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

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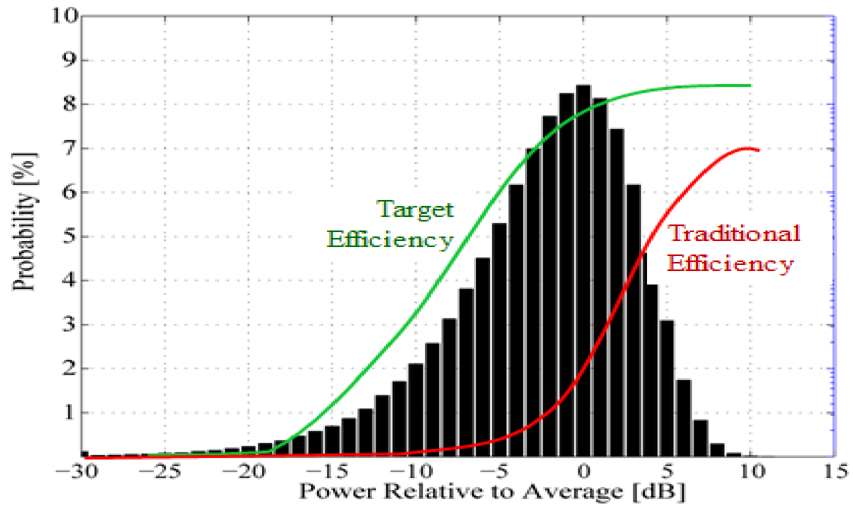
Workshop WME

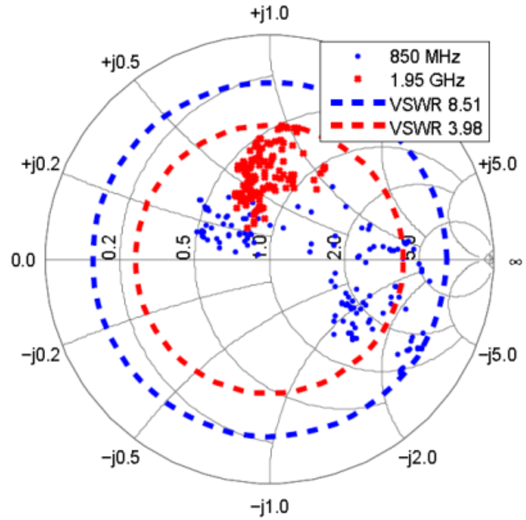
Outline

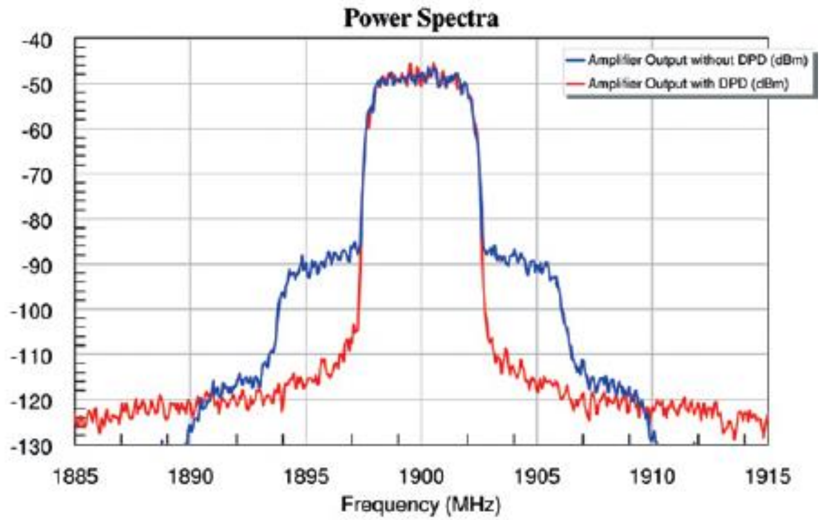
- **Overview of approaches for improving efficiency at power back-off**
- Supply modulation (envelope tracking)
  - GaN PA design (10GHz carrier)
  - Supply modulator (100MHz switching)
  - Integration and modeling
- Outphasing
  - Quasi-MMIC isolated and non-isolated
  - Measurements of load modulation 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

Main challenges in PA design

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

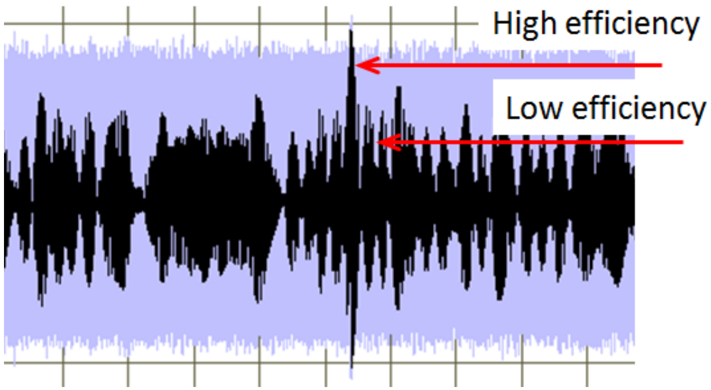




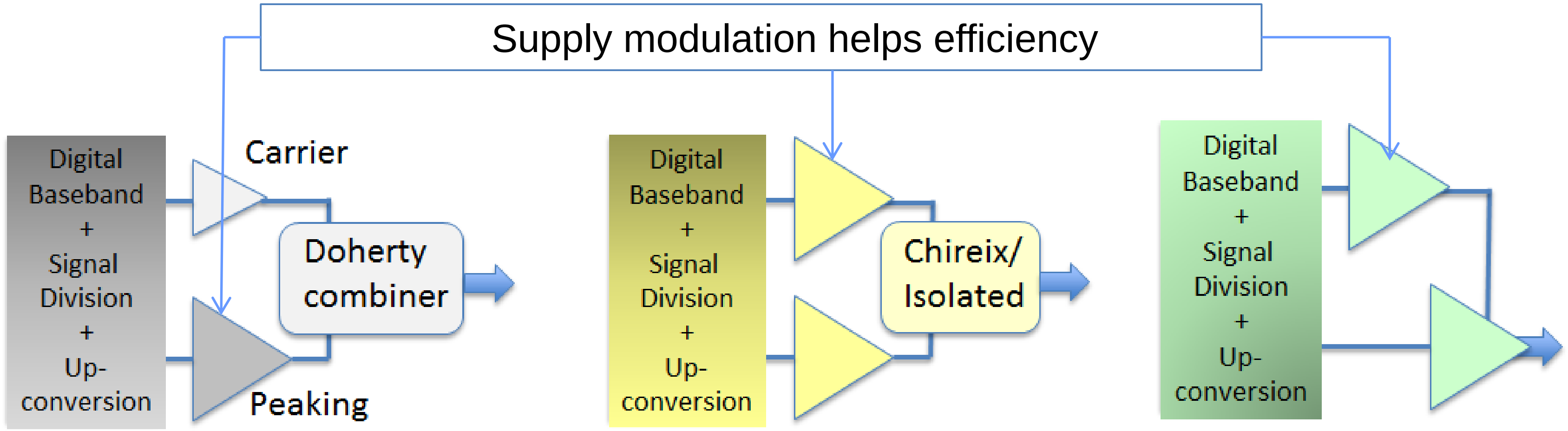


Amplifying high PAR signals

- Efficiency of RF front ends dictated by PA efficiency
- High-efficiency PAs are:
  - efficient only at peak power
  - highly nonlinear



- Approaches for efficiency enhancement for high PAR signals involve adding a second amplifier:
  - Doherty PA
  - Outphasing (Chireix)
  - Envelope tracking (ET)



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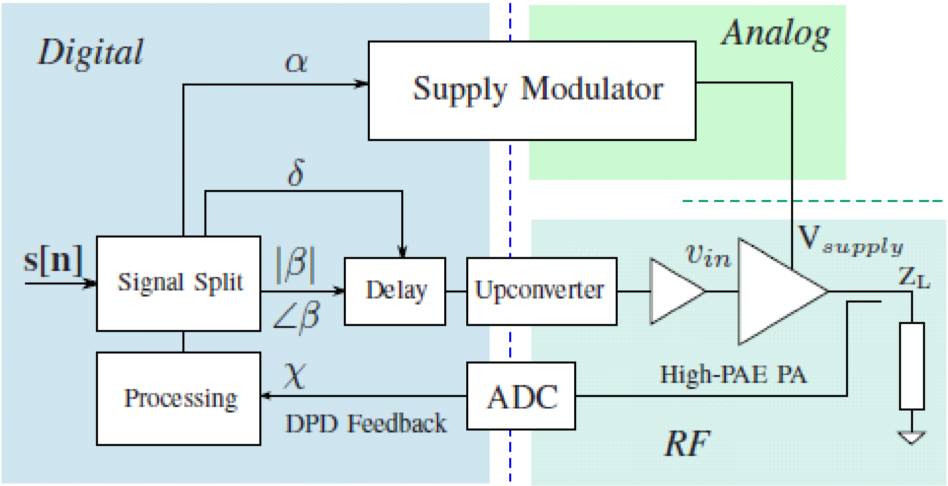
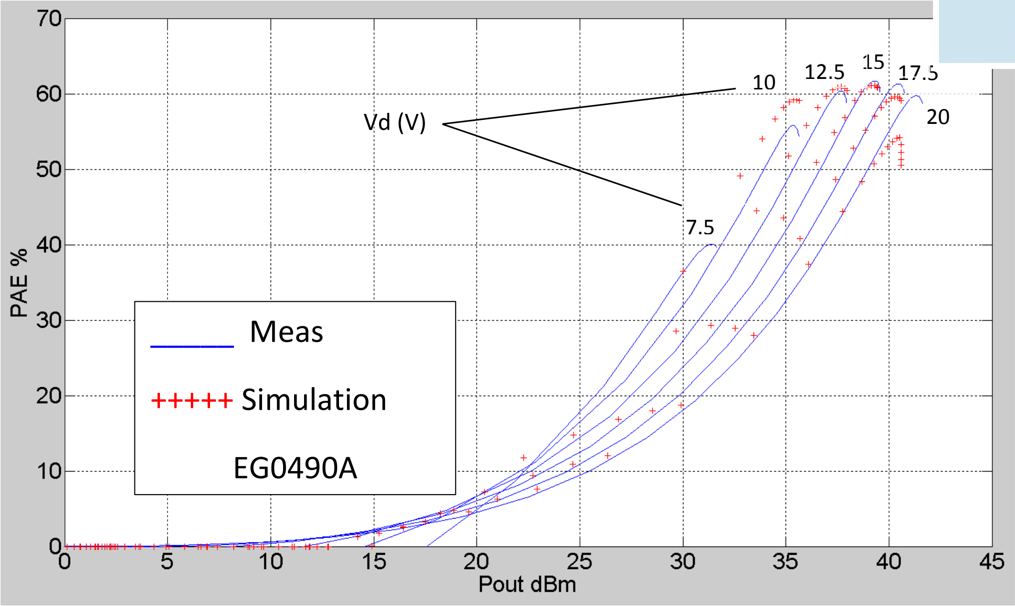
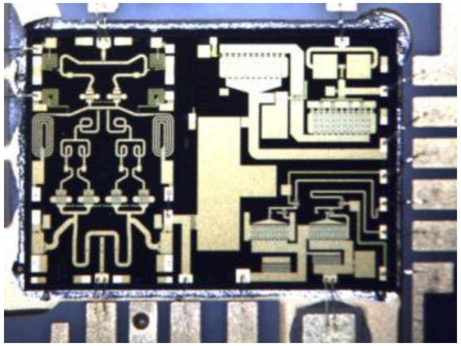
Supply modulation (Envelope Tracking)

- Amplifier designed over wide range of Vdd
- Supply modulator: efficient, high slew rate
- Various forms of distortion need linearizing



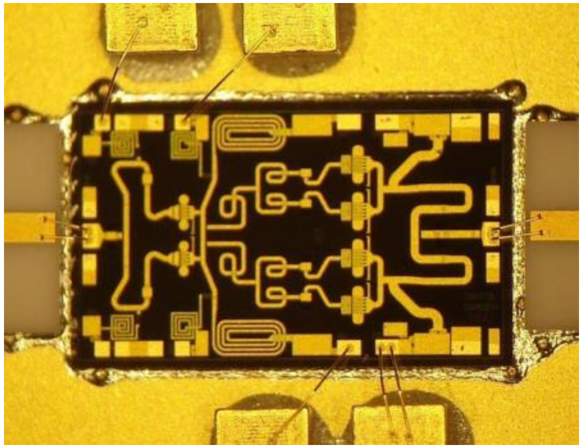




Goal:

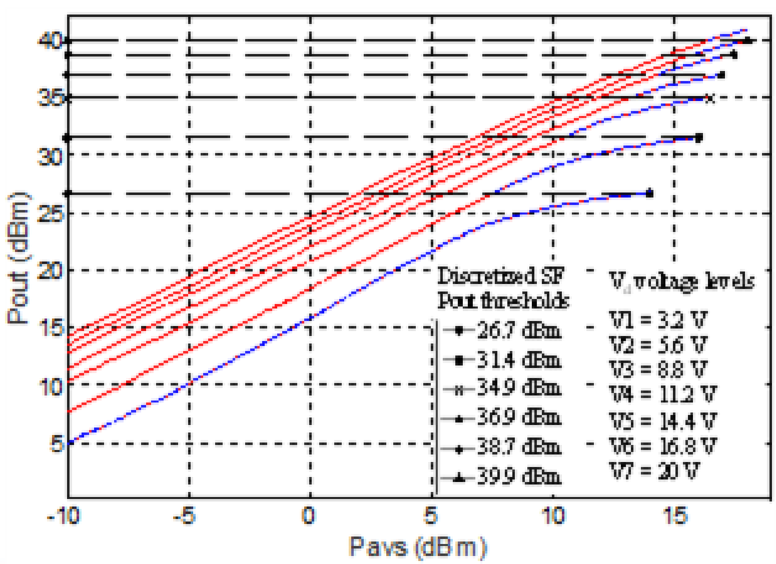
➢ Integrate PA with SM in the same GaN process

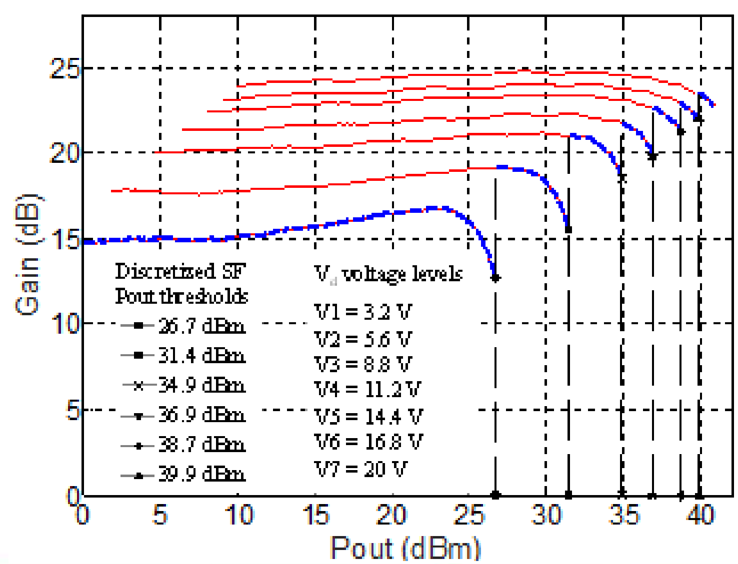
Example of a GaN MMIC X-band PA



- Pout>12W, PAE>65%
- Gsat>20dB, f=10GHz
- Qorvo GaN15 process
- Modelithics nonlinear model

