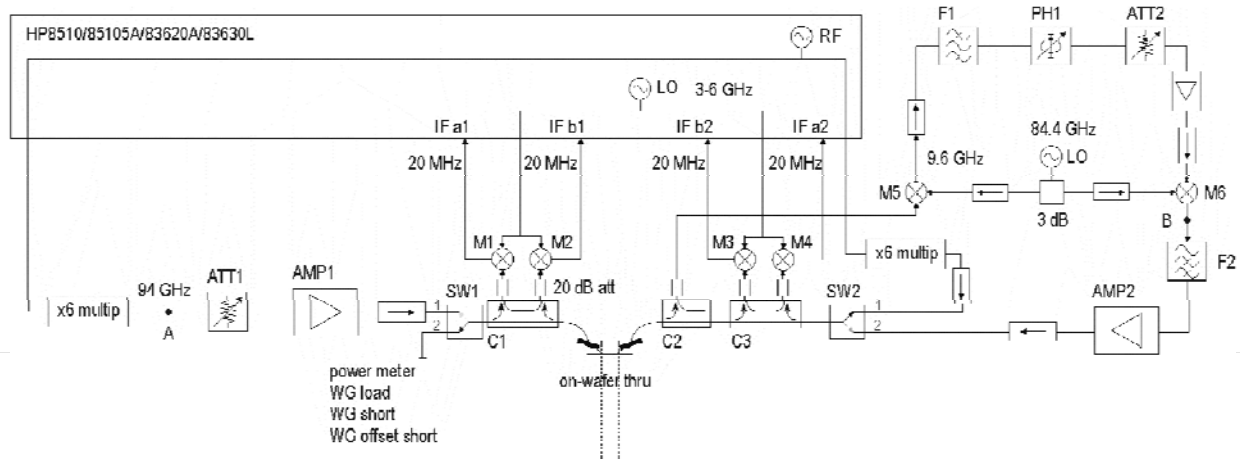
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# Load-pull system calibration – step 2

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



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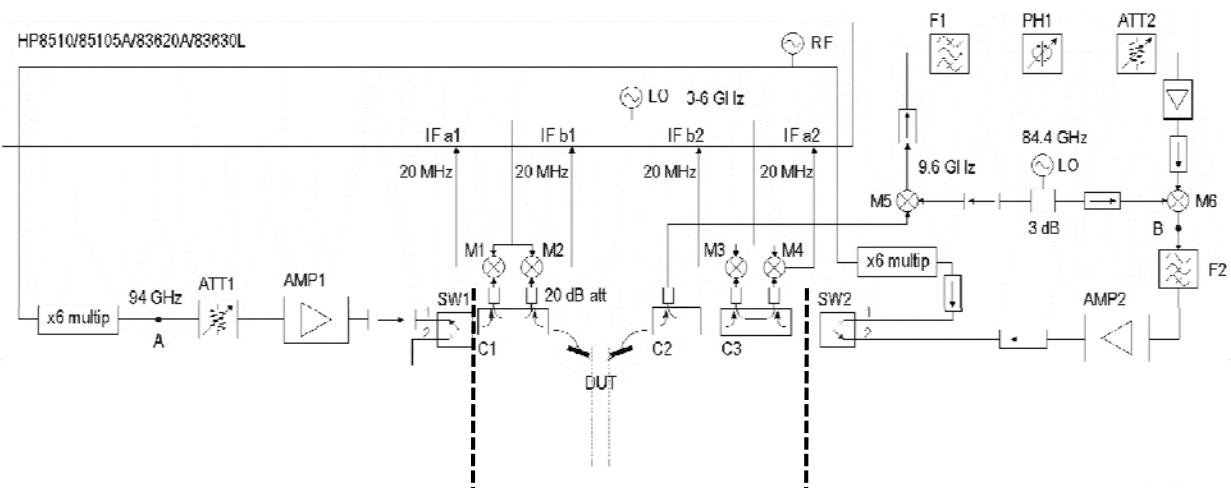
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# Measurement Phase

