

# RF Time domain measurements for power amplifier design

Introducing to waveform engineering

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## 1 Instrumentation

- Load-Pull Setups
- RF Time Domain Receivers
- Large Signal Network Analyzer (LSNA)

## 2 Modeling HEMTs

## 3 Design PA

- Time domain shaping
- 2 Stages PA design

## 4 HIP experiments

- Instrumentation
- Waveforms checking
- Stability
- Reliability

## 5 Harmonic Balance

- Links between instrumentation and simulation
- Using ADS for measurements

# Introduction

## Required Energy for Basestations in 2010 in Germany



■ **3300 GWh in 2010**

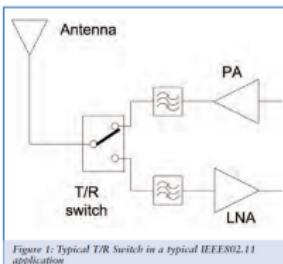
- This is 50% of the small Nuclear Power Plant Isar 1 (6200 GWh)
- This is 100% of the big Water Power Plants
  - Altenwörth (1970 GWh) and Greifenstein (1720 GWh)



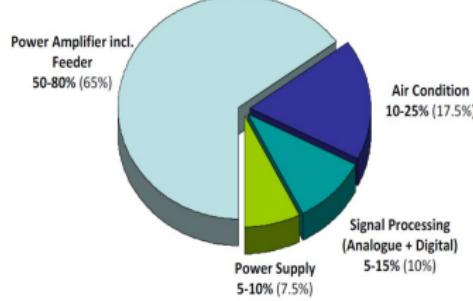
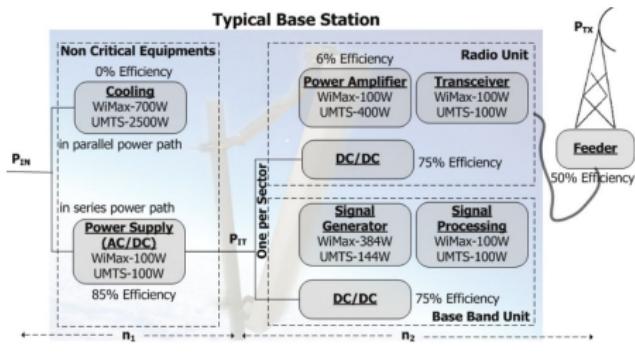
■ Urgent need for Basestations with improved efficiency

# Introduction

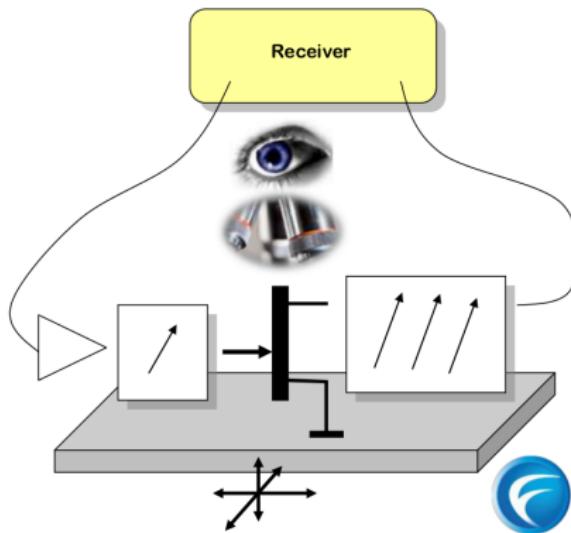
- Designing RF front-end



- Base-station example



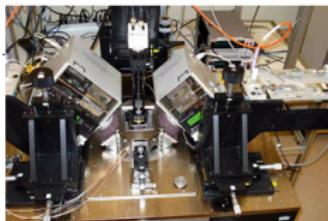
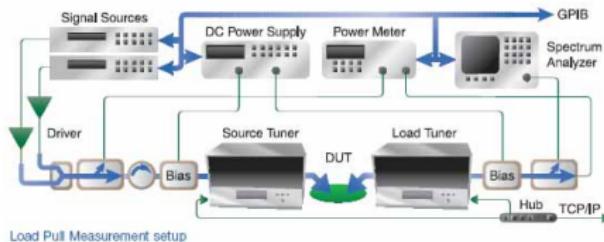
# Large Signal Characterizations



Setups are provided by tuner manufacturers :

- Maury Microwave (CAlifornia)
- Focus Microwave (CAnada)

# Load-Pull Setups

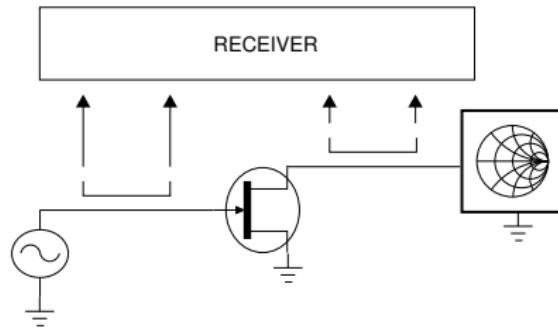


Integrated 2-40GHz Noise and Load Pull Test System

Limits of powermeters based systems :

- $Z_{in}|_{DUT}$  is not measured
- Measured Input power is an Available Power
- Measured Gain is the Transducer Gain

# Load-Pull Setup for modeling



We need a 4 input receivers system to get V/I or A/B waves as close as possible of the DUT

# RF Time domain receivers

Sampler based (LSNA) :

- MTA : Microwave Transition Analyzer (Hewlett-Packard)
- LSNA : Large Signal Network Analyzer (Hewlett-Packard)

Mixer based (NVNA) :

- PNA-X (Agilent)
- ZVxPlus (Rohde & Schwarz + NMDG)

Scope based :

- MB20/MB150 (Tektronix + Mesuro)
- ScopePlus (NMDG)

# Sampling Approach

## The Scopes : The Time Approach

- Real Spice-like analysis
- Complex Receivers (Interleaving Sampling)
- Memory Allocation Limits
- Not fitted for sparse signals

## The NVNA : The Frequency Approach

- Compressed Acquisition (dedicated to Sparse Signals)
- Fourier Analysis limitations
- Sequential measurements
- Dynamic Loss for modulated signals

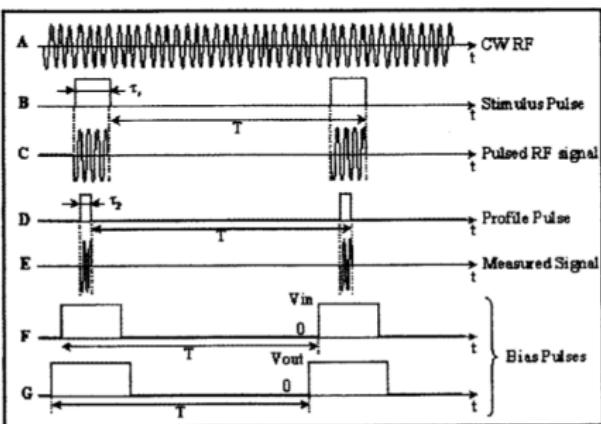
# Sampling Approach

## The Subsampling : The Time-Frequency Approach

- Compressed Acquisition (dedicated to Sparse Signals)
- No Fourier Analysis limitations
- One shot measurements
- No Dynamic Losses for modulated signals [4] [5]
- Very simple and robust technology (HP8510 samplers !!) [6]
- Tracking and Hold Amplifiers can be used for that [7]

# About dynamic in pulsed mode in frequency domain

## The Mixer Approach : [8]

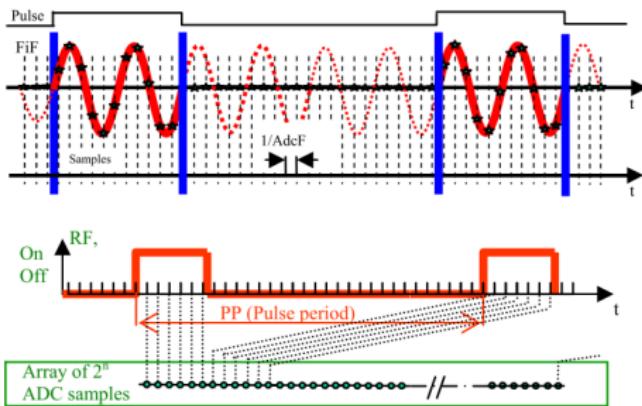


$$P_{\text{in the pulse}} = P_{\text{central frequency}} \cdot \left( \frac{T}{\tau_p} \right)^2$$

$$\Delta \text{dyn} = 20 \log_{10} \left( \frac{\tau_p}{T} \right)$$

# About dynamic in pulsed mode in time domain

The Sub sampling Approach : [4] [5]



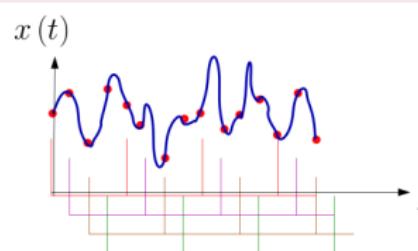
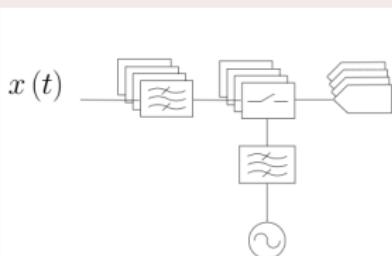
No dynamic lose  
150ns pulse profiling presented in [5]

# About RF scopes

The data issue :

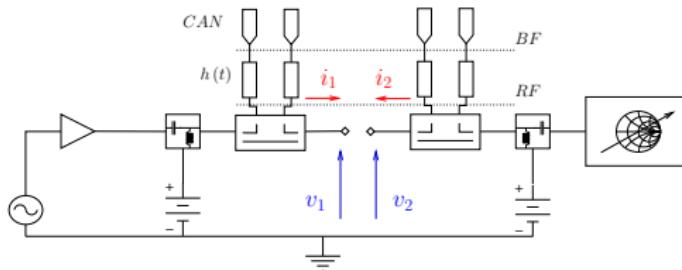
A 1 second frame sampled at 40 Gsample/s on 10 bits requires 50 Giga byte!!!

