X-parameter applications for characterizing and modeling power amplifiers for envelope tracking applications

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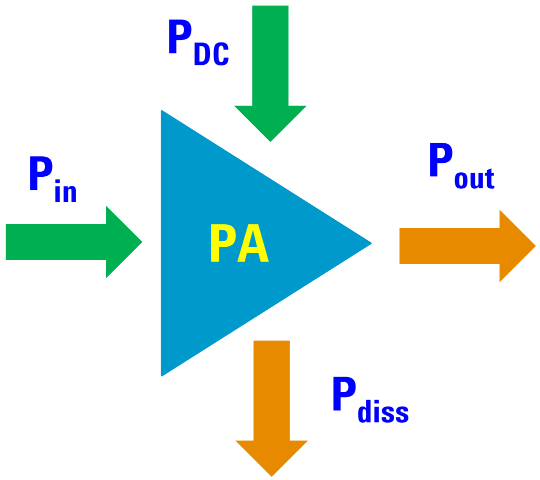
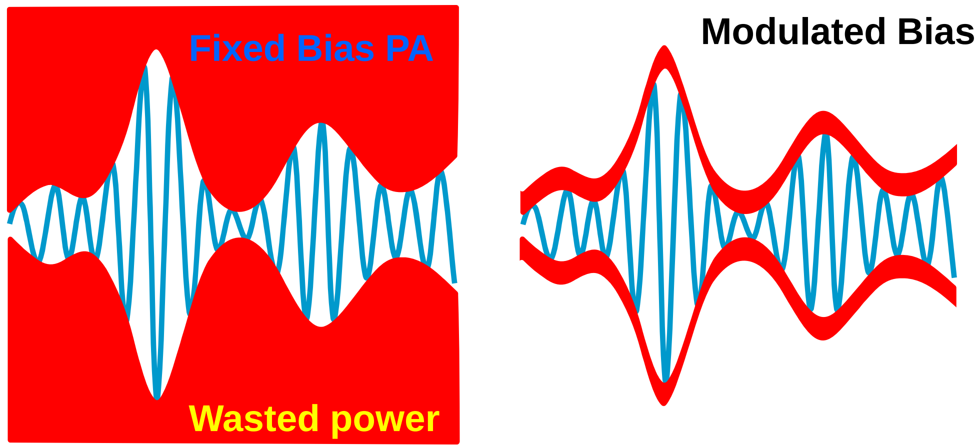
more details in session TU3F-1 Tues 13:50-14:10 ref [21]

Outline

- Introduction to ET
- Introduction to X-parameters
- X-parameter models for dynamic signals: quasi-static approximation
- Simulation-based X-parameter models for ET applications
- Measurement-based GaN PA X-parameter model
- Future work
- Conclusions

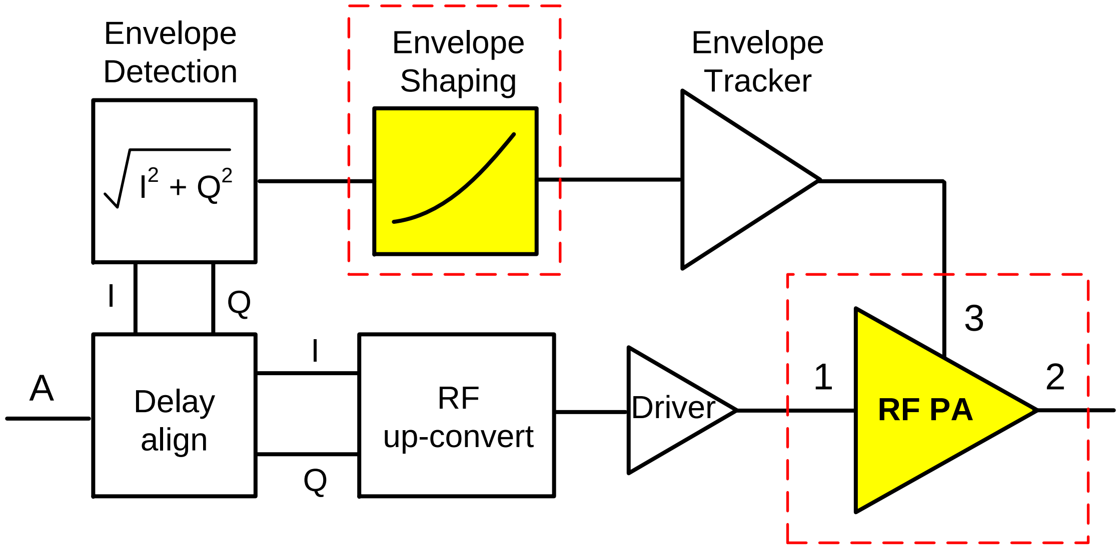
Envelope tracking





$$\mathrm{PAE} = \frac{P_{out} - P_{in}}{P_{DC}} = (G-1)\frac{P_{in}}{P_{DC}} = (G-1)\frac{V_{in} I_{in}}{V_{DC} I_{DC}}$$

Envelope tracking

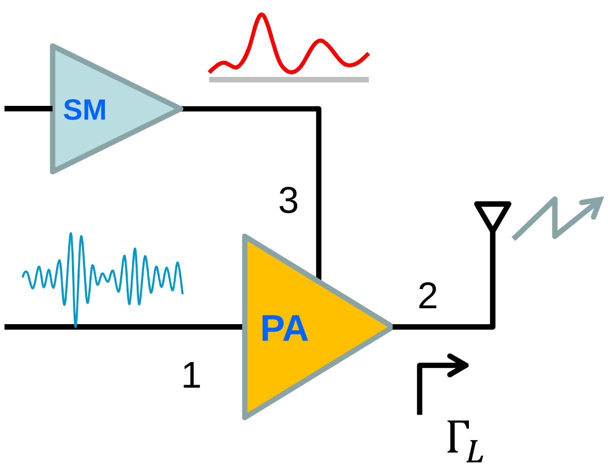


Shaping table depends on the properties of the RF PA, *viewed as a three-terminal component*.

X-parameters provides a procedural approach to characterize & model the RF PA for shaping table design, including bias and load effects.

Envelope tracking

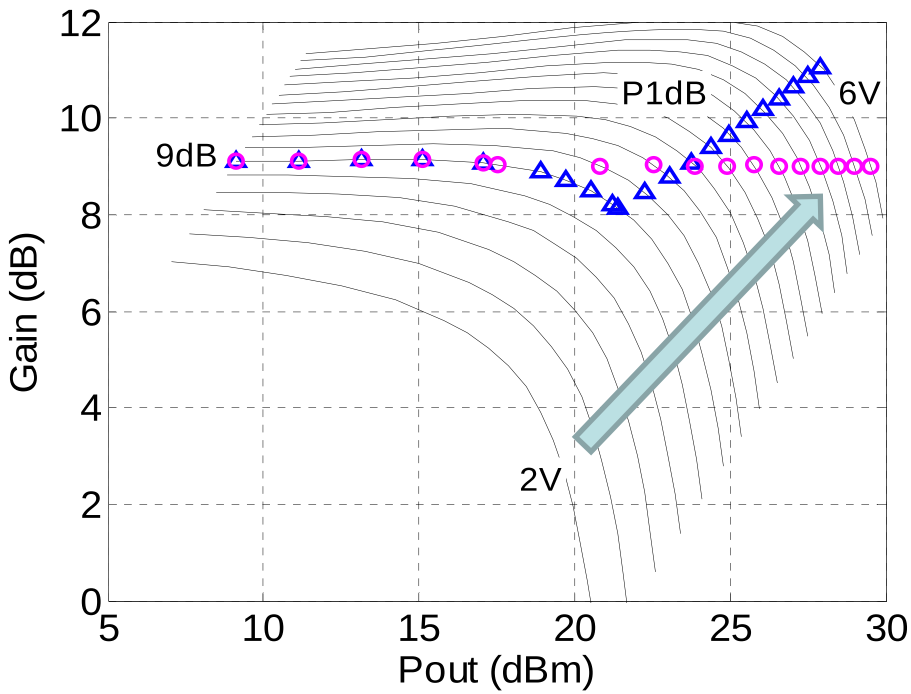
- Design considerations with ET
  - High PAR input signals
  - Varying supply voltage
  - Varying load



- XP model, which is a frequency domain black box behavioral model, is studied
- Design and characterization assumption:
  - SM is ideal
  - Interconnection impedance is minimum
  - PA is quasi-static to the supply voltage variation
  - Load is approximately matched (but more on this later)

Envelope tracking

Practical approach is designing the shaping using static characterization at multiple supply voltages under quasi-static assumption of the PA



- 9dB constant gain
- Maximizing efficiency using saturation point (P1dB)

Drain voltage is swept from 2 V to 6 V

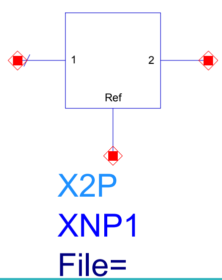
X-parameters

X-parameters are the scientifically correct extension of S-parameters to large-signal conditions.

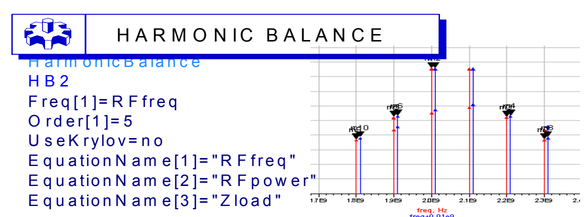
- Measurement and simulation based, identifiable from a simple set of automated NVNA measurements or directly from ADS circuit-level designs
- Vector nonlinearities (Magnitude *and* phase of distortion)
- Intrinsic DUT properties (calibrates out source impurities & multi-freq. mismatch)
- Cascadable (correct behavior in mismatched environment)
- Extremely accurate for high-frequency, distributed nonlinear devices
- Includes bias dependence

Measure X-parameters
-or-
Generate X-parameters from circuit-level designs

X-parameter Component : Simulate using X-parameters



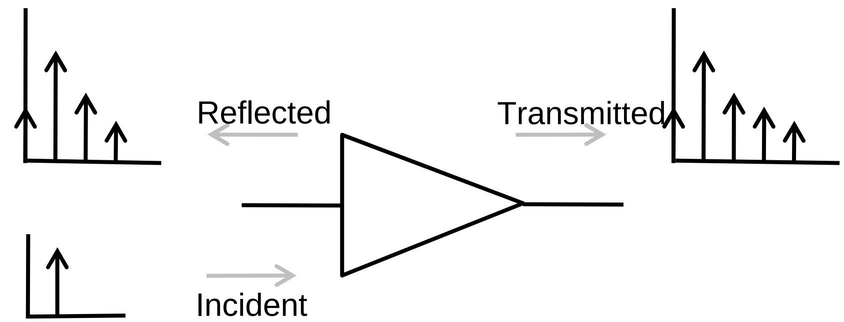
ADS, SystemVue & Genesys: Design using X-parameters

