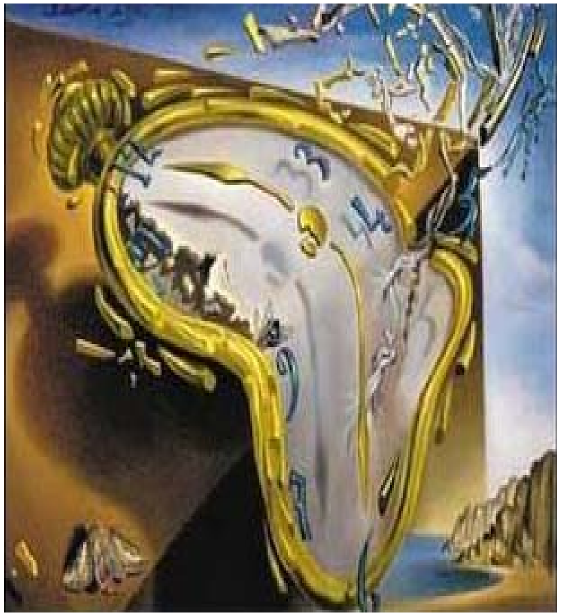
# Nonlinear Analog Behavioral Modeling of Microwave Devices and Circuits

Dr. David E. Root
Principle Research Scientist
High Frequency Technology Center
Agilent Technologies
Santa Rosa, CA

IEEE MTT-S DML Lecture #1
Bergen, Norway
May 7, 2010



# Acknowledgement

## Norway IEEE MTT/AP Chapter

Yngve Thodesen

Karl-Martin Gjertsen

Marius Ubostad

Jonny Langmyren

Peter Myhrberg

Bjorn Birkeland

Riccardo Giacometti

Giovanni Damore

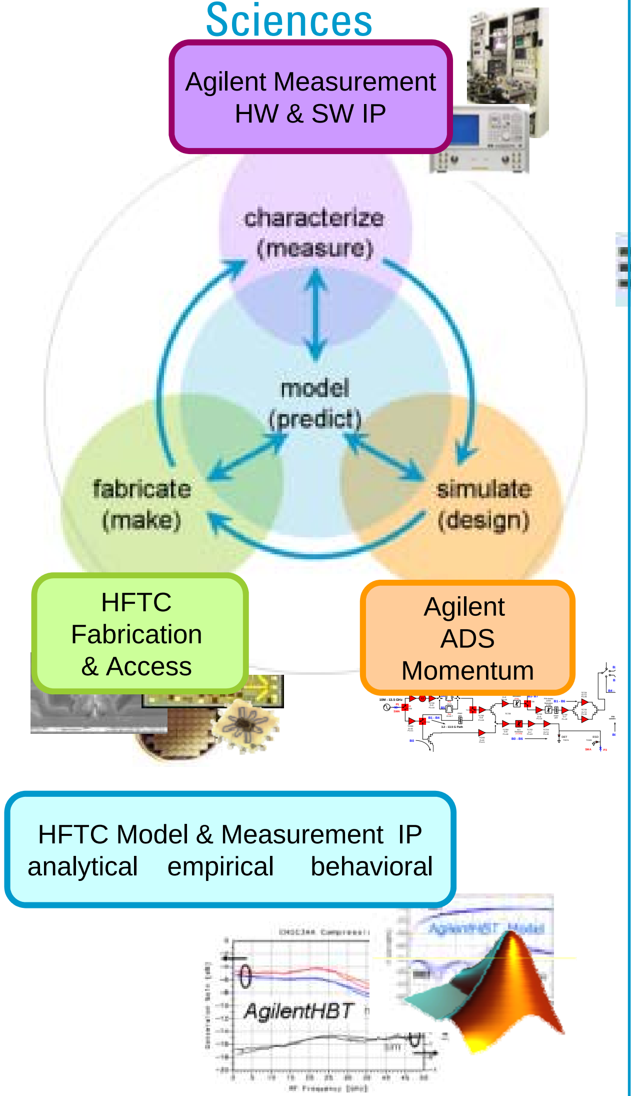
# Key Contributors

Loren Betts
Alex Cognata
Chad Gillease
Daniel Gunyan
Jason Horn
Masaya Iwamoto
Greg Jue
Dominique Schreurs
David Sharrit
Nick Tufillaro
Jan Verspecht
Jianjun Xu
John Wood

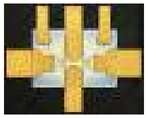
Agilent Management
Many others

# Agilent High Frequency Technology Center

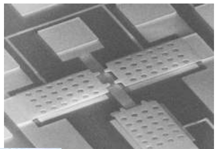
## Measurement and Modeling Sciences



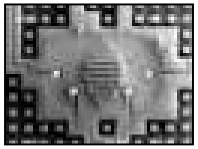
Integrated Diodes



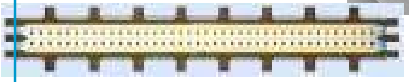
MEMS



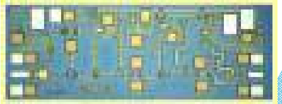
Liquid metal switches



Hyperabrupt Diodes

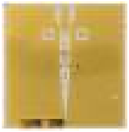


pHEMT & FET ICs

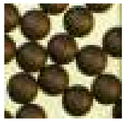


HBT ICs

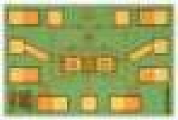
Thin Film



Ferromagnetics



Semiconductor switches



Internal and external technology

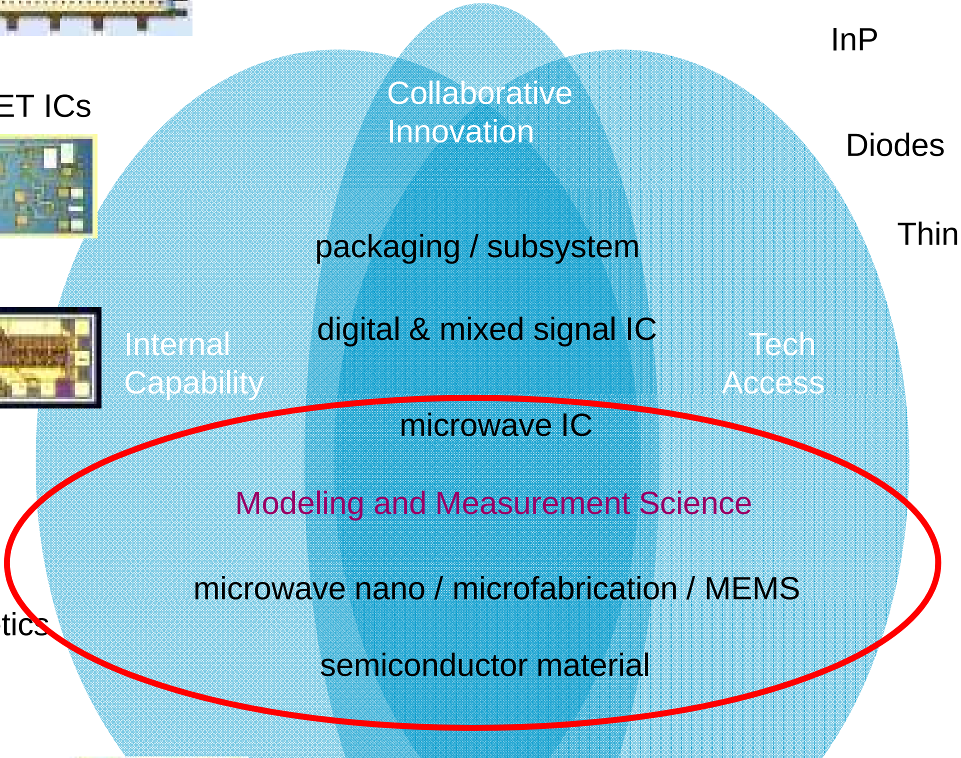
GaN

GaAs

InP

Diodes

Thin Film



# Outline

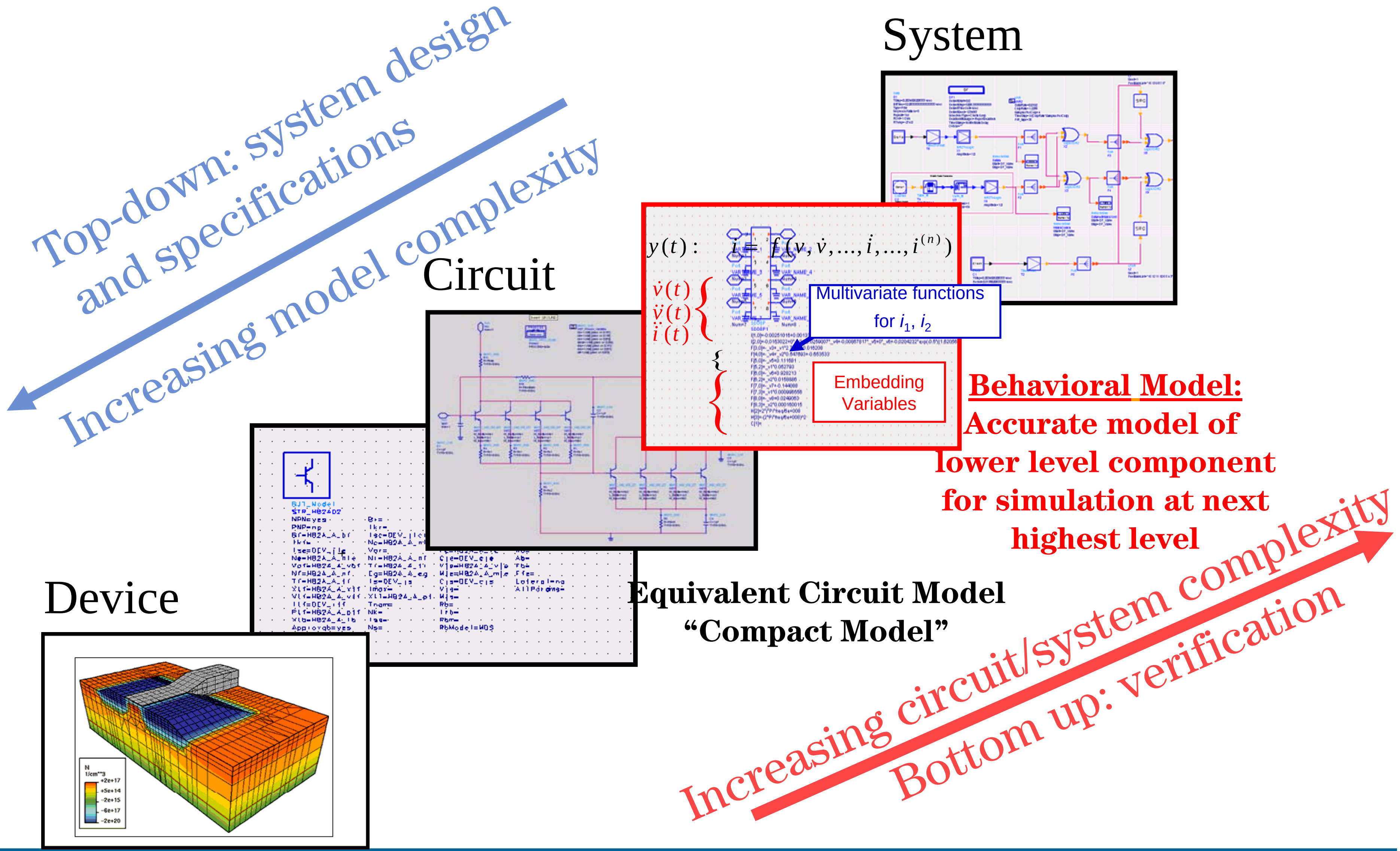
Introduction: Behavioral Models and NVNA

Functional Block Models

- Nonlinear Time Series
- X-parameters (PHD Model) in the Frequency Domain
- Mixed Time-Frequency Methods

Summary and Conclusions

# Introduction: Behavioral Modeling and Design Hierarchy

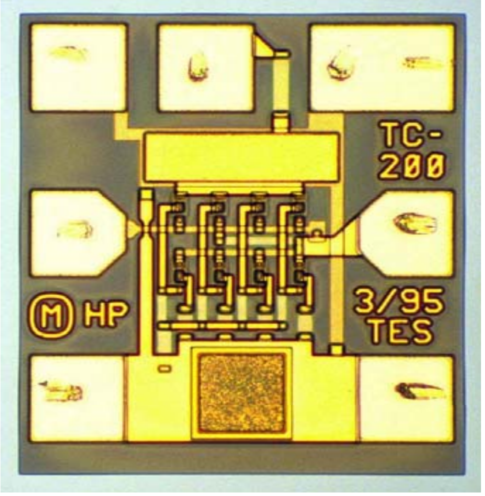


**Behavioral Model:**
**Accurate model of lower level component for simulation at next highest level**

**Equivalent Circuit Model**
**“Compact Model”**

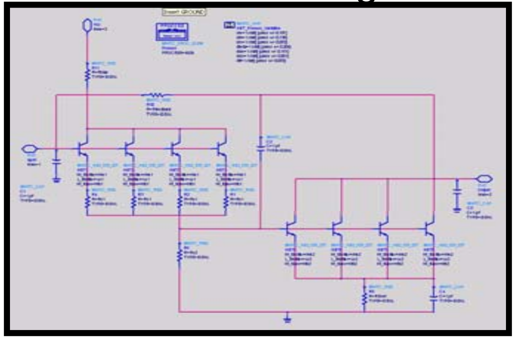
# Measurement-Based and Simulation-Based Models

Actual Circuit



***Amplifier or Mixer IC***

DC-20 GHz HBT Agilent HMMC 5200 amp [2]



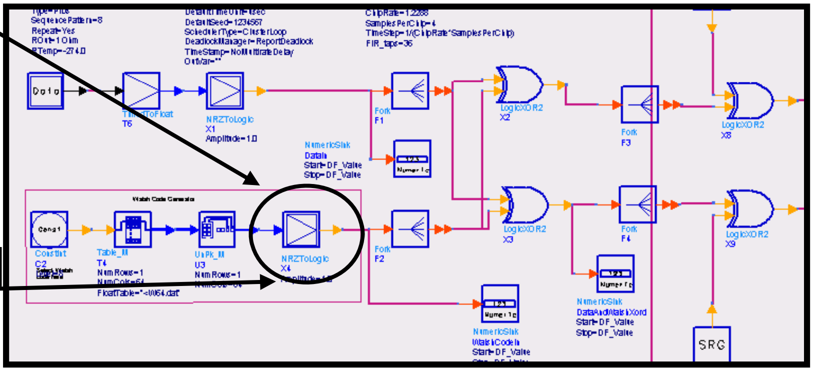
Detailed Circuit Model (SPICE/ADS) of IC

Generate Behavioral Model

## Measurement-Based Model

- Ckt. model may not exist
- Ckt. models may be inaccurate
- Completely protect design IP

***Design of Module or Instrument Front End***



## Simulation-Based Model

- Simulation speedup
- Design system before building/buying IC
- Completely protect design IP

Simple for Linear Ckts: S-parameters

# S-parameters as simplest behavioral model

- Easy to measure at high frequencies
    - measure voltage traveling waves with a (linear) vector network analyzer (VNA)
    - don't need shorts/opens which can cause devices to oscillate or self-destruct
- Relate to familiar measurements (gain, loss, reflection coefficient ...)
- Can cascade S-parameters of multiple devices to predict system performance
- Can import and use S-parameter files in electronic-simulation tools (e.g. ADS)
- BUT: No harmonics, No distortion, No nonlinearities, ...

  Invalid for nonlinear devices excited by large signals, despite *ad hoc* attempts

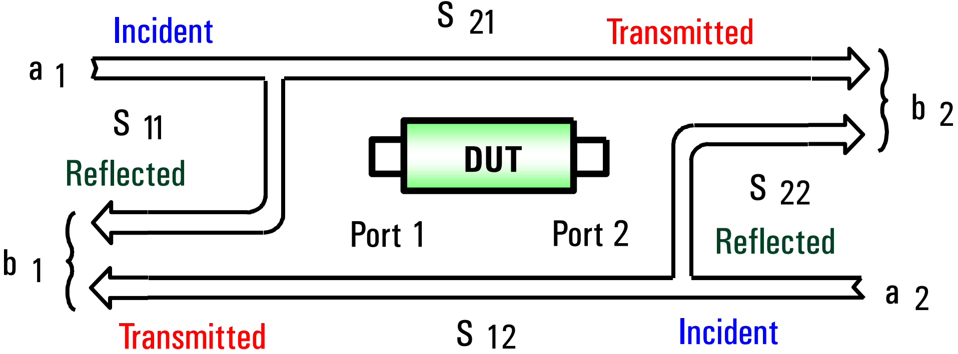
**Linear Simulation:**
Matrix Multiplication

***S-parameters***

$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$

**Measure with linear VNA:**
Small amplitude sinusoids



**Model Parameters:**
Simple algebra

$$S_{ij} = \left. \frac{b_i}{a_j} \right|_{\substack{a_k = 0 \\ k \neq j}}$$

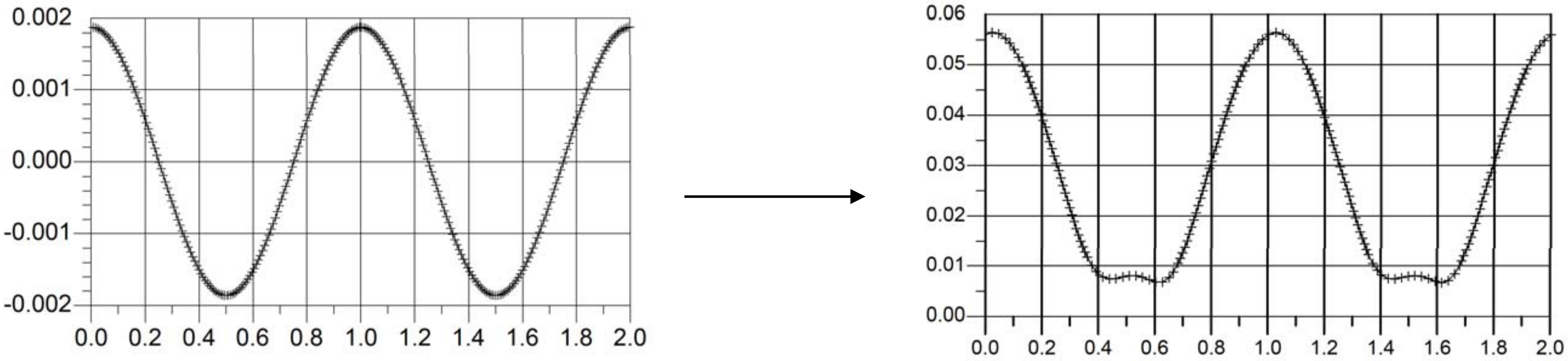
# Three Components of Behavioral Modeling

1. Model Formulation
   - Nonlinear ODEs in Time Domain (e.g. Transient Analysis; all others)
   - NL Spectral Map in Freq. Domain (e.g. Harmonic Balance) X-params
   - Mixed Domains (e.g. ODE-Coupled Envelopes in Circuit Env. Analysis)

2. Experiment Design
   - Stimulus needed to excite relevant dynamics

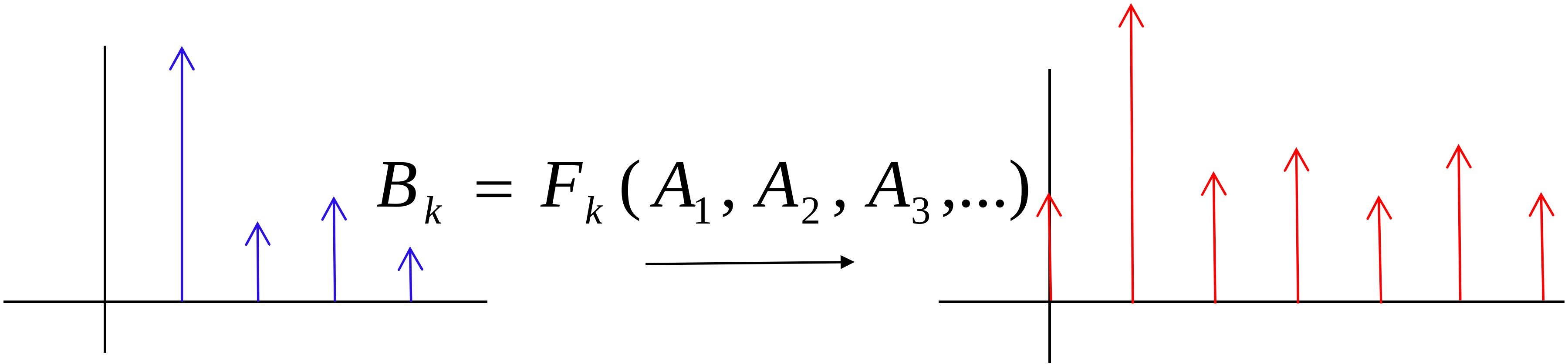
3. Model Identification
   - Procedure to determine model “parameters”

# Model Formulation: Time & Freq. Domains [1,6]



$$I(t) = F(V(t), \dot{V}(t), \ddot{V}(t), \ldots, \dot{I}(t), \ldots)$$

Natural for strongly nonlinear low-order (lumped) systems

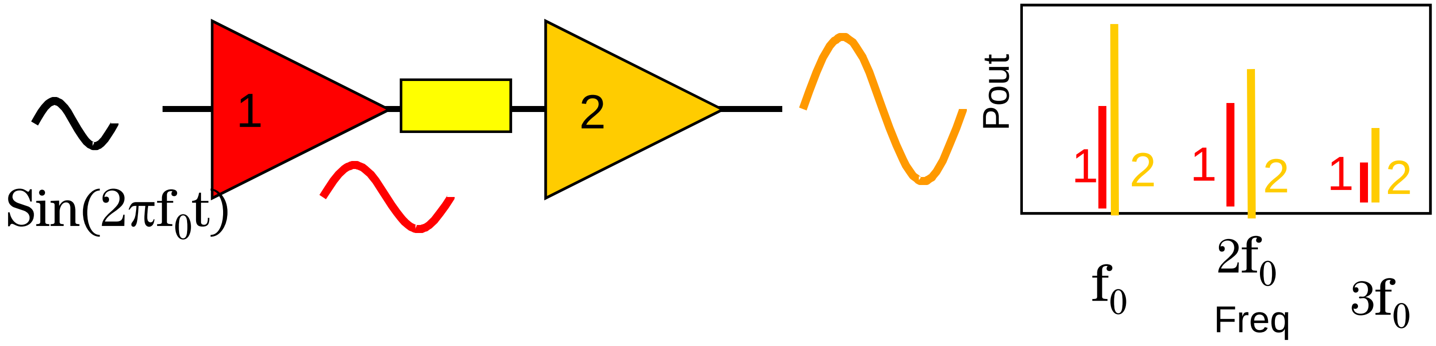


$$B_k = F_k(A_1, A_2, A_3, \ldots)$$

Freq. Domain natural for low-distortion, high-freq. ICs

Formulate model eqs. in language native to appropriate simulator

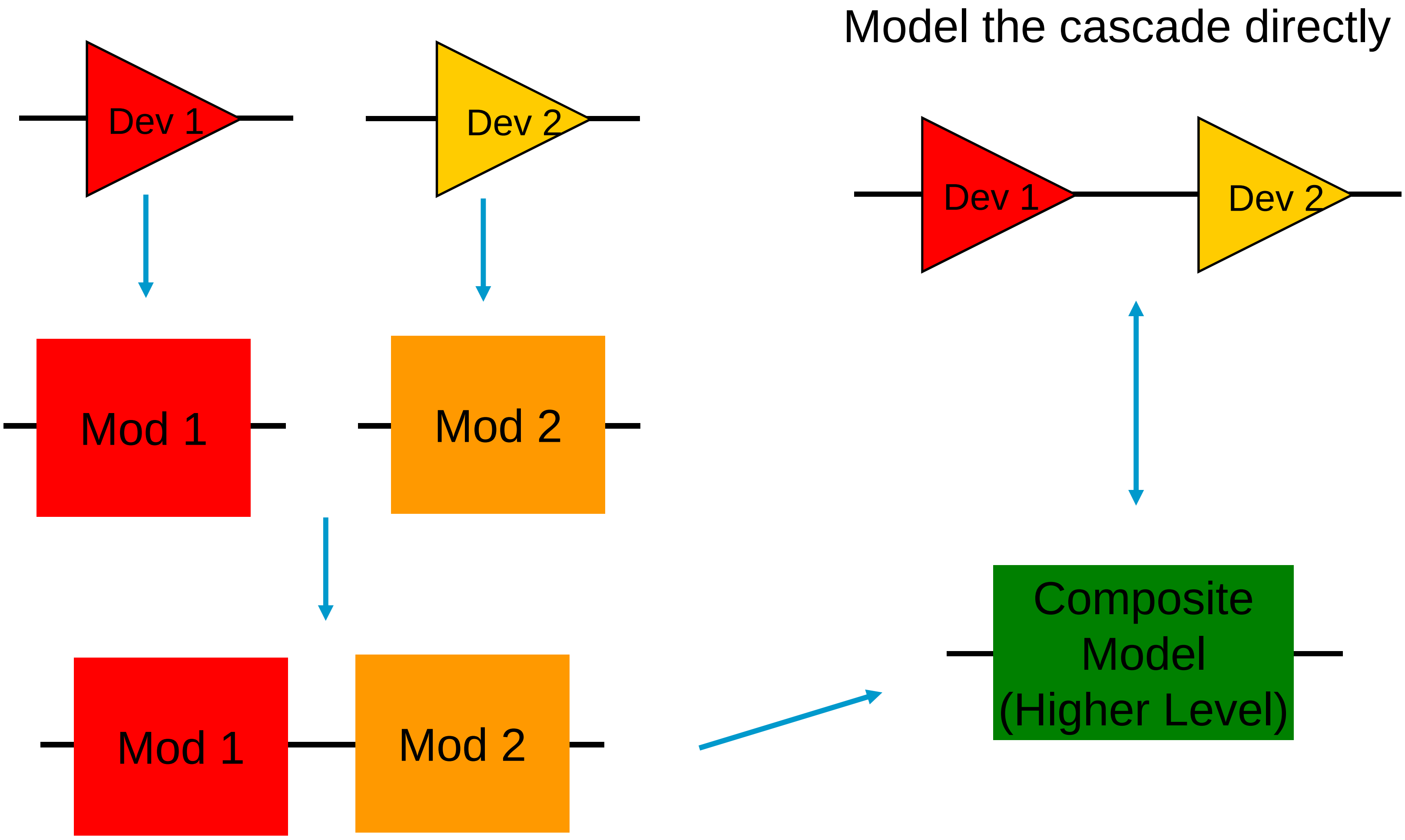
# Wanted: Cascadability of *Nonlinear Components*



Predict signal and harmonics (magnitude and phase) through chains of *cascaded* nonlinear components under drive

- Inter-stage mismatch is important to final results
  - Can not infer these effects from VNA measurements (even “Hot $S_{22}$”)
- Required for communication circuits and module design
- Linear S-parameter theory doesn’t apply!
  Most previous attempts to generalize S-parameters to nonlinear case are wrong!

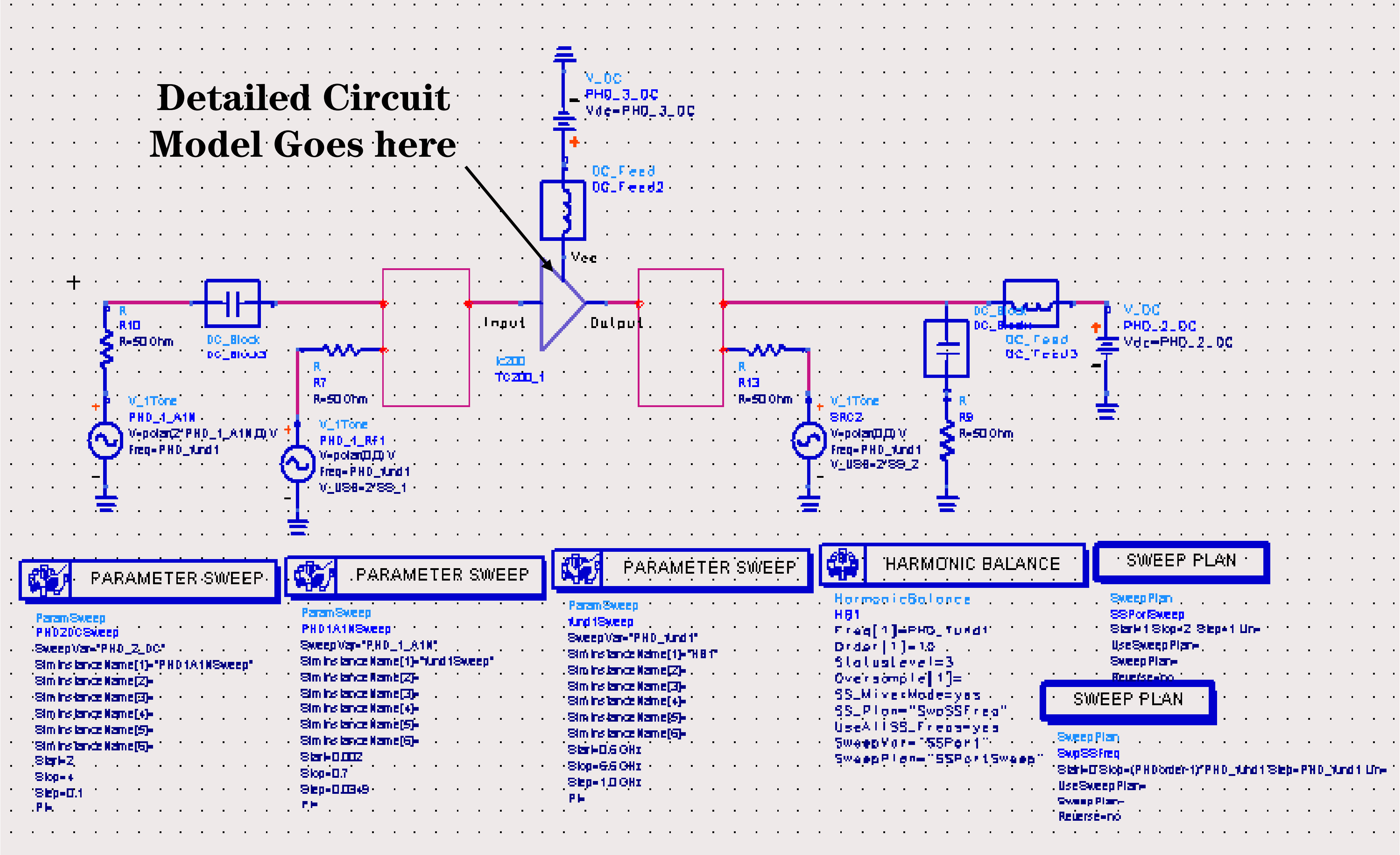
# Wanted: Hierarchical Modeling



Model the cascade directly

A cascade of many models *reduced to one*

# Experiment Design: Simulation



**Detailed Circuit Model Goes here**

ParamSweep
PHD2DCSweep
SweepVar="PHD_2_DC"
SimInstanceName[1]="PHD1A1NSweep"
SimInstanceName[2]=
SimInstanceName[3]=
SimInstanceName[4]=
SimInstanceName[5]=
SimInstanceName[6]=
Start=2
Stop=4
Step=0.1
Pt=

ParamSweep
PHD1A1NSweep
SweepVar="PHD_1_A1N"
SimInstanceName[1]="fund1Sweep"
SimInstanceName[2]=
SimInstanceName[3]=
SimInstanceName[4]=
SimInstanceName[5]=
SimInstanceName[6]=
Start=0.002
Stop=0.7
Step=0.0349
Pt=

ParamSweep
fund1Sweep
SweepVar="PHD_fund1"
SimInstanceName[1]="HB1"
SimInstanceName[2]=
SimInstanceName[3]=
SimInstanceName[4]=
SimInstanceName[5]=
SimInstanceName[6]=
Start=0.5 GHz
Stop=5.5 GHz
Step=1.0 GHz
Pt=

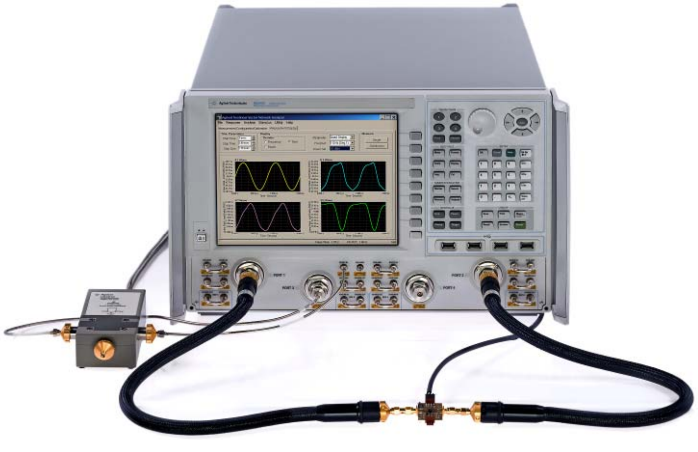
HarmonicBalance
HB1
Freq[1]=PHD_fund1
Order[1]=10
StatusLevel=3
Oversample[1]=
SS_MixerMode=yes
SS_Plan="SwpSSFreq"
UseAllSS_Freqs=yes
SweepVar="SSPort"
SweepPlan="SSPortSweep"

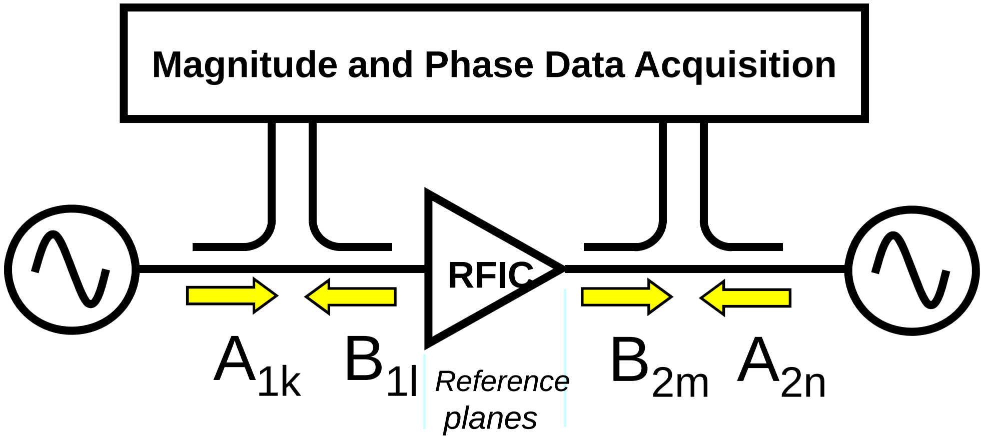
SweepPlan
SSPortSweep
Start=1 Stop=2 Step=1 Lin=
UseSweepPlan=
SweepPlan=
Reverse=no

SweepPlan
SwpSSFreq
Start=0 Stop=(PHDorder-1)*PHD_fund1 Step=PHD_fund1 Lin=
UseSweepPlan=
SweepPlan=
Reverse=no

# Experiment Design: Measurement

## Nonlinear Vector Network Analyzer [9,14] (NVNA)





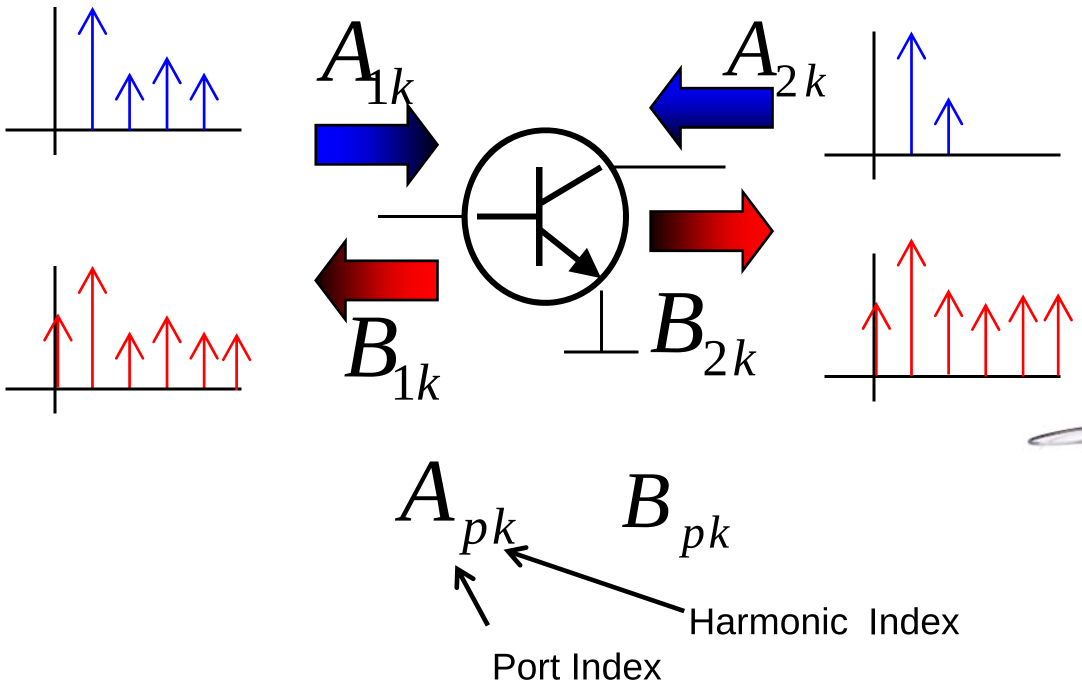
New phase calibration standard

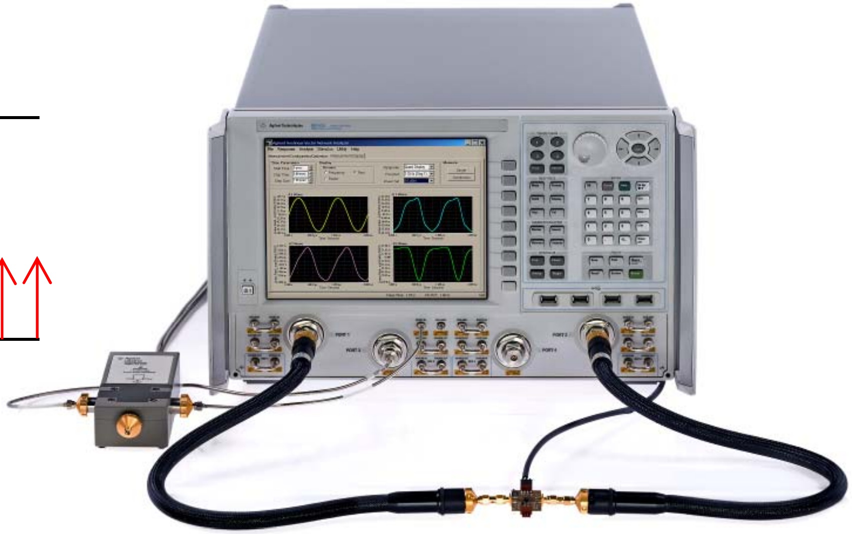
Calibrated magnitude *& phase* of harmonics/IMD

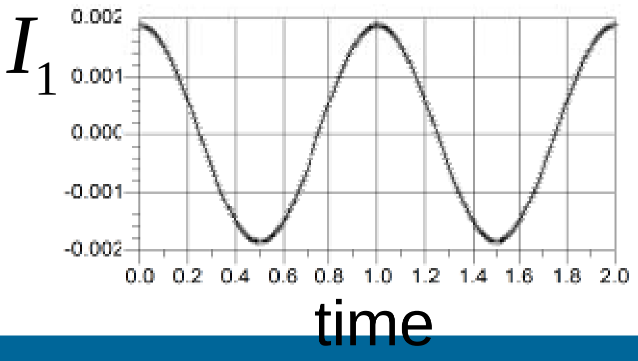
Measures under realistic large-signal conditions

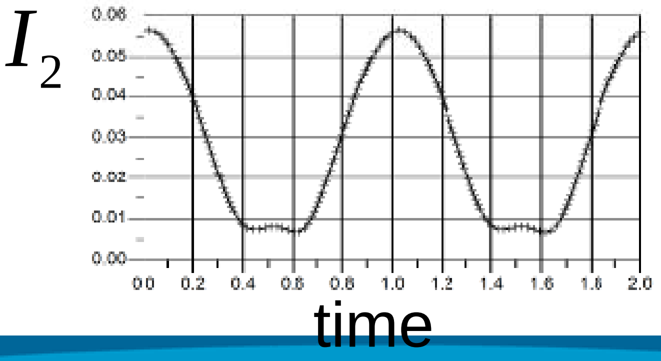
Based on Standard Agilent PNA Hardware
And custom reference generator

# Introduction: NVNA measurements complex spectra and waveforms









# Nonlinear Vector Network Analyzer (NVNA) [14]:

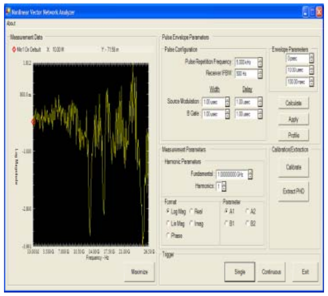
Network Analyzer

+

Phase Reference

+

Meas. Science
Algorithms & Software



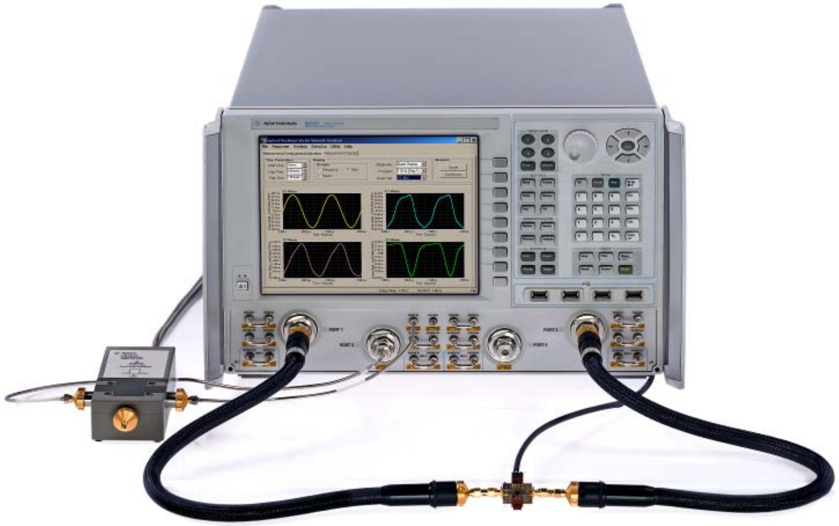
=

NVNA

NVNA = PNA-X + Phase Reference (custom InP IC)
+ Application SW and calibration (mag and phase)
two internal sources, internal switches, and an internal broadband combiner

NVNA measures *Magnitude and Phase* of all relevant frequency components (cross-frequency coherence) necessary to measure X-parameters!

