Millimeter-wave load-pull techniques

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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

Large signal Characterization

Basics	Applications

Basics

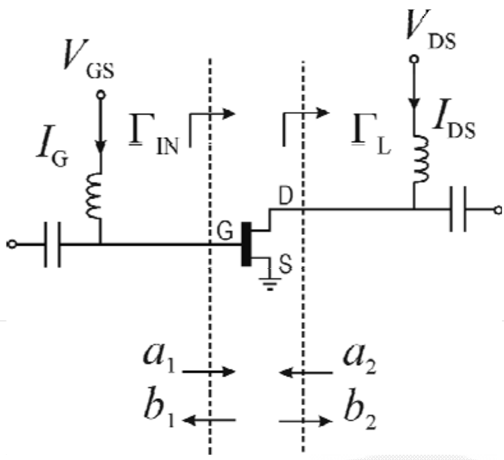
- Linear characterization (**small signal**) provides full information as long as the device under test (DUT) can be considered linear
  - e.g. passive components, transmission lines
- Active devices show nonlinear behavior when excited in realistic (**large signal**) conditions
- The extension of S-parameters to X-parameters might be too complicated
- What information do we really need?

Applications

- 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

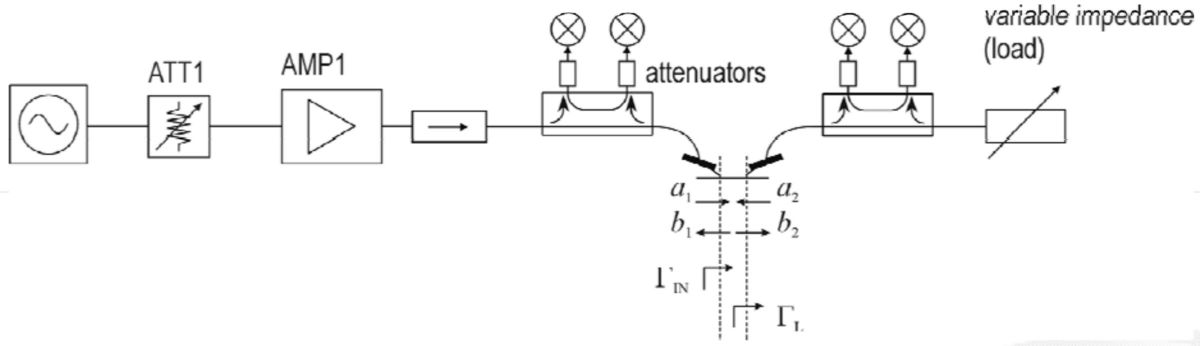
Basics of Large signal Characterization

- 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, $2f_0$,…, 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, $2f_0$,…, nf_0