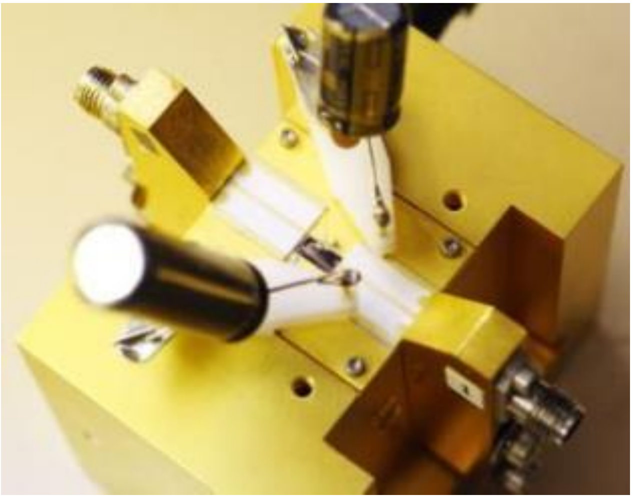
Measured Pout and Gain

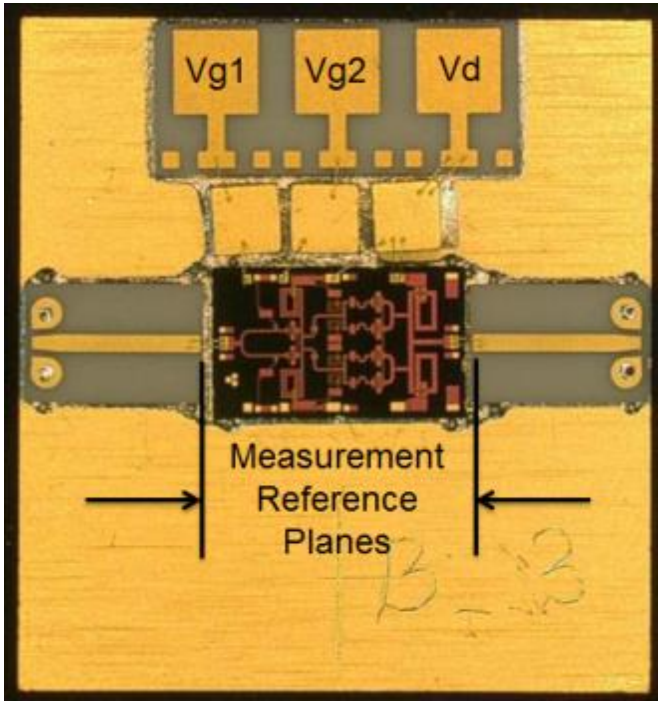




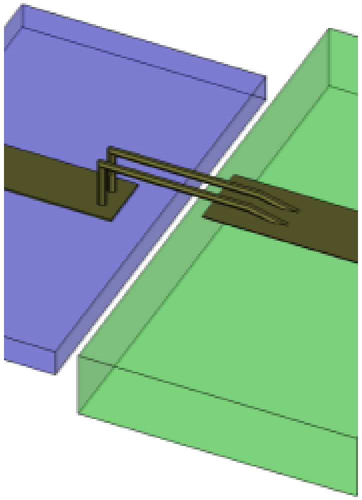
MMIC characterization

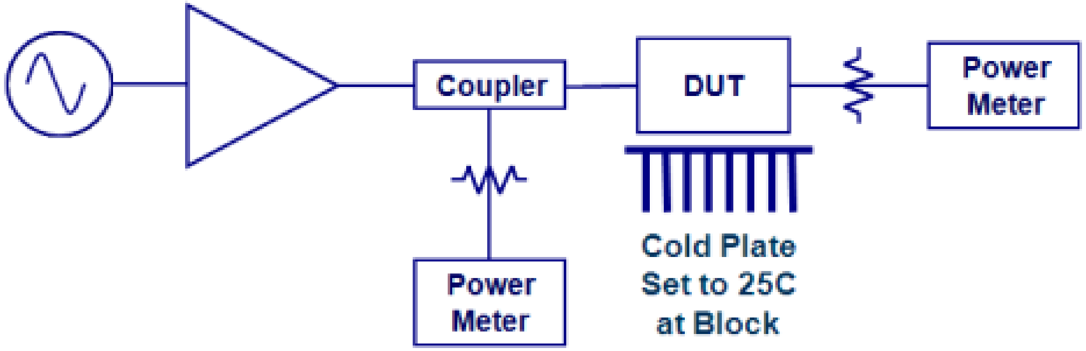
Fixture

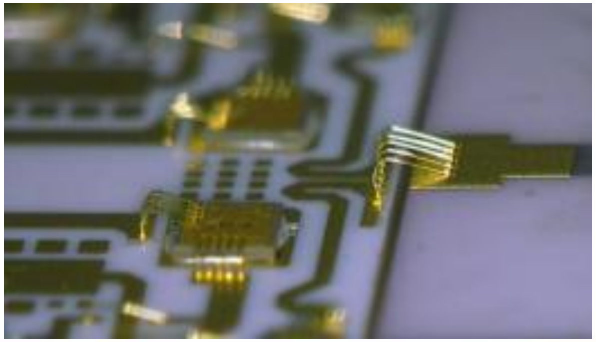




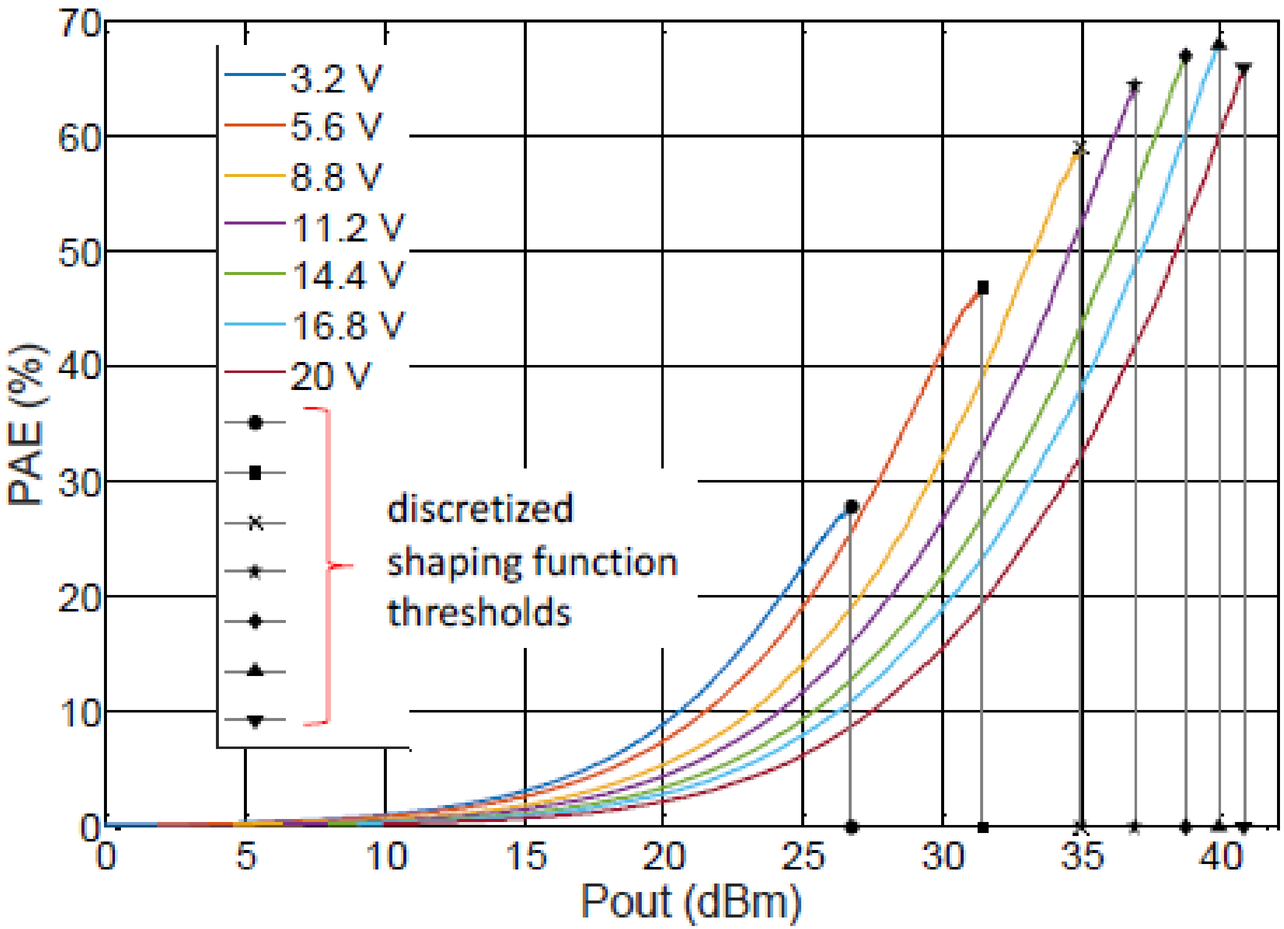
EM models for bondwires included in MMIC design







Static PAE vs. Pout

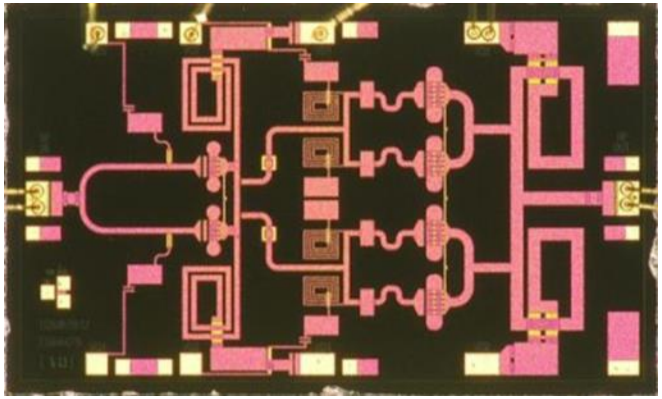


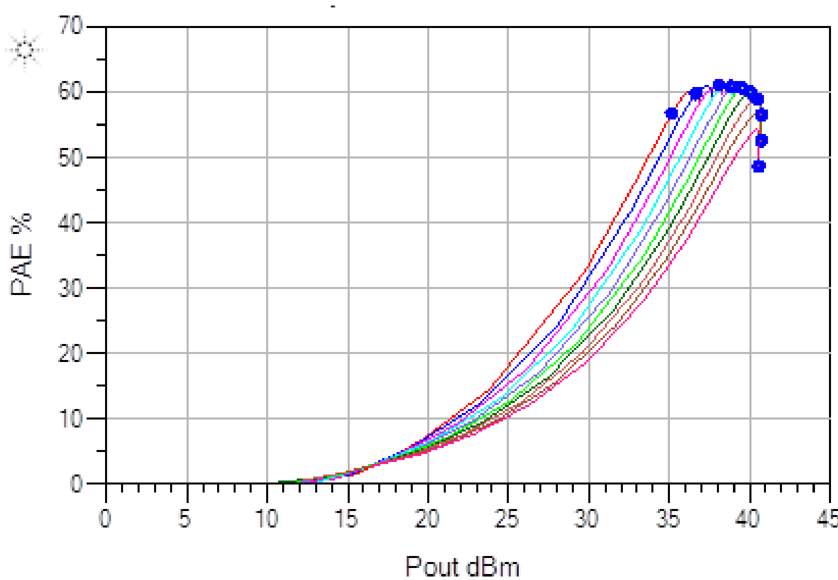
- Measured PAE of 10-W MMIC PA at 10GHz for a range of supply voltages
- PAE>60% over 6dB backoff

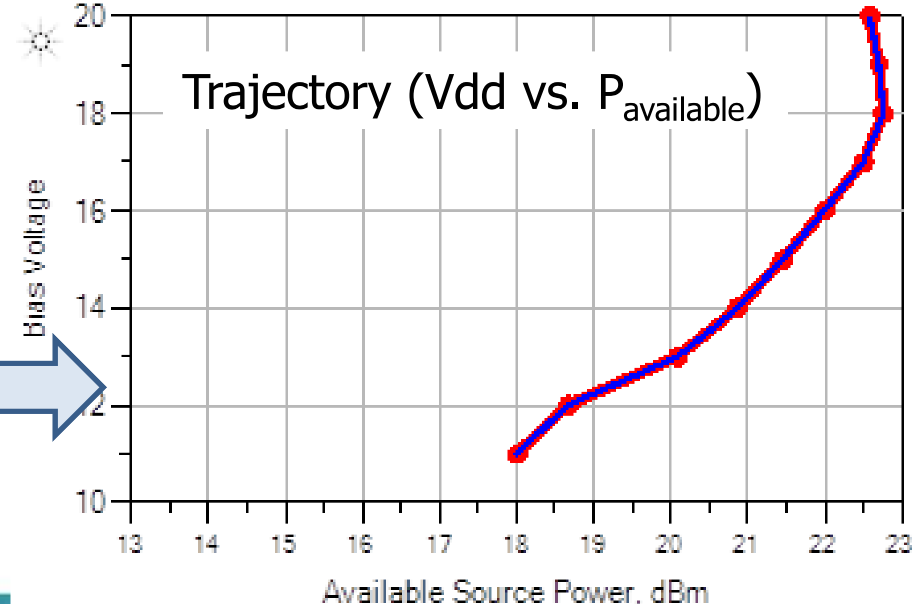
Real signal, integrated transmitter

- G = 18dB (constant)
- Both stages supply-modulated
- For reasonable AM/AM, 11V of voltage dynamic of the drain supply
- At low Vdd, gain drops
- Increasing gate bias voltage may improve the achievable dynamic range

PA MMIC EG0490A, two stages, 10W

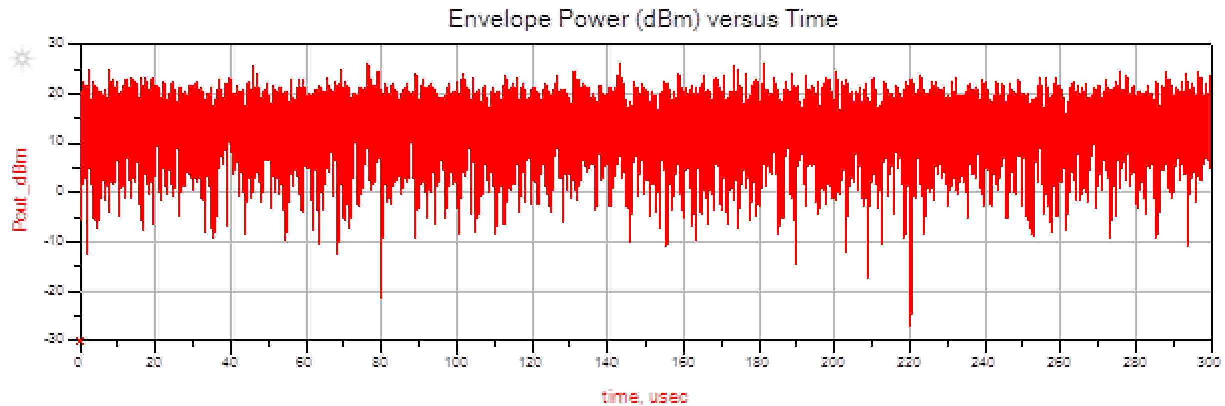






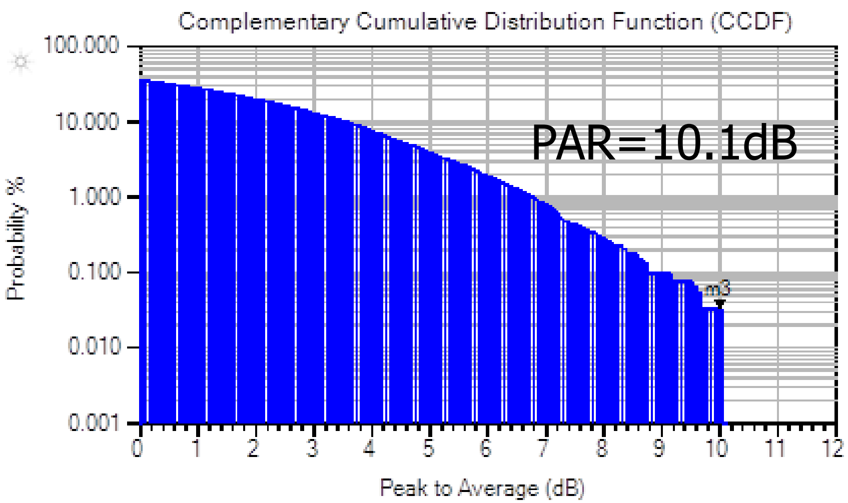
Signal Characteristics

Example: LTE 18MHz 3GPP standard signal, envelope transient simulation

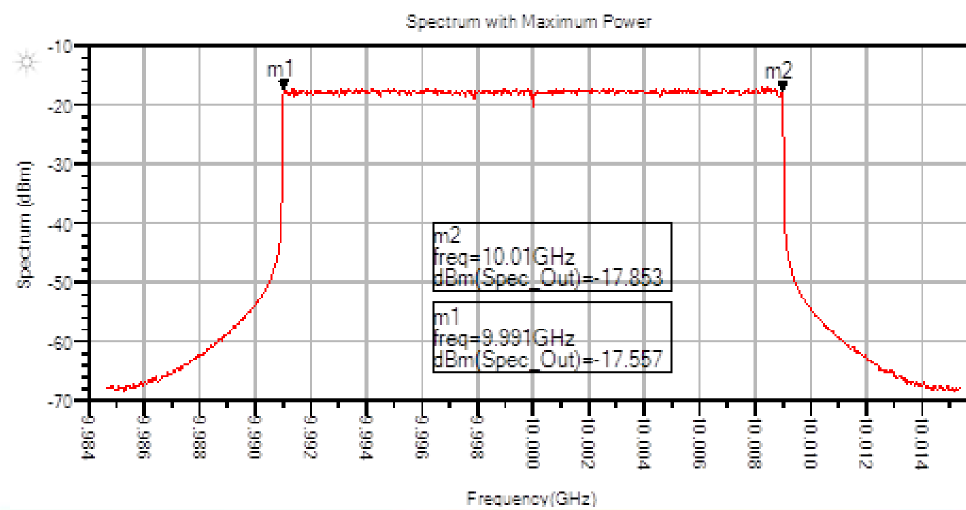


Envelope in time domain
Average power 16dBm

CCDF

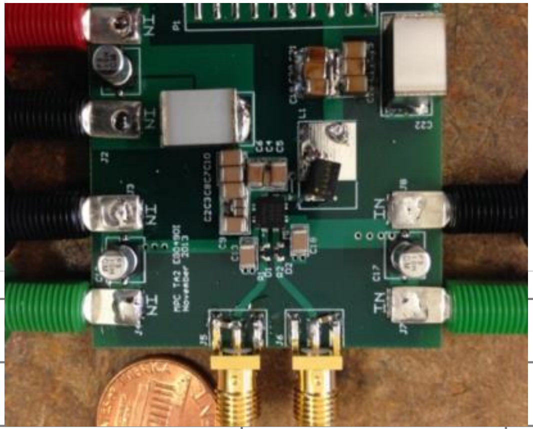


Spectrum

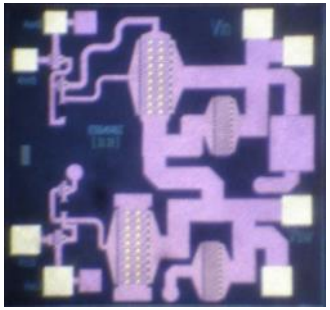


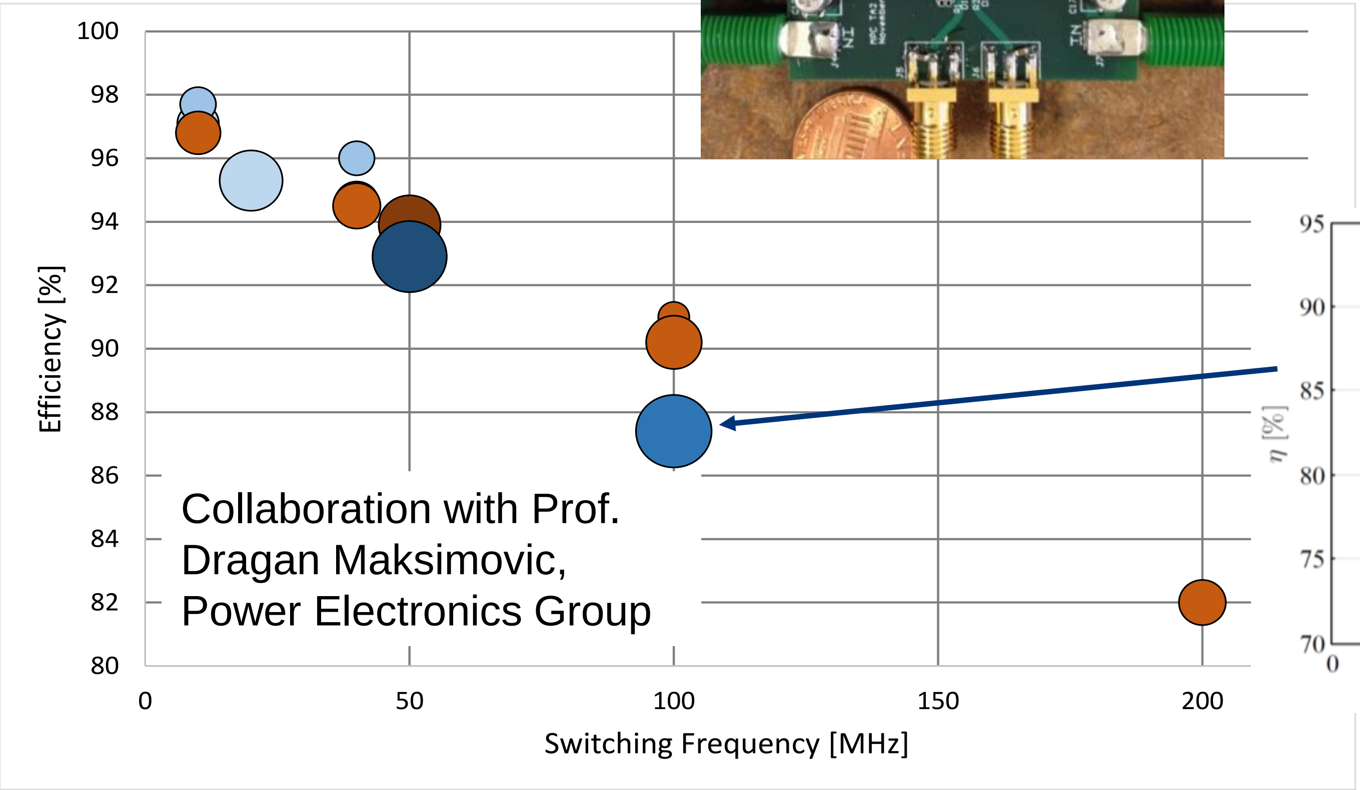
Example GaN Supply Modulator

- Switchers with integrated gate drivers, Qorvo GaN15
- η >90% , up to 200 MHz sw. frequency, up to 15 W peak power