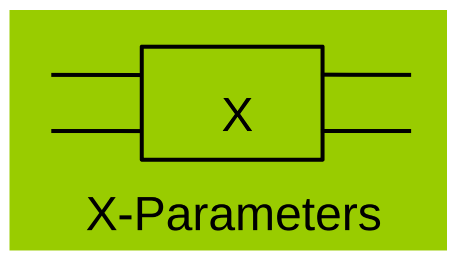


X-parameter use model

Measure

Agilent Nonlinear Vector Network Analyzer



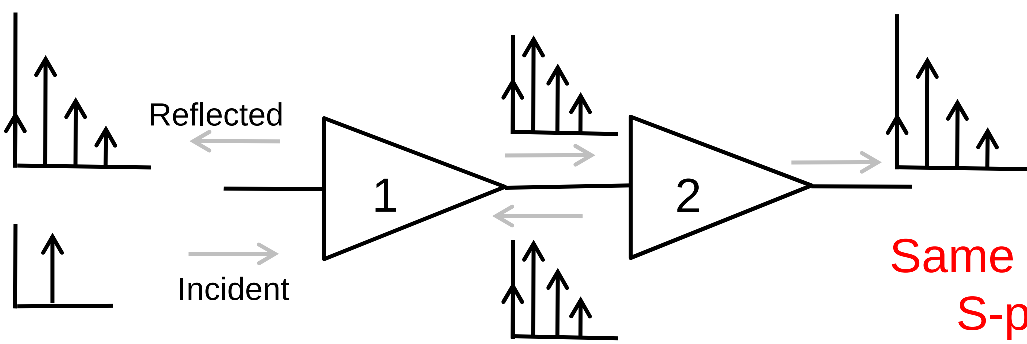


Model

$$B = X(A)$$

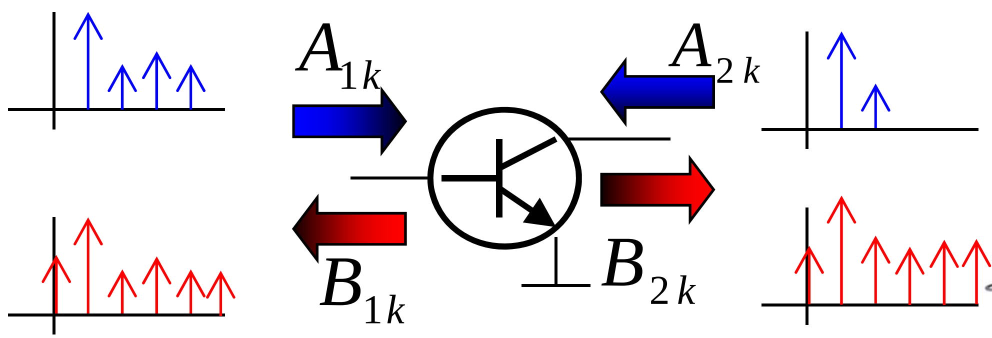
Design

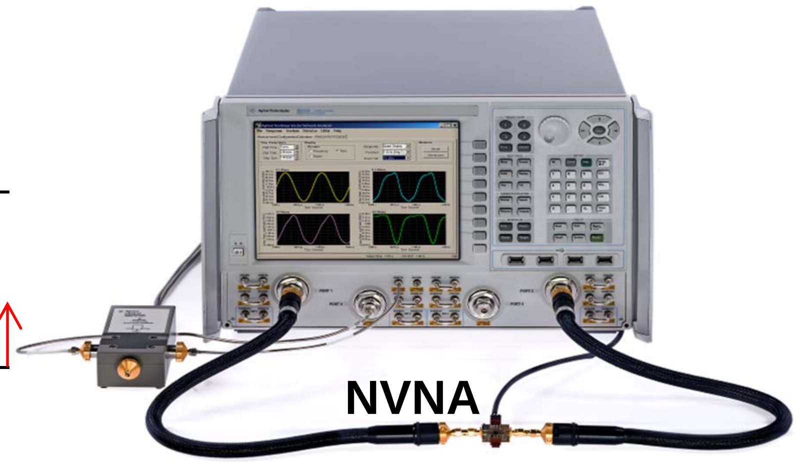
EDA Software



Same use model as
S-parameters
but much more powerful

Complex Spectra and Nonlinear Maps





$A_{p,k}$ $B_{p,k}$

Harmonic Index

Port Index

$$\boxed{B_{p,k} = F_{p,k}\left(A_{1,1}, A_{1,2}, A_{1,3}, \ldots, A_{2,1}, A_{2,2}, A_{2,3}, \ldots\right)}$$

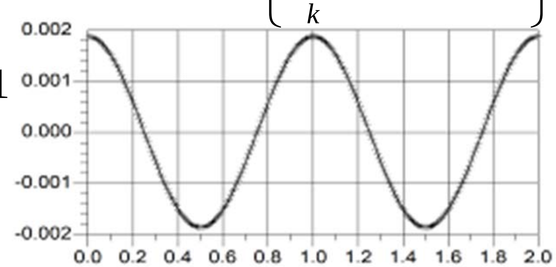
$$v_p(t) = \mathrm{Re}\left\{\sum_k V_{p,k} e^{jk\omega_0 t}\right\}$$

$$V_{p,k} = \sqrt{2Z_0} \cdot (A_{p,k} + B_{p,k})$$

$$I_{p,k} = \sqrt{\frac{2}{Z_0}} \cdot \left(A_{p,k} - B_{p,k}\right)$$

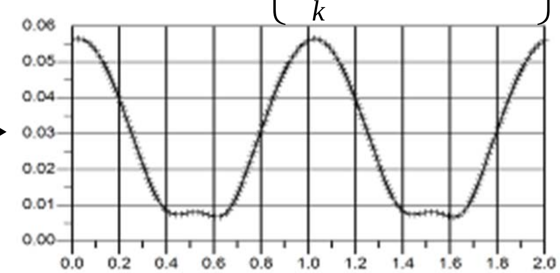
$$i_p(t) = \mathrm{Re}\left\{\sum_k I_{p,k} e^{jk\omega_0 t}\right\}$$

V_1



time

I_2



time

Time-invariance and spectral linearization

X-parameters allow us to simplify the general B(A) relations:
Trade efficiency, practicality, for generality & accuracy
Powerful, correct, and practical; Native Freq. Domain Model

DC dependence automatically included. NVNA controls DC supplies and synchronizes measurements with applied RF signal

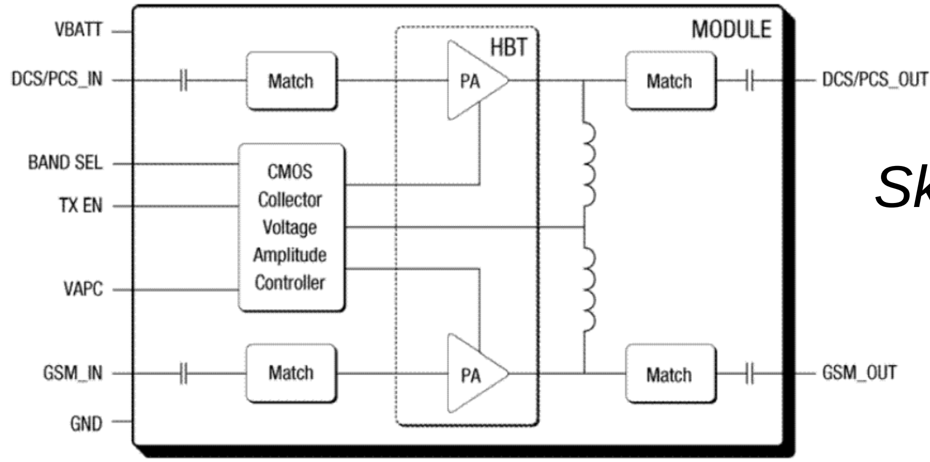
$$B_i = S_{i1}(DC)A_1 + S_{i2}(DC)A_2$$

The simplest X-parameters are just linear S-parameters

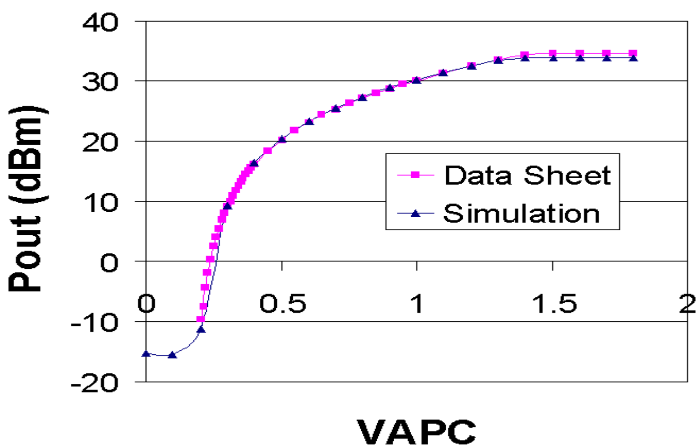
$$B_{e,f} = X_{ef}^{(F)}(DC,|A_{11}|)P^f + \sum_{g,h} X_{ef,gh}^{(S)}(DC,|A_{11}|)P^{f-h} \cdot A_{gh} + \sum_{g,h} X_{ef,gh}^{(T)}(DC,|A_{11}|) \; P^{f+h} \cdot A_{gh}^*$$

matched response *load & harmonic mismatch* *new* mismatch terms

X-parameters of GSM PA



Skyworks amp

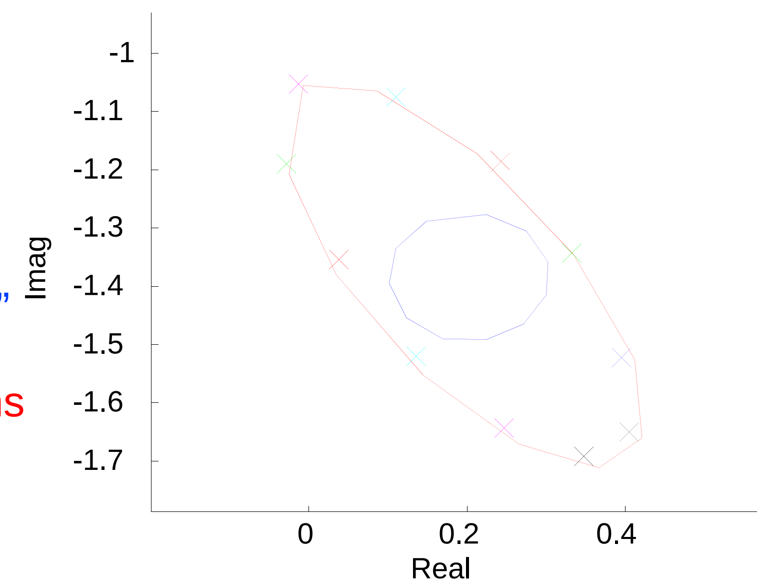


measured

"Hot S_{22}"

X-params

Mismatch versus phase at GSM_OUT

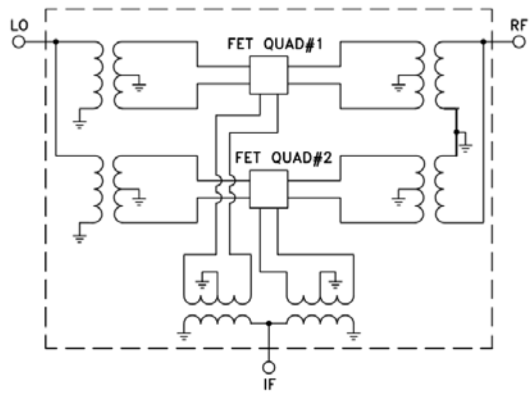


Horn *et al*., *EuMC 2009*

"X-parameters provide a nonlinear electronic interactive datasheet"