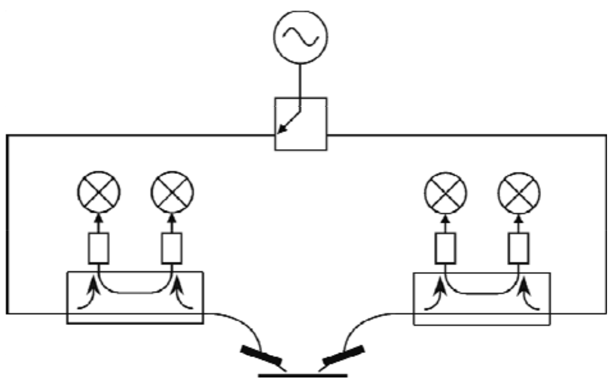
Load-pull measurements

- 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

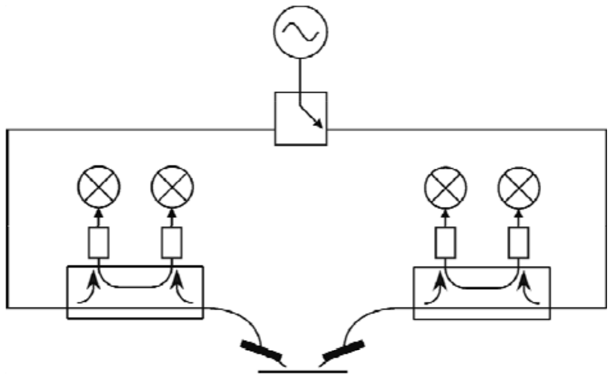
- Vector "VNA-like" calibration



On-wafer or
calibration substrate
standards

Load-pull calibration – vector calibration

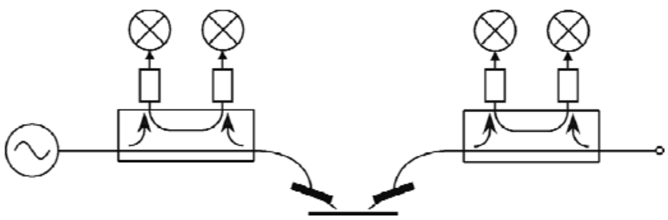
- Vector “VNA-like” calibration



On-wafer or
calibration substrate
standards

Load-pull calibration – power calibration

- Power calibration

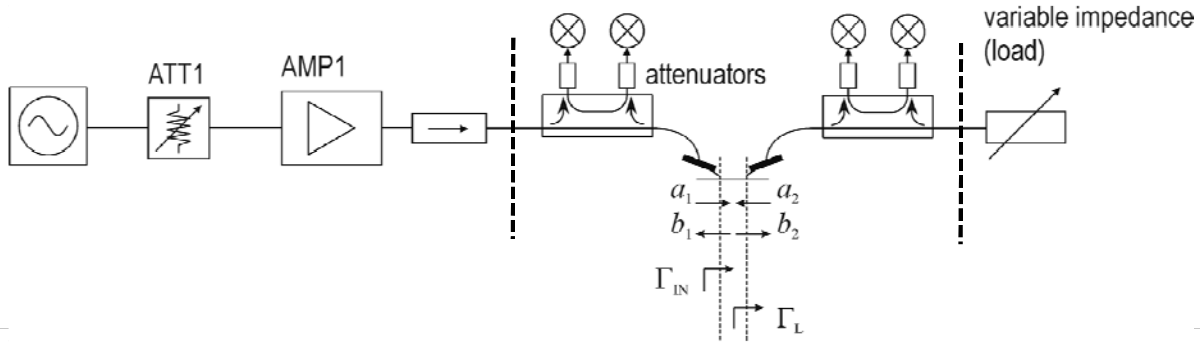


WG or coax
standards +
power meter

On-wafer or
calibration substrate
thru

Load-pull calibration

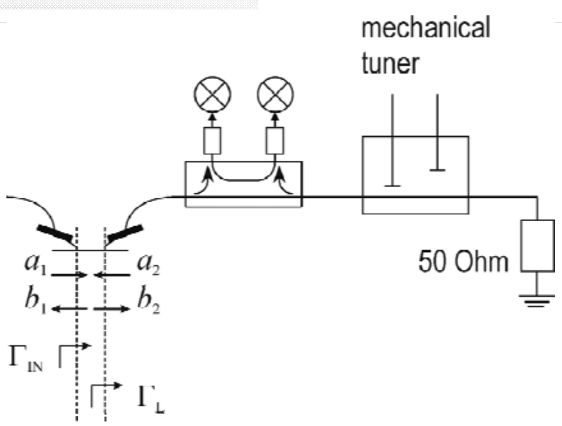
- After calibration it is possible to modify the set up at the right of reflectometer 2 and at the left of reflectometer 1, without affecting calibration



Solutions for tunable loads

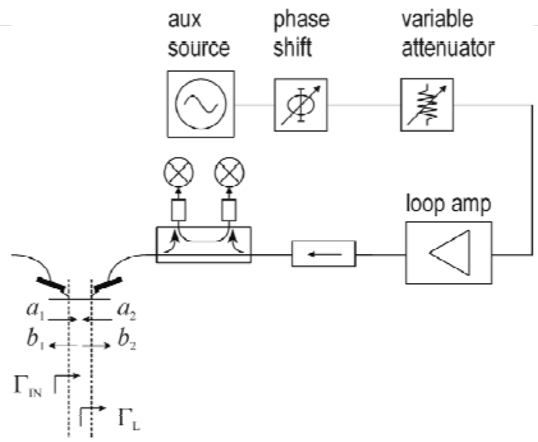
Mechanical Tuners	Active Load – open loop