# Nonlinear Vector Network Analyzer (NVNA) [14]



- Vector (amplitude/phase) corrected nonlinear measurements from 10 MHz to 50 GHz
  - Calibrated absolute amplitude and relative phase (cross-frequency relative phase) of measured spectra traceable to standards lab
  - 50 GHz of vector corrected bandwidth for time domain waveforms of voltages and currents of DUT
  - Multi-Envelope domain measurements for measurement and analysis of memory effects
  - X-parameters: Extension of Scattering parameters into the nonlinear region providing unique insight into nonlinear DUT behavior. Efficient measurements with phase control. External instrument control, pulsed, triggered measurements
  - X-parameter MDIF file read by ADS XnP component or nonlinear simulation and design.
  - X-parameter generation from detailed schematics within ADS simulator.
- Standard VNA HW with Nonlinear features & capability

# Outline

Introduction: Behavioral Models and NVNA

Functional Block Models

- Nonlinear Time Series
- X-parameters (PHD model) in the Frequency Domain
- Mixed Time-Frequency

Summary and Conclusions

# Nonlinear Time Series method of Behavioral Modeling [1,6]

# Dynamical Systems & State Space

The dynamics of the nonlinear system can be assumed to be described by a system of nonlinear ODEs

$$y^{(n)}(t) = f\left(y^{(n-1)}, \ldots y, x, \dot{x}, \ldots x^{(m)}\right)$$

**Order of time derivative**

$$\dot{\vec{u}}(t) = \vec{f}\left(\vec{u}(t), \vec{x}(t)\right)$$ Vector of State Equations

$$y(t) = h\left(\vec{u}(t), \vec{x}(t)\right)$$ Scalar output *y*(*t*)

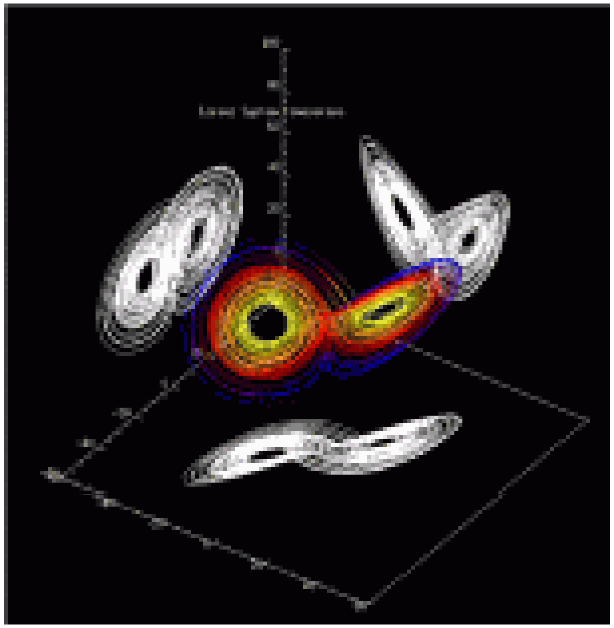
The sampled solution of the ODE, y(t), is a time-series

The solution of the dynamical equations for state variables, u(t), is a time-parameterized trajectory in Phase Space

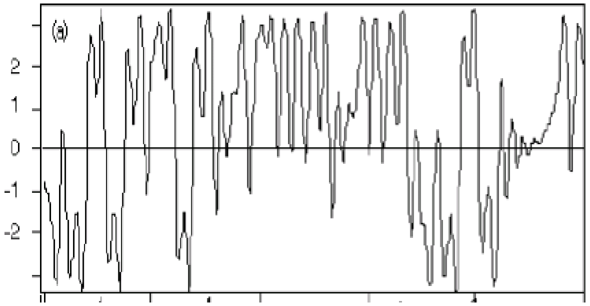
# Phase Space and Time Series

The multi-dimensional space spanned by the state variables is known as
phase space

Lorenz system

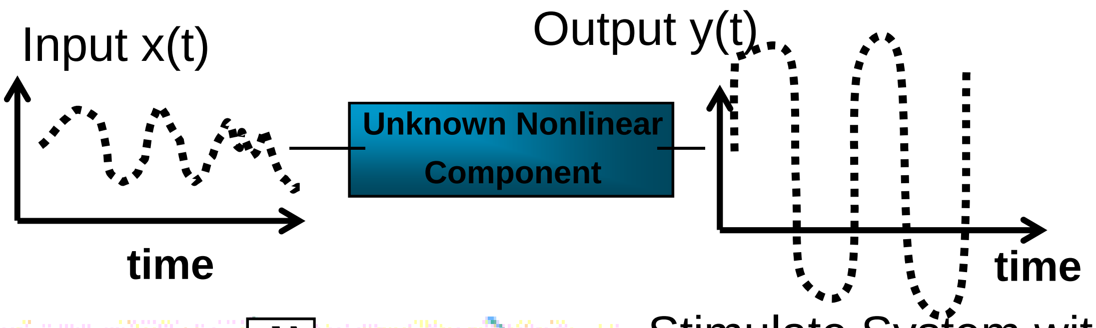


Any measurable output is a projection of this trajectory versus time:
a Time Series



# Nonlinear Time Series (NLTS)
# Phase Space Reconstruction by Embedding

NLTS Behavioral Modeling is *“inverse”* of solving known ODEs
Start from input & output time series and *discover dynamics*



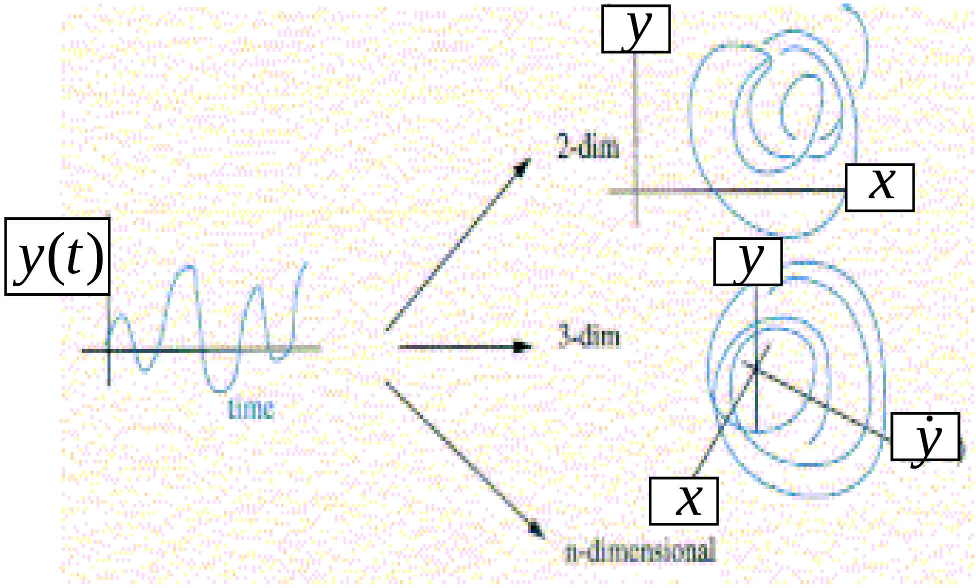
Input x(t)

Output y(t)

**Unknown Nonlinear Component**

**time**

**time**



Stimulate System with drive x(t)

Record Time Series output y(t)

Embed drive x(t) & response y(t)

Stop when trajectory single valued

This results in the *Nonlinear ODE*:

$$f\,(y(t),\dot{y}(t),x(t),\ldots)=0$$

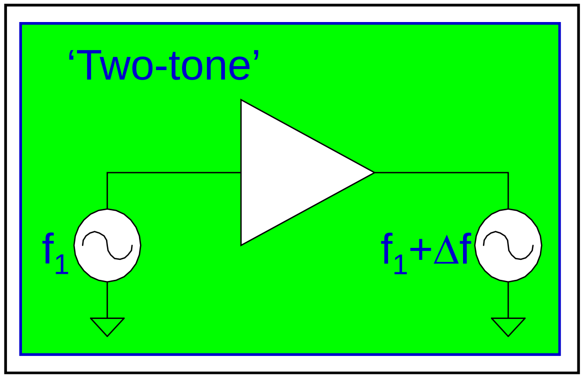
Approximate f with smooth function

Attach ODE Model to Circuit Simulator

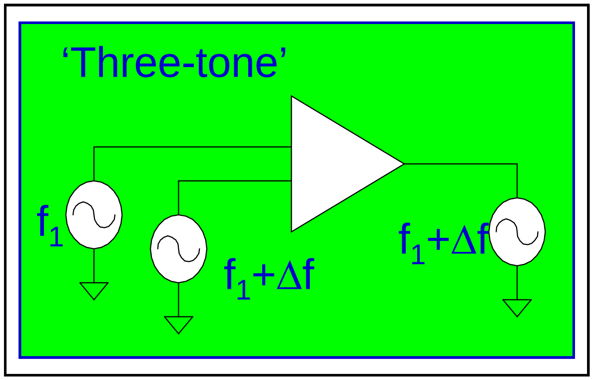
# Excitation Designs

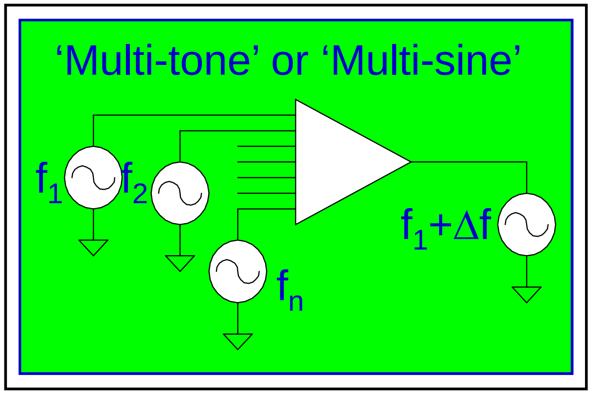
**Goal: stimulate all *relevant* (observable) dynamics**

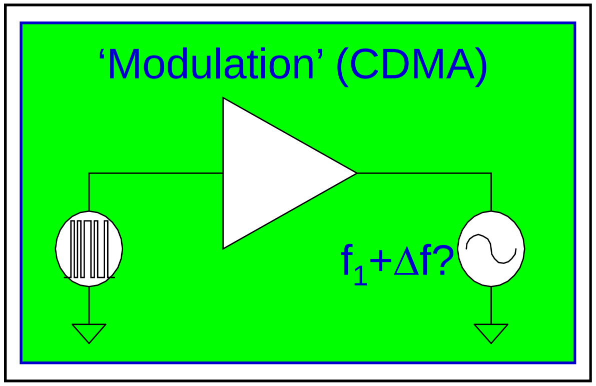
Sweep Power and Frequency to “cover phase space”



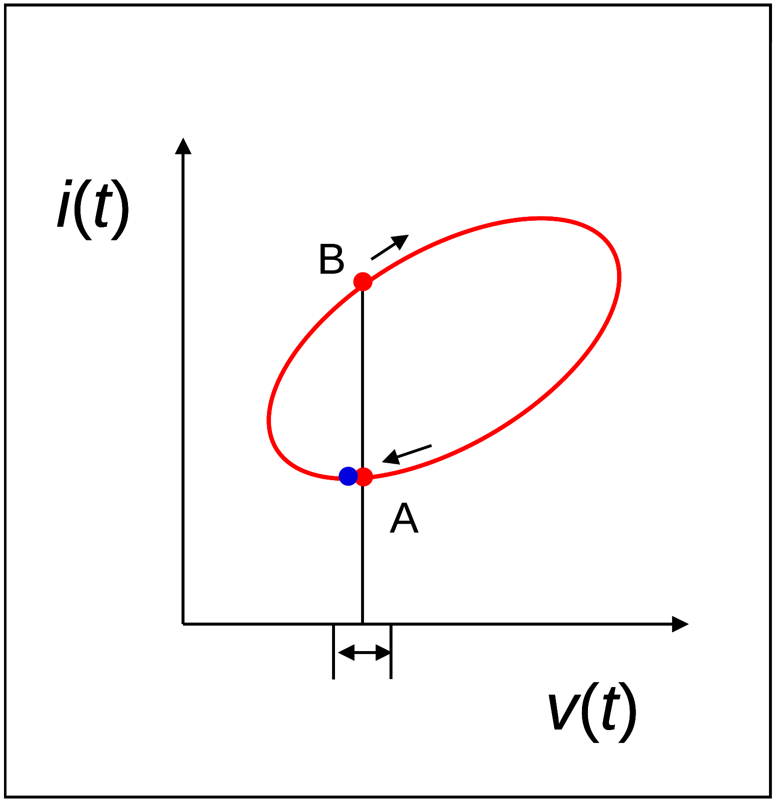
**Used for models**

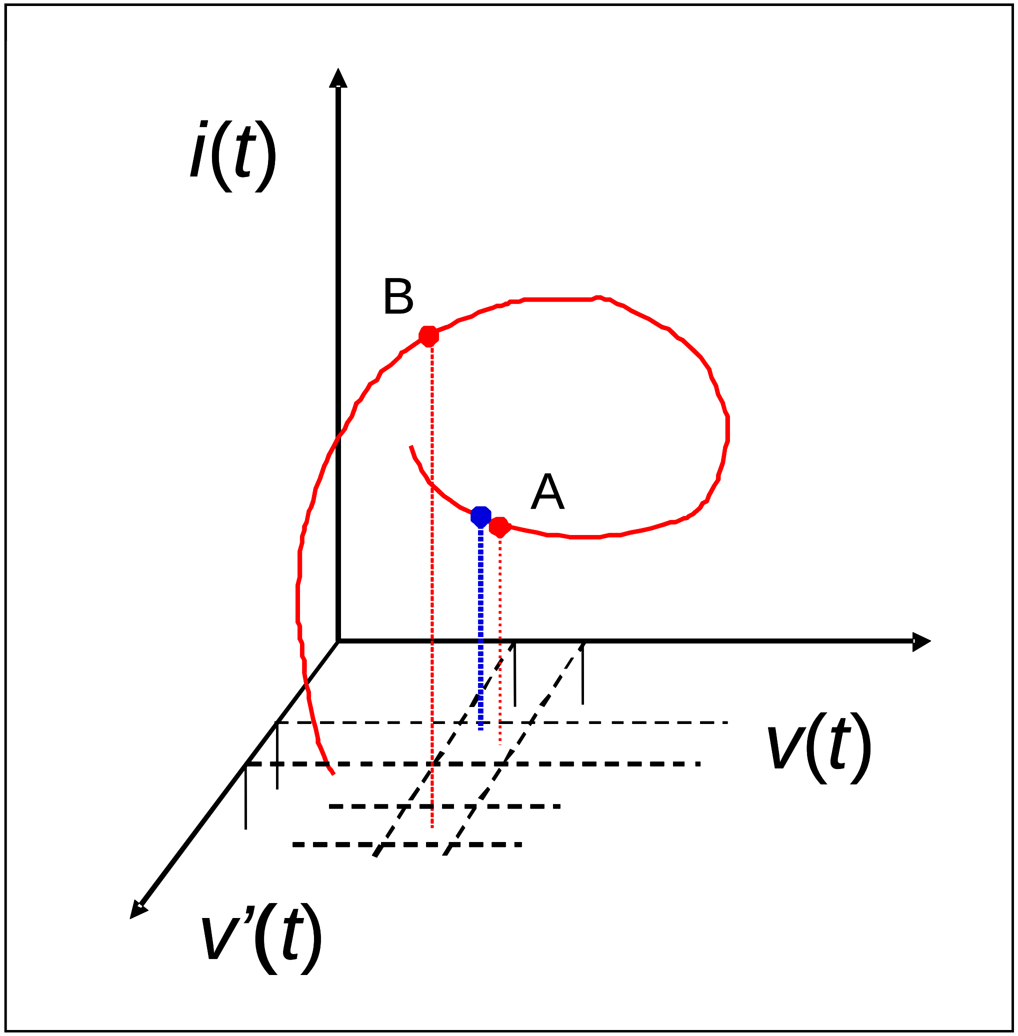






# Embedding: Building up phase space to define ODE





$$i(t) \neq i(v(t))$$

$$i(t) = i(v(t), \dot{v}(t))$$

# Model Identification: Nonlinear Time Series (NLTS)

**Stimulate / Excite System**
Sufficiently complex stimulus

$$x(t) \rightarrow [x(t), \dot{x}(t), ..., x^{(m)}(t)]$$
$$y(t) \rightarrow [y(t), \dot{y}(t), ..., y^{(n)}(t)]$$

**Embed:**
Create auxiliary variables
(represent waveform)

$$\begin{array}{cccccccc} x(t_1) & \dot{x}(t_1) & ... & x^{(m)}(t_1) & y(t_1) & \dot{y}(t_1) & ... & y^{(n)}(t_1) \\ x(t_2) & \dot{x}(t_2) & ... & x^{(m)}(t_2) & y(t_2) & \dot{y}(t_2) & ... & y^{(n)}(t_2) \\ . & . & ... & . & . & . & ... & . \\ x(t_p) & \dot{x}(t_p) & ... & x^{(m)}(t_p) & y(t_p) & \dot{y}(t_p) & ... & y^{(n)}(t_p) \end{array}$$

**Sample data:**

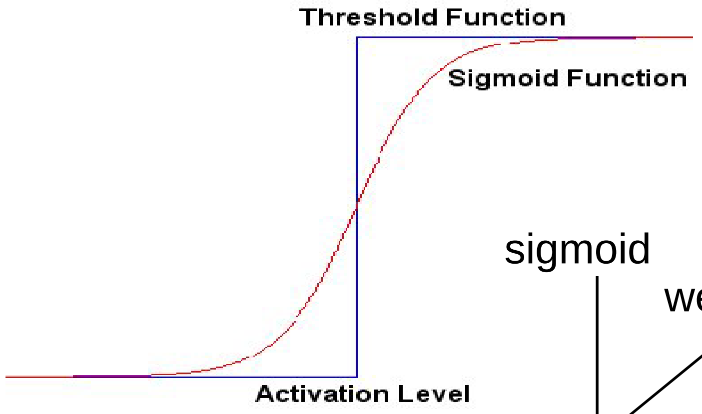
at high frequency
(or envelope;
hard if multiple timescales)

$$y^{(n)} = f(y^{(n-1)}, ...y, x, \dot{x}, ...x^{(m)})$$

**Fit:**
Nonlinear function *f*

# Function approximation Artificial Neural Networks

An ANN is a parallel processor made up of simple, interconnected processing units, called *neurons*, with weighted connections.

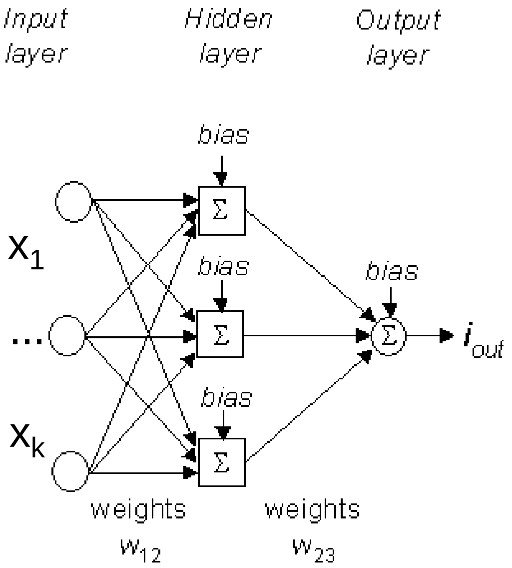


sigmoid

weights

biases

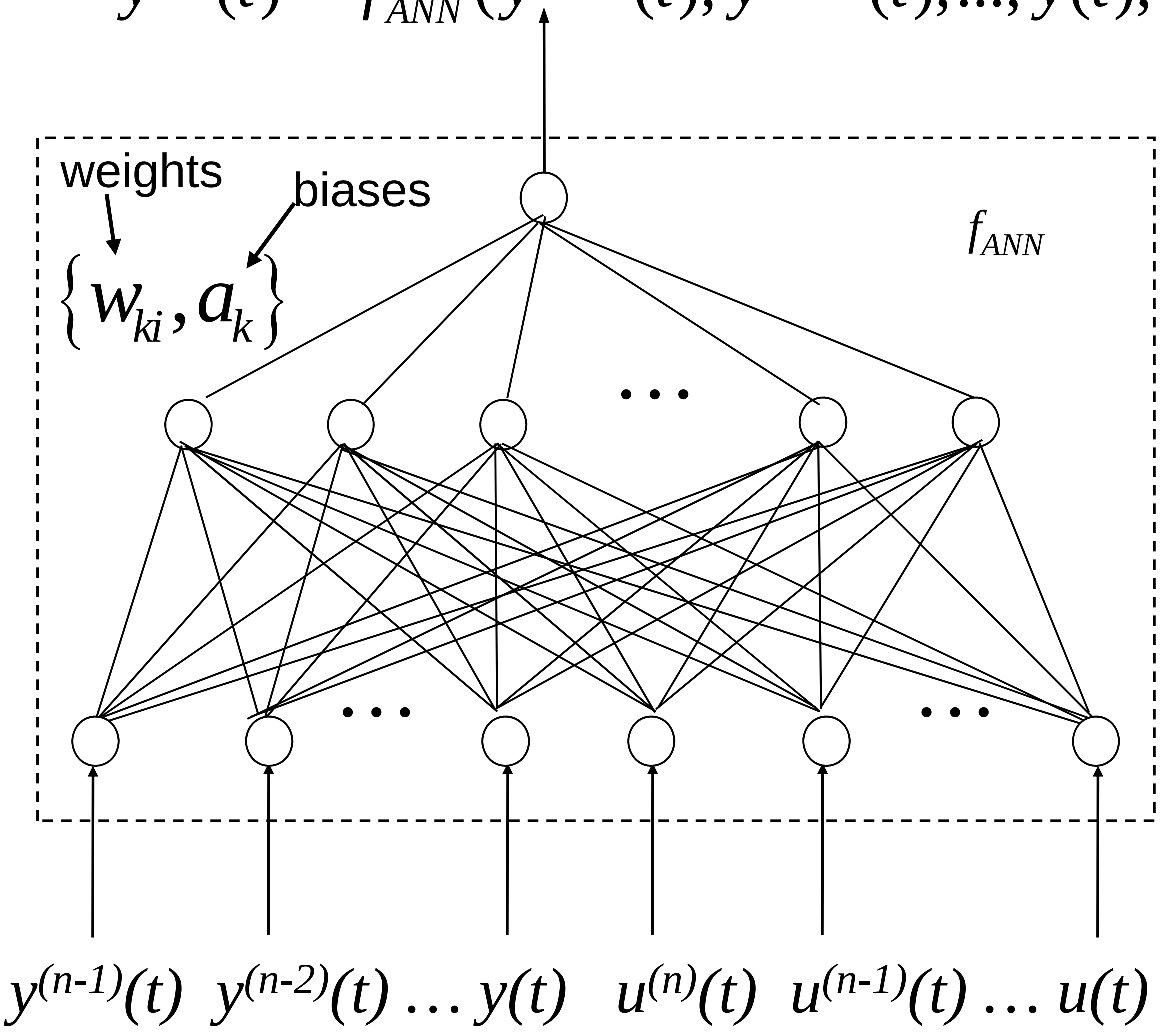
$$F(x_1,\ldots,x_K) = \sum_{i=1}^{I} v_i s\left( \sum_{k=1}^{K} w_{ki} x_k + a_i \right) + b$$



- •Universal Approximation Theorem: Fit “any” nonlinear function of any # of variables
- •Infinitely differentiable: *better for distortion than naïve splines or low-order polynomials*.
- •Easy to train (fit) using standard third-party tools (MATLAB)
- •Easy to train on scattered data

# Function approximation: Artificial Neural Networks

$$y^{(n)}(t) = f_{ANN}(y^{(n-1)}(t), y^{(n-2)}(t), \ldots, y(t), u^{(n)}(t), u^{(n-1)}(t), \ldots, u(t))$$



"Dynamic Neural Network"

$\{w_{ki}, a_k\}$ Obtained by *Training*

Can also define *f* by polynomials, radial basis functions, lookup tables etc.

# Model Implementation: ODE in circuit simulator

(after Zhang and Xu in [6])

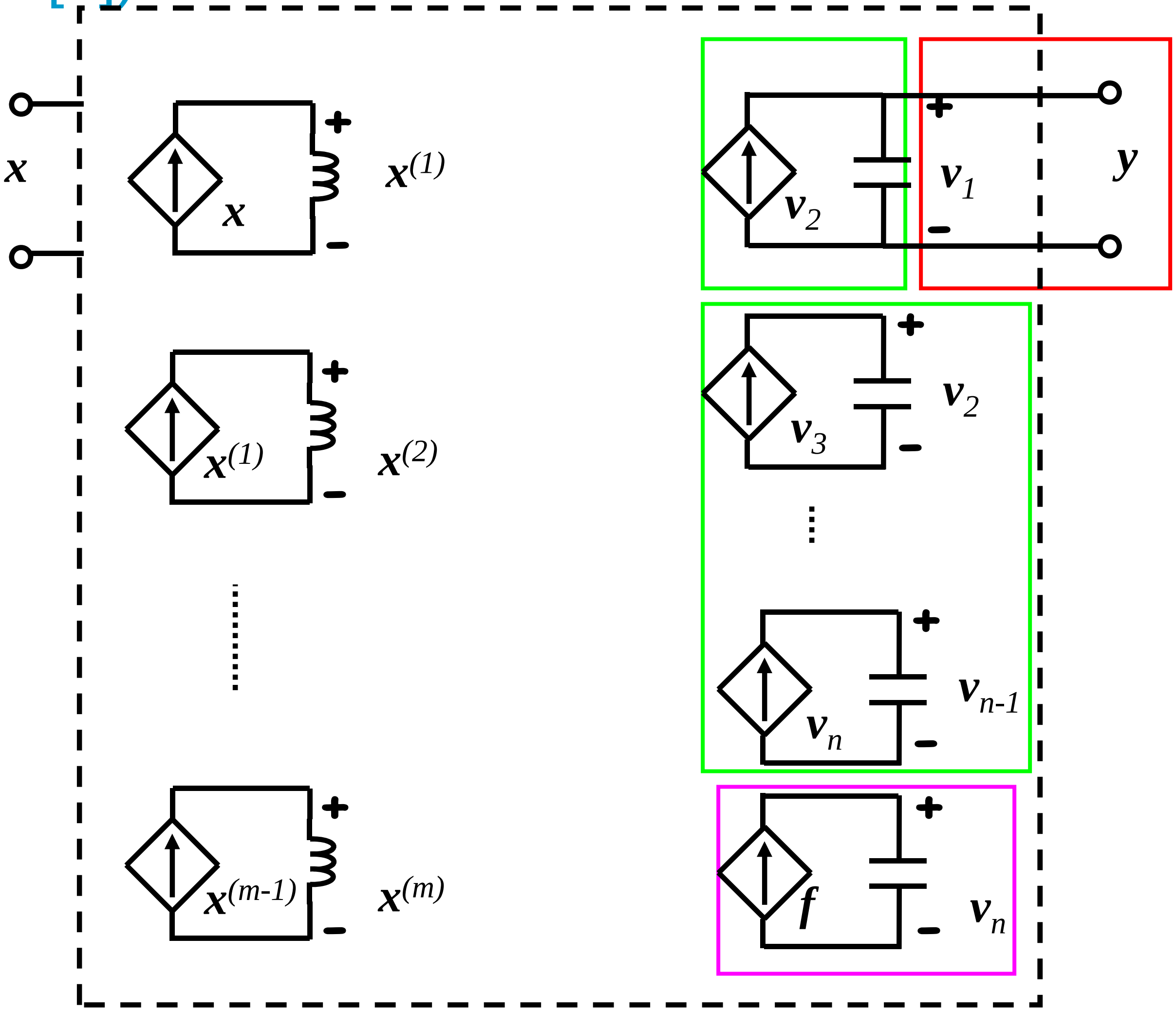
$$y^{(n)} = f(y^{(n-1)}, \ldots y, x, \dot{x}, \ldots x^{(m)})$$

$$v_1 = y$$

$$\dot{v}_1 = v_2$$

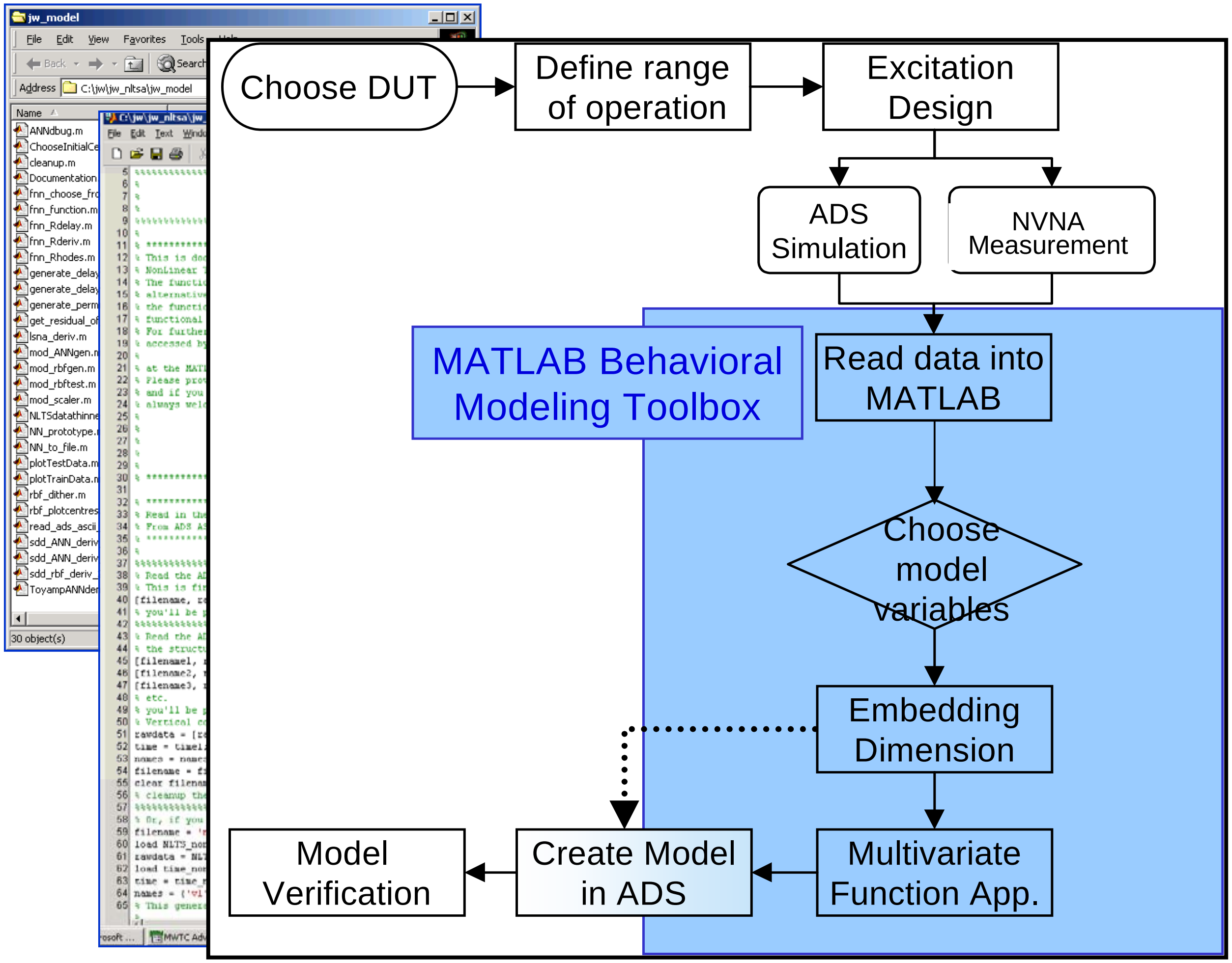
$$\vdots$$

$$\dot{v}_{n-1} = v_n$$



$$\dot{v}_n = f(v_{n-1}, v_{n-2}, \ldots, v, x, \dot{x}, \ldots, x^{(m)})$$

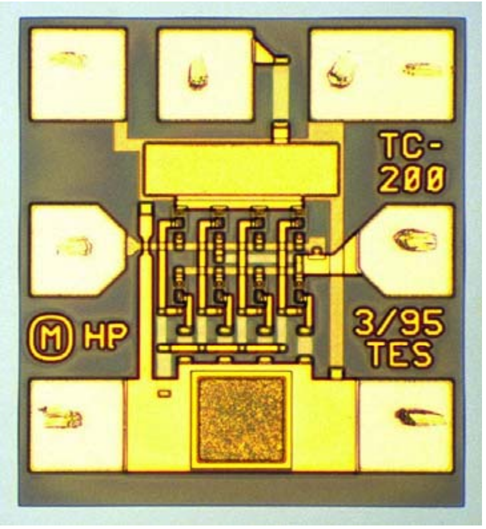
# NLTSA modeling flow

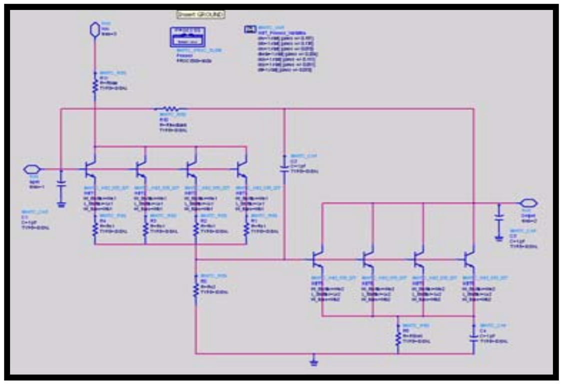


- *MATLAB* Toolbox, plus 3$^{rd}$-party software
- ‘*NLTSfile*’ structure
- ADS/NVNA-*MATLAB* interfaces
- ADS templates for
  - simulation
  - data display
  - model verification
- Model as SDD in ADS

# Example: GaAs HBT MMIC

Actual Circuit





Detailed ckt model

**DC-20 GHz GaAs HBT**

**(Agilent HMMC 5200 Amp)**

**Series-Shunt Amplifier**

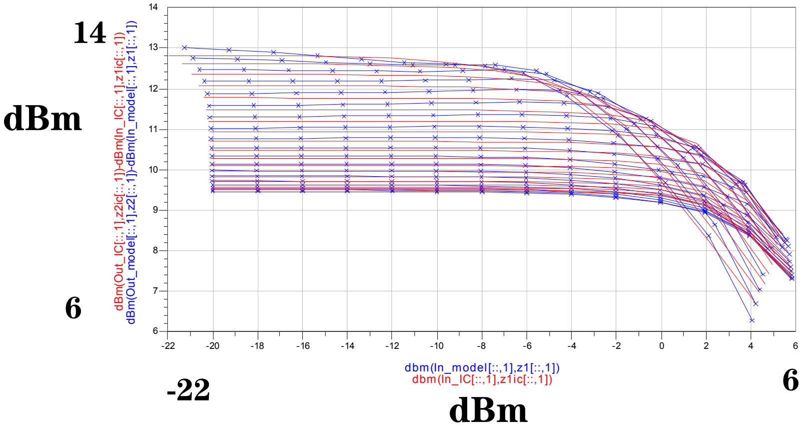
**Gain: 9.5 dB @ 1.5GHz**

# Results: NLTS Accuracy and Speed [1,6]

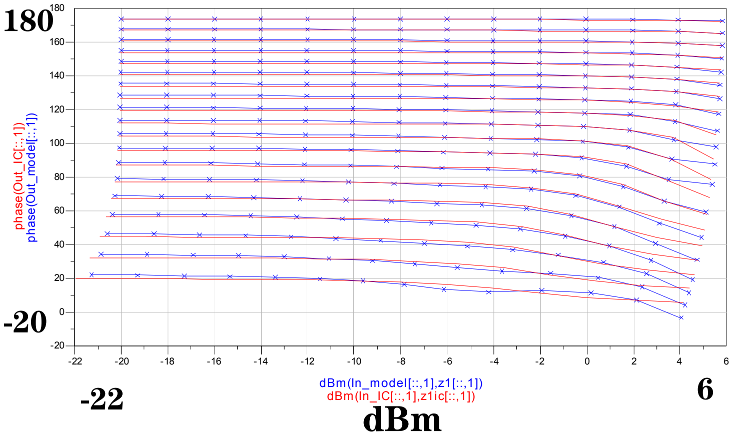
NLTS Behavioral model

Circuit model data

Fundamental Gain



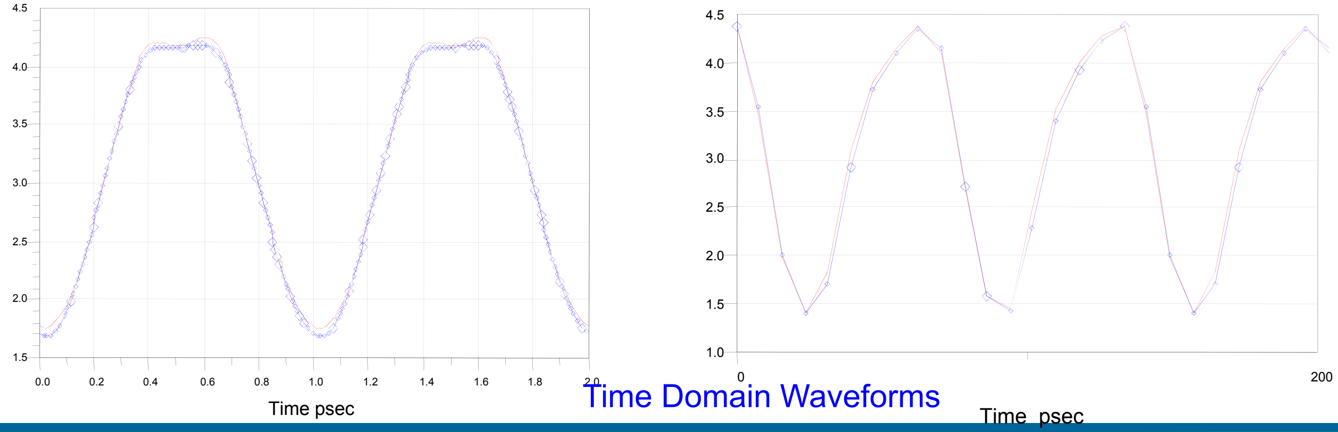
Fundamental Phase



**1 - 19 GHz**

$$I_i(t) = f_i(\dot{I}_i, V_1(t), V_2(t), \dot{V}_1(t), \dot{V}_2(t), V_1^{(2)}(t), V_2^{(2)}(t))$$

19 neurons

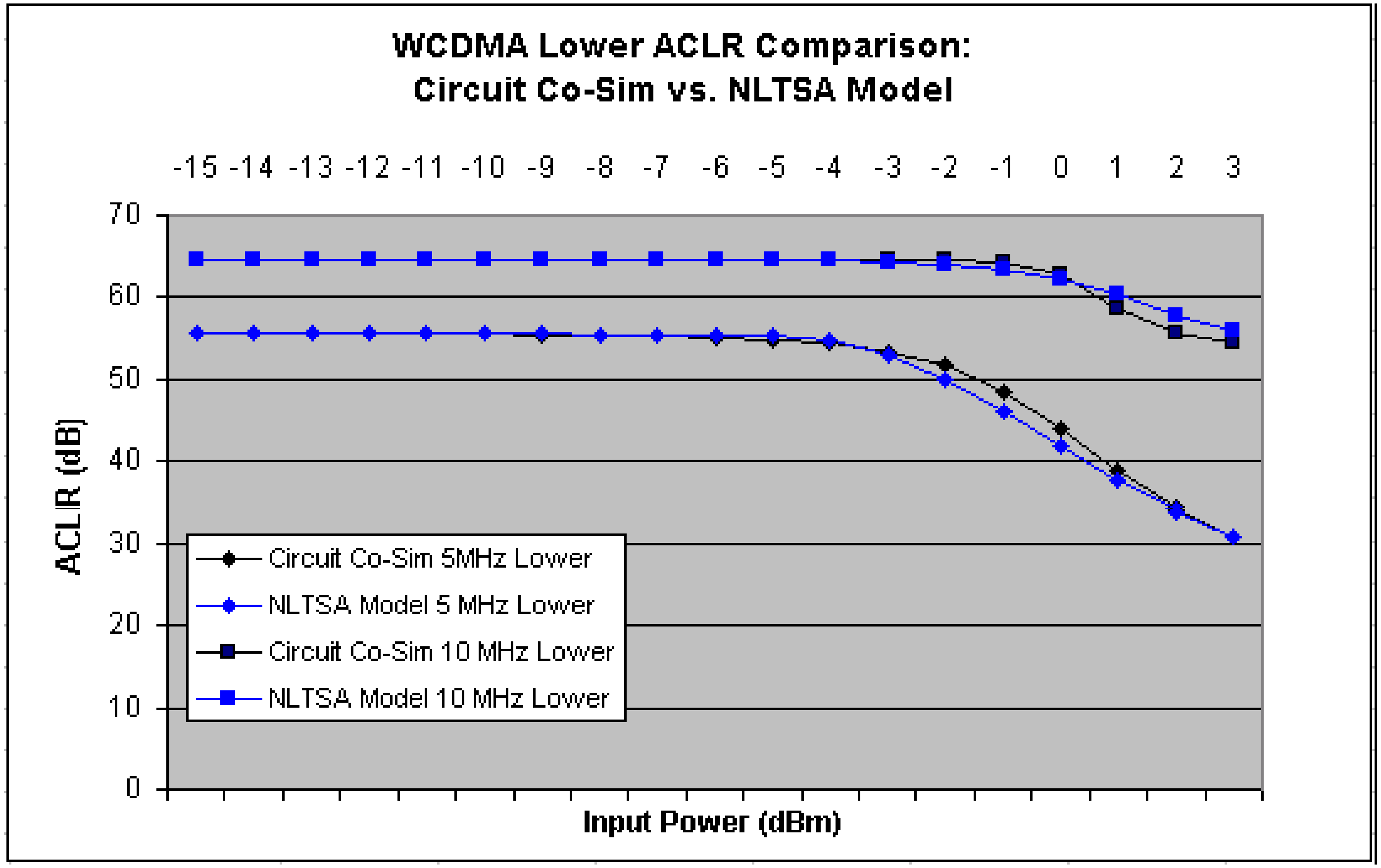


Time Domain Waveforms

**229.68 seconds**

**11315.67 seconds**

# Circuit Co-Simulation vs. NLTSA Model Results 3GPP WCDMA (lower) ACLR



**3GHz WCDMA**

**Model generated from only sinusoidal signals**

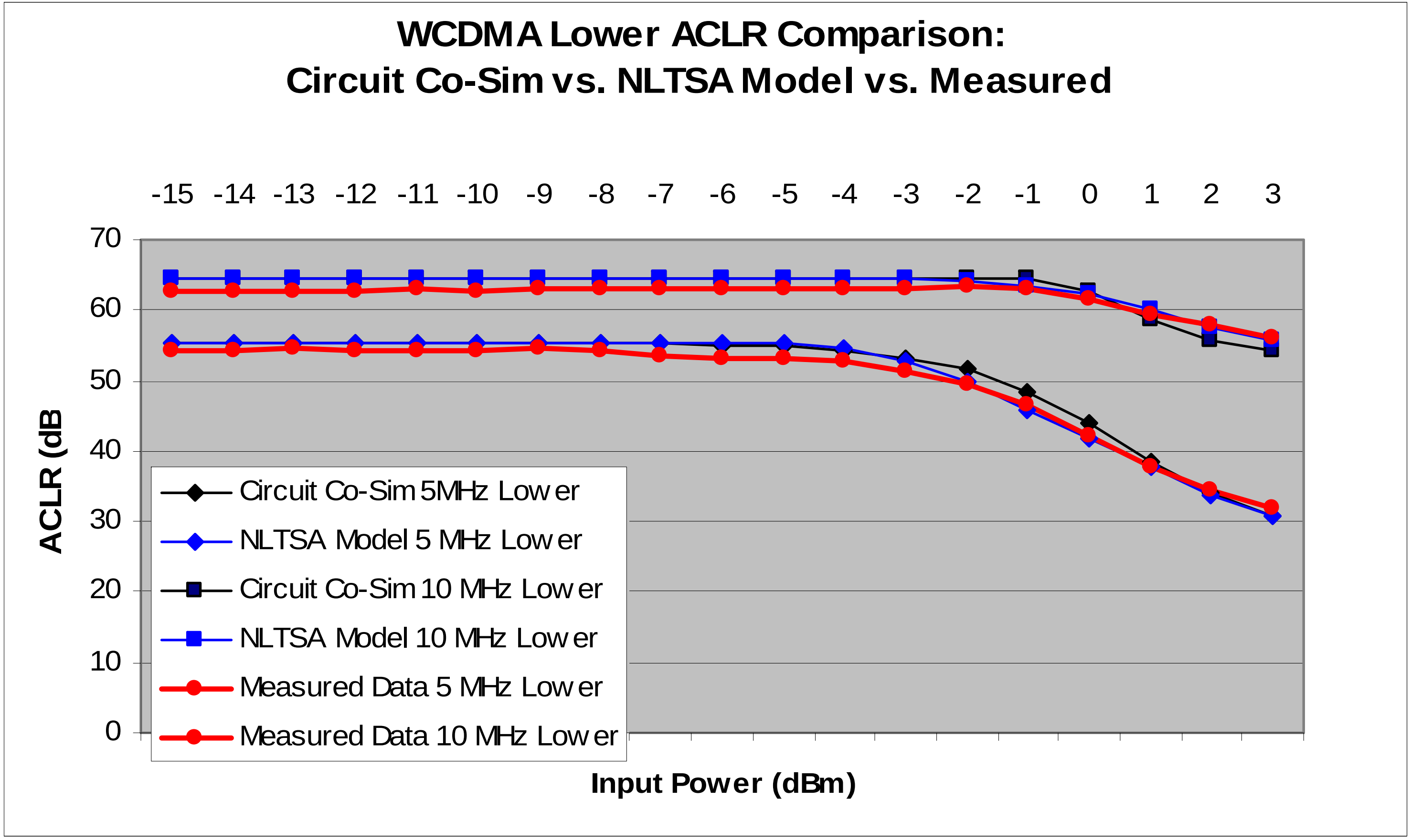
**294 sec/pt NLTS**

**1532 sec/pt Ckt.**

**40 neuron model**

Courtesy Greg Jue

# Circuit Co-Simulation vs. NLTSA Behavioral Model Results vs. Measured 3GPP WCDMA (lower) ACLR



**3GHz simulated**

**2.4GHz meas**

**Model is also *cascadable***

**Model works in TA, HB, Envelope**

# Outline

Introduction: Behavioral Models and NVNA

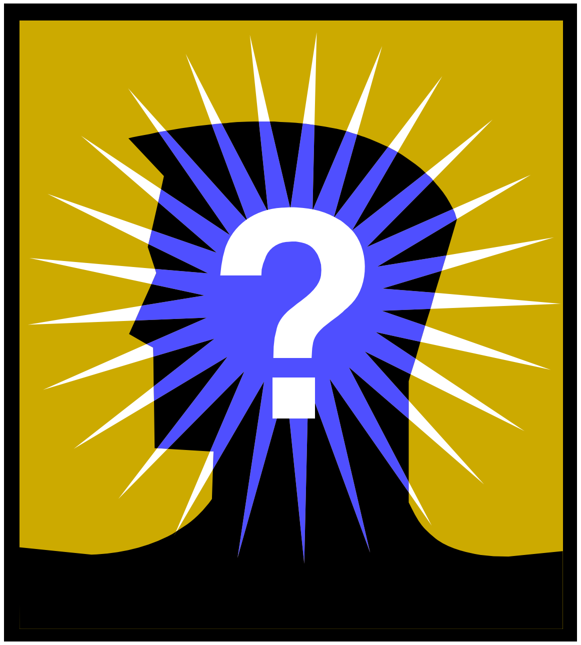
Functional Block Models

- Nonlinear Time Series
- X-parameters (PHD Model) in the Frequency Domain
- Mixed Time-Frequency Methods

Summary and Conclusions

# X-parameters (PHD model): a *nonlinear* paradigm

## “Is there an analogue with linear S-parameters to help with the nonlinear problem?”



Frequency Domain description is natural for high-frequency, distributed systems

Natural for Harmonic Balance Algorithms and NVNA data

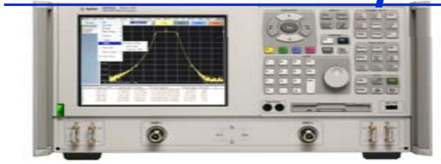
*Arbitrarily Nonlinear*; Not limited to Volterra Theory

# X-Parameters: The Nonlinear Paradigm

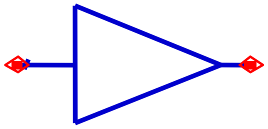
X-parameters are the mathematically correct superset of S-parameters, applicable to both large-signal and small-signal conditions, for linear and nonlinear components. *The math exists!*

We can measure, model, & simulate with X-parameters
Each part of the puzzle has been created
The pieces now fit together seamlessly

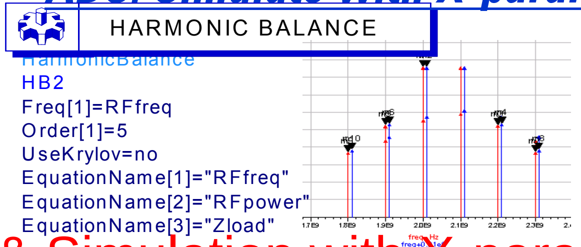
***NVNA: Measure X-params***



***X-parameter block***



***ADS: Simulate with X-params***



HarmonicBalance
HB2
Freq[1]=RFfreq
Order[1]=5
UseKrylov=no
EquationName[1]="RFfreq"
EquationName[2]="RFpower"
EquationName[3]="Zload"

Interoperable Nonlinear Measurement, Modeling & Simulation with X-params

“X-parameters have the potential to do for characterization, modeling, and design of nonlinear components and systems what linear S-parameters do for linear components & systems”

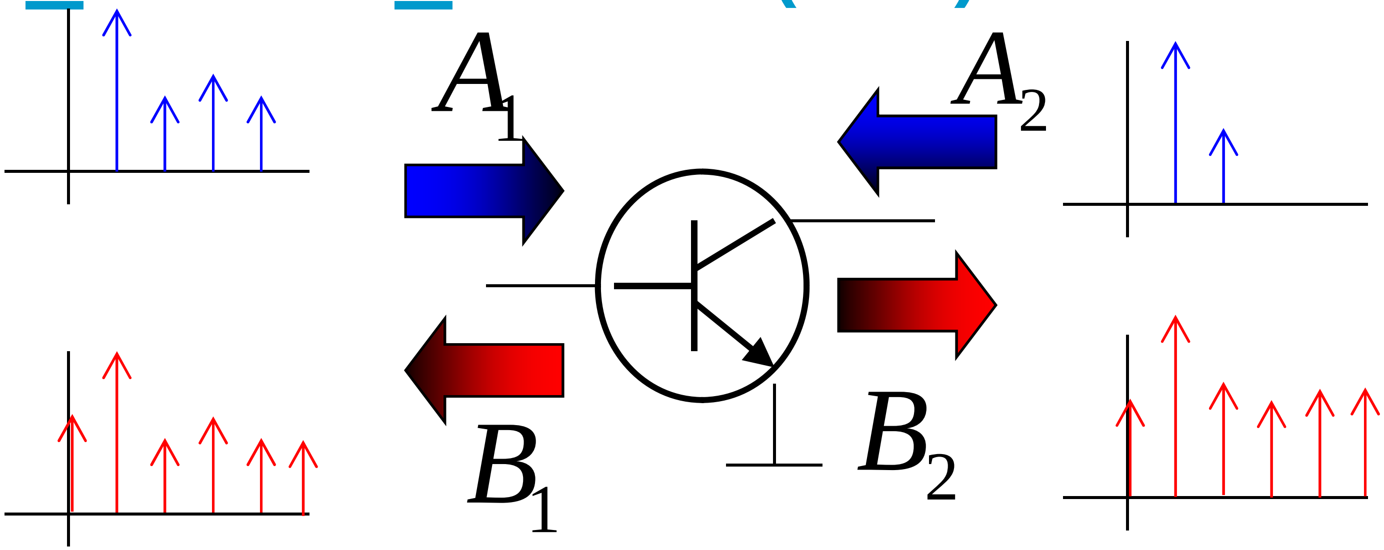
# X-Parameters: Why They are Important:

## Predict performance of cascaded NL components

Cascaded Nonlinear Amplifiers:
X-parameters enable nonlinear simulation from measured data in the presence of mismatch

- Unambiguously identifiable from a simple set of measurements
- Extremely accurate for high-frequency, distributed nonlinear systems
- Fully nonlinear vector quantities (Magnitude *and* phase of all harmonics)
- Cascadable (correct behavior in mismatched environment)

# X-parameters come from the Poly-Harmonic Distortion (PHD) Framework [3-6,12]



$$B_{1k} = F_{1k}(DC, A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots)$$
$$B_{2k} = F_{2k}(DC, A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots)$$

Port Index

Harmonic (or carrier) Index

Spectral map of complex *large* input phasors to *large* complex output phasors

Black-Box description holds for transistors, amplifiers, RF systems, etc.