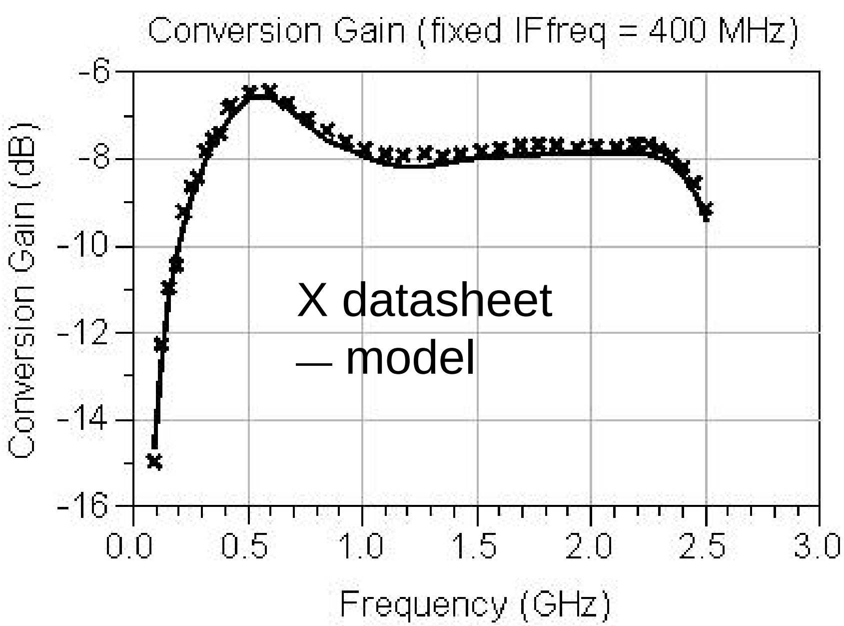
X-parameters of mixers: 3 rf ports

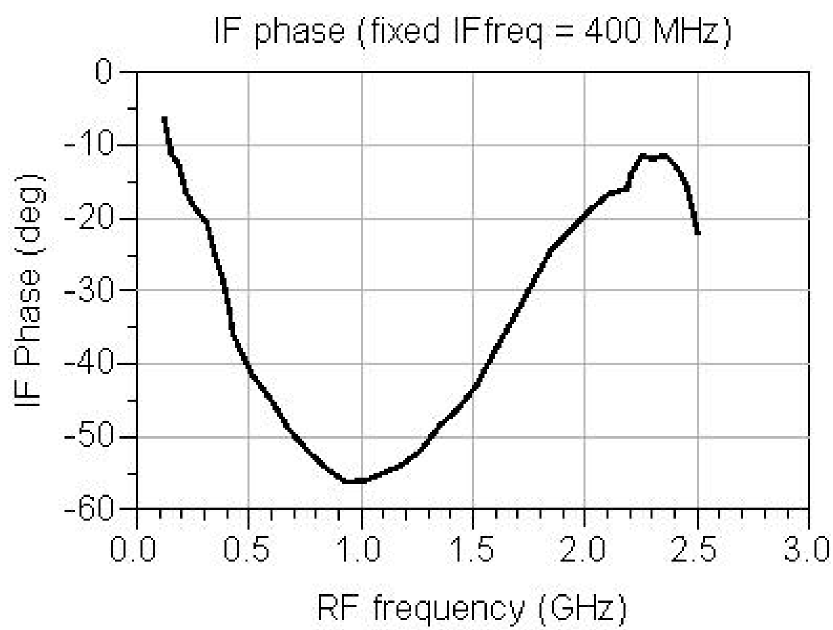
electrical schematic



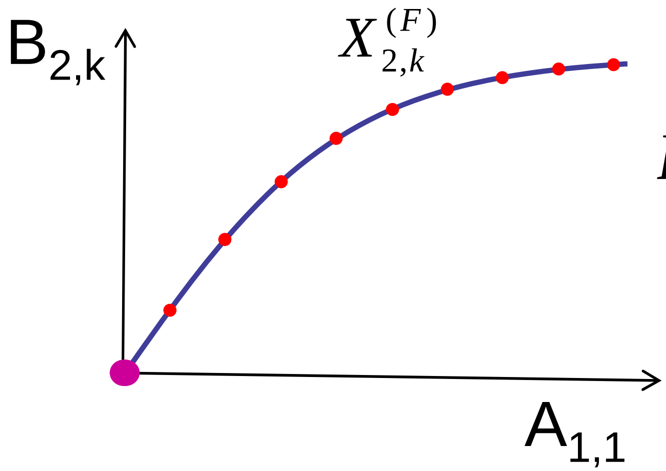
Mini-Circuits
LAVI-22VH+ (TB-433)
Double-balanced Mixer
3-ports

New measurement: IF Phase!





Simulation of dynamic signals



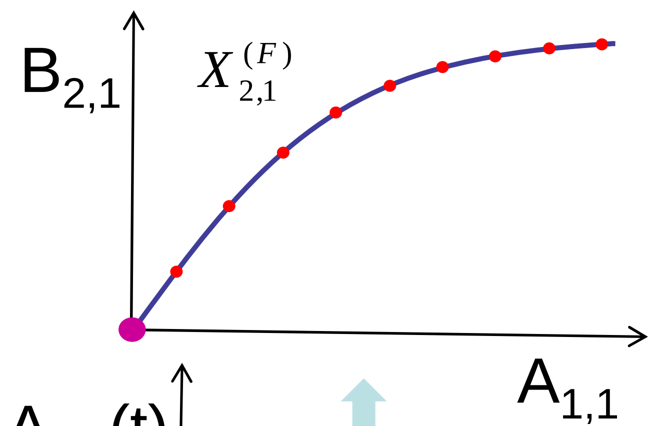
$$B_{2,k} = X_{2,k}^{(F)}\left(DC, \left|A_{1,1}\right|\right) e^{j\phi\left(A_{1,1}\right)}$$

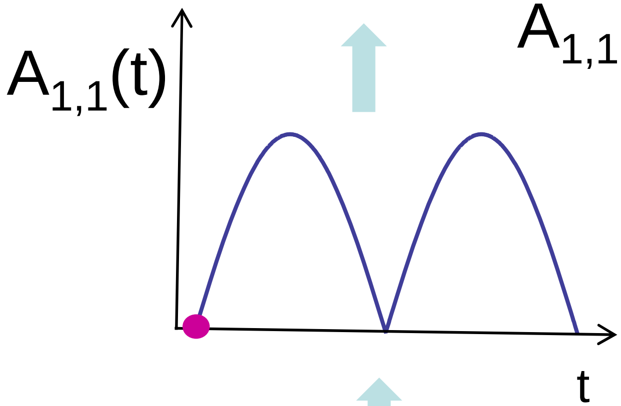
Now assume the signal is modulated in time: $A_{2,1} \rightarrow A_{2,1}(t)$

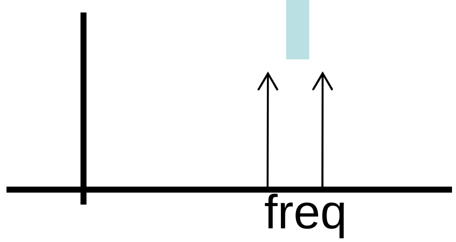
Quasi-static approximation: evaluate static X-parameter function at each time instant

$$B_{2,k}(t) = X_{2,k}^{(F)}\left(DC, \left|A_{1,1}(t)\right|\right) e^{j\phi\left(A_{1,1}(t)\right)}$$

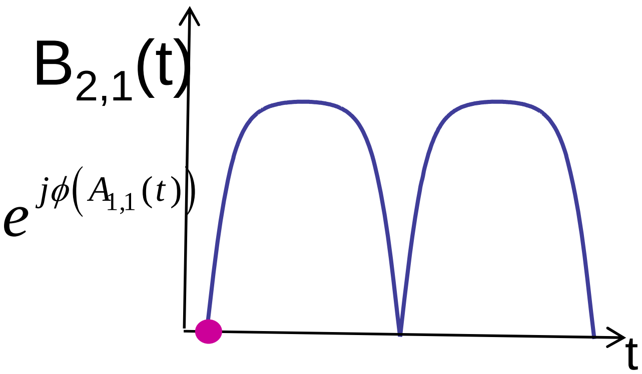
Simulating Dynamic signals (2)

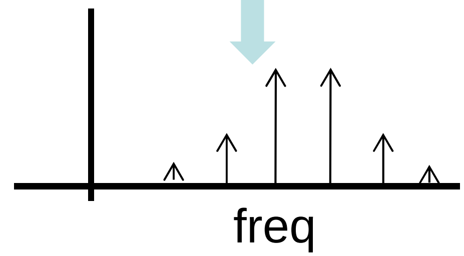






$$B_{2,1}(t) =$$
$$X^{(F)}_{2,1}\left(DC, \left|A_{1,1}(t)\right| \right) e^{j\phi\left(A_{1,1}(t)\right)}$$



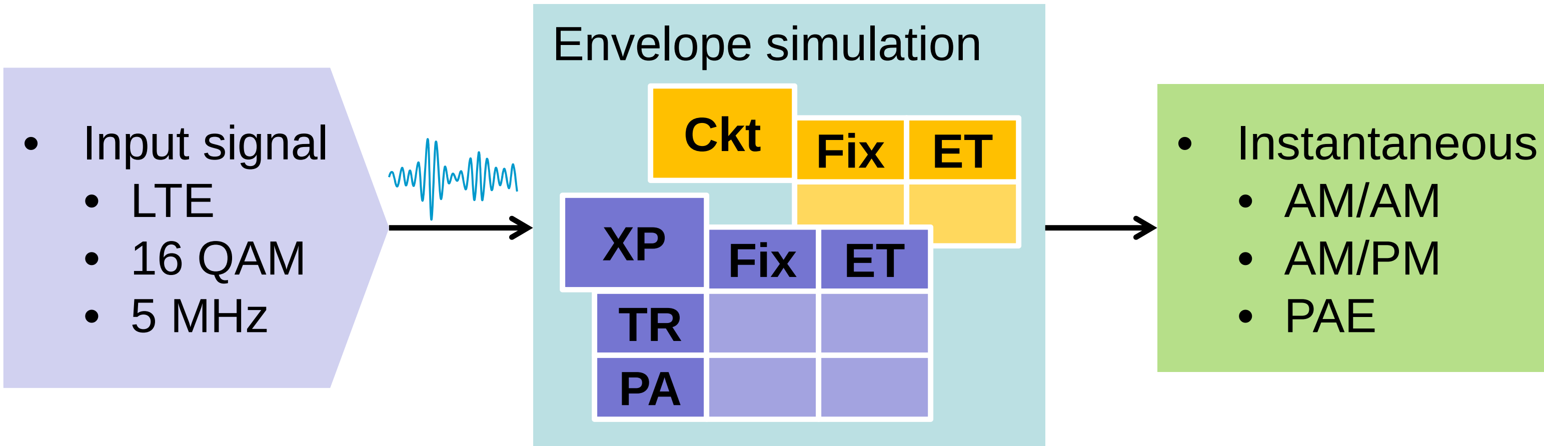


Envelope Domain:
same mechanism generates *spectral regrowth* from digitally modulated signals (e.g. estimates of ACPR, EVM)

<u>LIMITATIONS (Quasi-Static approximation):</u>
Symmetric intermods, independent of modulation rate
No BW dependence; No Memory
Valid in the slow modulation rate limit (narrow band)

$$B_{2,k}(t) = X^{(F)}_{2,k}\left(DC(t), \left|A_{1,1}(t)\right| \right) e^{j\phi\left(A_{1,1}(t)\right)}$$

