NIWeek

Design-oriented measurements of high-efficiency PAs for high PAR signals using an NI-based platform

Zoya Popovic and Tibault Reveyrand

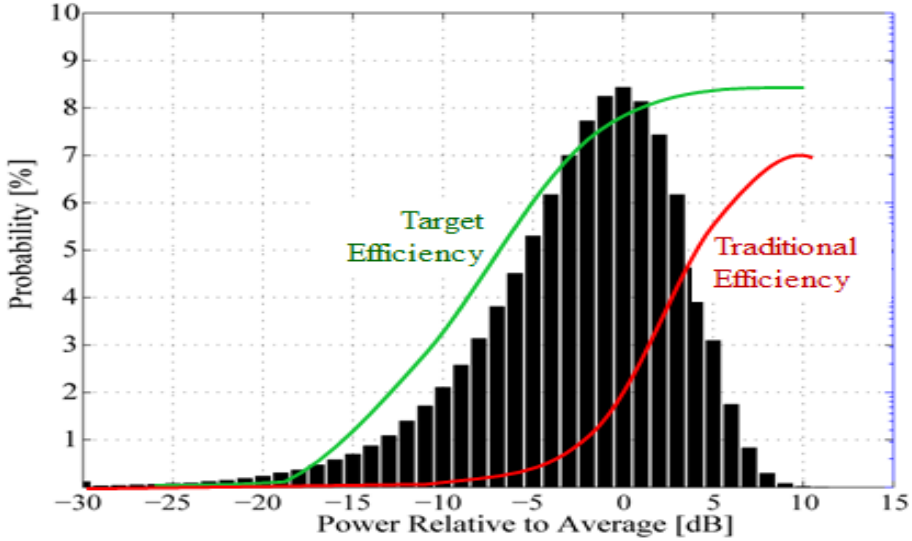
Department of Electrical, Computer and Energy Engineering
University of Colorado, Boulder

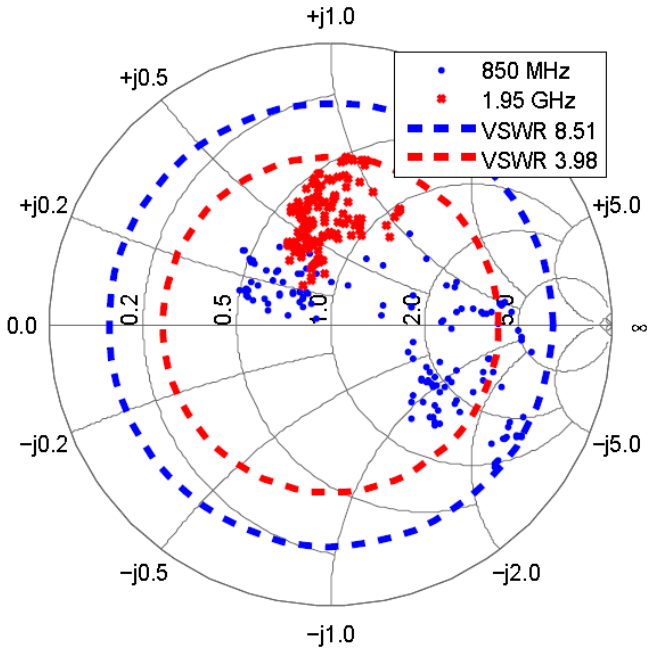
Outline

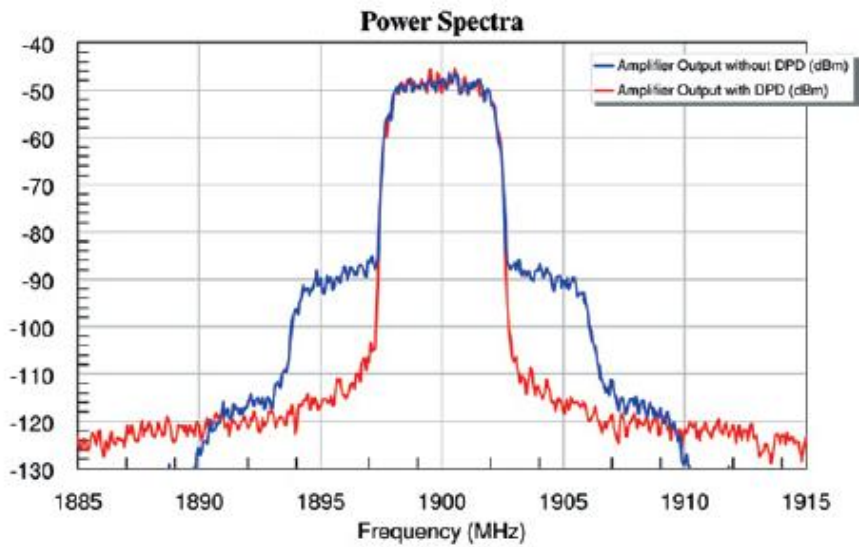
- **Overview of approaches for improving efficiency at power back-off**
- Supply modulation (envelope tracking)
  - GaN PA design (10GHz carrier)
  - Supply modulator (100MHz switching)
  - Integration and modeling
- Outphasing
  - Quasi-MMIC isolated and non-isolated
  - Measurements of load modulation internal to the PA
- Measurement challenges and approach to nonlinear measurements based on NI equipment in a LabView meta-instrument environment

Main challenges in PA design

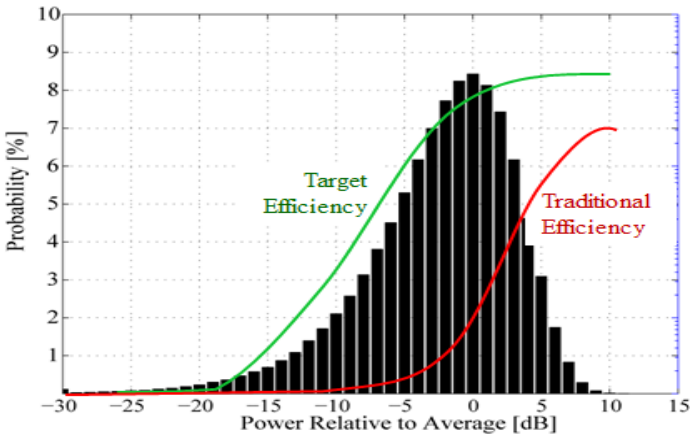
- Challenge 1: efficiency drops as output power drops
- Challenge 2: efficient PAs are nonlinear
- Challenge 3: load can vary

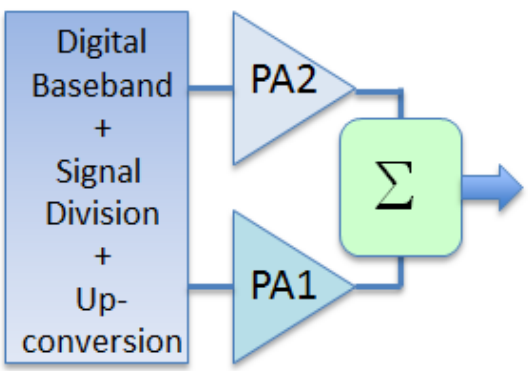




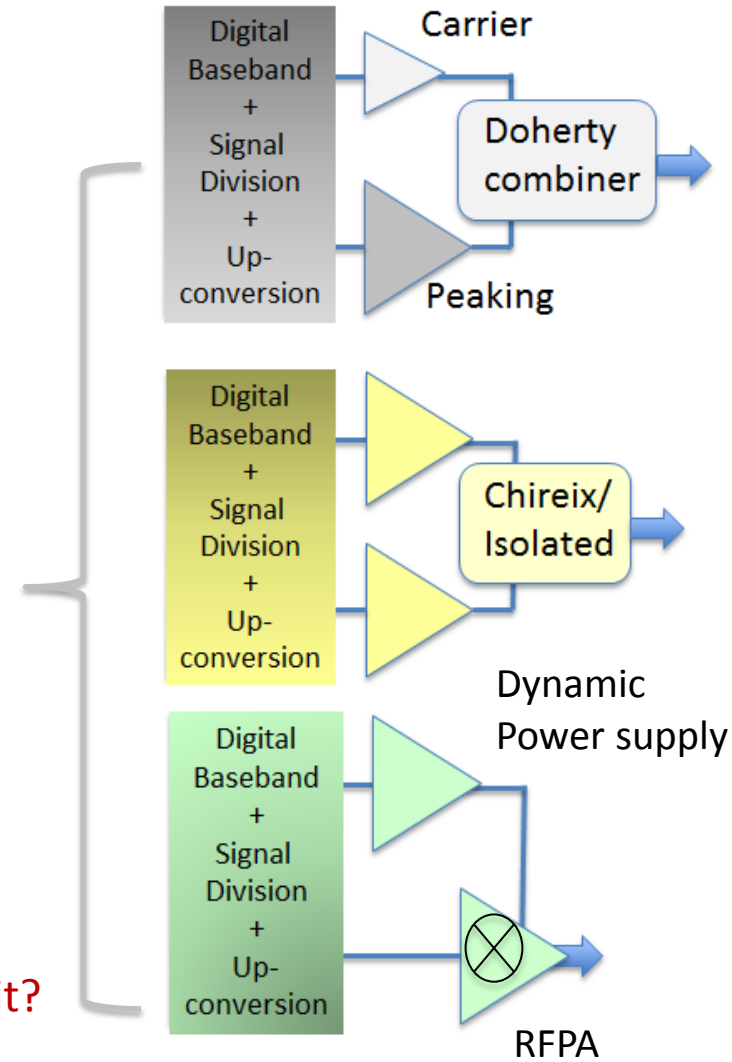


Transmitter architectures





- Need second PA
- Is the added complexity worth it?



Doherty PA:

- 6dB back-off
- 2 RFPAs, different size and bias
- BW limitation

Outphasing (LINC)

- 2 saturated RFPAs
- Isolated and non-isolated

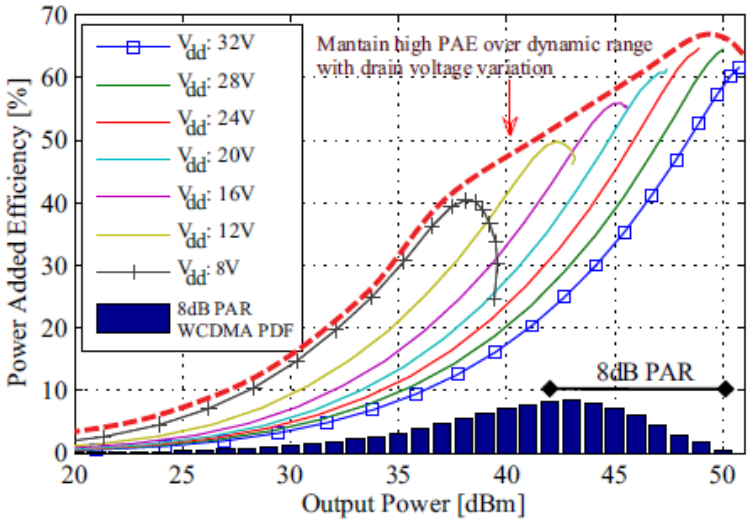
Envelope tracking

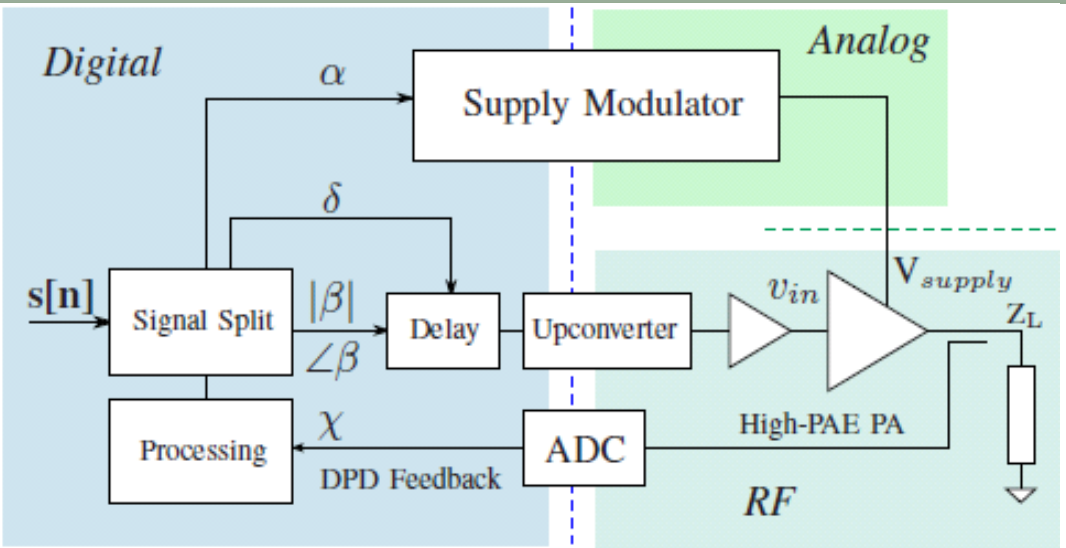
- RFPA and dynamic power supply

Outline

- Overview of approaches for improving efficiency at power back-off
- **Supply modulation (envelope tracking)**
  - **GaN PA design (10GHz carrier)**
  - **Supply modulator (100MHz switching)**
  - **Integration and modeling**
- Outphasing
  - Quasi-MMIC isolated and non-isolated
  - Measurements of load modulation internal to the PA
  - Outphasing with supply modulation
- Measurement challenges and approach to nonlinear measurements based on NI equipment in a LabView meta-instrument environment

Supply-Modulated Transmitters





High-efficiency PA (e.g. harmonically-tuned)

Improve maximum PA efficiency at a chosen power level with sufficient bandwidth for broadband signals

Efficient Supply Modulator

Maintain PA efficiency at average power by varying the drain supply voltage
Enable high slew rates for tracking broadband signals
Introduce minimal reduction in overall efficiency

Linearization

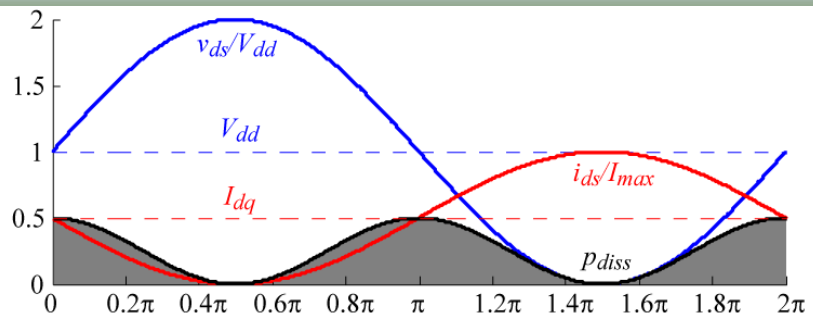
Restore linearity by identifying sources of distortion to simplify DPD

Integration and packaging

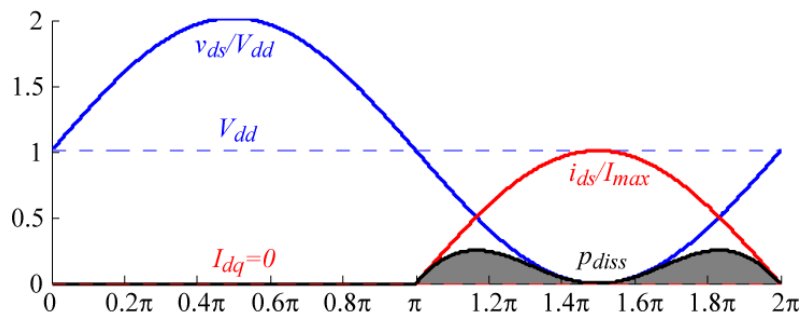
Integrate supply modulator with PA with minimal loading
Thermal management
Integration of various drivers

$$\mathrm{PAE} = \frac{\int_0^{V_{max}} f_{PDF}(V) \cdot [P_{out}(V) - P_{in}(V)]\, dV}{\int_0^{V_{max}} f_{PDF}(V) \cdot P_{DC}(V) dV}$$

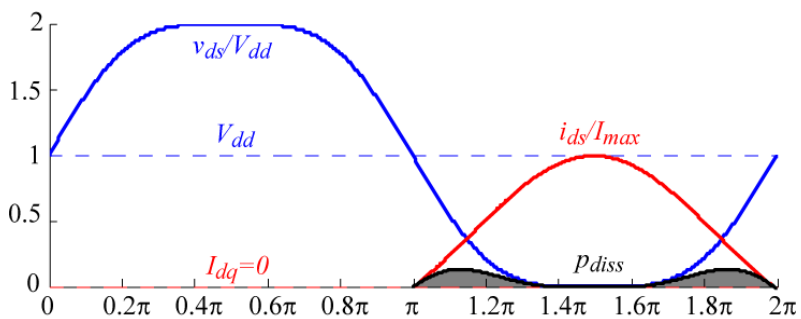
High-efficiency PA design



Ideal class-A drain waveforms



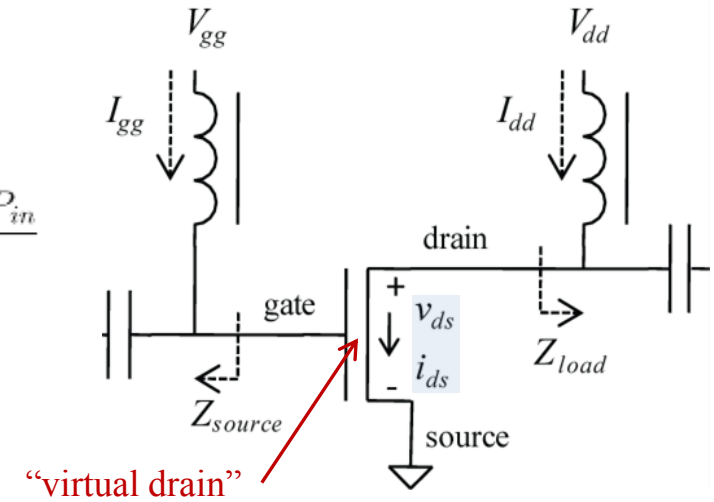
Ideal class-B drain waveforms



Ideal class F drain waveforms with only 3 harmonics

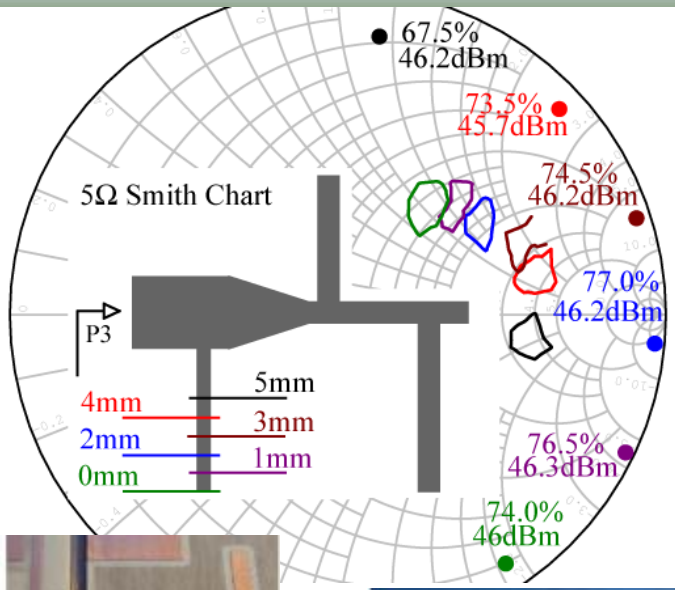
$$PAE = \frac{P_{out} - P_{in}}{P_{dd}}$$

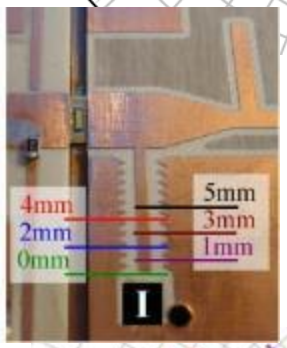
$$\eta_d = \frac{P_{out}}{P_{dd}}$$

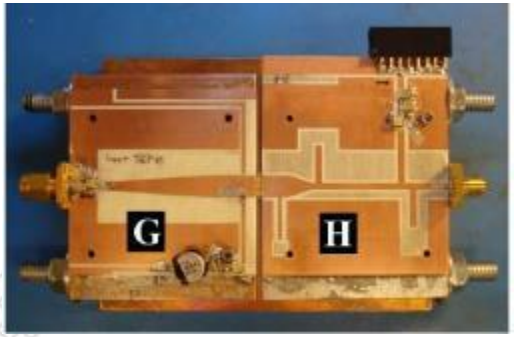


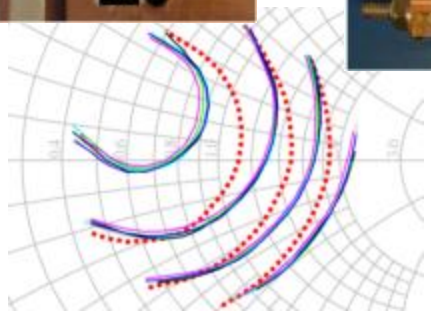
- Transistor power dissipation dominates
  - Reduced conduction angle
  - Avoids v_{ds}-i_{ds} overlap, power dissipation
- Waveform shaping (e.g. class F)
  - Voltage squaring, current peaking
  - 2nd harmonic short allows $2f_o$ current
  - 3rd harmonic open allows $3f_o$ voltage

Effects of 2nd and 3rd harmonic

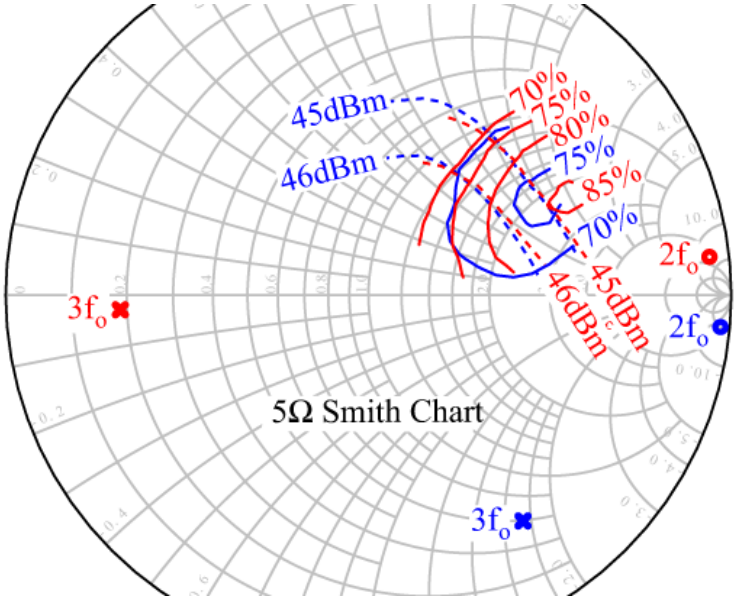








Consistent small-signal gain contours indicate that correct S-parameters were correctly de-embedded from load pull data after each cut.