# X-parameters: Simplest Case - driven with single large tone at port 1 [1] (derivation in lecture 2)

$$B_{e,f} = F_{e,f}(DC, A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots)$$

Concept: simplify general nonlinear spectral mapping by spectral linearization

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

Perfectly matched response

Mismatch terms:
linear in $A_{gh}$

Mismatch terms:
linear in $A^{*}_{gh}$

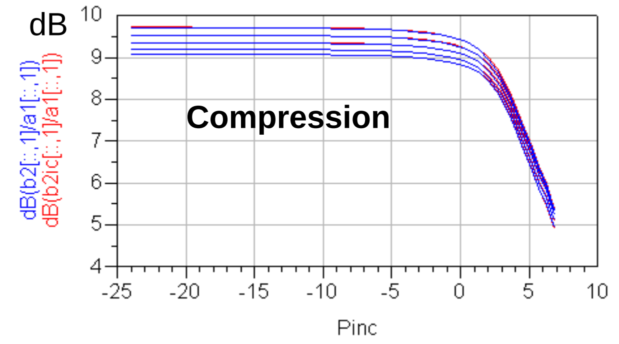
Not both g and h =1 in sums

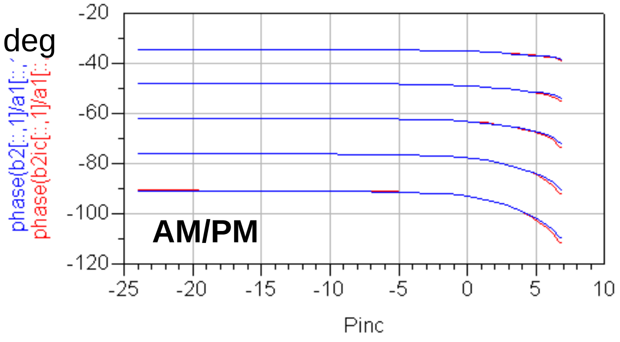
$$P = e^{j\varphi(A_{11})}$$

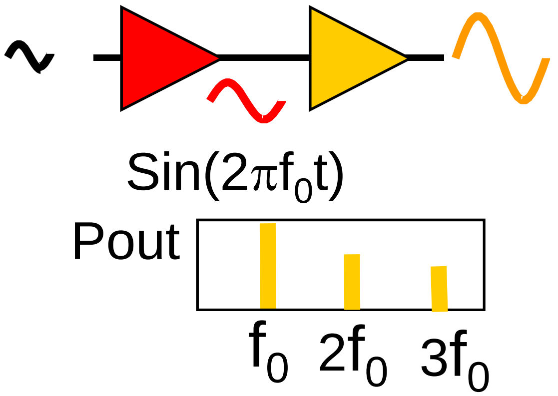
Phase terms come from time-invariance:

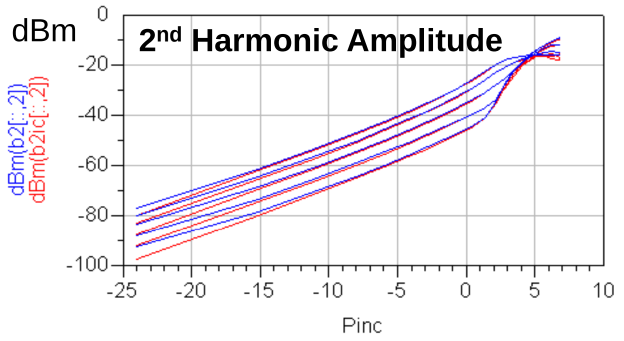
"Output of delayed input is just the delayed output"

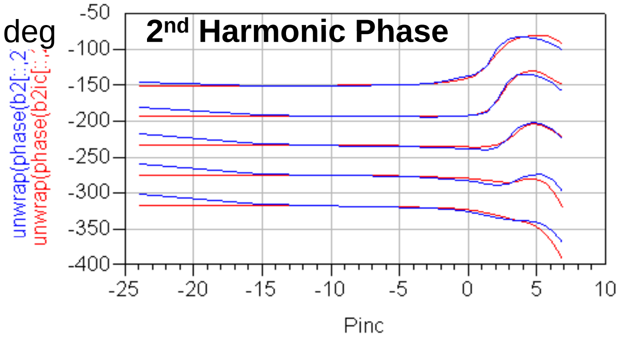
# X-parameter Results: Cascadability of Nonlinear Blocks







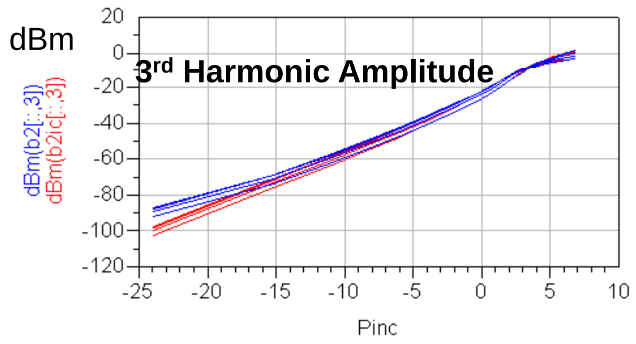


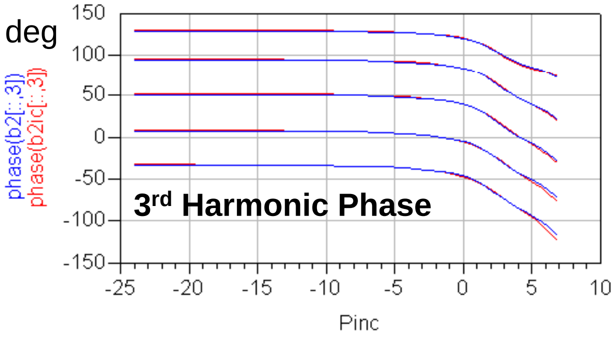


Cascaded PHD models

Cascaded Ckt. Models

0.6GHz – 6.0GHz

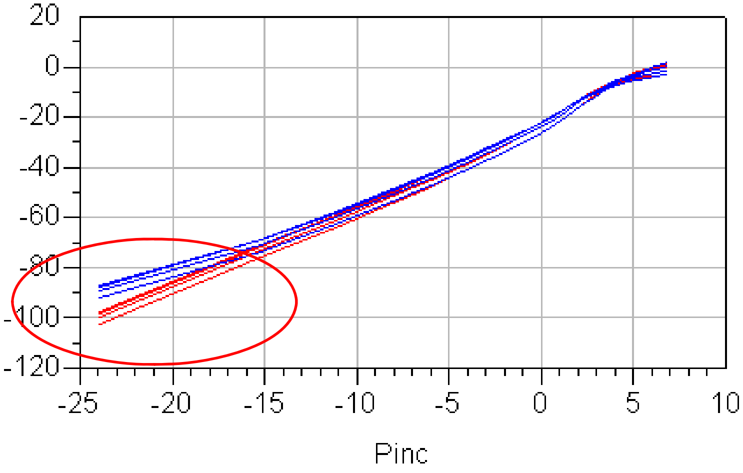


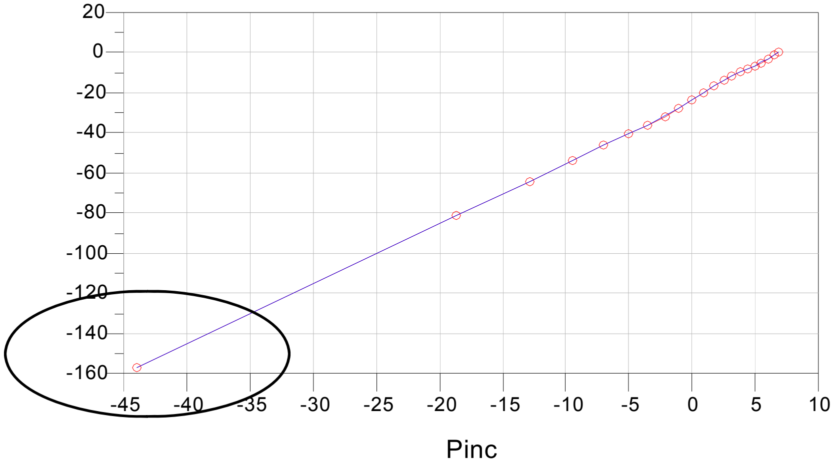


Does for distortion of *nonlinear components* what S-parameters do for linear components

# Improved Asymptotic Behavior

Volterra Theory Constraints Added for
Improved asymptotic behavior at low power

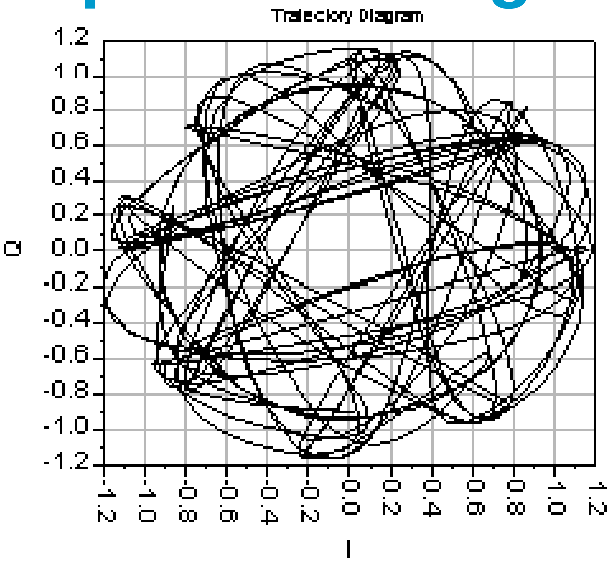


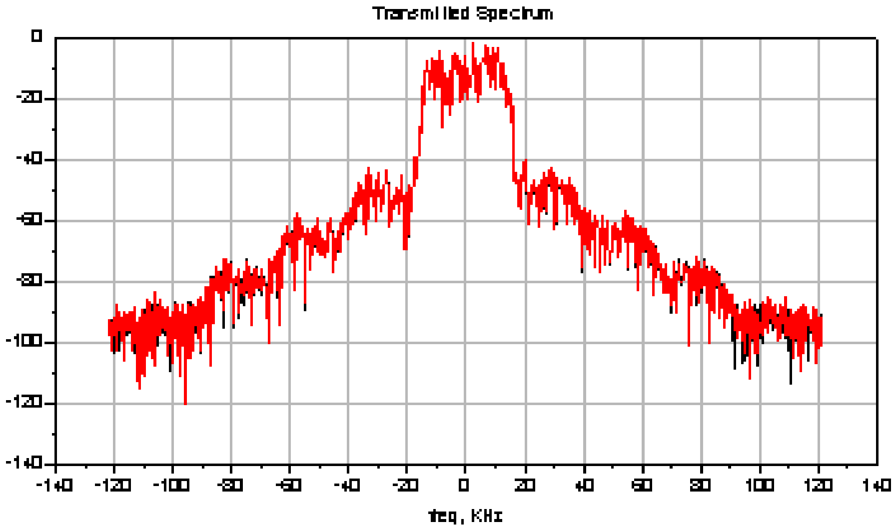


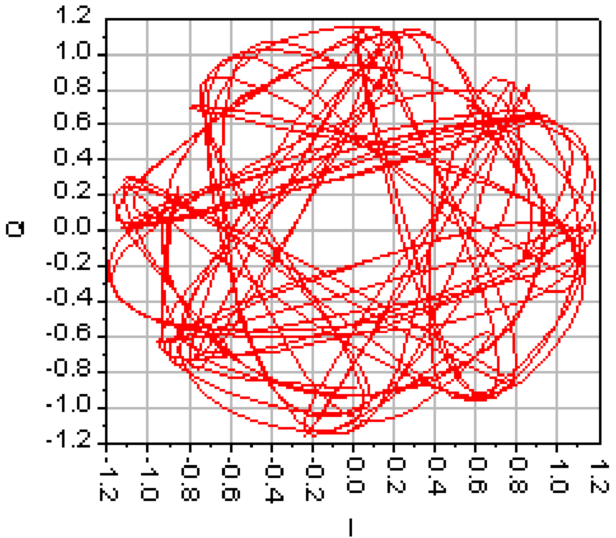
# X-parameters: HMMC 5200 Response to Digital Modulation

Circuit Model

X-parameters generated from ckt model



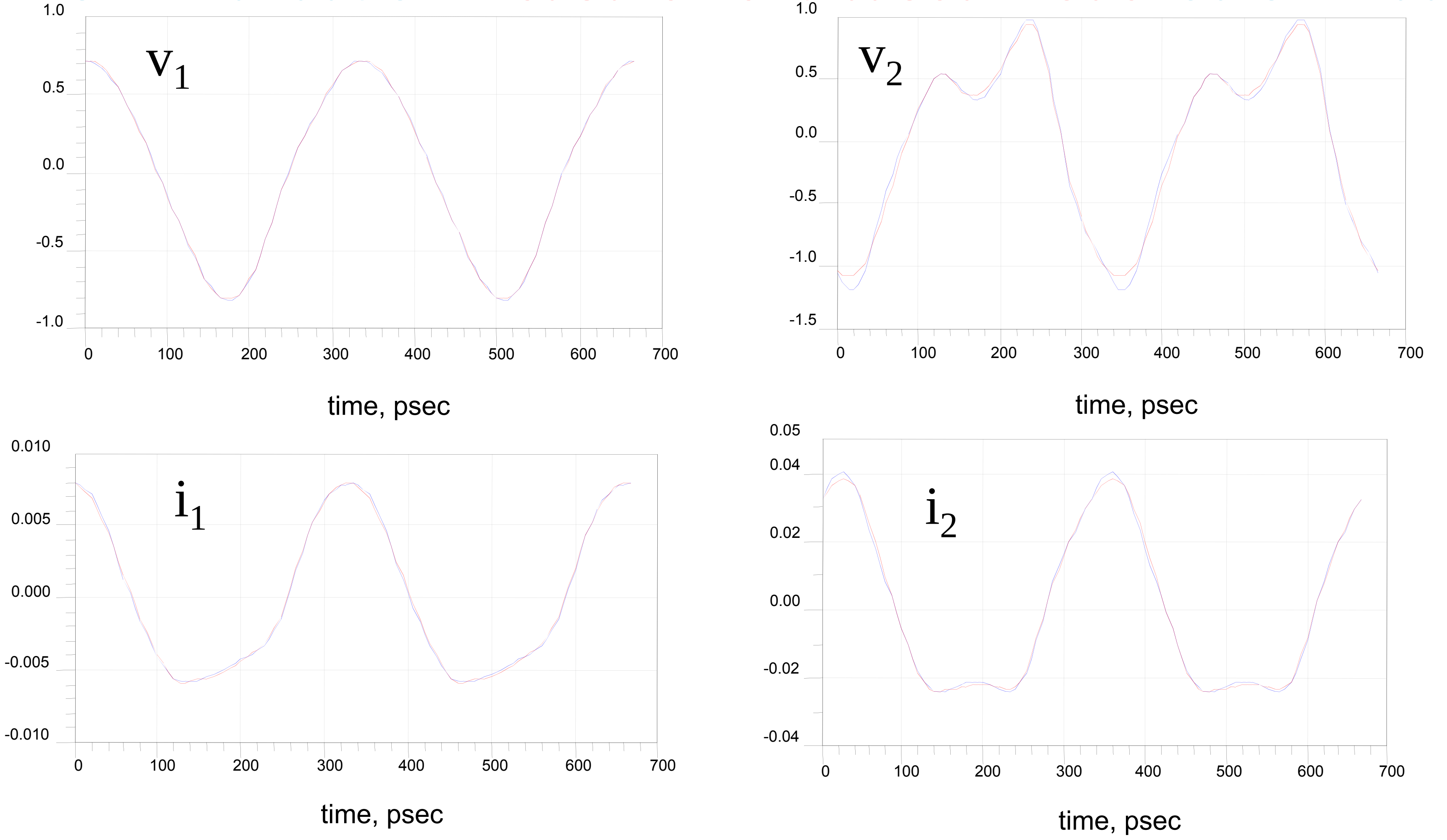




Excellent Results from Simple Excitations

# X-parameter Results: Transportability

## 27 Ohm validation measurement-based model 50 Ohm data



Measurement-Based X-parameter Model      Independent NVNA Data

# Rough Comparison of Methods and Applicability

**NLTSA**

Works in TA, HB, Envelope

Excellent for strongly nonlinear, but lumped (low order ODE) systems

Training non-algorithmic

Experiment design not fully solved

Not as robust for convergence

Scales well with complexity

Great gains in simulation speed

**X-Parameters**

Frequency Domain natural for highly linear, distributed, broad-band ckts

Experiment Design completely solved

Highly automated Model Identification

Works in HB & Envelope

Very robust for convergence

Always accurate if sampled densely

Complexity increases rapidly for multiple tones

# Outline

Introduction: Behavioral Models and NVNA

Functional Block Models

- Nonlinear Time Series
- X-parameters (PHD Model) in the Frequency Domain
- Mixed Time-Frequency Methods

Summary and Conclusions

# Envelope Domain for Long-Term Memory [7,8]

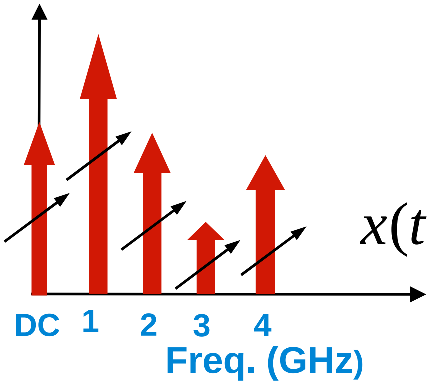
Applies to systems under large-signal modulated drives

Time-varying spectra for all inputs, outputs, & state variables

Perfectly suited for Circuit Envelope Analysis

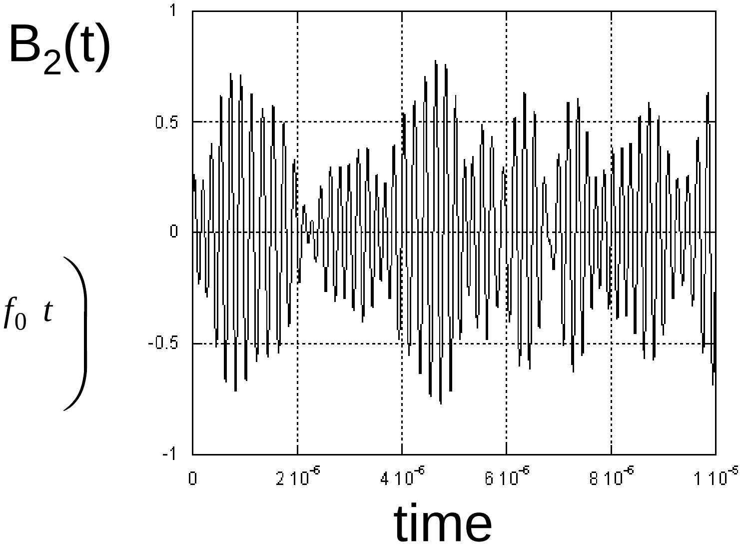
Well-matched for data from Nonlinear Vector Network Analyzer

Time-varying spectrum



$$x(t) = \mathrm{Re}\left( \sum_{h=0}^{H} X_h(t) \quad e^{j\ 2\pi\ h\ f_0\ t} \right)$$

Time Domain (envelope)



$X_h(t)$ set of *complex* (amplitude and phase) *waveforms* at each harmonic index h
Modeling problem: *map input envelopes to output envelopes*

# Envelope Domain for Long-Term Memory [7,8]

## *Merge* Frequency and Time Domains

Spectral mapping $B_{pk} = X_{pk}^{(F)}(A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots)$

$\rightarrow$ a differential equation *in the envelope domain*

$$\hat{B}_k = f_k(\hat{B}_k^{(1)}(t), \ldots, \hat{B}_k^{(n)}(t), \hat{A}_l(t), \hat{A}_l^{(1)}(t), \ldots, \hat{A}_k(t), \ldots, \hat{A}_k^{(m)}(t))$$

Order of time derivative

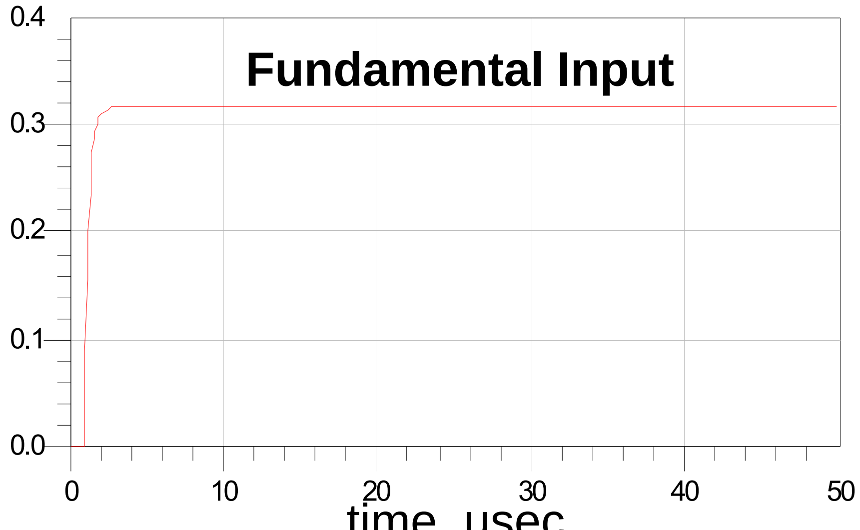
Envelope or carrier index

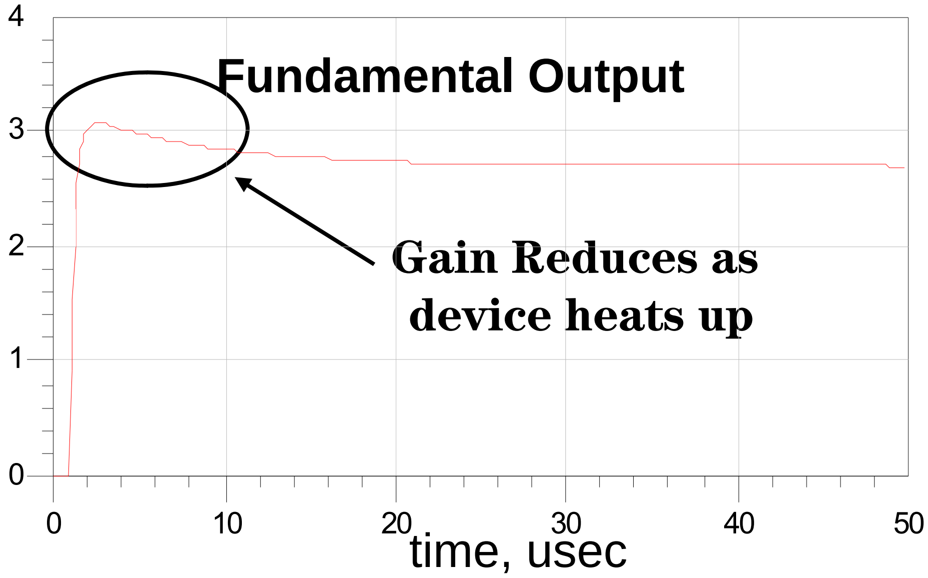
Example:

$$\hat{B}_{21}(t) = f_{21}(\hat{B}_{20}(t), \hat{A}_{11}(t))$$

$$\frac{d\hat{B}_{20}(t)}{dt} = g(\left\langle \left| \hat{A}_{11}(t) \right|^2 \right\rangle, \hat{B}_{21}(t))$$

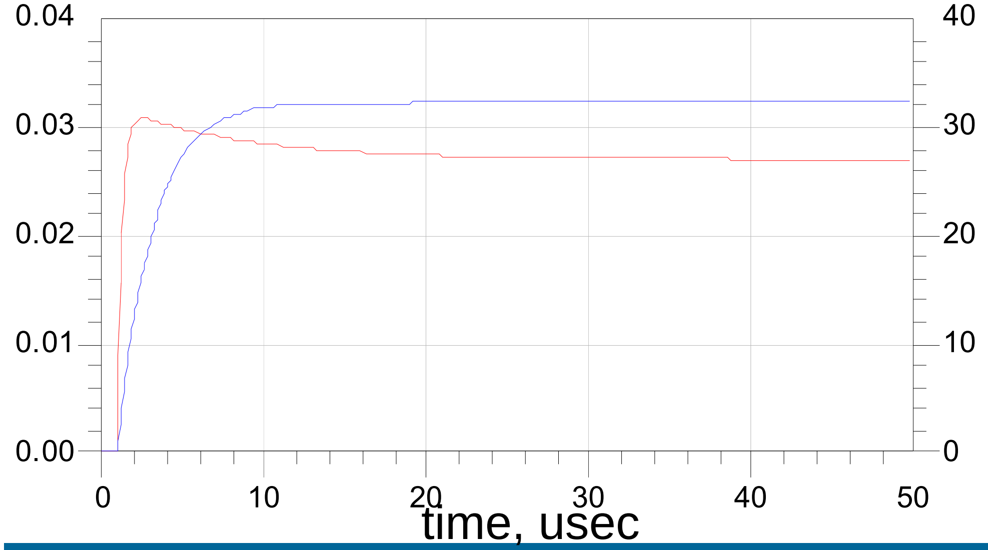
# Envelope Model: Amplifier with Self-Heating [8]


Fundamental Input


Fundamental Output

Gain Reduces as device heats up

**Third Harmonic Output Mag & Phase**



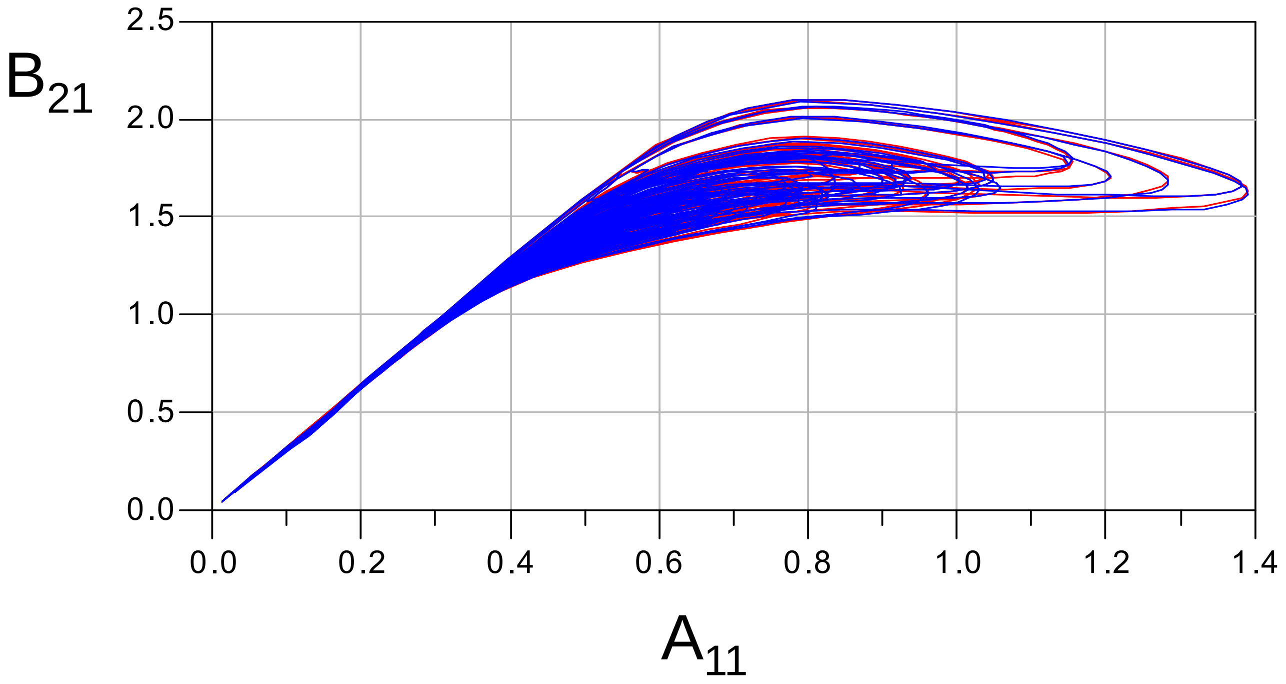
Pulsed RF signal at 1GHz:
Thermal Time Const. 10usec

Systematic approach to identifying “hidden” state variables for long-term memory IMS2007 [13]

# Dynamic Long-Term Memory PHD Models Envelope Differential Equations in ADS [7,8,13]

Verspecht et al in *2007 International Microwave Symposium Digest* [13]

X-parameters with dynamic memory (red)
compared to circuit-level model (blue)



# Conclusions

Powerful nonlinear device & behavioral modeling approaches in time, frequency, and mixed domains have been presented

- X-parameters are mature. Commercial solutions to measure, model, and simulate are available, supported, and expanding (see lecture 2).
- Time-domain (NLTSA) techniques could become practical soon.
- Envelope domain (dynamic X-parameters) is attractive for memory.

Emergence of commercially available Large-Signal HW & SW

- e.g. NVNA on modern PNA-X platform [9,14]
- e.g. nonlinear simulators with built-in XnP components & X-param analysis

Great opportunity for applications

- Specification of active components by *X-parameters*
- Device and behavioral modeling applications of NVNA measurements
- Stability analysis and matching power amplifiers under drive
- Active Signal Integrity

# References

[1] J. Wood, D. E. Root, N. B. Tufillaro, “A behavioral modeling approach to nonlinear model-order reduction for RF/microwave ICs and systems,” *IEEE Transactions on Microwave Theory and Techniques,* Vol. 52, Issue 9, Part 2, Sept. 2004 pp. 2274-2284

[2] Agilent HMMC-5200 DC-20 GHz HBT Series-Shunt Amplifier, Data Sheet, August 2002.

[3] J. Verspecht, M. Vanden Bossche, F. Verbeyst, “Characterizing Components under Large Signal Excitation: Defining Sensible `Large Signal S-Parameters'?!,” in *49th IEEE ARFTG Conference Dig*., Denver, CO, USA, June 1997, pp. 109-117.

[4] J. Verspecht, D.E. Root, J. Wood, A. Cognata, “Broad-Band, Multi-Harmonic Frequency Domain Behavioral Models from Automated Large-Signal Vectorial Network Measurements,” in *2005 IEEE MTT-S International Microwave Symposium Digest*, Long Beach, CA, USA, June 2005.

[5] D. E. Root, J. Verspecht, D. Sharrit, J. Wood, and A. Cognata, “Broad-Band Poly-Harmonic Distortion (PHD) Behavioral Models from Fast Automated Simulations and Large-Signal Vectorial Network Measurements”, *IEEE Transactions on Microwave Theory and Techniques* Vol. 53. No. 11, November, 2005 pp. 3656-3664

[6] J. Wood, D. E. Root, editors, **Fundamentals of Nonlinear Behavioral Modeling for RF and Microwave Design**, 1st ed. Norwood, MA, USA, Artech House, 2005.

[7] Root et al US Patent Publication # US2005102124 AA, Published 2005

[8] D. E. Root, D. Sharrit, J. Verspecht, “Nonlinear Behavioral Models with Memory: Formulation, Identification, and Implementation,” *2006 IEEE MTT-S International Microwave Symposium Workshop (WSL) on* Memory Effects in Power Amplifiers

[9] Blockley et al *2005 IEEE MTT-S International Microwave Symposium Digest*, Long Beach, CA, USA, June 2005.

[10] Jan Verspecht Patent US 7,038,468 B2
(issued May 2, 2006 based on a provisional patent 60/477,349 filed on June 11, 2003)

[11] Soury et al *2005 IEEE International Microwave Symposium Digest* pp. 975-978

[12] J. Verspecht and D. E. Root, “Poly-Harmonic Distortion Modeling,” *in IEEE Microwave Theory and Techniques Microwave Magazine*, June, 2006.

[13] J. Verspecht, D. Gunyan, J. Horn, J. Xu, A. Cognata, and D.E. Root, “Multi-tone, Multi-Port, and Dynamic Memory Enhancements to PHD Nonlinear Behavioral Models from Large-Signal Measurements and Simulations,” *2007 IEEE MTT-S Int. Microwave Symp. Dig.*, Honolulu, HI, USA, June 2007.

[14] Horn et al 2008 Power Amplifier Symposium, Orlando, Jan. 2008

# X-parameters*:

## A new paradigm for measurement, modeling, and design of nonlinear microwave & RF components

Dr. David E. Root
Principal R&D Scientist
High Frequency Technology Center
Santa Rosa, CA USA

IEEE MTT-S DML Lecture #2
Bergen, Norway
May 7, 2010

* X-parameters is a trademark of Agilent Technologies, Inc.

# Key Contributors

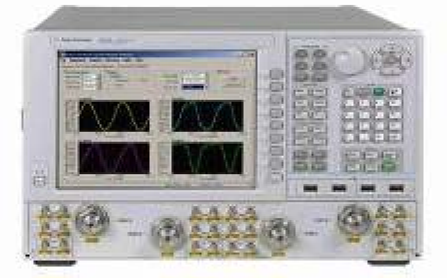
- Keith Anderson
- Loren Betts
- Radek Biernacki
- Chad Gillease
- Daniel Gunyan
- John Harmon
- Jason Horn
- Yuchen Hu
- Masaya Iwamoto
- Mihai Marcu
- Troels Nielson
- Greg Peters
- Mark Pierpoint
- Jack Sifri
- Mary Lou Simmermacher
- Gary Simpson
- Franz Sischka
- Darlene Solomon
- Tina Sun
- Yee Ping Teoh
- Dan Thomasson
- Jan Verspecht
- Kenn Wildnauer
- Jianjun Xu
- Yoshiyuki Yanagimoto

# Outline

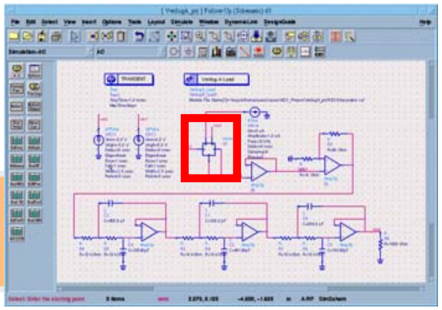
- Introduction: X-parameter Basics
- Survey of X-parameter benefits and applications
- Summary
- References and Links

# X-Parameters: Mainstream Nonlinear Interoperable Technology

Agilent Nonlinear Vector Network Analyzer



Electronic design automation software

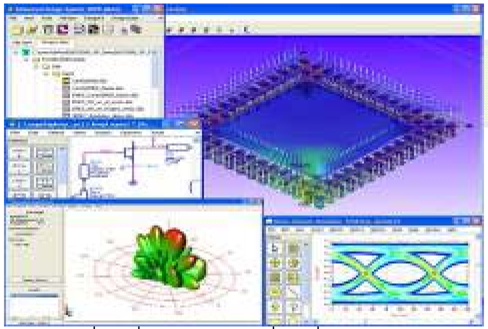


Nonlinear Measurements

Nonlinear Simulation & Design

Nonlinear Modeling

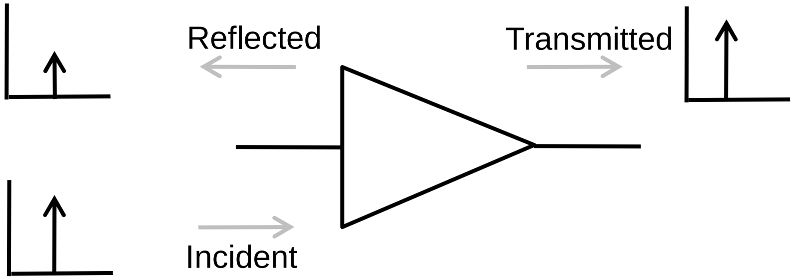
Customer Applications



$$B_{pm} = X^{F}_{pm}(|A_{11}|) + X^{S}_{pm,qn}(|A_{11}|)P^{m-n}A_{qn} + X^{T}_{pm,qn}(|A_{11}|)P^{m+n}A^{*}_{qn}$$

# S-parameters Solve All Small-Signal Problems

## But devices must operate linearly



Reflected

Transmitted

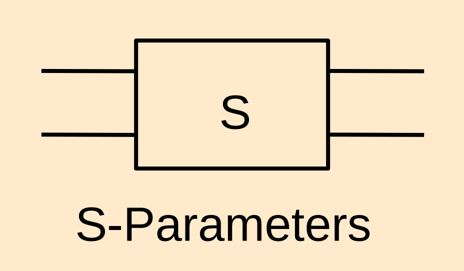
Incident

*Measure*

Agilent Vector Network Analyzer

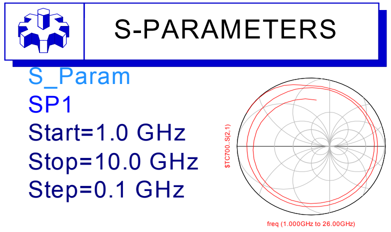
*Model*

$$B_1 = S_{11}A_1 + S_{12}A_2$$
$$B_2 = S_{21}A_1 + S_{22}A_2$$

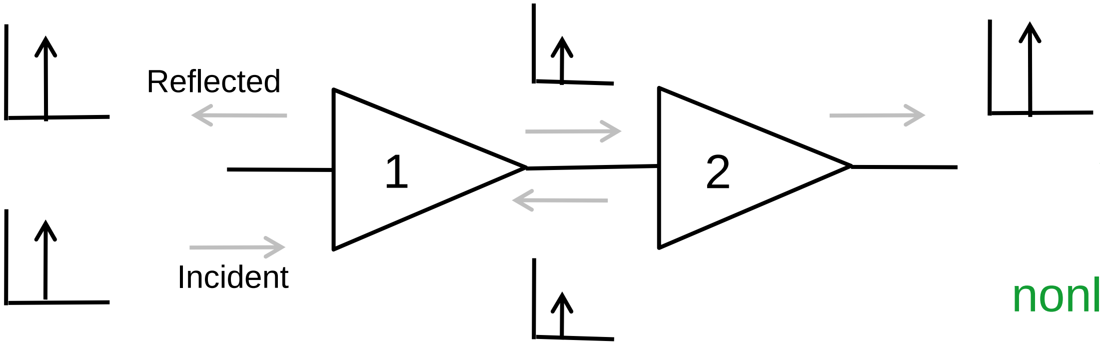


S-Parameters

*Design*



S_Param
SP1
Start=1.0 GHz
Stop=10.0 GHz
Step=0.1 GHz



Reflected

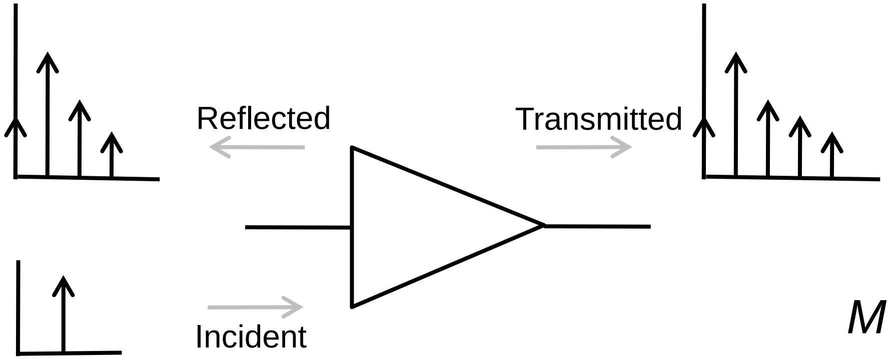
Incident

What about large-signal nonlinear problems?

# X-parameters Solve Nonlinear Problems

## Same use model as S-parameters, *but much more powerful*

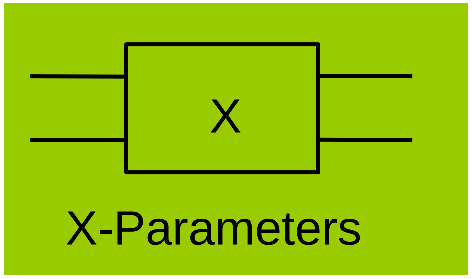
*Measure*



Nonlinear Vector
Network Analyzer

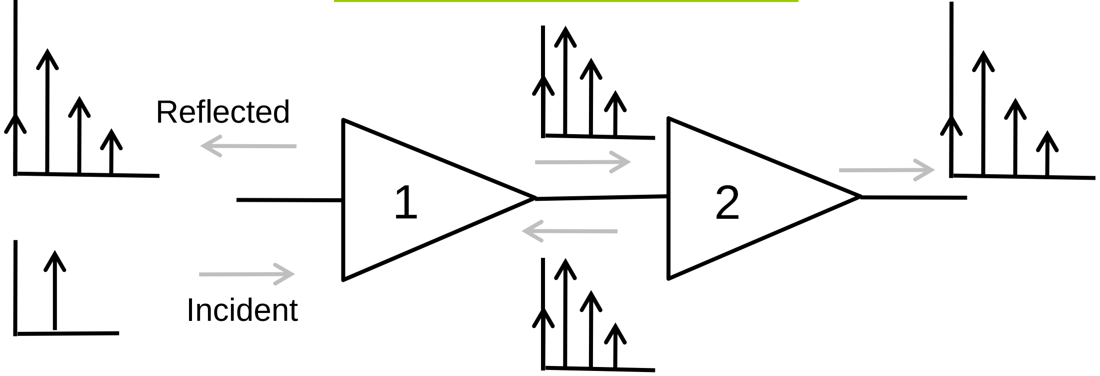
*Model*

$$
\begin{aligned}
B_{pm} &= X^{F}_{pm}(|A_{11}|)P^{m} \\
&+ X^{S}_{pm,qn}(|A_{11}|)P^{m-n}A_{qn} \\
&+ X^{T}_{pm,qn}(|A_{11}|)P^{m+n}A^{*}_{qn}
\end{aligned}
$$



*Design*

EDA Software



# Capturing the imagination of the industry

Solves real-world problems now

Interoperable characterization, modeling, and design solutions

Potential to do for nonlinear components and systems what S-parameters do for linear components and systems

Vol. 53 • No. 3

March 2010

Microwave Journal

X Parameters,

S-Functions, Poly-harmonic Distortion Models, Waveform Engineering, Hot S-22, NonLin-S, Active Harmonic Load Pull, NVNA, OpenWave Forum.