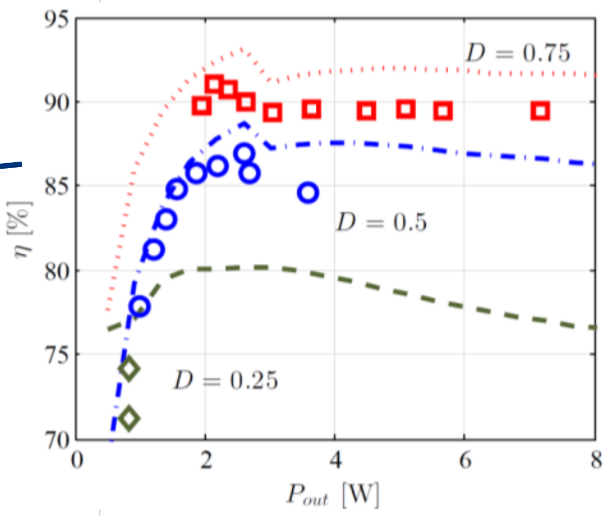


100 MHz, η>90% 10W peak
2.4 × 2.3mm, QFN package

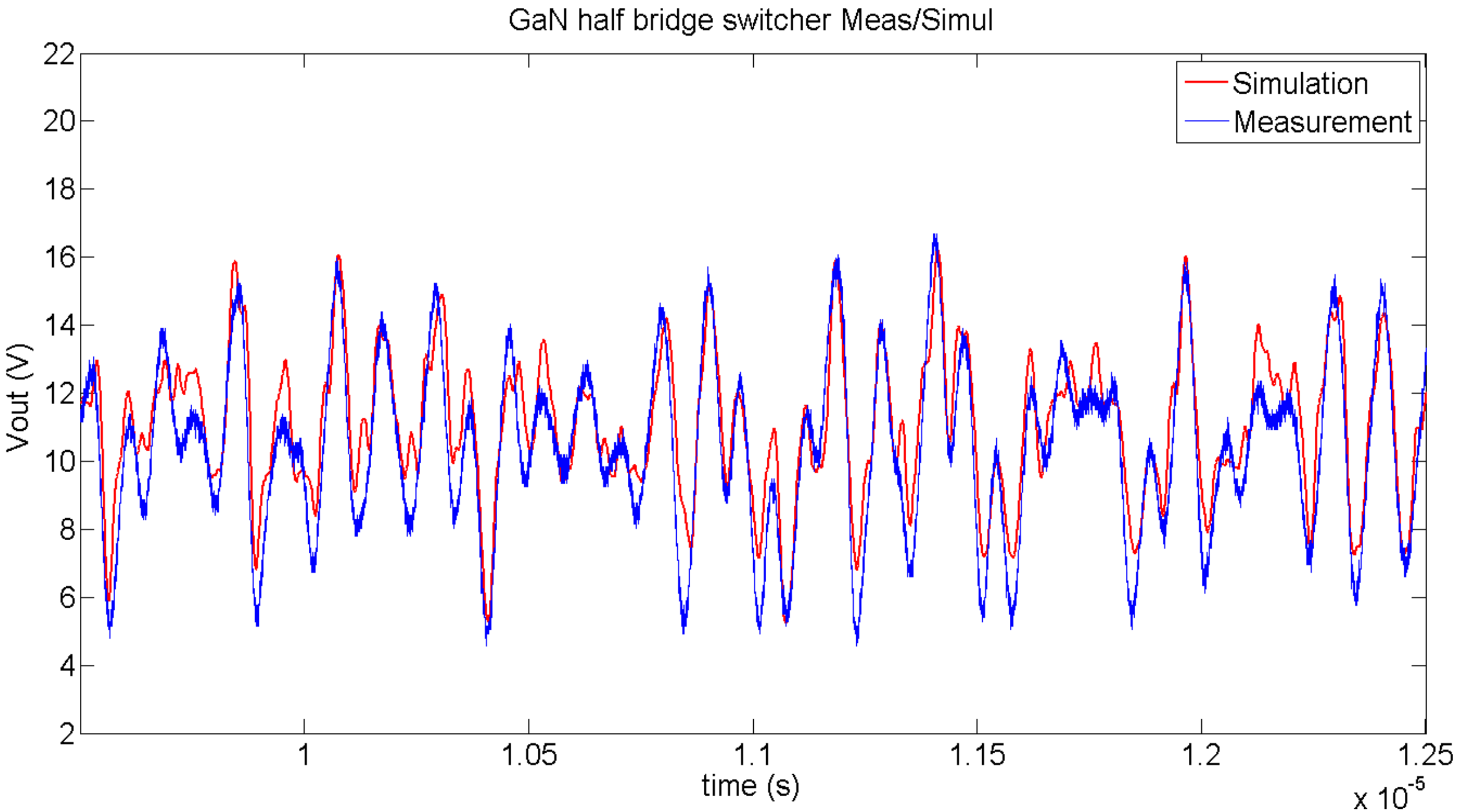




Collaboration with Prof. Dragan Maksimovic, Power Electronics Group

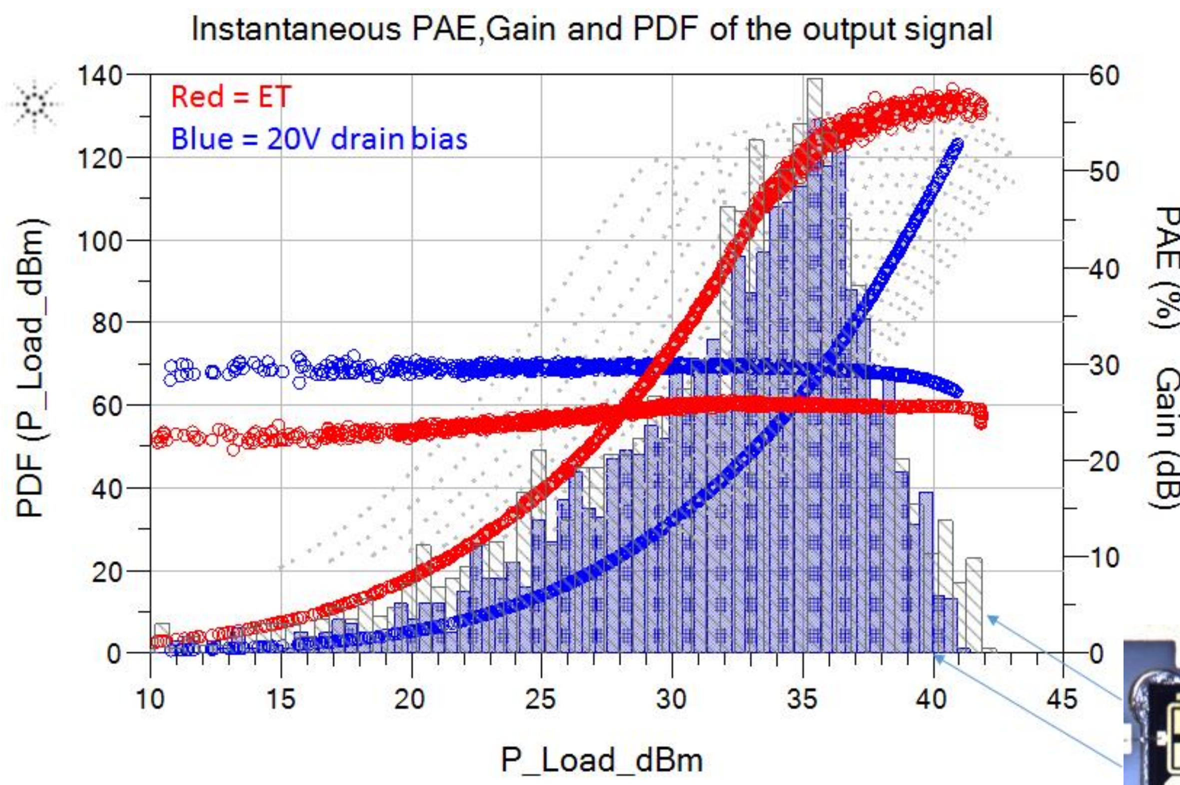


Measured vs. simulated DSM

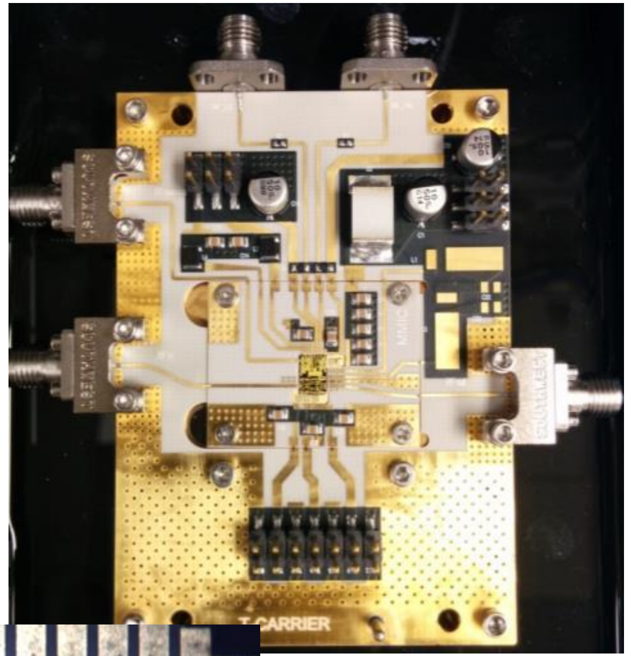


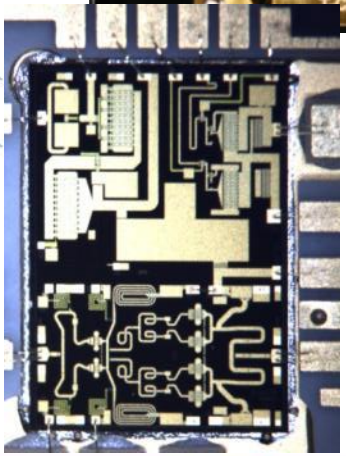
$$RMS\ error = 100 \times \sqrt{\frac{\sum_{t=1}^{n}\left(V_{out,t} - V_{in,t}\right)^2}{n}} \times \frac{1}{\left(V_{out\_max} - V_{out\_min}\right)} = \mathbf{4.5}\%$$

PA performance with LTE signal



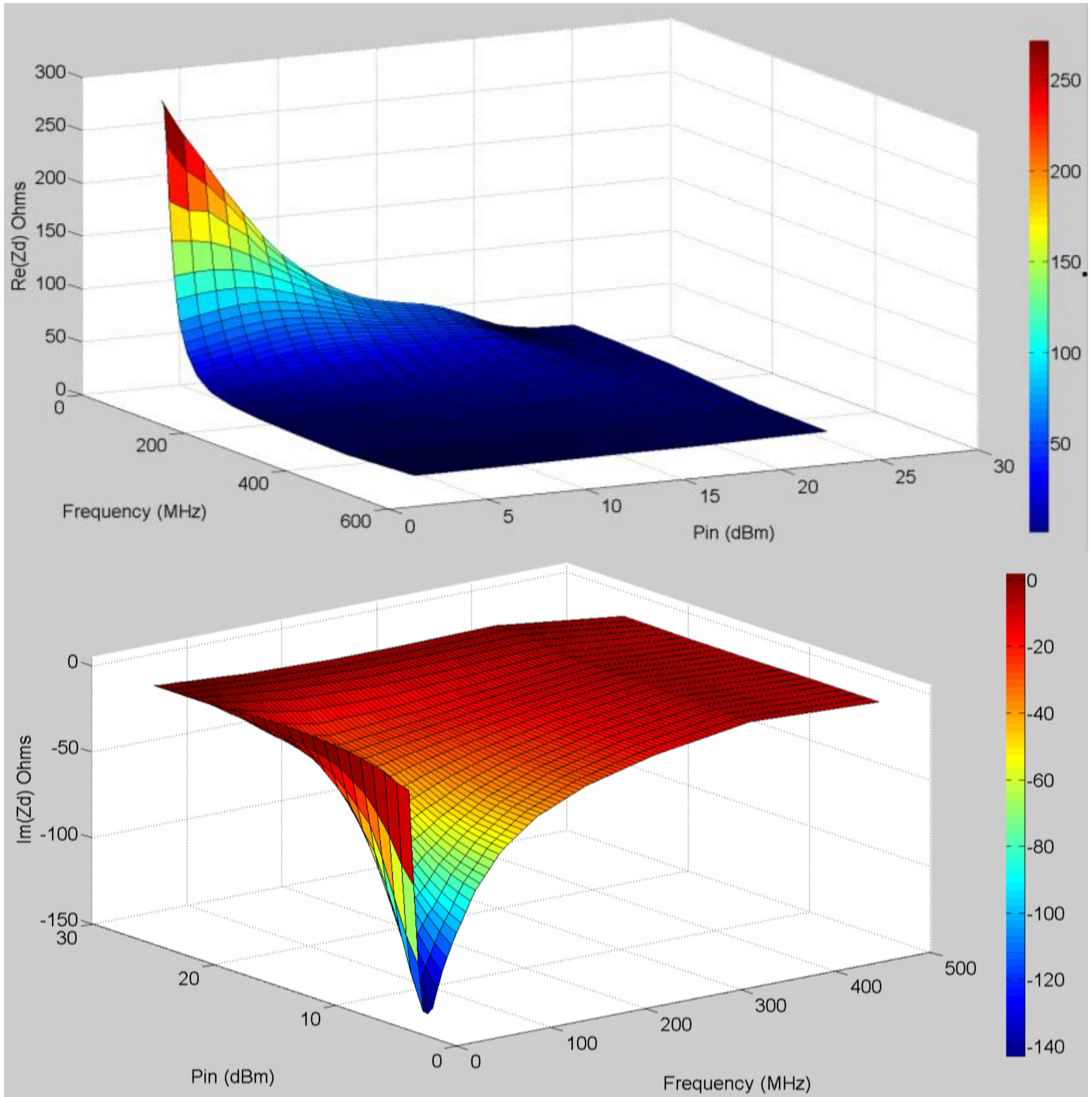
- PAPR = 10W /1.4W, 20-MHz OFDM, 10dB PAR, CPAE >40%
- PAPR = 6dB, 20-MHz QPSK, CPAE>45%





MMIC on carrier board
4mm x 5mm
Includes: 12-W PA, 100-MHz switcher and 500-MHz cascode PA

Measured static drain impedance, fixed V_{DD}



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.

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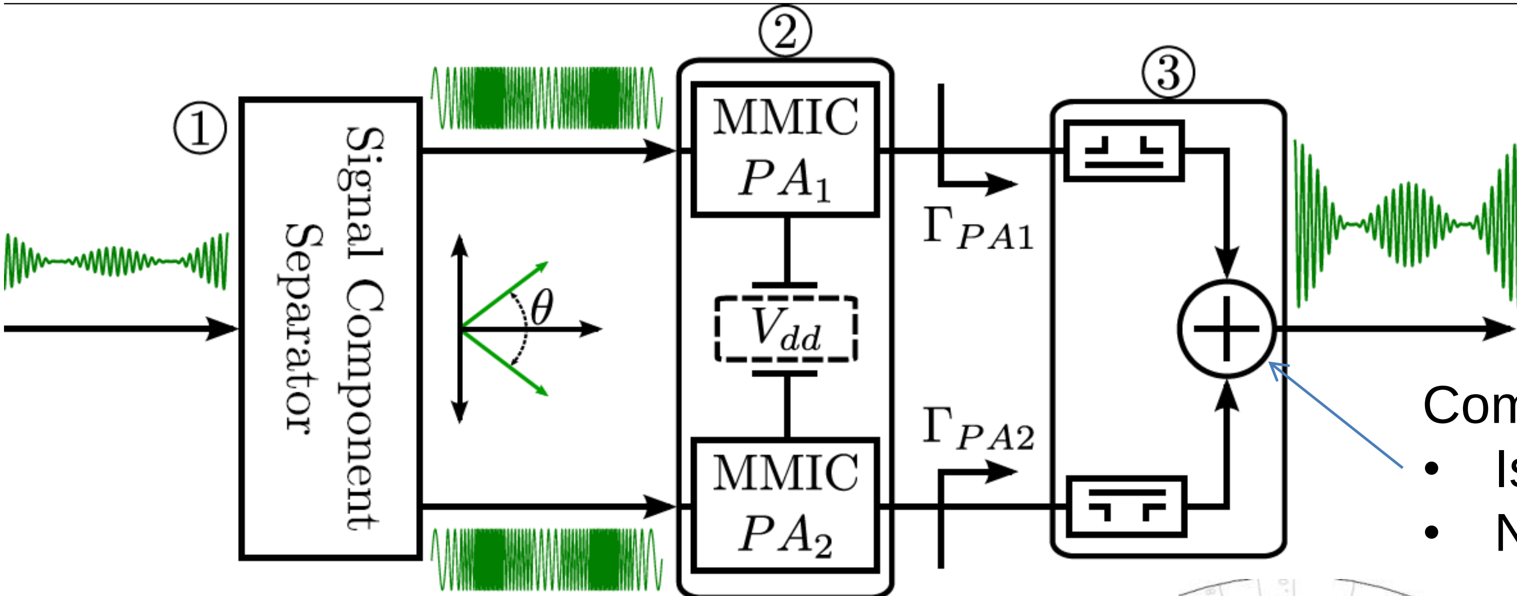
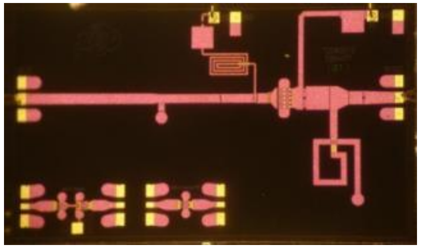
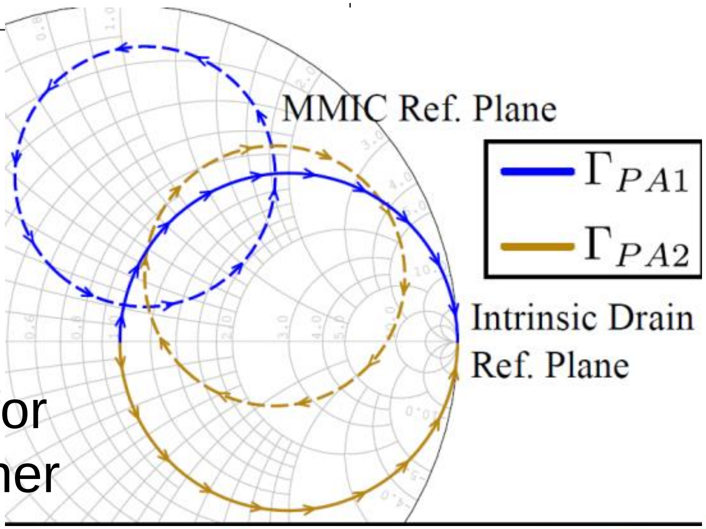
Quasi-MMIC outphasing PA