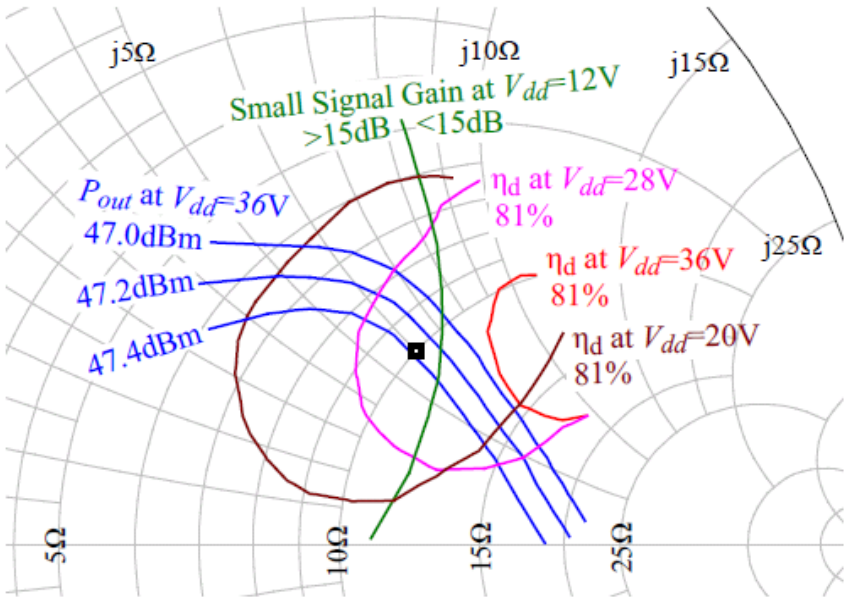


2nd harmonic and 2nd/3rd harmonic load pull for the TGF2023-10 GaN HEMT in chip/wire configuration biased at 28V drain voltage and with 300mA quiescent current.

	2nd Harmonic	2nd/3rd Harmonic
Output Power	31.6W	31.6W
Drain Efficiency	77%	85%
Power Consumed	41.0W	37.2W
Power Dissipated	9.4W	5.6W

High-Efficiency PA Design for SM

- PA design has to take into account:
  - small signal gain
  - efficiency and
  - output power over a range of supply voltages corresponding to an input envelope range
- Use **TriQuint 0.15um GaN:**
  - 20V CW
  - 100um SiC substrate
  - 60um diameter vias
  - 240, 300 and 1200 pF/mm^2
  - 50Ω/sq TaN resistors



Parameter	Condition	Typical
IMAX	Vds = 20 V	1.15 A/mm
Peak Gm	Vds = 20 V	380 mS/mm
Vp	Ids = 1 mA/mm	-3.5 V
BVGD	Ig < 1mA/mm	50 V
Ft	20V-200mA/mm	38 GHz
FMAX	20V-200mA/mm	140 GHz

- Modeling:
  - Fit class Ab/B over a range of Vds
  - Pulsed IV at 25 and 85 deg C
  - S-parameters at 5, 10, 15, 20 V for Idq=10 and 100mA/mm

  Load pull PAE and power tuned at Vd=20V

Example GaN15 reticle

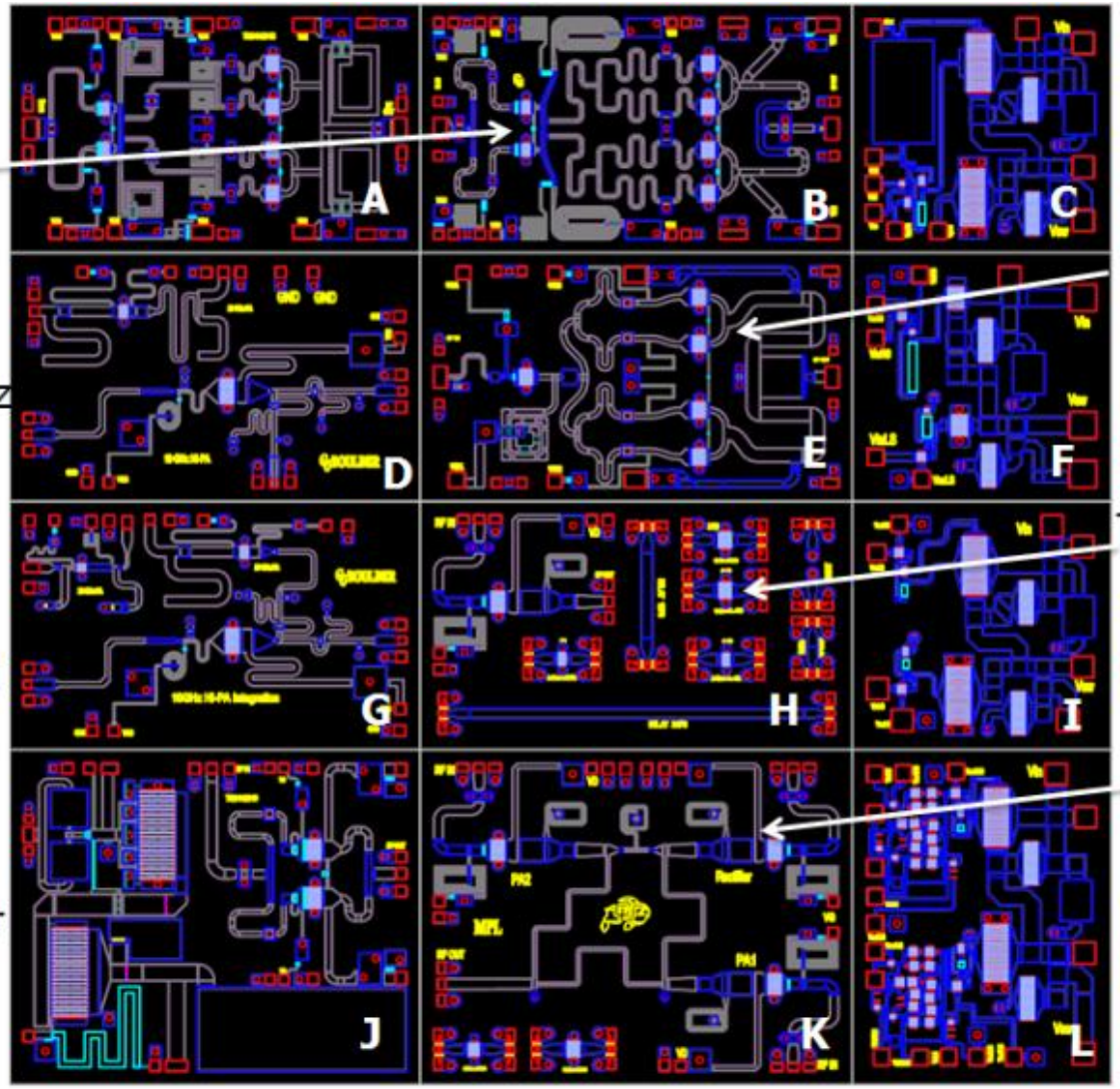
Class-E PA
10W

Class-AB PA

Class-AB
10GHz, 4W
Driver 20GHz
HI-PA

10GHz +
20GHz PA
HI-integrated

PA +
Cascode
Modulator



iDSM2
Bootstrap

10W,
Gsat=20dB

iDSM2 Pull-
up

Test structures

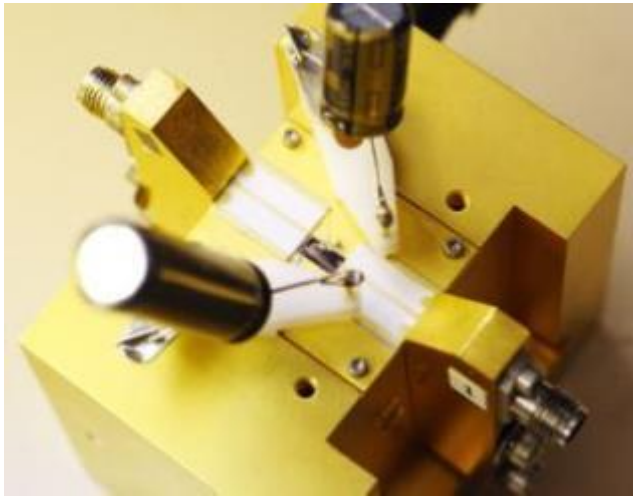
iDSM2 Active
pull-up

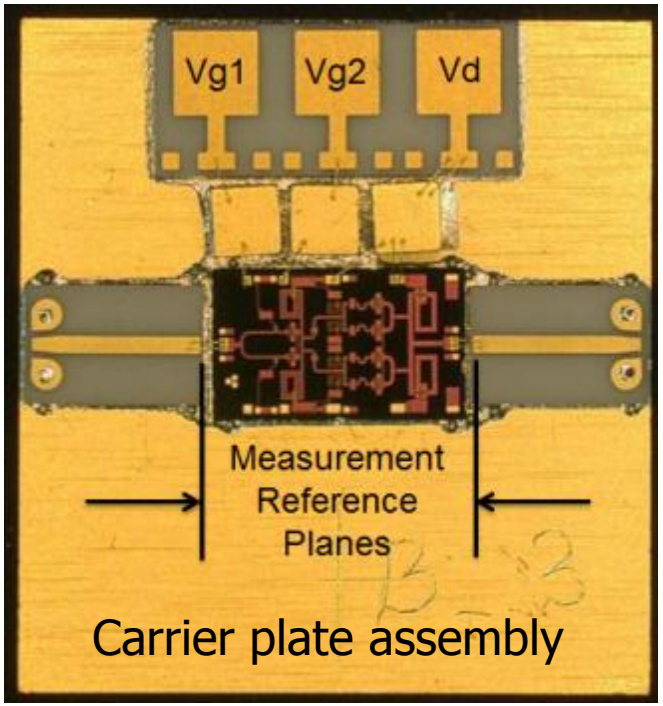
Outphasing

iDSM2 Active
pull-up
+level-shifter

High-Efficiency X-band MMIC PAs

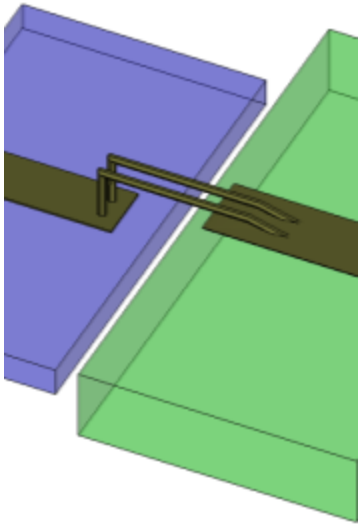
Fixture

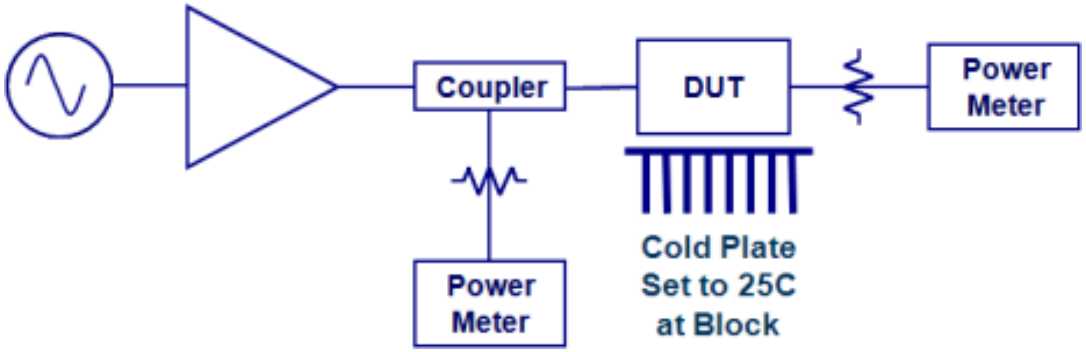


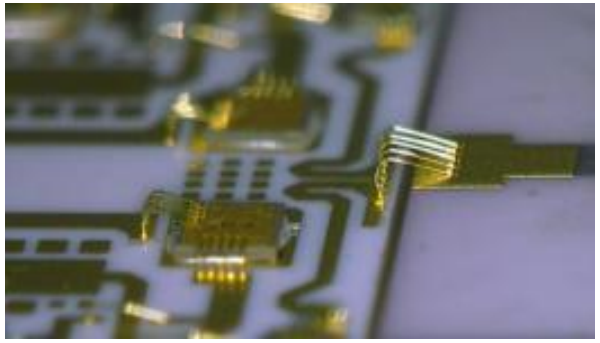


Carrier plate assembly

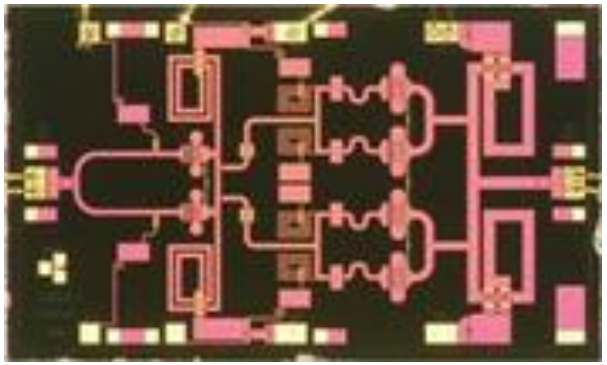
EM models for bondwires included in MMIC design



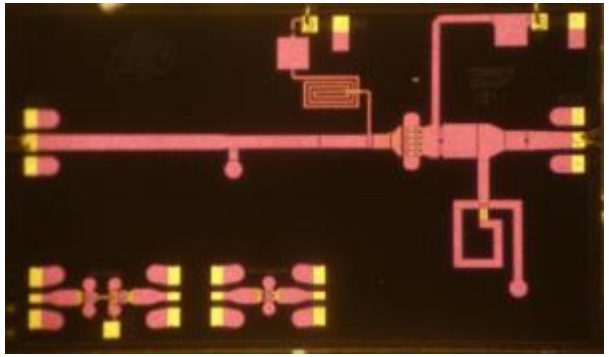




Examples of single PA X-band MMICs

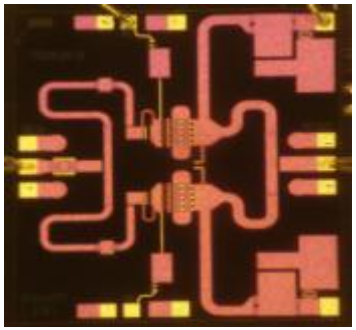


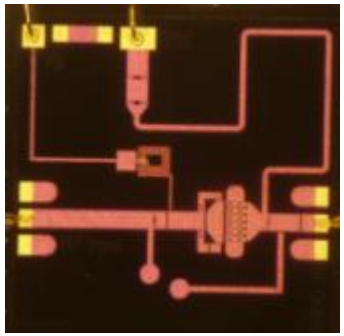
Circuit B:
2-Stage MMIC, combi
four 10x90um.
3.8mmx2.3mm