**Nonlinear Device Characterization** is heating up and everyone from test equipment manufacturers to software developers are involved. Will their efforts transform the microwave component industry?

MVP

Elektrobit MIMO-OTA Emulation

horizon house

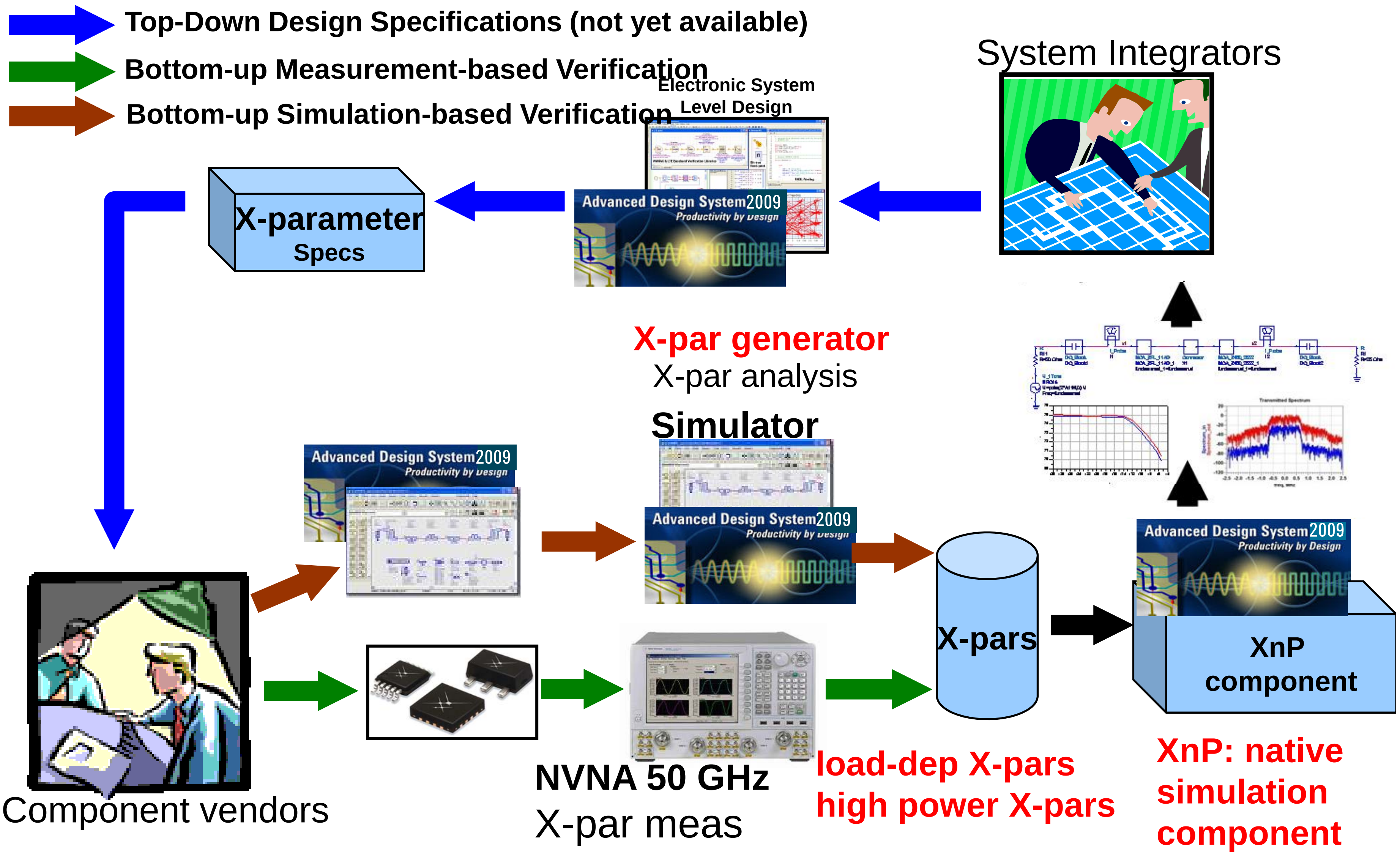
Founded in 1958

mwjournal.com

Changing the way the industry works

Continuous wave of innovations and award-winning research

# X-parameters: Hierarchical Design and Validation



- Top-Down Design Specifications (not yet available)
- Bottom-up Measurement-based Verification
- Bottom-up Simulation-based Verification

System Integrators

Electronic System Level Design

**X-parameter**
**Specs**

**X-par generator**
X-par analysis

**Simulator**

**X-pars**

**XnP**
**component**

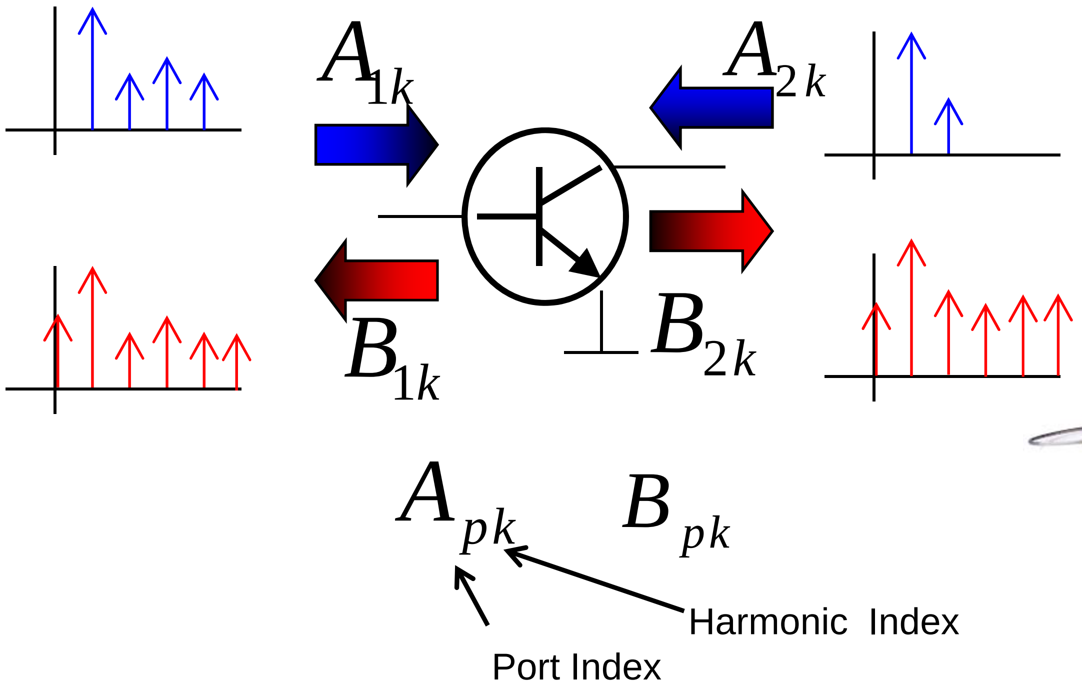
Component vendors

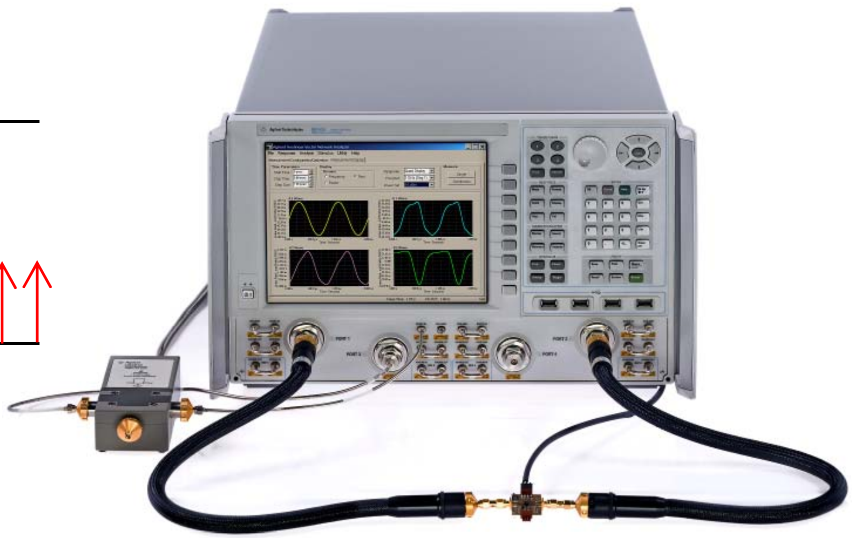
**NVNA 50 GHz**
X-par meas

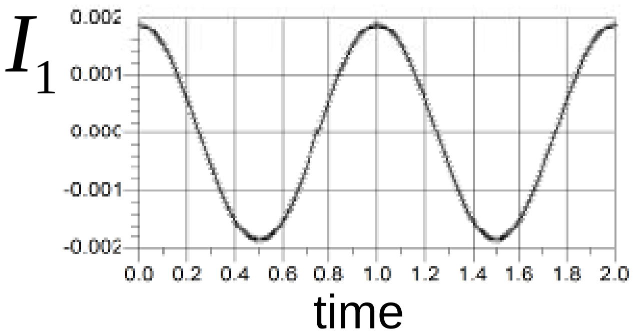
**load-dep X-pars**
**high power X-pars**

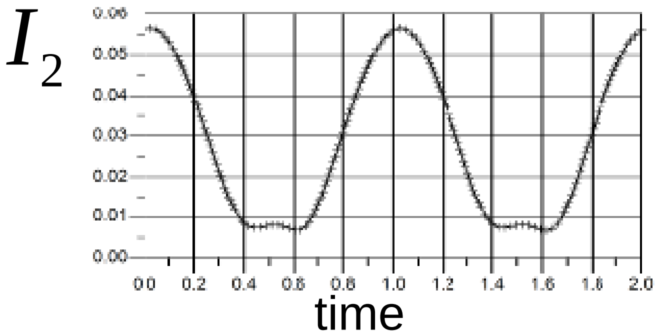
**XnP: native simulation component**

# Introduction: NVNA measurements complex spectra and waveforms







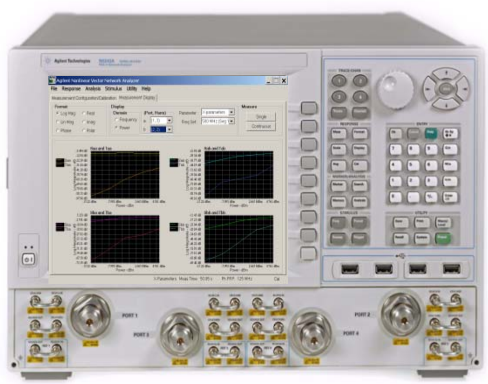


# Measurement-Based Modeling & Design Flow

“X-parameters enable predictive nonlinear design from NL data”

NVNA

Nonlinear Measurements

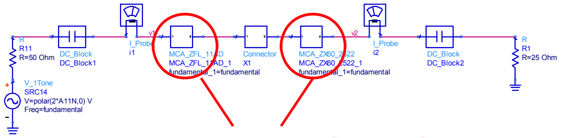


Data File

Drag and drop

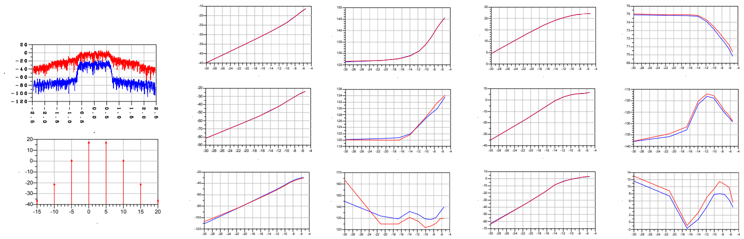
ADS

Simulation and Design



X-parameter blocks

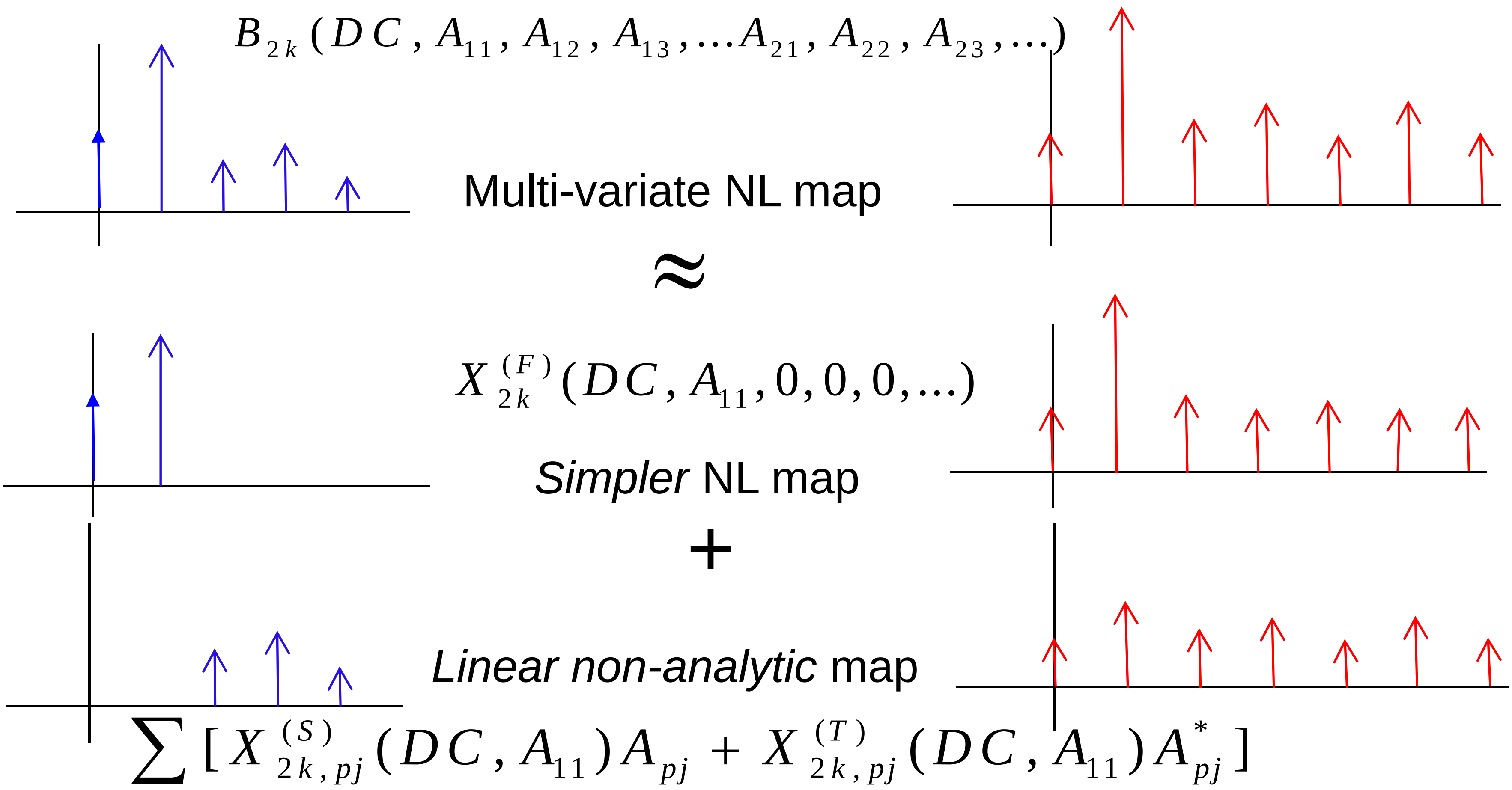
X-parameters enable accurate nonlinear simulation under small to moderate mismatch. (See later for large mismatch)



allowing prediction of component behavior in complicated nonlinear circuits.
IMD / ACPR exact in narrow-band limit

“X-parameters: the same use model as S-parameters *but much more powerful*”

# X-parameter Concept: Linearized Spectral Map around a Large-Signal Operating Point (LSOP)



Incident Port 1

Scattered Port 2

$$B_{2k}(DC, A_{11}, A_{12}, A_{13}, \ldots A_{21}, A_{22}, A_{23}, \ldots)$$

Multi-variate NL map

$$\approx$$

$$X_{2k}^{(F)}(DC, A_{11}, 0, 0, 0, \ldots)$$

*Simpler* NL map

$$+$$

*Linear non-analytic* map

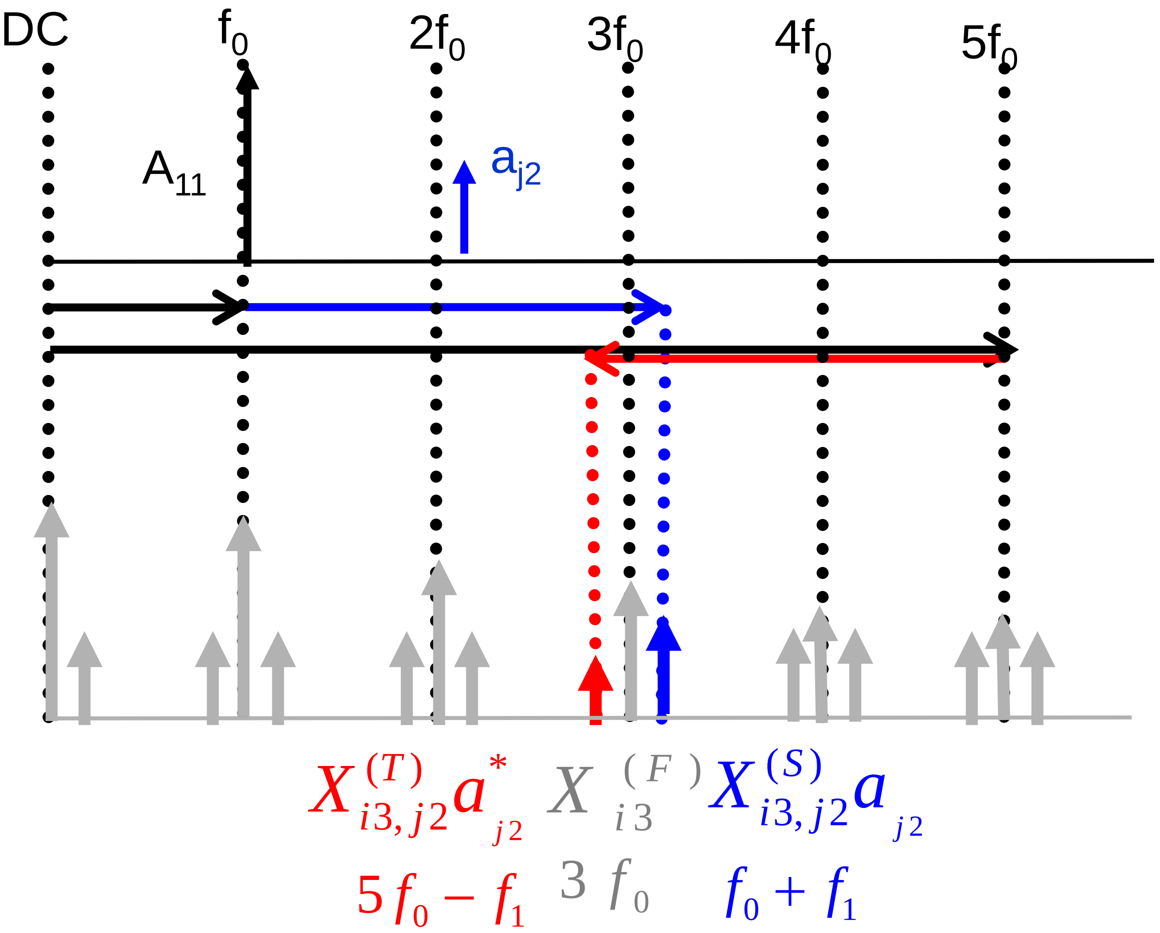
$$\sum [X_{2k,pj}^{(S)}(DC, A_{11}) A_{pj} + X_{2k,pj}^{(T)}(DC, A_{11}) A_{pj}^{*}]$$

X-pars include exact nonlinear mapping to totally linear (S-pars) & everything in between

*Trade simplicity for accuracy.*

# X-parameters: What they are & where they come from

- Scattering of multiple incident large-amplitude waves.
- Can be simplified according to linear or nonlinear dependence on inputs (simplicity vs accuracy)
- Measured on NVNA or generated in simulator
- Rules for computing the response to general signals given extracted X-parameters



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

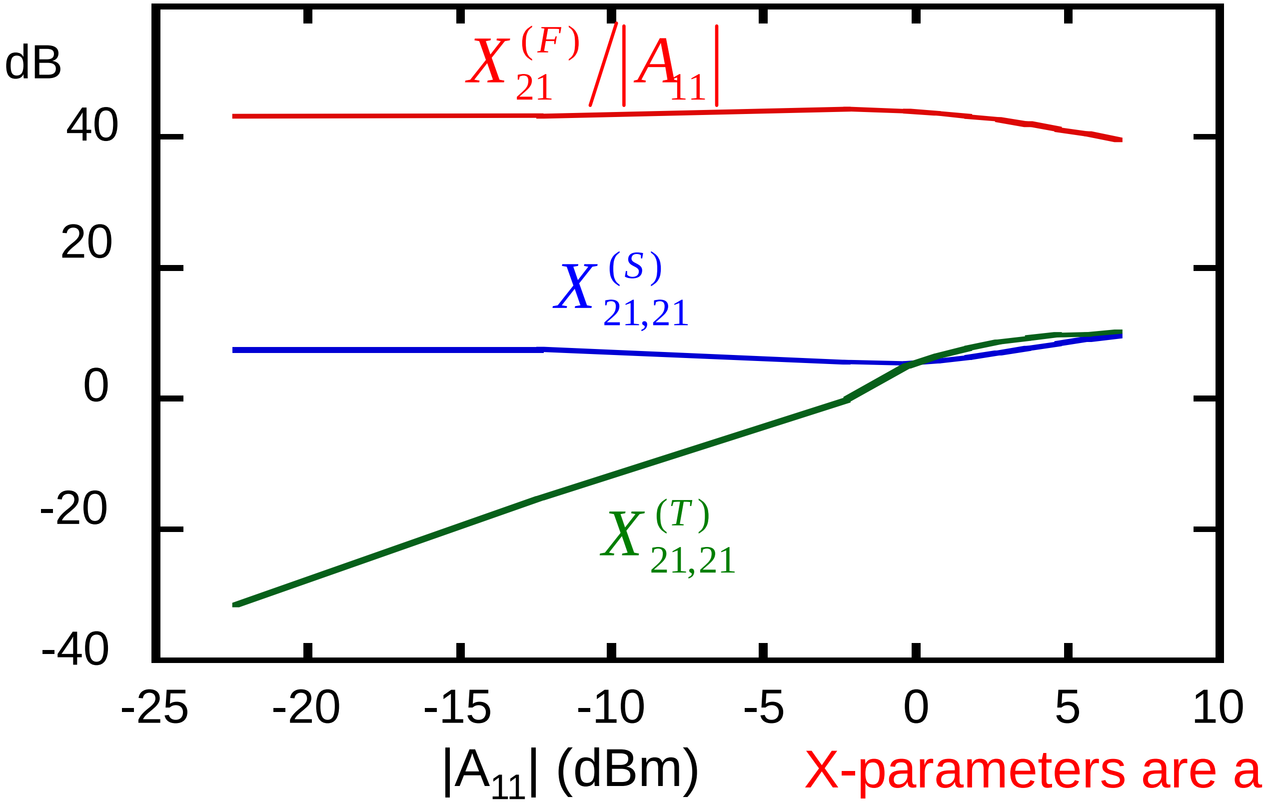
$$P = e^{j\varphi(A_{11})}$$

# Simplest X-parameters for a Power Amplifier

$$B_{11}(|A_{11}|) = X_{11}^{(F)}(|A_{11}|)P + X_{11,21}^{(S)}(|A_{11}|)A_{21} + X_{11,21}^{(T)}(|A_{11}|)P^2A_{21}^*$$

$$B_{21}(|A_{11}|) = X_{21}^{(F)}(|A_{11}|)P + X_{21,21}^{(S)}(|A_{11}|)A_{21} + X_{21,21}^{(T)}(|A_{11}|)P^2A_{21}^*$$

X-parameters reduce to (linear) S-parameters in the appropriate limit



$$X_{11}^{(F)}/|A_{11}| \xrightarrow[|A_{11}|\to 0]{} s_{11}$$

$$X_{21}^{(F)}/|A_{11}| \xrightarrow[|A_{11}|\to 0]{} s_{21}$$

$$X_{11,21}^{(S)}(|A_{11}|) \xrightarrow[|A_{11}|\to 0]{} s_{12}$$

$$X_{21,21}^{(S)}(|A_{11}|) \xrightarrow[|A_{11}|\to 0]{} s_{22}$$

$$X_{11,21}^{(T)}(|A_{11}|) \xrightarrow[|A_{11}|\to 0]{} 0$$

$$X_{21,21}^{(T)}(|A_{11}|) \xrightarrow[|A_{11}|\to 0]{} 0$$

X-parameters are a *superset* of S-parameters

# X-parameter Experiment Design & Identification [1,14]

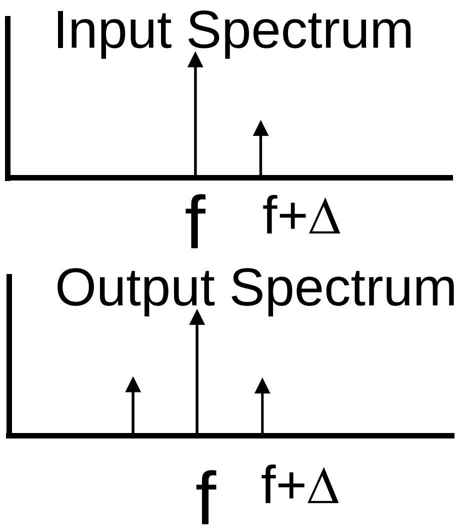
Stimulate port 1 with large tone at freq. $f$
Stimulate port 2 with small tone at freq. $f + \Delta$
Measure response at three different frequencies
Take limit as $\Delta$ goes to zero

$$X_{21}^{(F)} = B_{21}(f, |A_{1,1}|)P^{-1}$$

$$X_{21,21}^{(S)} = \frac{B_{21}(f+\Delta, |A_{11}|)}{A_{21}(f+\Delta)}$$

$$X_{21,21}^{(T)} = \frac{B_{21}(f-\Delta, |A_{11}|)}{A_{21}(f+\Delta)} e^{2j\phi(A_{11}-A_{21})}$$

Similarly for harmonics



*Optimal and orthogonal* experiment design and model identification

# X-Parameters and the Harmonic Jacobian [1]

X-parameters are the "modeling analog" of HB analysis
Write model equations in language native to simulator algorithms

From 1-tone HB analysis $X^{(F)}_{pm}(|A_{11}|) = B_{pm}P^{-m}$

$$X^{(S)}_{pm,qn}(|A_{11}|) = P^{-m+n} \left.\frac{\partial B_{pm}}{\partial A_{qn}}\right|_{A_{11}, A_{12}=0,\ldots A_{21}=0,\ldots} \qquad X^{(T)}_{pm,qn}(|A_{11}|) = P^{-m-n} \left.\frac{\partial B_{pm}}{\partial A^{*}_{qn}}\right|_{A_{11}, A_{12}=0,\ldots A_{21}=0,..}$$

from *known Jacobian of 1-tone HB analysis*.
Jacobian comes from I-V and $G_{ij}$, $C_{ij}$ from element constitutive relations

Never need 2-tone HB analysis. Faster, guaranteed spectrally linear

Most of the terms in the required Jacobian *are know ahead of time*

$$B_{e,f} = X^{(F)}_{ef}(|A_{11}|)P^{f} + \sum_{g,h} X^{(S)}_{ef,gh}(|A_{11}|)P^{f-h}A_{gh} + \sum_{g,h} X^{(T)}_{ef,gh}(|A_{11}|) \quad P^{f+h}A^{*}_{gh}$$

# X-Parameter: How they are measured:

## Experiment Design & Identification (2): Ideal Case

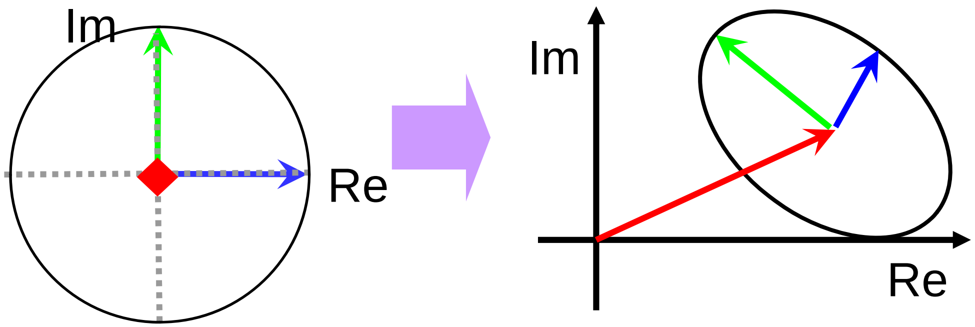
E.g. functions for $B_{pm}$ (port p, harmonic m) given small extraction tones $A_{qn}$ (port q, harmonic n)

$$B_{pm} = \underline{X_{pm}^{(F)}(|A_{11}|)} P^{m} + \underline{\underline{X_{pm,qn}^{(S)}(|A_{11}|) P^{m-n} A_{qn} + X_{pm,qn}^{(T)}(|A_{11}|) P^{m+n} A_{qn}^{*}}}$$

Perform 3 independent experiments with fixed $A_{11}$

input $A_{qn}$

output $B_{pm}$



$$B_{pm}^{(0)} = X_{pm}^{(F)}\left(|A_{11}|\right) P^{m}$$

$$B_{pm}^{(1)} = X_{pm}^{(F)}\left(|A_{11}|\right) P^{m} + X_{pm,qn}^{(S)}\left(|A_{11}|\right) P^{m-n} A_{qn}^{(1)} + X_{pm,qn}^{(T)}\left(|A_{11}|\right) P^{m+n} A_{qn}^{(1)}$$

$$B_{pm}^{(2)} = X_{pm}^{(F)}\left(|A_{11}|\right) P^{m} + X_{pm,qn}^{(S)}\left(|A_{11}|\right) P^{m-n} A_{qn}^{(2)} + X_{pm,qn}^{(T)}\left(|A_{11}|\right) P^{m+n} A_{qn}^{(2)*}$$

# X-parameter properties and benefits

Static nonlinearity (AM-AM) at any/all CW frequencies

High-frequency memory (AM-PM)

Large-signal output match (correct "Hot S22")

Harmonics (even and odd) at input and output ports

PAE and DC currents / voltages at supply ports

**Cascadable**: distortion through chains of components
Does for *driven nonlinear systems* what S-parameters do for linear systems

**Hierarchical:** apply to one component or multiple (e.g. multi-stage amp)

**Transportable:** mismatch at fundamental and harmonics taken into account

Can be used to simulate some *long-term memory* affects

Can be *generated from Simulation and Measurement*

*Highly automated* experiment design & model identification

# Outline

- Introduction: X-parameter Basics
- Survey of X-parameter benefits and applications
  - Cascading nonlinear blocks
  - Integrating handset amplifier into cell phone (customer example)
  - Load-dependent X-parameters and their harmonic tuning capability
  - High power X-parameter measurements
  - X-parameter generation from detailed schematics in ADS
  - X-parameter simulation component (XNP) built-in to ADS
  - Dynamic X-parameters: Long-term memory research
- Summary
- References and Links

# Measurement-based nonlinear design with X-parameters

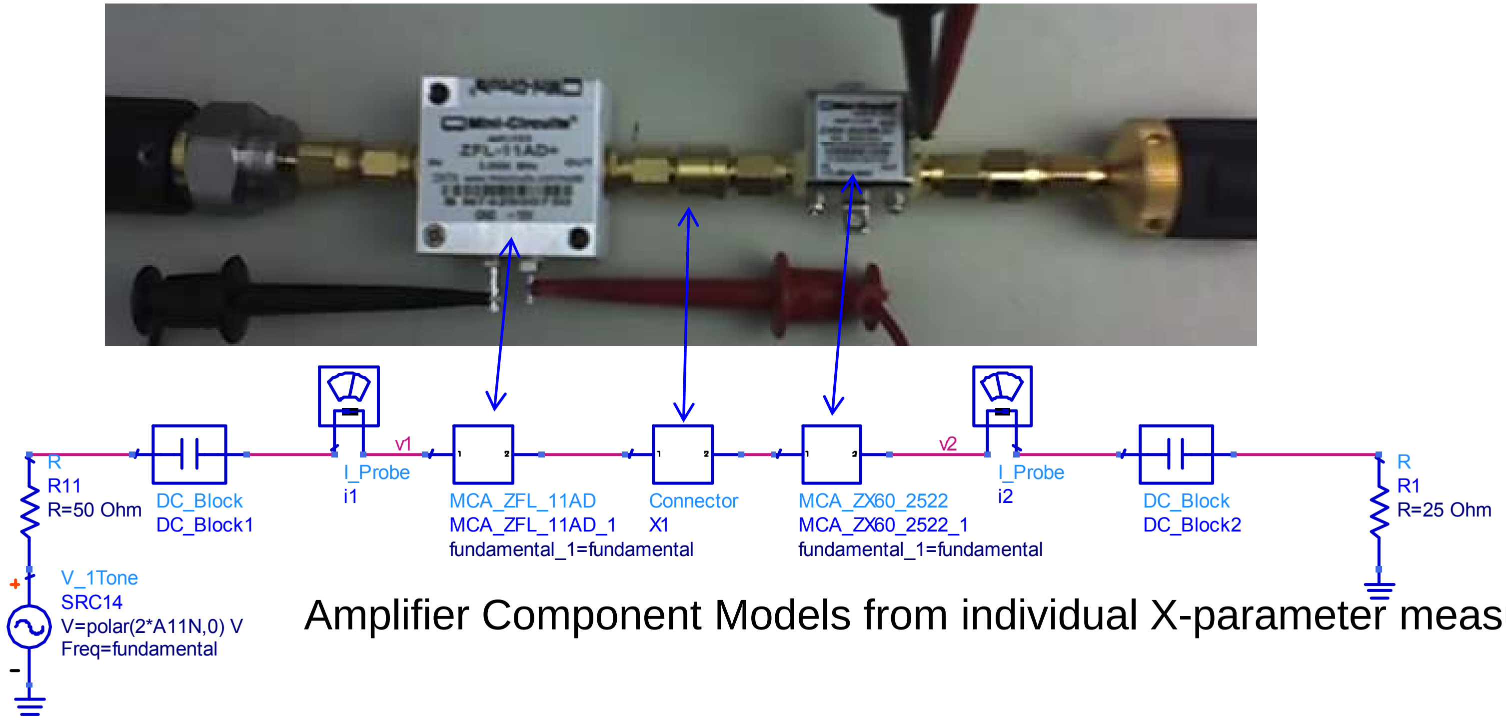
Source

ZFL-AD11+
11dB gain, 3dBm
max output power

Connector
80 ps
delay

ZX60-2522M-S+
23.5dB gain, 18dBm
max output power

Load



Amplifier Component Models from individual X-parameter measurements

# Results

## Cascaded Simulation vs. Measurement

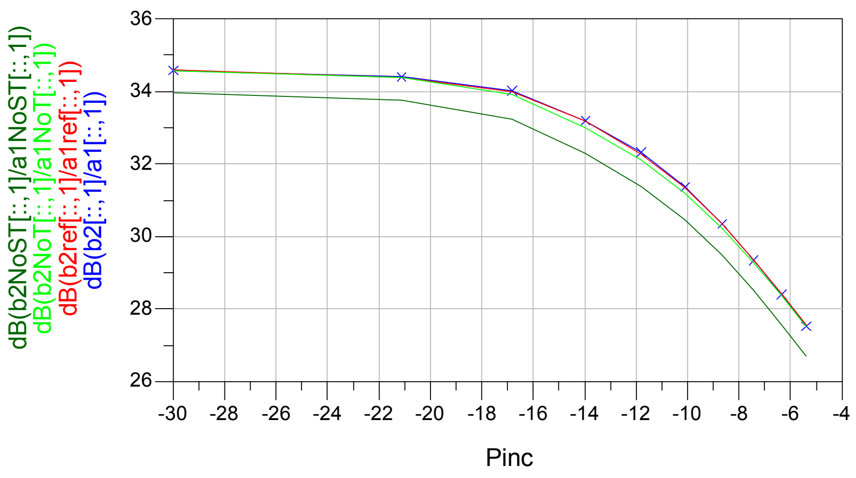
Red: Cascade Measurement

Blue: Cascaded X-parameter Simulation

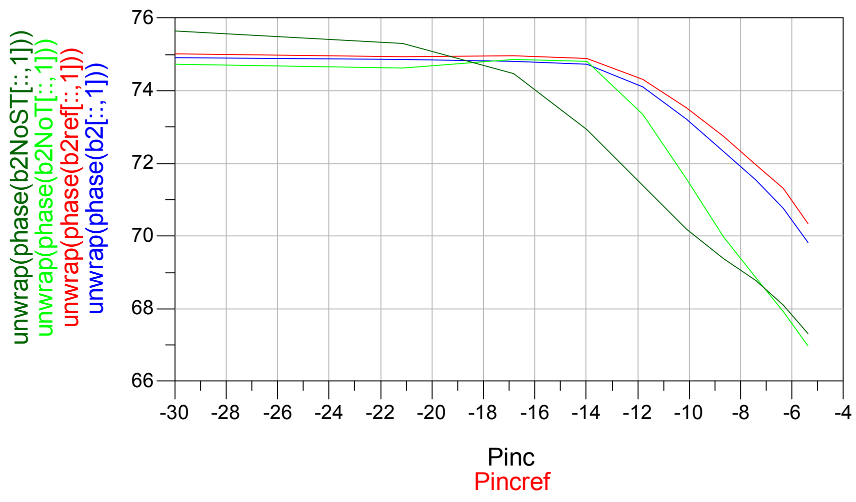
Light Green: Cascaded Simulation, No $X^{(T)}$ terms

Dark Green: Cascaded Models, No $X^{(S)}$ or $X^{(T)}$ terms

Fundamental Gain



Fundamental Phase

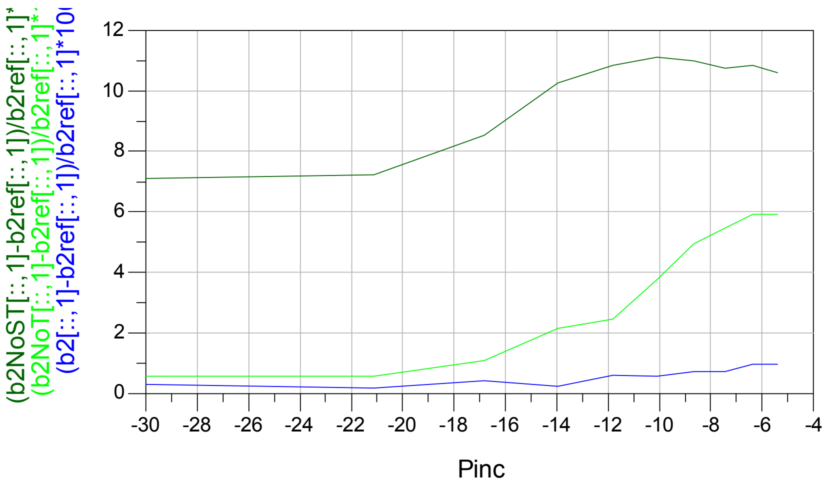


# Results

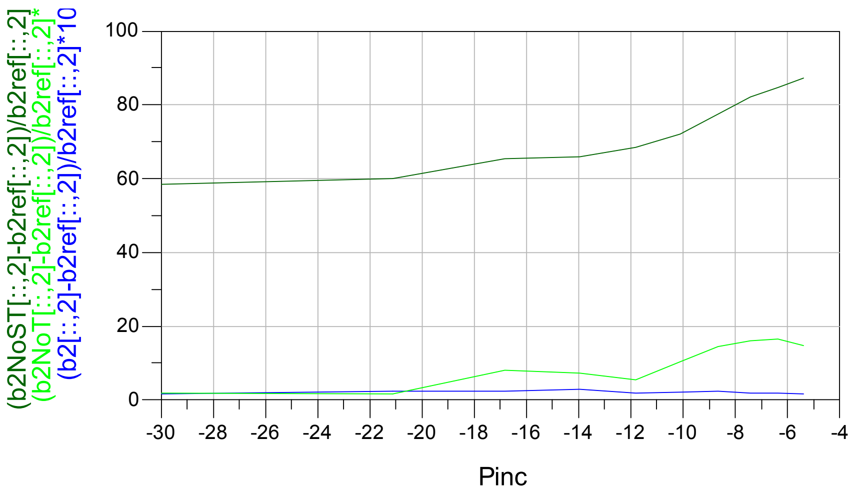
## Cascaded Simulation vs. Measurement

Red: Cascade Measurement
Blue: Cascaded X-parameter Simulation
Light Green: Cascaded Simulation, No $X^{(T)}$ terms
Dark Green: Cascaded Models, No $X^{(S)}$ or $X^{(T)}$ terms

Fundamental % Error



Second Harmonic % Error



"X-parameters enable predictive nonlinear design from NL data"

# X-parameters solve key, real customer problems
# Example: GSM amp. and cell phone integration

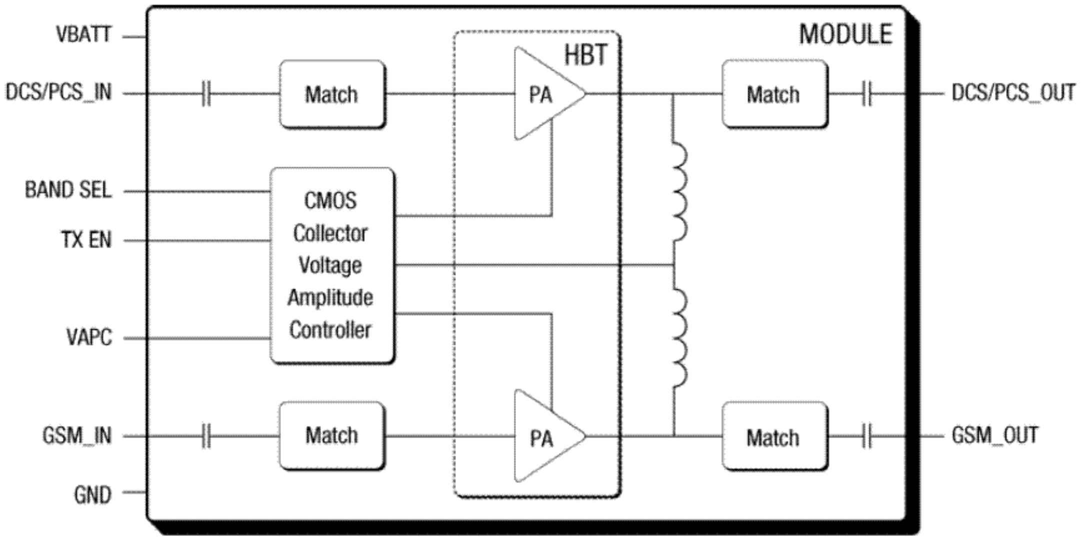
Horn et al *IEEE European Microwave Conference,* Amsterdam, October 2008

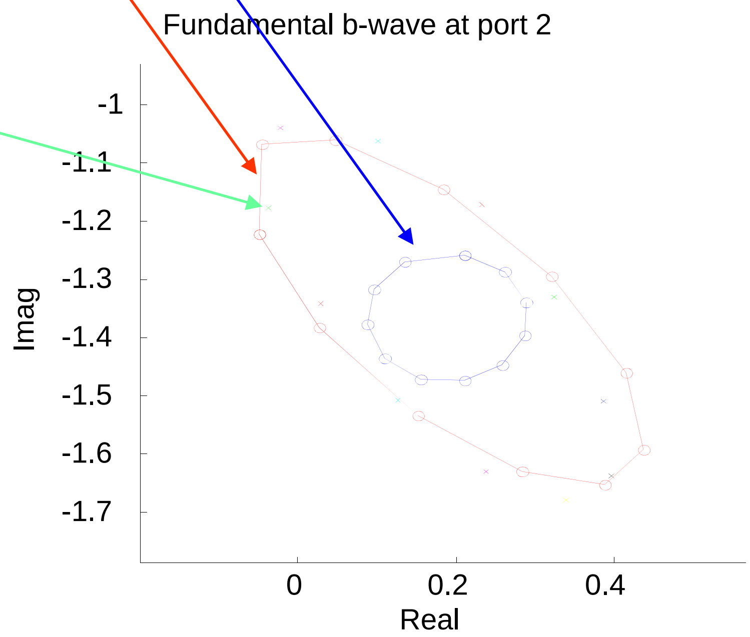
Blue circular shape Hot $S_{22}$ prediction