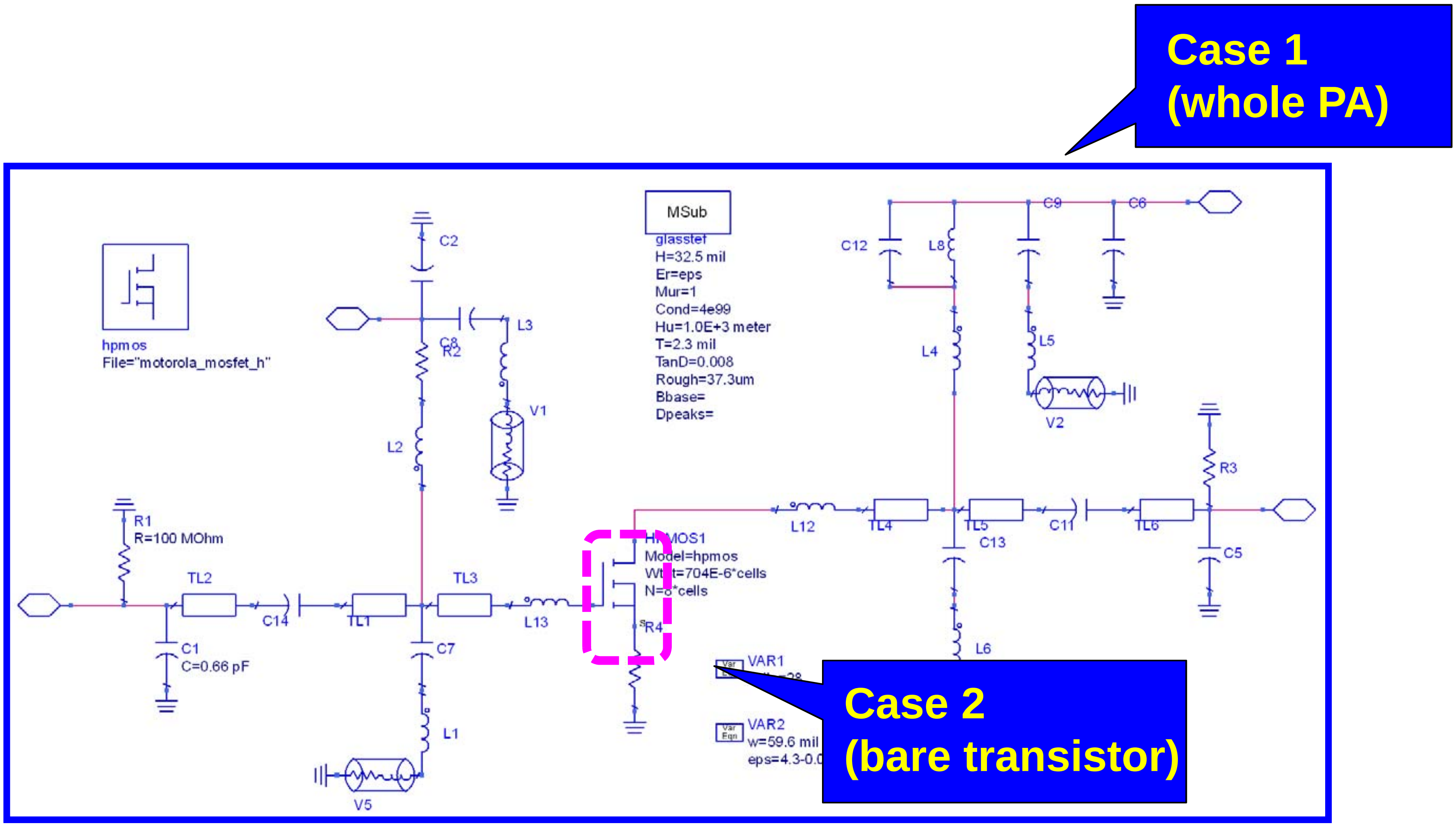
Simulation-based approach



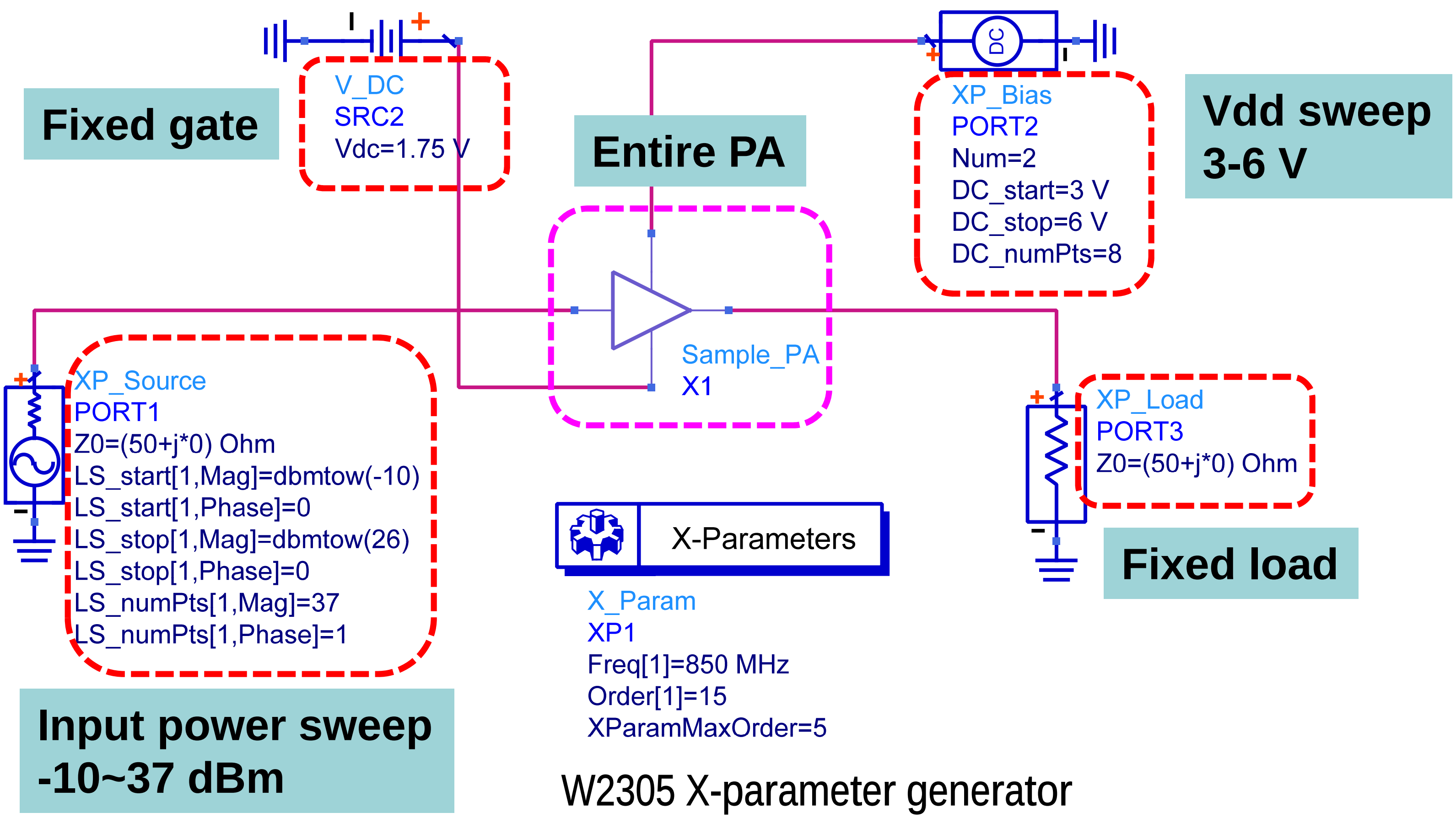
six cases where there is a dynamic signal

- XP models are extracted in two cases to show the sources of dynamic response contribution
  - entire circuit
  - bare transistor
- Fixed bias performance is compared to ET operation for the reference circuit model and the two X-parameter models

Simulation-based extraction

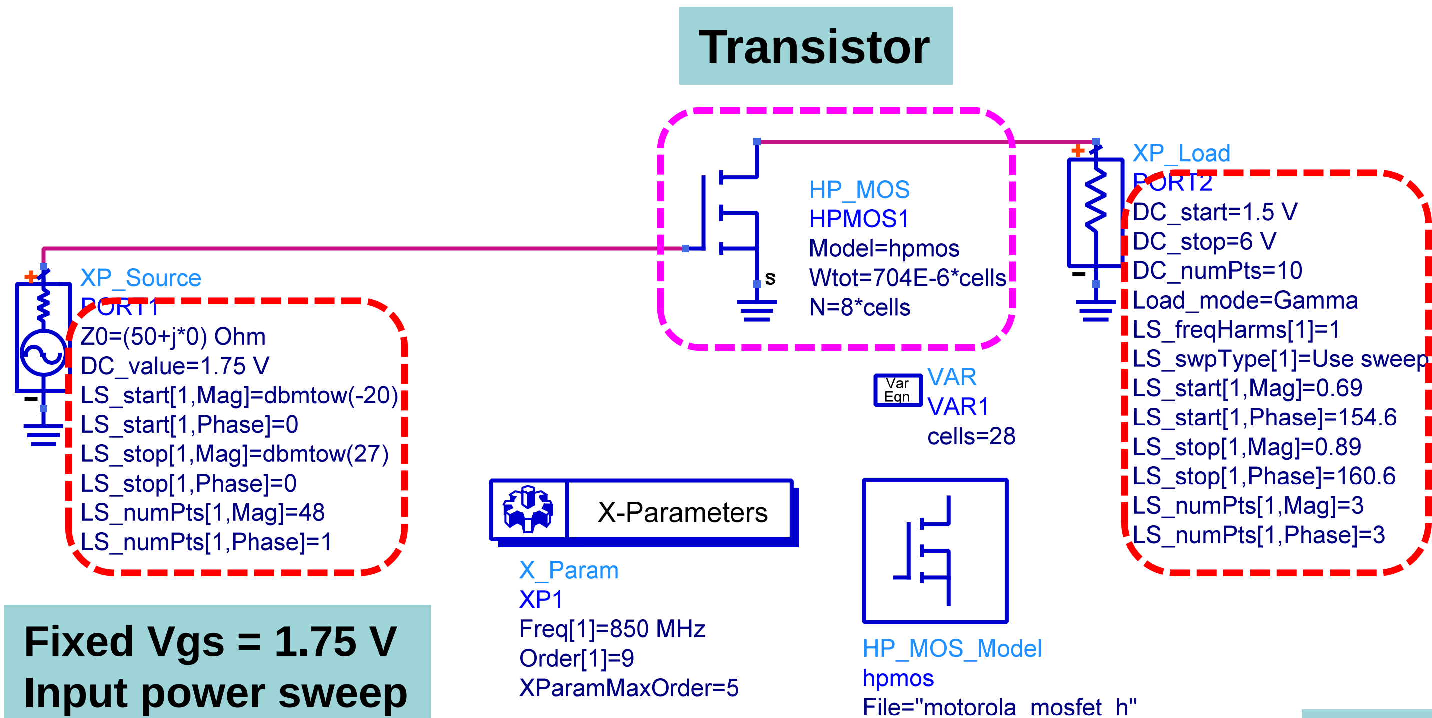


Generating the X-parameters (1)



W2305 X-parameter generator

Generating the X-parameters (2)

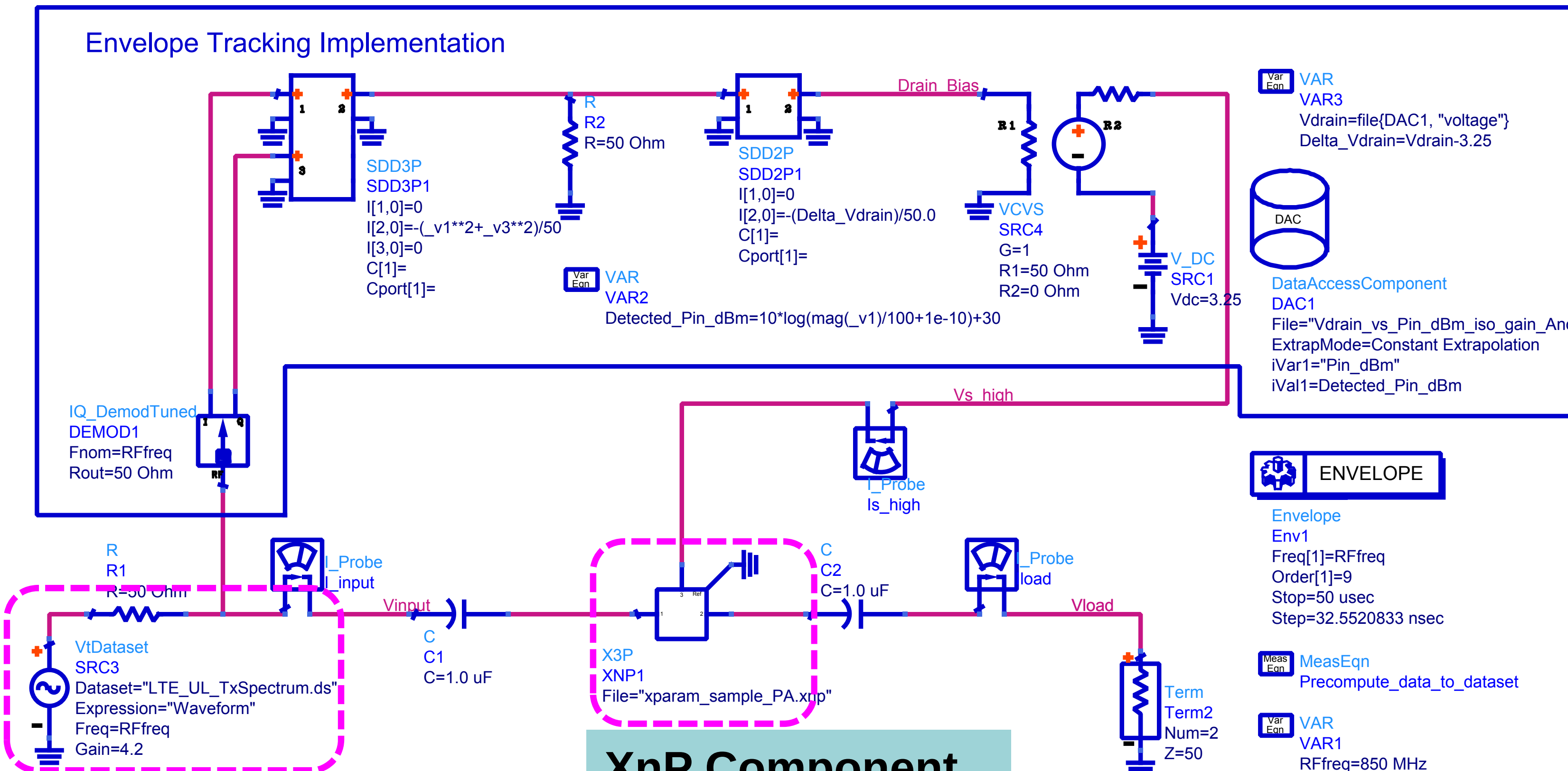


Vdd sweep
1.5-6 V
Load sweep
Mag:0.69 – 0.89
Phase:154.6°-160.6°

Fixed Vgs = 1.75 V
Input power sweep
-20~27 dBm

Suggested: Sweep load over a large region in the Smith Chart.
Sometimes active LP needed to go beyond it