Circuit F

Single stage, two
10x100um
2.0mmx2.3mm



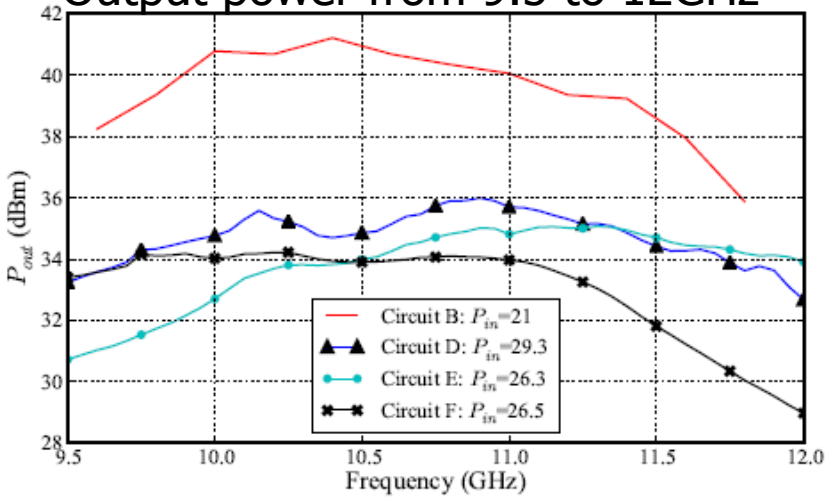


Circuits D/ E

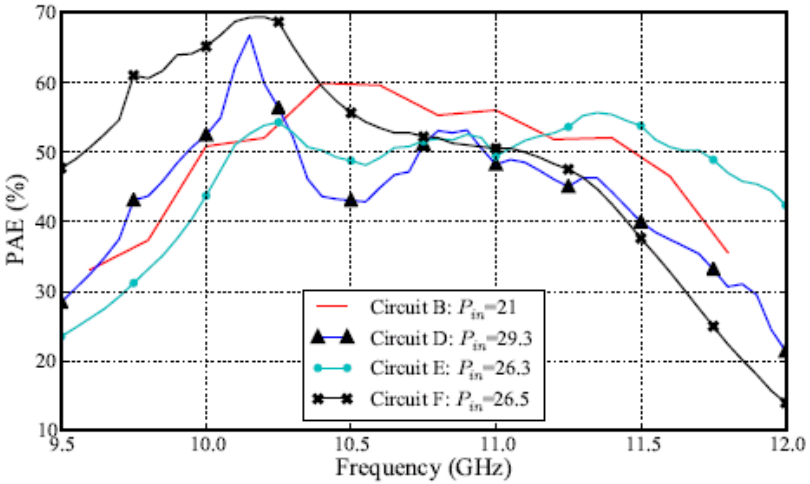
Single stage,
10x100um
3.8mmx2.3mm

and
12x100um
2.0mmx2.3mm

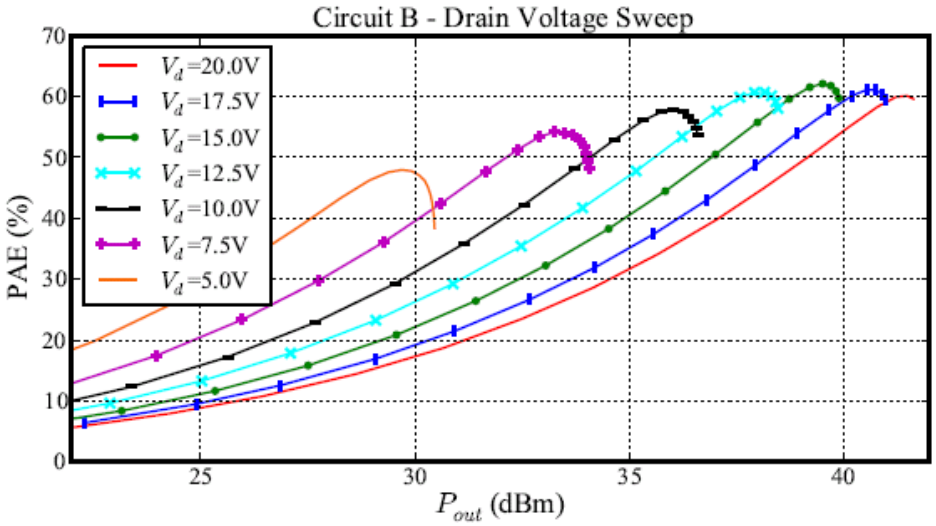
Output power from 9.5 to 12GHz

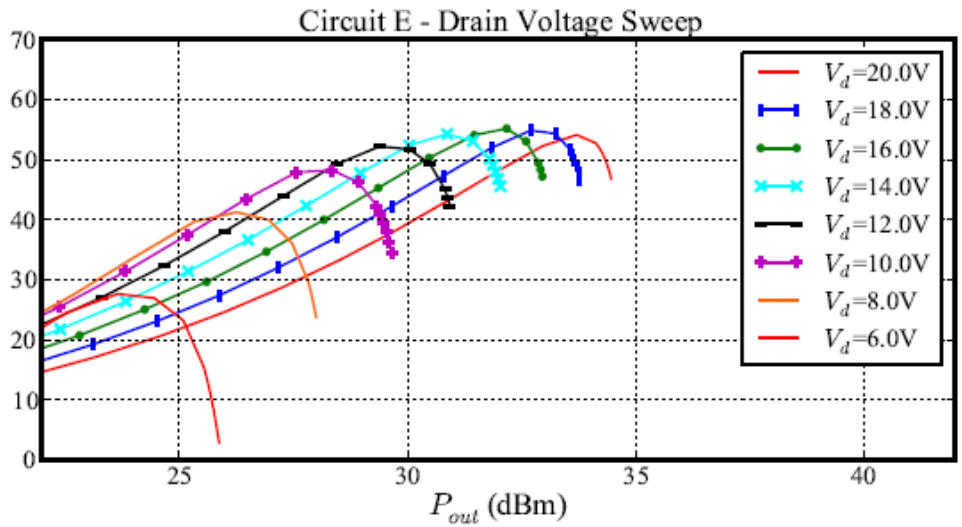


PAE from 9.5 to 12GHz



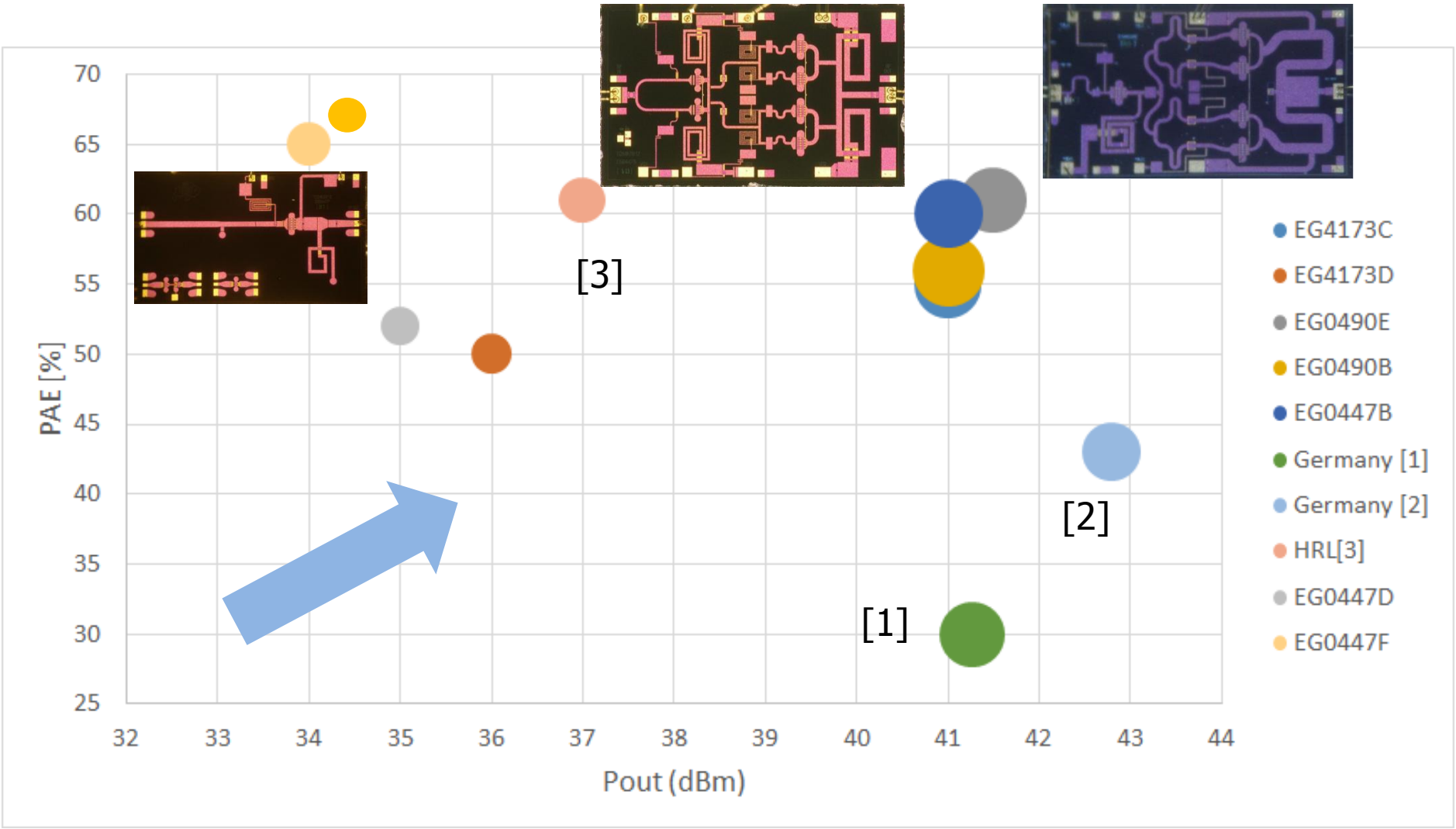
Static Supply Modulation Performance





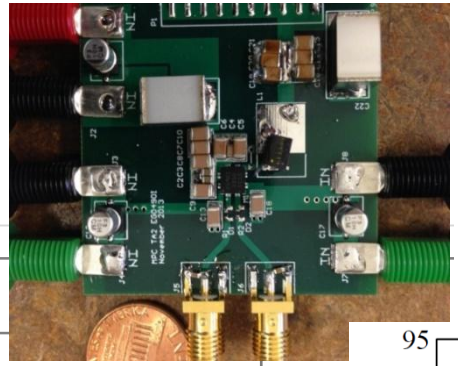
Circuit	B	D	E	F
Max PAE (%)	59.9	66.8	55.7	69.4
Max P_{out} (W)	13.2	3.98	3.22	2.64
Gate size (mm)	3.6	2.0	1.2	1.0
W/mm	3.68	1.99	2.69	2.64
BW at PAE=45% (GHz)	1.6	0.77	1.88	1.95
ΔP_{out} (dB) / ΔV_{ds} (V)	11/12.5	3.3/7	4.8/9	5.3/8

X-band MMIC PAs – state-of-the-art

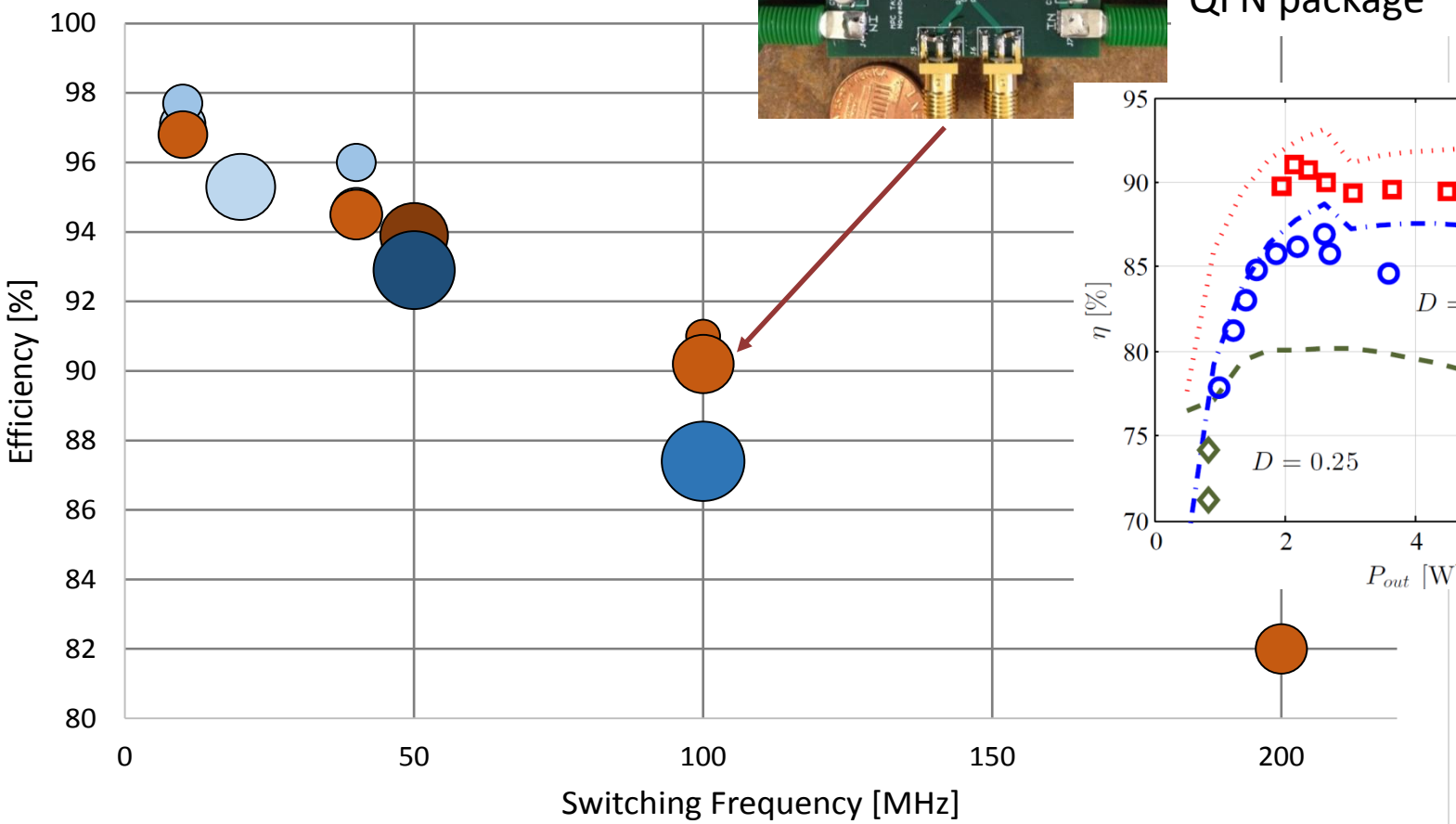


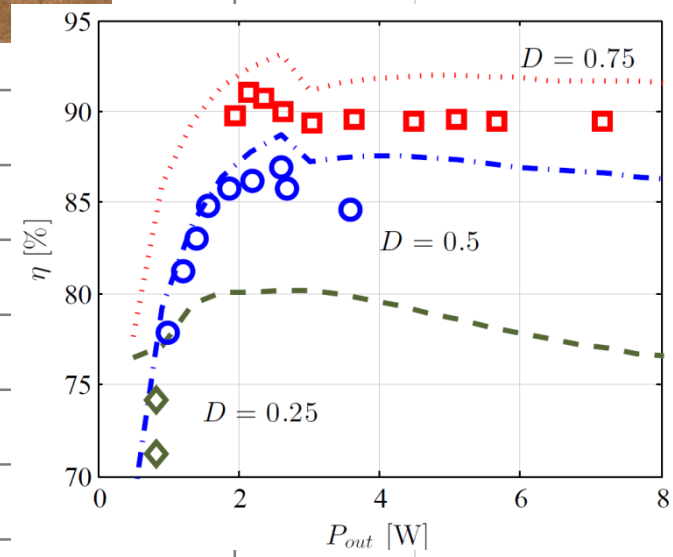
GaN Integrated Supply Modulators

- Switchers with integrated gate drivers
- η >90% , up to 200 MHz sw. frequency, up to 15 W peak power

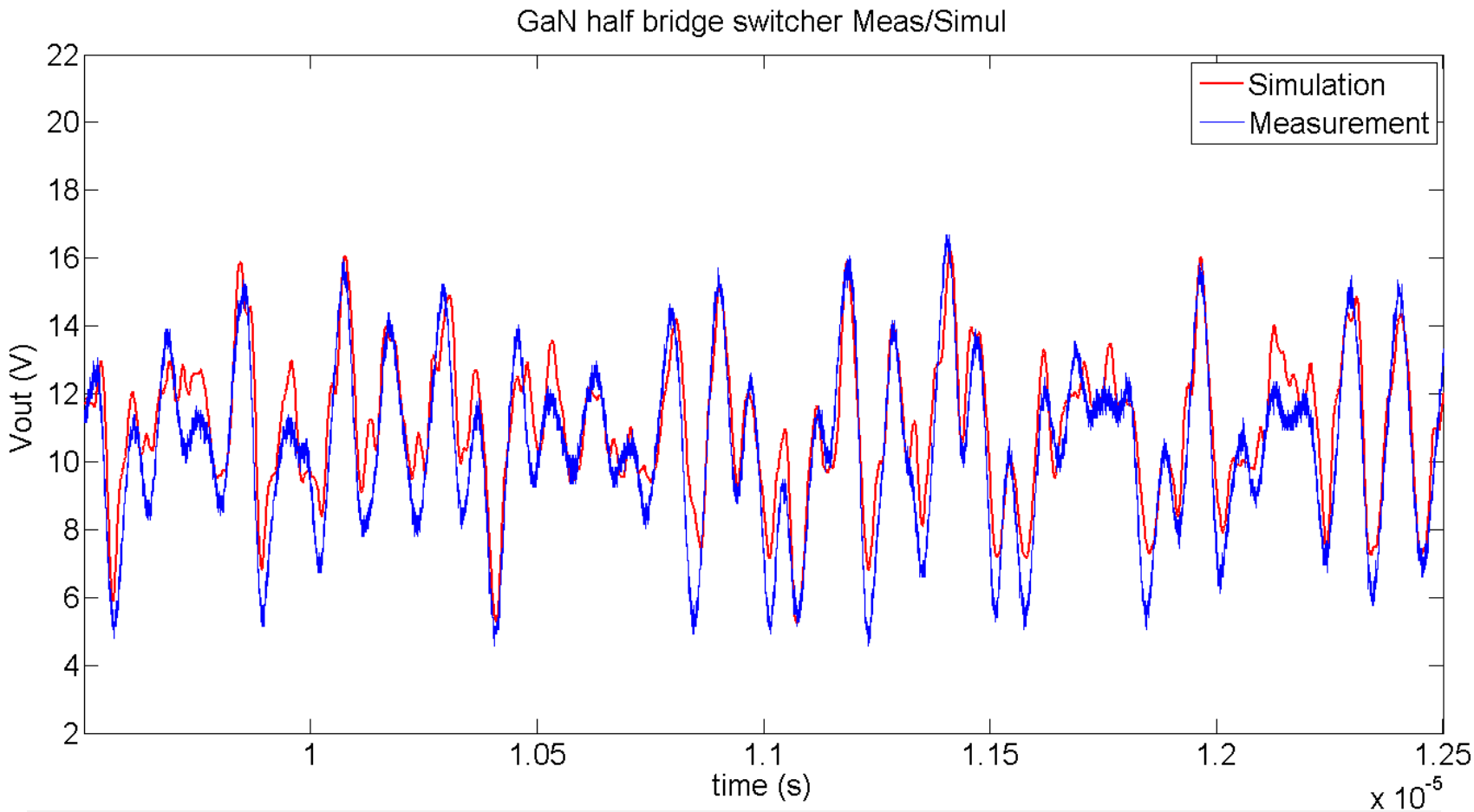


100 MHz, η>90%
10W peak
2.4 × 2.3mm in QFN package



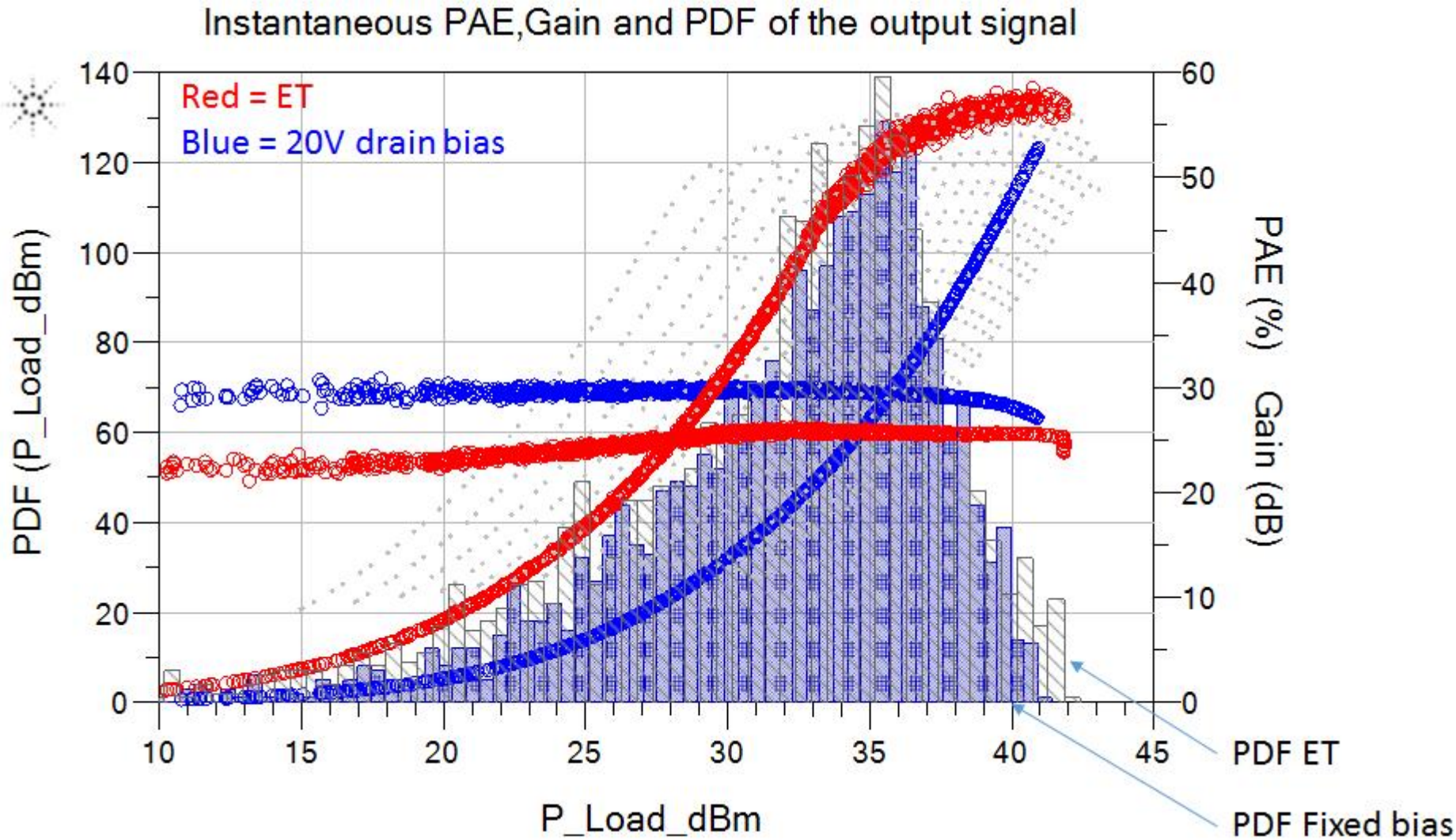


Measured vs. simulated DSM



$$RMS\ error = 100 \times \sqrt{\frac{\sum_{t=1}^{n}\left(V_{out,t} - V_{in,t}\right)^2}{n}} \times \frac{1}{\left(V_{out\_max} - V_{out\_min}\right)} = \mathbf{4.5\%}$$