The technology issue :

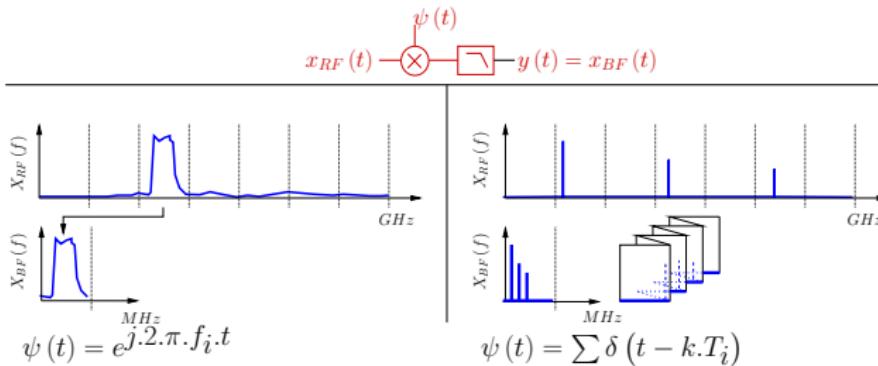


# Vectorial based setup

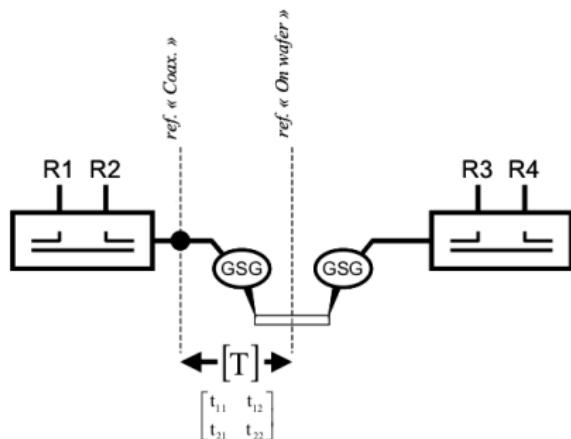
- Generic Measurement Setup



- Downconversion RF to low frequency



# LSNA calibration [9]



## 8 Error Terms Matrix

$$\begin{pmatrix} a_1 \\ b_1 \\ a_2 \\ b_2 \end{pmatrix}_{\text{On wafer}} = \tilde{K} \begin{pmatrix} 1 & \beta_1 & 0 & 0 \\ \gamma_1 & \delta_1 & 0 & 0 \\ 0 & 0 & \alpha_2 & \beta_2 \\ 0 & 0 & \gamma_2 & \delta_2 \end{pmatrix} \begin{pmatrix} R1 \\ R2 \\ R3 \\ R4 \end{pmatrix}$$

Relative LRRM, SOLT or TRL

$$\begin{bmatrix} 1 & \beta_1 & 0 & 0 \\ \gamma_1 & \delta_1 & 0 & 0 \\ 0 & 0 & \alpha_2 & \beta_2 \\ 0 & 0 & \gamma_2 & \delta_2 \end{bmatrix}$$

Coax. SOL + Power + Phase

$$\begin{pmatrix} a_1 \\ b_1 \end{pmatrix}_{\text{Coax.}} = \tilde{L} \begin{bmatrix} 1 & \lambda \\ \mu & v \end{bmatrix} \begin{pmatrix} R1 \\ R2 \end{pmatrix}$$

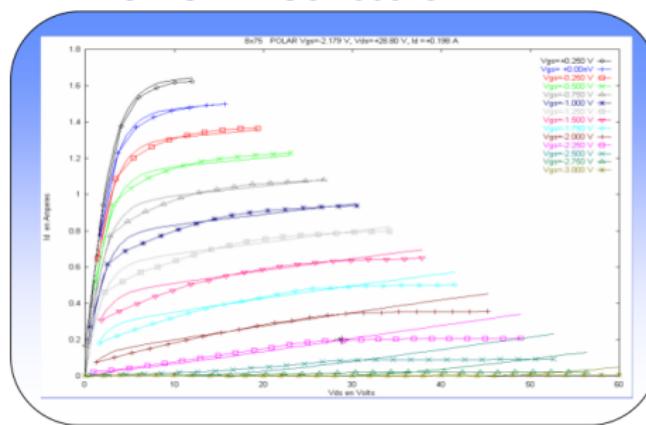
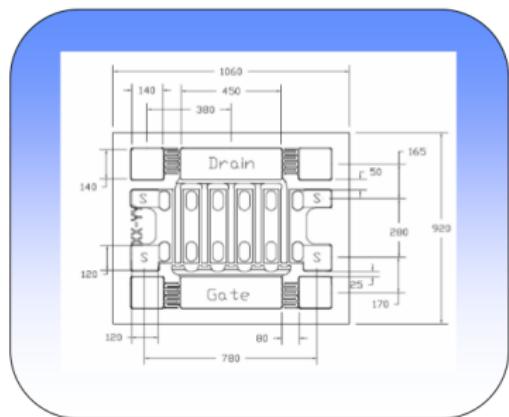
Reciprocity

$$\text{Det}[T]=1$$

$$\tilde{K}(f) = \pm \sqrt{\tilde{L}^2(f) \left( \frac{\nu(f) - \lambda(f)\mu(f)}{\delta(f) - \beta(f)\gamma(f)} \right)}$$

# Compact HEMT Model Extraction

Device used : 15 W GaN HEMT from CREE CGH60015D

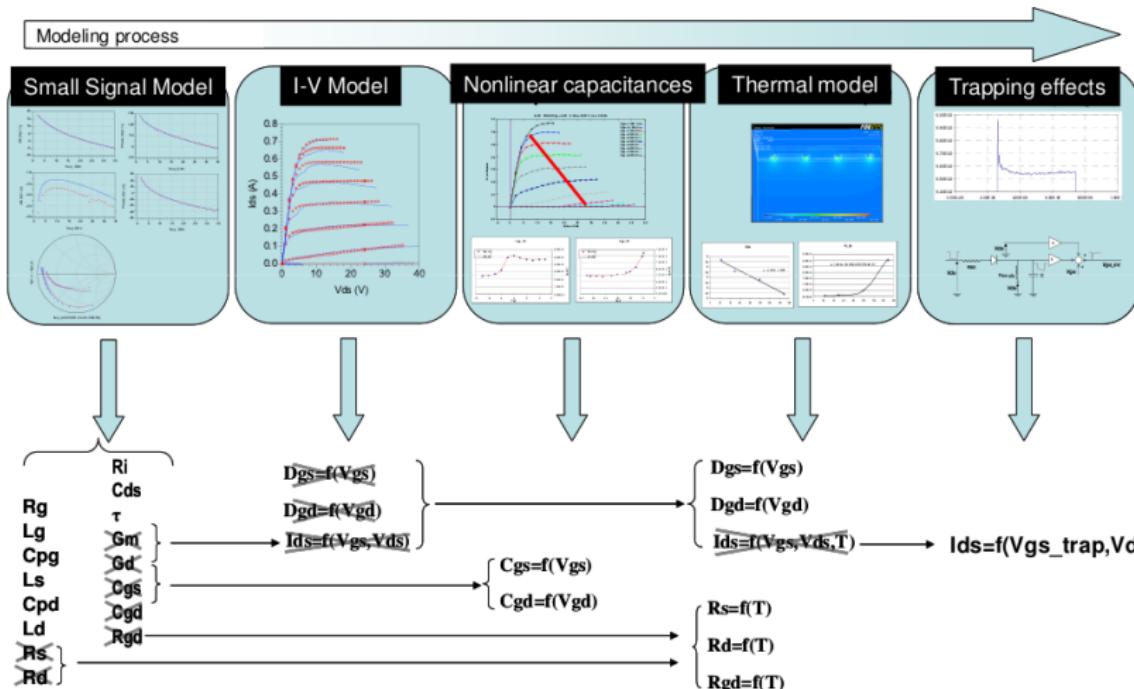


Characteristics of transistor used:

- ✓  $V_{BK} > 100V$
- ✓  $R_{dson} \sim 2 \text{ ohm}$
- ✓  $C_{ds} = 0.9 \text{ pF}$
- ✓  $C_{gs} = 8 \text{ pF}$
- ✓  $R_g = 0.5 \text{ ohm}$

**Device size 2mm**

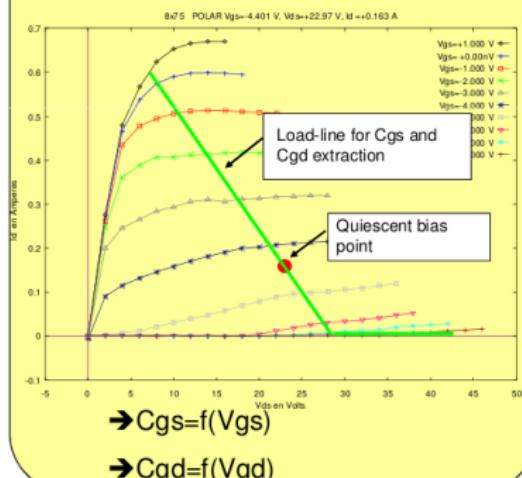
# Modeling Flow



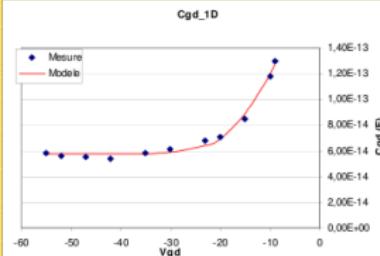
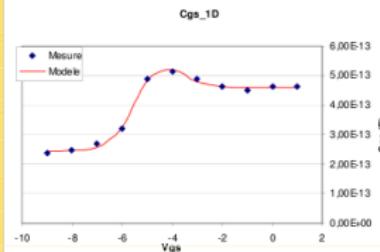
# Non linear Capacitances

## Capacitances

C<sub>gs</sub> et C<sub>gd</sub> extracted from [S] parameters along the optimal load-line



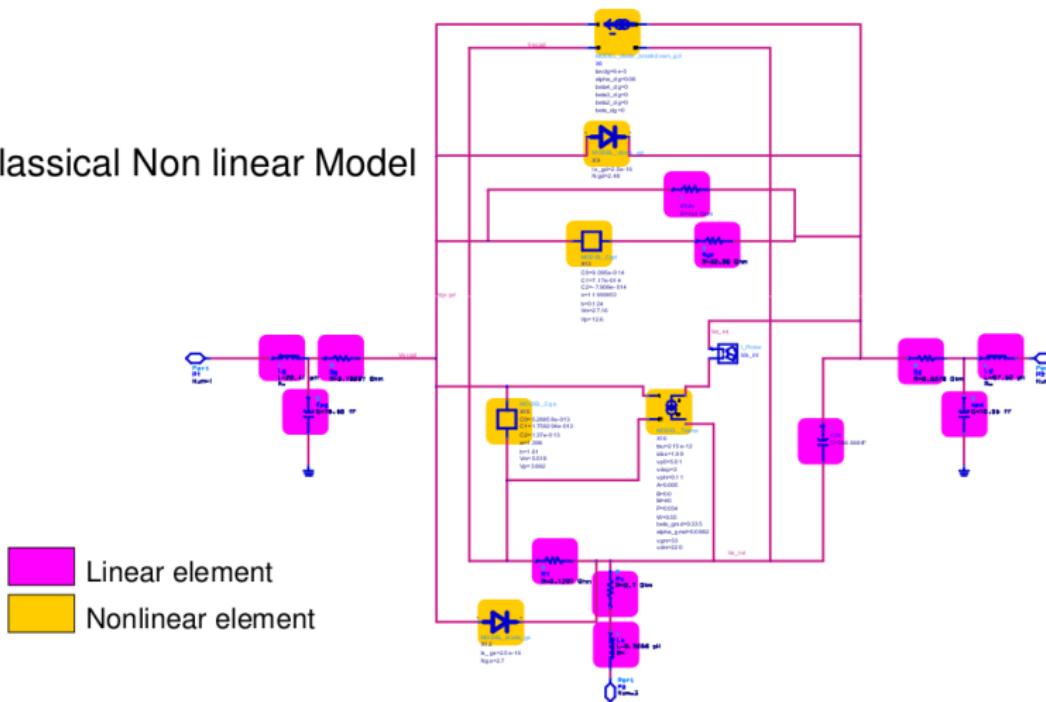
## Equations



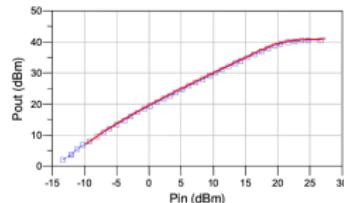
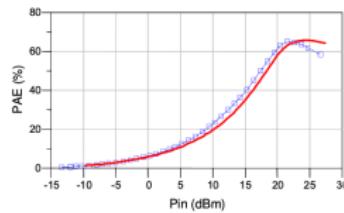
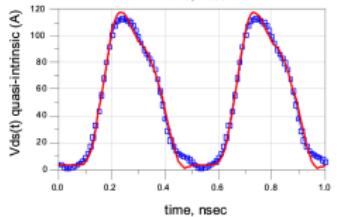
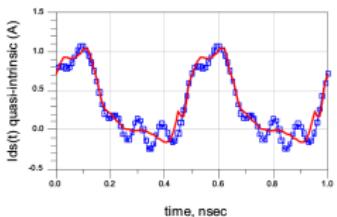
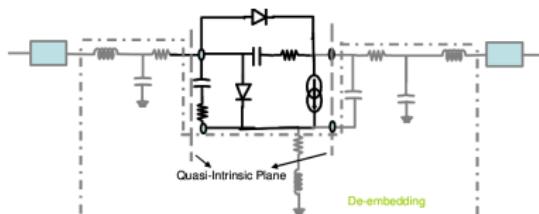
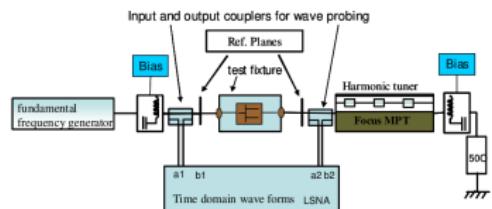
$$C_{gs} = C_0 + (C_1 - C_0) \cdot (0.5 + 0.5 \cdot \tanh(a \cdot (V_{gs} + V_m))) \\ - C_2 \cdot (0.5 + 0.5 \cdot \tanh(b \cdot (V_{gs} + V_p)))$$

## Model in Agilent ADS

Classical Non linear Model



# Large Signal Validation (Class E) [10]



# Harmonic Injection PA [11]

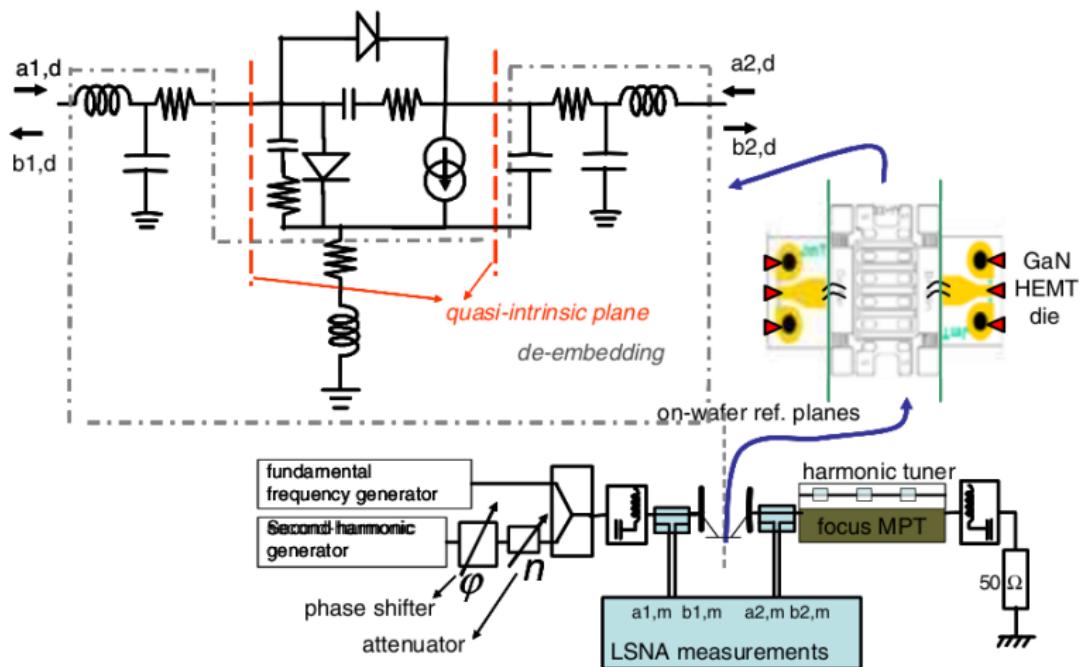
## Impact of the gate-source voltage on class $F$ and $F^{-1}$