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 $|\Gamma|=0.95$

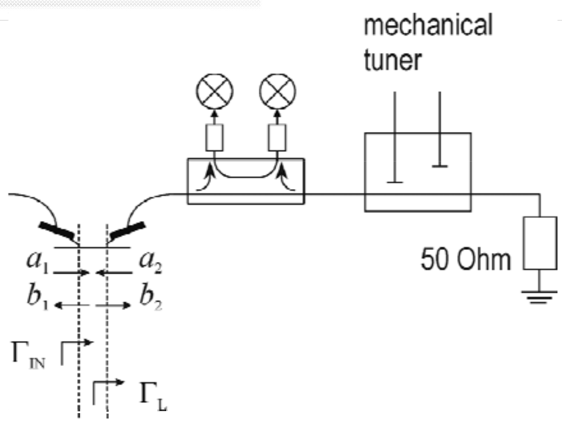
Active Load – open loop



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

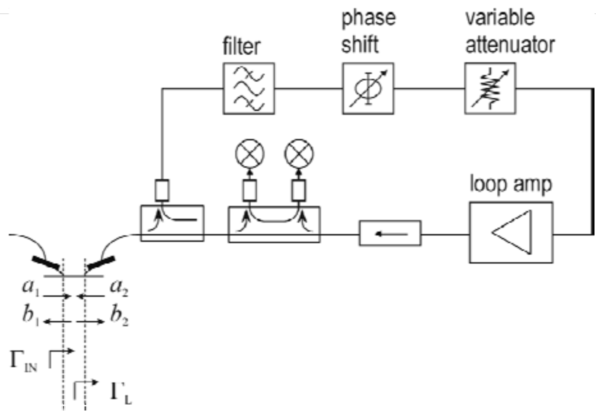
Solutions for tunable loads

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

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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Load-pull measurements above 60 GHz

Active Loads

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

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Load-pull measurements above 60 GHz

In Situ Tuners

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

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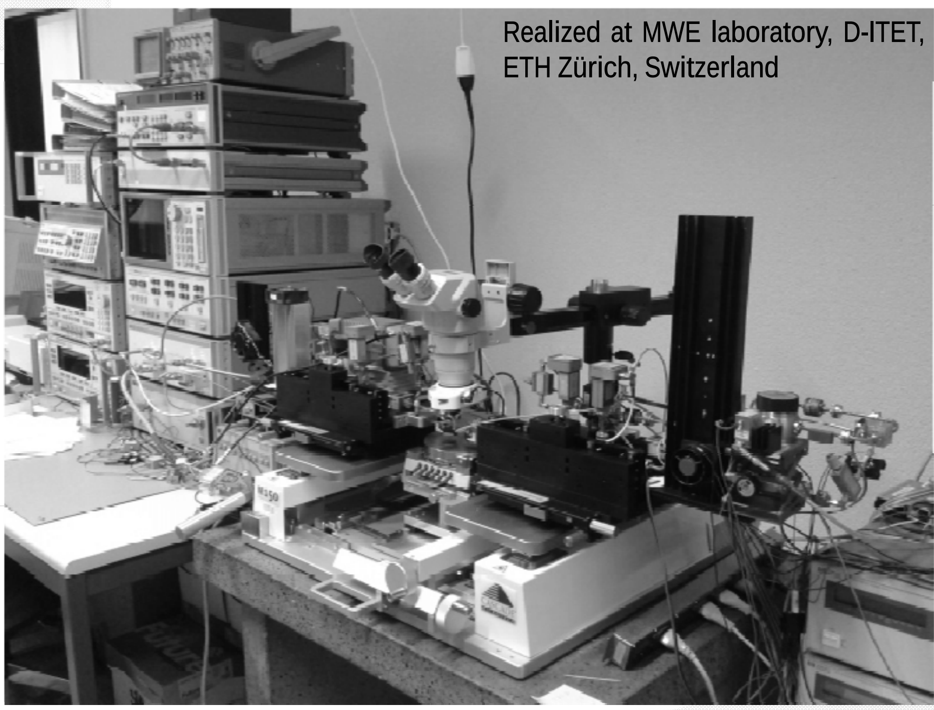
94 GHz on-wafer active-loop load-pull system