Ideal envelope tracking



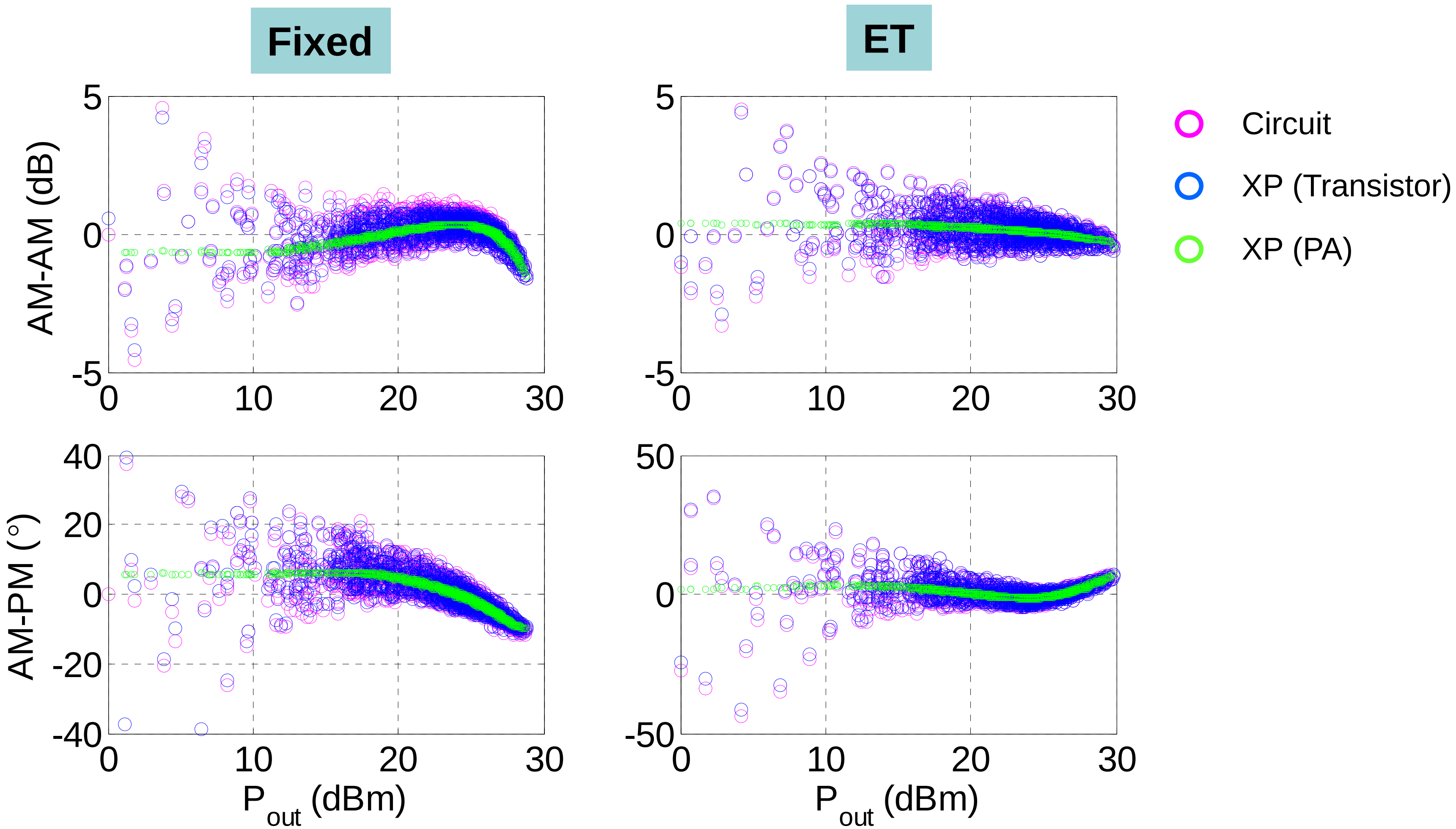
Shaping Table from X-par model

XnP Component for the sample PA

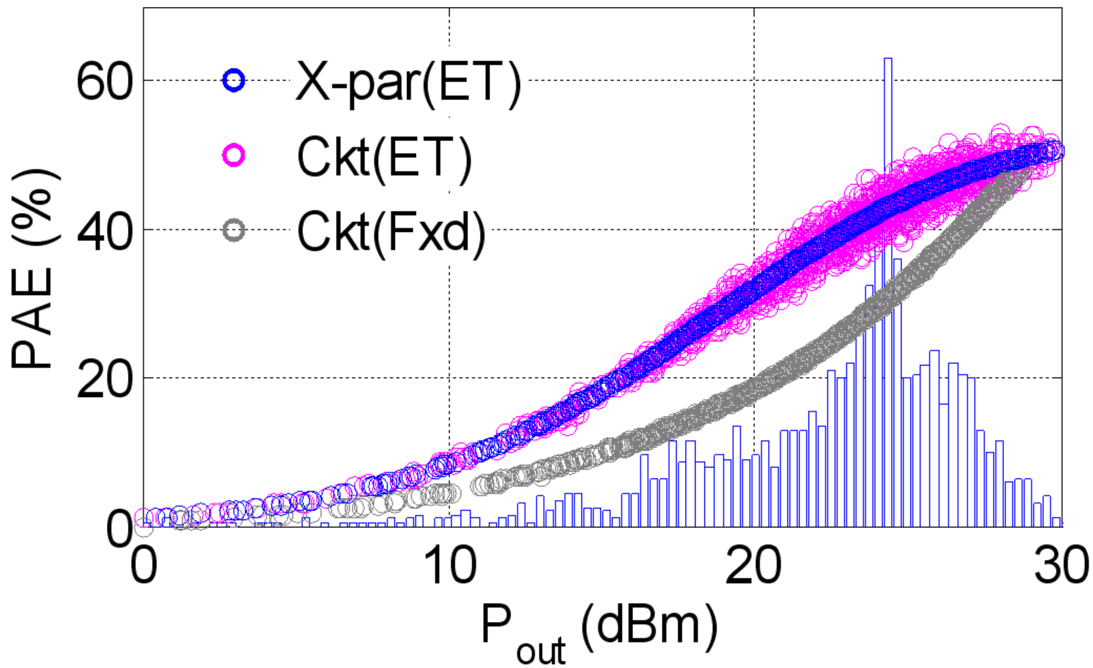
LTE UL 16 QAM

ADS ET examples can be downloaded from [1]:
http://edocs.soco.agilent.com/display/eesofkcads/Applying+envelope+tracking+to+Improve+Efficiency