PA performance with LTE signal



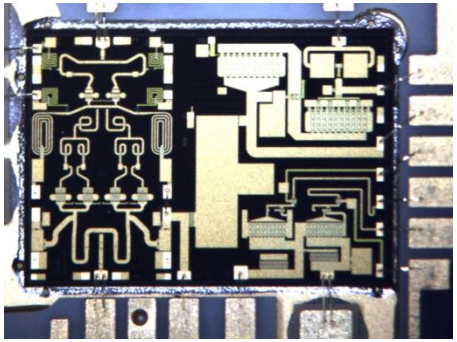
Single-Chip Integrated ET-PA

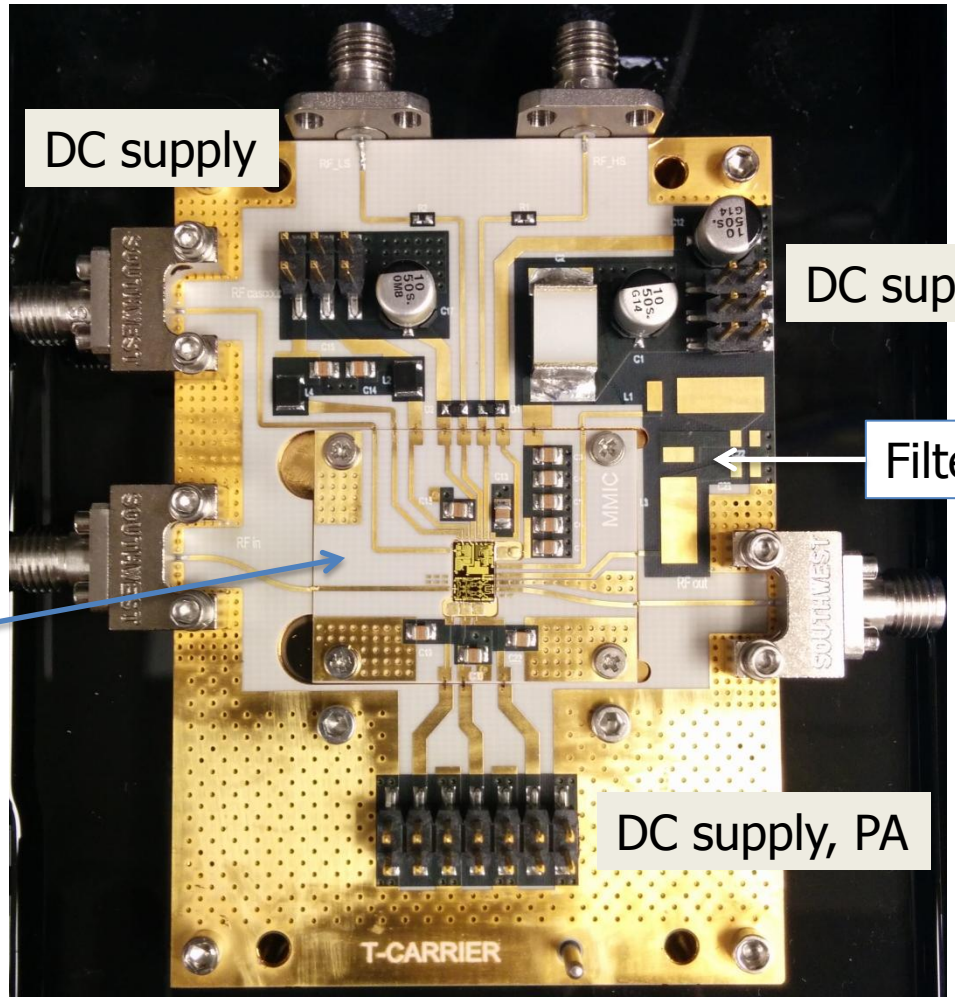
Switcher drive inputs

RF VHF/UHF input

X-band input

MMIC carrier board

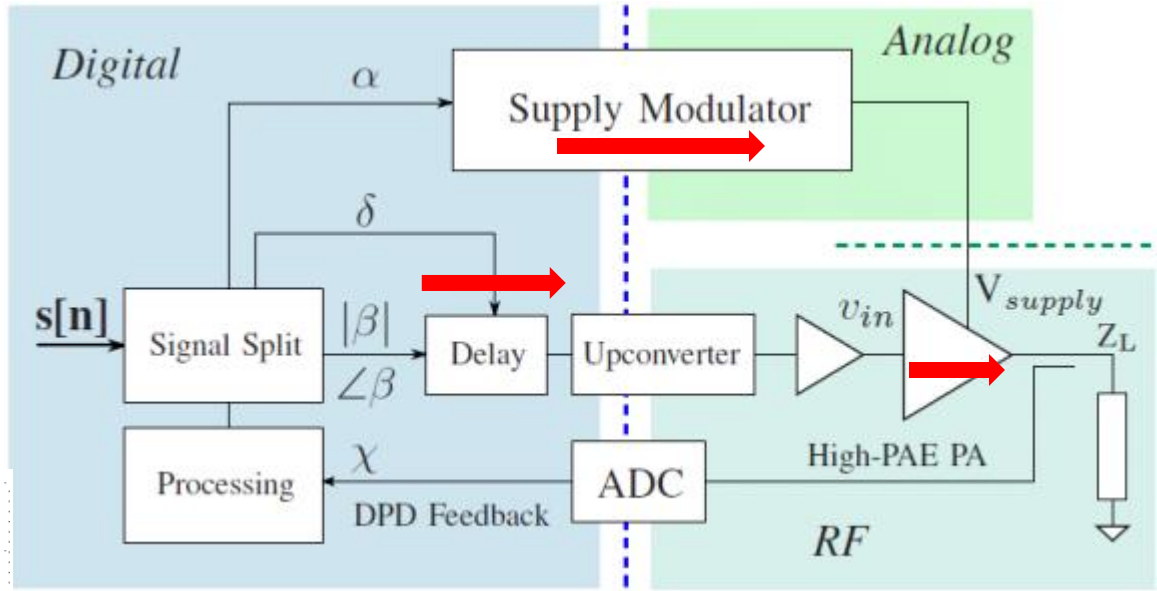


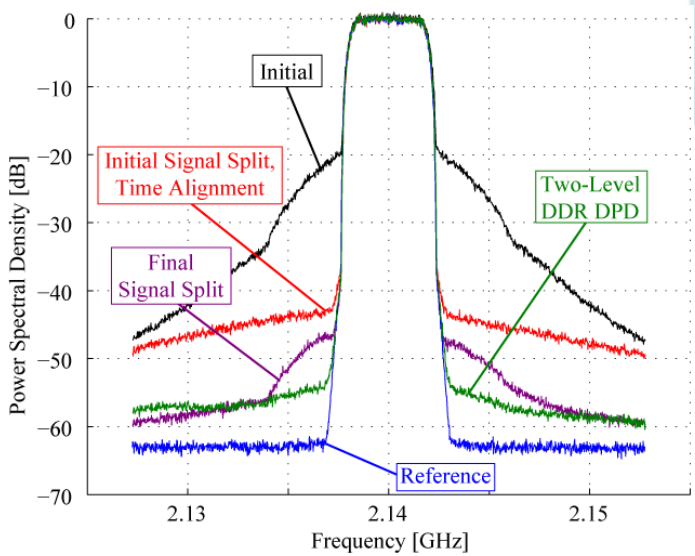


X-band
modulated output

Integration Issues: Linearization

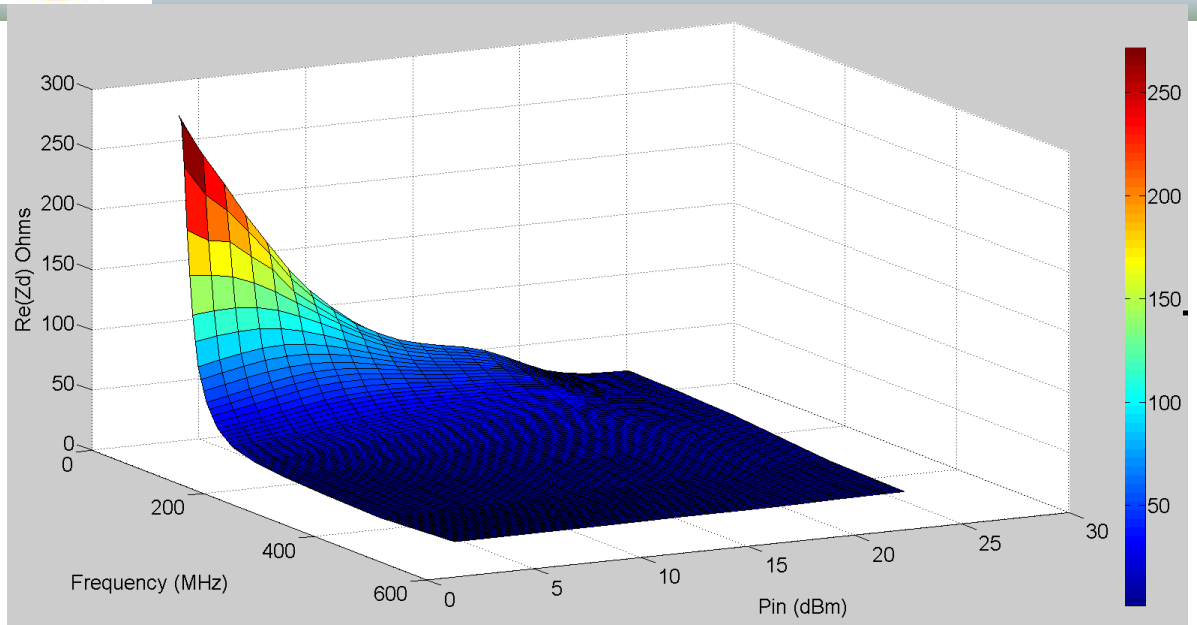
Supply modulator issues:
- Supply sensitivity
- High slew rate
- Dynamic load
- Linearization

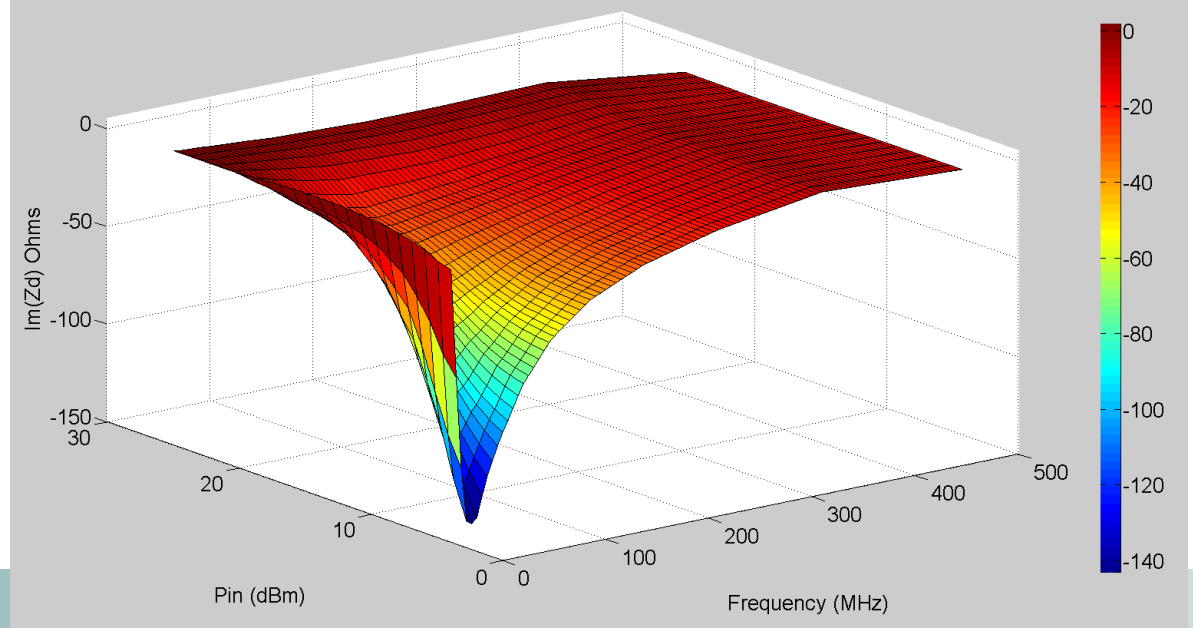




- SM modulator gain and phase distortion
- RFPA gain variation with V_{supply}
- Path delay difference between the vin and Vsupply paths occurs when both v_{in} and V_{supply} are changing over time
- Nonlinear memory

Measured static drain impedance, fixed VDD





Vdd = 15V
Vg1=-2.8V, Vg2=-3.75V

Trends similar to simulations.

Real part is high at low frequencies and decreases to reach 1.5Ω at 500MHz.

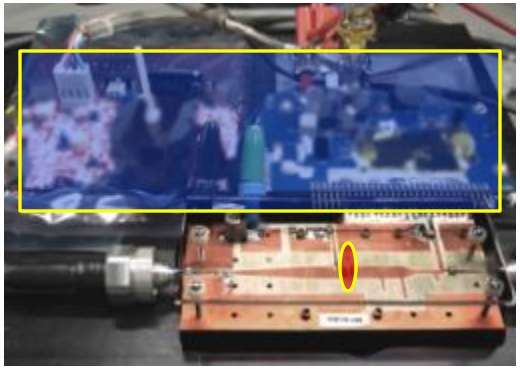
At saturation, the real part remains under 20 Ω.

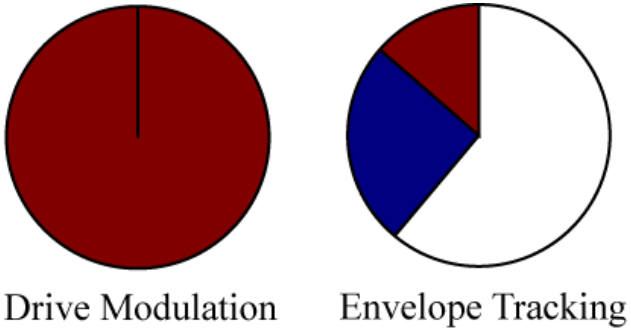
At low power, the drain impedance is highly capacitive and becomes almost purely real at compression.

Is it worth it? – S-band results

- Drive modulated conditions
  - Same W-CDMA signal
  - Same PA
  - Constant 32V V_{dd}
  - Achieves similar linearity
- Power consumption
  - ET requires **43% less power**
  - ET operates **75% longer from battery**
- Power dissipation
  - ET system produces **61% less heat**
  - RF transistor operates **86% cooler**

	Drive (A)	Optimized Traj
Peak/Average Power	40W / 8.5W	40W / 8.5W
RFPA drain eff.	30%	76%
SM efficiency	N/A	69%
ACP at 5 / 10MHz	-57/-58.3 dBc	-55.7/-57.8dBc
Transmitter efficiency	30%	52.5%
Supply power	28.3W	16.4W

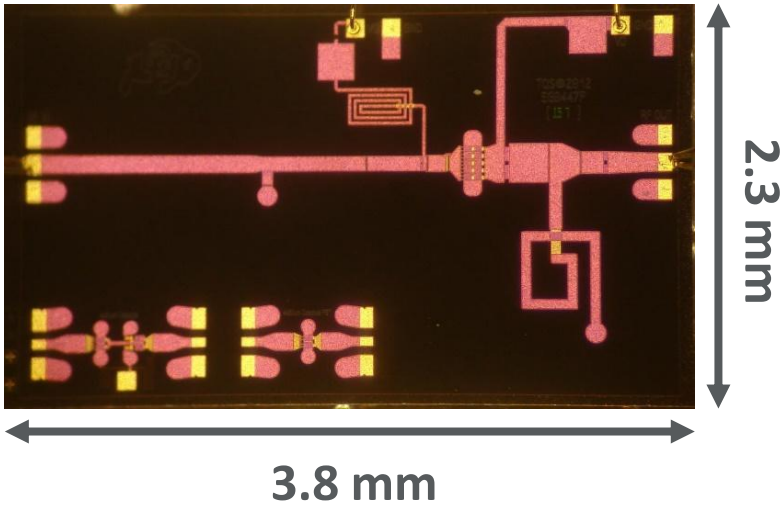


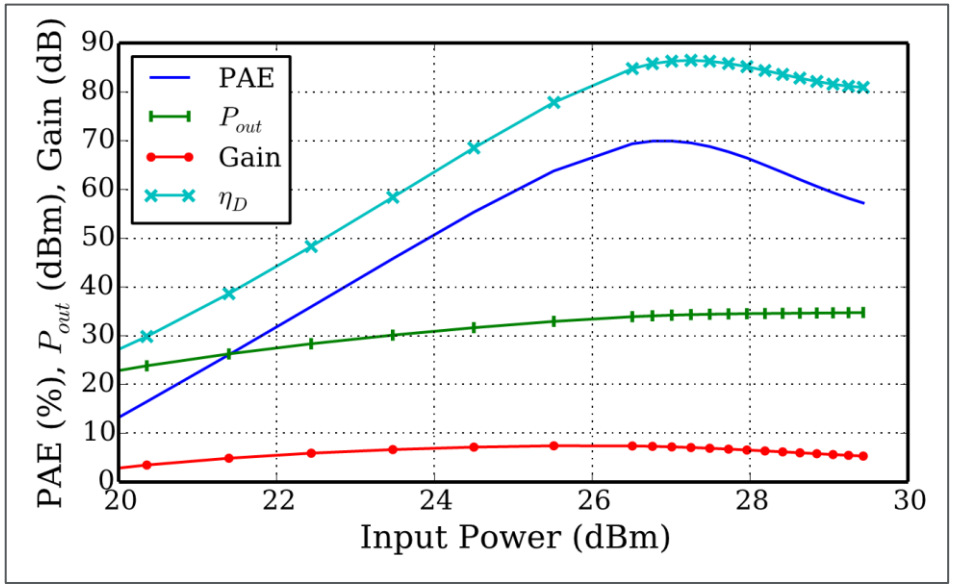


Outline

- Overview of approaches for improving efficiency at power back-off
- Supply modulation (envelope tracking)
  - GaN PA design (10GHz carrier)
  - Supply modulator (100MHz switching)
  - Integration and modeling
- **Outphasing**
  - **Quasi-MMIC isolated and non-isolated**
  - **Measurements of load modulation internal to the PA**
- Measurement challenges and approach to nonlinear measurements based on NI equipment in a LabView meta-instrument environment

PA element for outphasing PAs

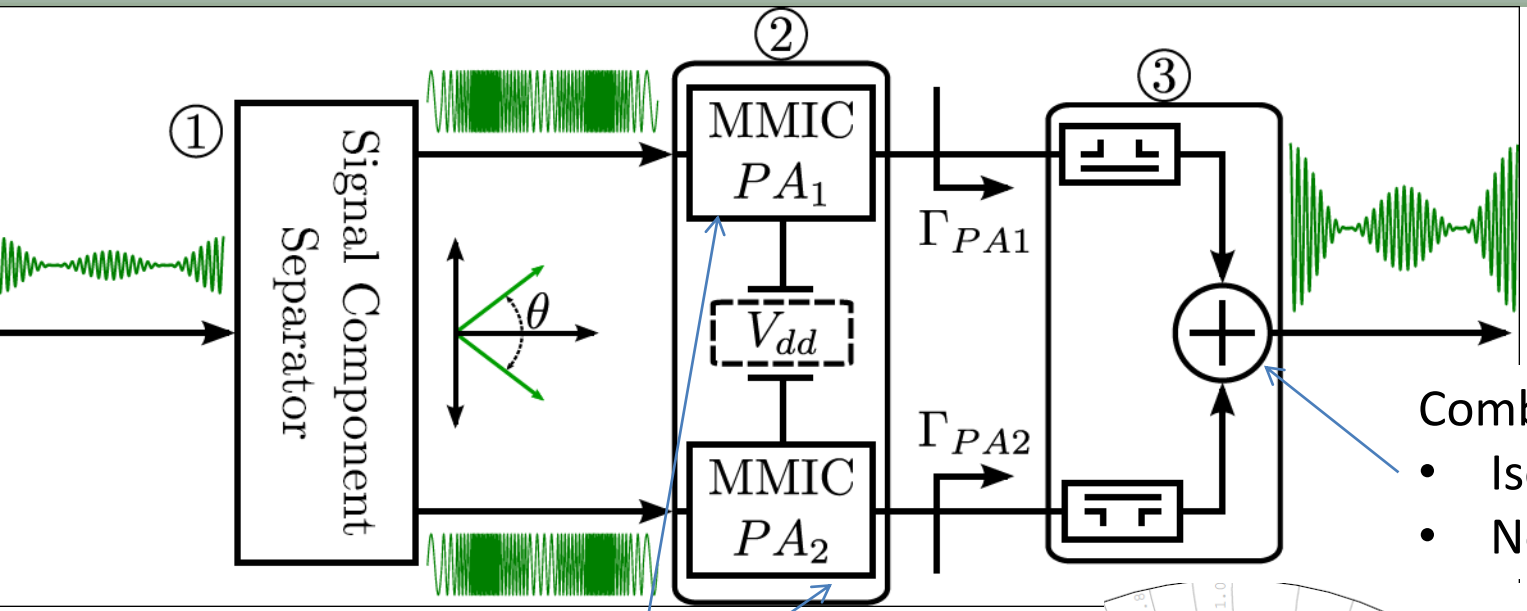




- Single-stage
- Biased in class-B
- GaN MMIC PA (TriQuint 0.15 µm)
- 10 x 100 µm FET

- V_{DD} = 20 V, V_G = -4.0 V
- f_0 = 10.1 GHz
- Peak PAE = 70%
- P_{out} = 2.7 W
- Gain = 7.2 dB

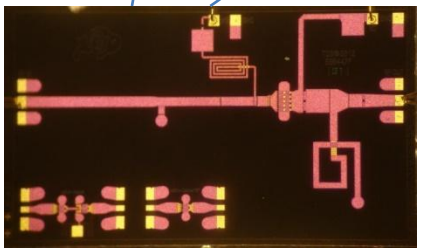
Quasi-MMIC outphasing PA



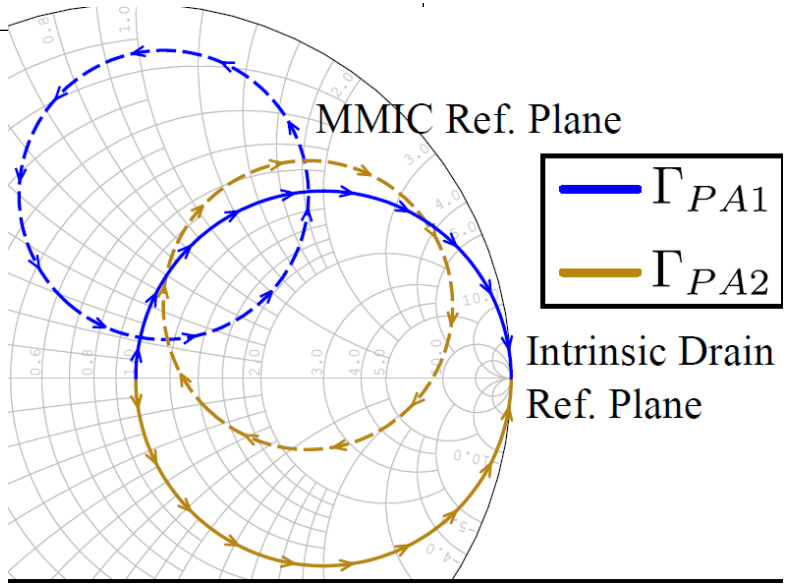
Combiner:

- Isolated
- Non-isolated

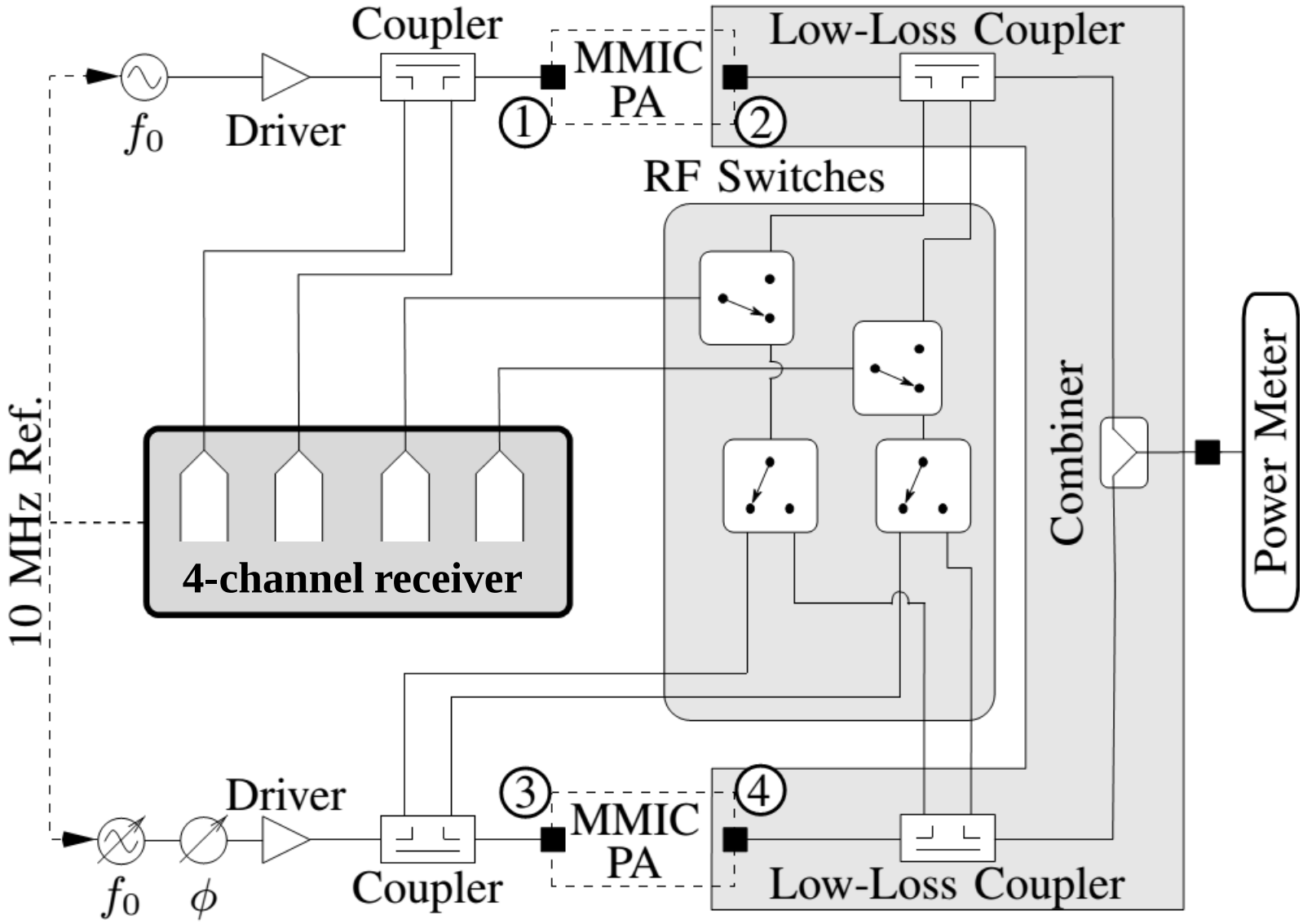
Digital



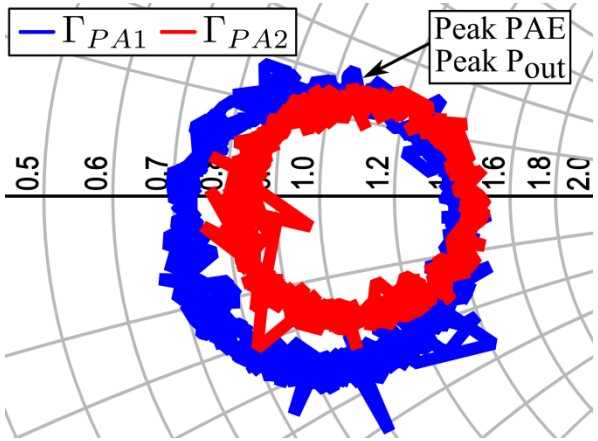
Load pull contours for non-isolated combiner

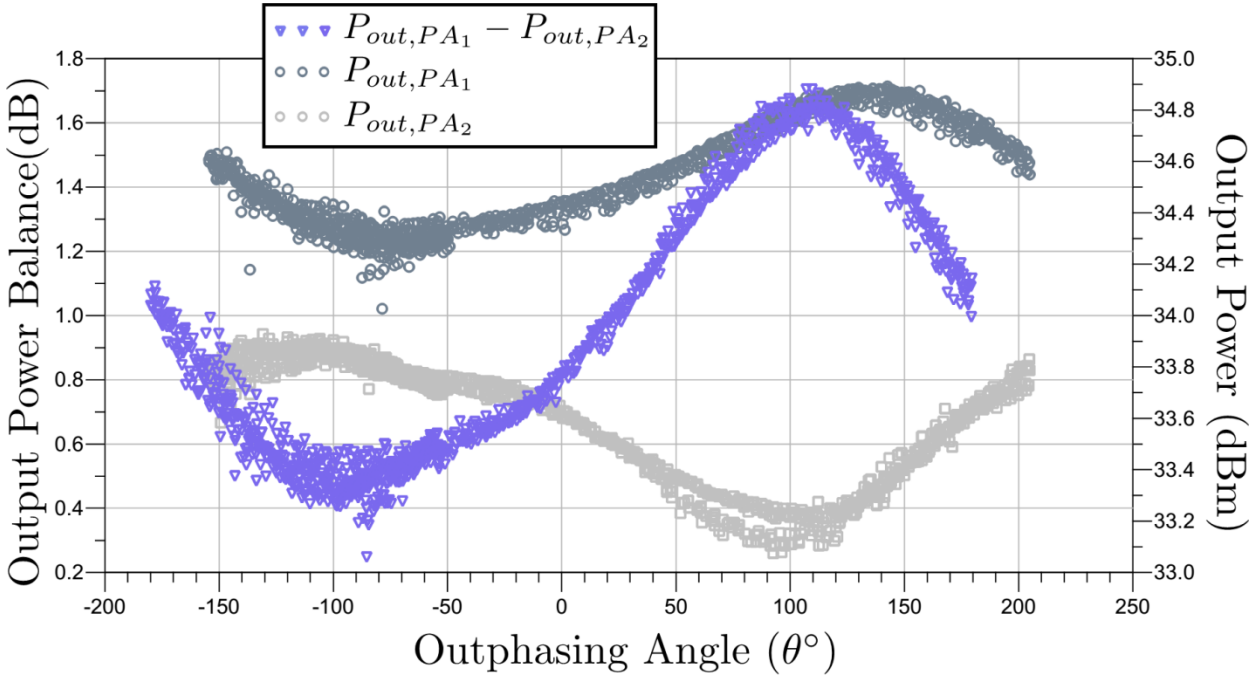


Internal PA Load Modulation



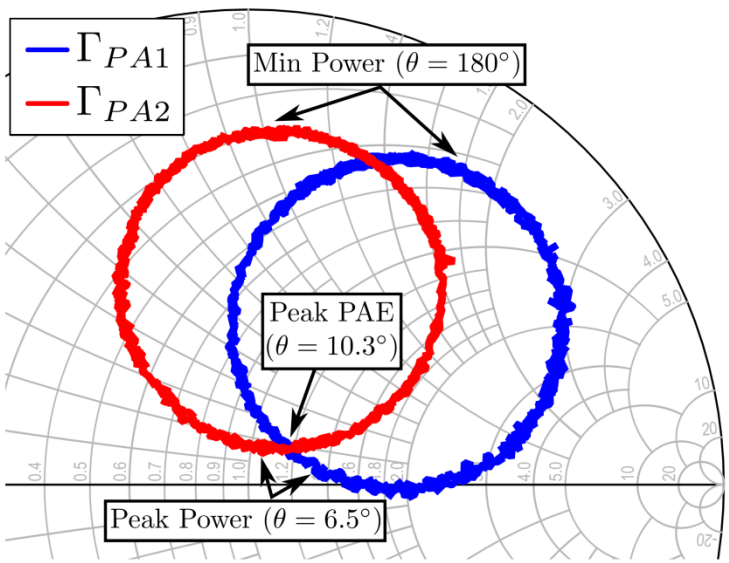
Isolated Outphasing PA

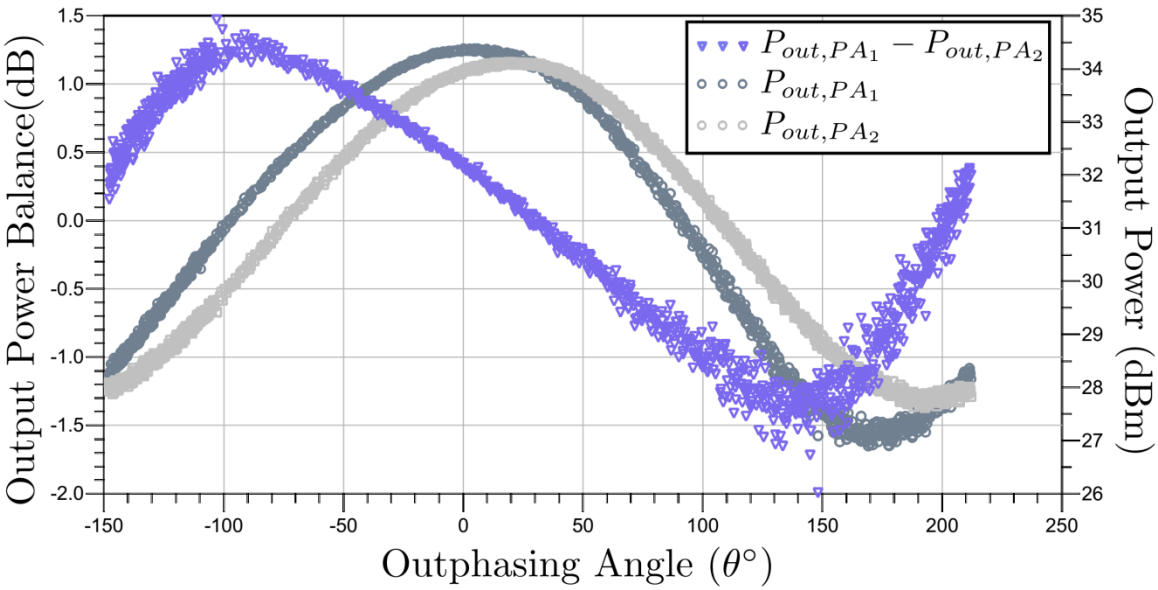




- Finite isolation yields minimal load modulation
- PAs rotate in opposite direction around contours
- 0.4 – 1.7 dB internal PA Pout imbalance caused by varying load

Non-Isolated Outphasing PA

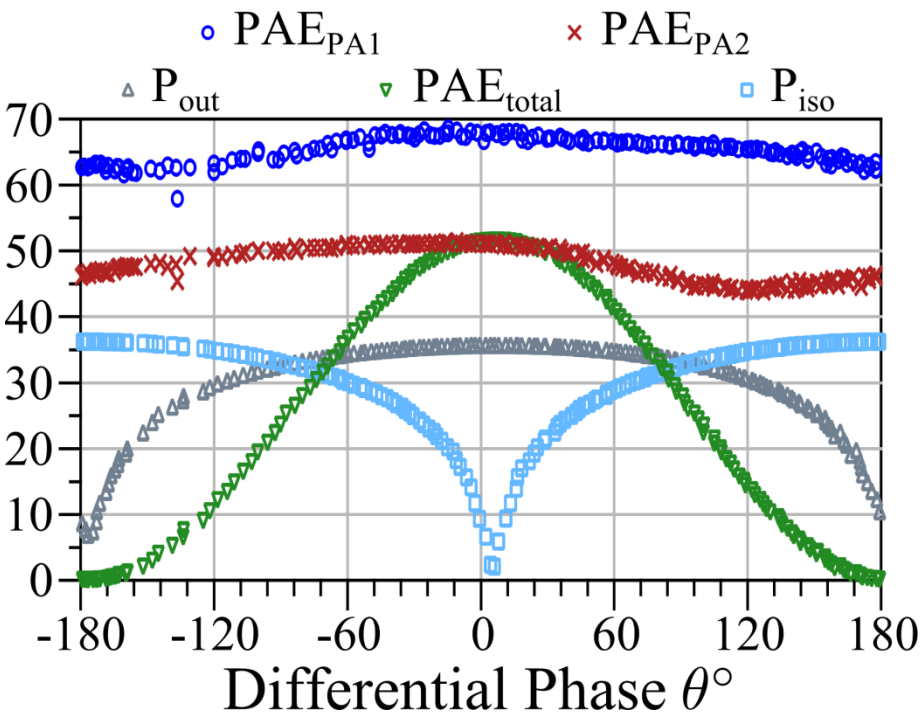




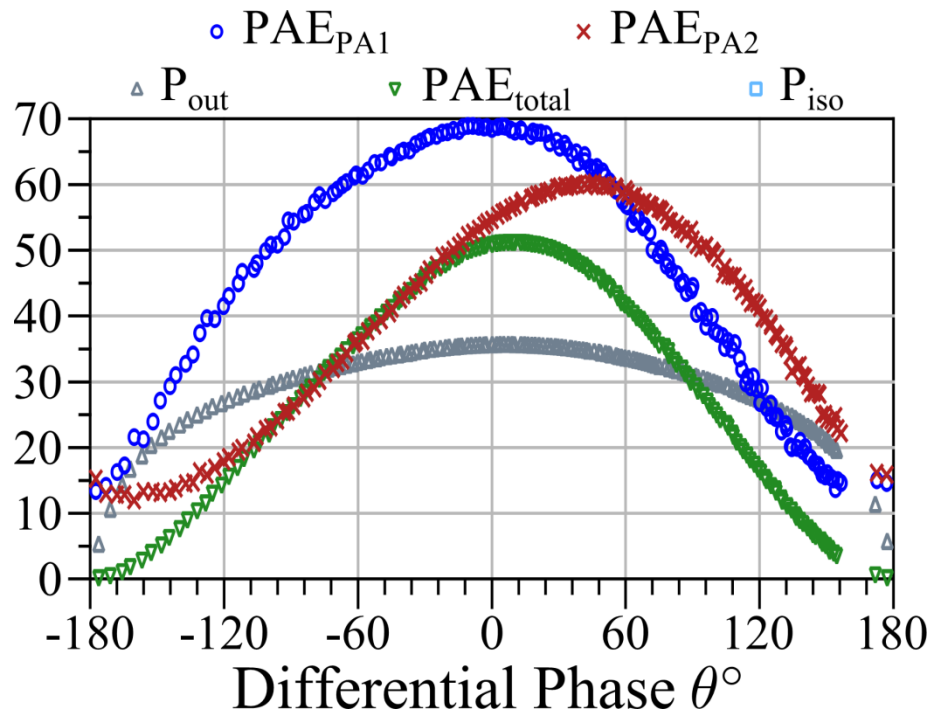
- Load modulation shows slight CW rotation due to ±1.5 dB internal PA Pout imbalance
- Peak power occurs near peak PAE
- Minimum Pout of 3.6 dBm near edge of smith chart

Comparison

Isolated



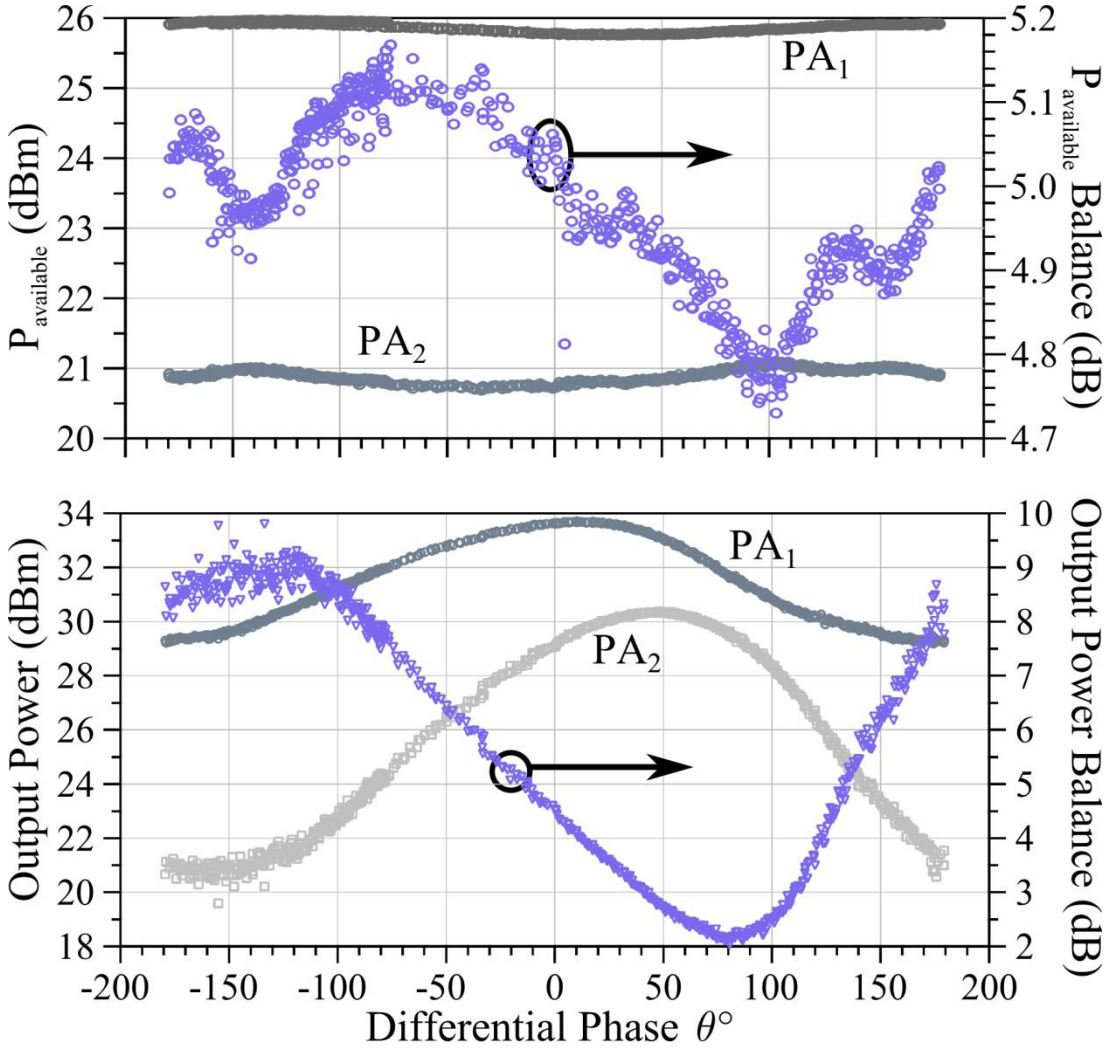
Non-isolated

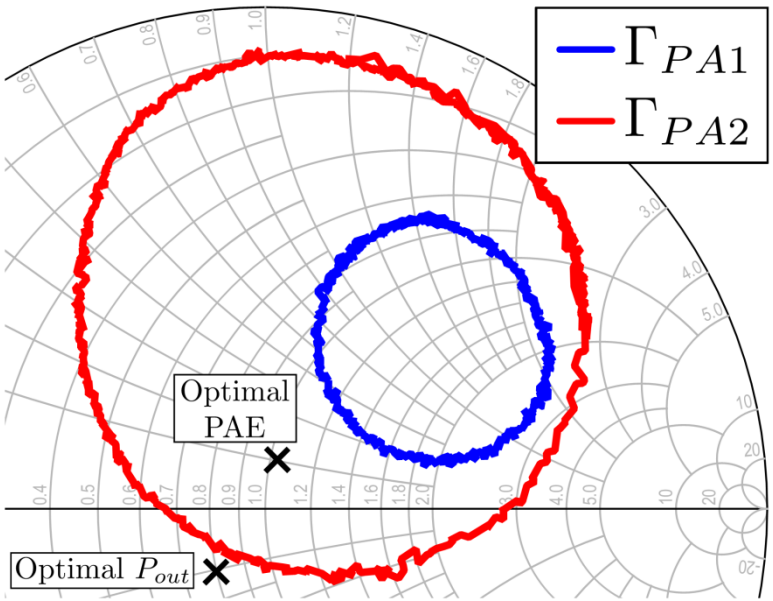


- Peak Pout = 35.8 dBm / 36.8dBm
- Peak PAE = 41.6 % / 59%
- Integrated design: 1 dB less loss

Peak Pout = 35.7 dBm / 37dBm
Peak PAE = 41.5 % / 60% (L=1.3dB)
8 % improvement in PAE at 4 dB OPBO

Effect of Power Unbalance





- 5±0.25 dB forced available power imbalance
- 2-9 dB internal PA Pout imbalance

Outline

- Overview of approaches for improving efficiency at power back-off
- Supply modulation (envelope tracking)
  - GaN PA design (10GHz carrier)
  - Supply modulator (100MHz switching)
  - Integration and modeling
- Outphasing
  - Quasi-MMIC isolated and non-isolated
  - Measurements of load modulation internal to the PA
  - Outphasing with supply modulation
- **Measurement challenges and approach to nonlinear measurements based on NI equipment in a LabVIEW environment**

RF instrumentation in LabVIEW: an equation to be solved

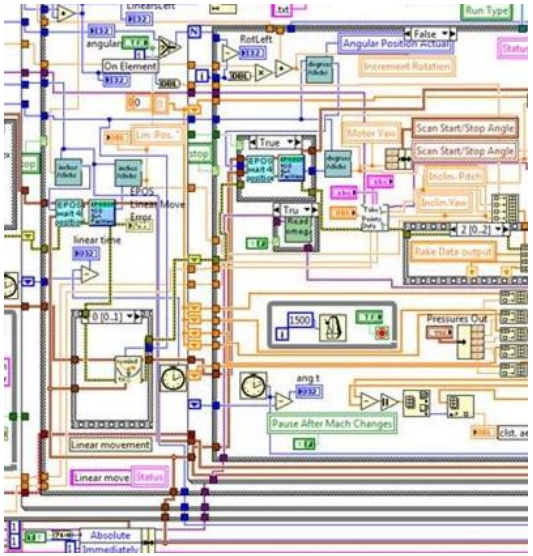
THE GOOD

- Build a GUI with two clicks ;
- Does not require any hard programming skills.

THE BAD

- LabVIEW code is difficult to read in big projects ;
- Mix of GUIs, algorithms and instrumentation drivers ;
- VISA interface is UNIVERSAL but...
- IVI is not:
  - Many DLLs ;
  - No universal handle manager in LabVIEW ;
  - Open/Closing sessions not convenient.

... and THE UGLY



Nevertheless, there is a hope...