- ▶ 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



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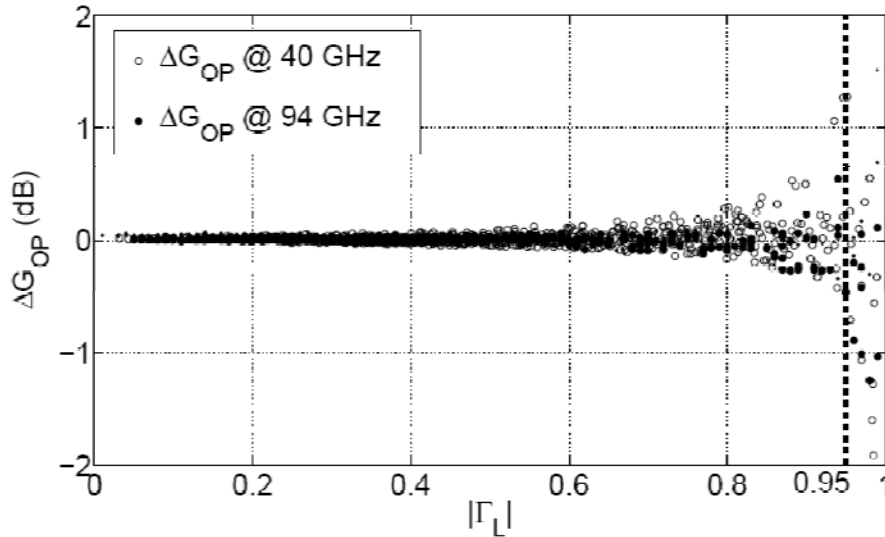
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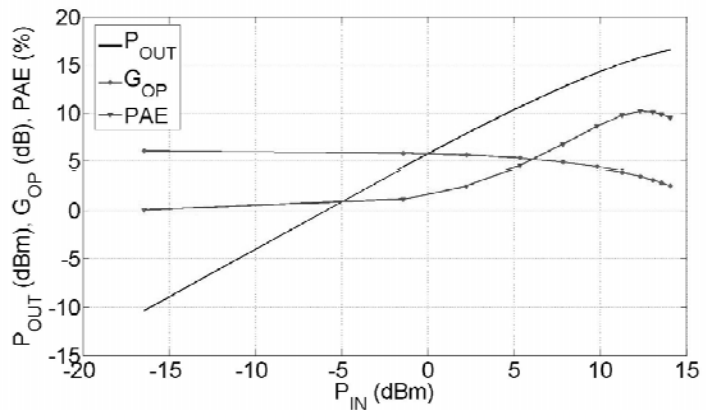
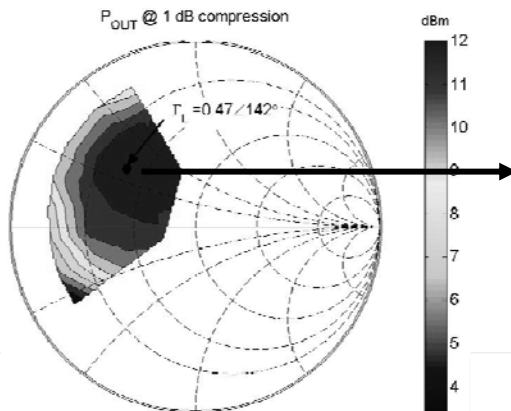
# Residual error comparison

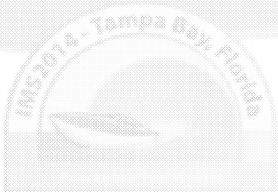
- ▶ A "thru" (on-wafer direct connection) should have 0 dB gain
- ▶ Its gain variation vs.  $\Gamma_L$  is taken as an estimation of the accuracy of the measurement



# Measurement examples

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

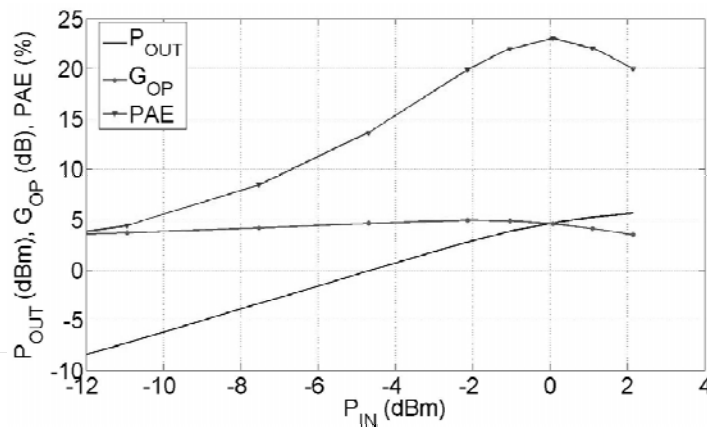
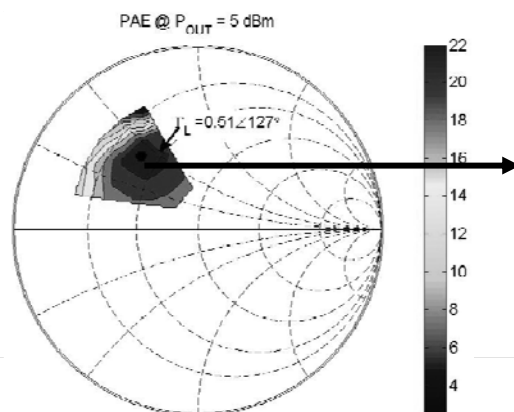




## Measurement examples

### ▶ 0.3x8.4 $\mu\text{m}^2$ InP/GaAsSb DHBT

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



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## 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

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