- 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

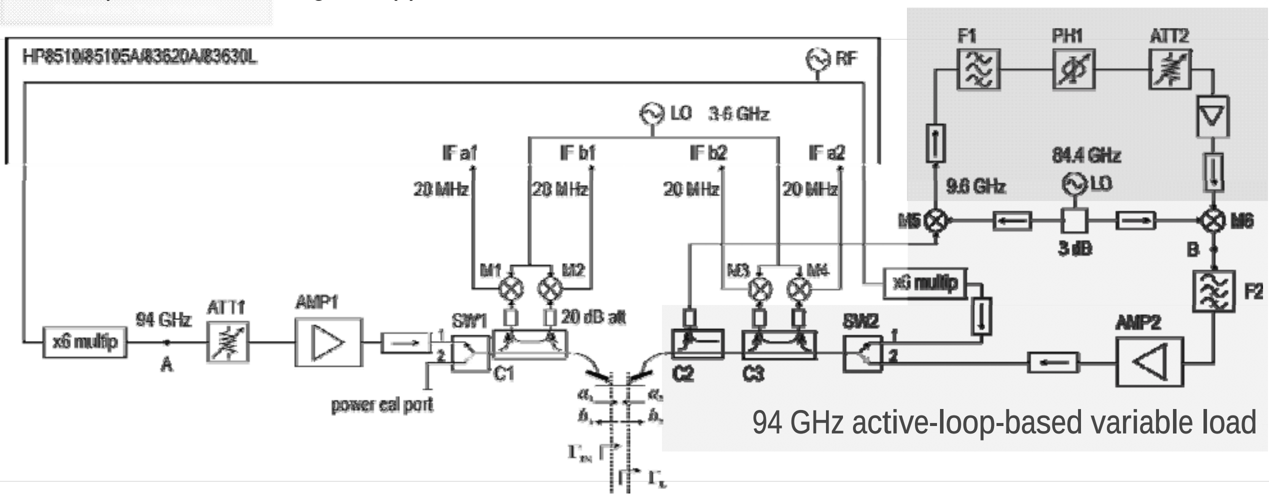
94 GHz on-wafer active-loop load-pull system



Realized at MWE laboratory, D-ITET, ETH Zürich, Switzerland

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

- Simplified block diagram (*)

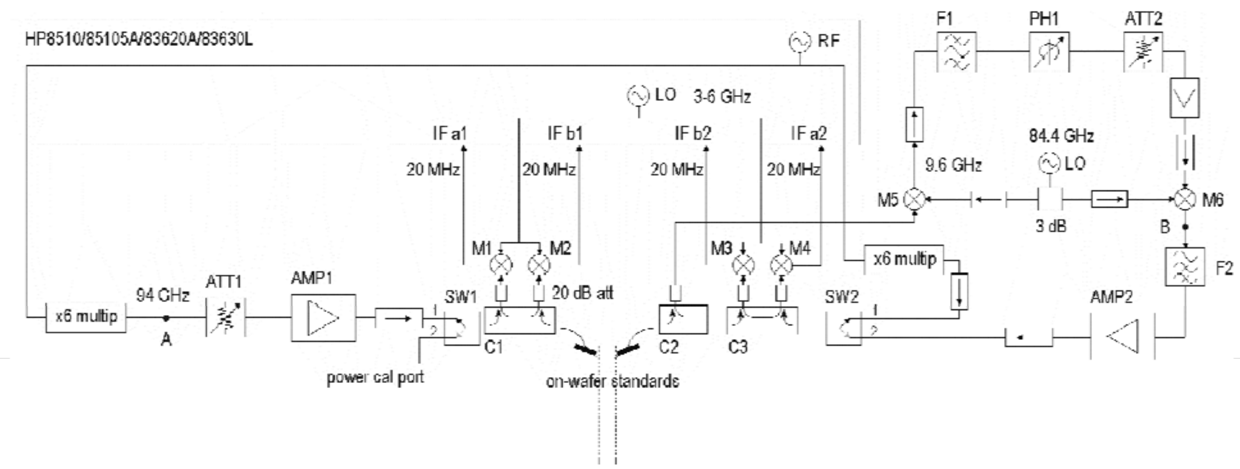


- **Novelty** – the *down-conversion-based* active loop
  - Similar techniques exist to realize IF loads, at a few hundreds of MHz

(*) 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.