- Cree 15W GaN HEMT @ 2GHz
- Gate voltage shape leads to the aperture time of the drain-source current
- $I_{DC}$  is then reduced
- This method is compliant with class  $F$  but not class  $F^{-1}$

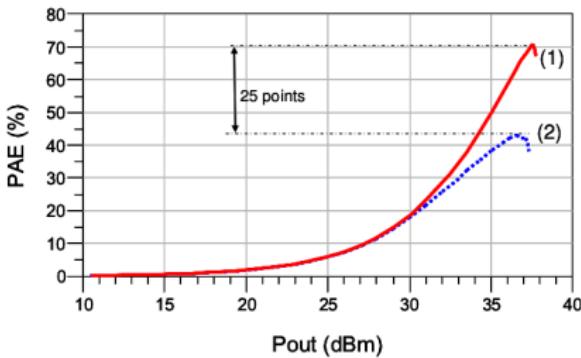
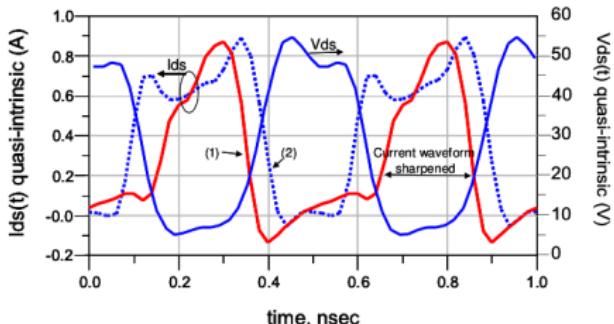
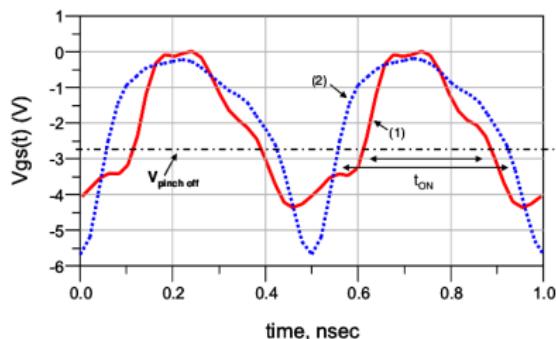
## Requirements for such investigations

- On-wafer Multi-harmonic time domain measurements
- Compact modeling (de-embedding)

# Time Domain Waveform Measurement Setup

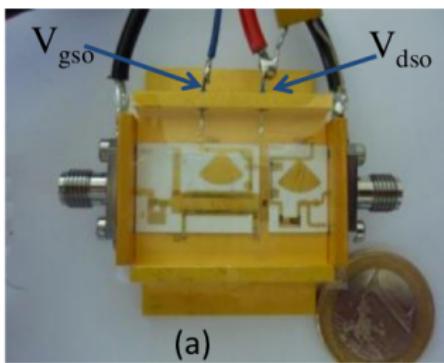


# Measurements Results : effect of injection [12]

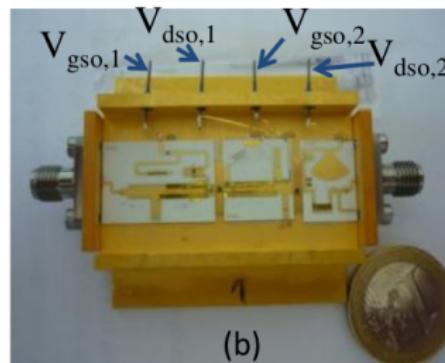


- ➊ (1) Optimal second harmonic injection at the input.
- ➋ (2) Input second harmonic terminated into  $50\Omega$ .

# Design a 2 stages PA by waveform engineering [13]



(a)

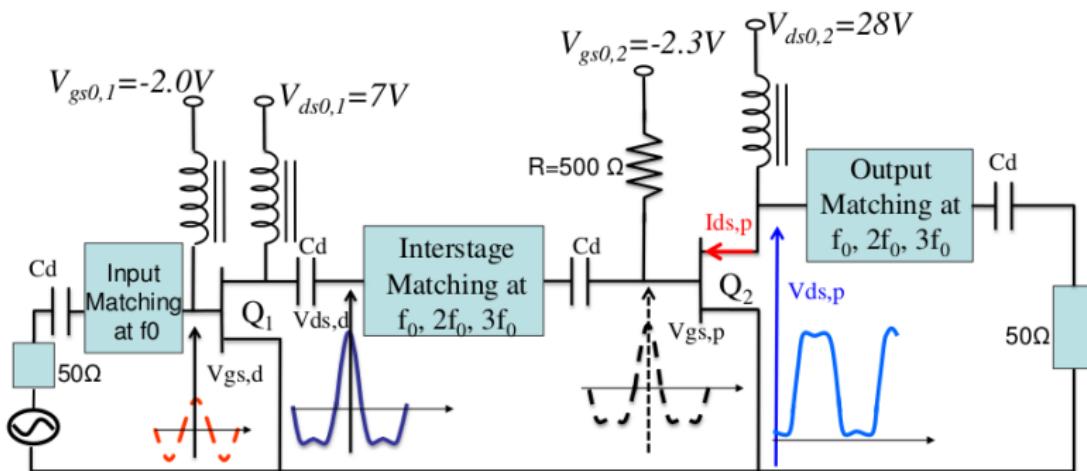


(b)

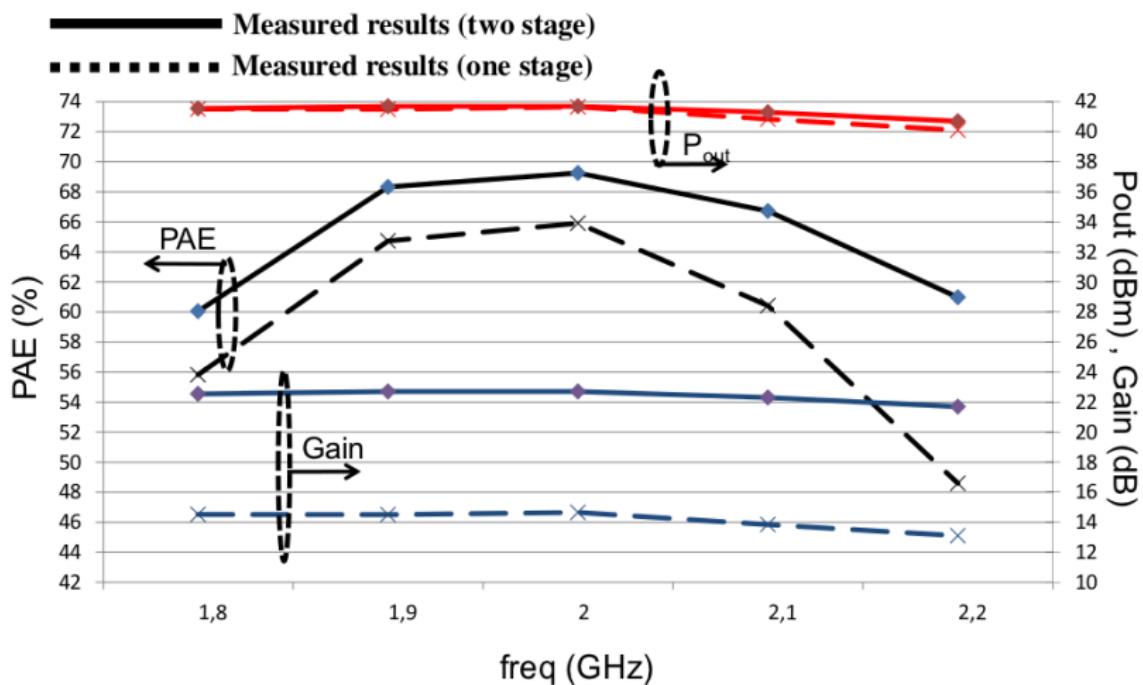
Two demonstrators have been released

- (a) is a single PA.
- (b) is the same PA including a second harmonic injection (driver).