RF instrumentation is based on a very limited number of instruments:

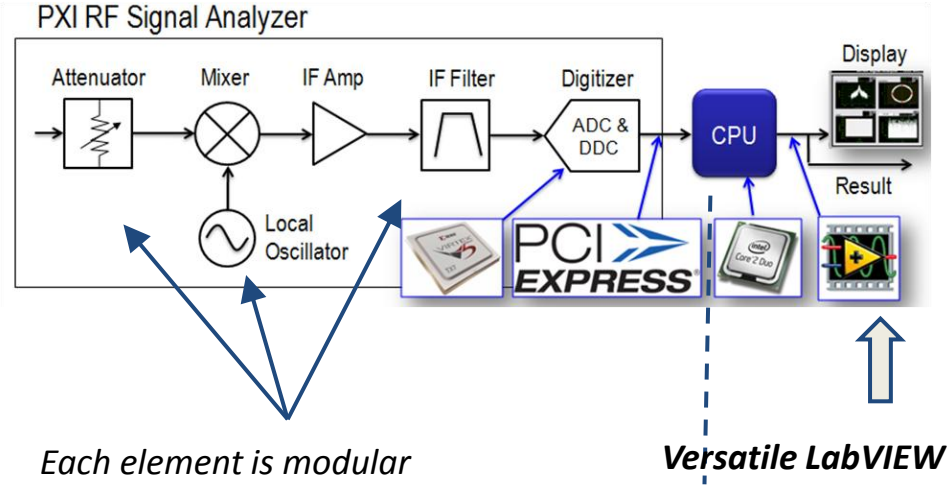
- Power meters ;
- RF Sources ;
- DC power supplies ;
- Scopes ; and
- just one big analyzer.

A LabVIEW "open instrument"

"Redefining RF and Microwave Instrumentation with open software and modular hardware"

Existing approach on commercial PXI RF receiver

One single PXI module



Each element is modular

Versatile LabVIEW software

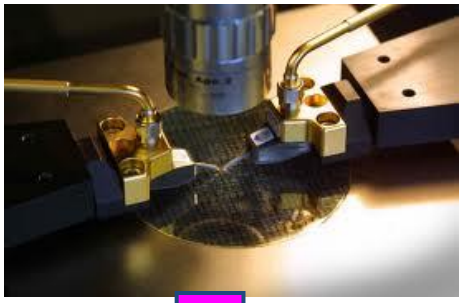
Our approach for research and academics: open LSNA

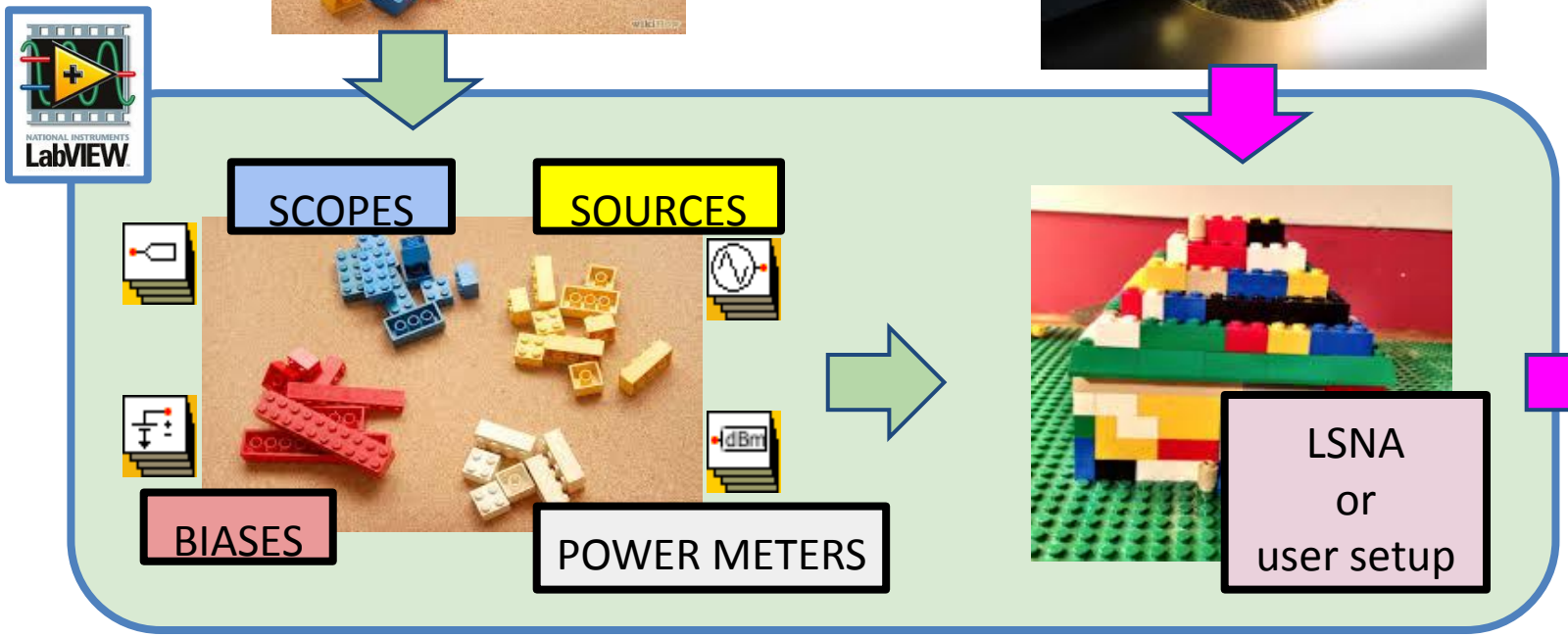
Goal : improve flexibility and creativity for researchers and academics in instrumentation.

LabVIEW for RF instrumentation

Available Instrumentation

Device Under Test



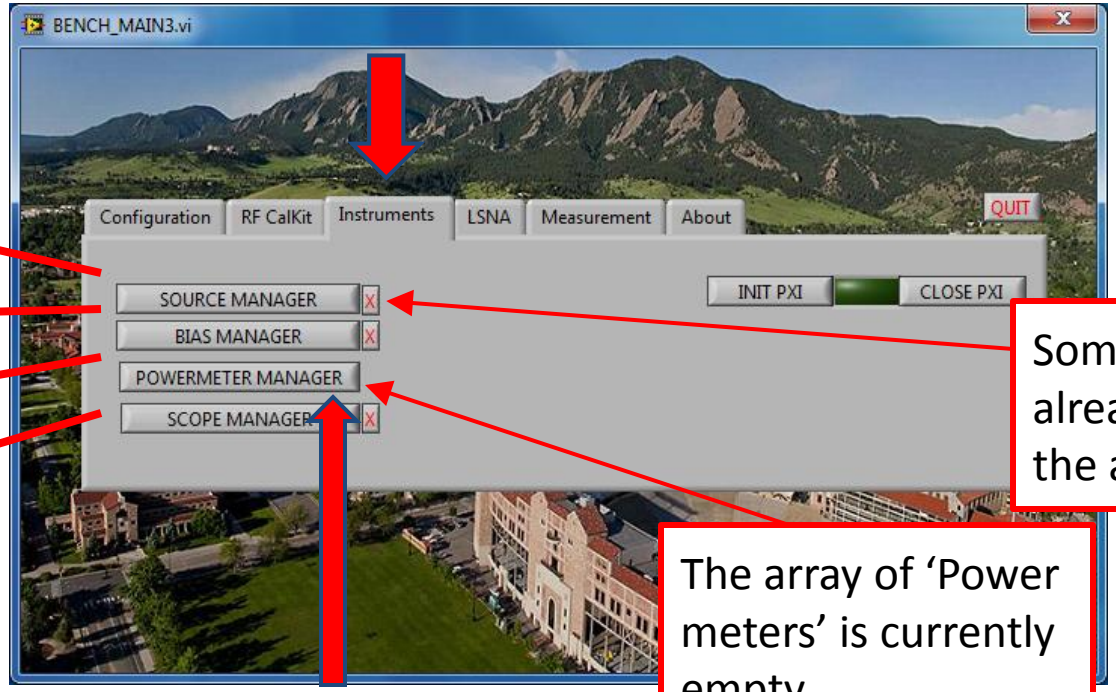


Simulation Platform

Arrays of Instruments

Meta-Instrument

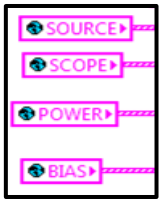
Instrument Managers



Some elements are already defined in the array of 'Sources'.

The array of 'Power meters' is currently empty.

ONE VI ONLY
TO ACCESS
ARRAYS OF
INSTRUMENTATION

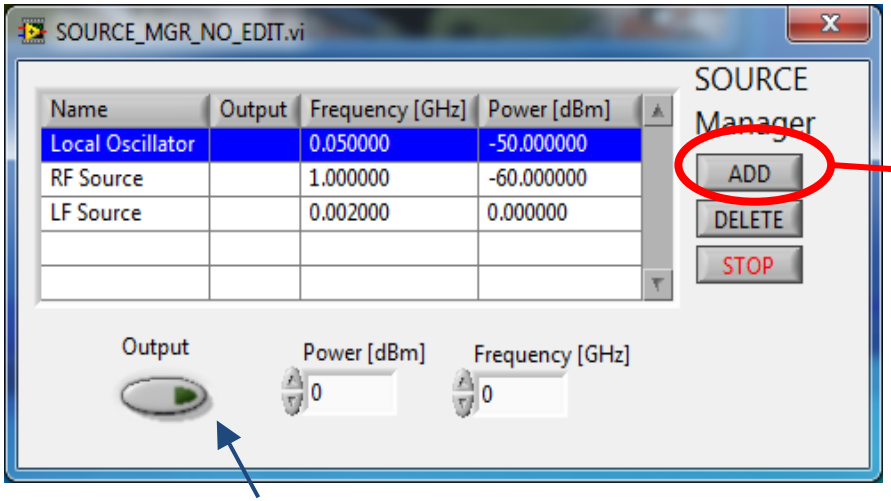


Global_Bench.vi

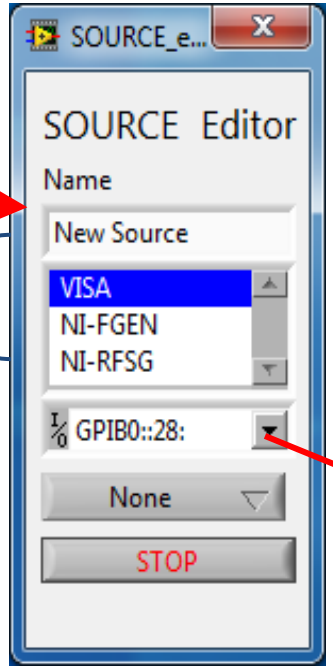
Some GUIs (Sources and Scopes) includes PXI session init and close on the fly.
Array can be deleted by clicking on the 'X'.

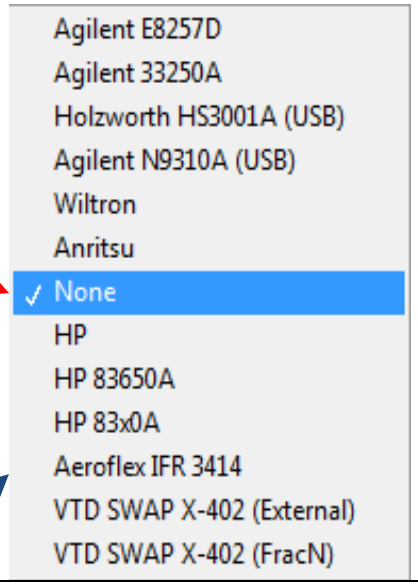
Arrays of instruments are defined by GUI and located in a global variable.

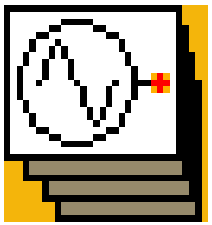
IM Example: CW sources



Interactive control (useful with PXI sources). Open and Close PXI session on the fly if needed.





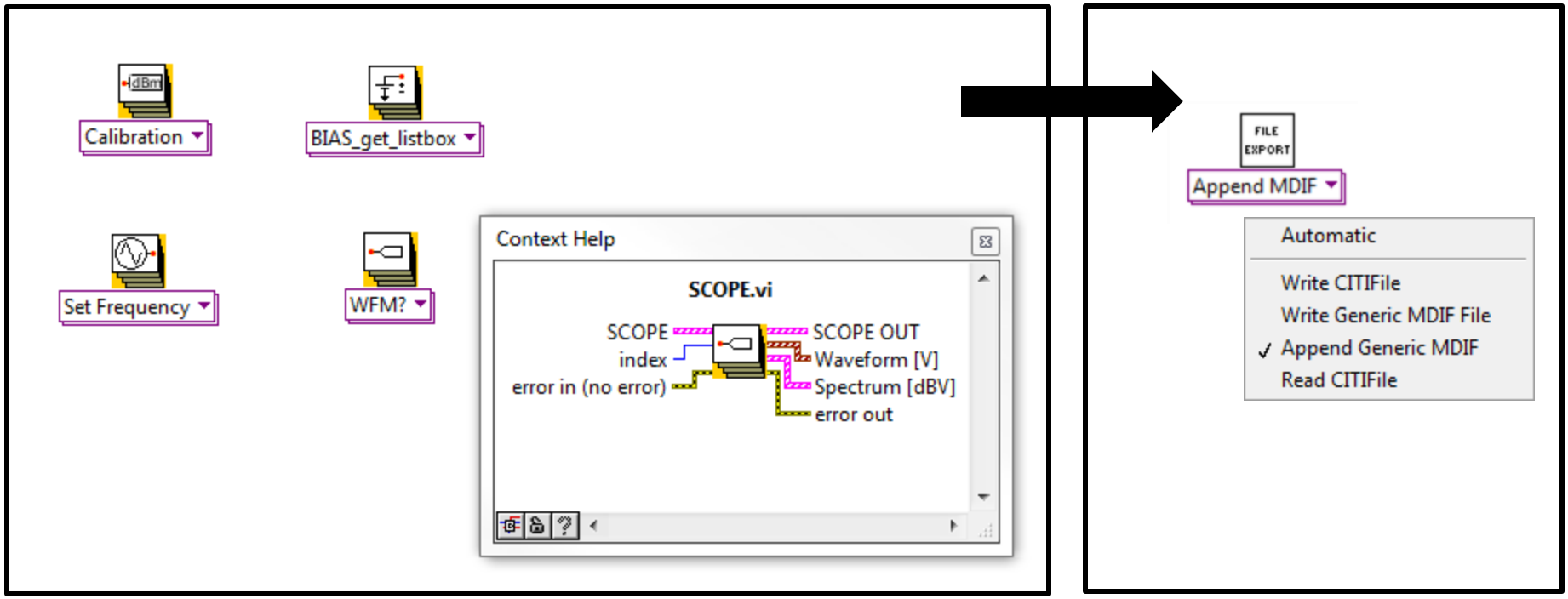


All instrumentation in a lab previously defined in low-level drivers. Here we have 3 driver families : VISA, NI-FGEN (LF PXI) and NI-RFSG (RF PXI)

List of instrumentation previously defined in low-level drivers.(Typedef file)
Here is the list for VISA instruments.

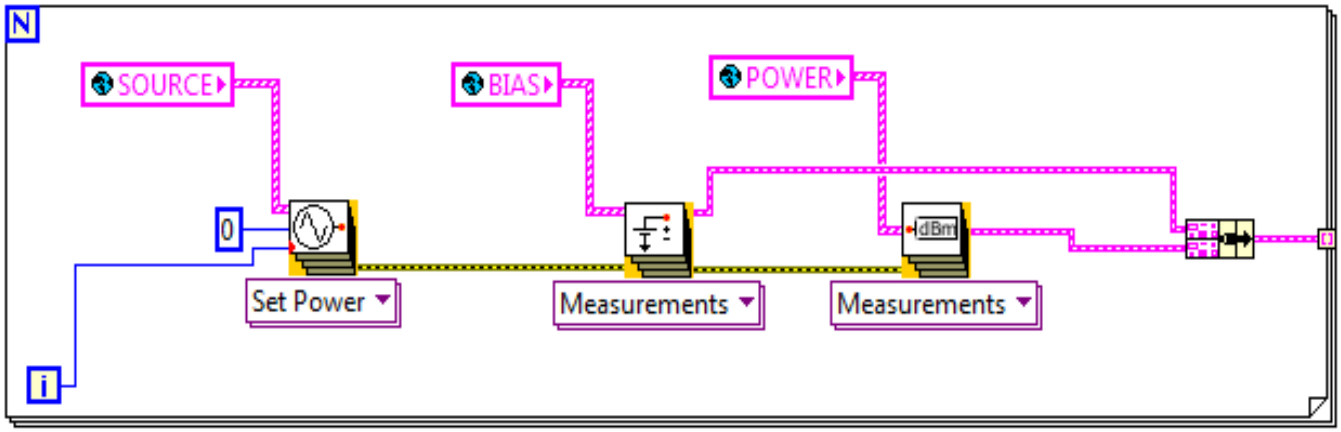
Make your own VI

Here is the library



Generic MDIF file can be read by Keysight ADS Data Display and specific file formats for AWR Microwave Office

Example: Pout(Pin)



Ready to build a data set

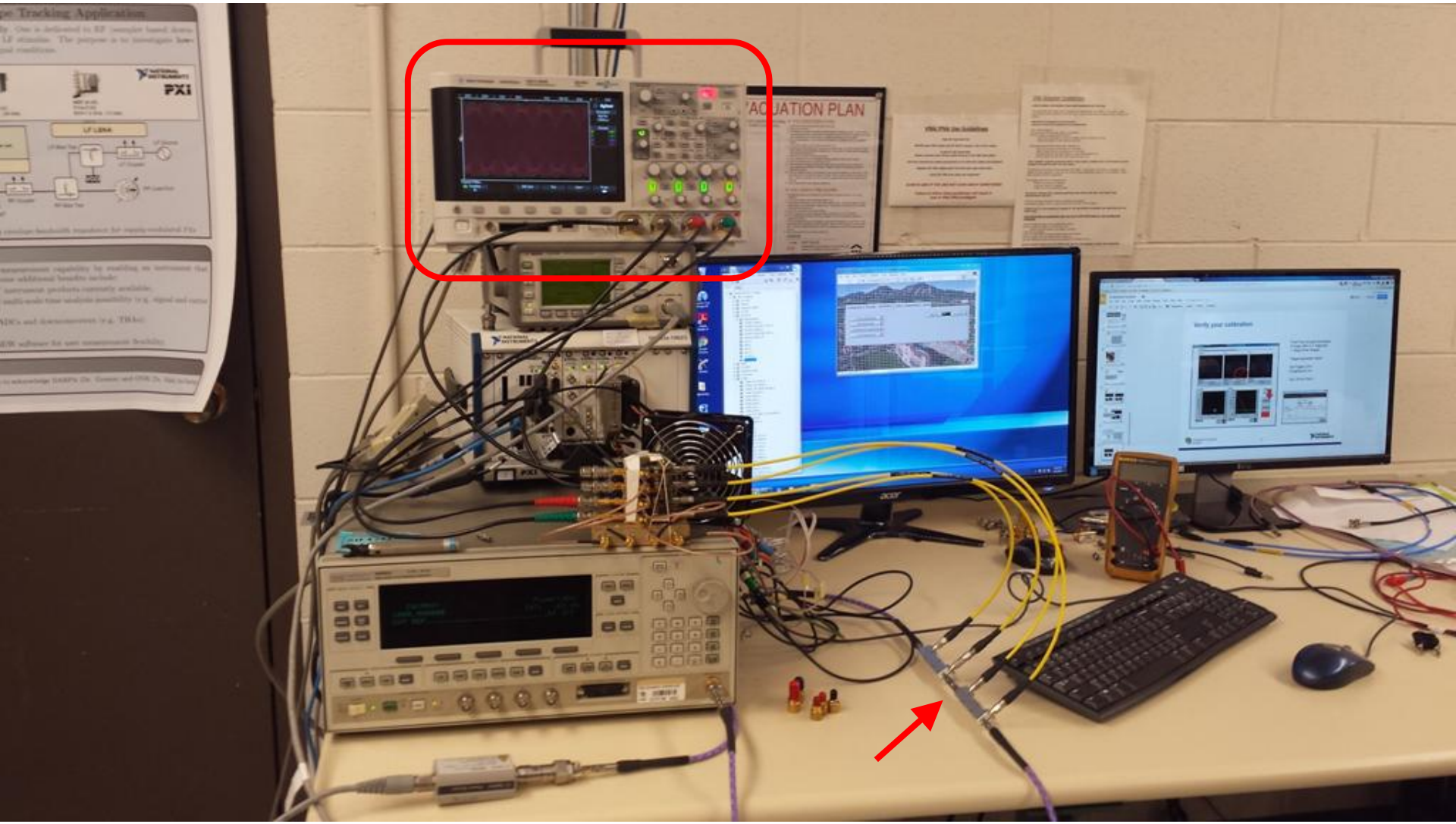
Set Power Driving Source

Get All Biases

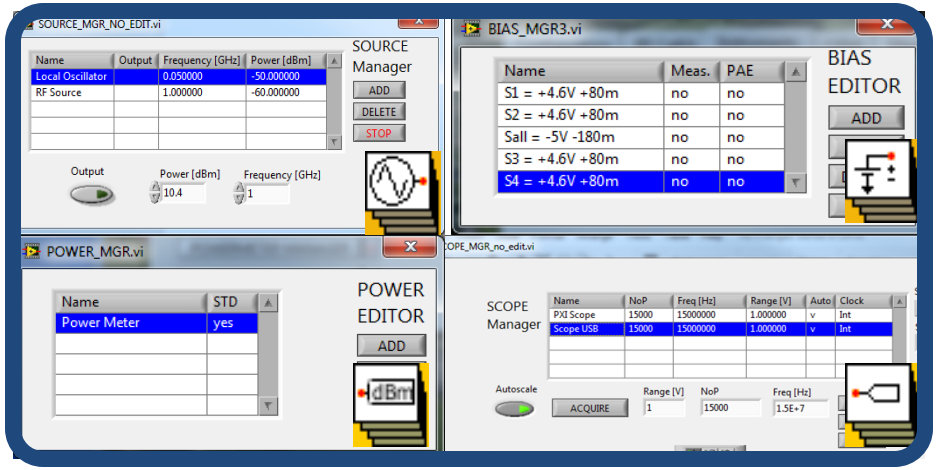
Get All RF Power

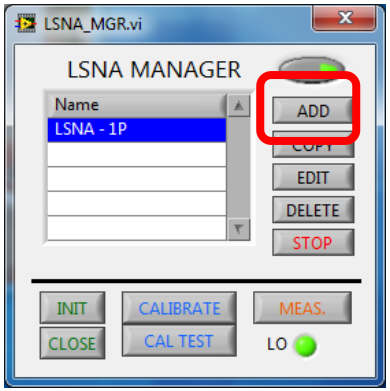
- Makes LabVIEW code lighter and clean ;
- Generic Library highlights concepts more than drivers and acquisition protocol ;
- Data-set fully integrated to simulation platform for direct measurement/simulation comparison ;