*Red Elliptical shape: X-parameter prediction*

Measurements
small colored crosses

*Skyworks* amp

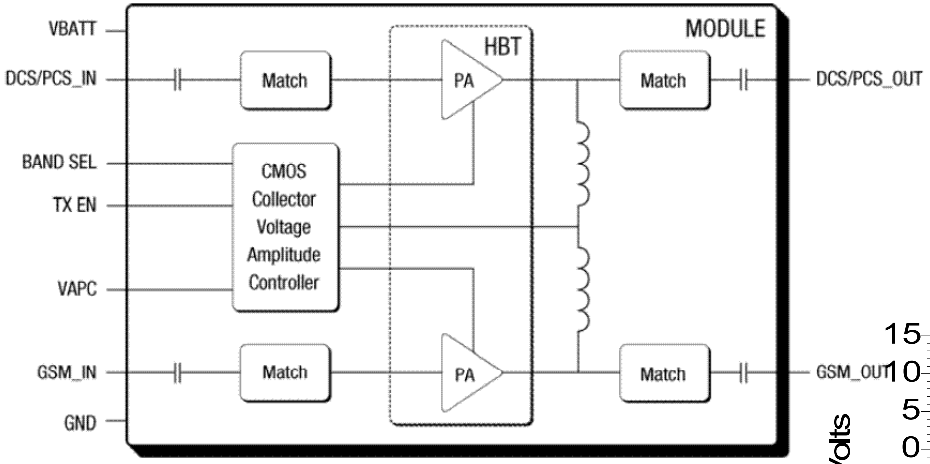




Allowed *Sony-Ericsson* to take into account second-harmonic mismatch on amp in system integration

"X-parameters predict output match under large input drive *Hot* $S_{22}$ does not"

# Complete X-parameter Model of GSM Amplifier

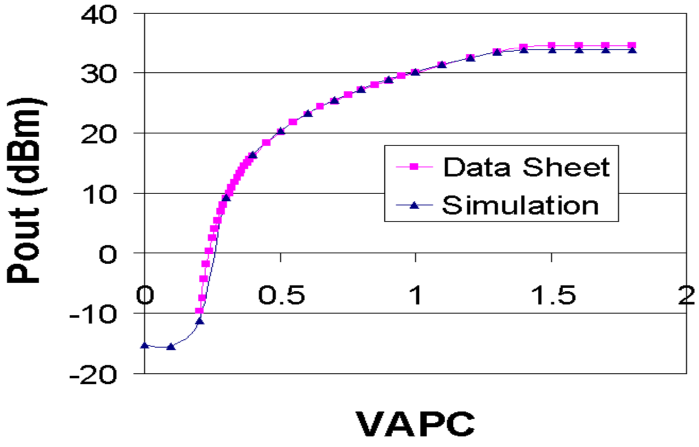


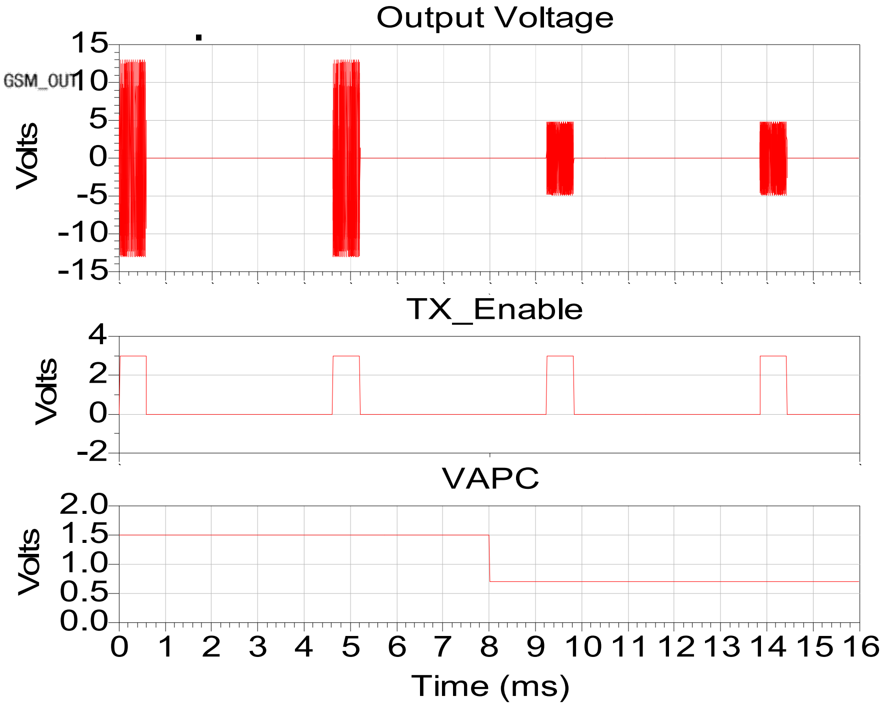
"We didn't think this was possible"

– Sony-Ericsson engineer
Joakim Eriksson, Ph.D

Unprecedented capability

Data acquisition 30x faster





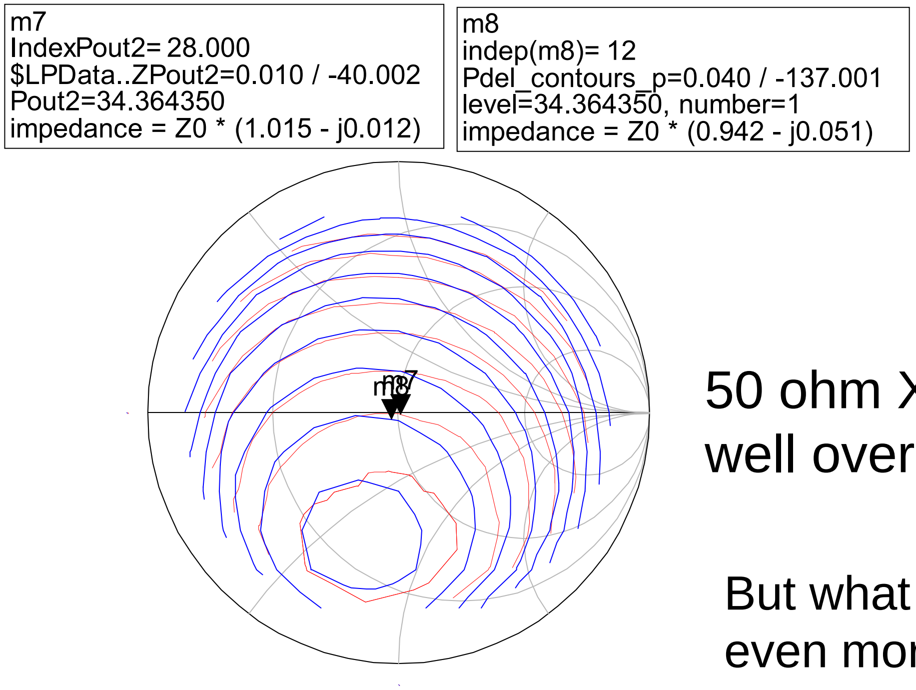
*"X-parameters provide a nonlinear electronic interactive datasheet based on data"*

# Load-dependence of another GSM commercial Amp from X-parameters measured at only 50 ohms

### 900 MHz Vbatt=3.7, Vapc = 1.4

System Integrator wants to use X-parameters to compare performance among vendor parts within their system

Pout, 1dBm contour spacing



m7
IndexPout2= 28.000
$LPData..ZPout2=0.010 / -40.002
Pout2=34.364350
impedance = Z0 * (1.015 - j0.012)

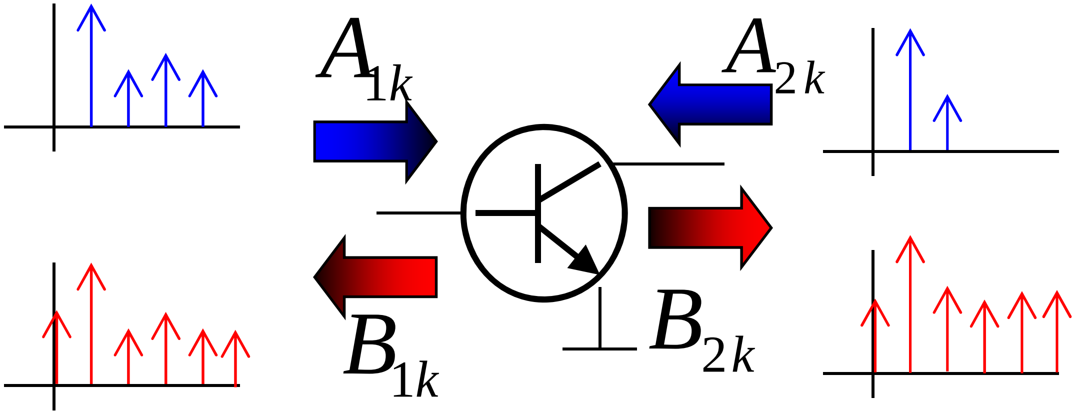
m8
indep(m8)= 12
Pdel_contours_p=0.040 / -137.001
level=34.364350, number=1
impedance = Z0 * (0.942 - j0.051)

Red: LoadPull measurements
Blue: Simulations using X-parameters *extracted in 50 ohms*

50 ohm X-parameters, predict performance well over a wide range of impedance

But what if we want
even more accuracy?

# X-parameters with load-dependence



$$B_{1k} = F_{1k}(DC, A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots)$$

$$B_{2k} = F_{2k}(DC, A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots)$$

Harmonic (or carrier) Index

Port Index

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

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

$$B_{e,f} = X^{(F)}_{ef}(DC,|A_{11}|,|A_{21}|,\theta)P^{f} + \sum_{g,h} X^{(S)}_{ef,gh}(DC,|A_{11}|,|A_{21}|,\theta)P^{f-h}\cdot A_{gh} + \sum_{g,h} X^{(T)}_{ef,gh}(DC,|A_{11}|,|A_{21}|,\theta)\;\; P^{f+h}\cdot A^{*}_{gh}$$

$$B_{e,f} = X^{(F)}_{ef}(DC,|A_{11}|,\Gamma_{2})P^{f} + \sum_{g,h} X^{(S)}_{ef,gh}(DC,|A_{11}|,\Gamma_{2})P^{f-h}\cdot A_{gh} + \sum_{g,h} X^{(T)}_{ef,gh}(DC,|A_{11}|,\Gamma_{2})\;\; P^{f+h}\cdot A^{*}_{gh}$$

“X-parameters *unify S-parameters and Load-Pull”*

# NVNA+Load-Pull = Instant Large-Signal Model

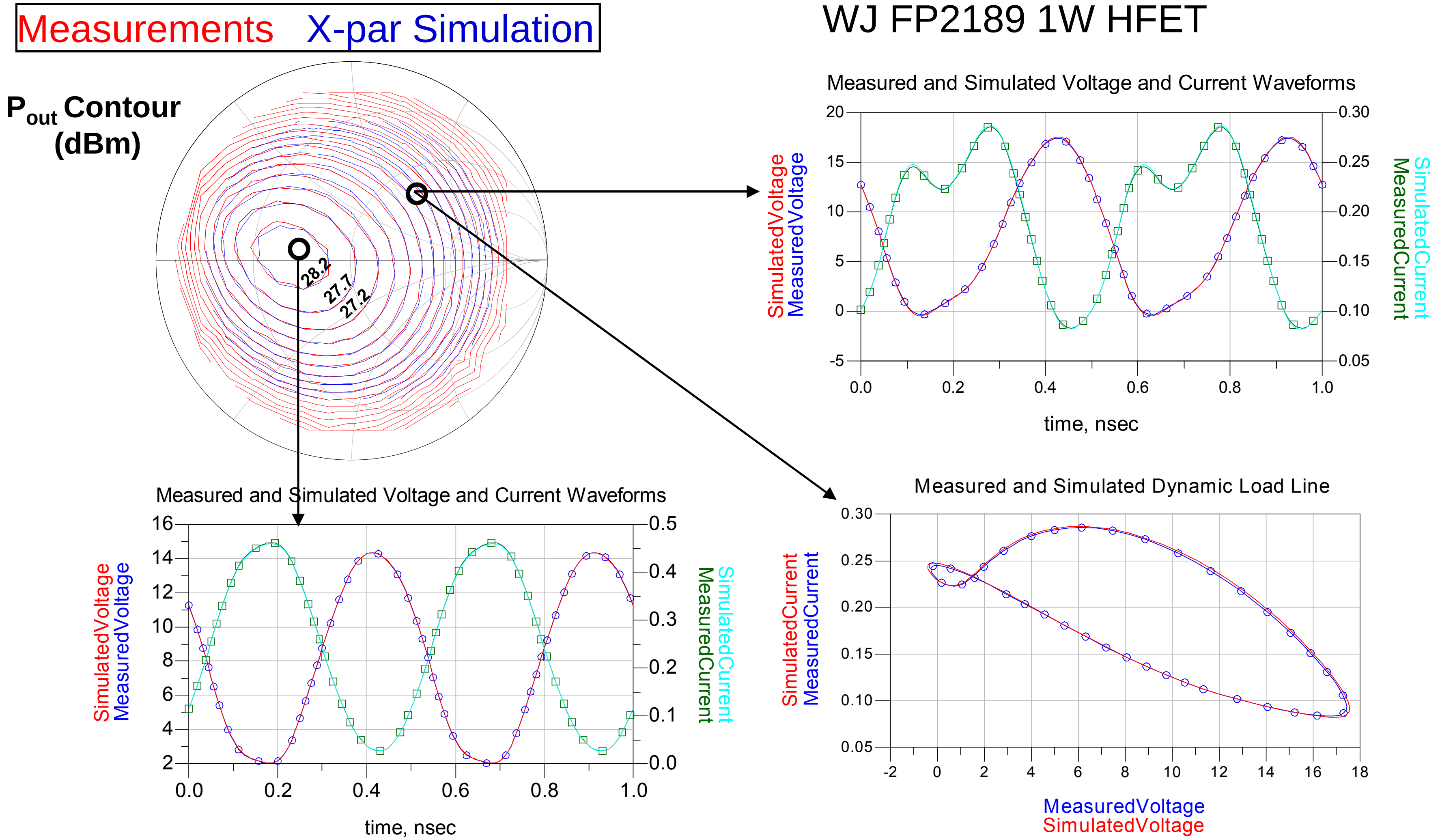
- Drag and drop measured X-parameters for immediate ADS simulation "This is a breakthrough for the industry."

– Gary Simpson Maury Microwave

NVNA +
Load-Pull

# Load-Dependent X-Parameters of a FET

G. Simpson et al *IEEE ARFTG Conference*, December, 2008

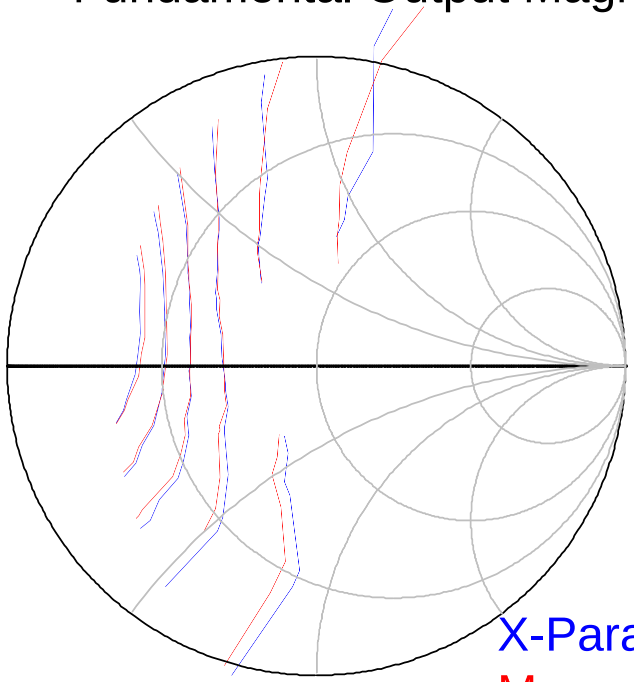


***Experimental Harmonic Balance***

***X-parameters unify S-parameters and load-pull***

# *Harmonic Load-Tuning Predictions* from X-parameters

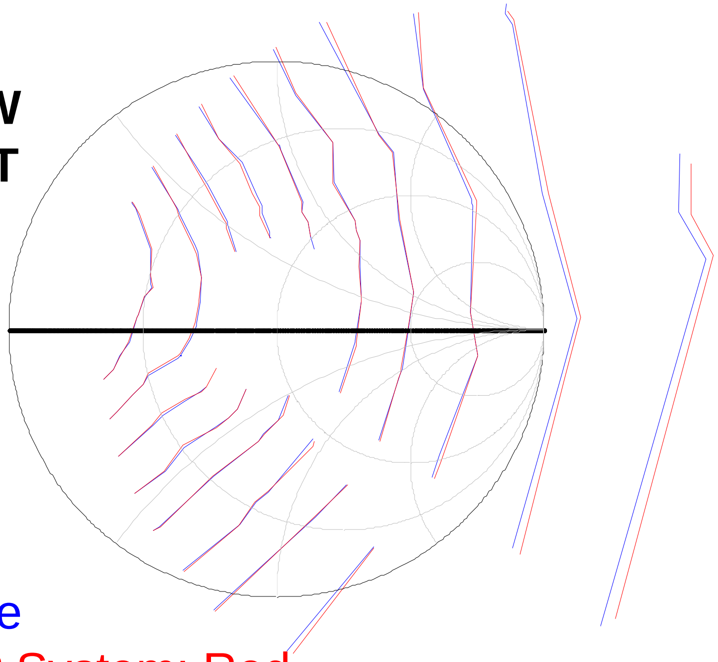
Horn et al, *IEEE Power Amplifier Symposium*, September, 2009



Fundamental Output Magnitude

**Cree CGH40010 10 W**
**RF Power GaN HEMT**

Contours vs. 2nd
Harmonic Load
(Fixed input power
and fundamental load)



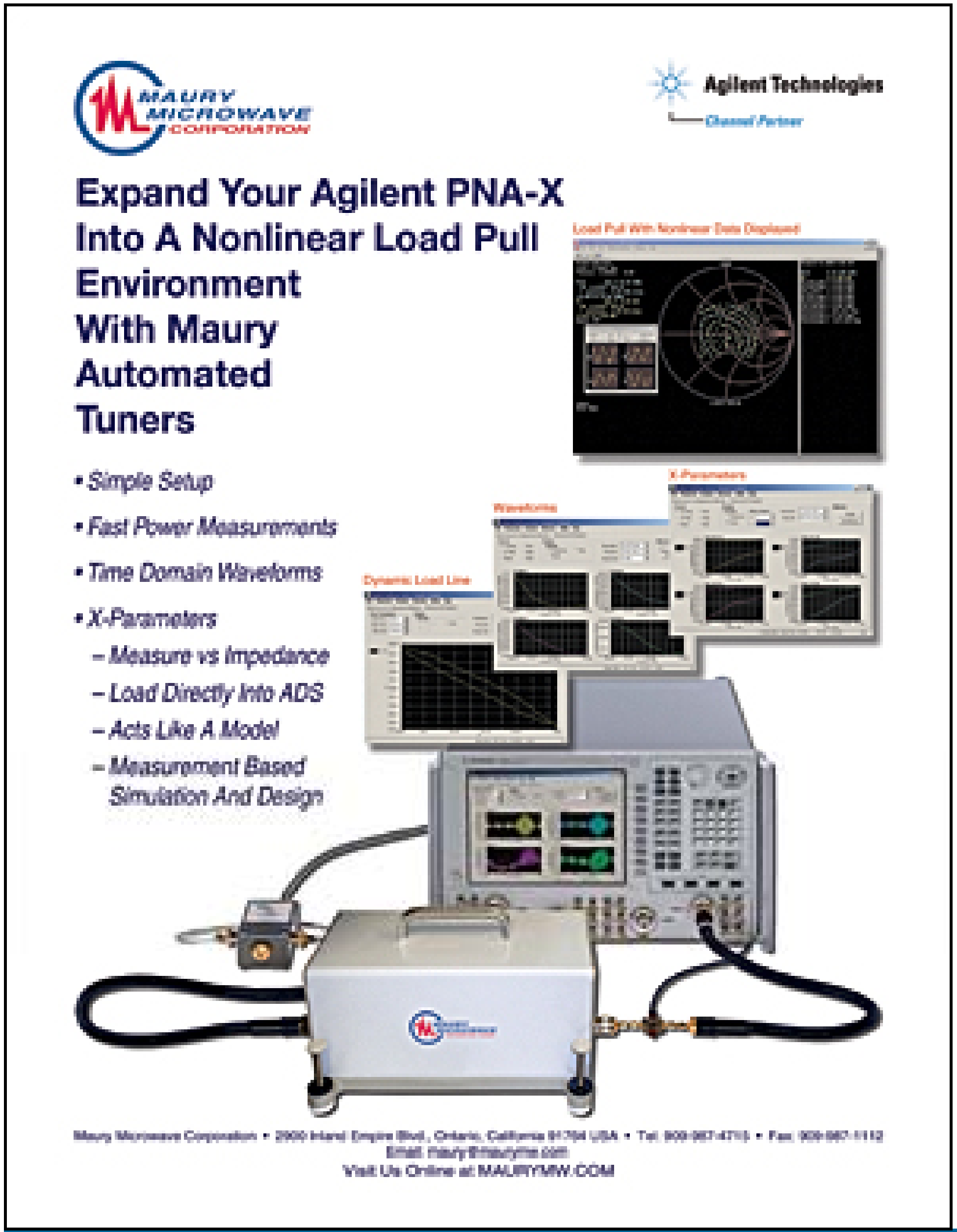
Second Harmonic Output Magnitude

X-Parameter Prediction: Blue

Measured with Harmonic LP System: Red

*Key Agilent IP* calibrates out uncontrolled harmonic impedances presented by tuner & re-grids impedance data for accuracy and interpolation in ADS

*Harmonic load-pull may be unnecessary! Simpler, cheaper, faster alternatives exist*



MAURY MICROWAVE CORPORATION

Agilent Technologies
Channel Partner

## Expand Your Agilent PNA-X Into A Nonlinear Load Pull Environment With Maury Automated Tuners

- *Simple Setup*
- *Fast Power Measurements*
- *Time Domain Waveforms*
- *X-Parameters*
  - *Measure vs Impedance*
  - *Load Directly Into ADS*
  - *Acts Like A Model*
  - *Measurement Based Simulation And Design*

Maury Microwave Corporation • 2900 Inland Empire Blvd., Ontario, California 91764 USA • Tel: 909-987-4715 • Fax: 909-987-1112
Email: maury@maurymw.com
Visit Us Online at MAURYMW.COM

Simple Setup
Fast, automated measurements
Time-domain waveforms

*Load-dependent X-parameters as a measurement-based device model*
***"The data is the model"***

Useful for:
- High-power device characterization
- X-parameter transistor models
- multi-stage amps w. large mismatch

Control power, frequency, bias and load at fundamental frequency: faster, fewer data, simpler setup than harmonic L-P

- *Get sensitivity to harmonic loads at output and input ports without having to control harmonic impedances*
- *Estimate the effects of source-pull on device performance in ADS without having to control source impedance*

# Load-dependent X-parameters versus harmonic load-pull

Root et al *INMMiC Conference,* April, 2010
Horn et al *submitted to IEEE CSICS2010*

## Load-dependent X-pars

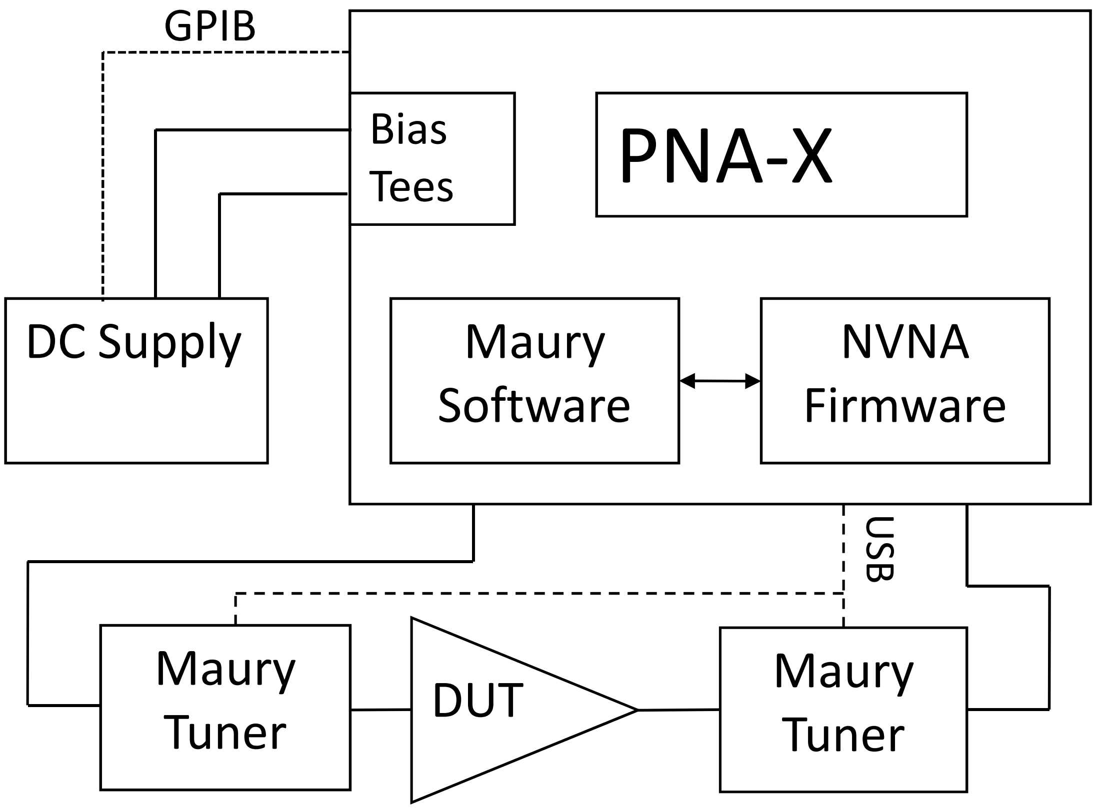
- *One output tuner* to vary load at fundamental frequency. At each load inject small tones at 2nd and 3rd harmonic freqs
  (9x(1+2x2) = 45 measurements, actually ~99 measurements)
- Measured DC – 4th harmonic
- Take into ADS. Present 729 independent loads to model

## Harmonic load-pull validation

- *Three output tuners* to vary loads at fundamental, second, and third harmonics independently
  (9x9x9 = 729 measurements)
- Measured DC - 4th harmonic

Compare waveforms, PAE, dynamic load-lines, etc.

# Load-dependent X-parameter model for GaN HEMT:



9 load states x 3 x 2

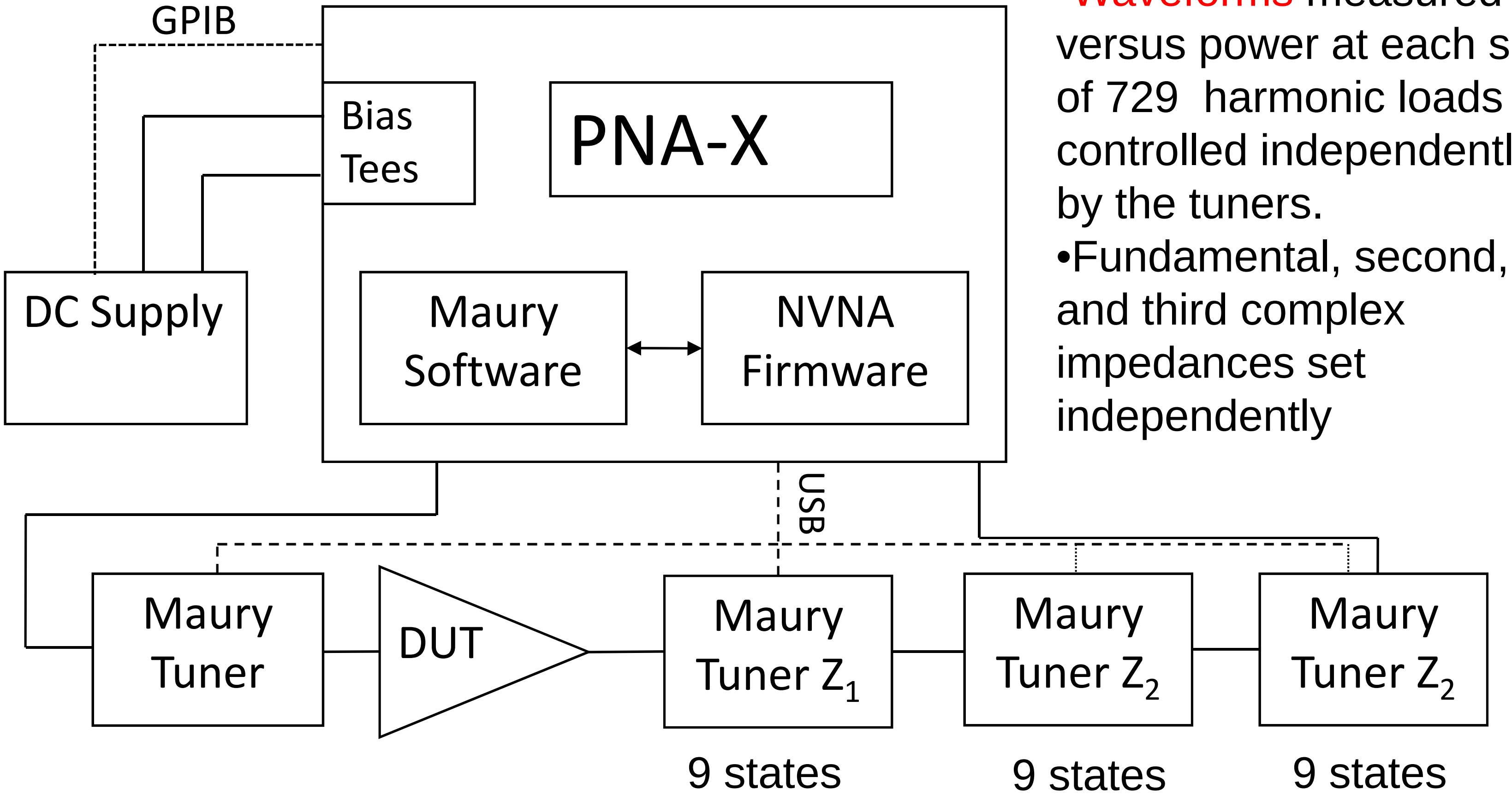
X-parameter file taken into ADS
for independent validation

Cree
CGH40010
**GaN HEMT**
10 W packaged
transistor

- 900 MHz
- Measure Load-dependent X-parameters vs power at 9 impedances
- 4 harmonics measured
- probe tones at $2^{nd}$ and $3^{rd}$ harmonics
- harmonic impedances uncontrolled

# Harmonic Load-pull Setup: For Validation Only

J. Horn et al *Submitted to CSICS2010*



- Waveforms measured versus power at each set of 729 harmonic loads as controlled independently by the tuners.
- Fundamental, second, and third complex impedances set independently

# Load-dependent X-parameters versus harmonic load-pull

**Load-dependent X-pars**

- *One output tuner* to vary load at fundamental frequency. At each load inject small tones at 2nd and 3rd harmonic freqs (9x(1+2x2) = 45 measurements, actually ~125 measurements)
- Measured DC – 4th harmonic
- Take into ADS. Present 729 independent loads to model

**Harmonic load-pull validation**

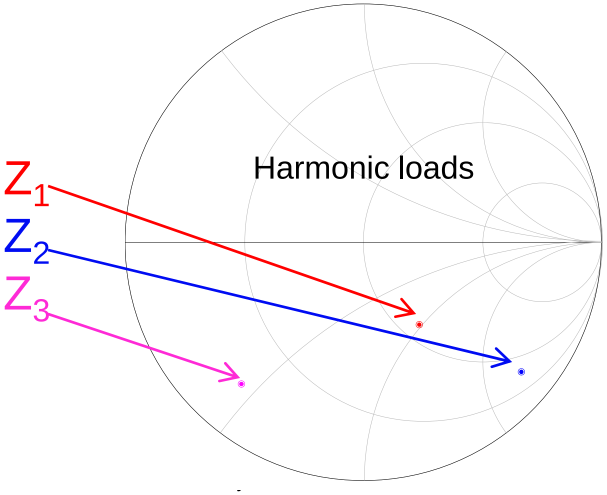
- *Three output tuners* to vary loads at fundamental, second, and third harmonics independently (9x9x9 = 729 measurements)
- Measured DC - 4th harmonic

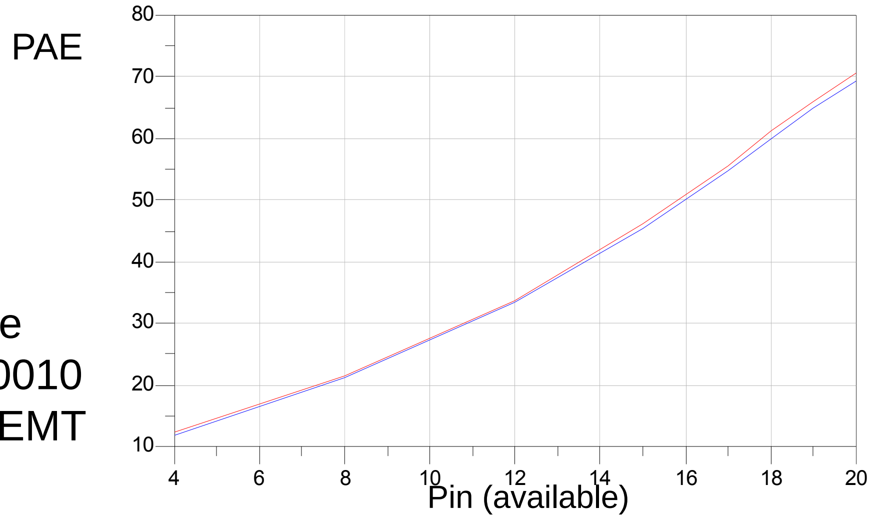
Compare waveforms, PAE, dynamic load-lines, etc.

# Prediction of GaN HEMT *harmonic-load dependence* from fundamental-only load-dependent X-pars

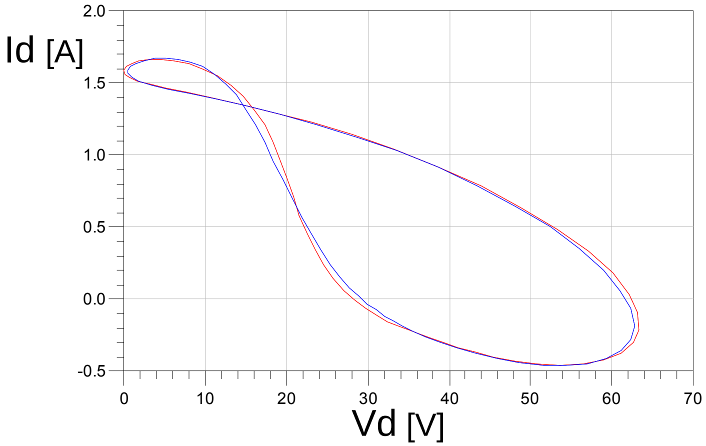
Courtesy of J. Horn

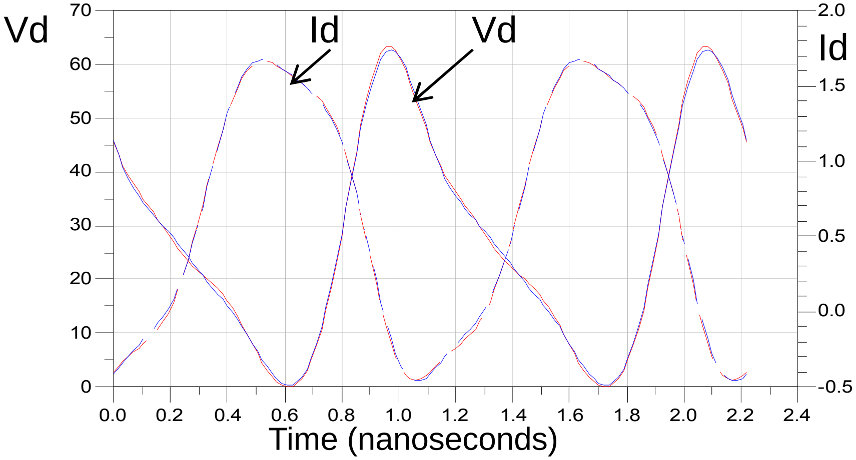
J. Horn et al, *submitted to CSICS2010*





Cree
CGH40010
GaN HEMT

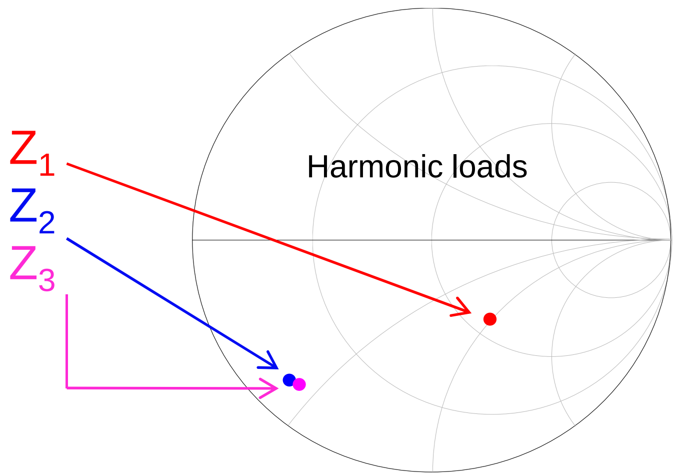




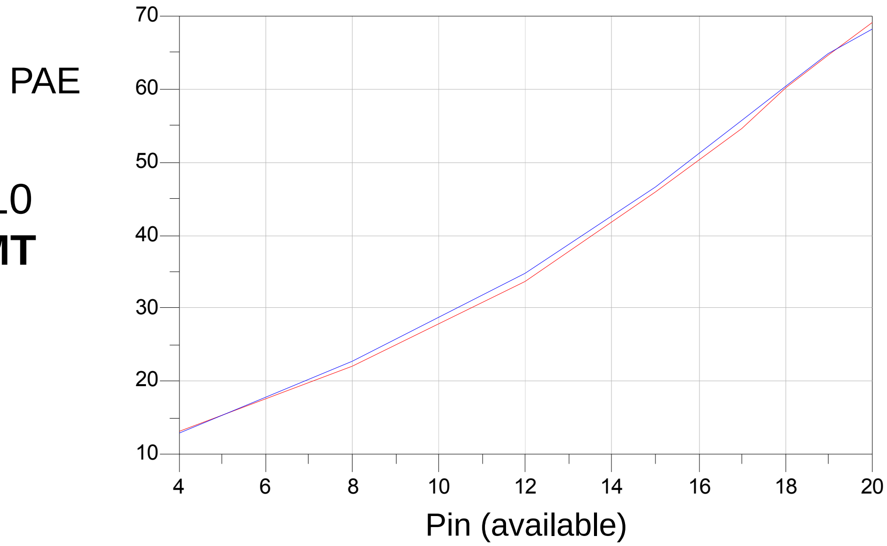
X-parameter model

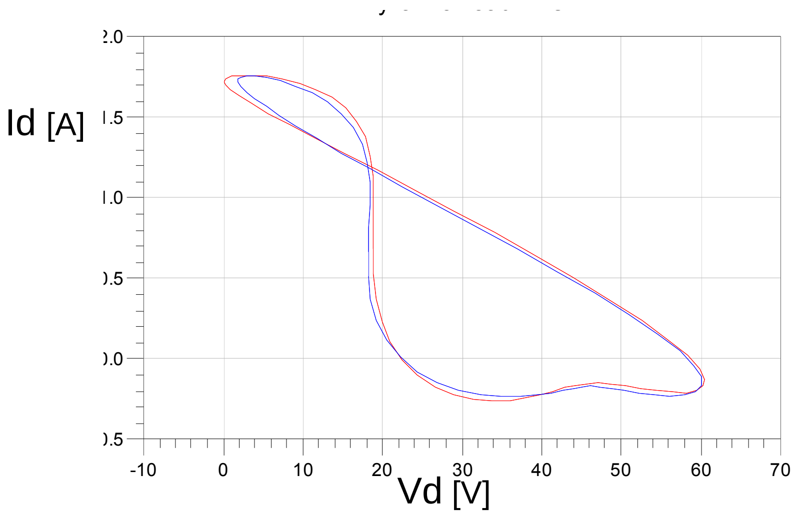
Harmonic time-domain load-pull measurements

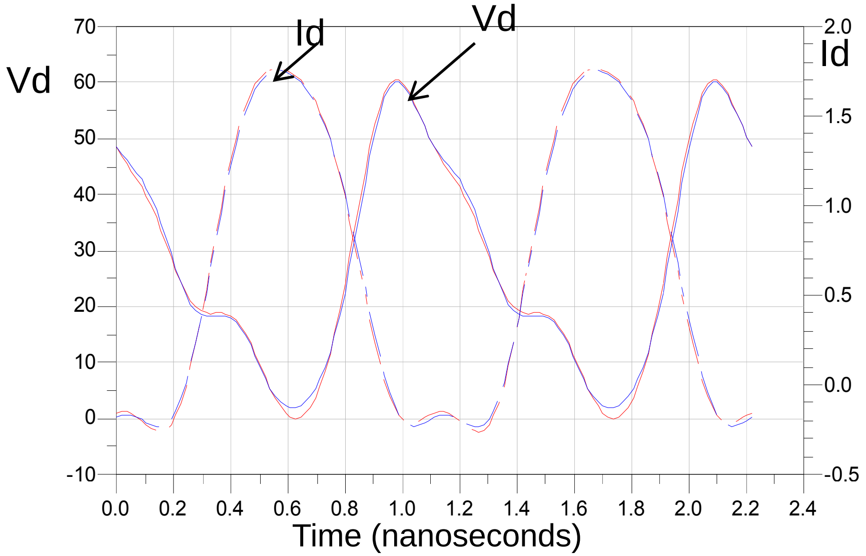
# Prediction of GaN HEMT *harmonic-load dependence* from fundamental-only load-dependent X-pars



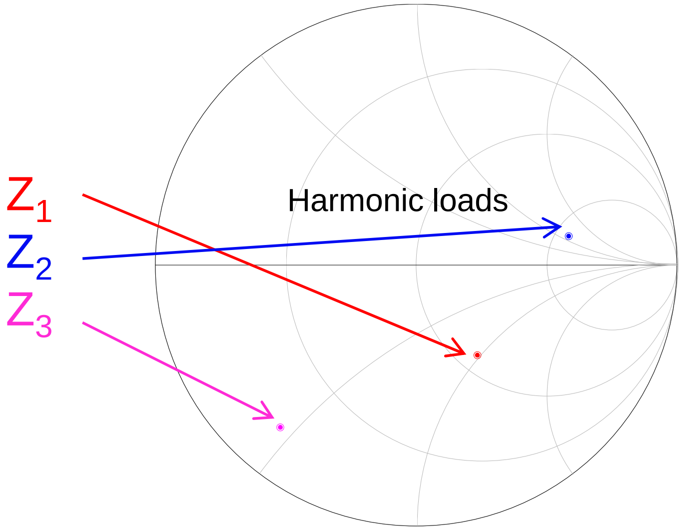
Cree
CGH40010
**GaN HEMT**



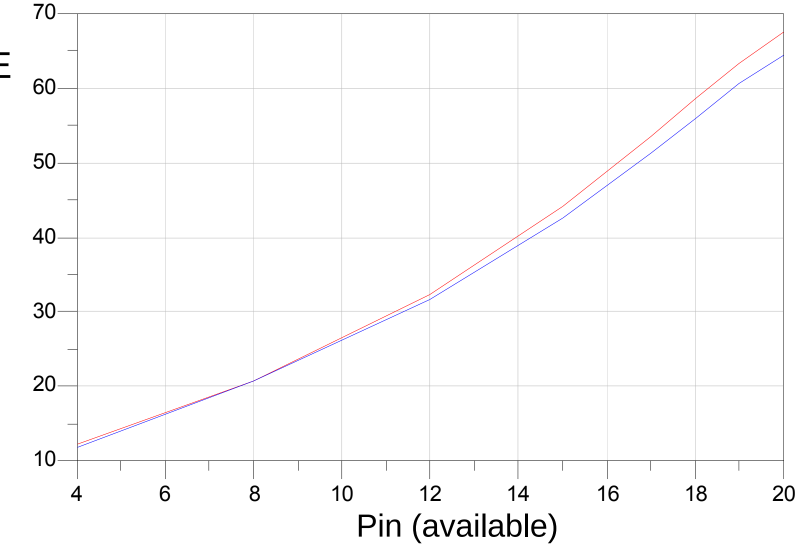


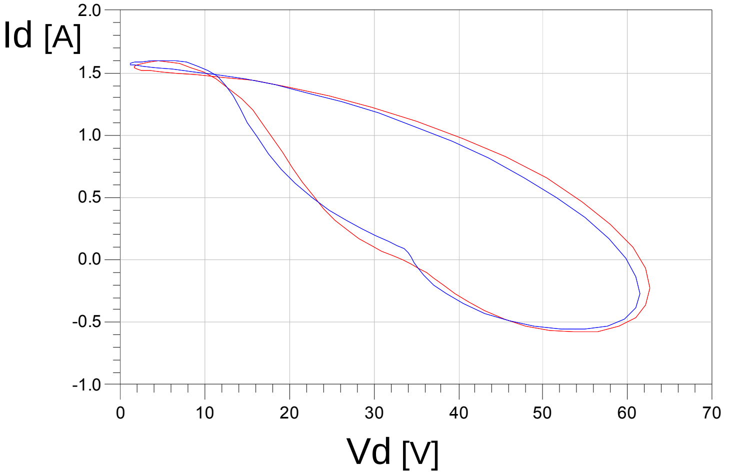


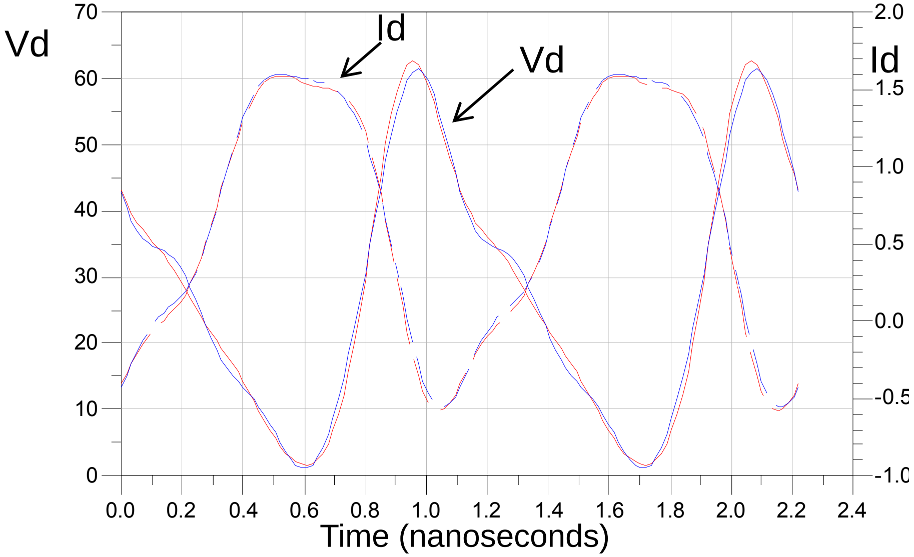
# Prediction of GaN HEMT *harmonic-load dependence* from fundamental-only load-dependent X-pars