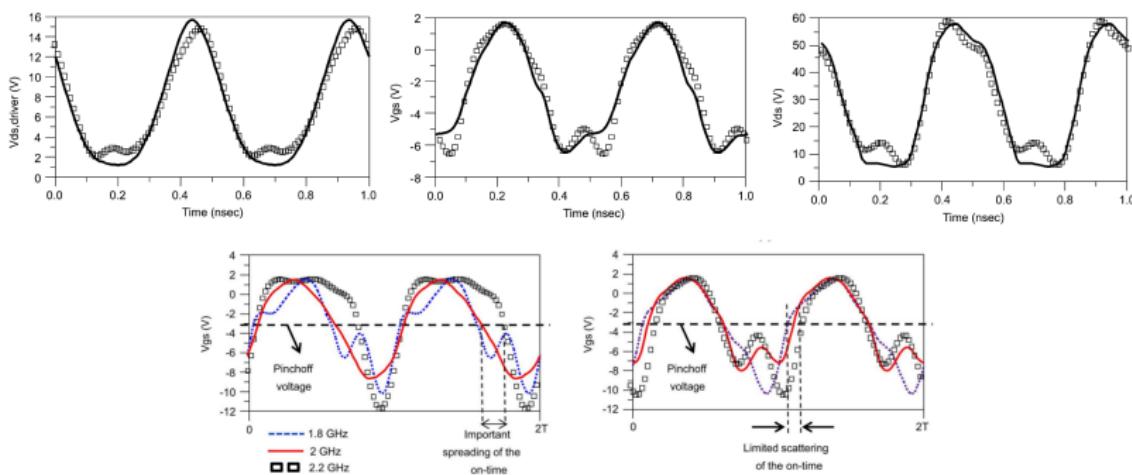
# 2 stages PA topology [14]



# Measurements results at 4dB compression

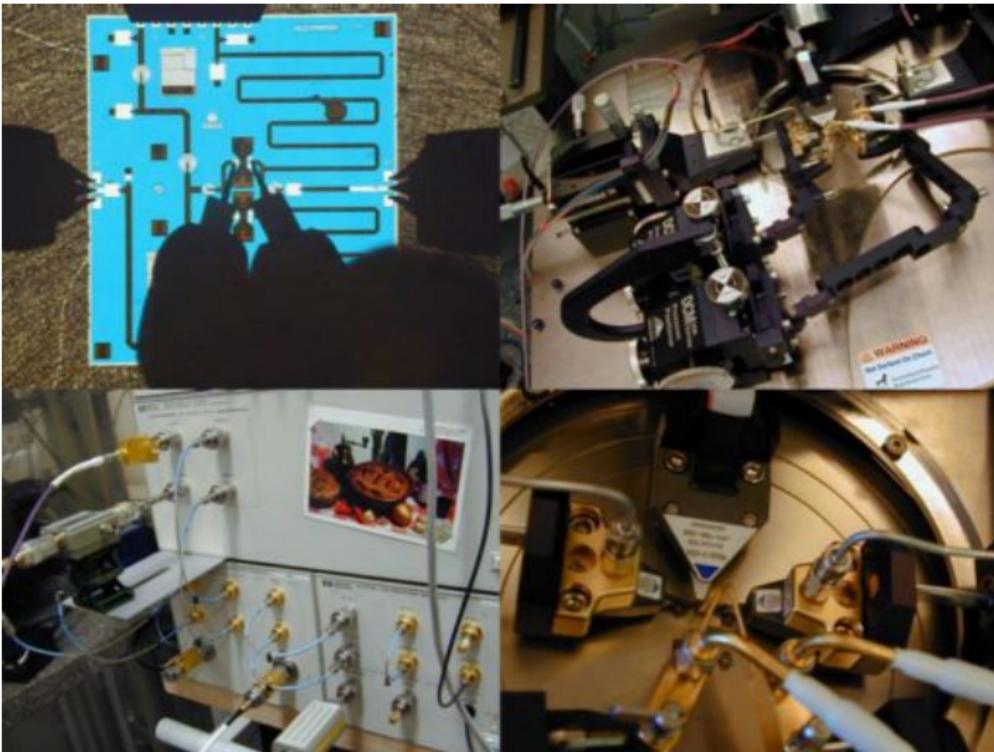


# HIP Measurements results



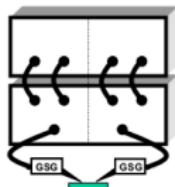
- Top : Comparison Measurement/Simulation on Q1 drain, Q2 gate and Q2 drain voltages.
- Bottom : Gate voltage of the power stage vs. frequency.

# Signal Integrity with High Impedance Probes [15]



# System Calibration

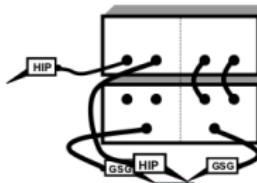
## 1. NVNA calibration (LRRM)



$$\begin{pmatrix} v1 \\ il \\ v2 \\ i2 \end{pmatrix}_{LSNA} = \begin{bmatrix} \alpha_1 & \beta_1 & 0 & 0 \\ \gamma_1 & \delta_1 & 0 & 0 \\ 0 & 0 & \alpha_2 & \beta_2 \\ 0 & 0 & \gamma_2 & \delta_2 \end{bmatrix} \cdot \begin{pmatrix} r1 \\ r2 \\ r3 \\ r4 \end{pmatrix}_{LSNA}$$

→ Ref. plane = voltage standard

## 2. Calibration with 1 HIP



- HIP @ ref. plane
- « Sweep-sin »
- Measurements :
  - >  $V_2$  (NVNA calibrated)
  - >  $V_{HIP}$  (raw data)

$$\Rightarrow \tilde{K}(f) = \frac{v_2(f)}{v_{HIP}(f)}$$

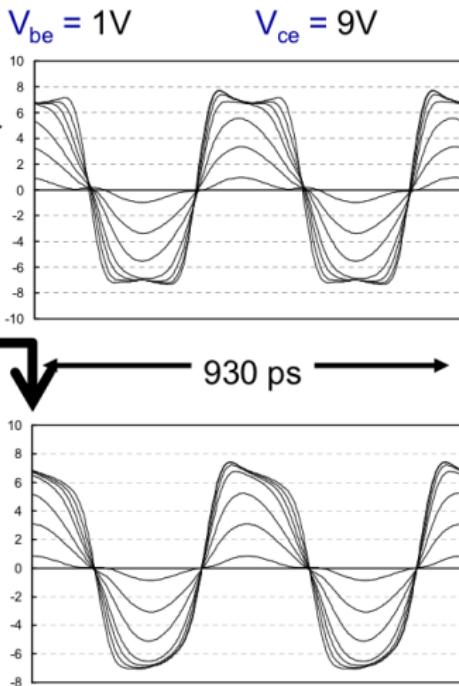
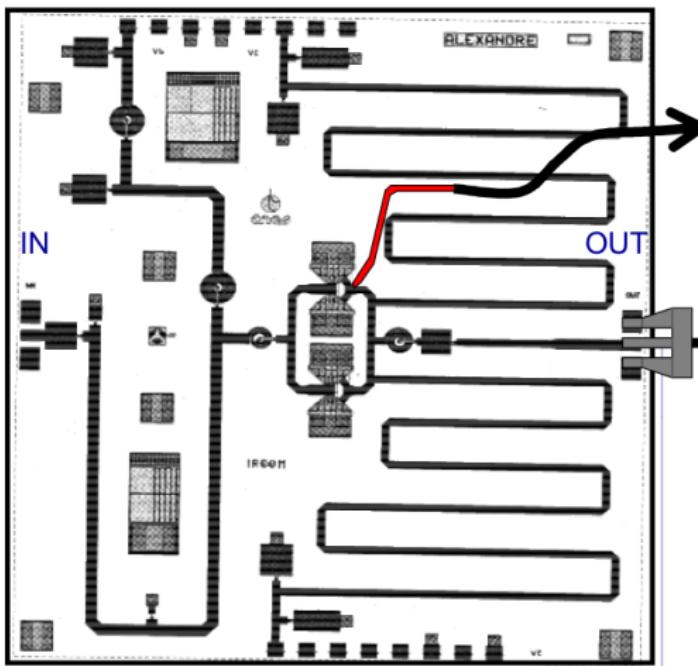
## 3. Define a new error-matrix (NVNA + 2 HIPs)