Combiner:
- Isolated
- Non-isolated

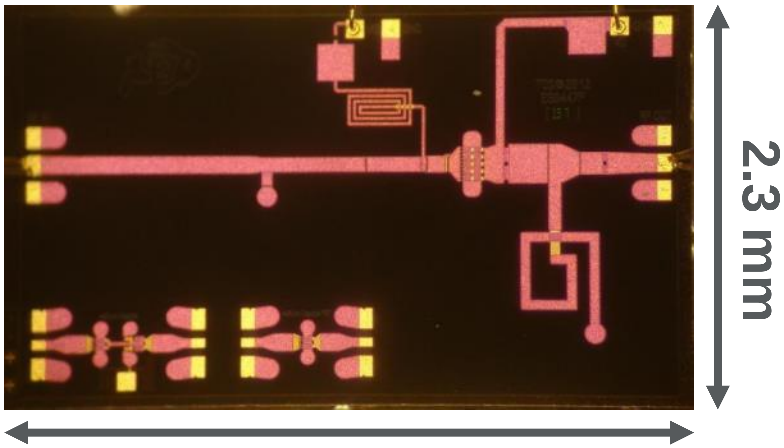
Digital

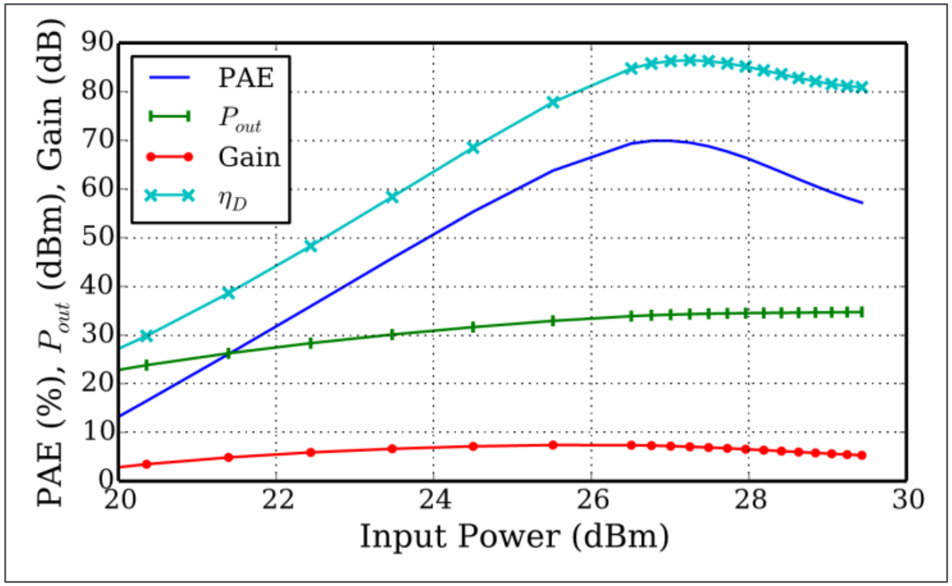




Load pull contours for non-isolated combiner

PA element for outphasing PAs

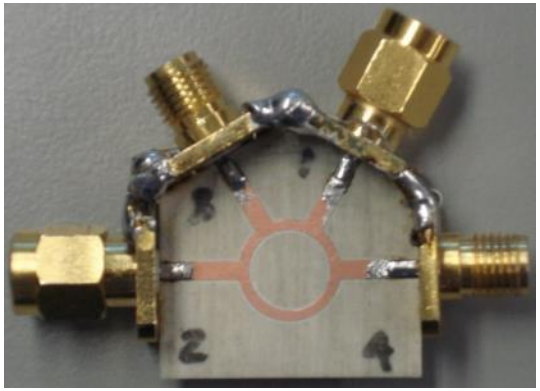




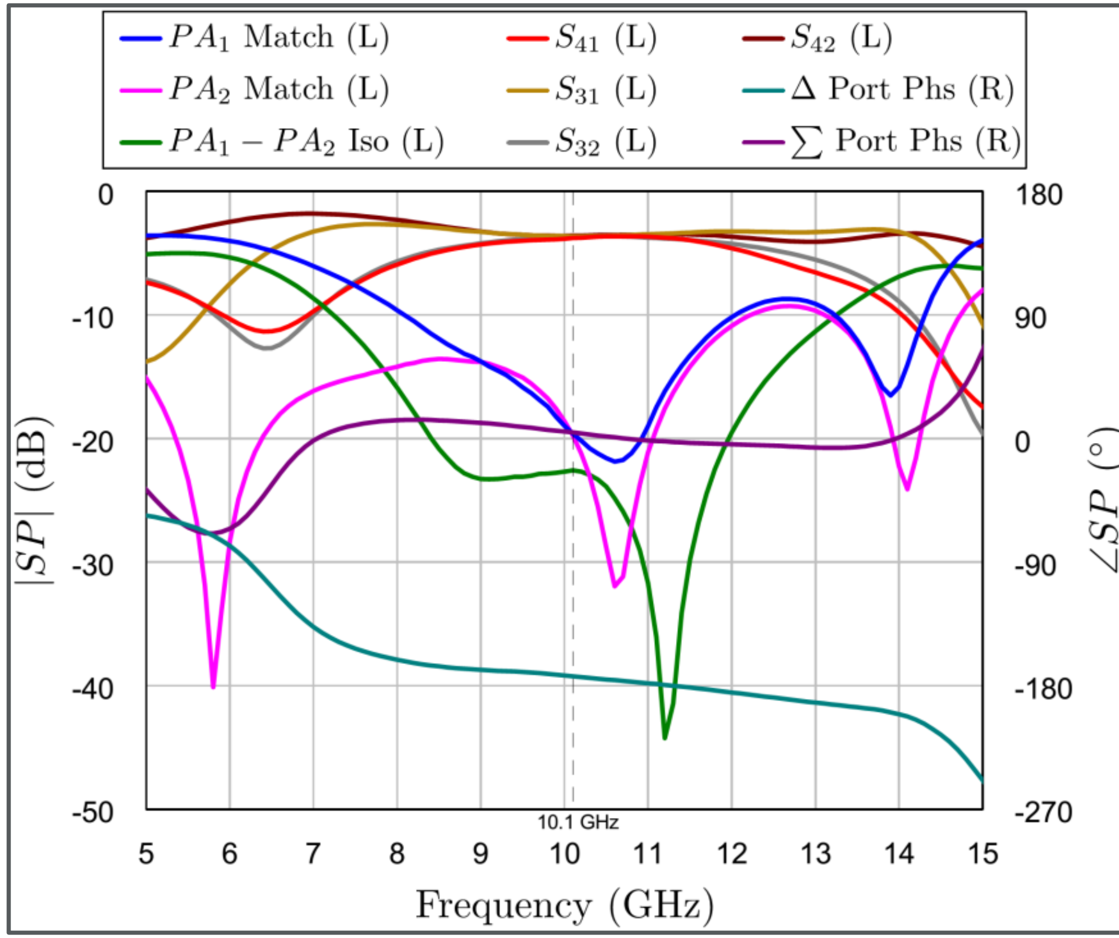
- Single-stage
- Biased in class-B
- GaN MMIC PA (TriQuint 0.15 µm)
- 10 x 100 µm FET

- 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

Isolated combiner

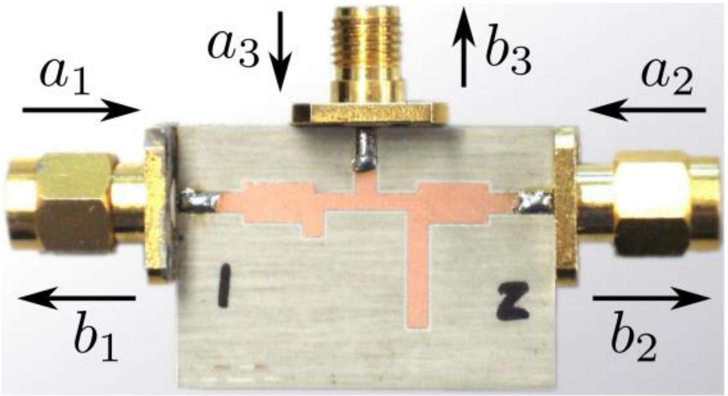


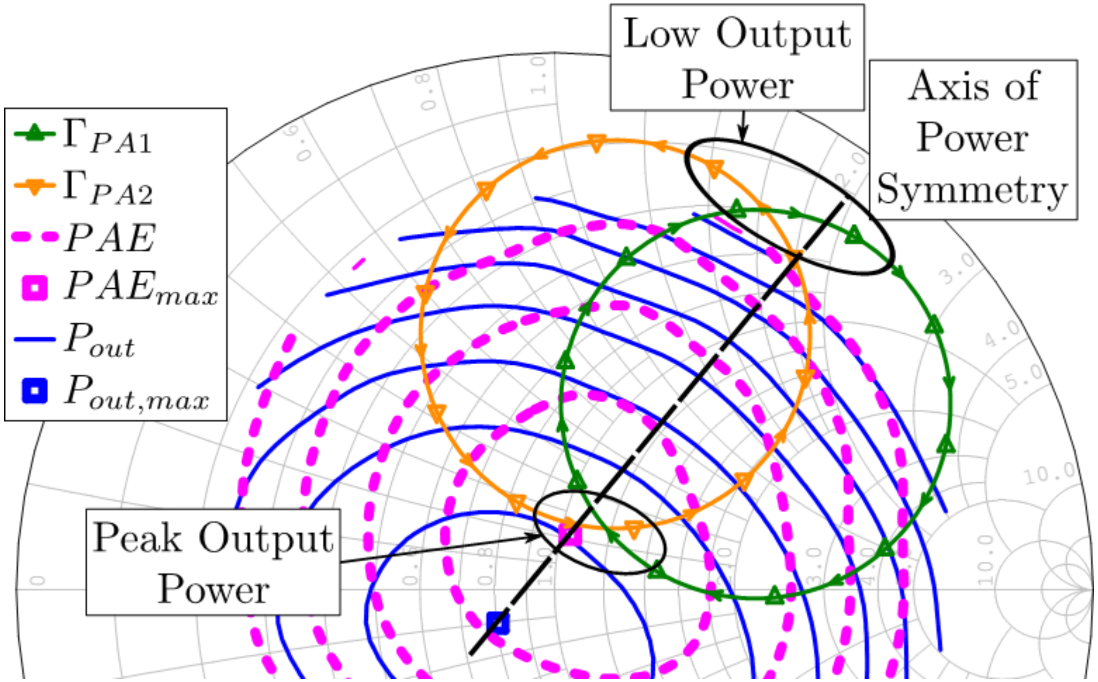
- 180° rat-race
- 30 mil Ro4350B
- < 1.4 dB loss
- 22.5 dB isolation
- > 19.5 dB return loss



- 4.5° sum port phase
- 173° diff port phase

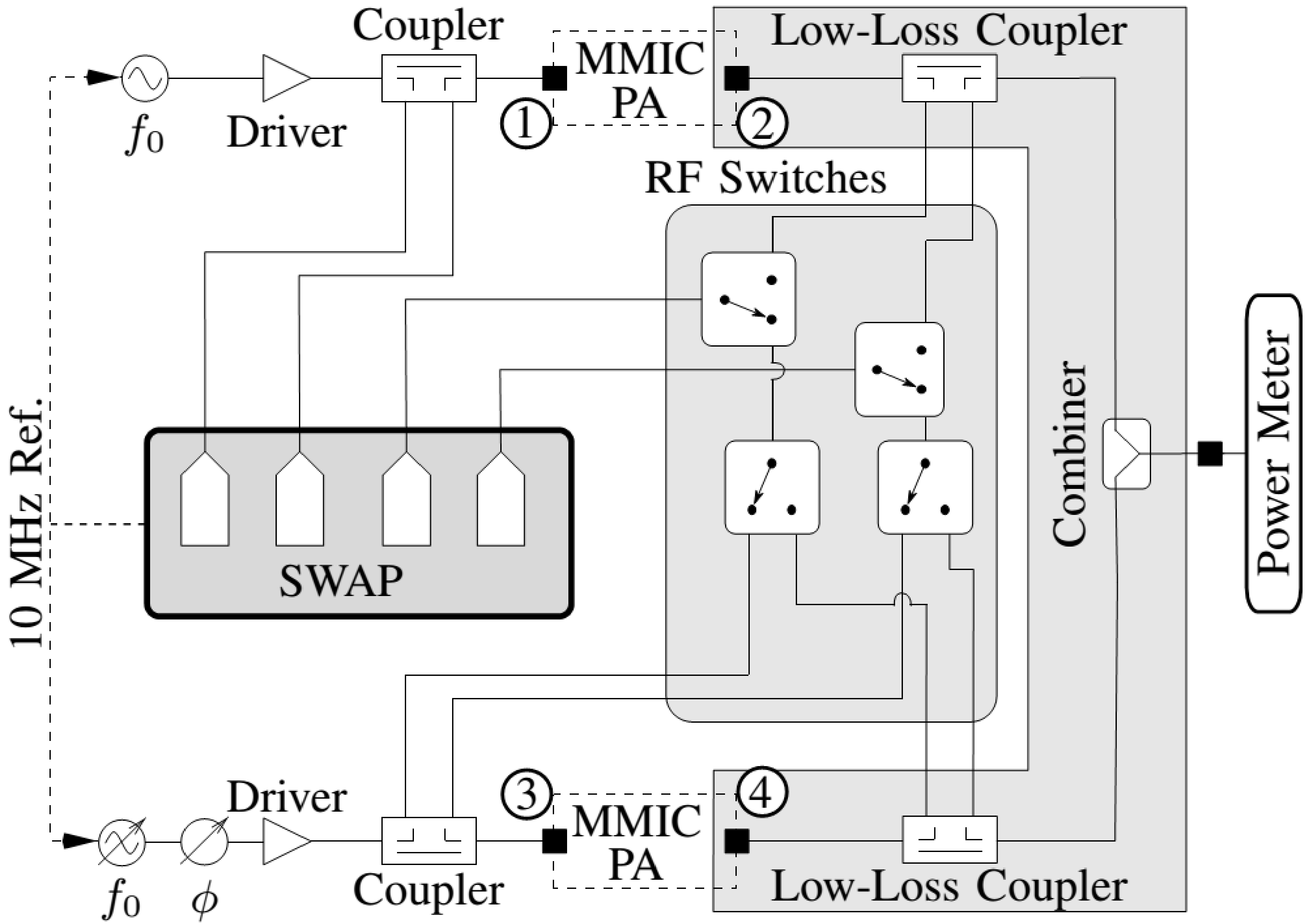
Non-isolated Combiner



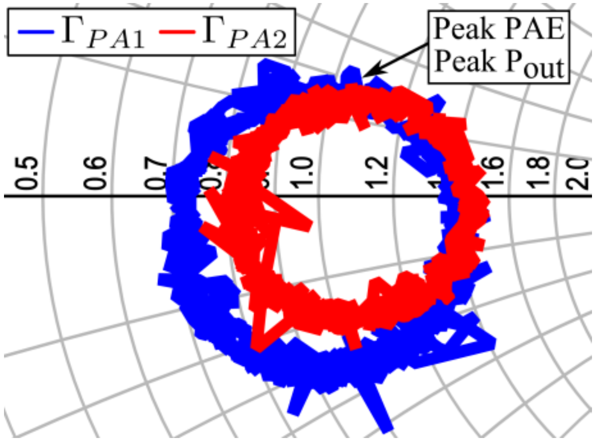


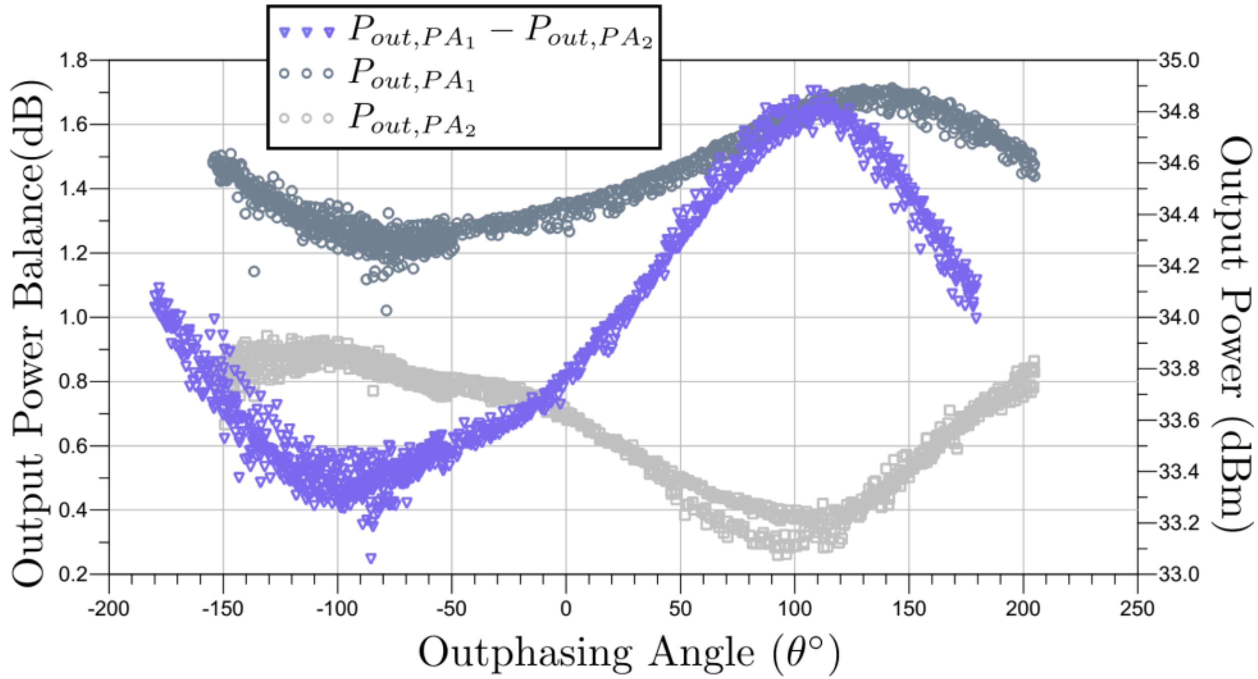
- Shunt susceptances and tuned 90° TLs
- Load modulation intersects at peak PAE load
- Internal PA power balance reasonably maintained

Internal PA Load Modulation



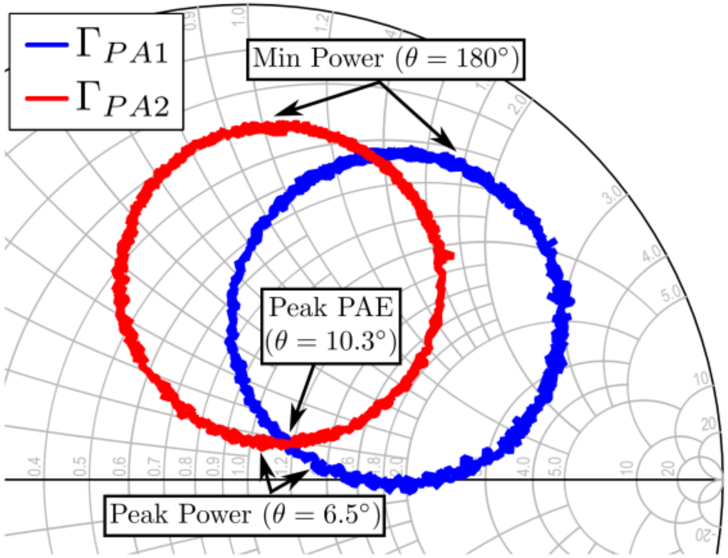
Isolated Outphasing PA

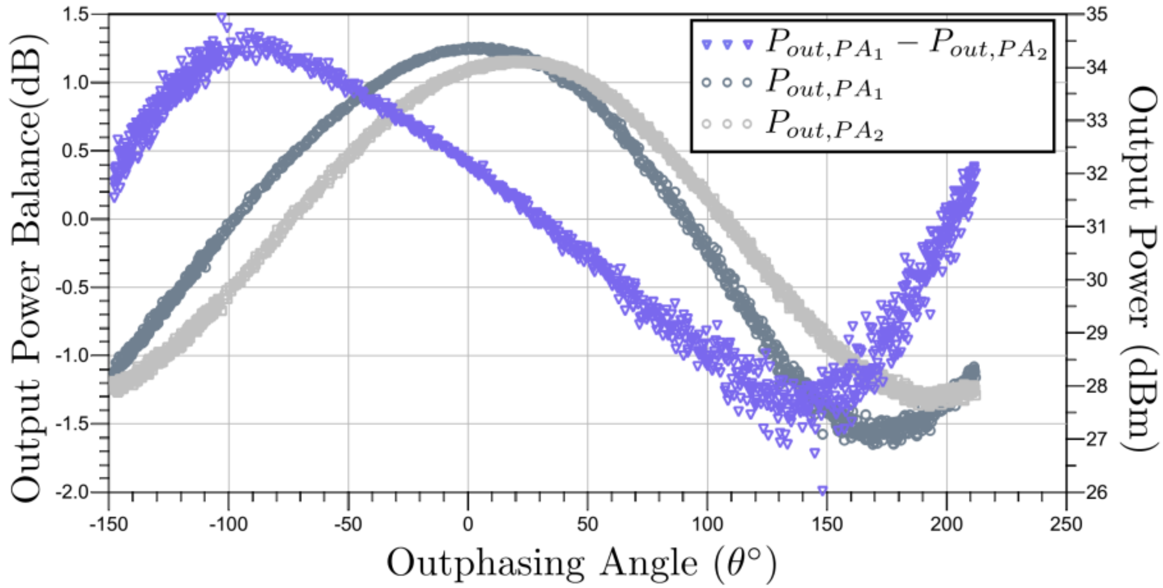




- Finite isolation yields minimal load modulation
- PAs rotate in opposite direction around contours
- 0.4 – 1.7 dB internal PA Pout imbalance caused by varying load