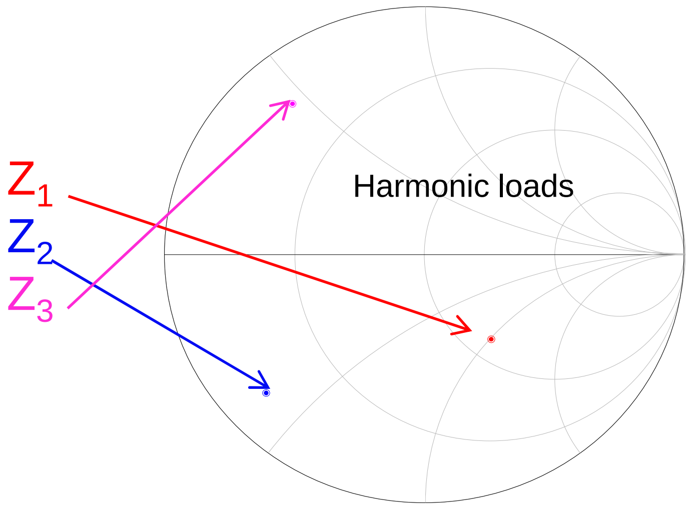
Cree
CGH40010
**GaN HEMT**



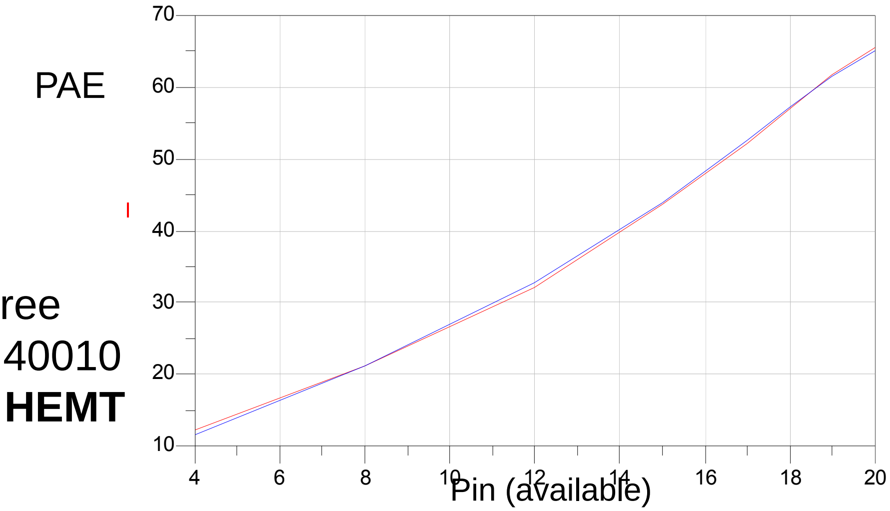


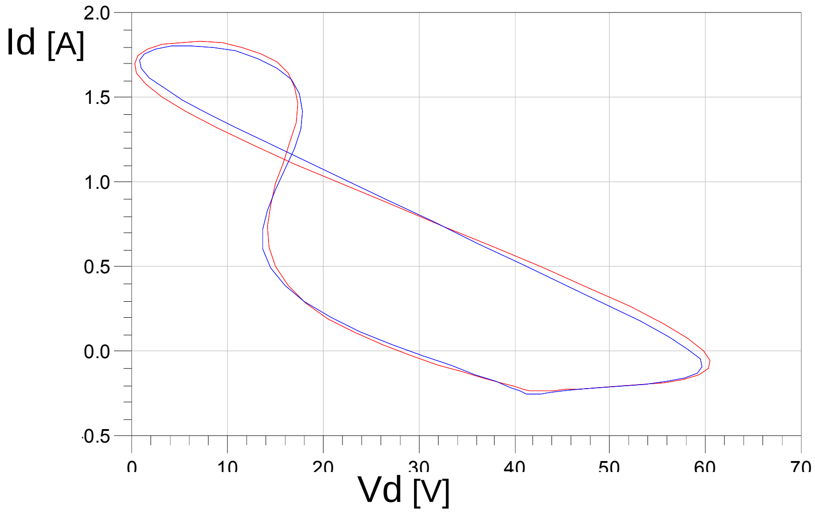


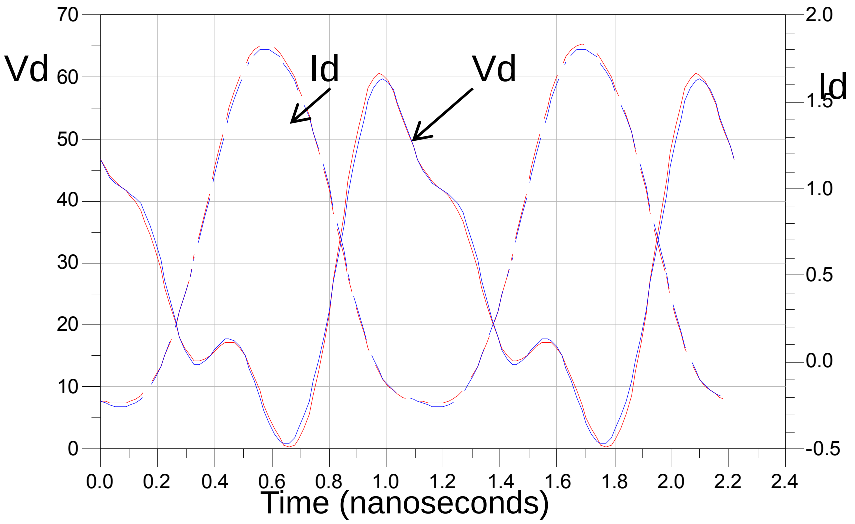
# Prediction of GaN HEMT *harmonic-load dependence* from fundamental-only load-dependent X-pars



Cree
CGH40010
**GaN HEMT**







# Summary:
# Fundamental-only load-dependent X-parameters

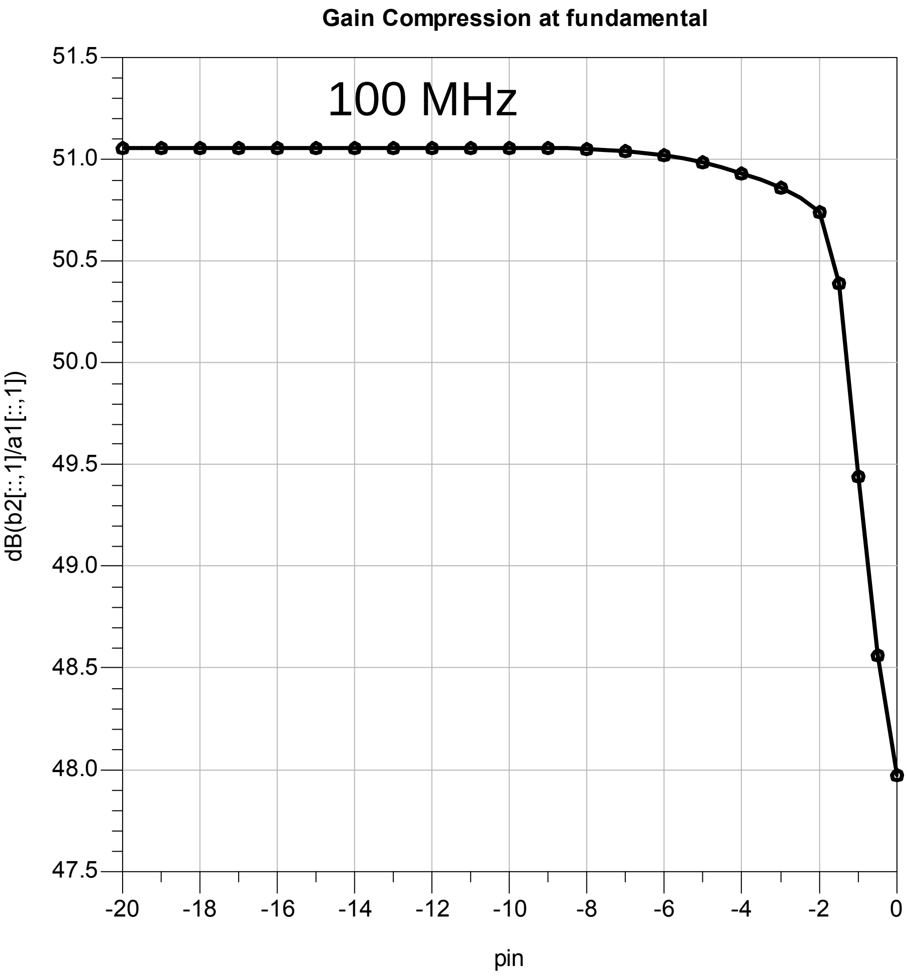
- Full two-port nonlinear functional block model for simulation
  - ***Accounts for load-tuning dependence of device performance*** without the requirement of independently controlling harmonic loads
  - Use to design matching networks, multi-stage amps, Doherty amps., …
- Large data / time reduction compared to harmonic load-pull
  - X-parameter model scales linearly in number of loads N
  - Harmonic L-P scales as $N^H$ *H* = no. of controlled harmonic loads
- Harmonic load-pull may be unnecessary
  - Validates "principle of harmonic superposition" (Verspecht et al 1997)
  - Source-pull unnecessary (Horn et al *submitted to CSISC 2010*]) except for power transfer

# X-parameters at 100W

## (courtesy K. Anderson)

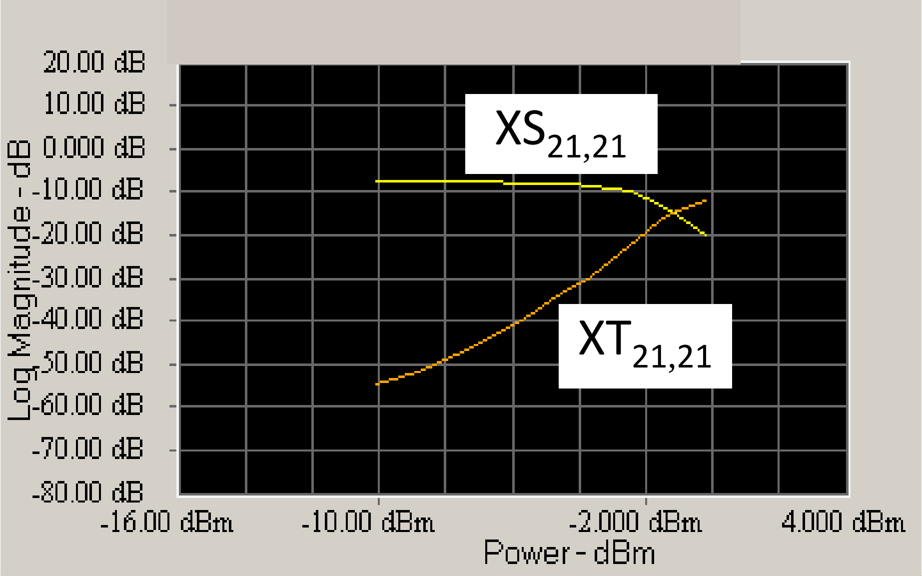
Mini-Circuits ZHL-100W-52

| Parameter | Description |
|---|---|
| Part Number | ZHL-100W-52 |
| Pout max (@1dB compression) | 45dBm (min, 50M-500MHz)<br>47dBm (typ, 50M-500MHz) |
| Pout max (@3dB compression) | 46.5dBm (min, 50M-500MHz)<br>48.5dBm (typ, 50M-500MHz) |
| Pin max (no damage) | +3dBm |
| Gain | 48dB (min)<br>50dB (typ) |
| Input VSWR | 1.45:1 (typ) |
| Output VSWR | 2.5:1 (typ) |

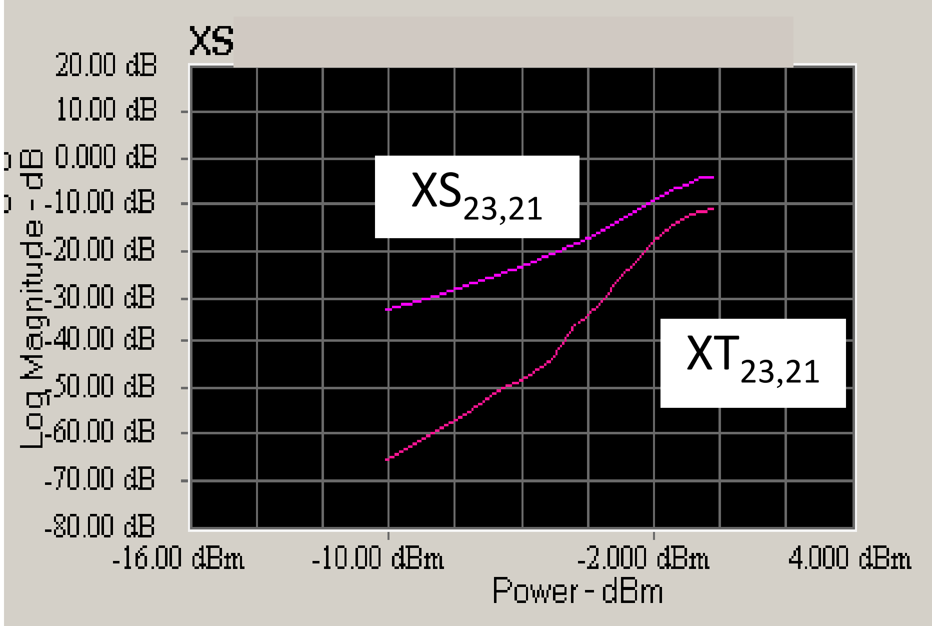


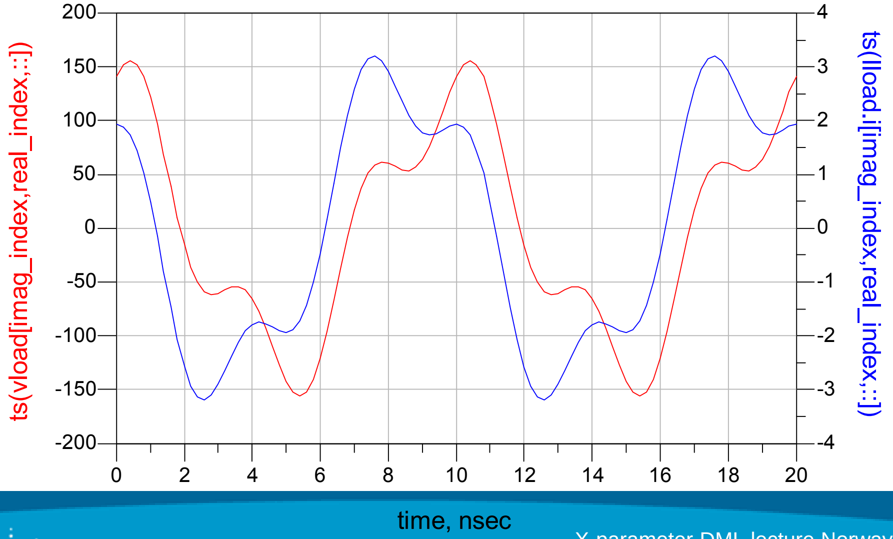
X-parameters have been measured at 250 W

# X-parameters at 100W

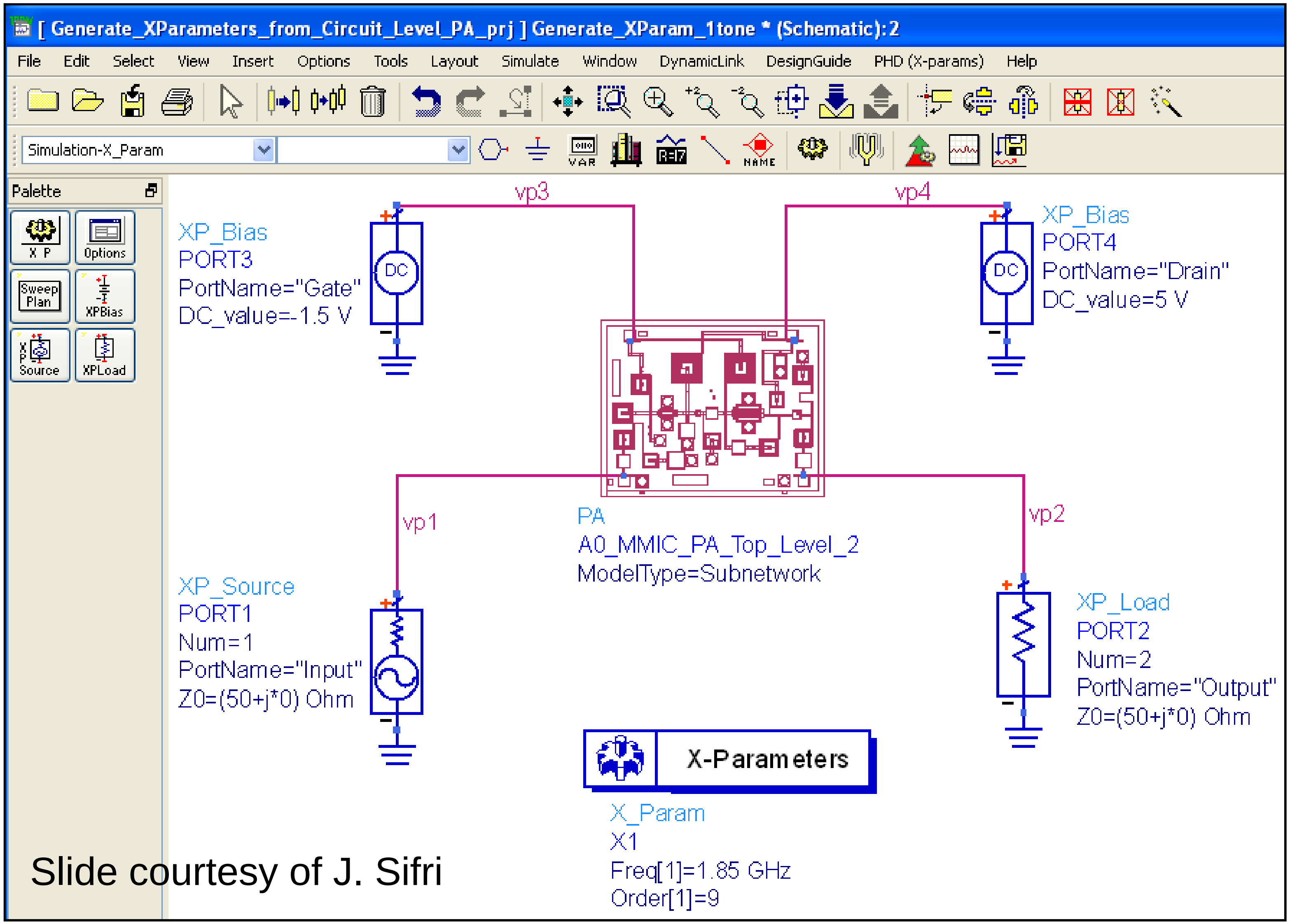


5 harmonics, magnitude and phase: fund=150 MHz





# Generate an IP-Protected X-parameter model



XP_Bias
PORT3
PortName="Gate"
DC_value=-1.5 V

XP_Bias
PORT4
PortName="Drain"
DC_value=5 V

PA
A0_MMIC_PA_Top_Level_2
ModelType=Subnetwork

XP_Source
PORT1
Num=1
PortName="Input"
Z0=(50+j*0) Ohm

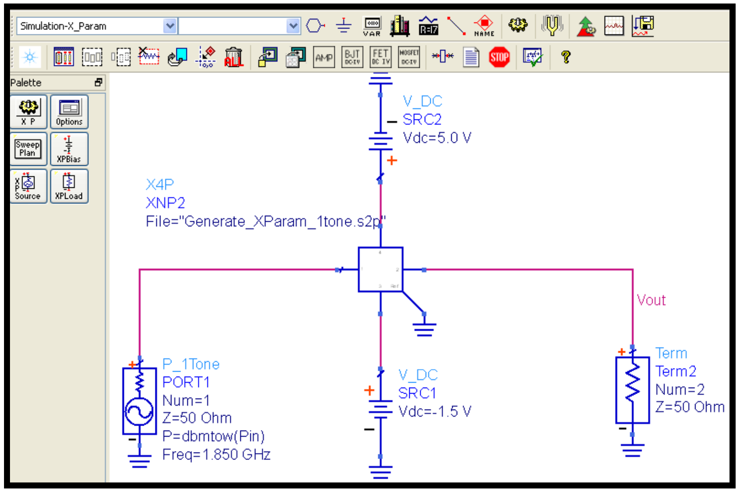
XP_Load
PORT2
Num=2
PortName="Output"
Z0=(50+j*0) Ohm

X_Param
X1
Freq[1]=1.85 GHz
Order[1]=9

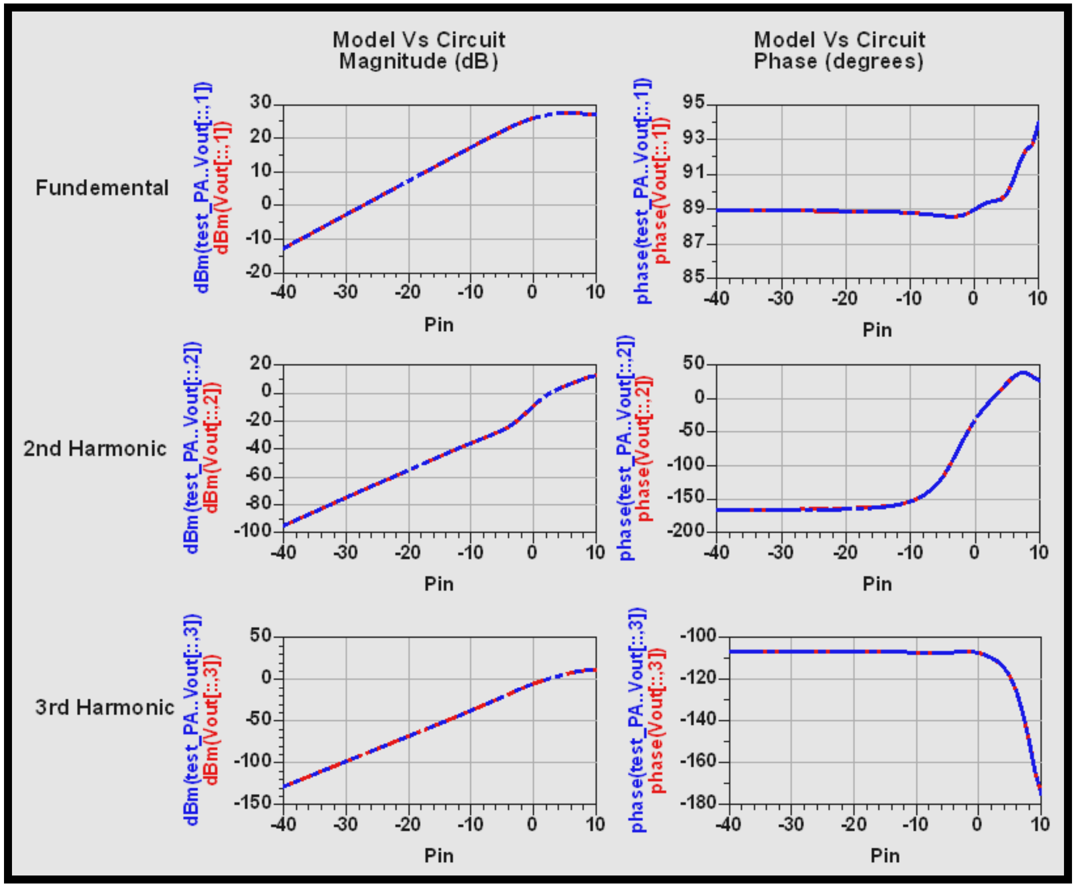
Slide courtesy of J. Sifri

# Single Tone Amp model with 50 ohm load

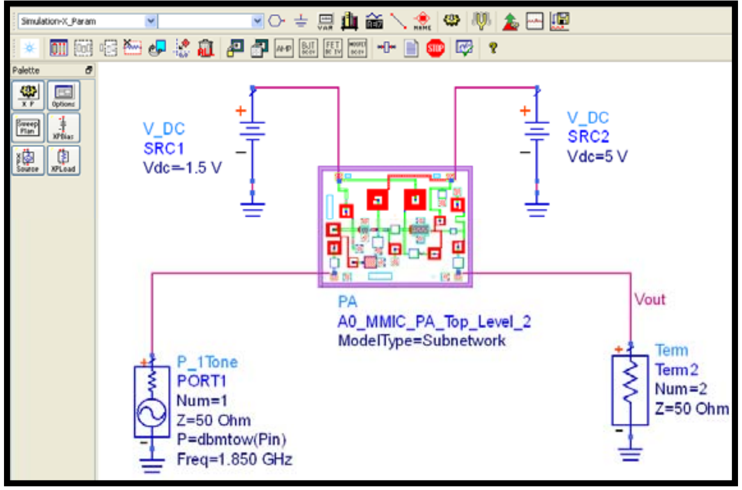
## IP-protected model; Fast X-parameter simulation component (20x faster)



## X-pars Vs ckt-level PA Results



## Test the PA circuit



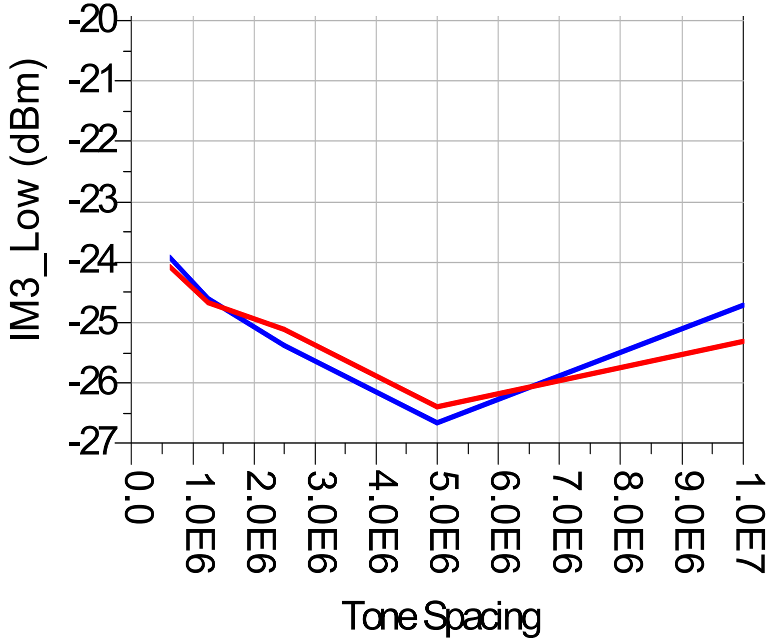
# **Soon:** Two-tone X-parameter NVNA measurements

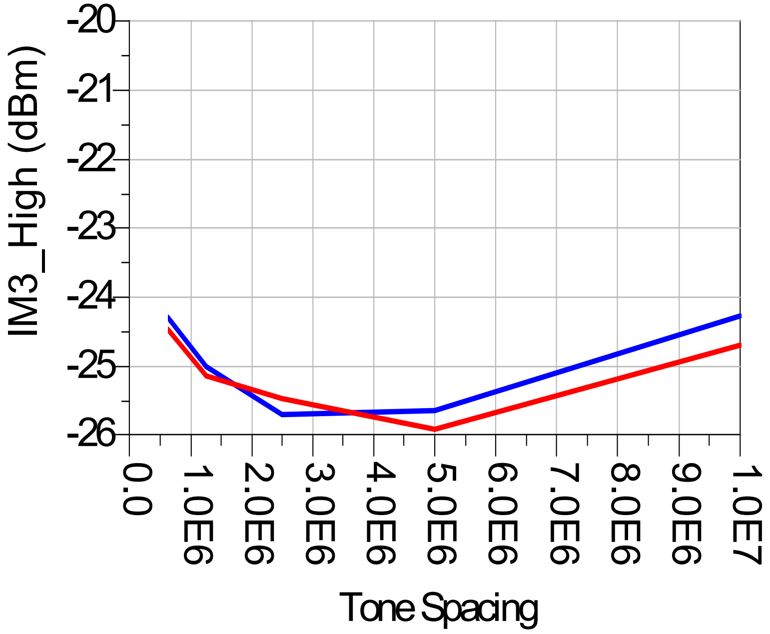
- Magnitude *and Phase* of intermod products and sensitivity to mismatch
- Measure and simulate freq-dependence & asymmetry of complex intermods
- Design nonlinear circuits that cancel distortion
- ADS X-parameter generator and XnP component can do this already

Red = 2-Tone X-parameters prediction

Blue = Independent measured data

Courtesy J. Horn

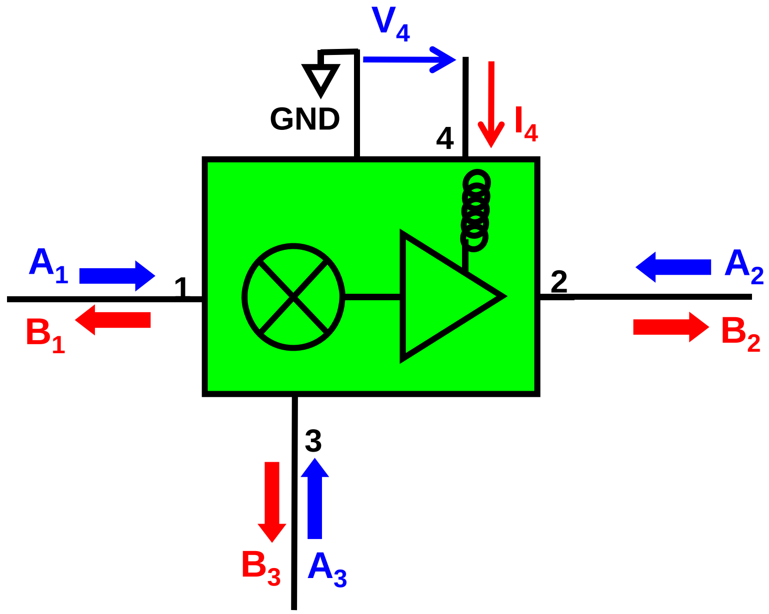




# 3-Port X-parameter Measurements

For characterization and measurement-based simulation of three-port components (mixers, converters, switches)

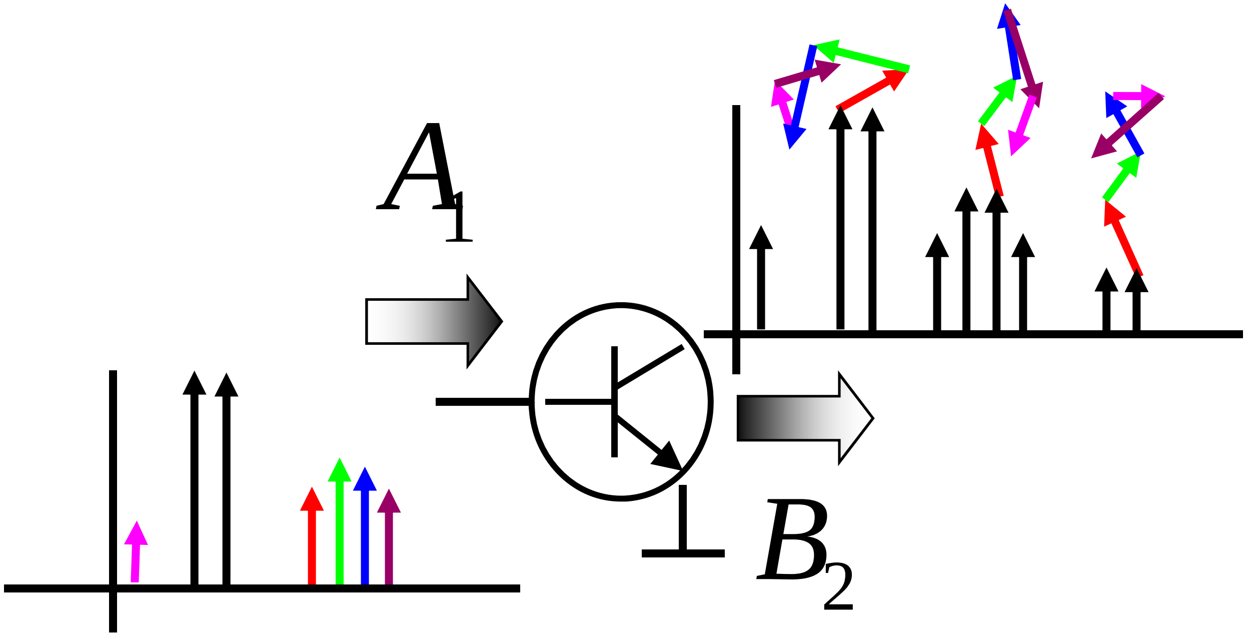
Note: ADS can already generate and simulate with multi-port, multi-tone X-parameters



Here A and B waves include *multiple spectral components*

# Multi-tone, Multi-port X-parameters: Two large signals at different frequencies at different ports

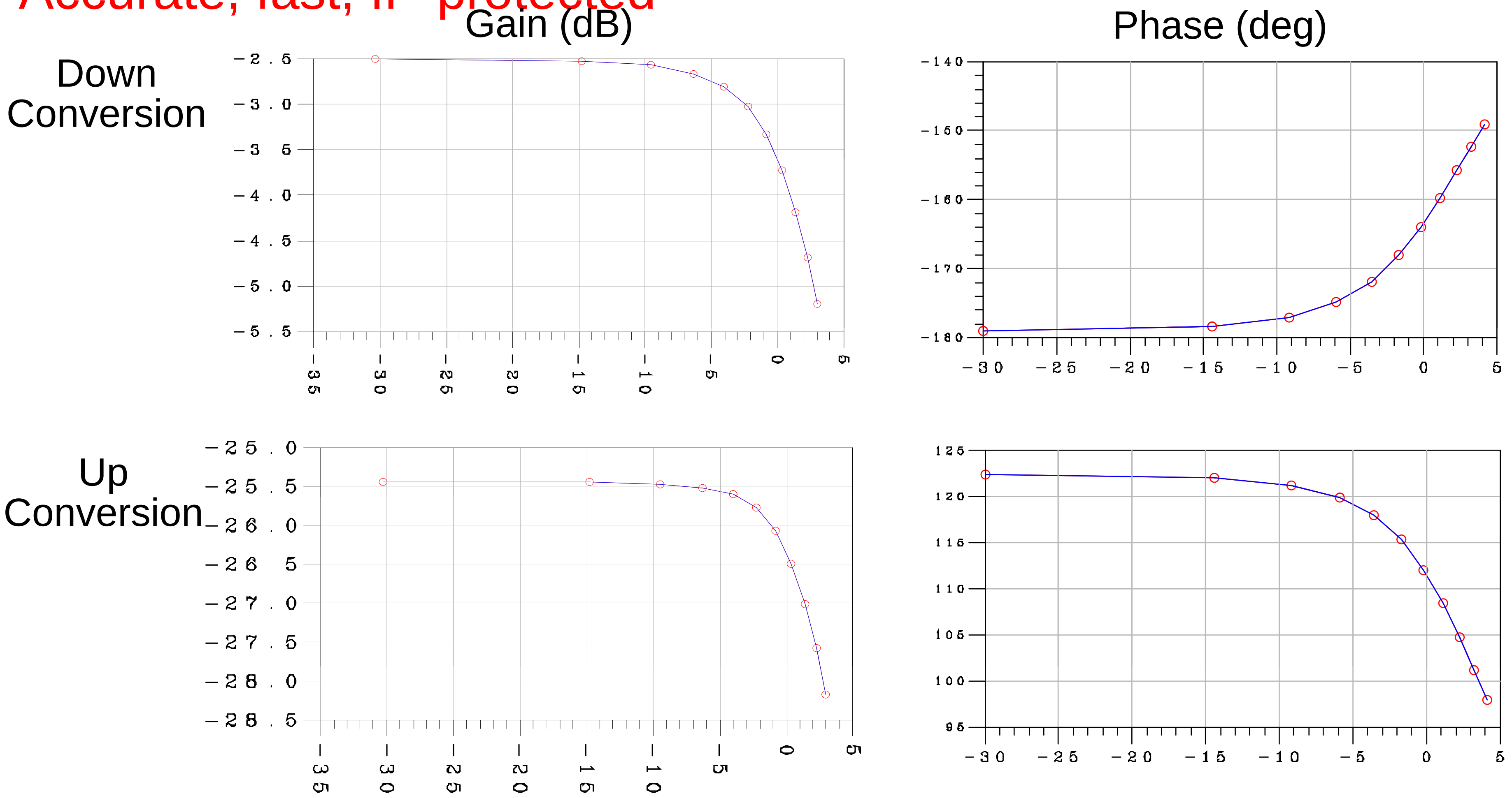
Less restrictive approximation to the general theory:
Linearization around the multi-tone nonlinear responses



$$B_{i,kl} = X^{(F)}_{i,kl}\left(A_{1,10}, A_{2,01}, 0, 0, \ldots\right) + \begin{array}{c}\text{Terms } \textit{linear} \text{ in the} \\ \text{remaining components}\end{array}$$

# *Mixers:* X-parameters extracted from an Agilent DC-50 GHz InP-based Mixer 1GC1-8068: Mismatched (10 Ohms) at IF

Accurate, fast, IP-protected



Simulation-based

LO: 45 GHz RF: 45.1 GHz LO power = 3.5 dBm

Circuit Model (solid blue) X-parameter Model (red points)

# *Mixers:* X-parameters extracted from an Agilent DC-50 GHz InP-based Mixer 1GC1-8068: Mismatched (10 Ohms) at IF

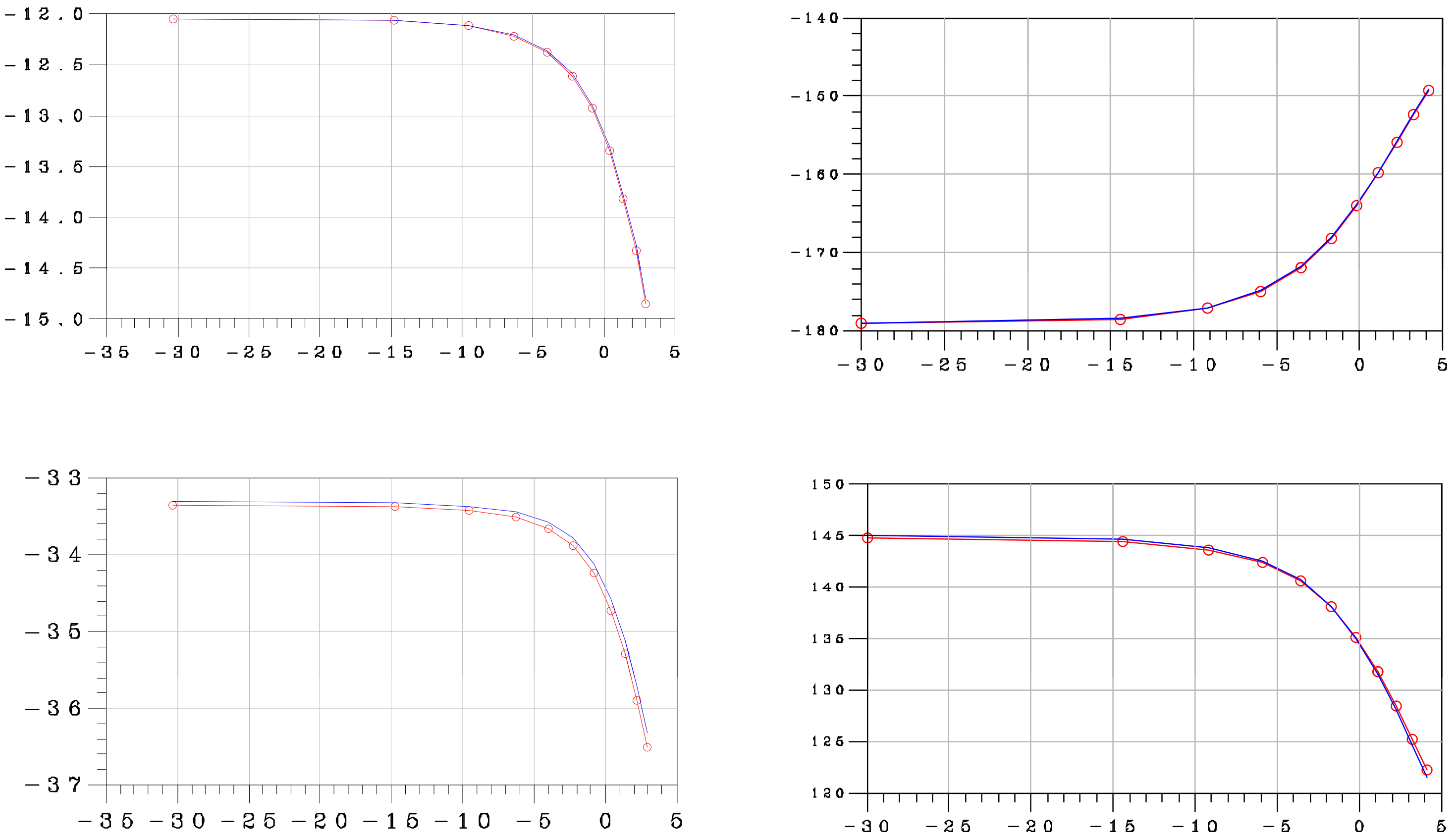
## Accurate, fast, IP-protected

Gain (dB)

Phase (deg)

Down Conversion

Up Conversion



Simulation-based

LO: 45 GHz RF: 45.1 GHz LO power = 3.5 dBm

Circuit Model (solid blue) X-parameters (red points)

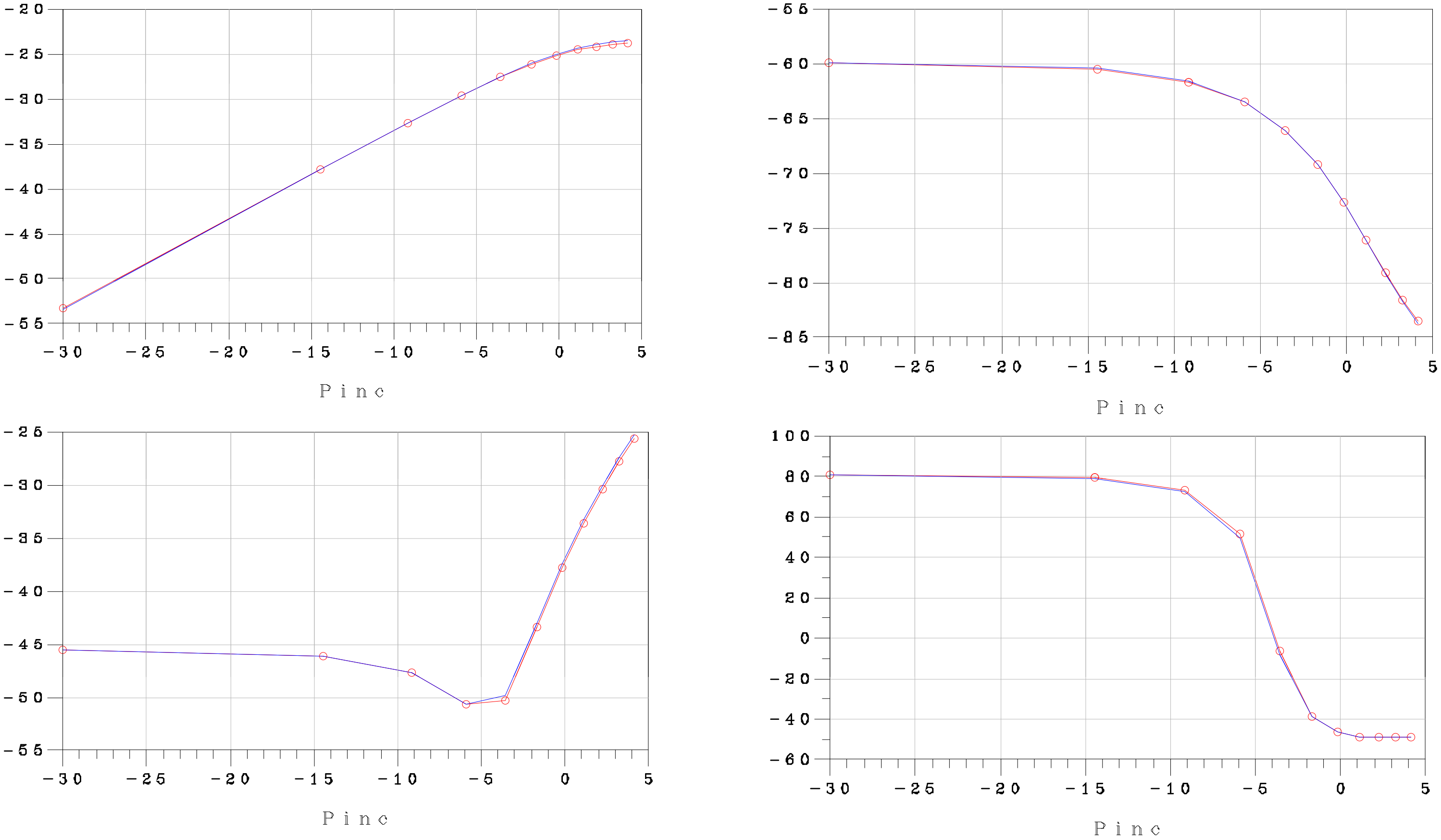
# Two Fundamentals: 50 GHz Integrated Mixer Mismatched load (10 Ohms) at IF

Gain (dB)

Phase (deg)

LO Leakage

RF Leakage

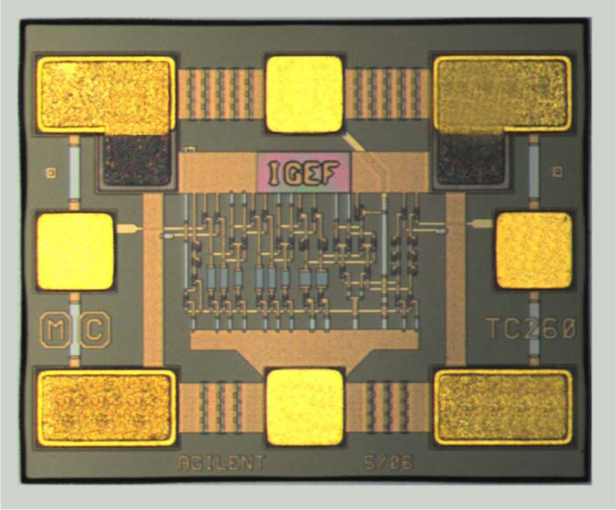


Simulation-based

LO: 45 GHz RF: 45.1 GHz LO power = 3.5 dBm

Circuit Model (solid blue) X-parameter Model (red points)

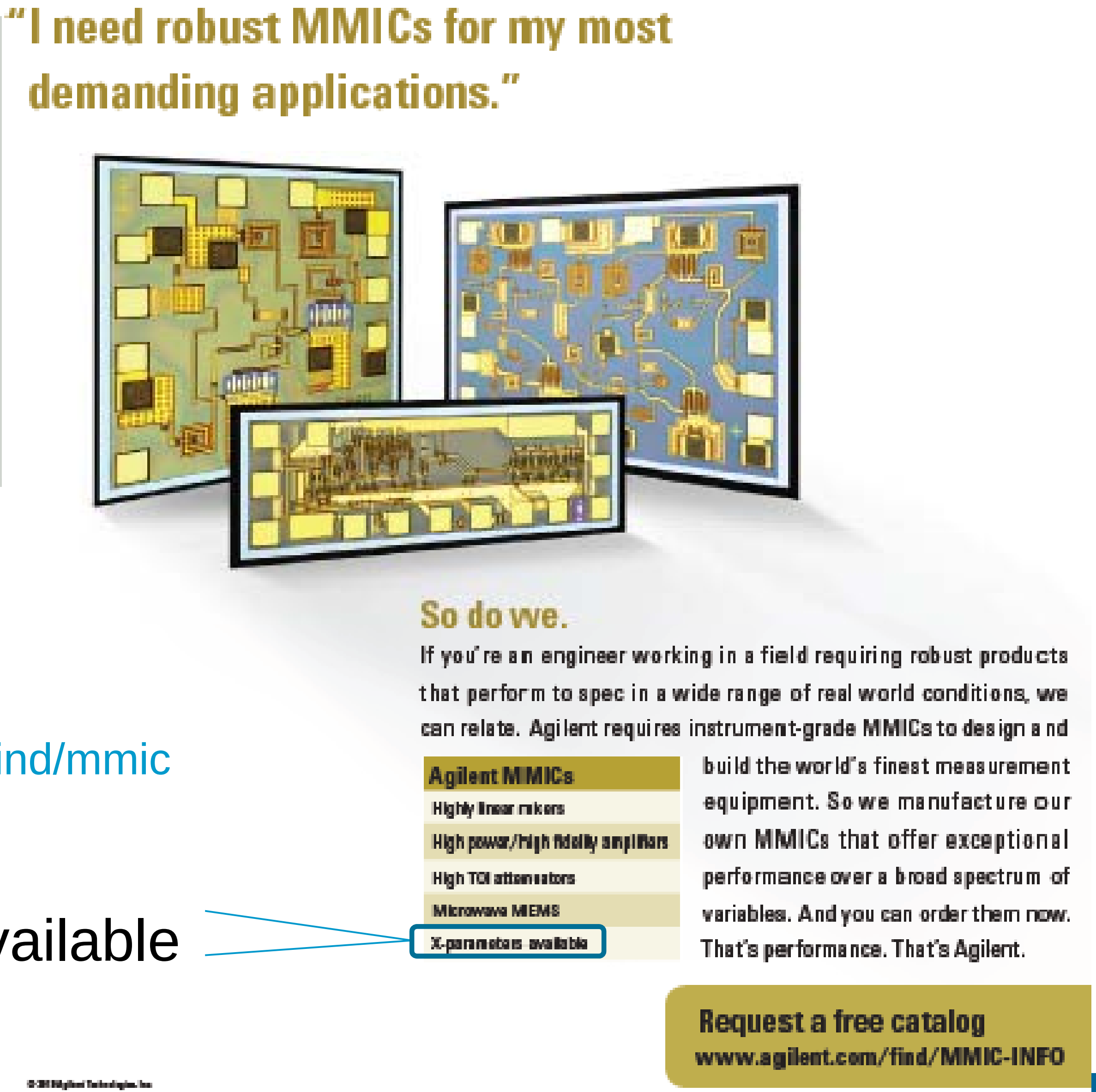
# Agilent MMICs: Available for purchase



**50 GHz InP-based Mixer**
**Part number:** 1GC1-8068

See: http://www.agilent.com/find/mmic

X-parameters available



"I need robust MMICs for my most demanding applications."