### Measurement of 2 voltages

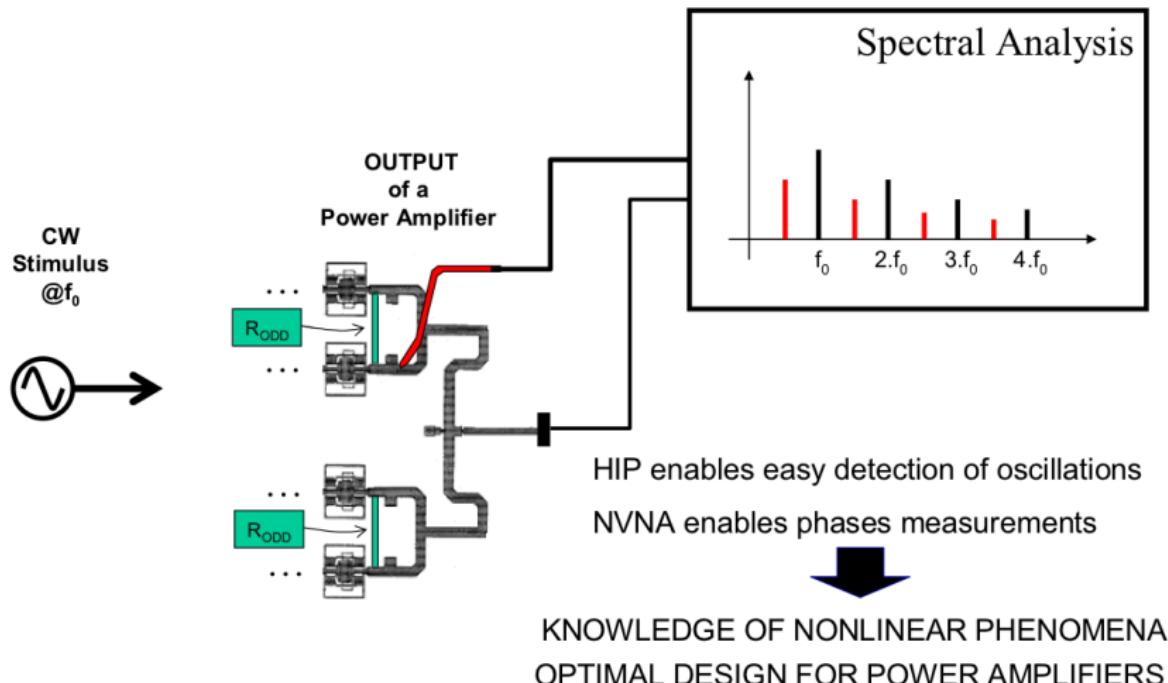
$$\begin{pmatrix} v1 \\ il \\ v2 \\ i2 \end{pmatrix} = \begin{bmatrix} \tilde{K}_1 & 0 & 0 & 0 \\ 0 & \tilde{K}_2 & 0 & 0 \\ 0 & 0 & \alpha_2 & \beta_2 \\ 0 & 0 & \gamma_2 & \delta_2 \end{bmatrix} \cdot \begin{pmatrix} r1 \\ r2 \\ r3 \\ r4 \end{pmatrix}$$

$v1(t) \Leftrightarrow v1(t)$   
 $i1(t) \Leftrightarrow v2(t)$

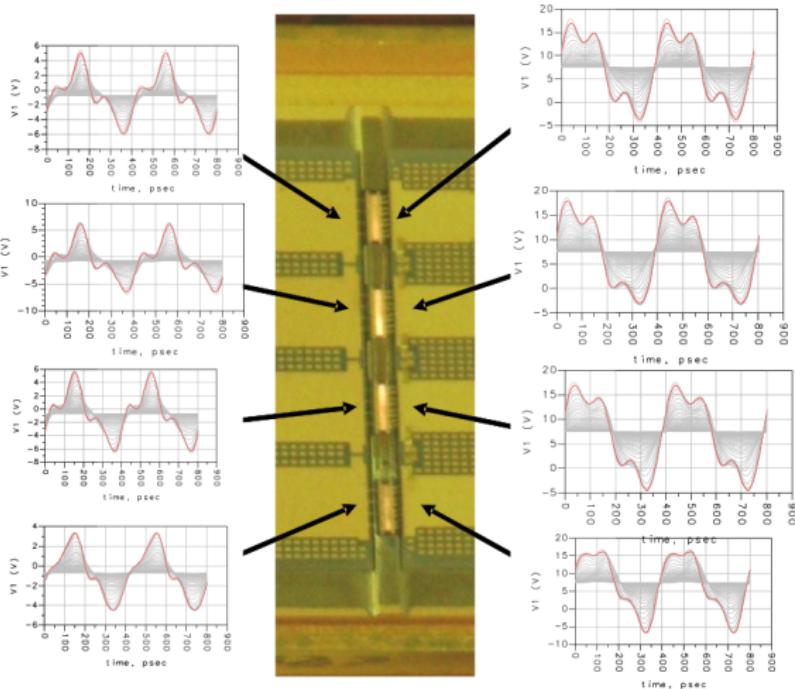
# Waveform Checking



# Stability Analysis

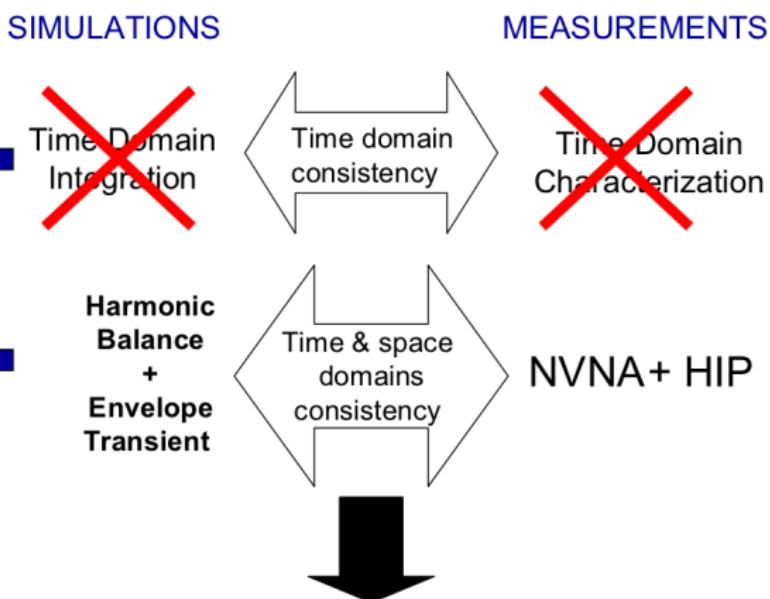


# Reliability Analysis [16]



# Measurement Based Waveform Engineering of SSPAs

Analysis...  
Identification...  
Understanding...  
  
of  
  
DYNAMICS  
NONLINEAR  
PHENOMENA



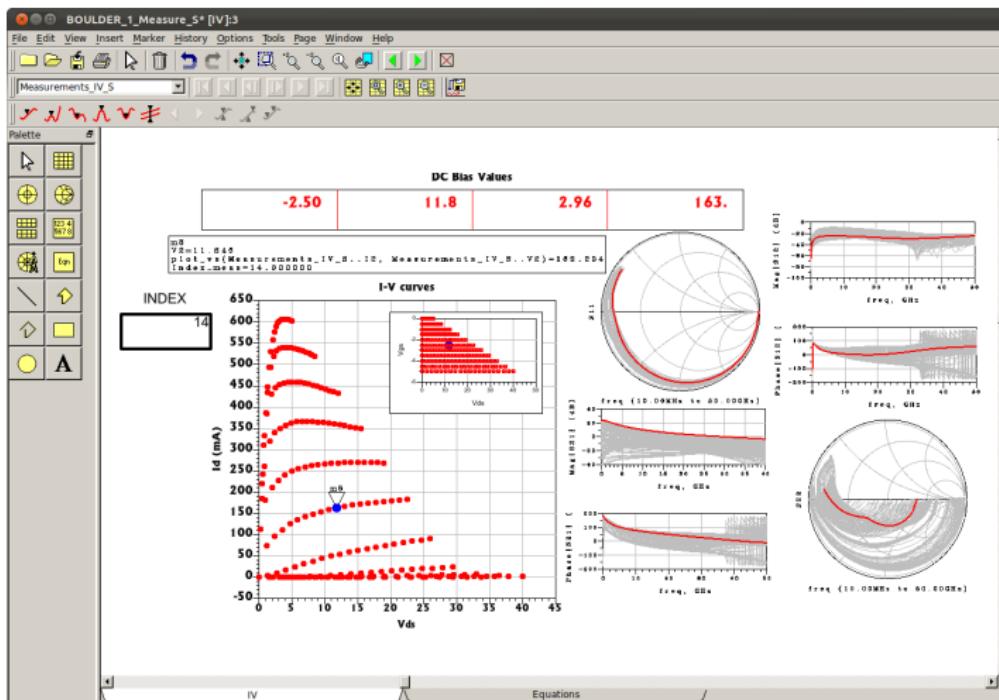
# Using ADS for measurements

External Software are supposed to help the customer.