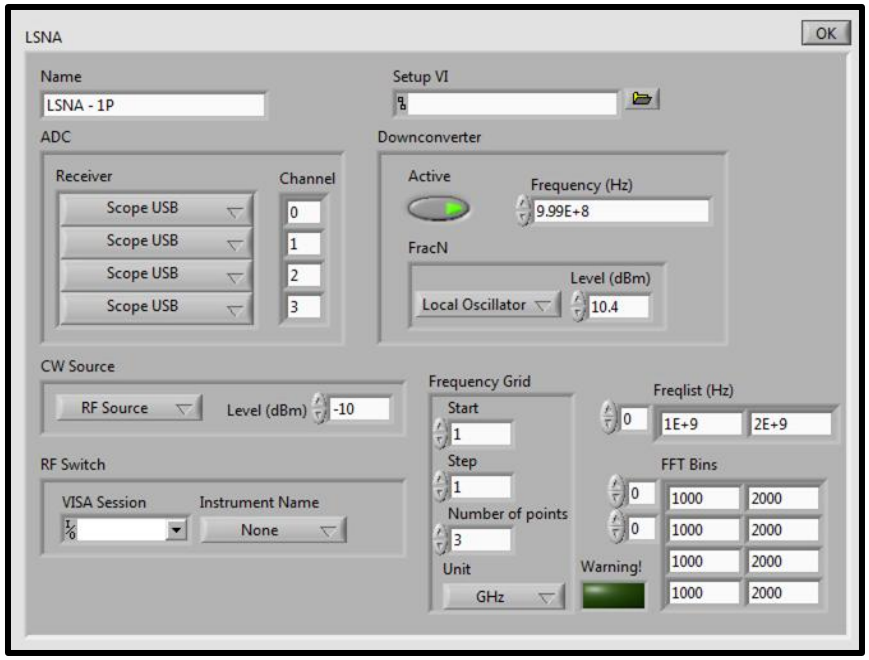
Meta-instrument example: 2-port LSNA bench



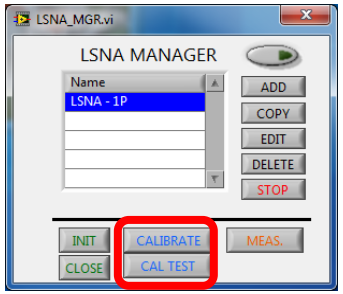
Bench example, 2 ports

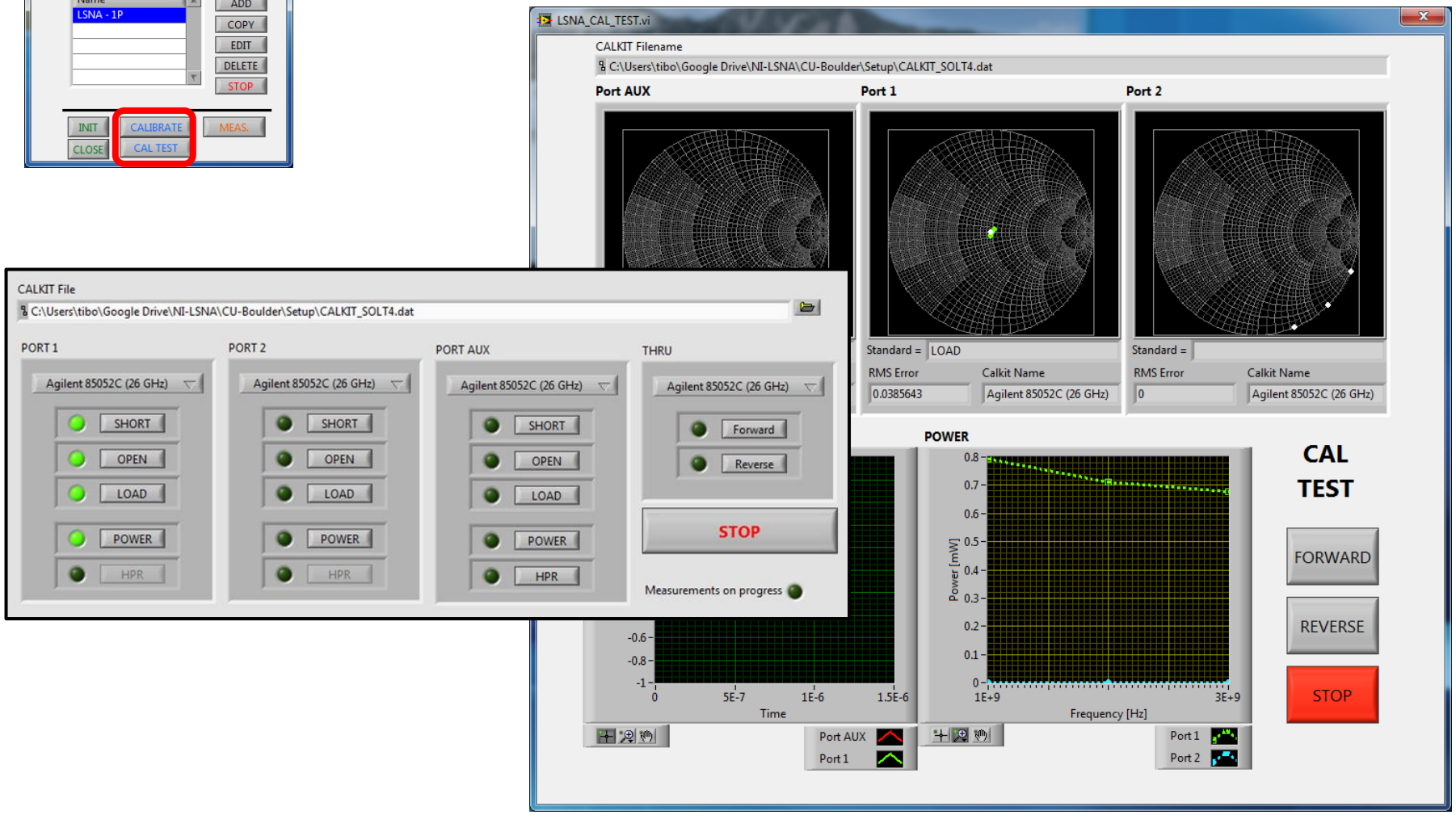




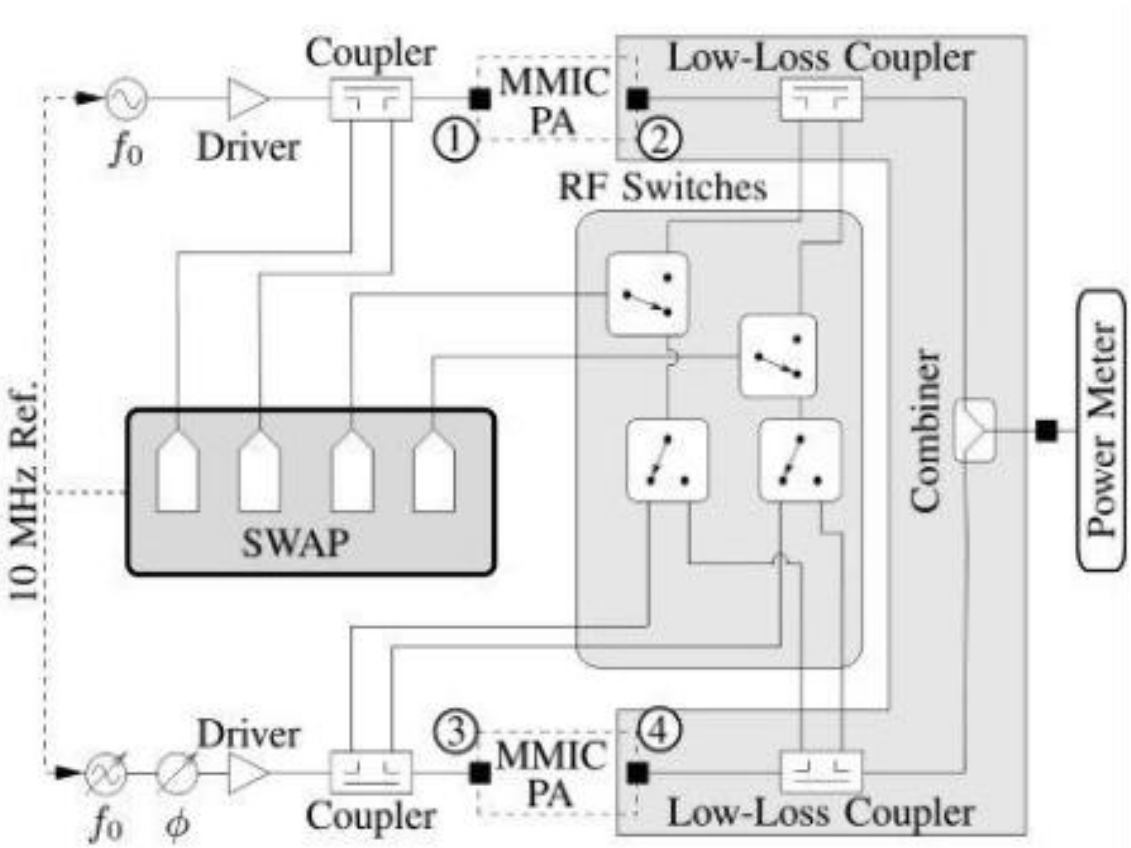


Calibration





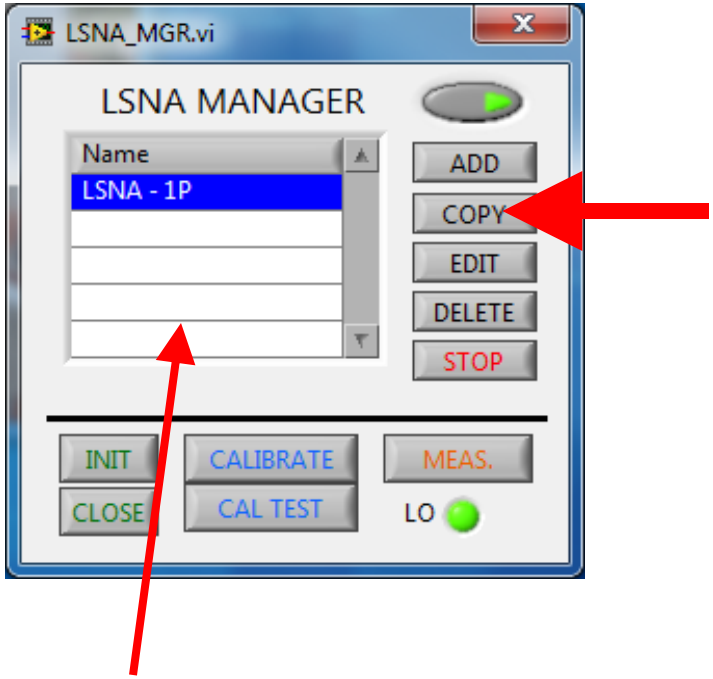
Application: outphasing PAs

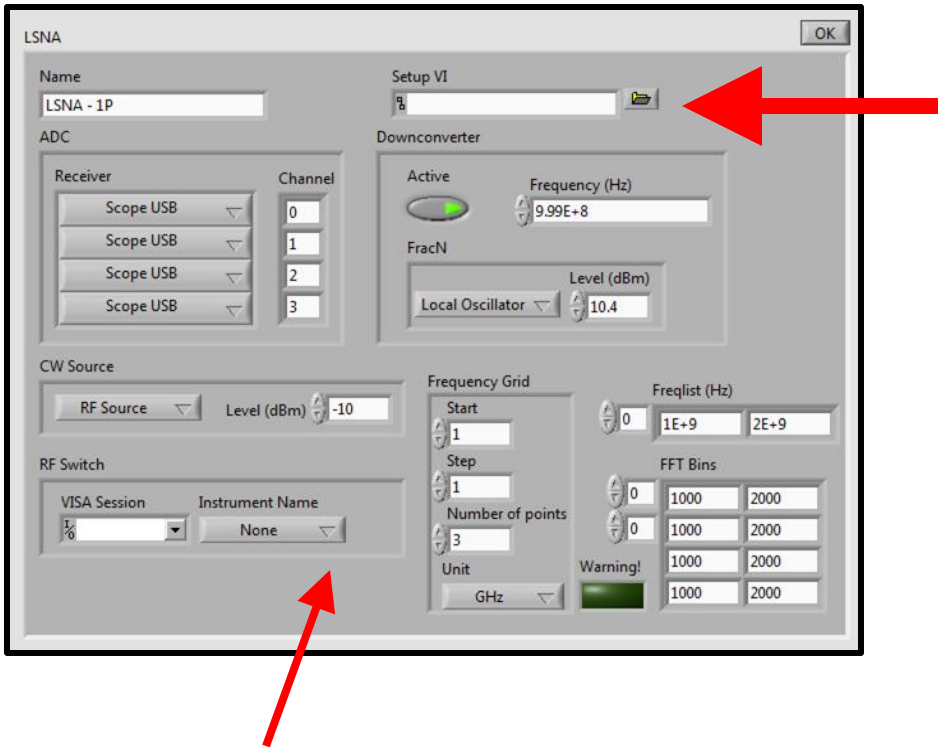


Measurements of internal load modulation

Requires Three identical 2-port RF LSNAs, but with different calibration matrices and initialization scripts (to setup the RF switches)

Measuring internal load modulation





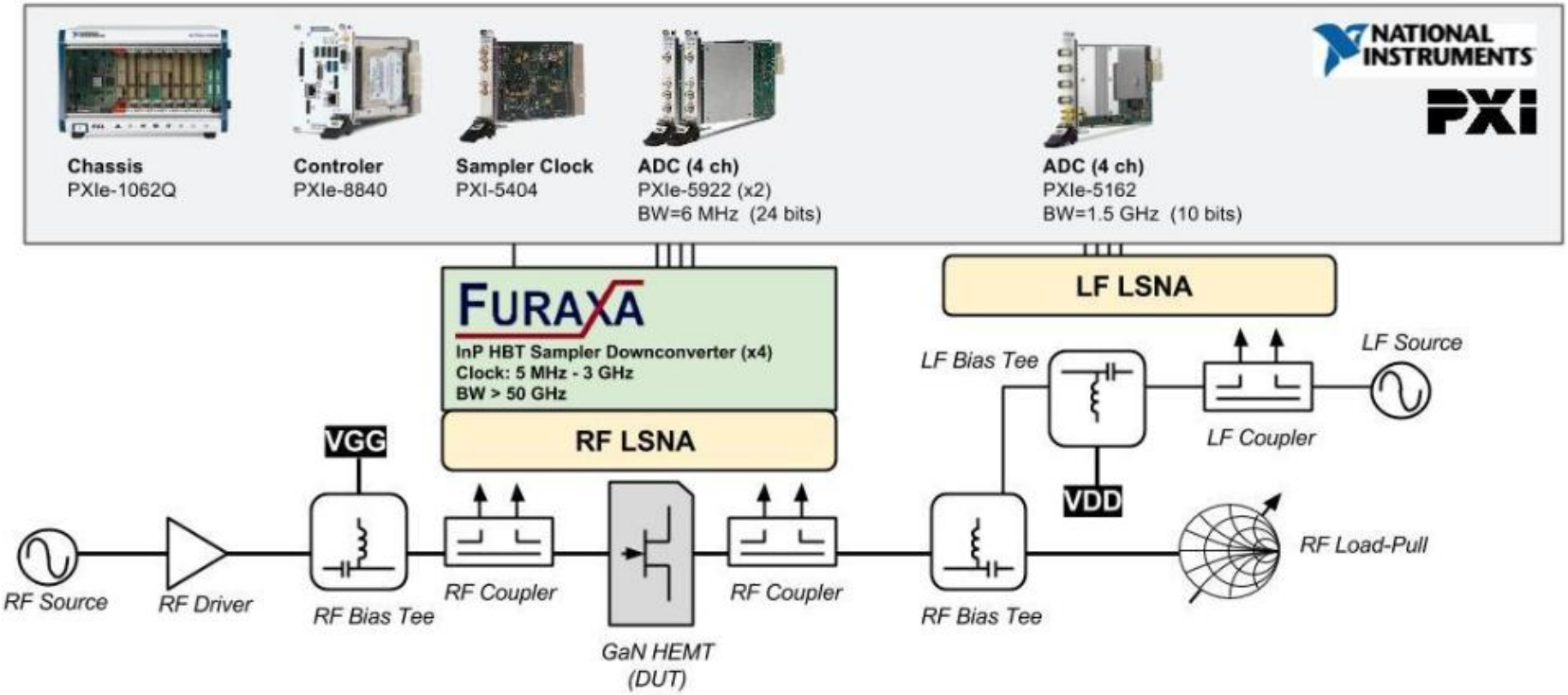
1. Create an LSNA and copy it twice

2. Update the field Setup VI with the script to enable the correct RF-switch position.

3. Each of the 3 LSNAs is calibrated independently.

4. All LSNA measurements are performed sequentially in just one call.

Measuring envelope tracking PAs



LF S-parameters under large signal condition is a minimal configuration to optimize filter between the LF modulator (PWM signal) and the RF-PA (Analog signal)

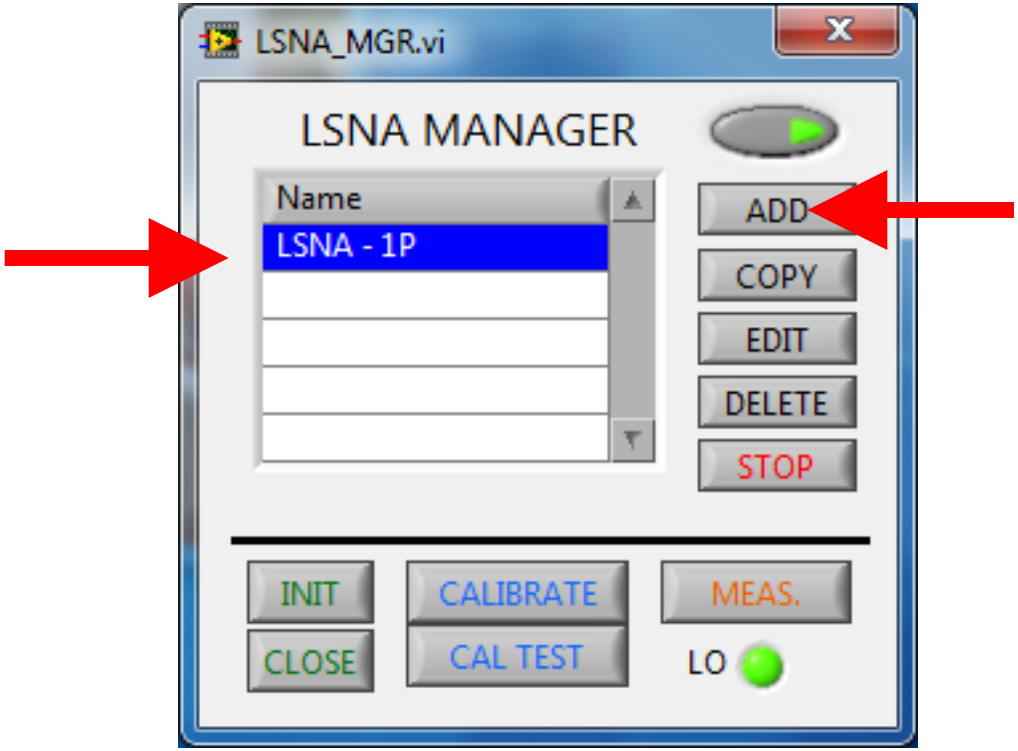
ET PA measurement

Create 2 different LSNAs.

One includes a downconverter, the other one doesn't.