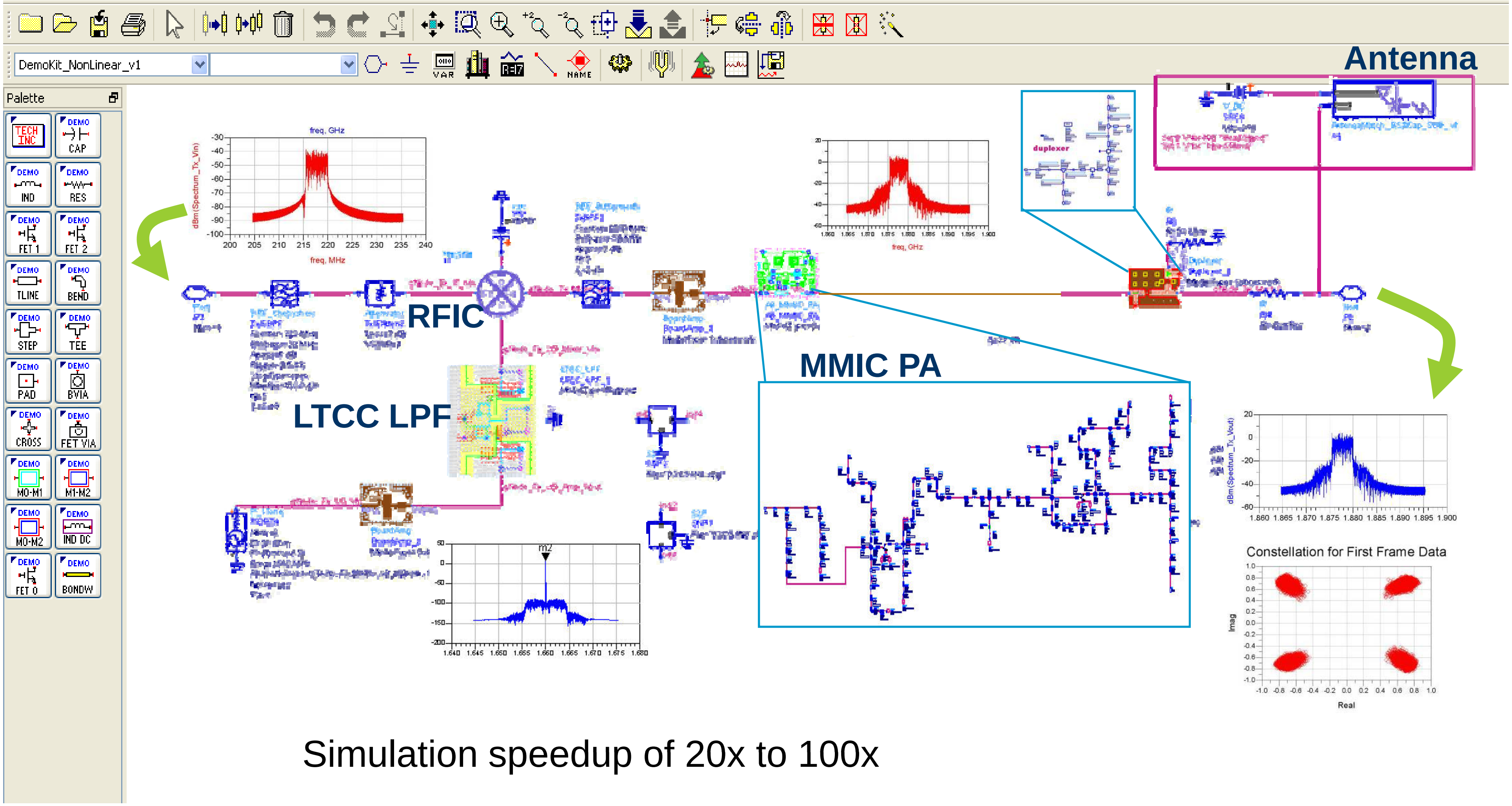
## So do we.

If you're an engineer working in a field requiring robust products that perform to spec in a wide range of real world conditions, we can relate. Agilent requires instrument-grade MMICs to design and build the world's finest measurement equipment. So we manufacture our own MMICs that offer exceptional performance over a broad spectrum of variables. And you can order them now. That's performance. That's Agilent.

| Agilent MMICs |
|---|
| Highly linear mixers |
| High power/high fidelity amplifiers |
| High TOI attenuators |
| Microwave MEMS |
| X-parameters available |

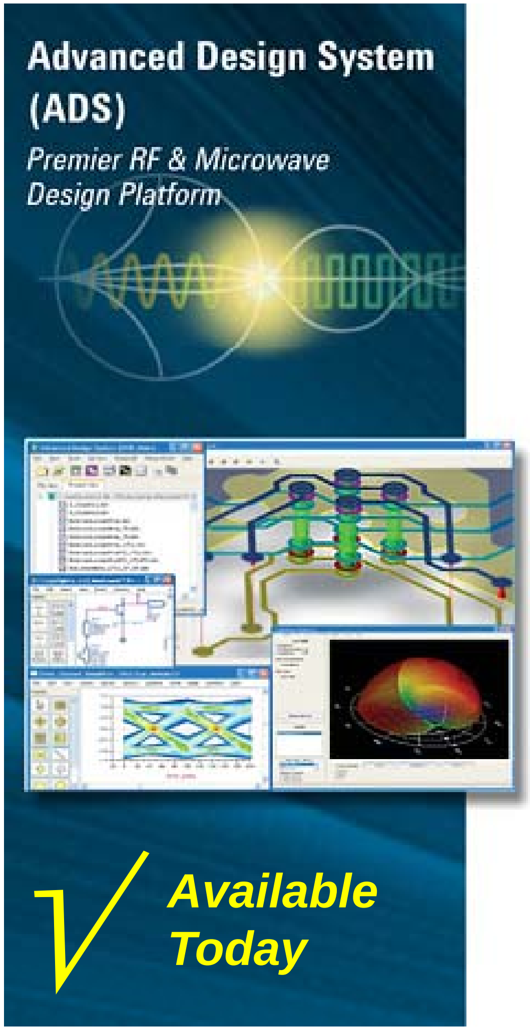
**Request a free catalog**
**www.agilent.com/find/MMIC-INFO**

# Design Nonlinear RF Systems

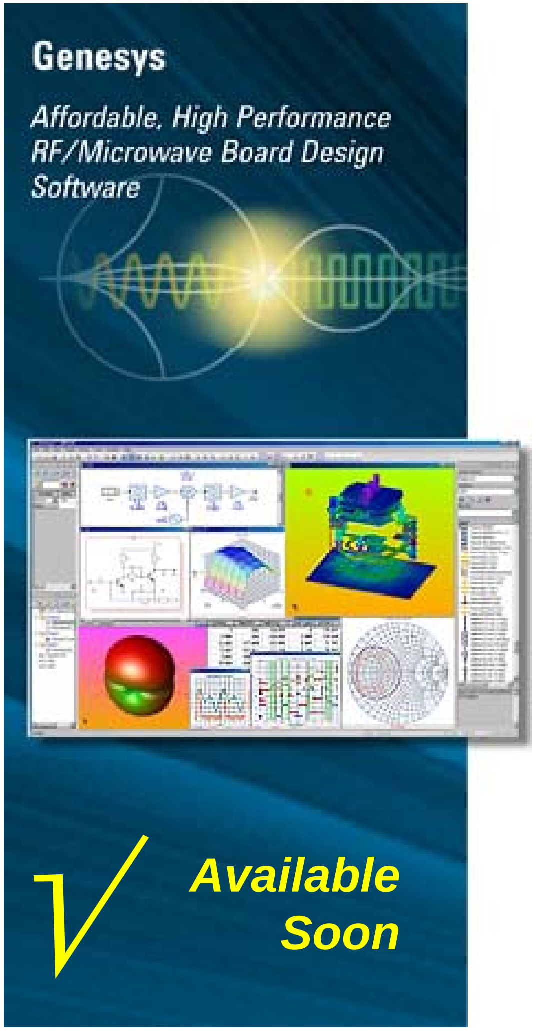


Simulation speedup of 20x to 100x

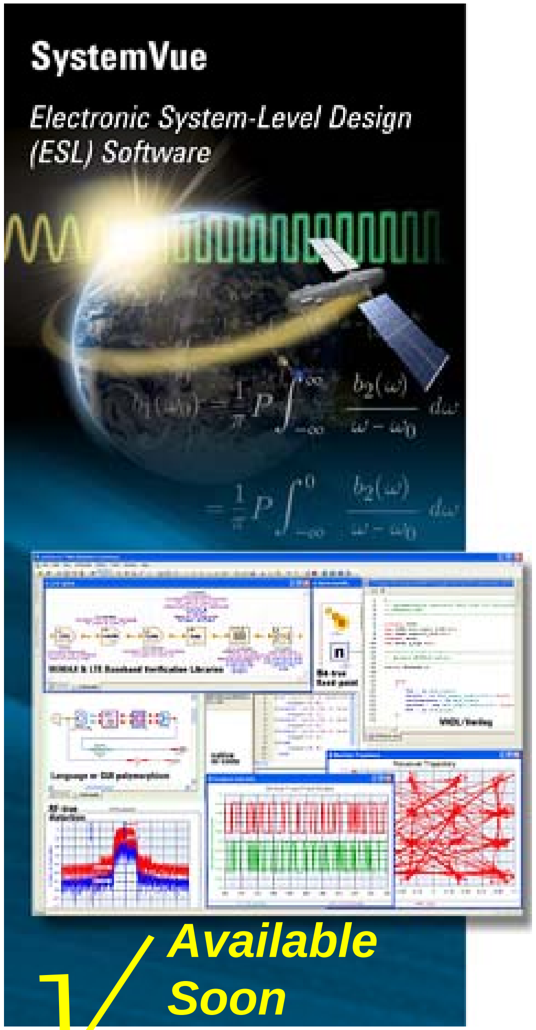
# X-Parameter technology available in commercial EDA SW



√ **Available Today**



√ **Available Soon**



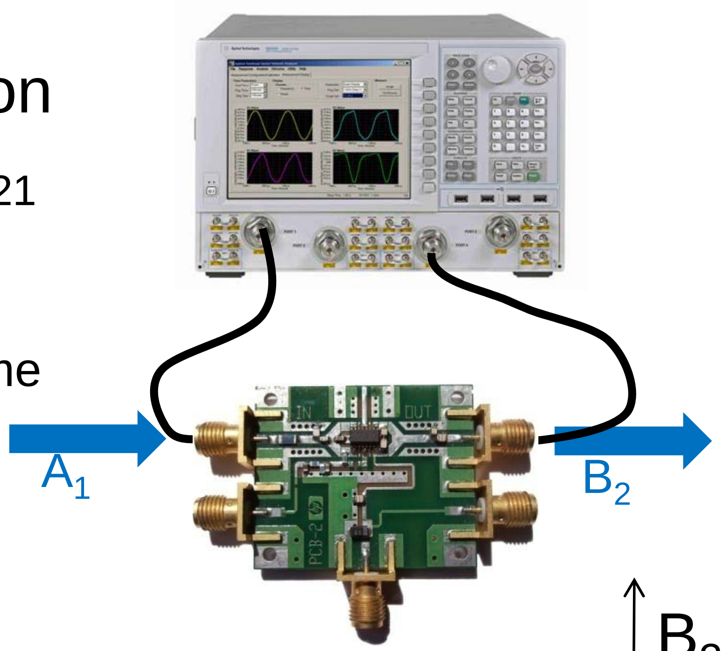
√ **Available Soon**

# Extending X-parameters to long-term memory

## Original X-parameters are Static Spectral Mappings

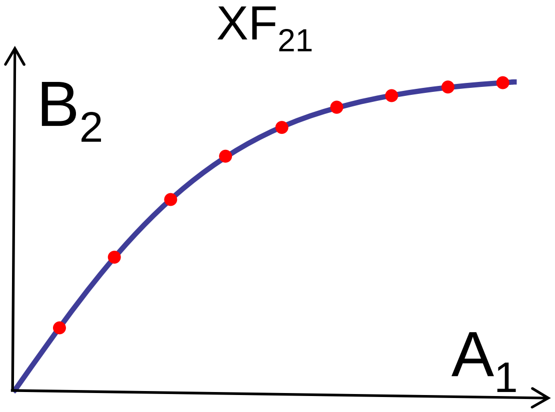
Slides courtesy J. Verspecht

NVNA



Static transmission X-parameter: $XF_{21}$

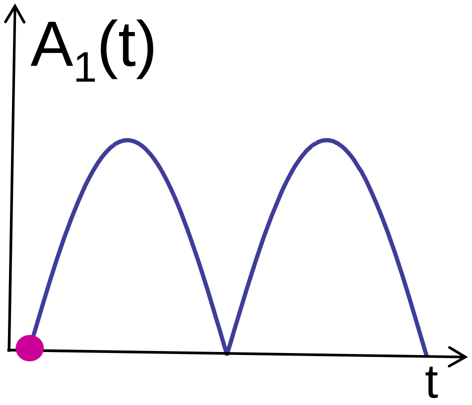
Can be measured under True CW, pulsed DC or Pulsed RF conditions



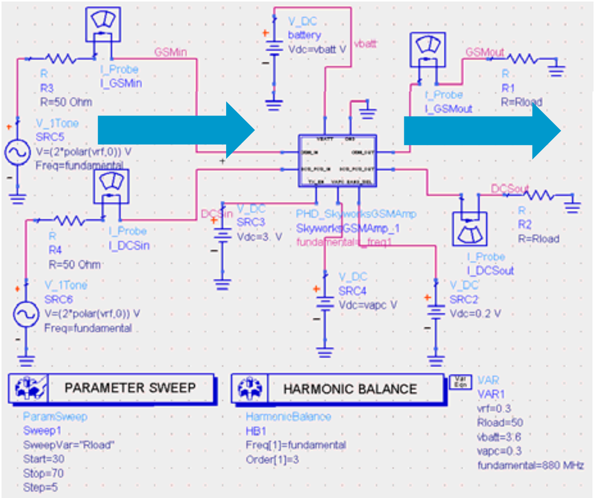
Frequency Domain:

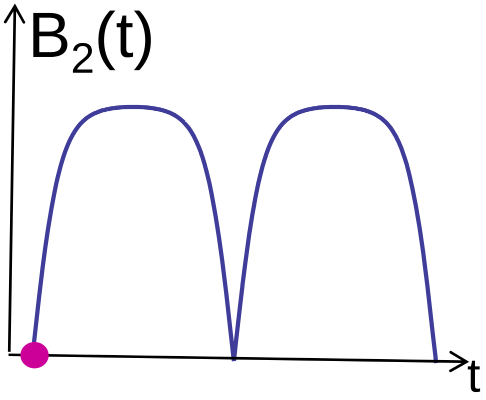
$$B_2 = XF_{21}\left(\left|A_1\right|\right)e^{j\varphi(A_1)}$$

# Modulation Simulated in Envelope Domain:



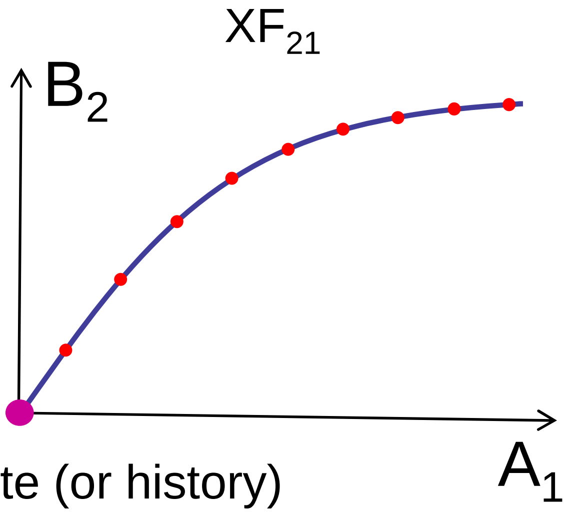
ADS envelope simulator





## Envelope Domain:

$$B_2(t) = XF_{21}\left(\left|A_1(t)\right|\right)e^{j\varphi(A_1(t))}$$



X-parameters determine Quasi-Static Response

- No “BW” effects
- Symmetric intermods independent of envelope rate (or history)

# Memory Effects: Beyond Static X-parameters

**Memory Effects:**

When output depends not only in instantaneous input but also on past input values

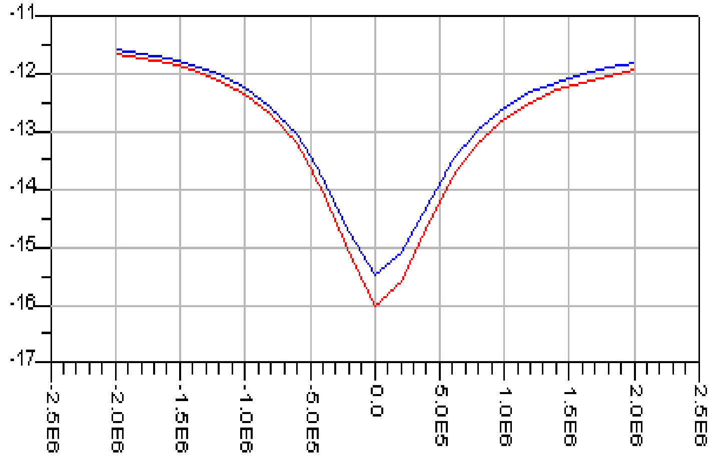
- Response to fast input envelope variations may violate quasi-static assumption for use in envelope domain for estimation of response to modulated signals

- Physical causes of memory: Dynamic self-heating, bias-line interaction, trapping effects caused by *additional dynamic variables* – multiple time-scale problem

    IM3 products asymetric

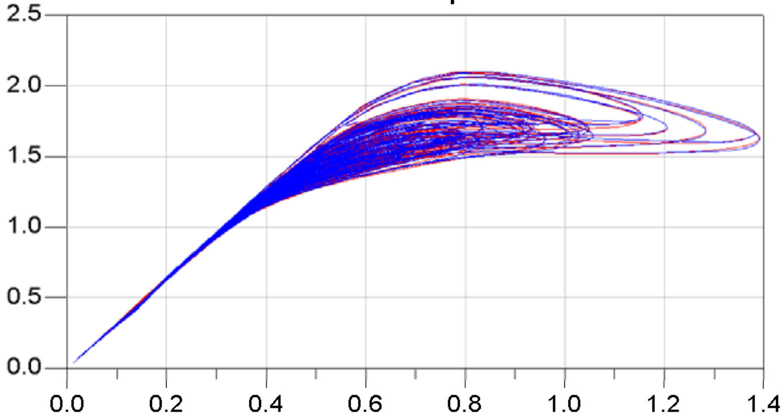
    Depend on tone spacing

HBT IM3 [dBm] versus tone separation [Hz]



Hysteresis in compression plot

Gain-compression

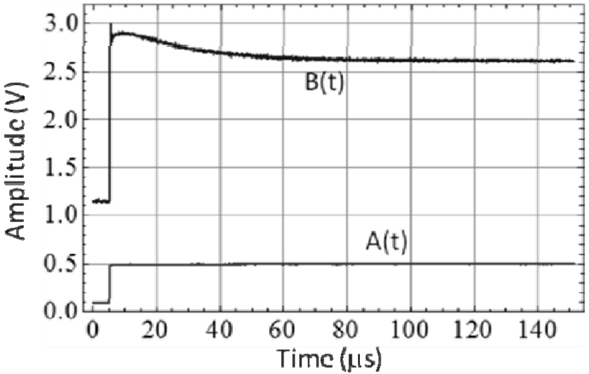


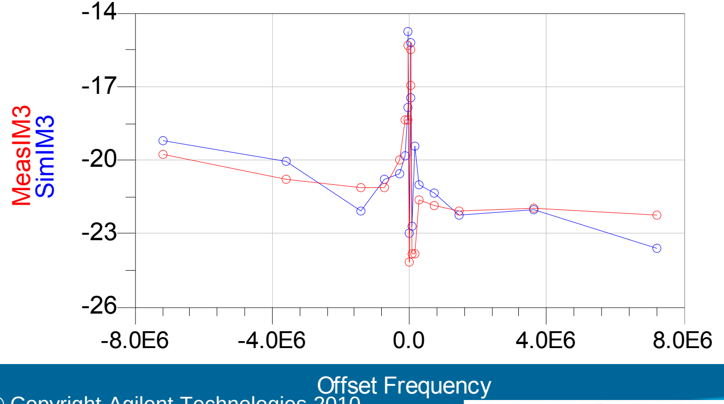
# Dynamic X-parameters: Long-Term Memory

## Fundamental “hidden variable” theory

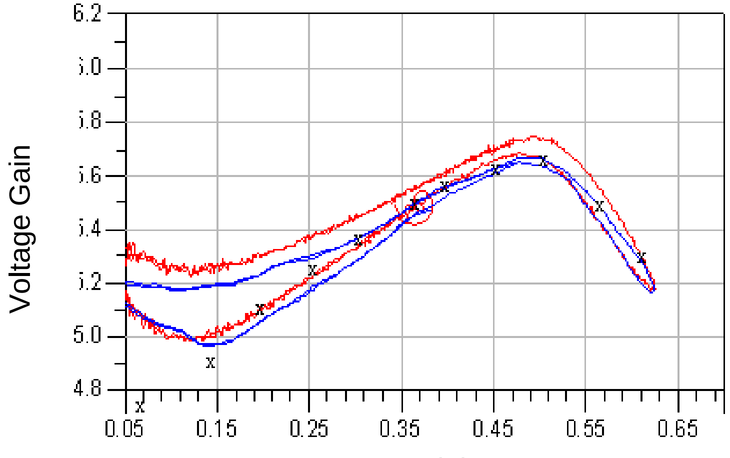
Verspecht et al “Extension of X-parameters to include long-term dynamic memory effects,” *IEEE MTT-S Int’l Microwave Symposium Digest,* 2009. pp 741-744

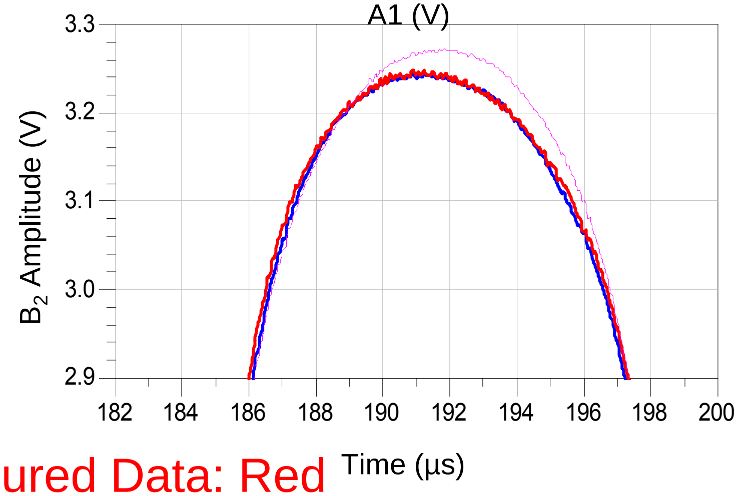
$$B(t)=\left\{XF_{21}\left(\left|A(t)\right|\right)+\int_{0}^{\infty}G\left(\left|A(t)\right|,\left|A(t-u)\right|,u\right)du\right\}e^{j\varphi(A(t))}$$





Anadigics AWT6282





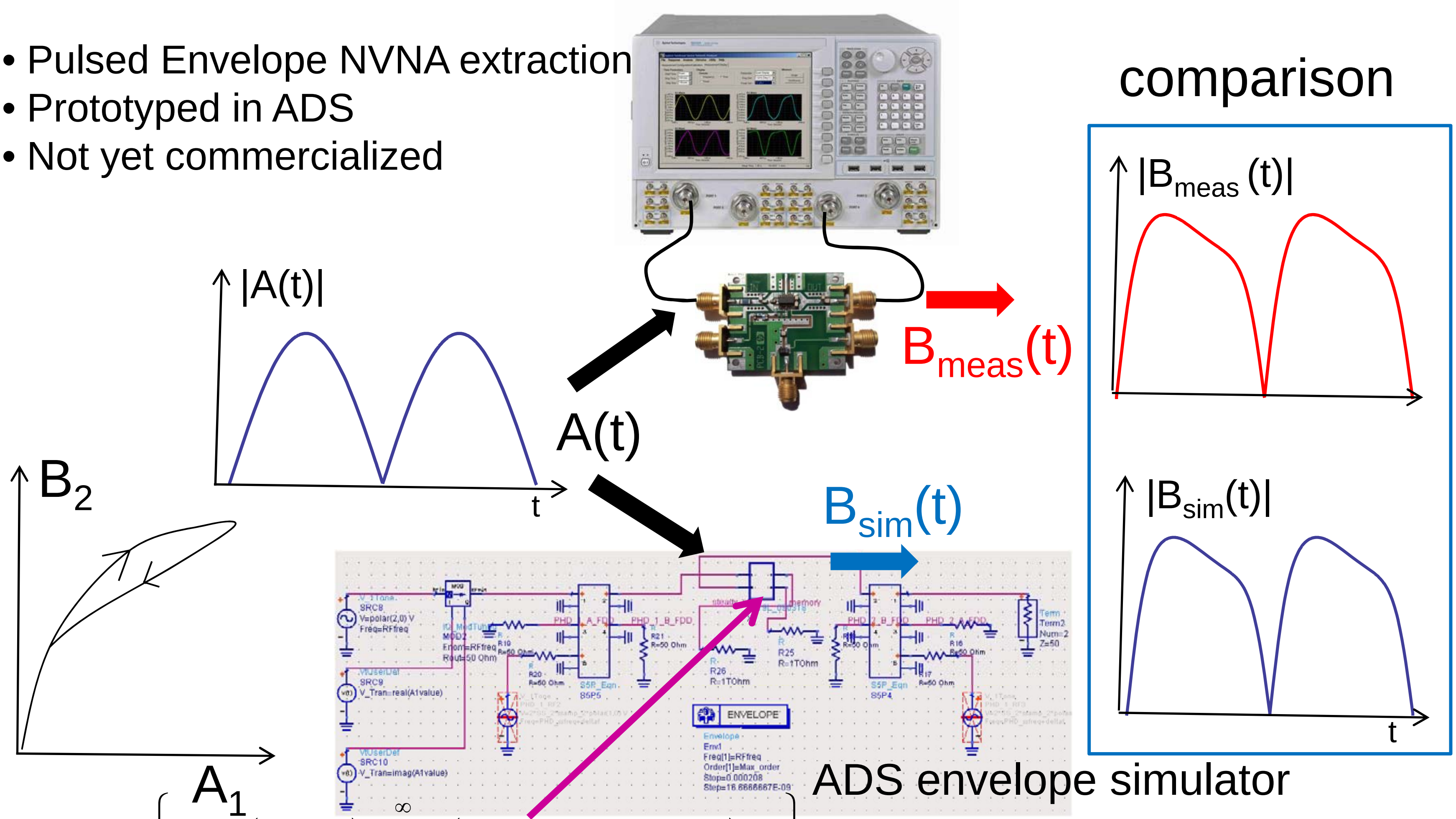
Measured Data: Red

Memory model prediction: Blue

Static X-parameter prediction: Magenta

# Dynamic X-parameters Beyond Quasi-Static

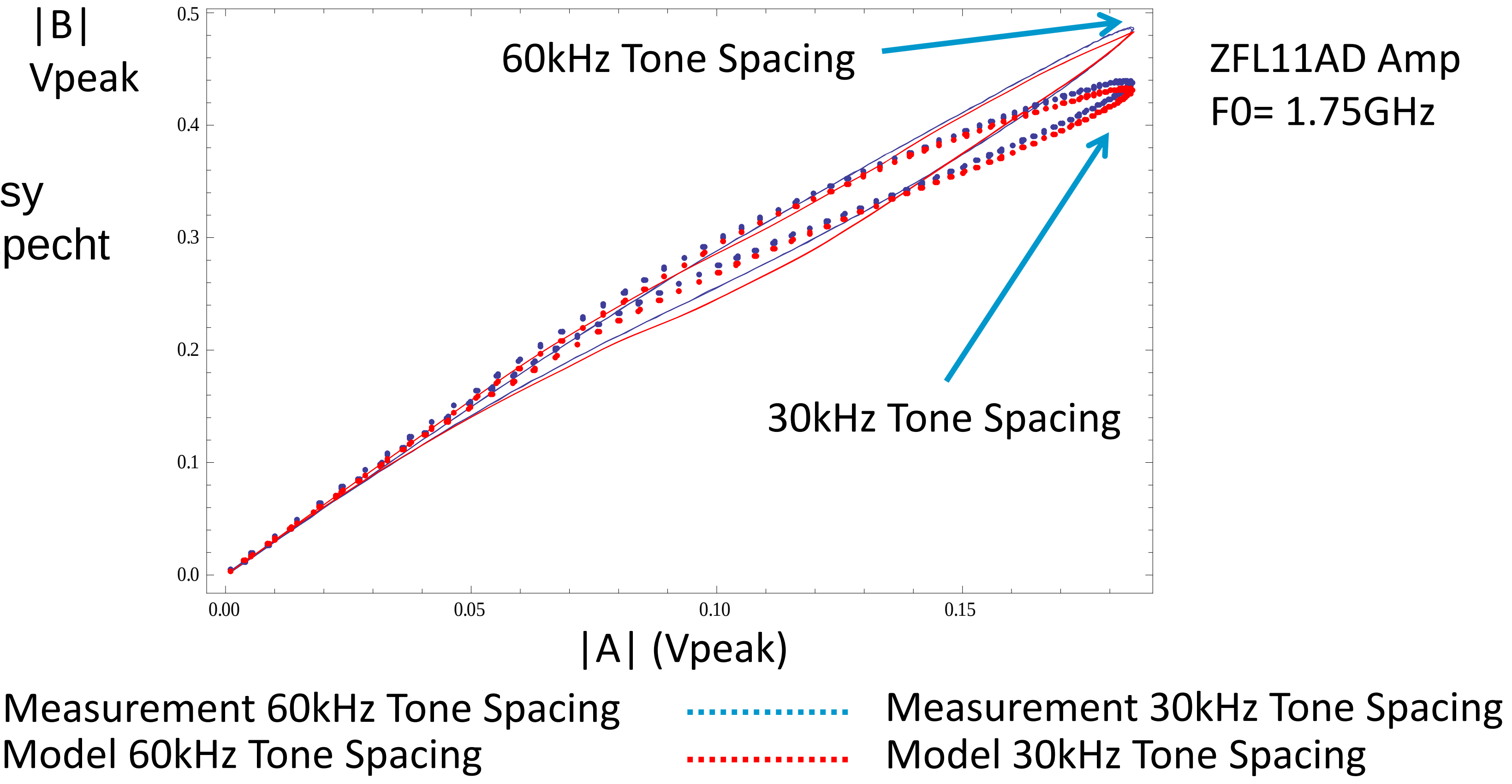
- Pulsed Envelope NVNA extraction
- Prototyped in ADS
- Not yet commercialized



$$B(t) = \left\{ XF_{21}\left(\left|A(t)\right|\right) + \int_{0}^{\infty} G\left(\left|A(t)\right|, \left|A(t-u)\right|, u\right) du \right\} e^{j\varphi(A(t))}$$

# Dynamic X-parameters Predict Memory Effects

Courtesy
J. Verspecht



See Latest Research Results on Dynamic X-parameters

J. Verspecht, J. Horn, D. E. Root "A Simplified Extension of X-parameters to Describe Memory Effects for Wideband Modulated Signals"

ARFTG Conference Session 2-1 Friday, May 28, 2010 10:20AM (Hilton)

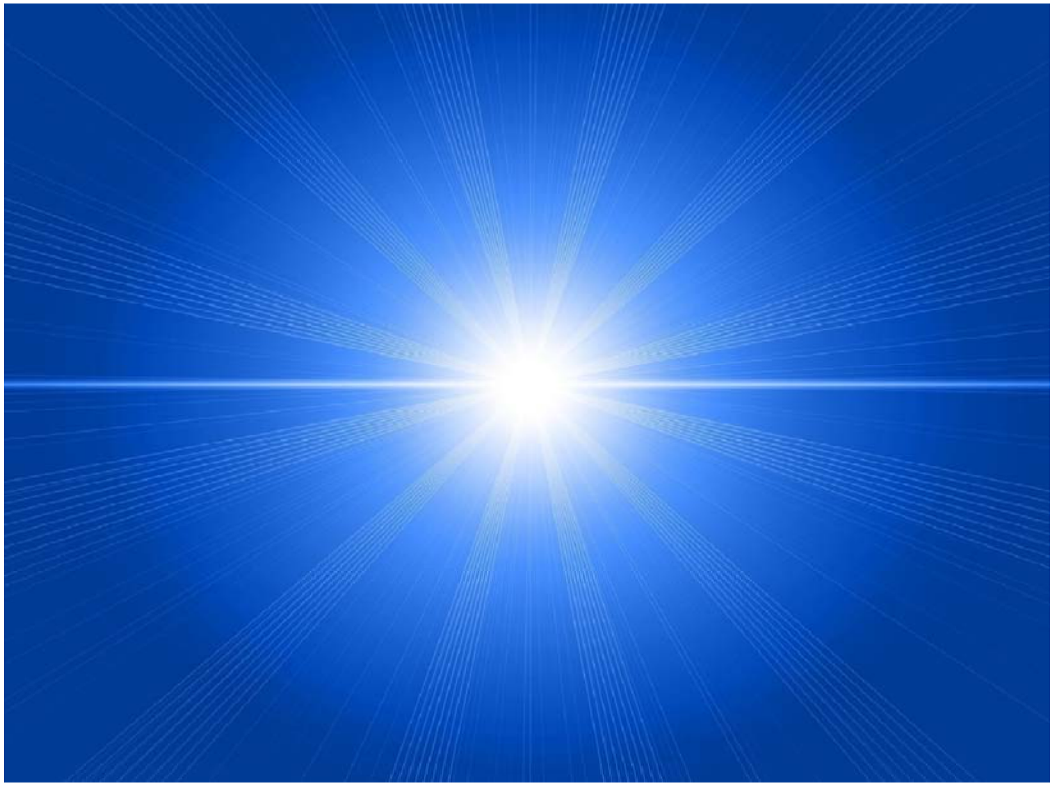
# Summary: X-parameter universe is expanding rapidly

**Powerful, practical interoperable solutions for nonlinear characterization, modeling, and design of microwave and RF**

**X-parameters: "doing for nonlinear components and systems what S-parameters do for linear components and systems"**

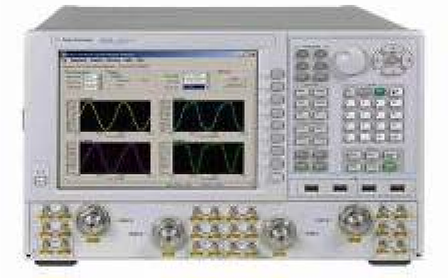
## Applications

- X-parameters for GSM amp.
- Load-dependent X-parameters
- 50 GHz Agilent NVNA
- High-Power X-parameter meas.
- X-parameter generator in ADS
- XnP component in ADS
- Two-tone measured X-pars
- Three-port measured X-pars
- Memory: Dynamic X-params
- Device modeling
- Education, training, app. notes
- **Industry is adopting paradigm**

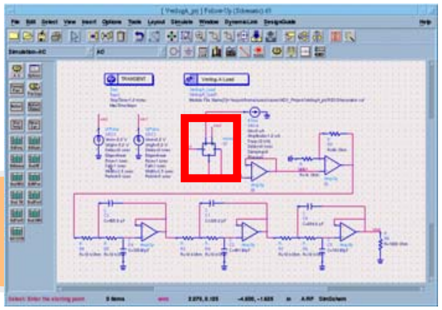


# X-Parameters: Agilent Completes the Nonlinear Puzzle!

Agilent Nonlinear Vector
Network Analyzer



Electronic design
automation software

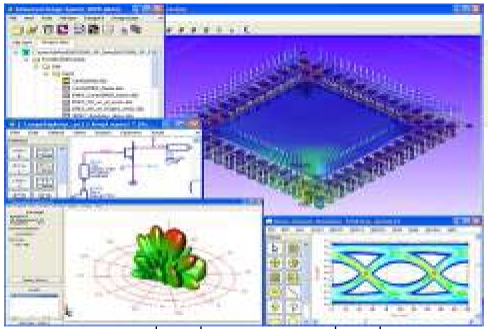


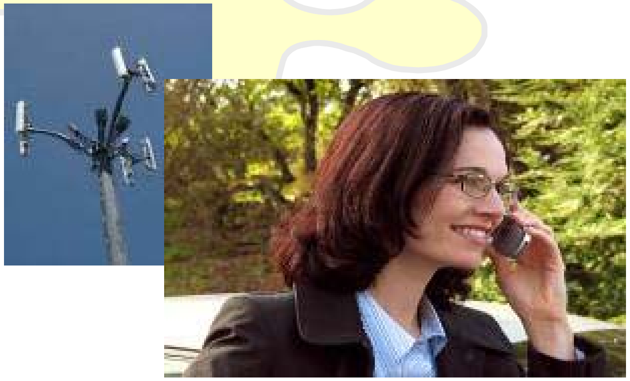
Nonlinear
Measurements

Nonlinear
Simulation & Design

Nonlinear
Modeling

Customer
Applications





$$B_{pm} = X^{F}_{pm}(|A_{11}|) + X^{S}_{pm,qn}(|A_{11}|)P^{m-n}A_{qn} + X^{T}_{pm,qn}(|A_{11}|)P^{m+n}A^{*}_{qn}$$

# Selected References and Links

1. D. E. Root, J. Horn, L. Betts, C. Gillease, J. Verspecht, “X-parameters: The new paradigm for measurement, modeling, and design of nonlinear RF and microwave components,” Microwave Engineering Europe, December 2008 pp 16-21. http://www.nxtbook.com/nxtbooks/cmp/mwee1208/#/16
2. D. E. Root, “X-parameters: Commercial implementations of the latest technology enable mainstream applications” Microwave Journal, Sept. 2009, http://www.mwjournal.com/search/ExpertAdvice.asp?HH_ID=RES_200&SearchWord=root
3. J. Verspecht and D. E. Root, “Poly-Harmonic Distortion Modeling,” in *IEEE Microwave Theory and Techniques Microwave Magazine*, June, 2006.
4. D . E. Root, J. Verspecht, D. Sharrit, J. Wood, and A. Cognata, **“**Broad-Band, Poly-Harmonic Distortion (PHD) Behavioral Models from Fast Automated Simulations and Large-Signal Vectorial Network Measurements,” *IEEE Transactions on Microwave Theory and* Techniques Vol. 53. No. 11, November, 2005 pp. 3656-3664
5. Verspecht, J.; Horn, J.; Betts, L.; Gunyan, D.; Pollard, R.; Gillease, C.; Root, D.E.; “Extension of X-parameters to include long-term dynamic memory effects,” *IEEE MTT-S International Microwave Symposium Digest,* 2009. pp 741-744, June, 2009
6. J. Verspecht, J. Horn, D. E. Root “A Simplified Extension of X-parameters to Describe Memory Effects for Wideband Modulated Signals,” *Proceedings of the 75th IEEE MTT-S ARFTG Conference*, May, 2010
7. J. Xu, J. Horn, M. Iwamoto, D. E. Root, “Large-signal FET Model with Multiple Time Scale Dynamics from Nonlinear Vector Network Analyzer Data,” *IEEE MTT-S International Microwave Symposium Digest,* May, 2010.
8. J. Horn, S. Woodington, R. Saini, J. Benedikt, P. J. Tasker, and D. E. Root; “Harmonic Load-Tuning Predictions from X-parameters,” *IEEE PA Symposium*, San Diego, Sept. 2009
9. D. Gunyan , J. Horn, J Xu, and D.E.Root, “Nonlinear Validation of Arbitrary Load X-parameter and Measurement-Based Device Models,” *IEEE MTT-S ARFTG Conference*, Boston, MA, June 2009
10. G. Simpson, J. Horn, D. Gunyan, and D.E. Root, “Load-Pull + NVNA = Enhanced X-Parameters for PA Designs with High Mismatch and Technology-Independent Large-Signal Device Models, ” *IEEE ARFTG Conference,* Portland, OR December 2008.
11. J. Horn, J. Verspecht, D. Gunyan , L. Betts, D. E. Root, and Joakim Eriksson, “X-Parameter Measurement and Simulation of a GSM Handset Amplifier,” *2008 European Microwave Conference Digest* Amsterdam, October, 2008
12. J. Verspecht, D. Gunyan, J. Horn, J. Xu, A. Cognata, and D.E. Root, “Multi-tone, Multi-Port, and Dynamic Memory Enhancements to PHD Nonlinear Behavioral Models from Large-Signal Measurements and Simulations,” *2007 IEEE MTT-S Int. Microwave Symp. Dig.,* Honolulu, HI, USA, June 2007.
13. http://www.agilent.com/find/x-parameters for X-parameters
14. http://www.agilent.com/find/nvna for NVNA
15. http://www.agilent.com/find/mmic for Agilent MMICs
16. http://www.agilent.com/find/x-parameters-info for information about X-parameter open standards

# Survey and Trends in Nonlinear Transistor Modeling Methodologies

Dr. David E. Root
Principal R&D Scientist
High Frequency Technology Center
Santa Rosa, CA USA

IEEE MTT-S Lecture #3
Bergen, Norway
May 7, 2010

# Key Contributors

- Alex Cognata
- Daniel Gunyan
- Jason Horn
- Masaya Iwamoto
- Alexander Pekker
- Dominique Schreurs
- Jonathan Scott
- Gary Simpson
- Franz Sischka
- Paul Tasker
- John Wood
- Jianjun Xu

# Presentation Outline

- Introduction
- I-V modeling
- Nonlinear Charge Modeling
- Non Quasi-Static Effects & Dispersion Modeling
- Electro-Thermal Modeling
- Advanced Measurements
- NVNA data and advanced dynamical FET modeling
- Symmetry Considerations
- Summary & Conclusions

# Introduction

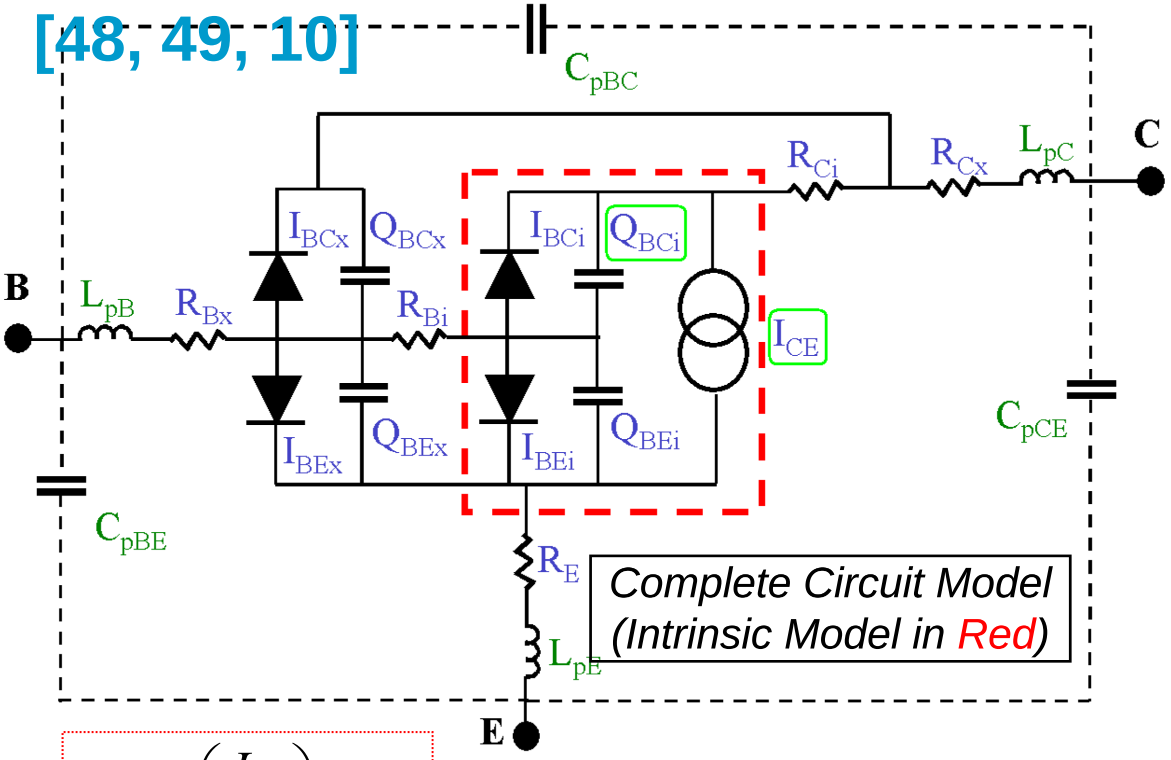
*All models* are wrong, but *some* are *useful*."