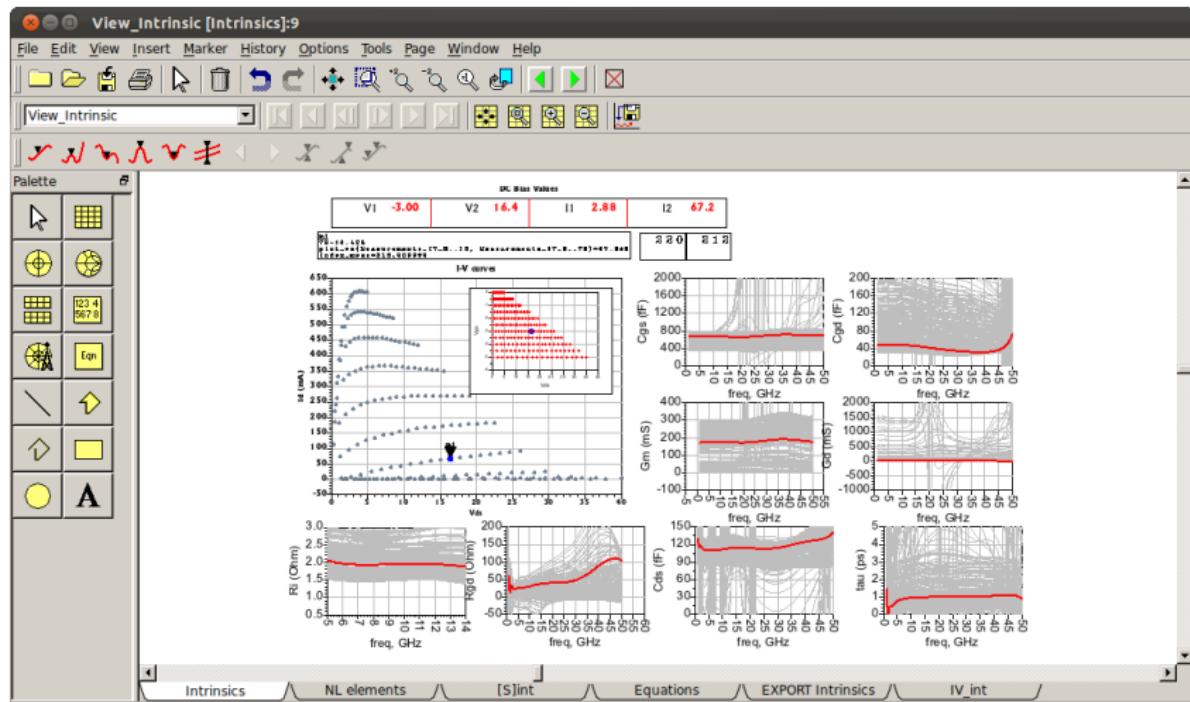
- Agilent IC-CAP (HEMT Modeling - Agilent)
- IV-CAD (Data display and Modeling - Maury)
- Load-Pull Explorer (Data display - Focus)
- ...

But the final design tool is Agilent ADS. You should forget about S2P files and only care of dataset...

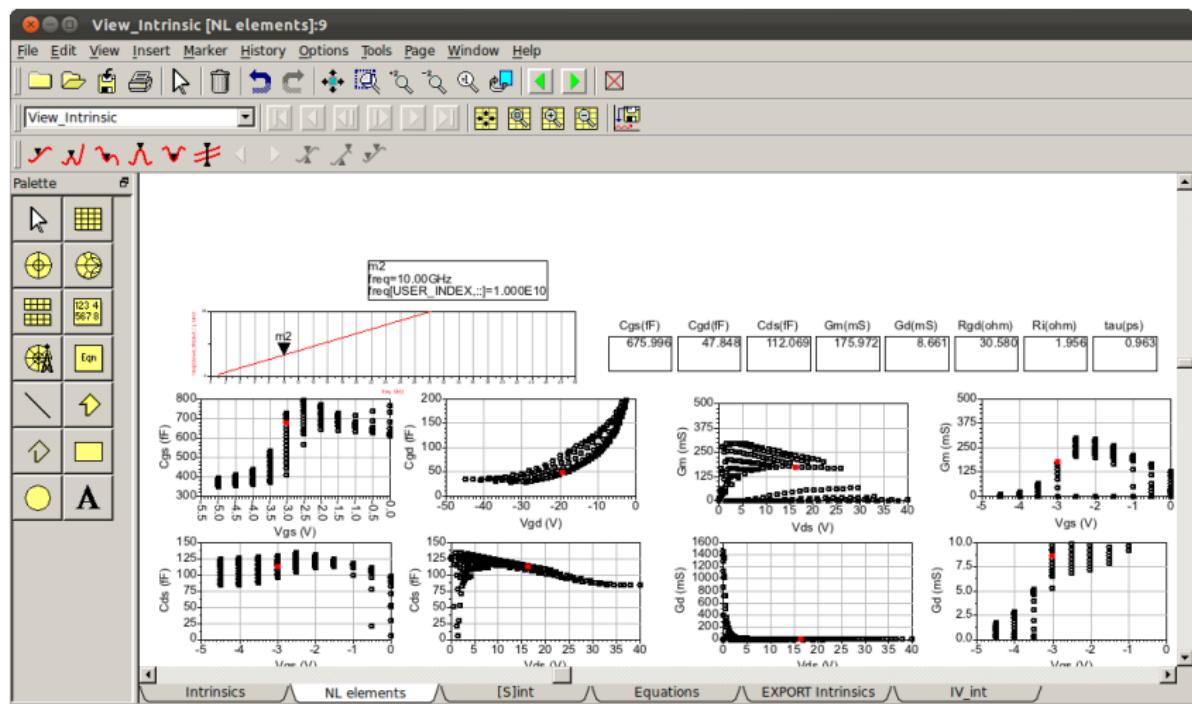
# Using ADS for measurements : IV-[S] measurements



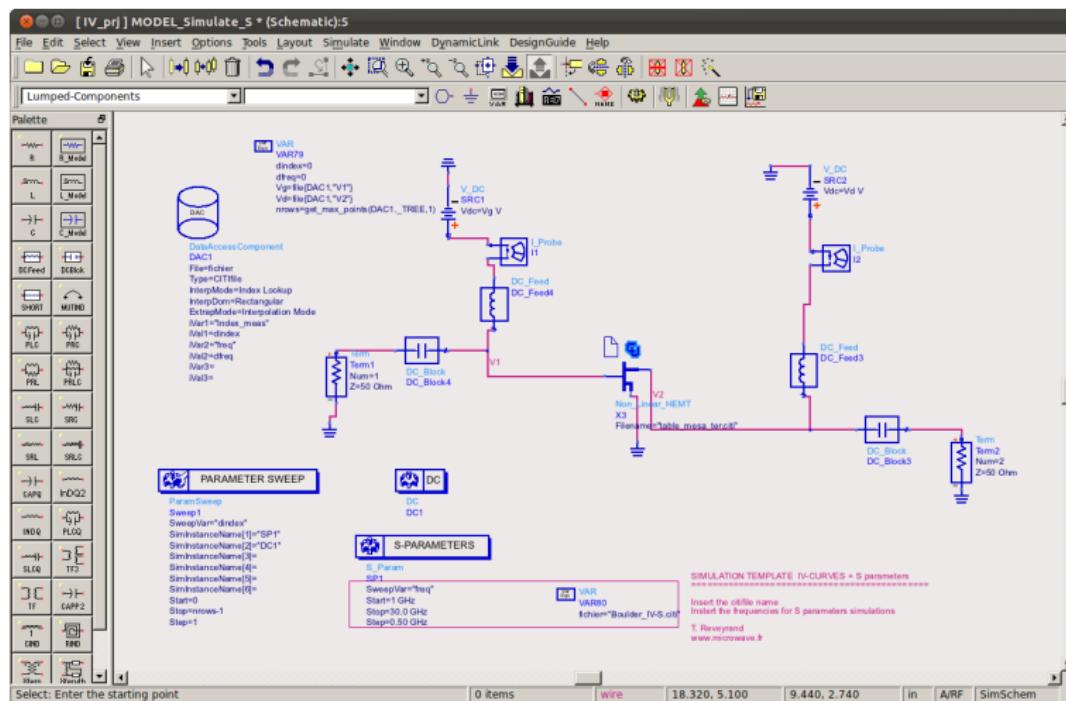
# Using ADS for measurements : HEMT Modeling



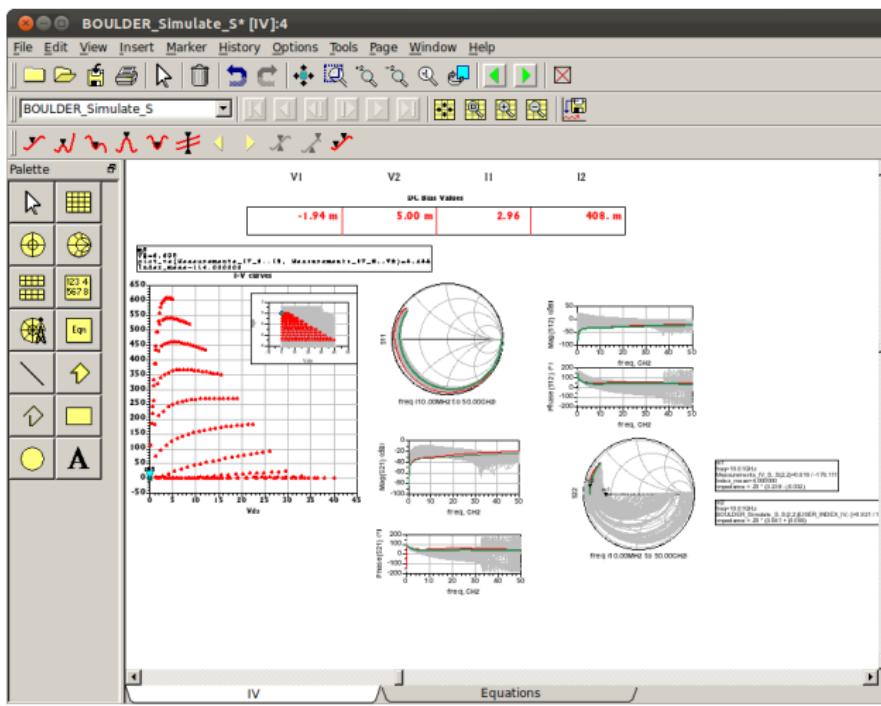
# Using ADS for measurements : HEMT Modeling