Non-Isolated Outphasing PA

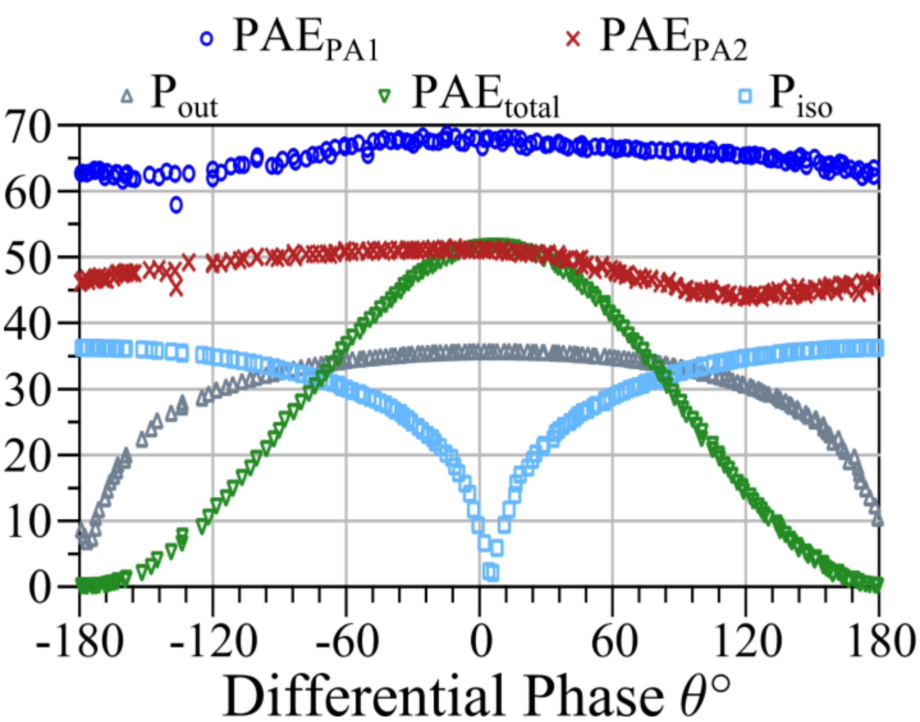




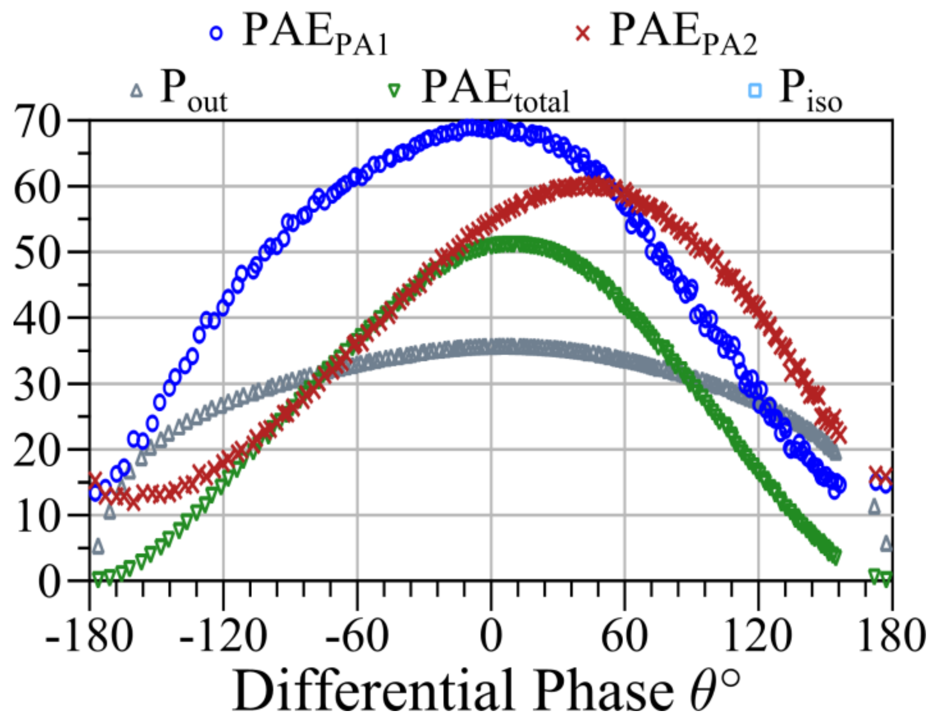
- Load modulation shows slight CW rotation due to ±1.5 dB internal PA Pout imbalance
- Peak power occurs near peak PAE
- Minimum Pout of 3.6 dBm near edge of smith chart

Comparison

Isolated



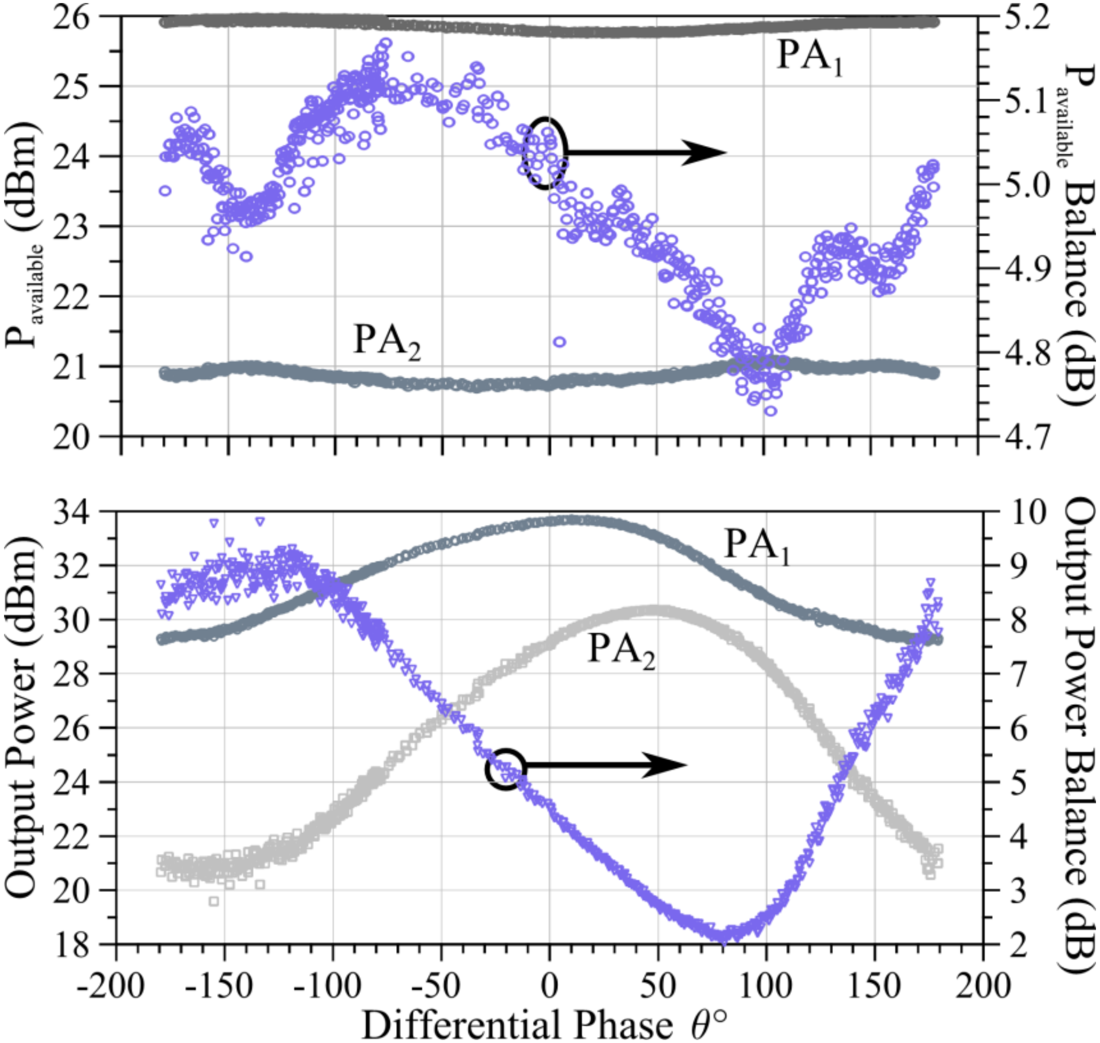
Non-isolated

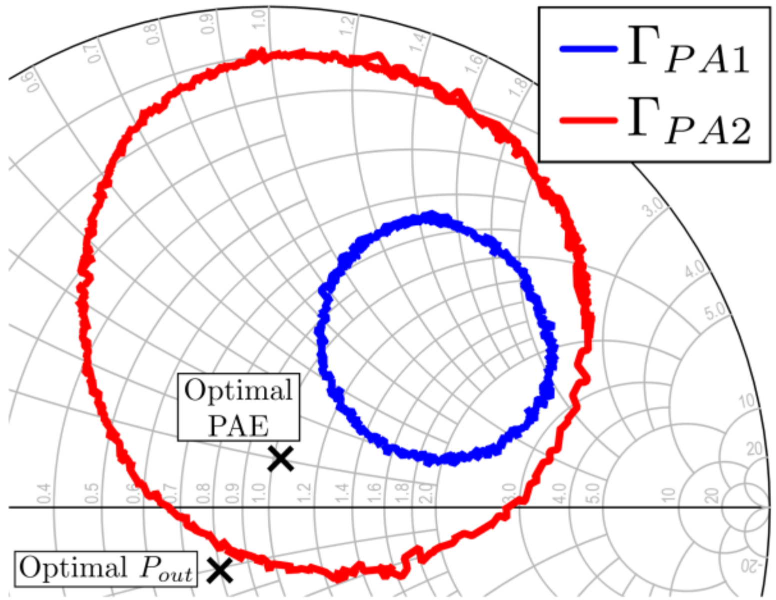


- Peak Pout = 35.8 dBm / 36.8dBm
- Peak PAE = 41.6 % / 59%
- Integrated design: 1 dB less loss

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

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RF instrumentation in LabVIEW

Connecting Minds. Exchanging Ideas.

THE GOOD

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

THE BAD

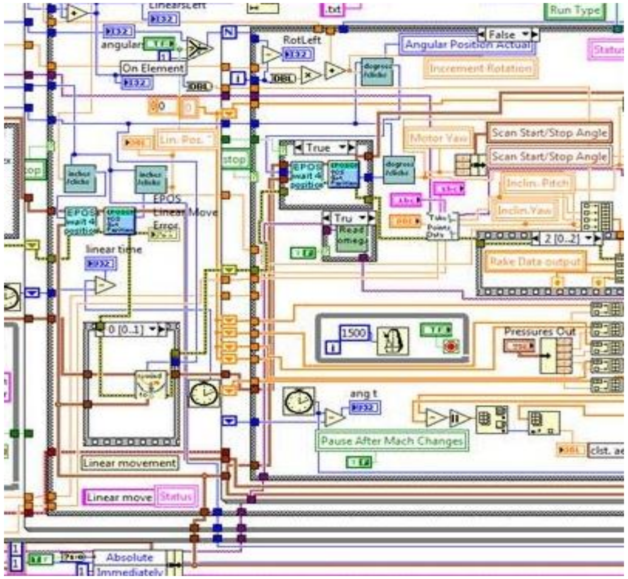
- LabVIEW code is difficult to read in big projects ;
- Mix of GUIs, algorithms and instrumentation drivers ;
- VISA interface is UNIVERSAL but...
- IVI is not:
    - Many DLLs ;
    - No universal handle manager in LabVIEW ;
    - Open/Closing sessions not convenient.

Nevertheless, there is a hope...

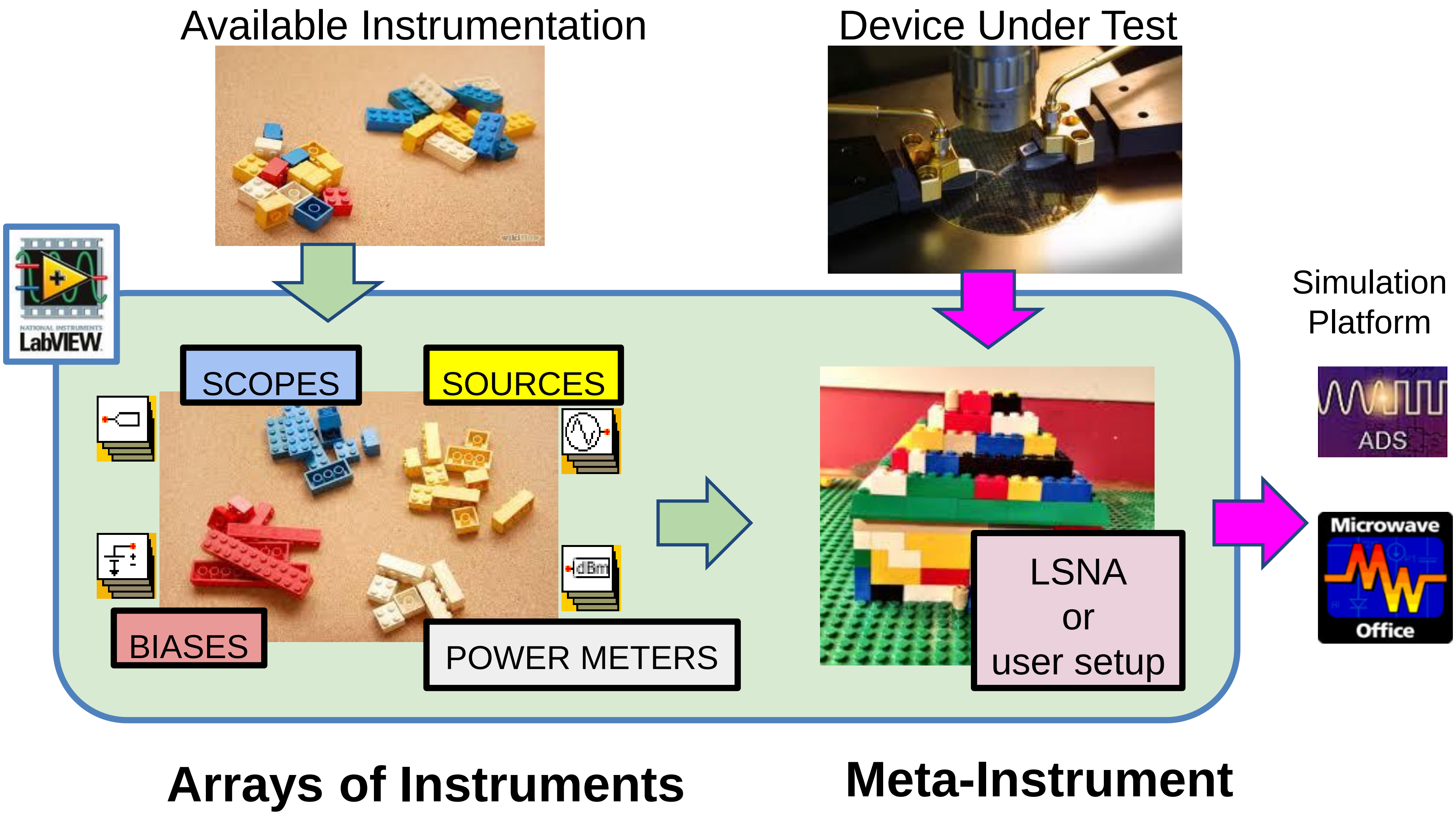
RF instrumentation is based on a very limited number of instruments:

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

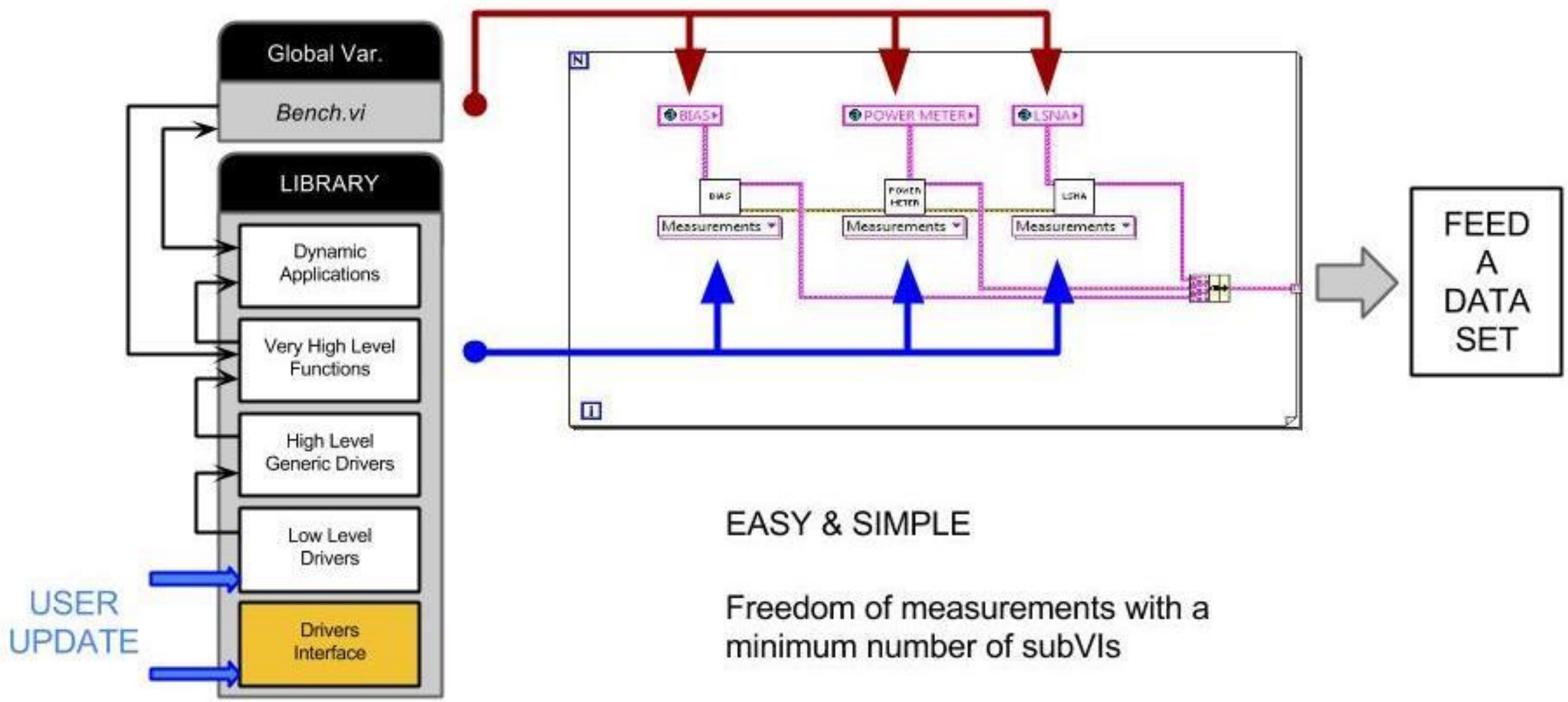
… and THE UGLY



RF instrumentation in LabVIEW



LabVIEW Toolbox Principle



EASY & SIMPLE

Freedom of measurements with a minimum number of subVIs

LabVIEW Toolbox Principle

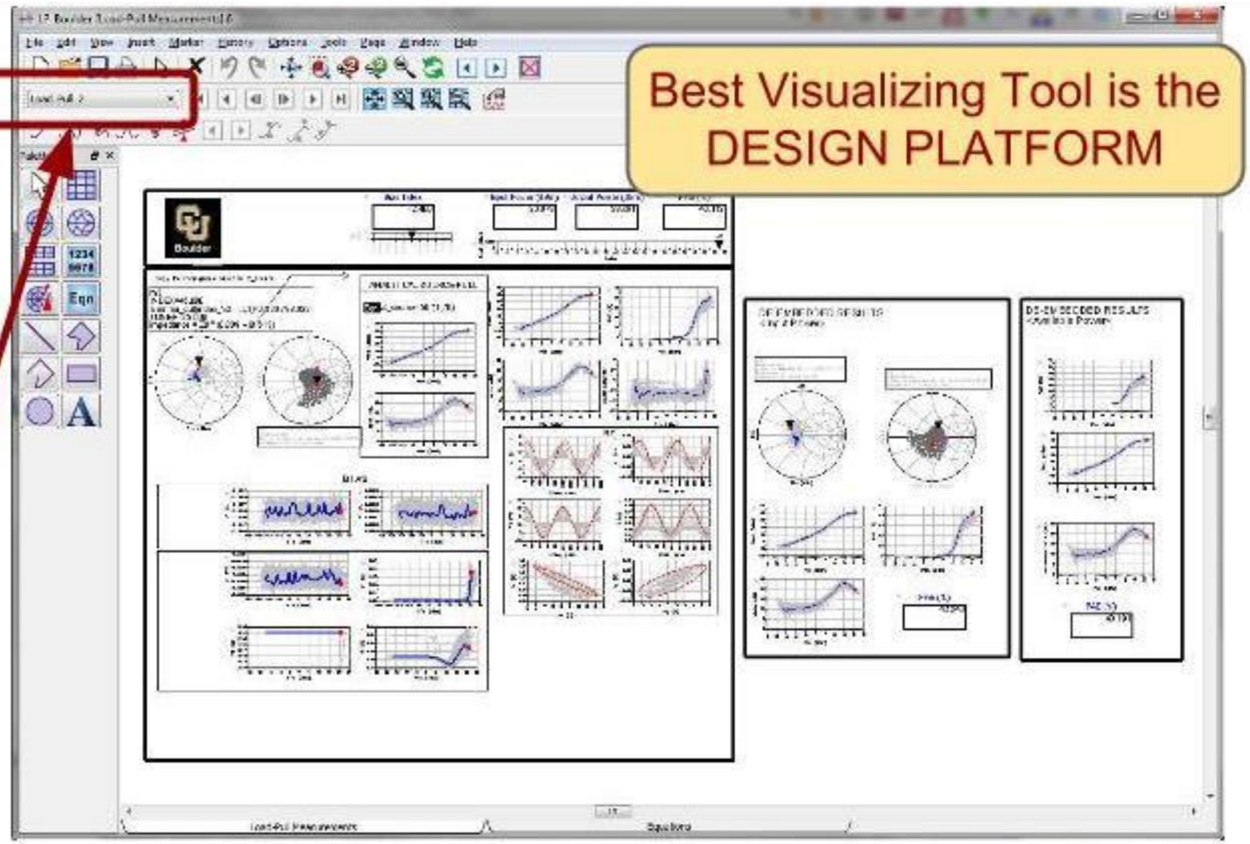
Connecting Minds. Exchanging Ideas.