Simulation-based validation



Simulation-based validation

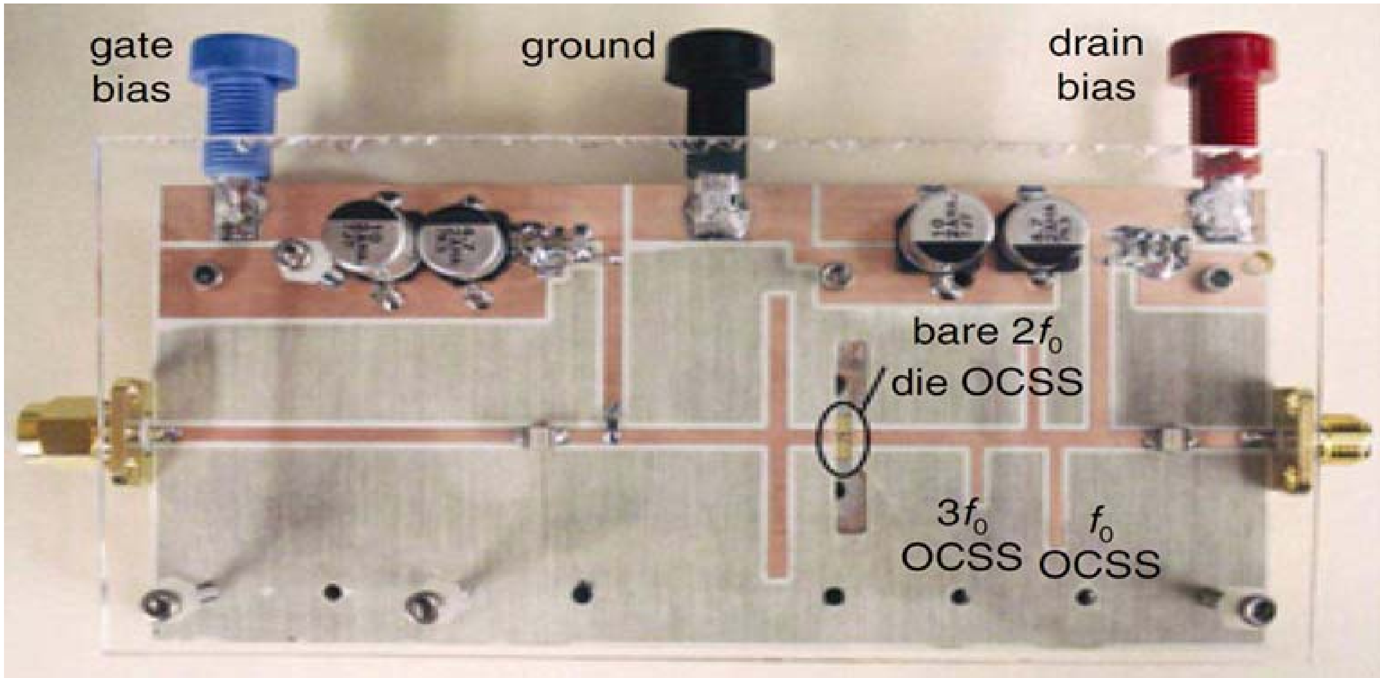


PAE_{avg} (%)	
XP(ET)	43.3
Ckt(ET)	42.4
Ckt(Fix)	31.7

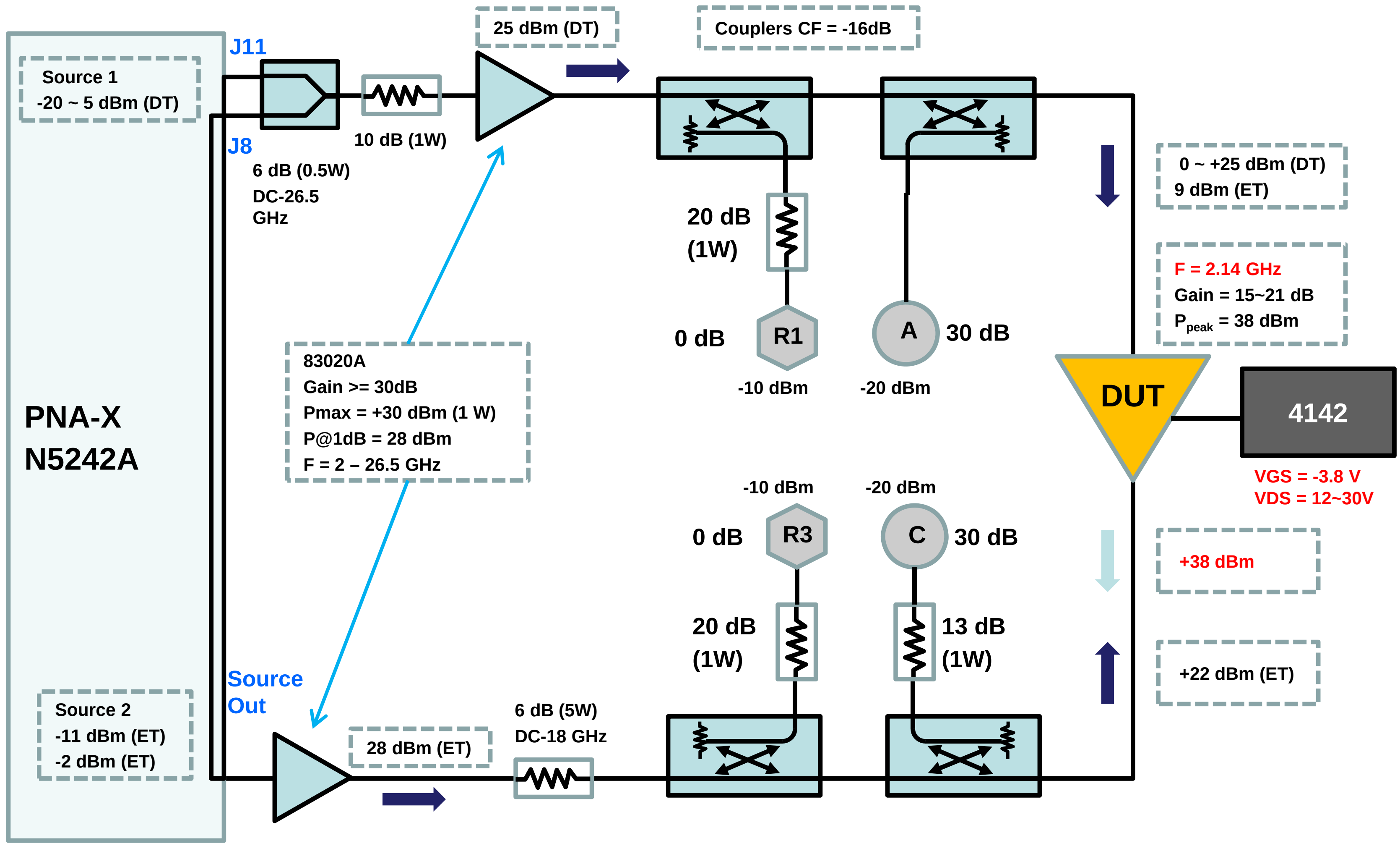
- Instantaneous PAE was calculated using LTE signals and drawn over the histogram of the signals.
- Both XP and circuit model predict PAE improvement over fixed bias as expected.
- It is interesting to notice that, under ET, the instantaneous PAE predicted by the circuit model shows wider spreading than fixed bias.

Measurement-based X-parameters

- GaN HEMT 8 W Class-F^{-1} (Triquint TGF2023-02)
- Drain voltage sweep : 12 ~ 30 V
- Load-pull performed with *VTD SWAP-X402* (now Agilent)