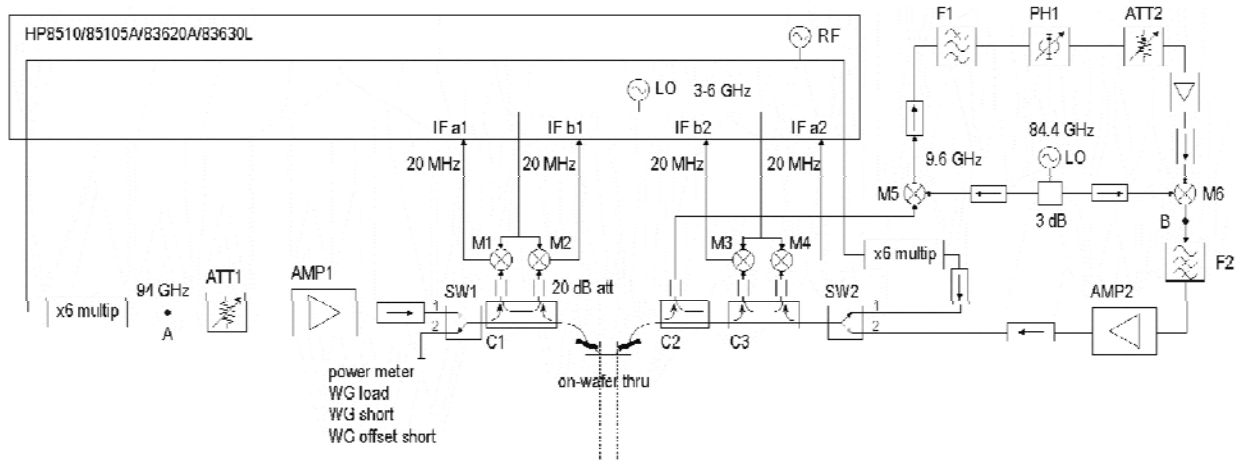
Load-pull system calibration – step 1

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



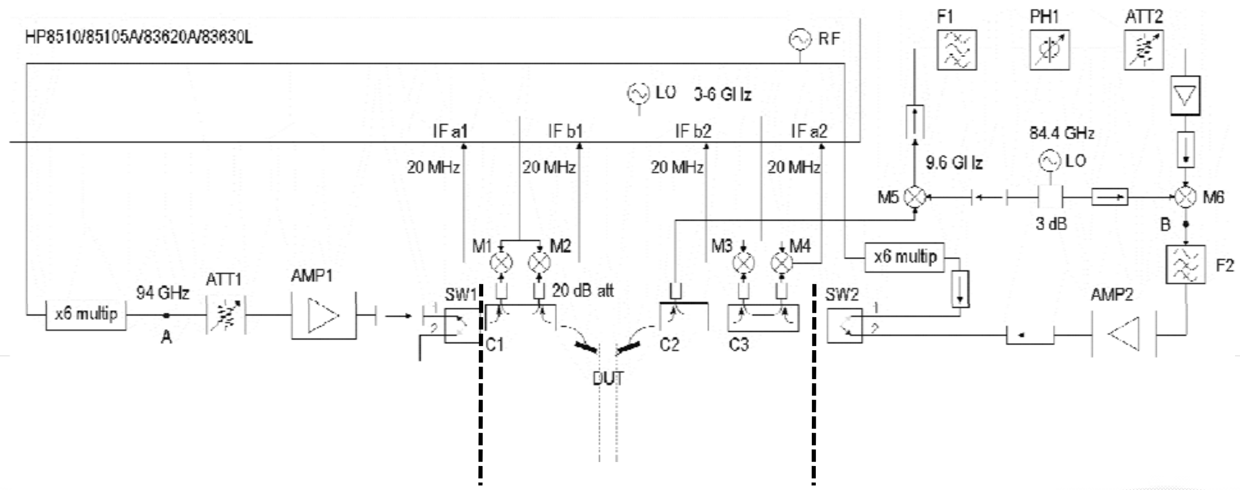
Load-pull system calibration – step 2

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



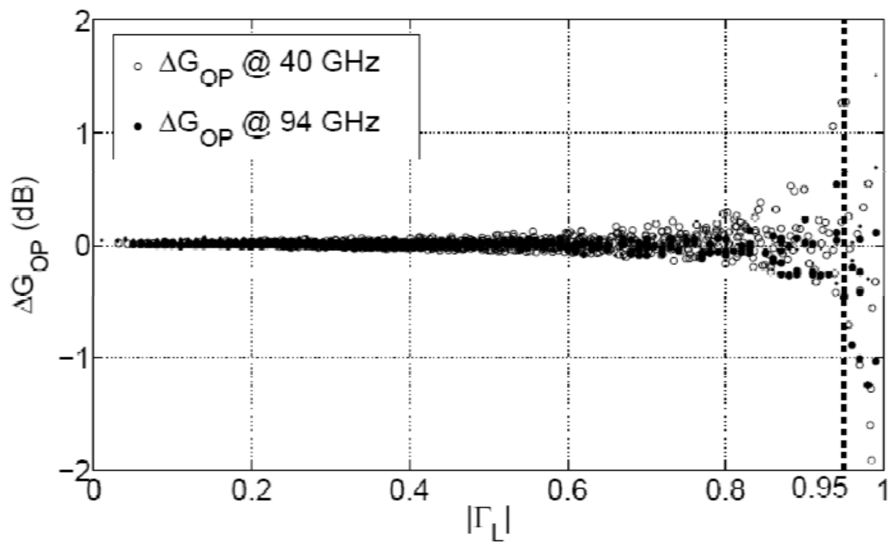
Measurement Phase

- 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