FEED
A
DATA
SET

1. *EXPORT DATA in **MDIF***

2. *IMPORT in DATA DISPLAY tool*

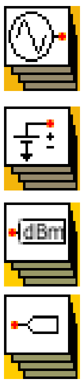
Switching datasets allow to compare easily measurements and simulations.

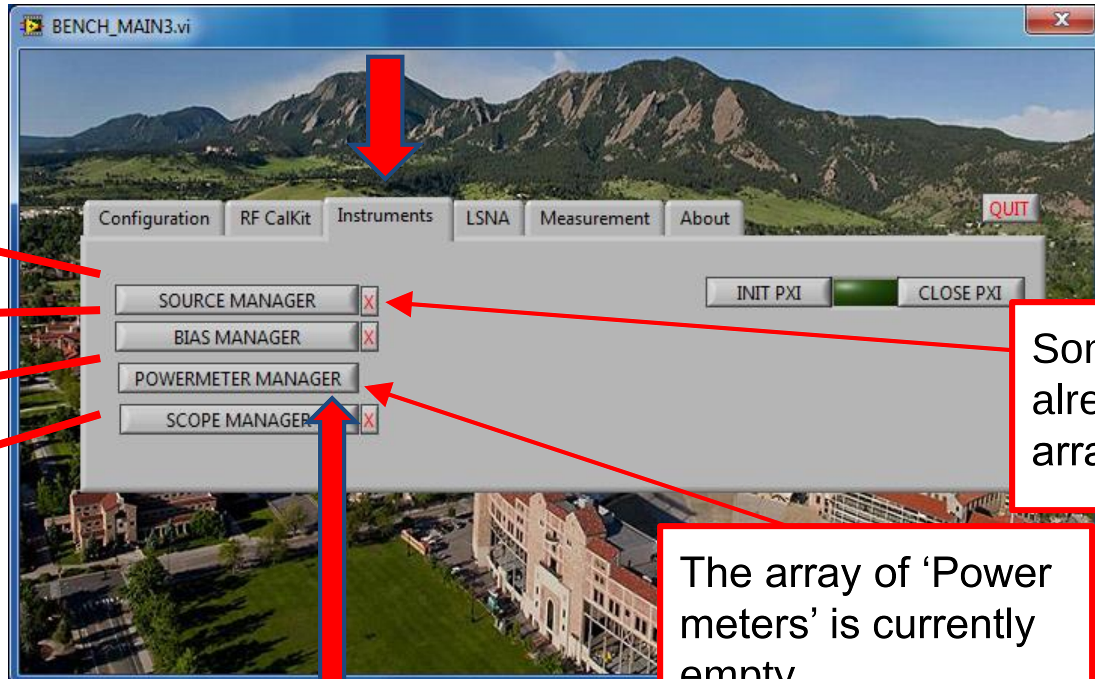


Best Visualizing Tool is the DESIGN PLATFORM

LSNA Load-Pull Measurements in Keysight ADS

Instrument Manager

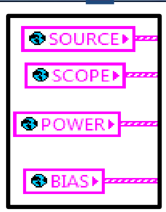




Some elements are already defined in the array of ‘Sources’.

The array of ‘Power meters’ is currently empty.

ONE VI ONLY
TO ACCESS
ARRAYS OF
INSTRUMENTATION

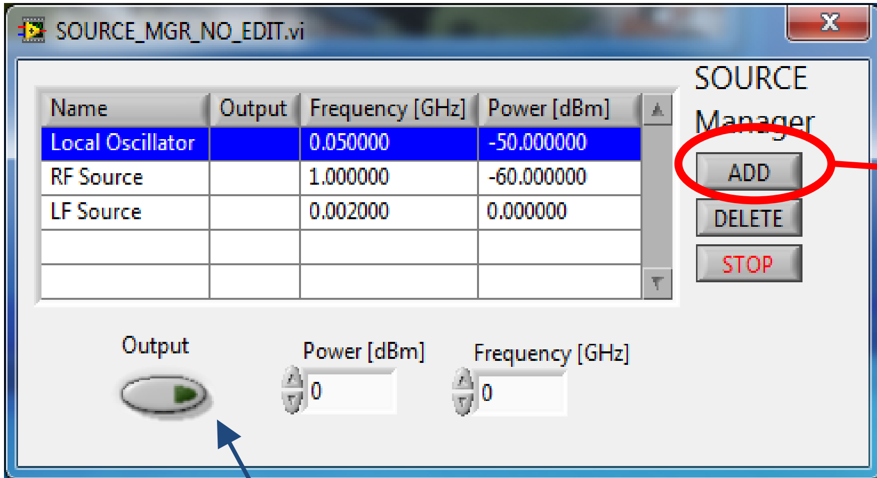


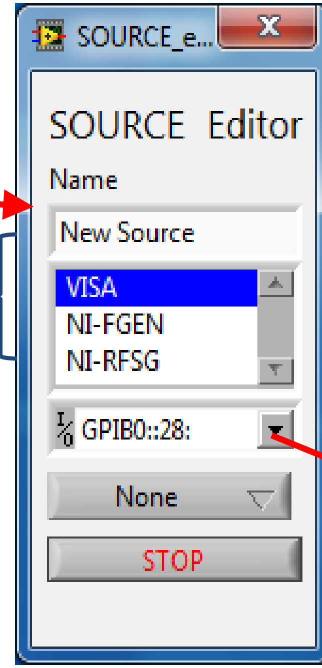
Bench.vi

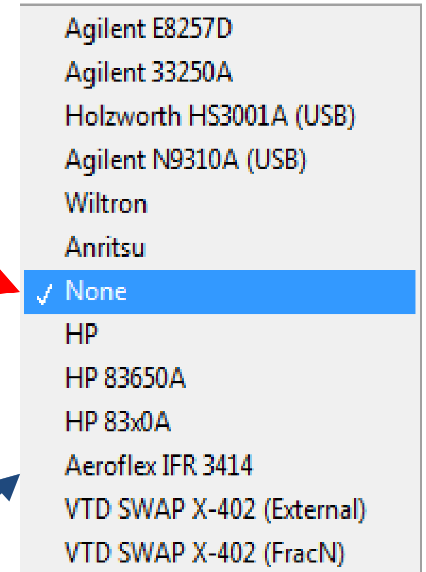
Some GUIs (Sources and Scopes) includes PXI session init and close on the fly.
Array can be deleted by clicking on the ‘X’.

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

Instrument Manager Example







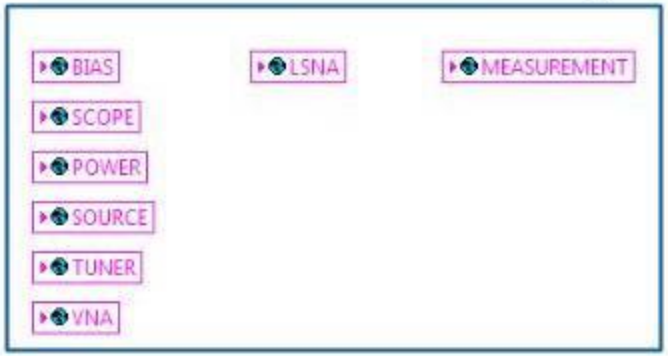
Interactive control (useful with PXI sources). Open and Close PXI session on the fly if needed.

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)

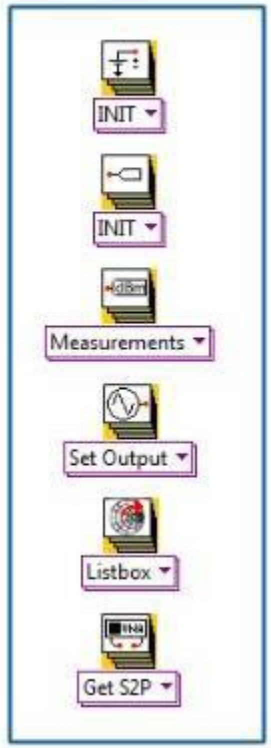
List of instrumentation previously defined in low-level drivers.(Typedef file) Here is the list for VISA instruments.

Complete Library

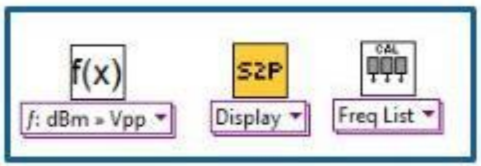
Global Variable BENCH.VI describes any bench…



BENCH_MGR to Load/Save/Switch ON/OFF any bench



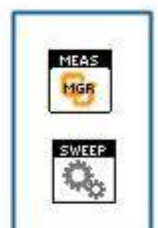
One VI only per instrument family. Final code is totally hardware independent.



Additional Tools

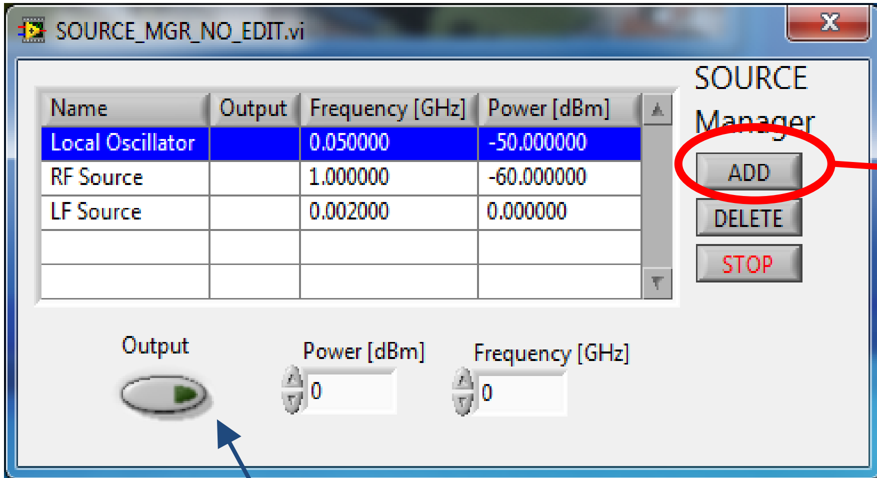
One VI per meta-instrument

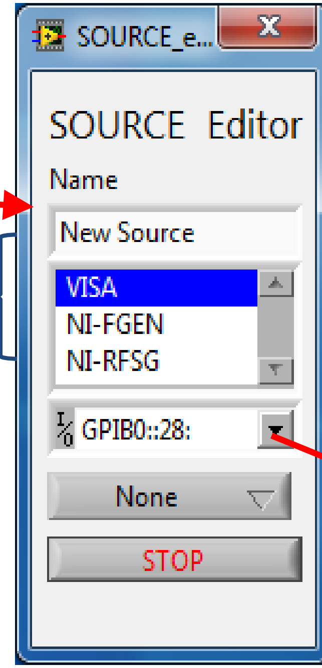
Measurements Export

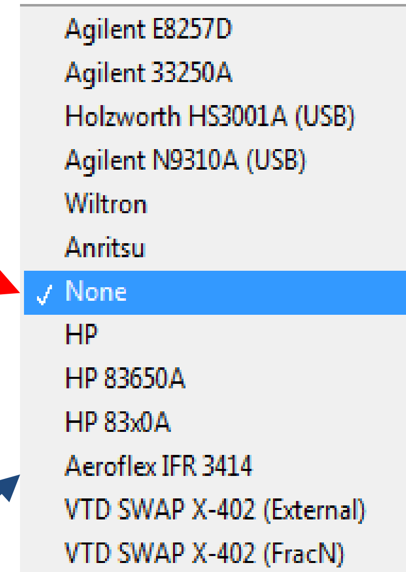


Measurements and Sweep-plans functions will be merged in a single VI as well.

Configuration Example: CW Source





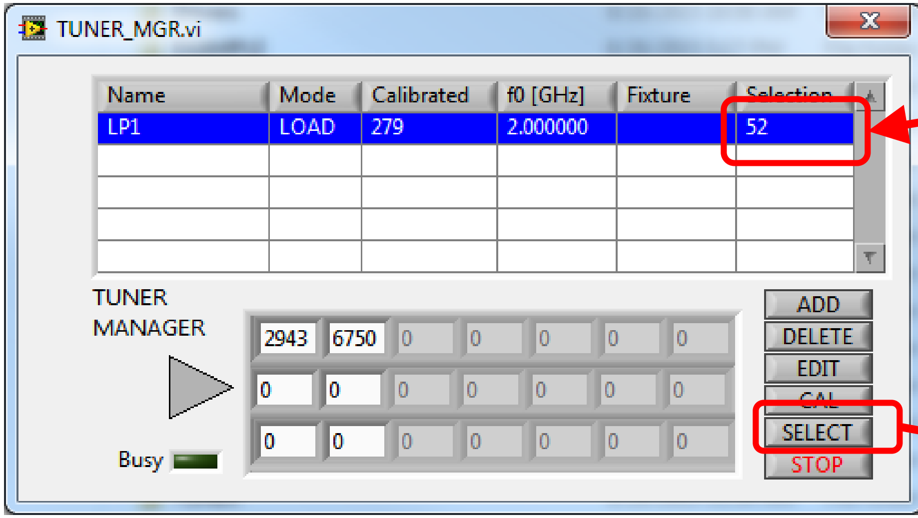


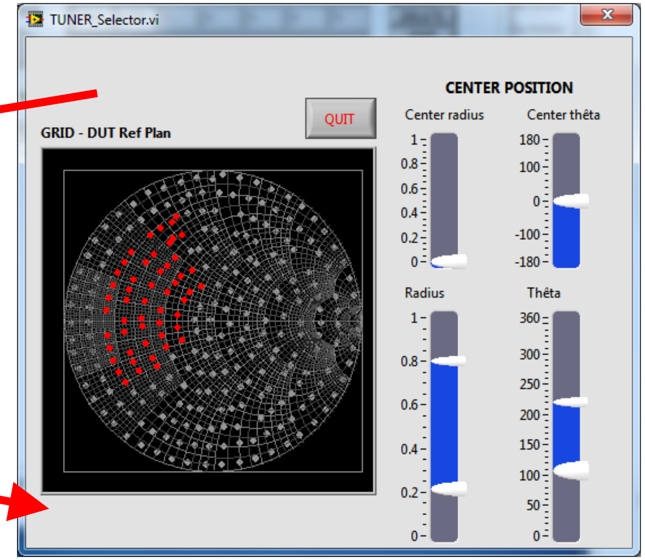
Interactive control (useful with PXI sources). Open and Close PXI session on the fly if needed.

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)

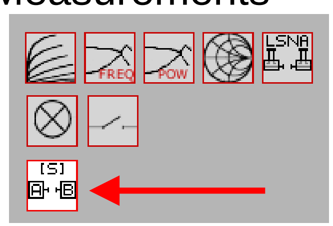
List of instrumentation previously defined in low-level drivers.(Typedef file) Here is the list for VISA instruments.

Configuration Example: Load-Pull

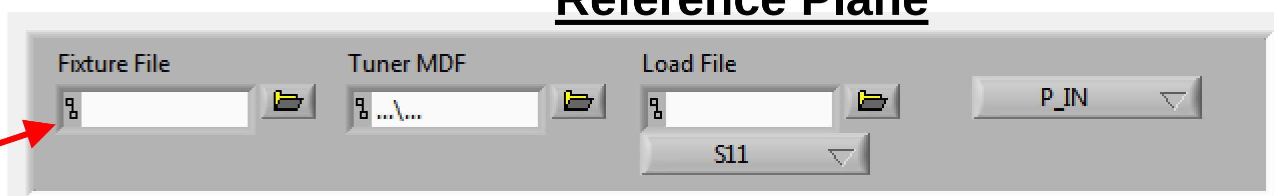




"Fixture File" may be extracted from SOLT CalKit Measurements

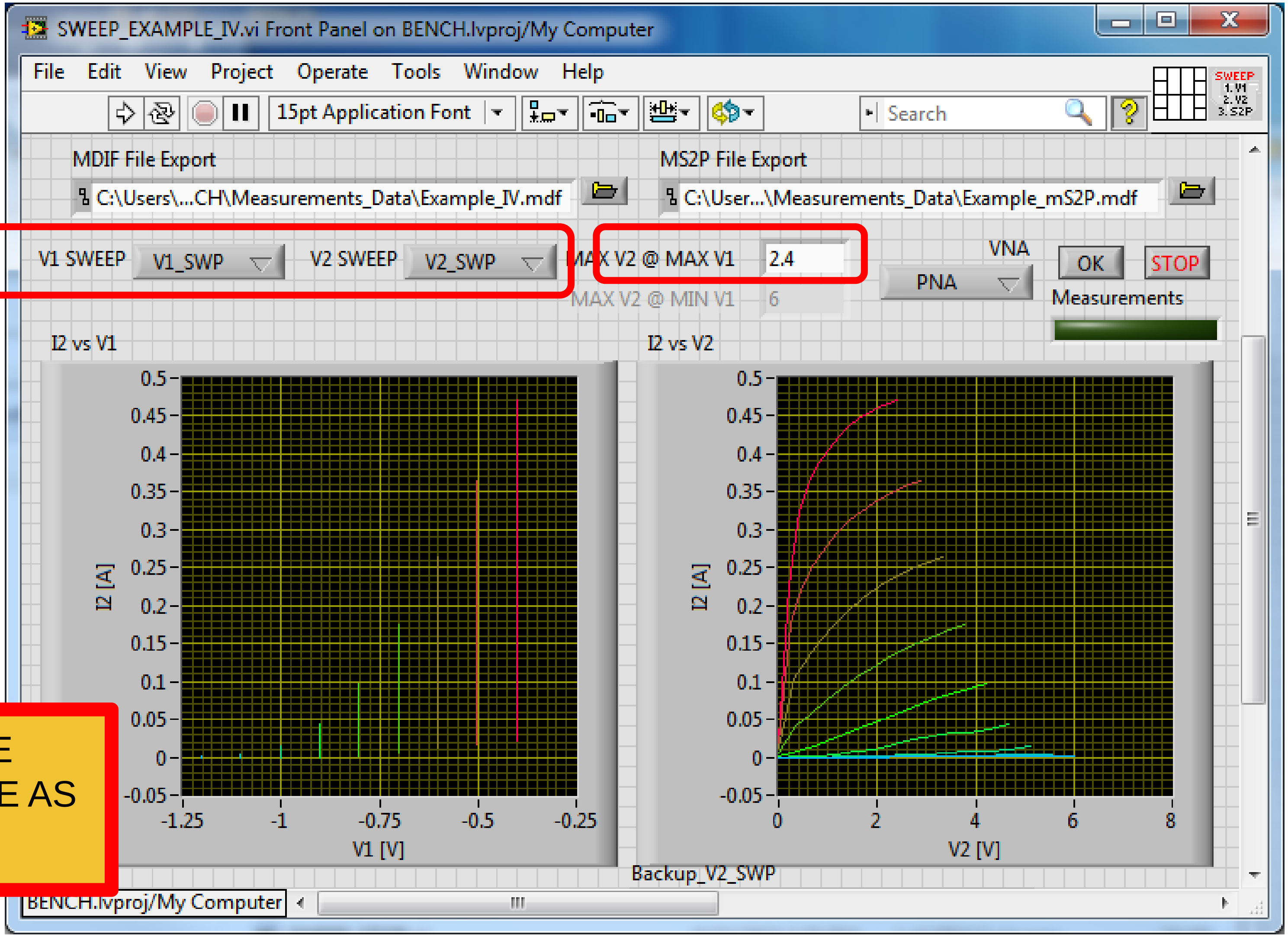


Impedance Selection @ DUT Reference Plane



Program Example: IV-S

User defined 'Sweep plans'



READY TO USE AND AVAILABLE AS EXAMPLE.