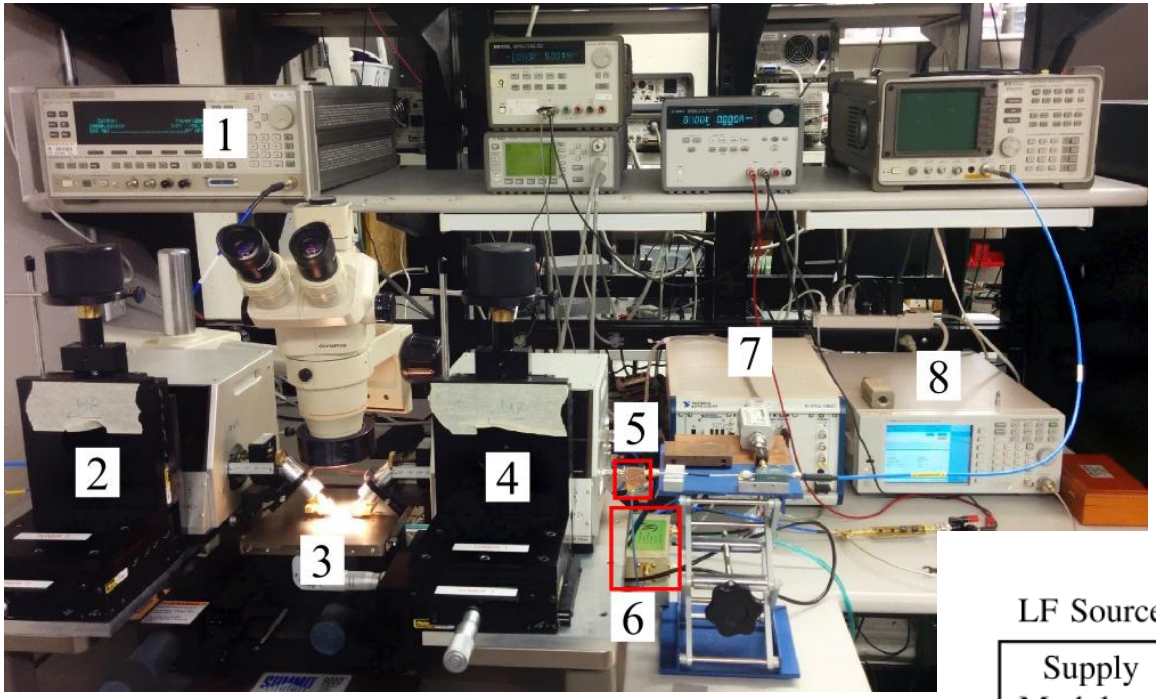
Each LSNA is related to its calibration matrix.

All LSNA measurements will be performed sequentially in a single 'LSNA Measurements" call



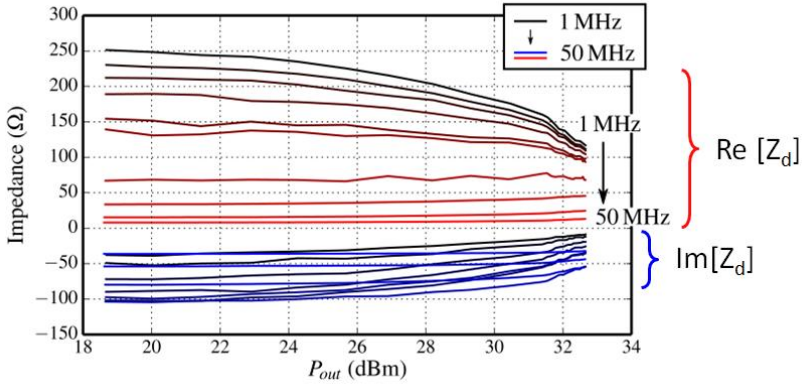
Measurements performed in LF 1 port LSNA + Power meters for the moment

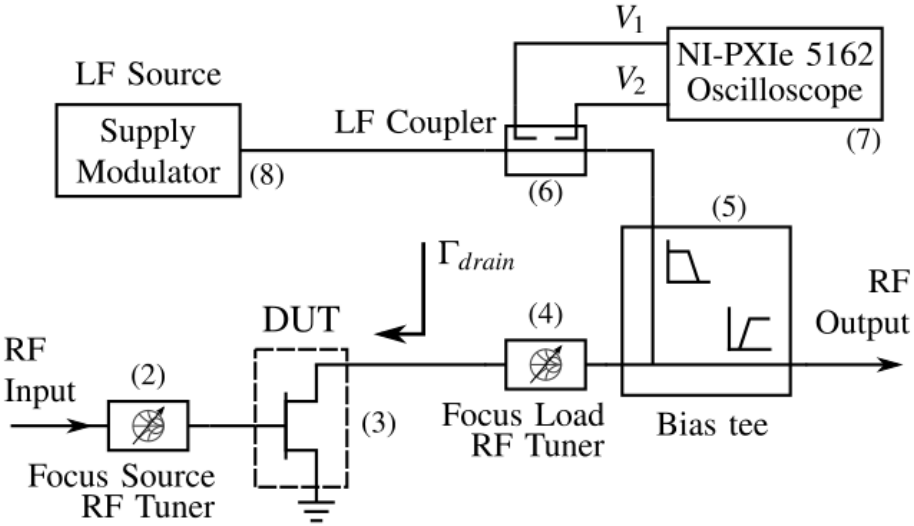
Low-frequency LSNA



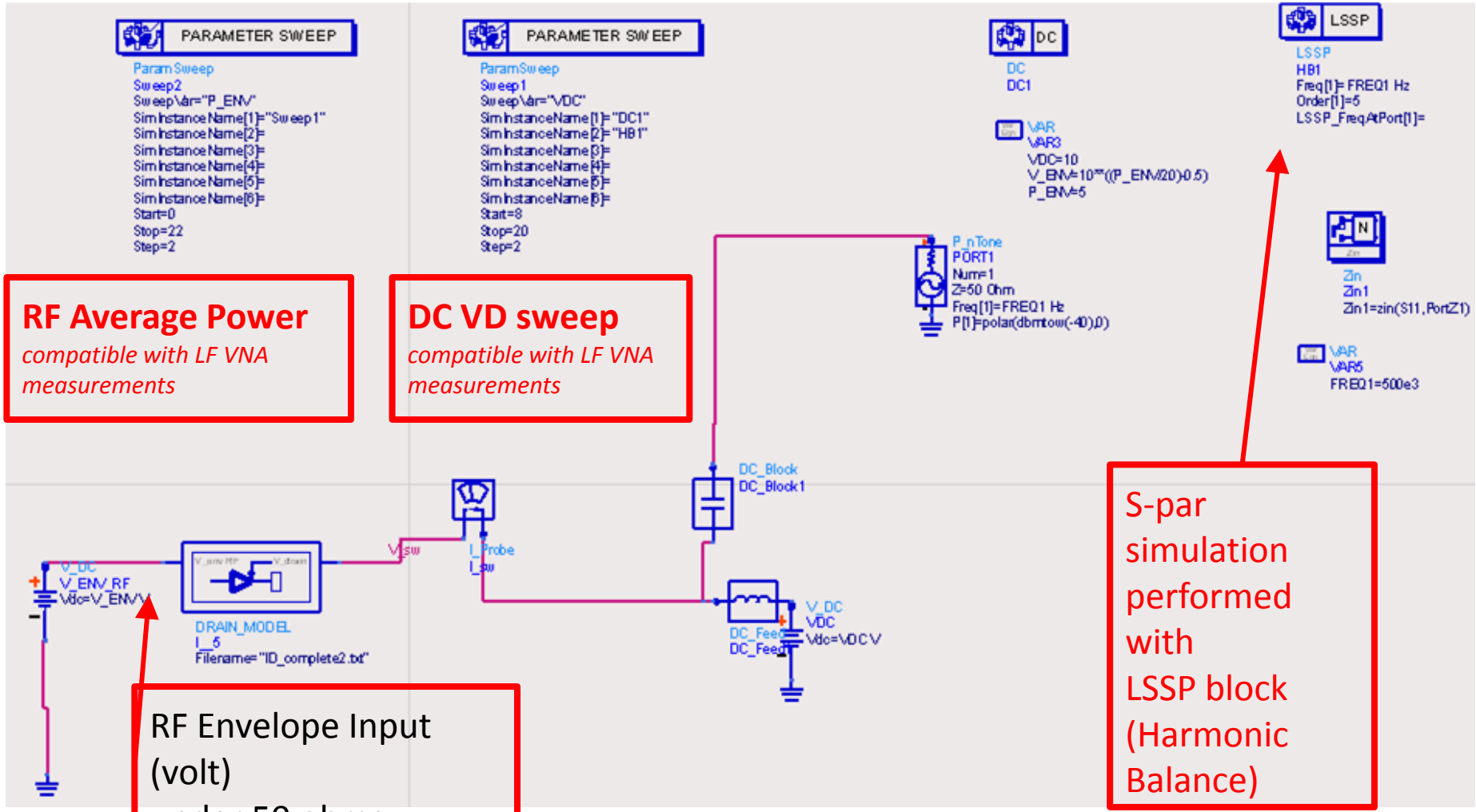
Problem to solve:

Transistor models do not predict low-frequency (modulation) drain terminal impedance





LF drain impedance ET-PA measurements/simulations



S-par simul will not take into account non-linear Gd

Example: Extracting a model...

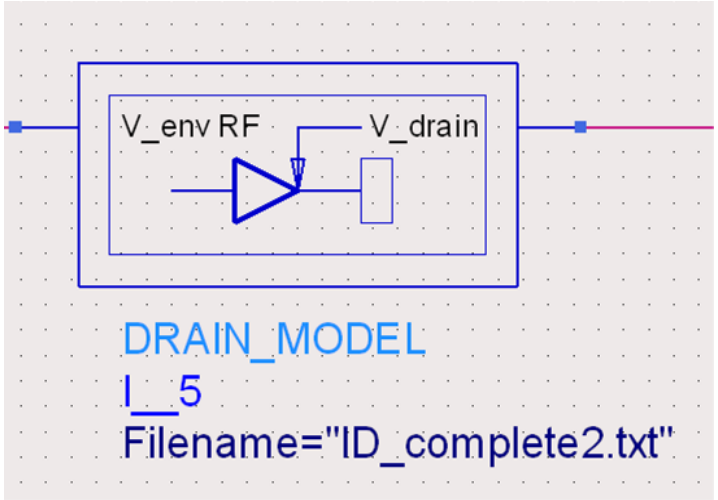
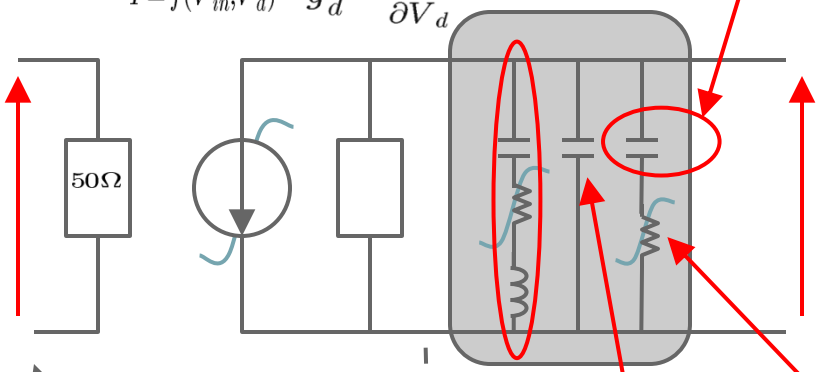


Table based model.
It included
measured
ID=f(Pav,Vd)
And extracted Gd

Very simple circuit

Very big capacitance (transition between DC and LF)

$I = f(V_{in}, V_d) \quad g_d = \frac{\partial I}{\partial V_d}$



gd compensation

Output capacitance

$$|V_{in}(V)| = 10^{\left\{\frac{Prf(dBm)}{20} - 0.5\right\}}$$

: Non linear elements

EXTRACTED FROM I(V)

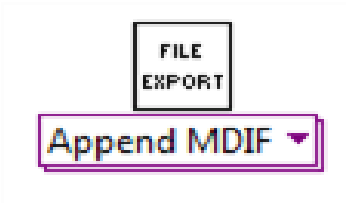
Resonance (can be seen on real{Y22})

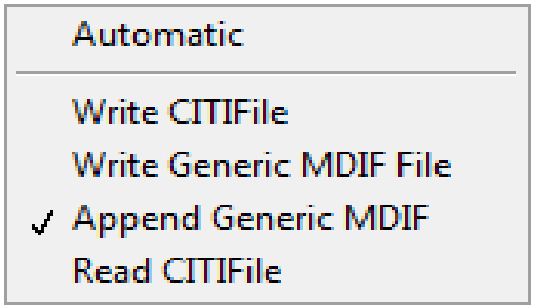
EXTRACTED FROM S-par

Example: comparison

Measurements:

Converted in Generic MDIF and loaded directly in the data display



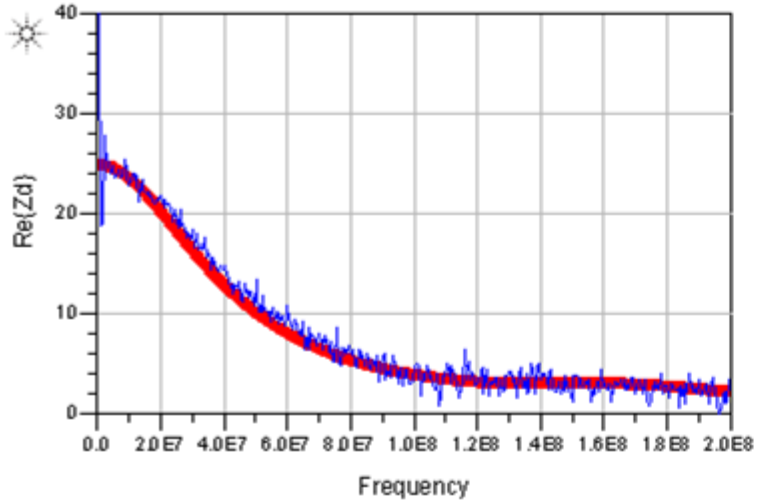


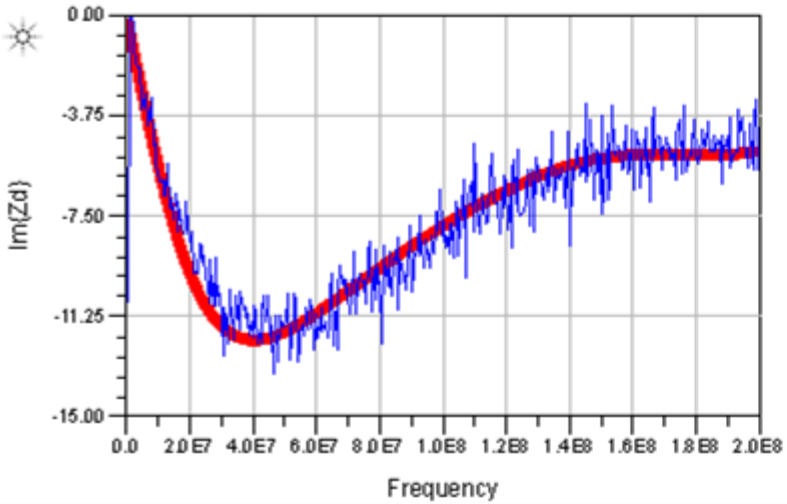
Simulations:

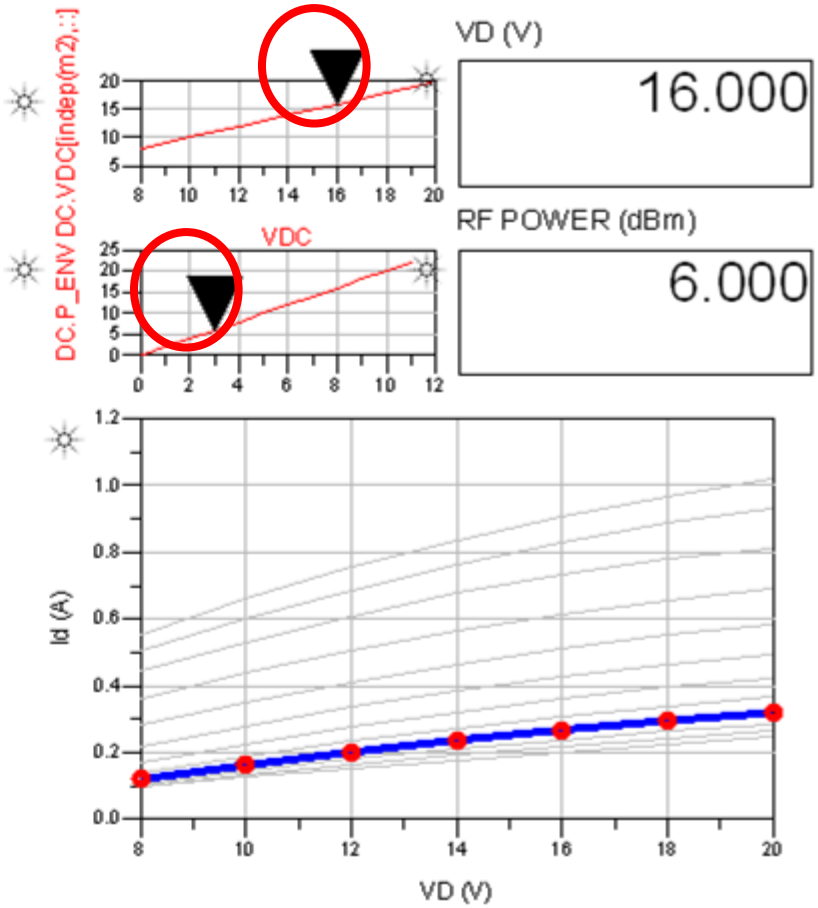
Performed for the same sweep range

Comparison in the simulation platform

Example: results

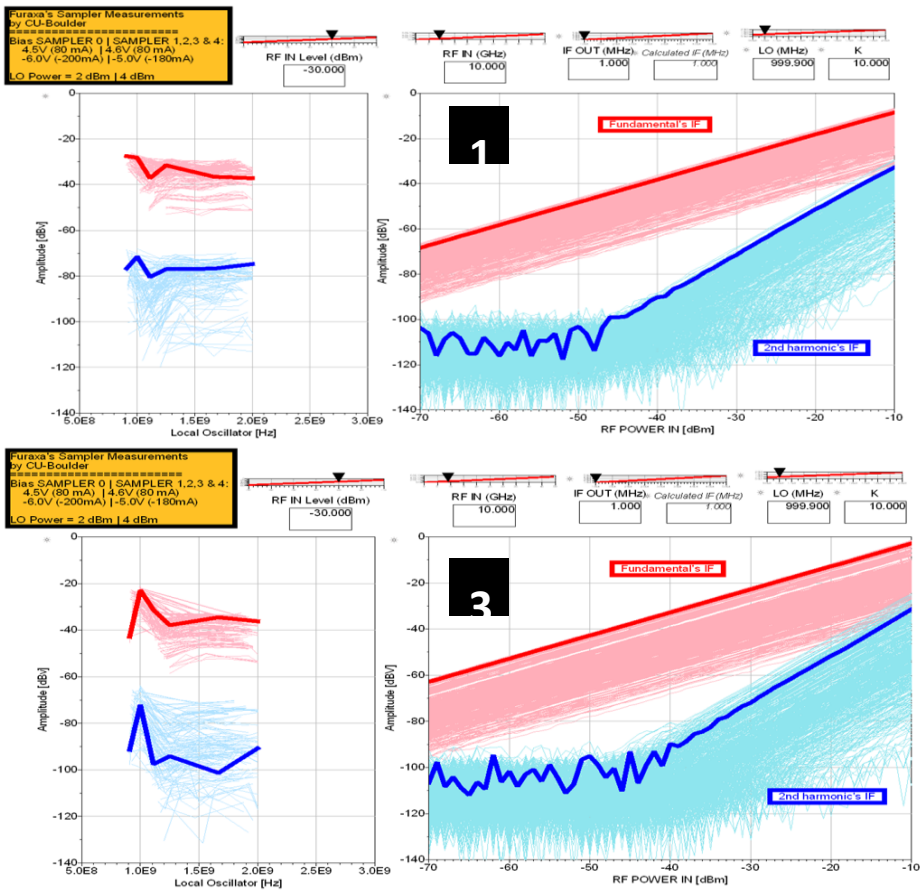


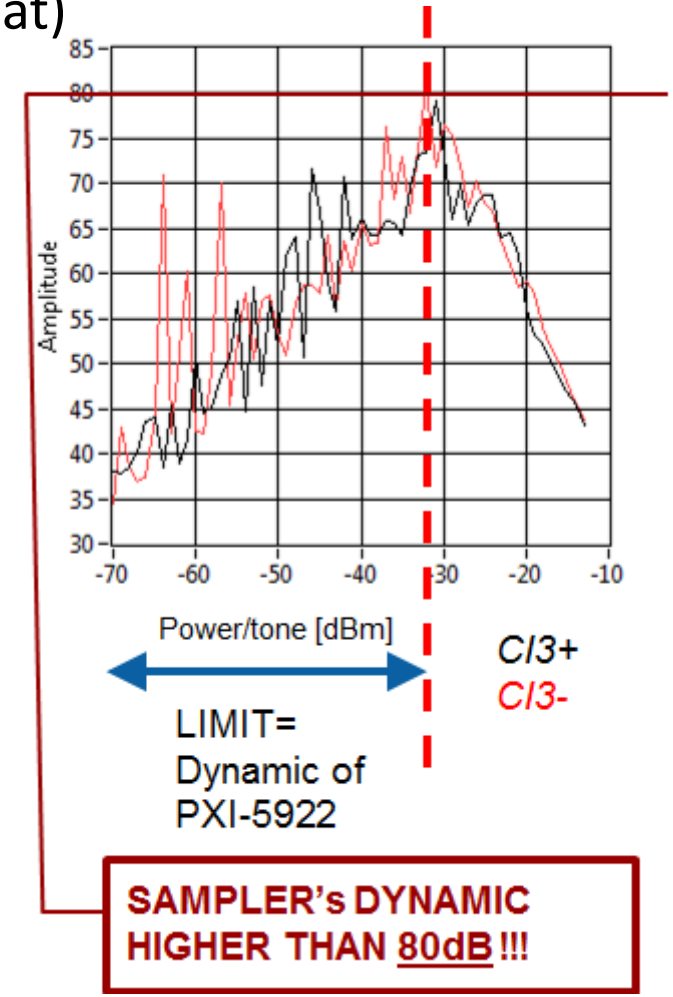




Example: self-characterization

- Samplers characterized with NI PXI-5922 (15MS/s)
- Data displayed in Keysight ADS – Goal is to display in AWR MWO (but this needs improved Generic MDIF file format)





Summary

- LAbVIEW-based LSNA under development
- Enables non-standard design-oriented measurements in a modular flexible fashion
- Measurement capability already demonstrated through several design applications:
  - Internal load modulation in outphasing PAs
  - Low-frequency drain impedance measurements under large-signal RF carrier excitation for a ET-PA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