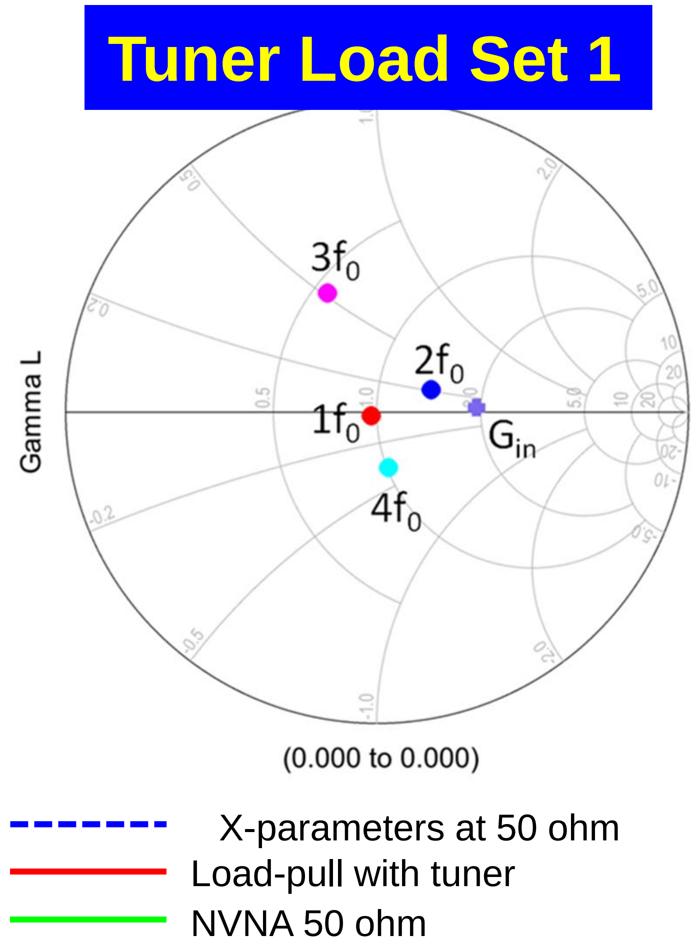


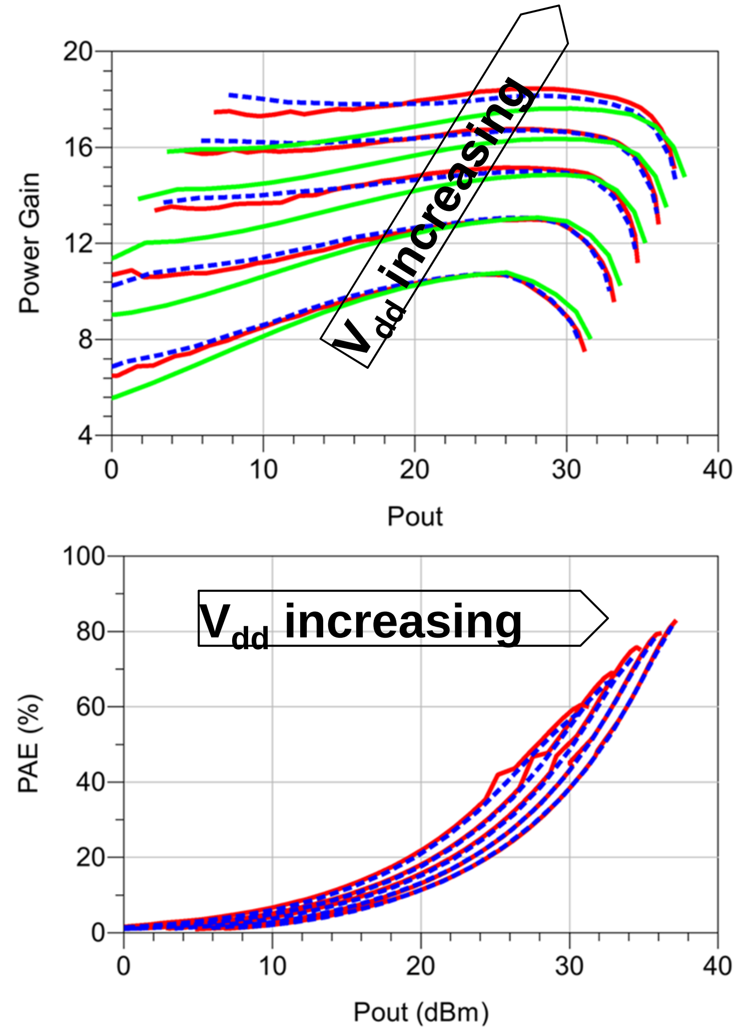
X-par extraction for 8 W GaN PA



Validation of measurement-based X-parameter model

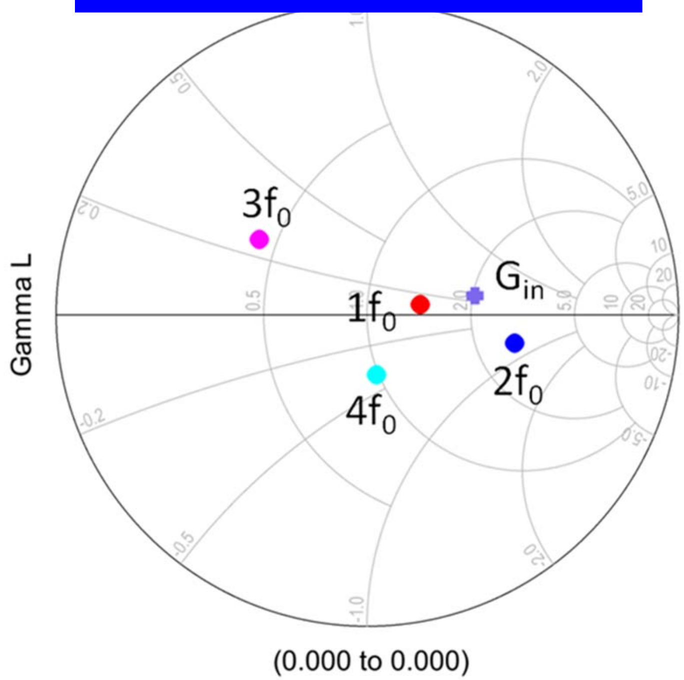
Load-sensitivity of X-par model

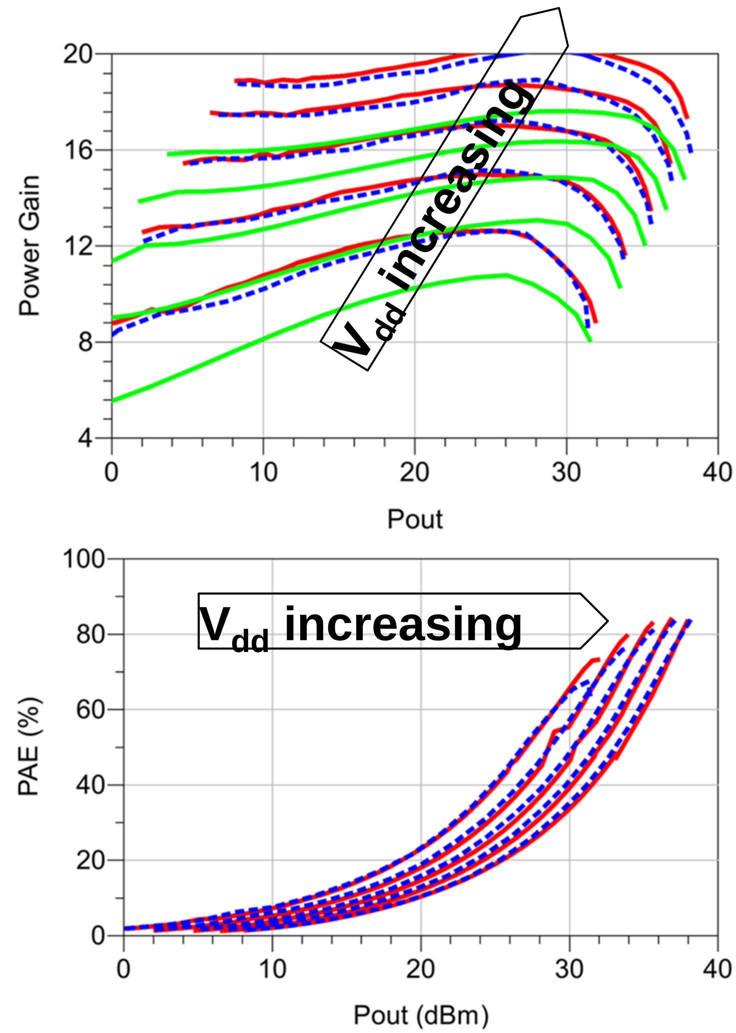




Validation of measurement-based X-parameter model

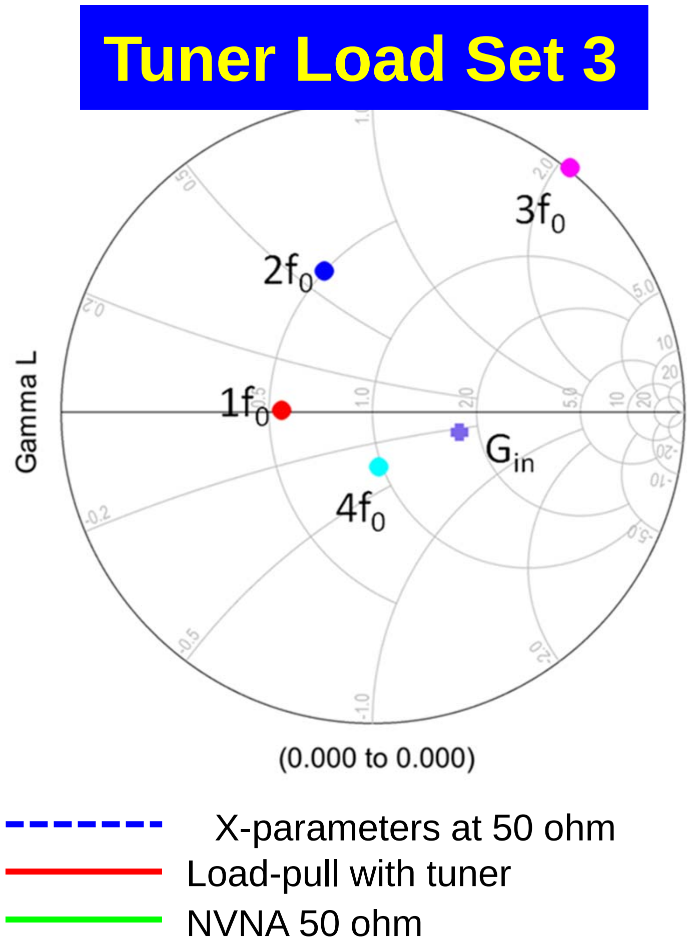
Tuner Load Set 2

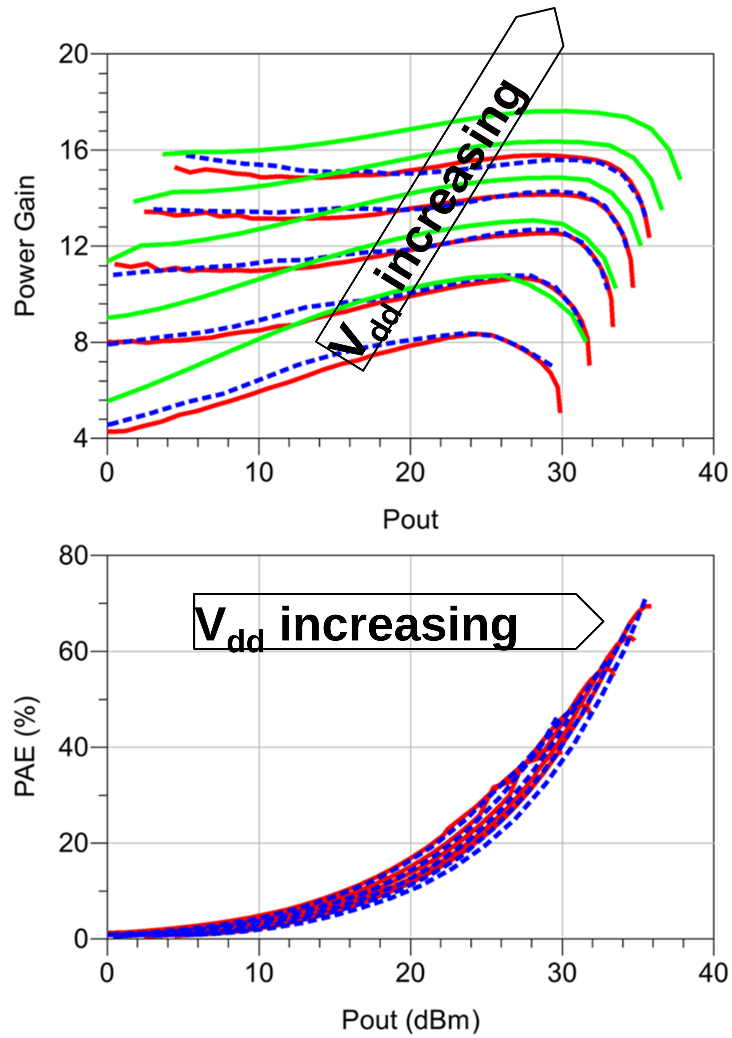




- X-parameters at 50 ohm
- Load-pull with tuner
- NVNA 50 ohm

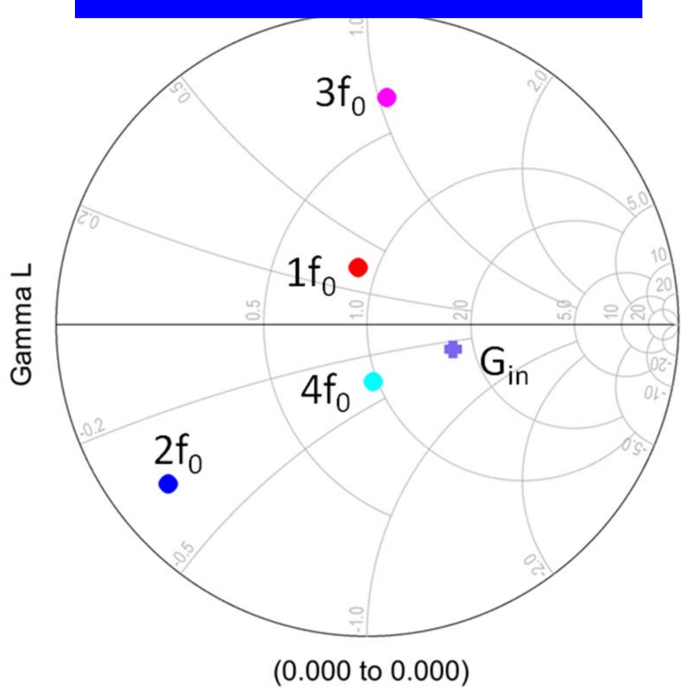
Validation of measurement-based X-parameter model



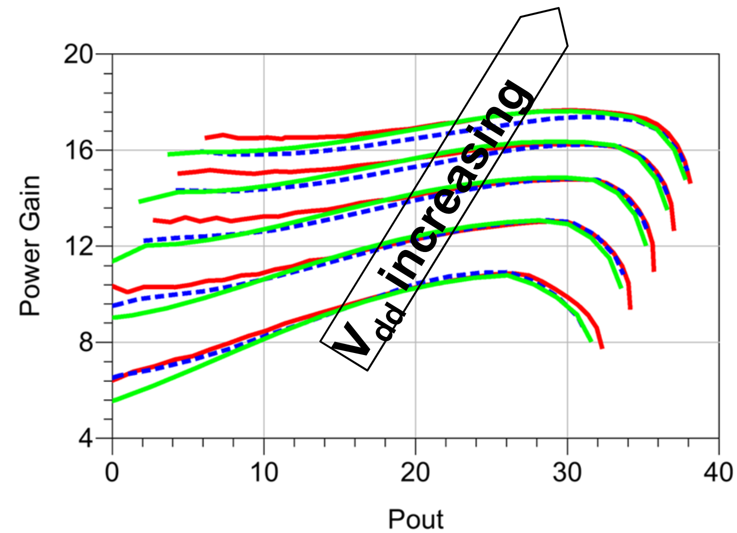


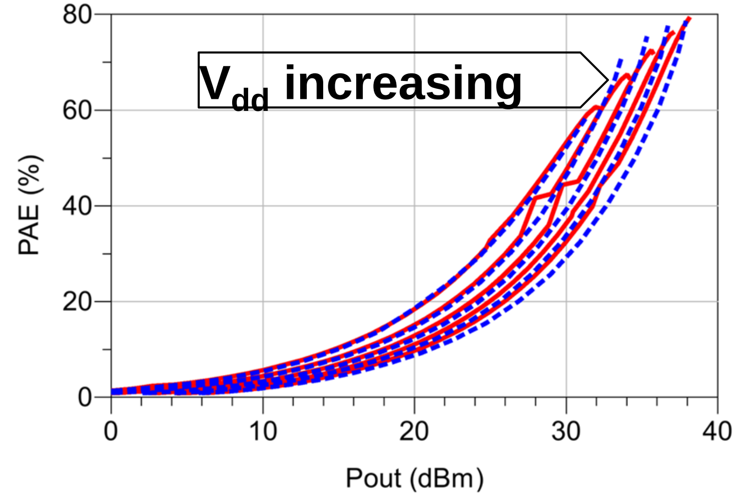
Validation of measurement-based X-parameter model

Tuner Load Set 4



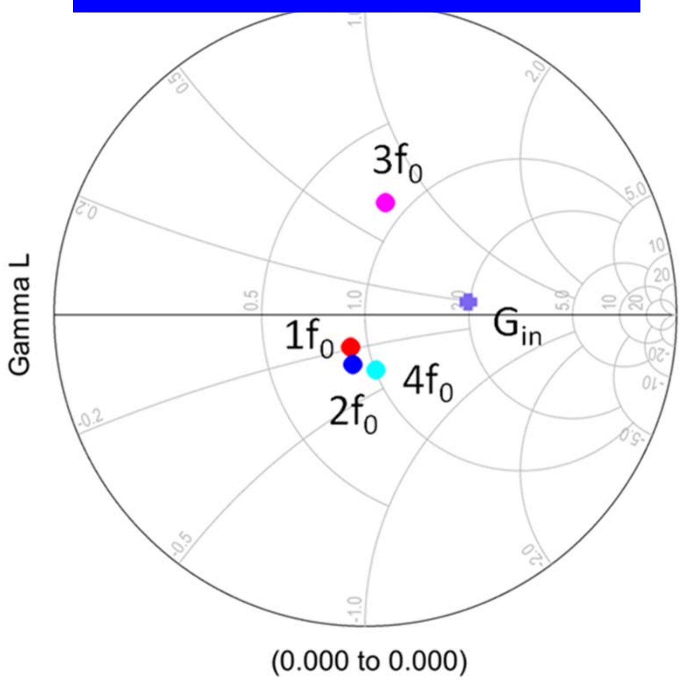
X-parameters at 50 ohm
Load-pull with tuner
NVNA 50 ohm