Program Example: IV-S

THIS IS THE COMPLETE LABVIEW CODE.
YES! **IT'S LIGHT!**

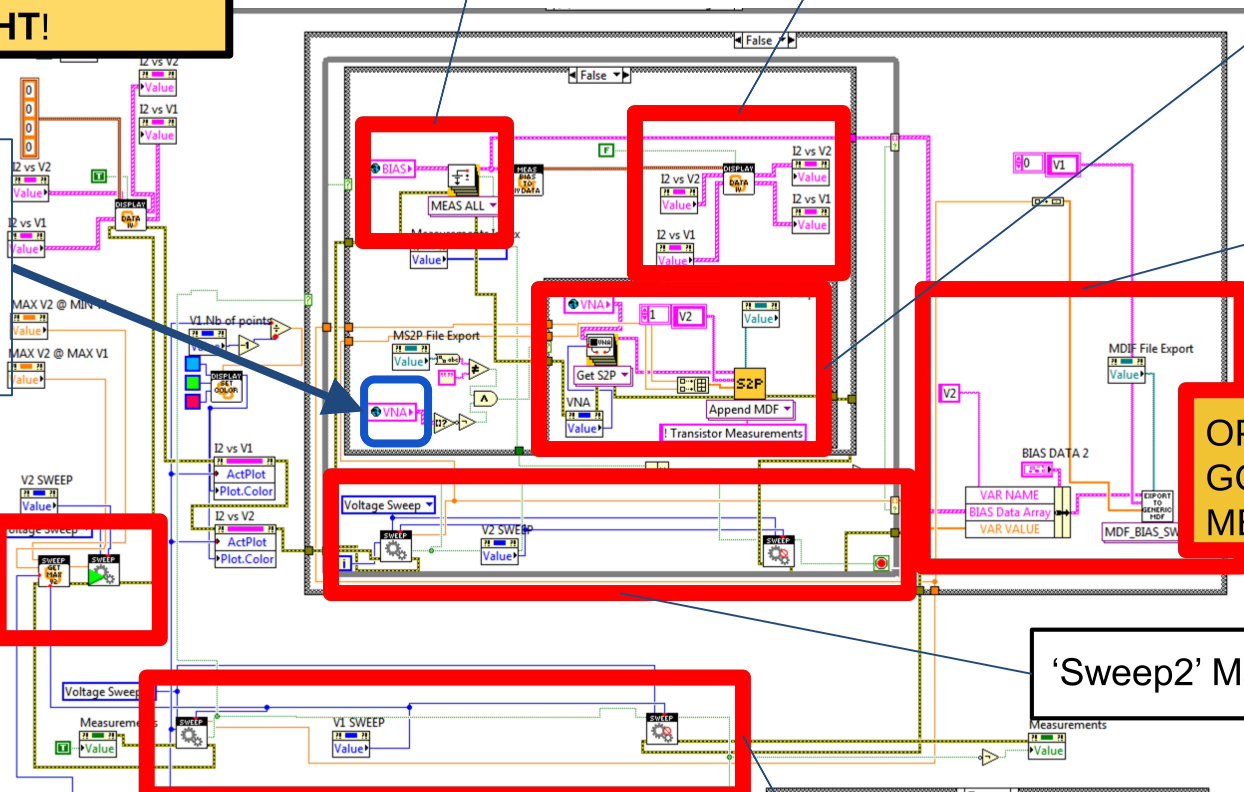
Wireless LabVIEW
The complete Bench is stored in a global variable

All Biases Measurements

I-V Display

S2P Measurements (optional)
mS2P Export
(Append file)

MDIF Export
(Append file)



OPEN SOURCE
GOOD FOR EXOTIC MEASUREMENTS

Update 'Sweep2' plan on the fly

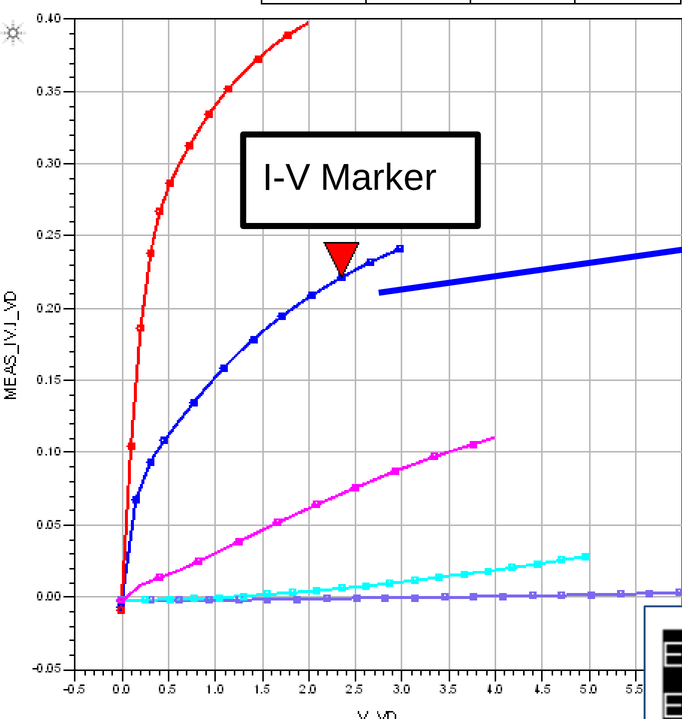
'Sweep2' Management

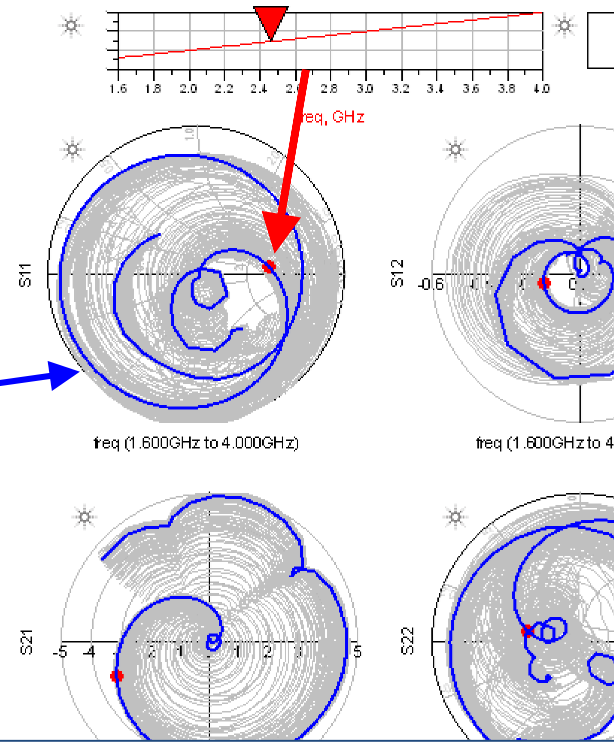
'Sweep1' Management

Program Example: IV-S

index_V1	index_V2
3	15

-0.614	0.001	2.347	0.221





Keysight ADS can convert directly (no simulation needed) any Generic MDF / mS2P files in datasets.

Possibility to superpose simulation results.

Interactive 'data display' template is possible with 3 equations only!

```
Eqn index_V1=m1_V1_index
Eqn index_V2=find_index(MEAS_IV..V_VD[index_V1,::],indep(m1))
Eqn index_freq=find_index(MEAS_S2P..freq[index_V1,index_V2,::],indep(m2))
```

Hardware Example: Source-Pull

RF Source
(NI PXIe-5652)

Local Oscillator
(HP 83620A)

ONE PORT LSNA WITH MIXERS

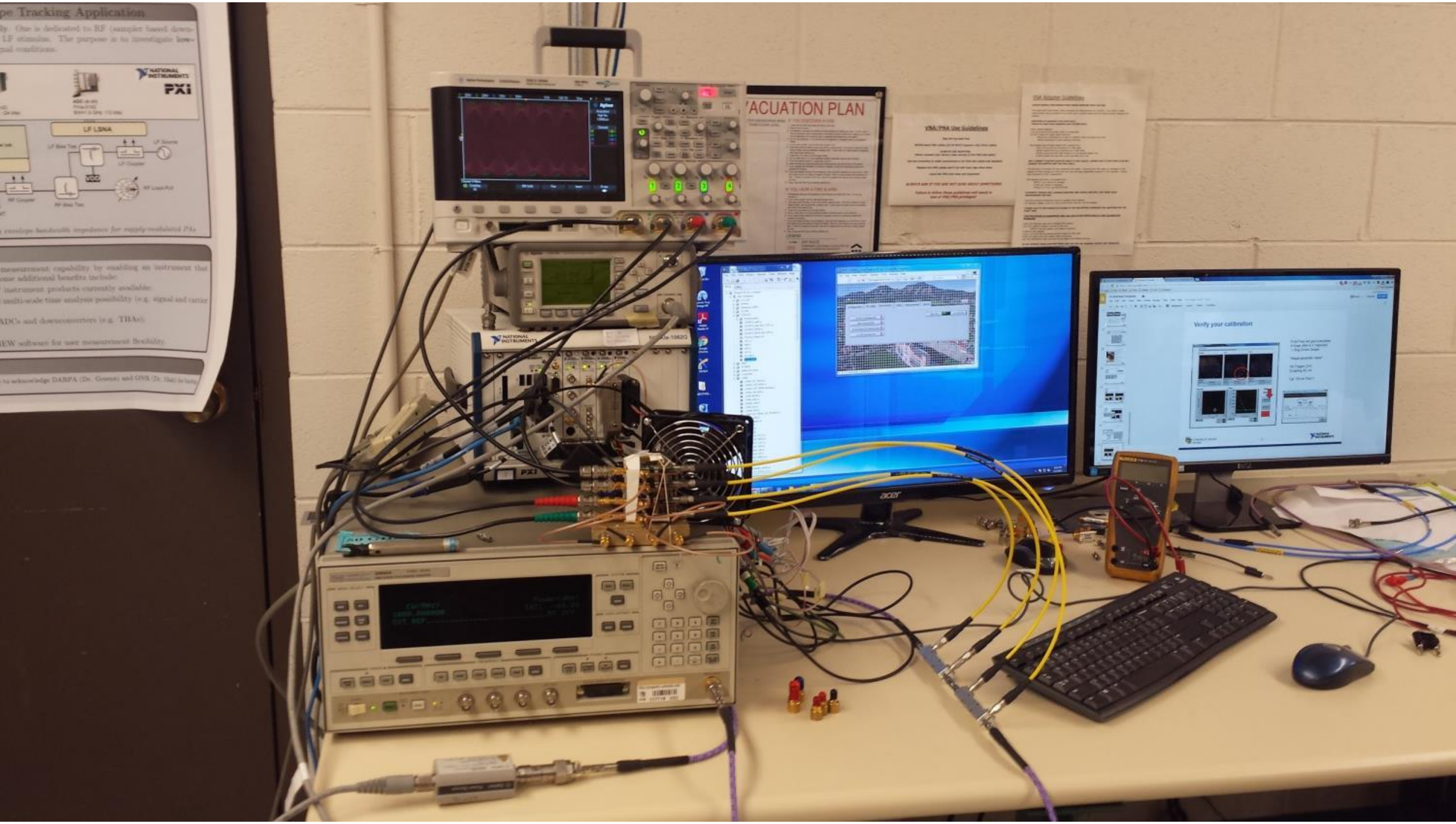
Scope (NI PXI-5922)

Power Splitter (Mini Circuits ZX10-2-42)
Mixers (Marki M10204SA and M10208MA)

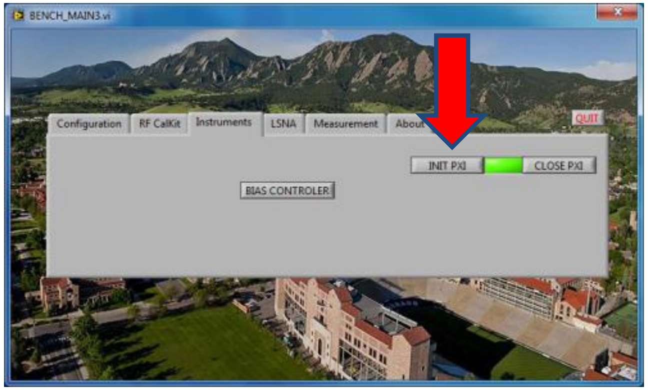
DUT ref. plane

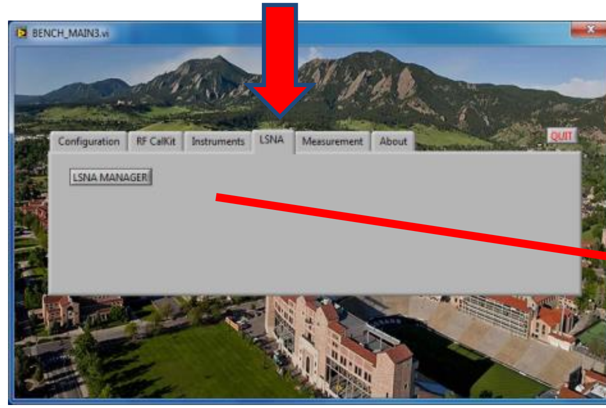
Source-Pull removed for real impedance measurements (indeed, **cheaper than a Source Tuner**)
Load-Pull measured like before (Power meter for receiver)

Hardware Example: LSNA

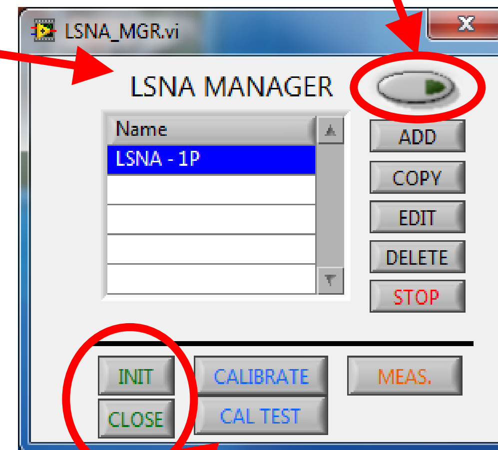


LSNA object in the Toolbox





Bias the RF samplers

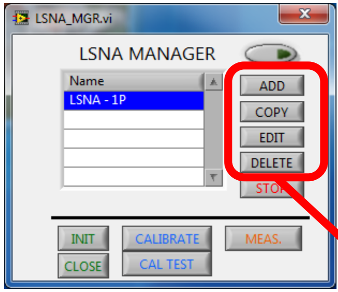


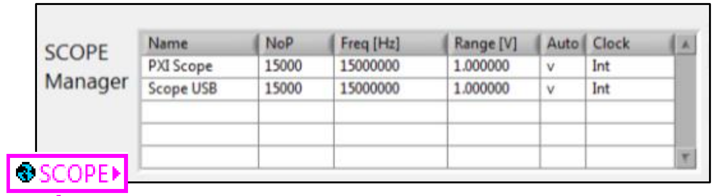
- Once the bench is initialized, we can edit LSNAs ;
- LSNAs are managed as standard instruments: user defines an array of LSNAs ;
- LSNA works like a scope but requires a calibration procedure and test ('CALIBRATE' and 'CAL TEST' buttons) to calculate and validate a 8-terms error matrix ;
- Each LSNA contains a hardware structure (next slide), calibration measurements and a 8-error term matrix ;
- Several LSNAs can have exactly the same hardware configuration (click on 'COPY' to do it). It enables to consider several error term matrix ;
- 'MEAS.' perform a single point PA measurement before to launch user defined loops of acquisitions.

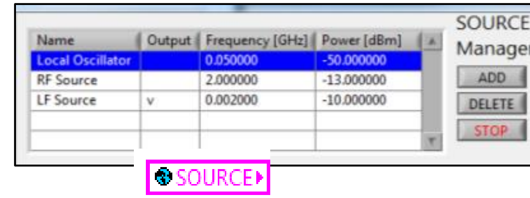
Switch ON/OFF Local Oscillator and perform user defined VI for selected LSNA

LSNA object in the Toolbox

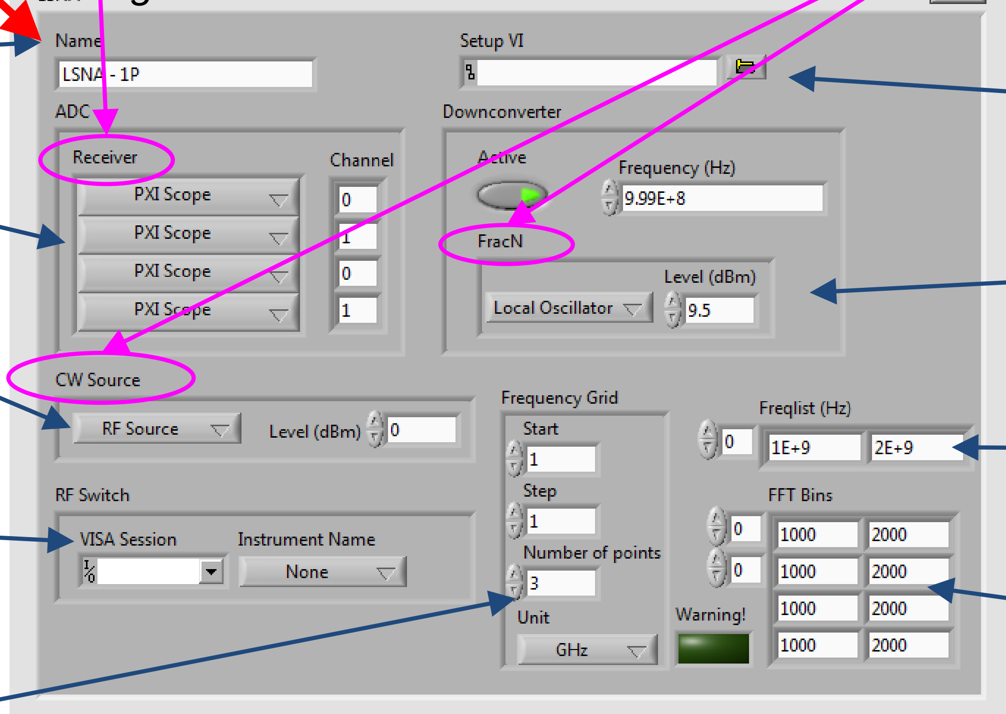
Connecting Minds. Exchanging Ideas.







each 'ring' is auto populated according to global variables



Name of the current LSNA

Independant 4 channels receivers

CW Source for calibration

Optional GPIB controller for RF mode SPTD switches *(VTD SWAP X-402 compatible)*

RF Freqlist and FFTbin generator for LSNA user

Additional User VI for initialisation (e.g. SPDT matrix configuration)

Local Oscillator (optional)

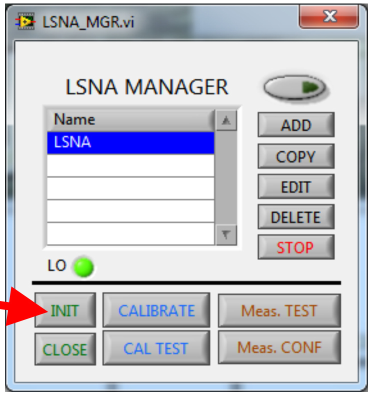
RF Freqlist (Size = N)