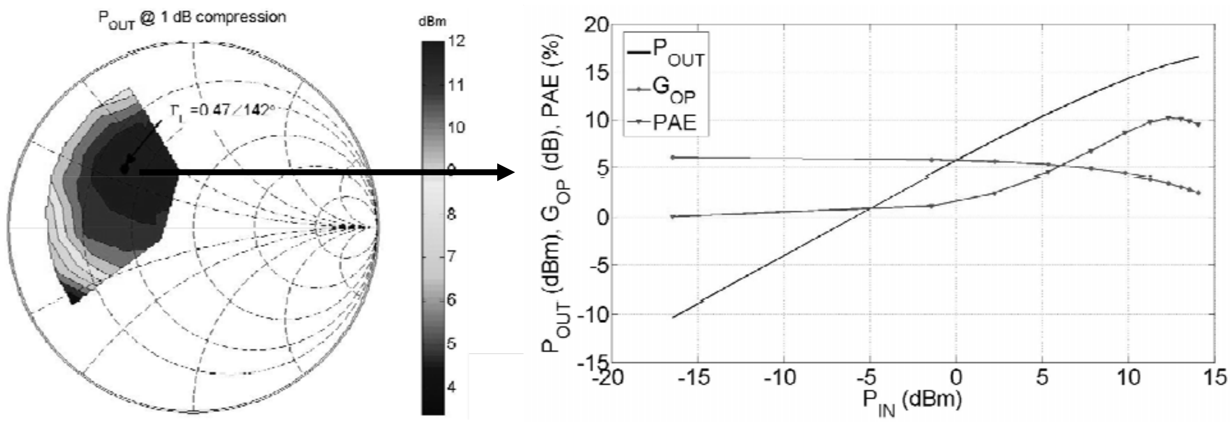
Residual error comparison

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



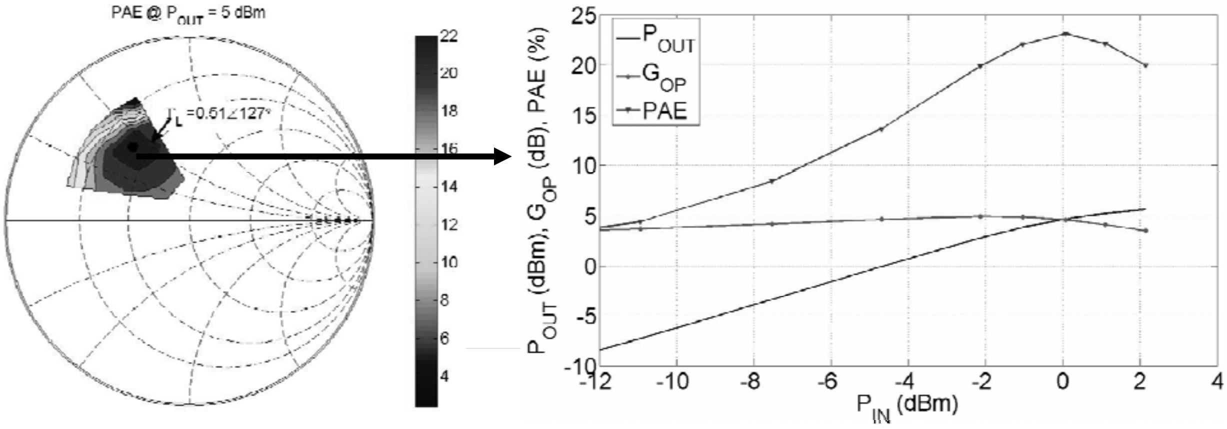
Measurement examples

- $0.1\text{x}100\mu m^2$ GaN HEMT
  - V_{DS}=5 V, V_{GS}=-3V (class A)



Measurement examples

- 0.3x8.4μm[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