Validation of measurement-based X-parameter model

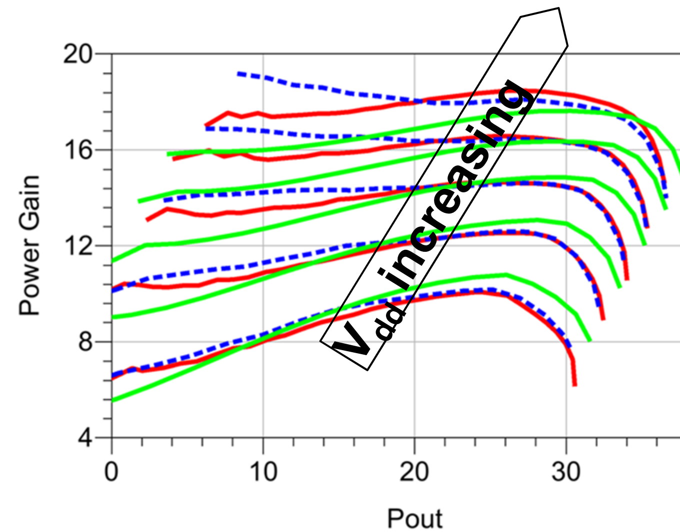
Tuner Load Set 5

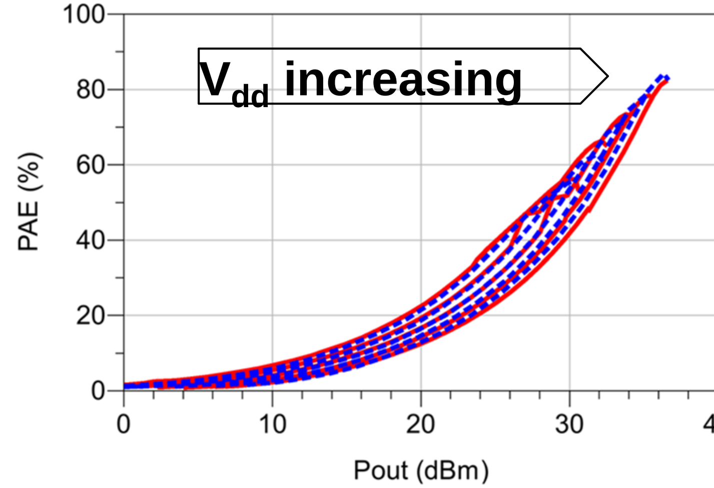


X-parameters at 50 ohm

Load-pull with tuner

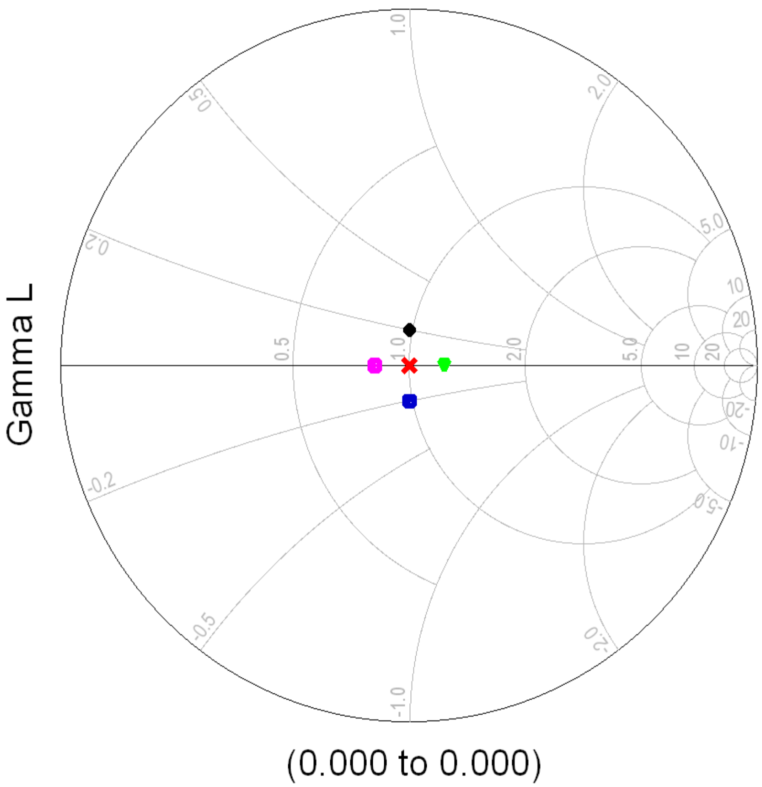
NVNA 50 ohm



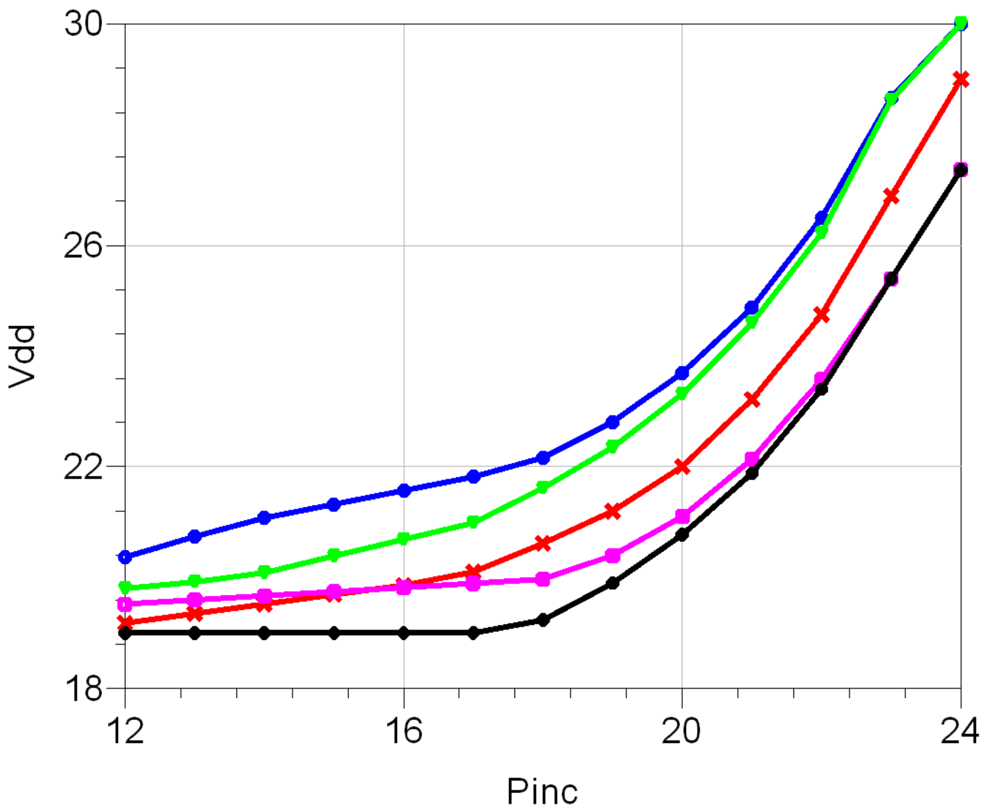


Load-dependence of shaping table

Loads variation



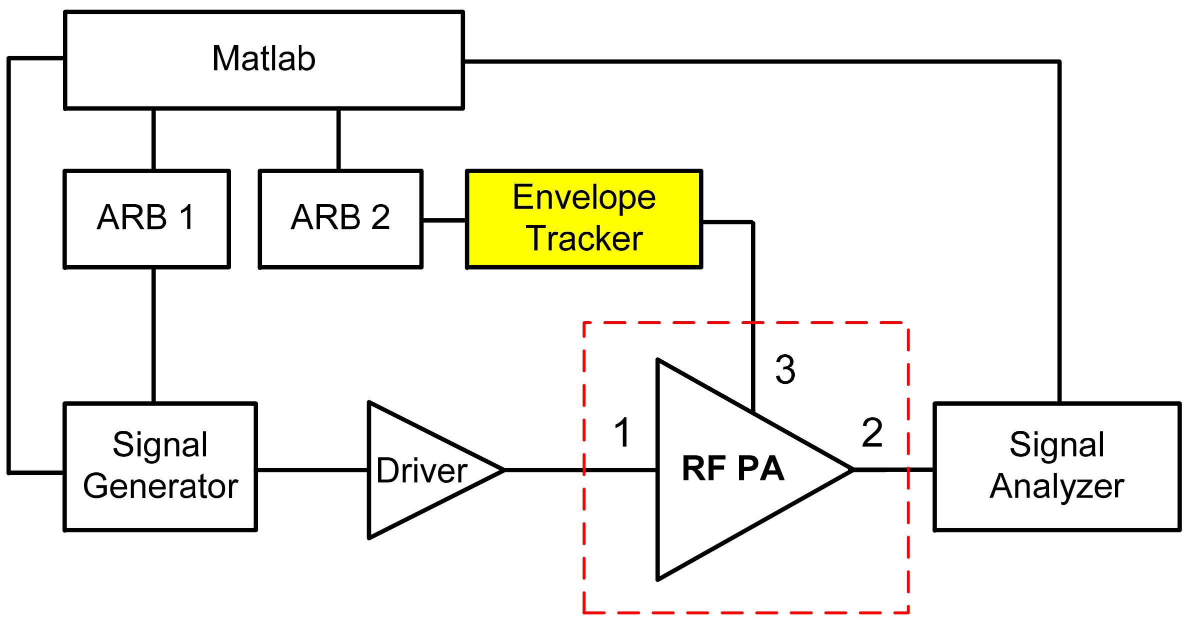
Shaping table



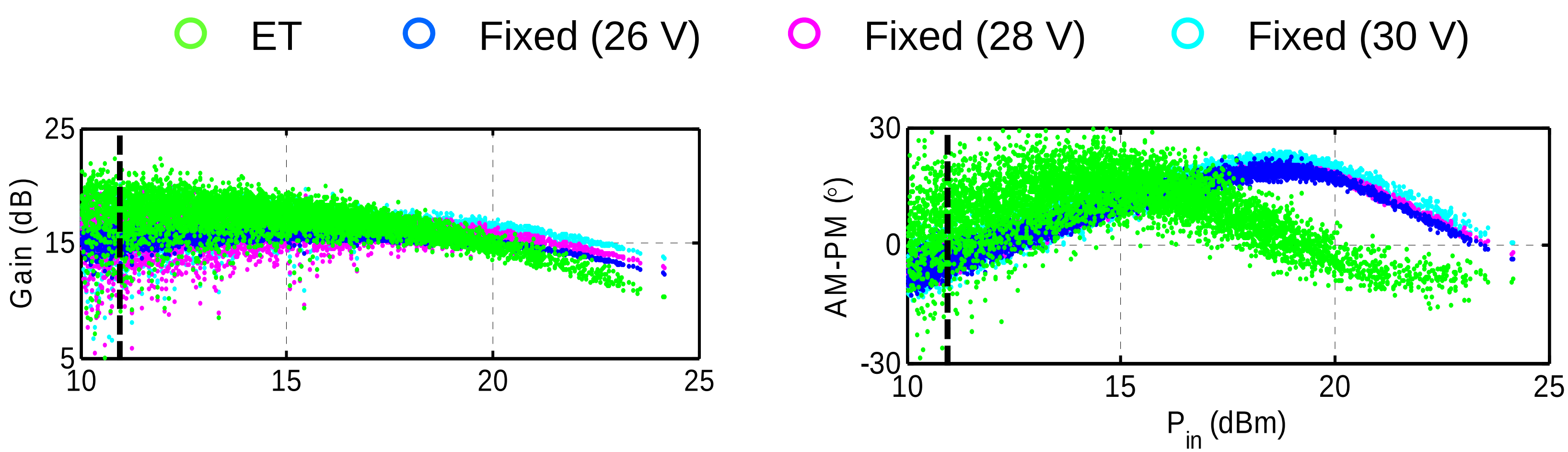
ET measurement setup

- The WCDMA test signal was fed to the RF signal generator through arbitrary signal generator
- The shaped signal based on the XP model was fed the supply modulator through another synchronized arbitrary signal generator
- The supply modulator from [4], which has 70 MHz bandwidth and 32 V_{max}, was used for the test

- WCDMA test model 1
  - 3.84 MHz
  - 10.3 dB PAR
  - 30.72 MHz sample rate
  - 1 ms repetition
  - 28.8 dBm Pout.avg



Results for GaN PA



Measured Results On GaN PA	Fixed Bias operation	ET operation
PAE	40.3%	57.8%
Output power	30.6 dBm	31.3 dBm
conditions	Averaged over 26, 28, & 30 V fixed bias conditions	21 V average bias over PDF

Discussion

- Static XP model based shaping table design shows significant PAE improvement under ET operation
- ET operation showed more gain compression and wider AM-PM spreading than under constant bias operation
  - lack of linearity improvement might be attributed to increased memory effects under dynamic biasing different from the ideal assumption in the simulation
  - Quasi-static assumption is likely valid when the supply modulator is ideal
  - Supply modulator output impedance and inter-connection impedance between the modulator and the PA may not be ideal
  - Slew-rate and bandwidth of the tracking amplifier are high and are not likely the problem

Suggestions for future work

- Treat RFPA as three-terminal "incommensurate mixer" X-parameter model

$$
\begin{aligned}
B_{2,[n,m]} &= X^{(F)}_{2,[n,m]}\left(\left|A_{1,[1,0]}(t)\right|,\left|A_{3,[0,1]}(t)\right|\right)P^{n}_{1,[1,0]}(t)P^{m}_{3,[0,1]}(t)\\
&+\sum_{n',m',p} X^{(S)}_{2,[n,m];p,[n',m']}\left(\left|A_{1,[1,0]}(t)\right|,\left|A_{3,[0,1]}(t)\right|\right)A_{p,[n',m']}P^{n-n'}_{1,[1,0]}(t)P^{m-m'}_{3,[0,1]}(t)\\
&+\sum_{n',m',p} X^{(T)}_{2,[n,m];p,[n',m']}\left(\left|A_{1,[1,0]}(t)\right|,\left|A_{3,[0,1]}(t)\right|\right)A^{*}_{p,[n',m']}P^{n+n'}_{1,[1,0]}(t)P^{m+m'}_{3,[0,1]}(t)
\end{aligned}
$$

See talk WE3D-4 14:50-15:10 ref. [22]

Suggestions for future work (2)

- Application of Dynamic X-parameters to ET applications: beyond quasi-static approximation
- Characterize the modulator and take it into better account in the design

Conclusions

- The envelope simulation and measurement results show good quantitative agreement for the static nonlinearity of the PA versus power and drain voltage, and also as a function of load
- The load-sensitivity of the lookup table predicted by the XP model was independently validated by time-domain loadpull measurement

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