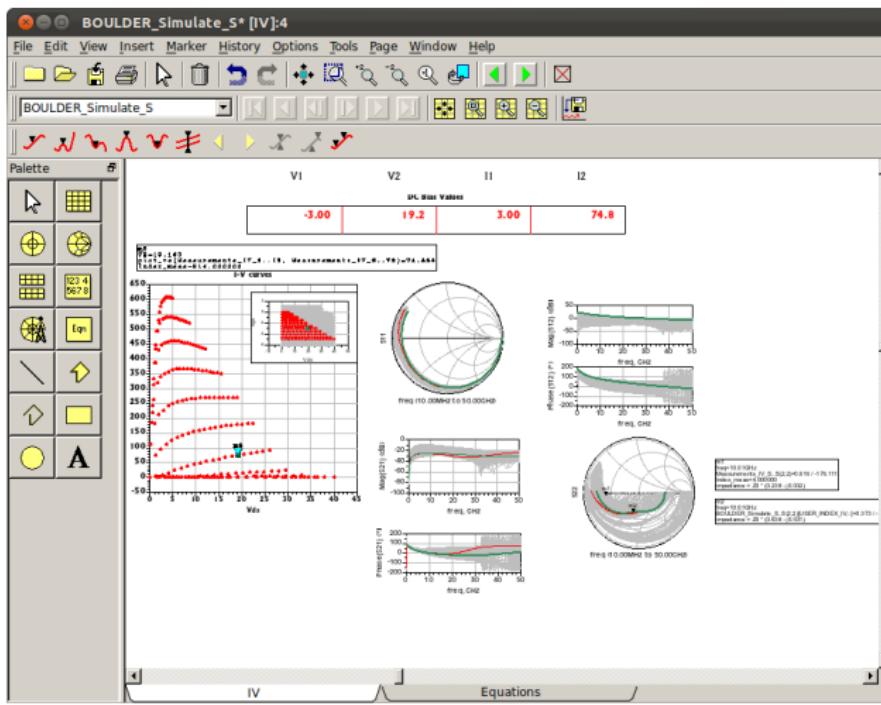
# Using ADS for measurements : HEMT Modeling



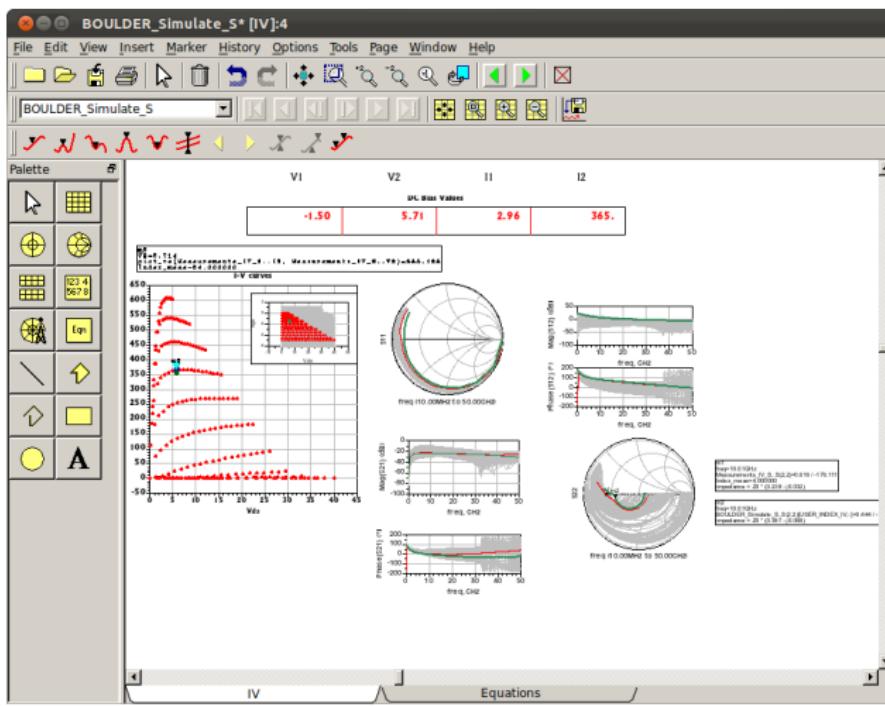
Using ADS for measurements : HEMT Modeling



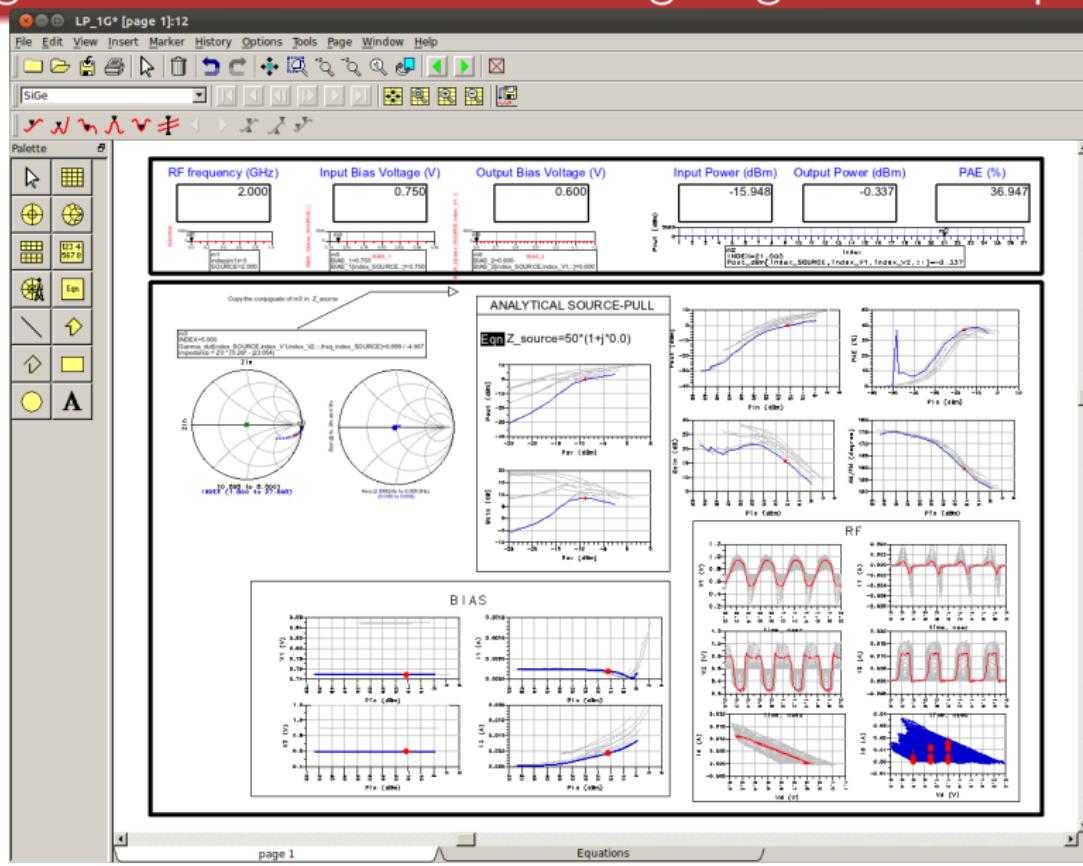
# Using ADS for measurements : HEMT Modeling



# Using ADS for measurements : HEMT Modeling



# Using ADS for measurements : Large Signal data display



# Conclusion

This presentation was about all the design flow in RF design.

- Instrumentation
- HEMT Modeling
- Design Topology

High efficiency power amplifier designs are related to time domain waveform. Characterizations, modelings and simulations have to be self consistent in a time domain analysis.

# References |

- [1] Helmut Vogler. Microwave components research and innovation in the eu – a company perspective. 2008.
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- [4] F. De Groote, O. Jardel, T. Reveyrand, J.P. Teyssier, and R. Quéré. Very small duty cycles for pulsed time domain transistor characterization. *Proceedings of the European Microwave Association Vol*, 112 :117, 2008.
- [5] J. Faraj, F. De Groote, J.P. Teyssier, J. Verspecht, R. Quéré, and R. Aubry. Pulse profiling for algan/gan hemts large signal characterizations. In *Microwave Conference, 2008. EuMC 2008. 38th European*, pages 757–760. IEEE, 2008.
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- [7] S. Ahmed, M. Saad-el dine, T. Reveyrand, G. Neveux, D. Barataud, and J. Nebus. Time-domain measurement system using track amp ; hold amplifier applied to pulsed rf characterization of high power gan devices. In *Microwave Symposium Digest (MTT), 2011 IEEE MTT-S International*, page 1, june 2011.

## References II

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