FFT Bins (Size = 4xN) *each receiver may have independent sampling frequencies*

LSNA Embedded Calibration

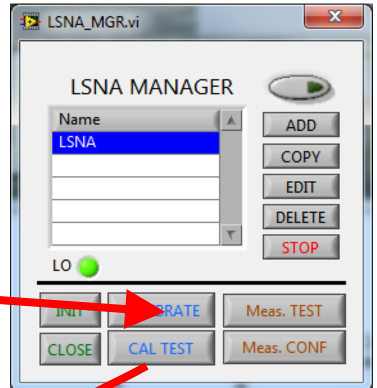
CALIBRATE THE LSNA

1

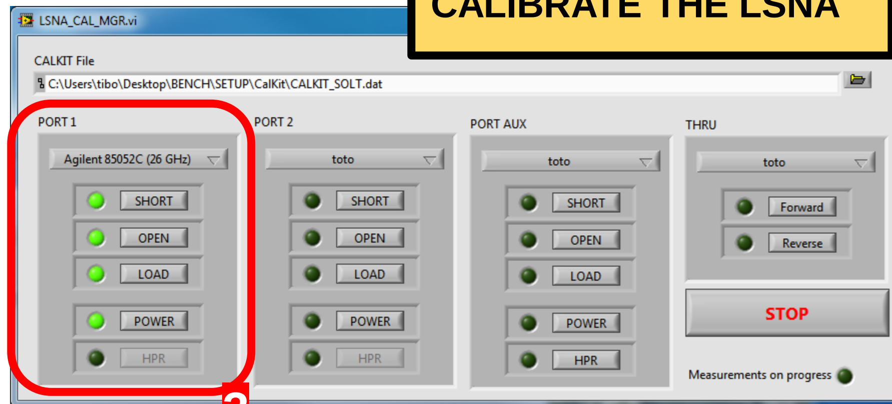


Init the system

2



Calibrate the system

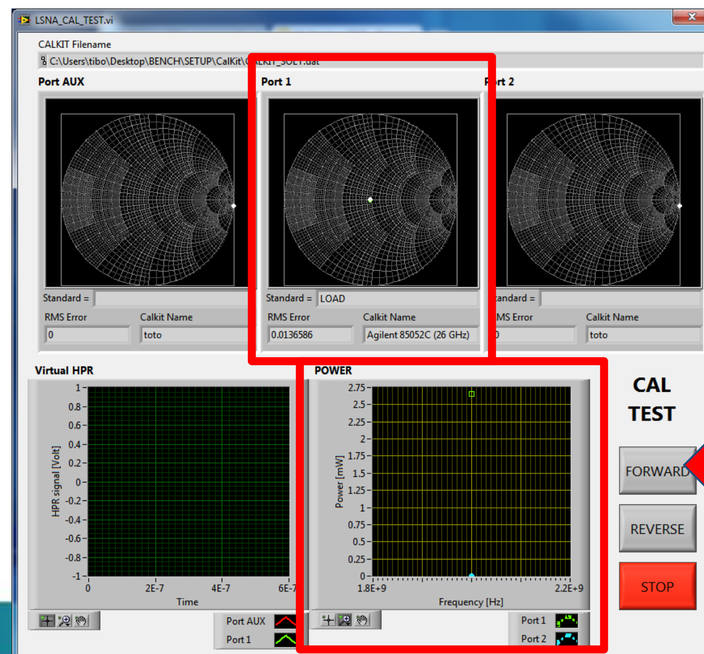


3

Calibration Manager

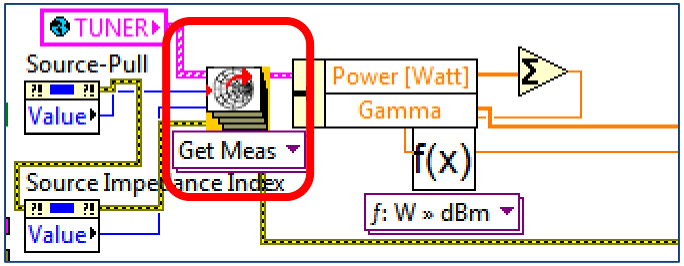
4 Launch "CAL TEST"

The calibrated measured data are automatically compared to the CalKit definitions.

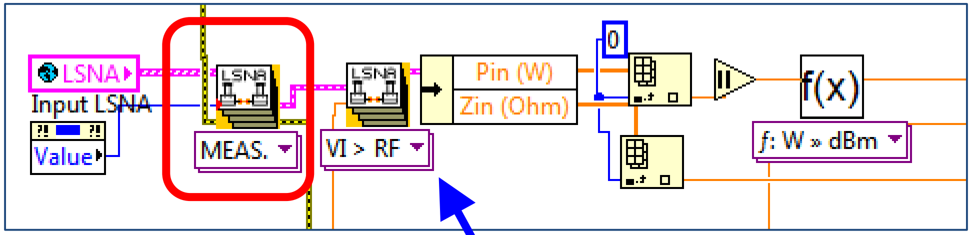


User can check the calibration on port 1 (Gamma - top- and Power -bottom-). Only in Forward mode in this case.

Develop your code!



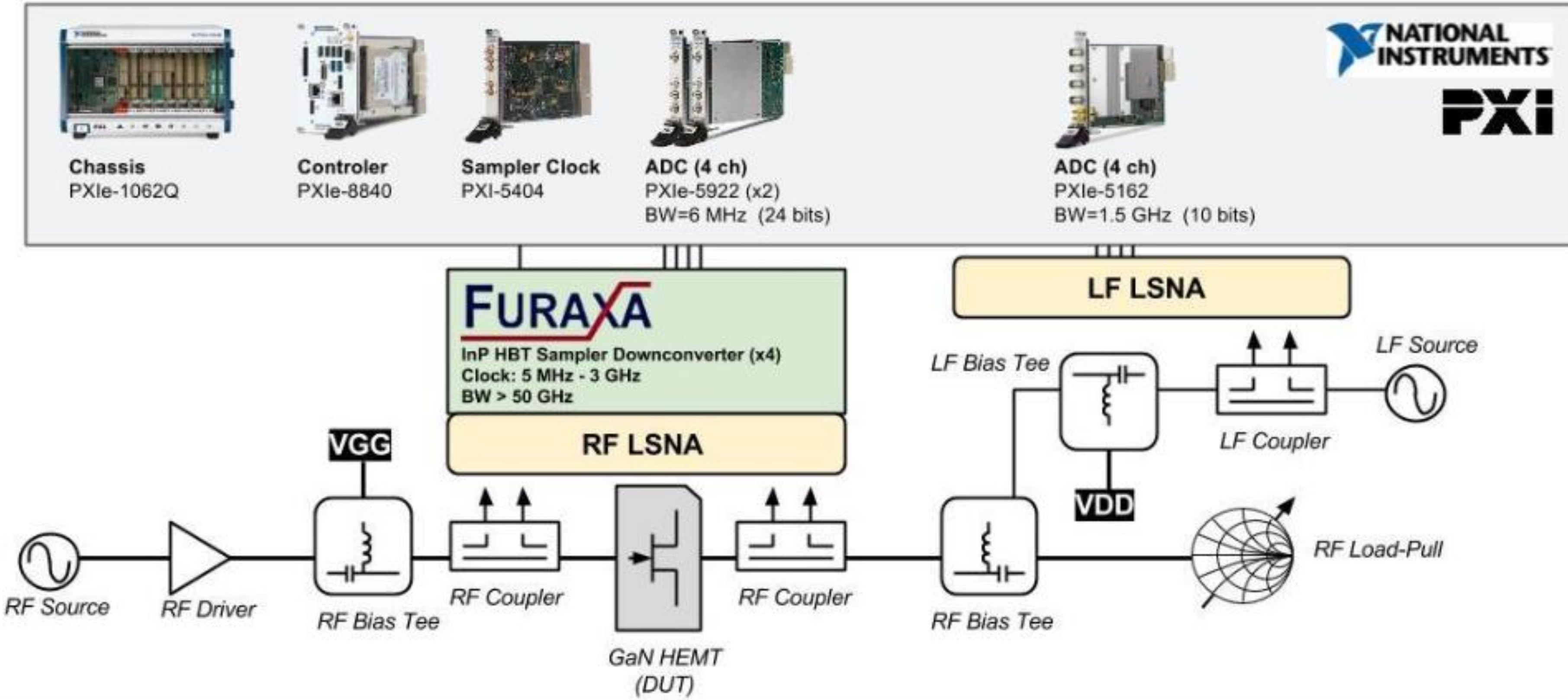
Calibrated measurements with a power-meter based Load-Pull



Calibrated measurements with a LSNA

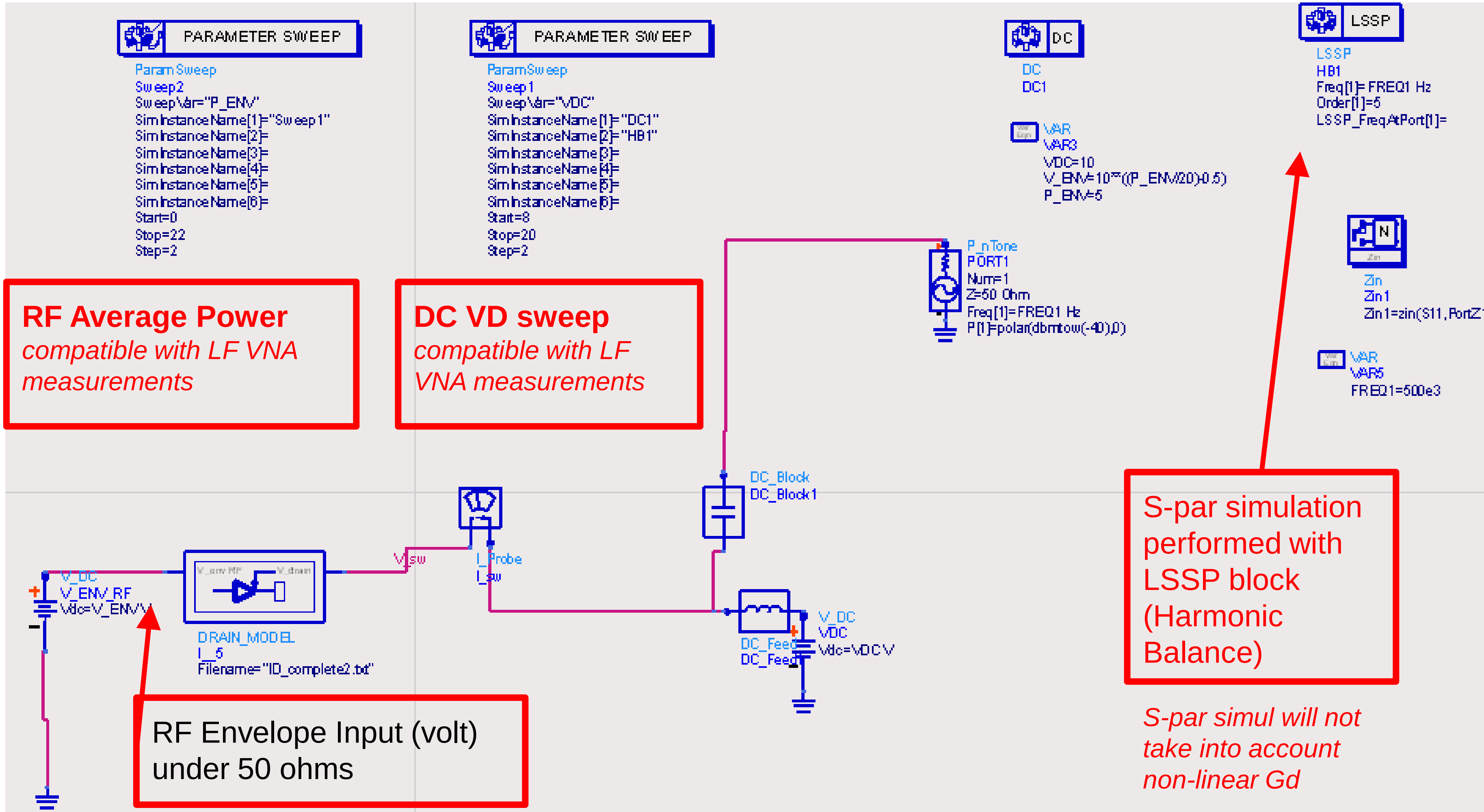
A LSNA releases V and I data. "VI > RF" give access to common RF data

Envelop Tracking Example



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)

Envelop Tracking Example



Envelop Tracking Example

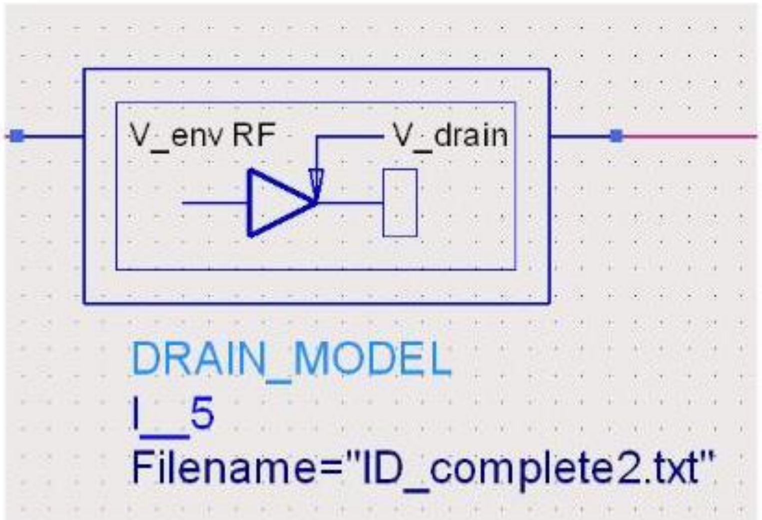
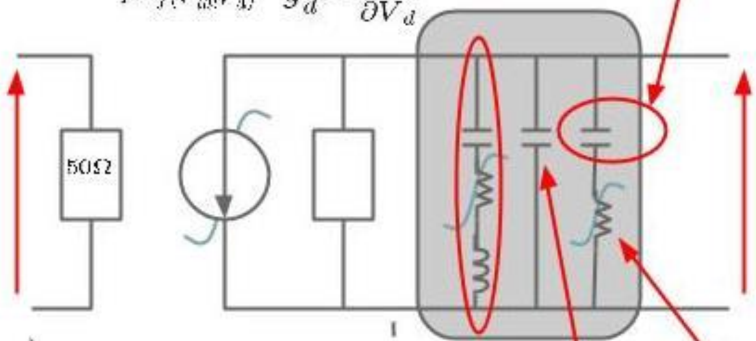


Table based model.
It included measured ID=f(Pav,Vd)
And extracted Gd

Very simple circuit

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

Very big capacitance (transition between DC and LF)



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

$\int$: Non linear elements

*listed in the *.txt file*

gd compensation

Output capacitance

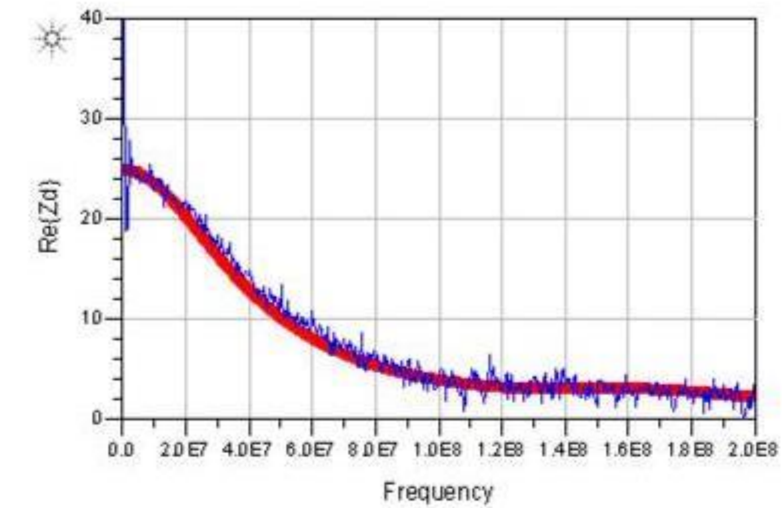
Resonance (can be seen on real{Y22})

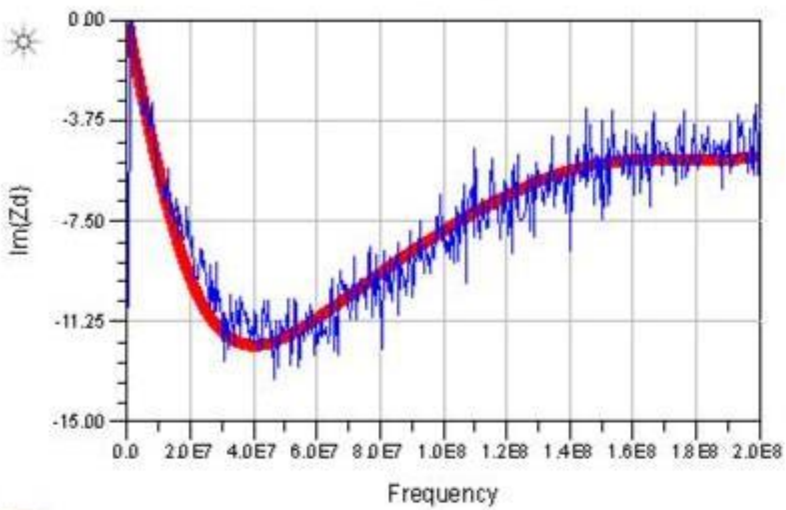
EXTRACTED FROM I(V)

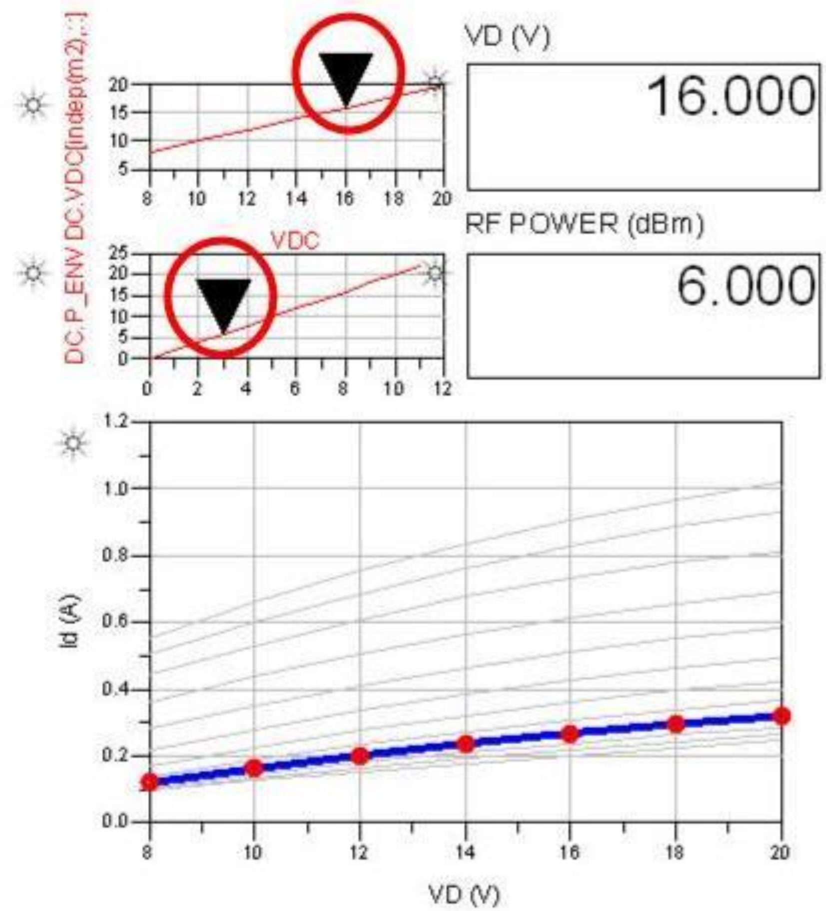
EXTRACTED FROM S-par

Envelop Tracking Example

Connecting Minds. Exchanging Ideas.







More about this LabVIEW Toolbox ?

- AVAILABLE
- FREE
- OPEN SOURCE

WWW.MICROWAVE.FR/LABVIEW

Thank you !

Questions?