- statistician George Box

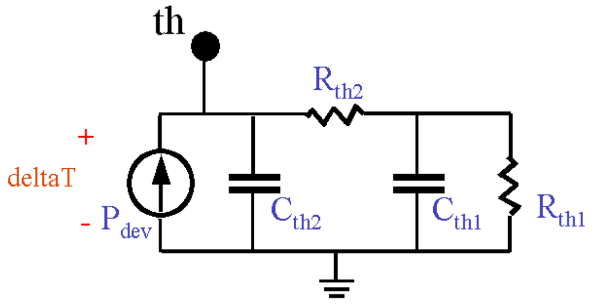
"All models are approximations.
Some models are useful."

- attributed to Mike Golio and others

# Compact Transistor Models (AgilentHBT model) [48, 49, 10]



Complete Circuit Model
(Intrinsic Model in Red)



*Thermal Subcircuit*
*(Two-Poles)*

**Coupled nonlinear ordinary differential equations in the time domain**

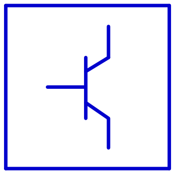
**Equivalent Circuit with nonlinear elements**

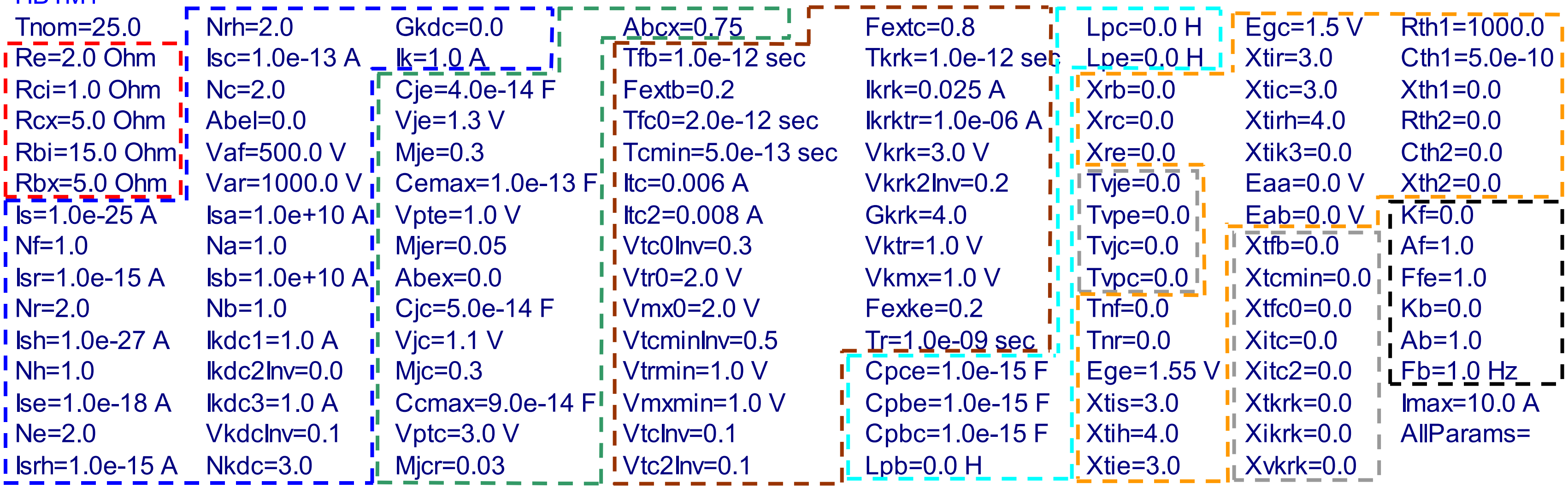
$$I_{CE} = \frac{\left(\frac{I_{cf}}{q3}\right) - I_{cr}}{d}$$

$$Icrit1 = IKDC3\left(1 - \frac{V_{BCi} - VJC}{VKDC}\right)$$

$$q3 = \frac{\sqrt{\left(\frac{1}{IKDC2}(Icf - Icrit1)\right)^2 + \left(\frac{IKDC1}{IKDC2}\right)^2} + \left[\left(\frac{1}{IKDC2}(Icf - Icrit1)\right) - \left(\frac{IKDC1}{IKDC2}\right)\right]}{2} + 1 - q3_o$$

# Agilent HBT Model Parameters (over 100)





AgilentHBT_Model
HBTM1
Tnom=25.0
Re=2.0 Ohm
Rci=1.0 Ohm
Rcx=5.0 Ohm
Rbi=15.0 Ohm
Rbx=5.0 Ohm
Is=1.0e-25 A
Nf=1.0
Isr=1.0e-15 A
Nr=2.0
Ish=1.0e-27 A
Nh=1.0
Ise=1.0e-18 A
Ne=2.0
Isrh=1.0e-15 A

Nrh=2.0
Isc=1.0e-13 A
Nc=2.0
Abel=0.0
Vaf=500.0 V
Var=1000.0 V
Isa=1.0e+10 A
Na=1.0
Isb=1.0e+10 A
Nb=1.0
Ikdc1=1.0 A
Ikdc2Inv=0.0
Ikdc3=1.0 A
VkdcInv=0.1
Nkdc=3.0

Gkdc=0.0
Ik=1.0 A
Cje=4.0e-14 F
Vje=1.3 V
Mje=0.3
Cemax=1.0e-13 F
Vpte=1.0 V
Mjer=0.05
Abex=0.0
Cjc=5.0e-14 F
Vjc=1.1 V
Mjc=0.3
Ccmax=9.0e-14 F
Vptc=3.0 V
Mjcr=0.03

Abcx=0.75
Tfb=1.0e-12 sec
Fextb=0.2
Tfc0=2.0e-12 sec
Tcmin=5.0e-13 sec
Itc=0.006 A
Itc2=0.008 A
Vtc0Inv=0.3
Vtr0=2.0 V
Vmx0=2.0 V
VtcminInv=0.5
Vtrmin=1.0 V
Vmxmin=1.0 V
VtcInv=0.1
Vtc2Inv=0.1

Fextc=0.8
Tkrk=1.0e-12 sec
Ikrk=0.025 A
Ikrktr=1.0e-06 A
Vkrk=3.0 V
Vkrk2Inv=0.2
Gkrk=4.0
Vktr=1.0 V
Vkmx=1.0 V
Fexke=0.2
Tr=1.0e-09 sec
Cpce=1.0e-15 F
Cpbe=1.0e-15 F
Cpbc=1.0e-15 F
Lpb=0.0 H

Lpc=0.0 H
Lpe=0.0 H
Xrb=0.0
Xrc=0.0
Xre=0.0
Tvje=0.0
Tvpe=0.0
Tvjc=0.0
Tvpc=0.0
Tnf=0.0
Tnr=0.0
Ege=1.55 V
Xtis=3.0
Xtih=4.0
Xtie=3.0

Egc=1.5 V
Xtir=3.0
Xtic=3.0
Xtirh=4.0
Xtik3=0.0
Eaa=0.0 V
Eab=0.0 V
Xtfb=0.0
Xtcmin=0.0
Xtfc0=0.0
Xitc=0.0
Xitc2=0.0
Xtkrk=0.0
Xikrk=0.0
Xvkrk=0.0

Rth1=1000.0
Cth1=5.0e-10
Xth1=0.0
Rth2=0.0
Cth2=0.0
Xth2=0.0
Kf=0.0
Af=1.0
Ffe=1.0
Kb=0.0
Ab=1.0
Fb=1.0 Hz
Imax=10.0 A
AllParams=

| | | | |
|---|---|---|---|
| Resistances: | 5 | Parasitics: | 6 |
| DC Currents: | 26 | Temp., DC & R's: | 22 |
| Depletion Charge: | 14 | Temp., Charges: | 12 |
| Delay Charge: | 25 | Noise: | 6 |

# Transistor Modeling

- Compact Models: Equivalent circuit models for IC design formulated in the time-domain. Examples are BSIM models for MOSFET, Angelov model for GaAs FETs, Gummel-Poon models for bipolars, AgilentHBT model for III-V HBTs
- "Compact" models can be complex (> 100 parameter values)
- Parameters typically extracted from DC and S-pars  
  ***Ironic*** for a nonlinear model
  - Some devices may not be able to be characterized under DC and static operating conditions (power, temperature)
  - Advanced models may not be identifiable from only DC and S-parameter data.
  - No direct evidence that these nonlinear models will reproduce large-signal behavior

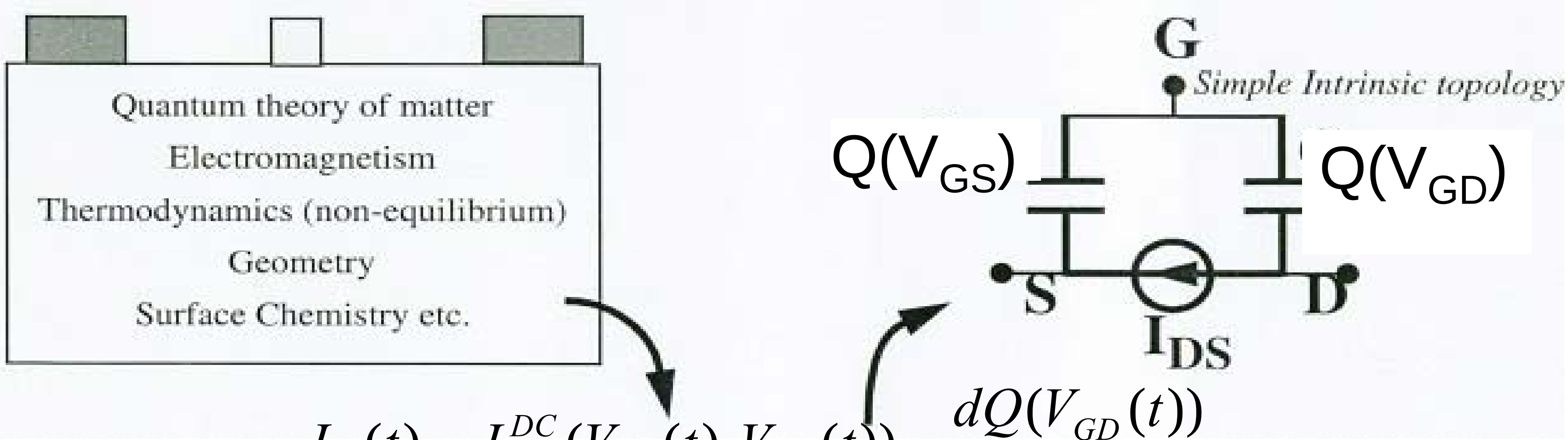
# Device Requirements and Modeling Implications

- Linearity: Harmonic & Intermod. Distortion; ACPR; AM-AM; AM-PM
- Efficiency: PAE; Fundamental Output Power; Self-biasing
- Memory: Slow thermal effects, slow trapping phenomena
- Modeling Challenges from
- Device physics (III-V transport, trapping dynamics)
  Complex signals, multiple time-scale dynamics
  Amplifier, switch, and mixer applications
  Wide variety of device designs in many material systems
- Accuracy required over
- Bias, frequency, and temperature; power;
- Different types of models may be required at different stages in the development of a technology

# Physical Models to Circuit (compact) Models [16,17]

**Shockley:** Physical PDEs and approximations such as *field-independent mobility, gradual channel approximation*, etc.:

Derive *terminal dynamics* and *constitutive relations*:



Quantum theory of matter

Electromagnetism

Thermodynamics (non-equilibrium)

Geometry

Surface Chemistry etc.

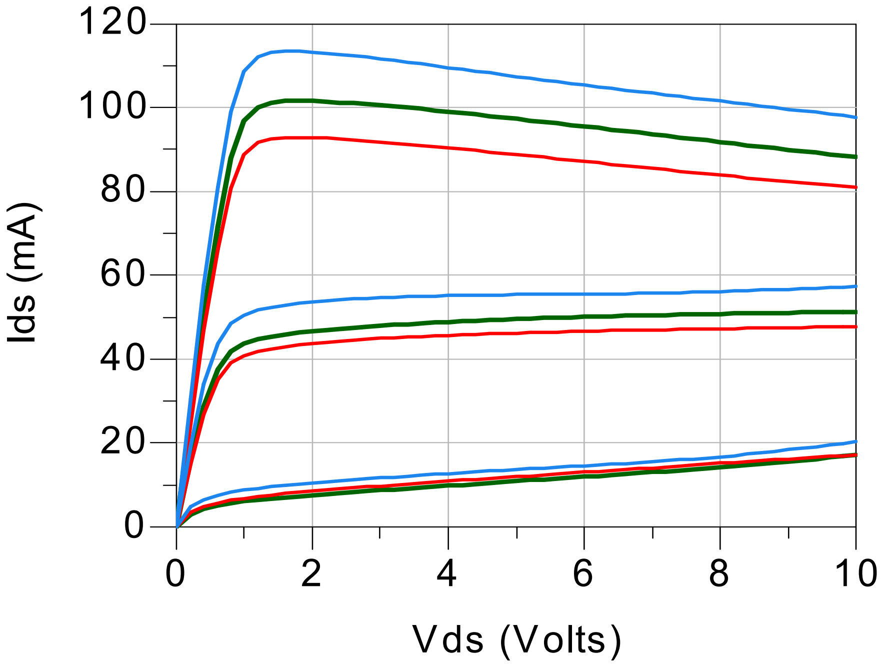
$$I_D(t) = I_D^{DC}(V_{GS}(t), V_{DS}(t)) - \frac{dQ(V_{GD}(t))}{dt}$$

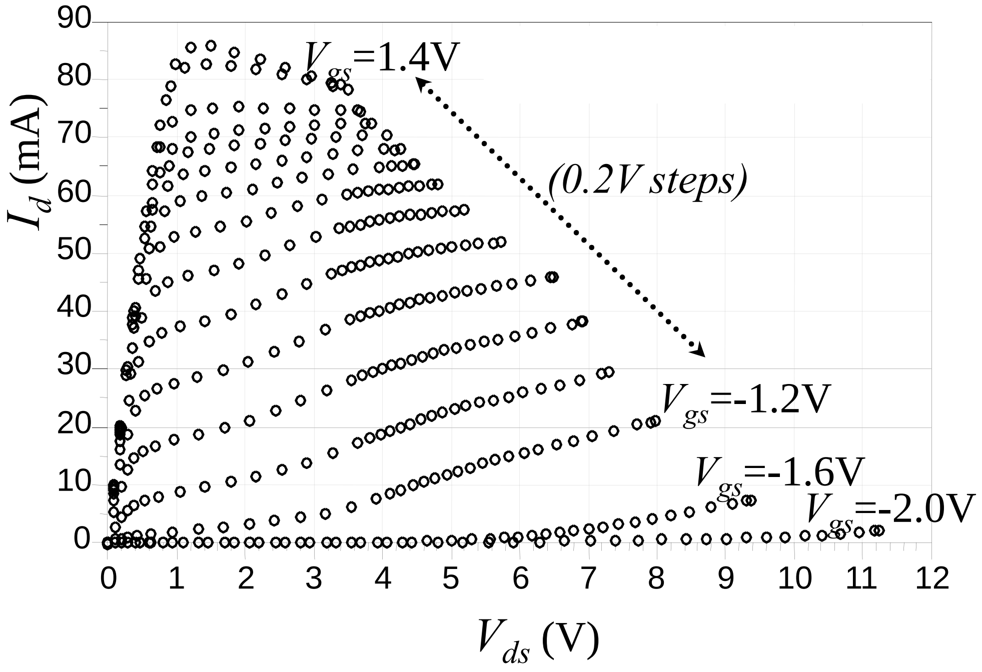
$$I_G(t) = \frac{dQ(V_{GS}(t))}{dt} + \frac{dQ(V_{GD}(t))}{dt}$$

$$I_D^{DC}(V_{GS}, V_{DS}) = \frac{W\mu q N_D a}{\varepsilon L}\left(V_{DS} - \frac{2}{3}\left[\sqrt{\frac{2\varepsilon}{qN_D a^2}}\left((V_{DS} + \phi - V_{GS})^{3/2} - (\phi - V_{GS})^{3/2}\right)\right]\right)$$

$Q(V) = -WL\sqrt{2q\varepsilon N_D(\phi - V)}$ (up to a constant)

# Typical characteristics of real devices not ideal





**MESFET** 3 temperatures

**pHEMT**

**Typical Features of real device often not captured by simple physics-based models**

Non-zero, and sometimes negative, output conductance
Drain-voltage dependent “pinch-off voltage”
Higher drain current at *lower* ambient temperature (near Vp)

# Measurement-Based (Empirical) Modeling

## “The Device Knows Best”

Electrons know where to go, even if the modelers don’t!

***Use device data as much as possible*** **in the model**

Useful for circuit design when good measurements are available, and when no good (fast, robust, extractable) physical models are available

- Empirical models (fitting closed-form functions to data)
- Table-based models with spline interpolation
- Neural-network based models

**Experiment Design:**

measure the device I-V (and Q-V)

**Model Identification**

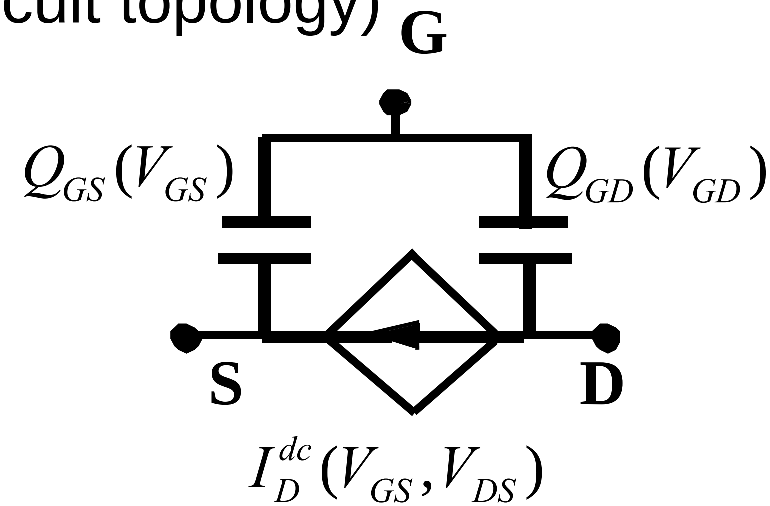
fit the empirical expressions to data (parameter extraction)
or store data and interpolate

# Empirical Models

The same dynamics (equivalent circuit topology)

$$I_D(t) = I_D^{DC}(V_{GS}(t), V_{DS}(t)) - \frac{dQ_{GD}(V_{GD}(t))}{dt}$$

$$I_G(t) = \frac{dQ_{GS}(V_{GS}(t))}{dt} + \frac{dQ_{GD}(V_{GD}(t))}{dt}$$



**Large-Signal Equivalent Circuit**

Modified Constitutive Relations for easy fitting (Curtice Cubic[7])

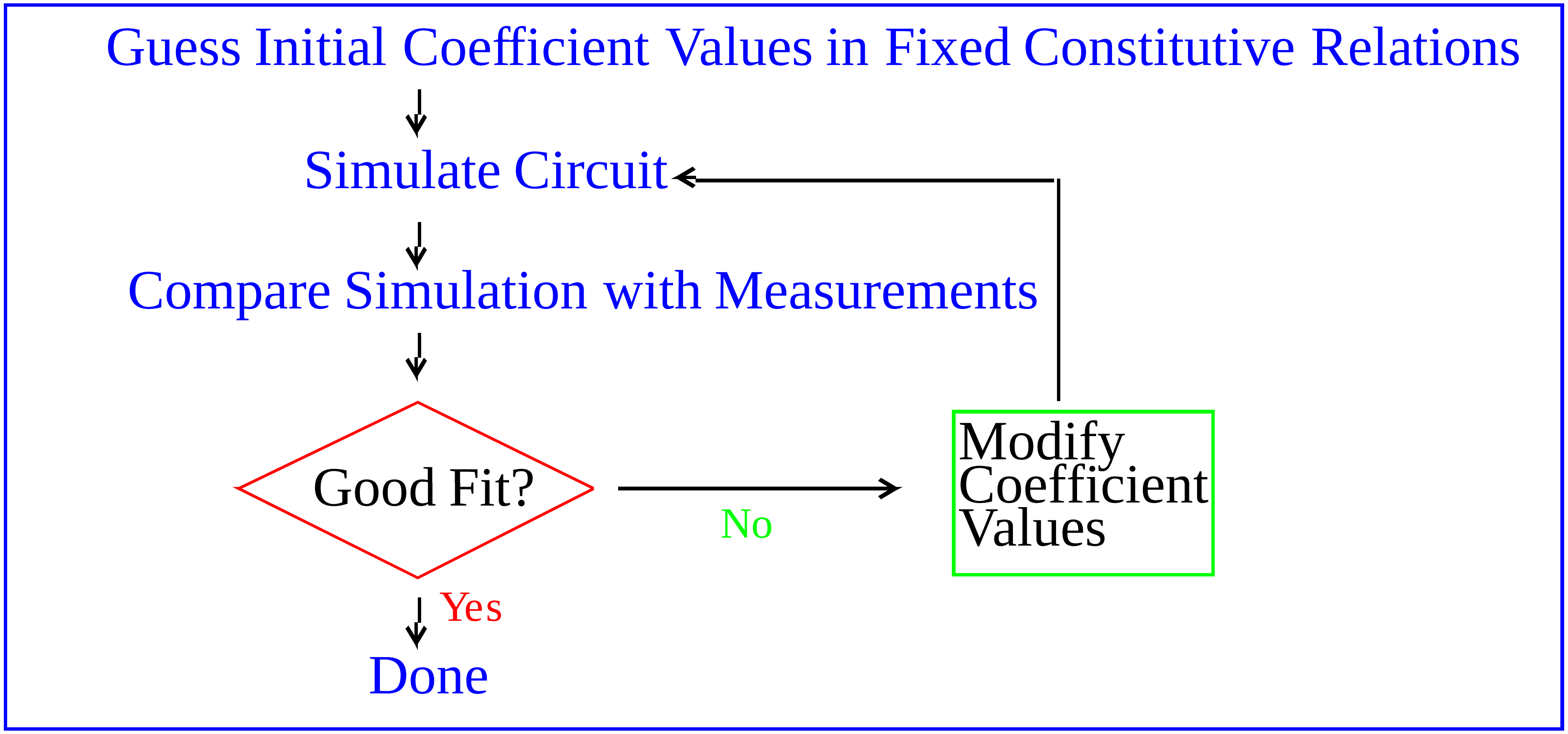
$$I_D^{DC}(V_{GS}, V_{DS}) = \left(A_0 + A_1V_1 + A_2V_1^2 + A_3V_1^3\right) tanh(\gamma V_{DS})$$

$$Q_{GS}(V) = -\frac{C_{j0}\phi}{\eta + 1}\left(1 - \frac{V}{\phi}\right)^{\eta+1} \qquad Q_{GD}(V) = C_{GD0}V$$

# Experiment Design: Measure DC I-V curves

## Model Identification (1): minimize error

$$I_D^{DC}(Vgs, Vds) = \left(A_0 + A_1V_1 + A_2V_1^2 + A_3V_1^3\right)\cdot \tanh(\gamma V_{ds})$$



Guess Initial Coefficient Values in Fixed Constitutive Relations

Simulate Circuit

Compare Simulation with Measurements

Good Fit?

No

Modify Coefficient Values

Yes

Done

# Issues with parameter extraction

Optimization-based parameter extraction can be:

- Slow (simulate circuit and update parameters hundreds of times)
- Sensitive to initial parameter values
- Non-repeatable
- Can get stuck in local minima of optimizer cost function
- Require user interaction
- Good parameter values depend on good data

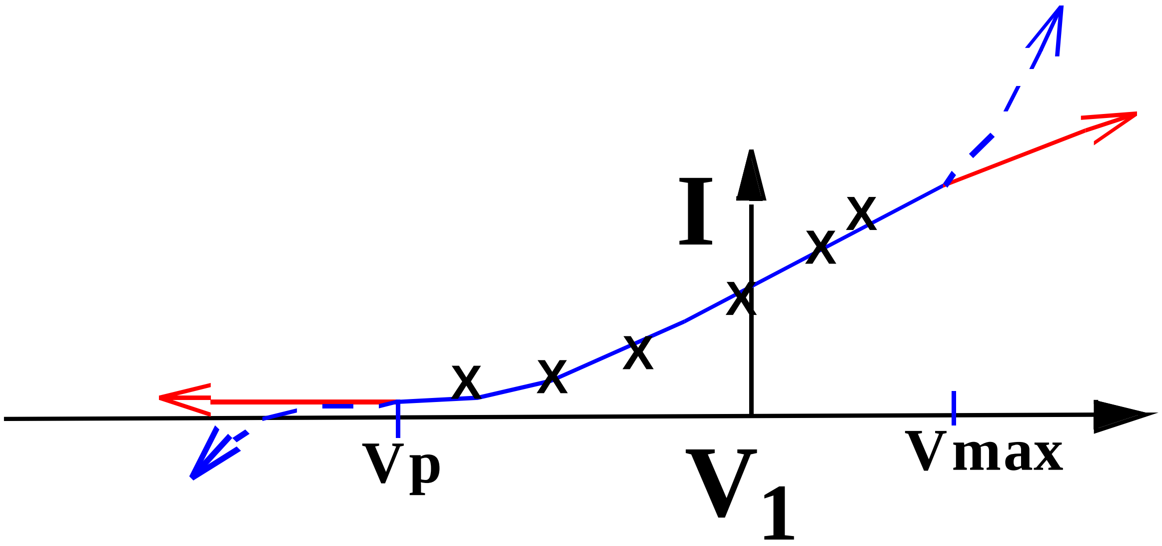
- May never achieve good fit

(constitutive relations may not be flexible enough)
Changes to constitutive relations -> changes to extraction routines

# Parameter Extraction: What can go wrong

(Curtice Cubic example also see [30])

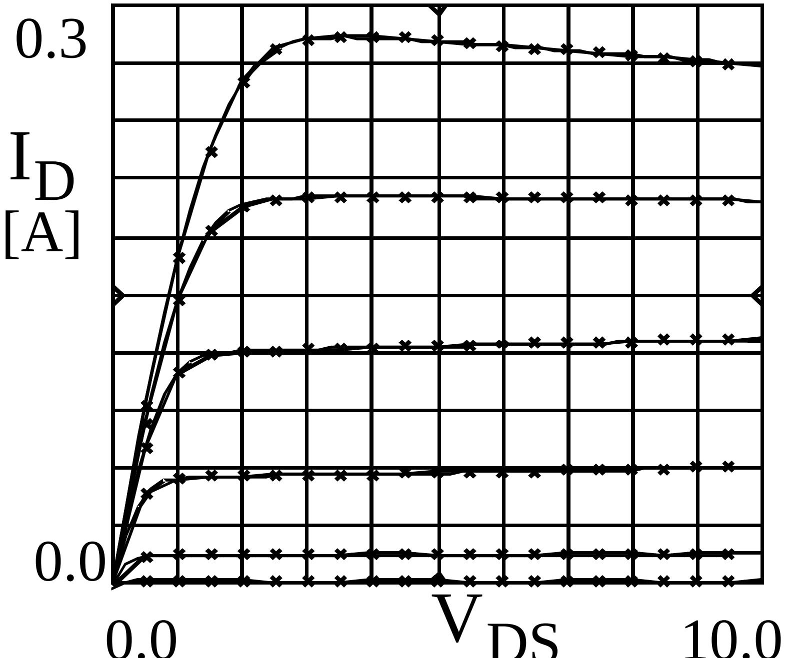
$$I_D^{DC}(V_1,V_2) = \left(A_0 + A_1V_1 + A_2V_1^2 + A_3V_1^3\right)tanh(\gamma V_2)$$



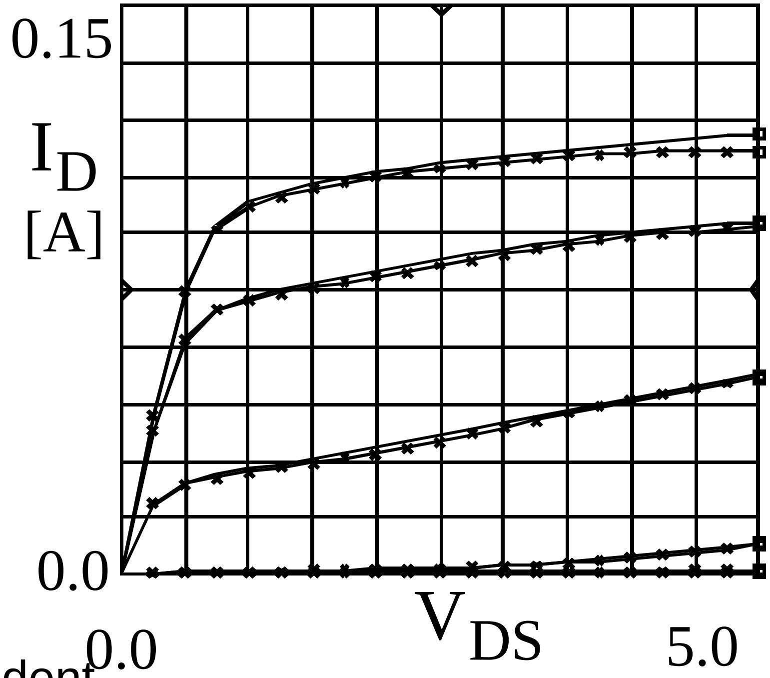
# Table-Based Models: Accurate and General [3,17,21]

*Measure, transform data, tabulate, interpolate, scale*

**Vertical Power Si MOSFET**



**GaAs pHEMT**

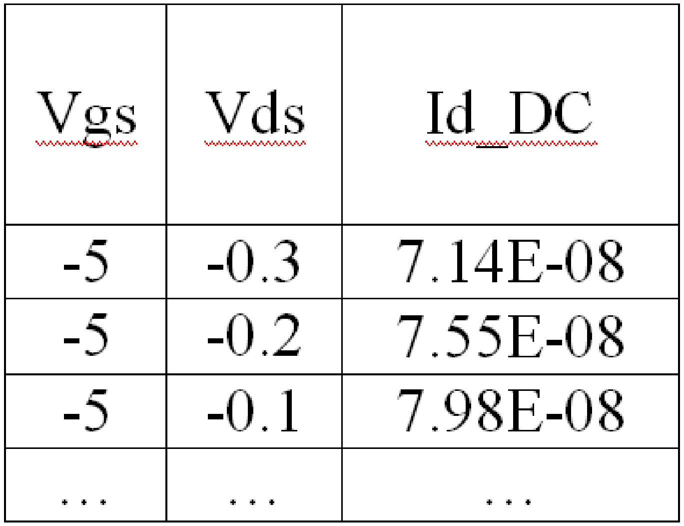


Process and Technology Independent

# Table Models

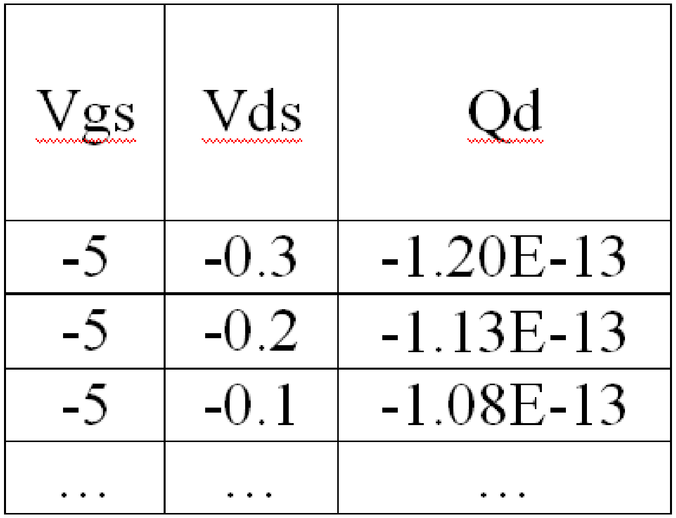
Constitutive Relations are interpolated from data

Table 1



| Vgs | Vds | Id_DC |
|---|---|---|
| -5 | -0.3 | 7.14E-08 |
| -5 | -0.2 | 7.55E-08 |
| -5 | -0.1 | 7.98E-08 |
| … | … | … |

Table 2



| Vgs | Vds | Qd |
|---|---|---|
| -5 | -0.3 | -1.20E-13 |
| -5 | -0.2 | -1.13E-13 |
| -5 | -0.1 | -1.08E-13 |
| … | … | … |

$$I_d(t) = \text{Interpolate}\{\text{Table1}, [V_{gs}(t), V_{ds}(t), I_{d\_dc}]\}$$

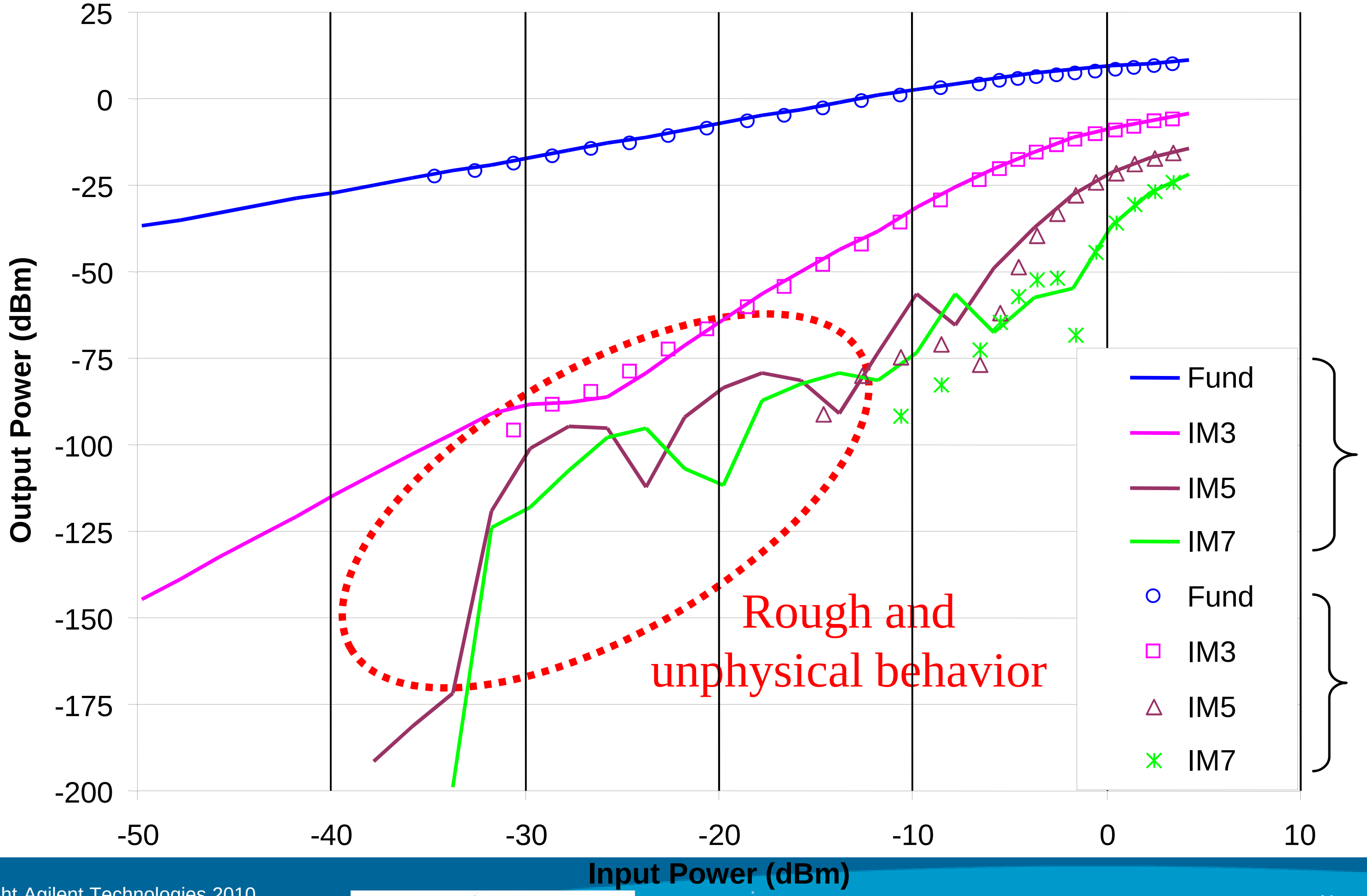
$$+\frac{d}{dt}\text{Interpolate}\{\text{Table2}, [V_{gs}(t), V_{ds}(t), Q_d]\}$$

Works well for dc, S versus bias & freq., med-high power signals

# Warning: Interpolation algorithms may limit table models! [43]

Two-tone Intermodulation

**Original *HPFET Model* with ADS splines vs Measured**



Rough and unphysical behavior

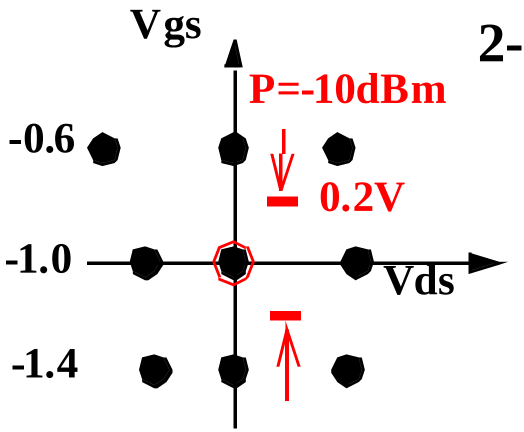
**Spline-based Root Model**

**Measured**

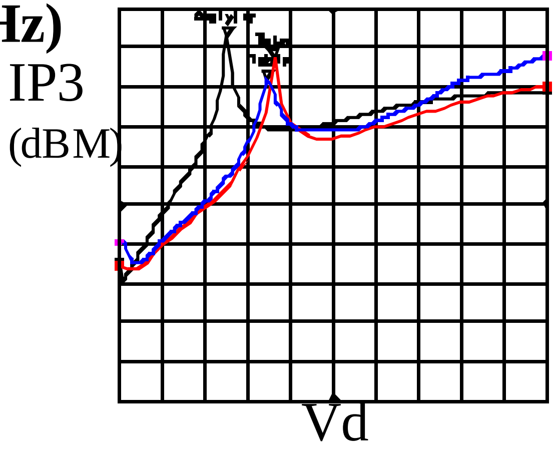
# Naïve Splines Limit Distortion Accuracy [17, 8]

**2-tones @ 100MHz (+1MHz)**

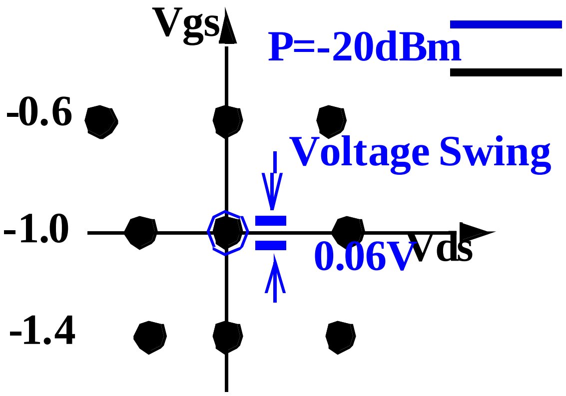
Si NJFET
Table Model



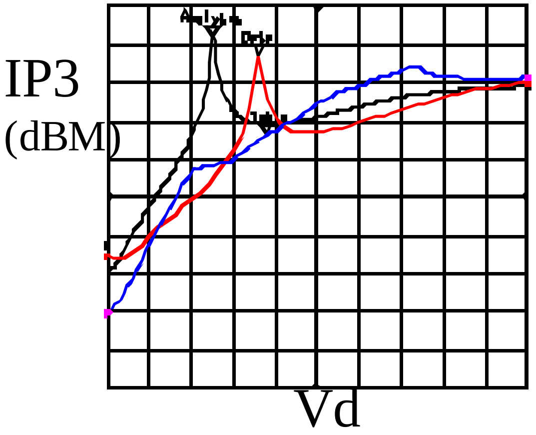
(a) Vg=-1V Power=-10dBm



Data
HPFET table model
Curtice analytic model



(b) Vg=-1V Power=-20dBm

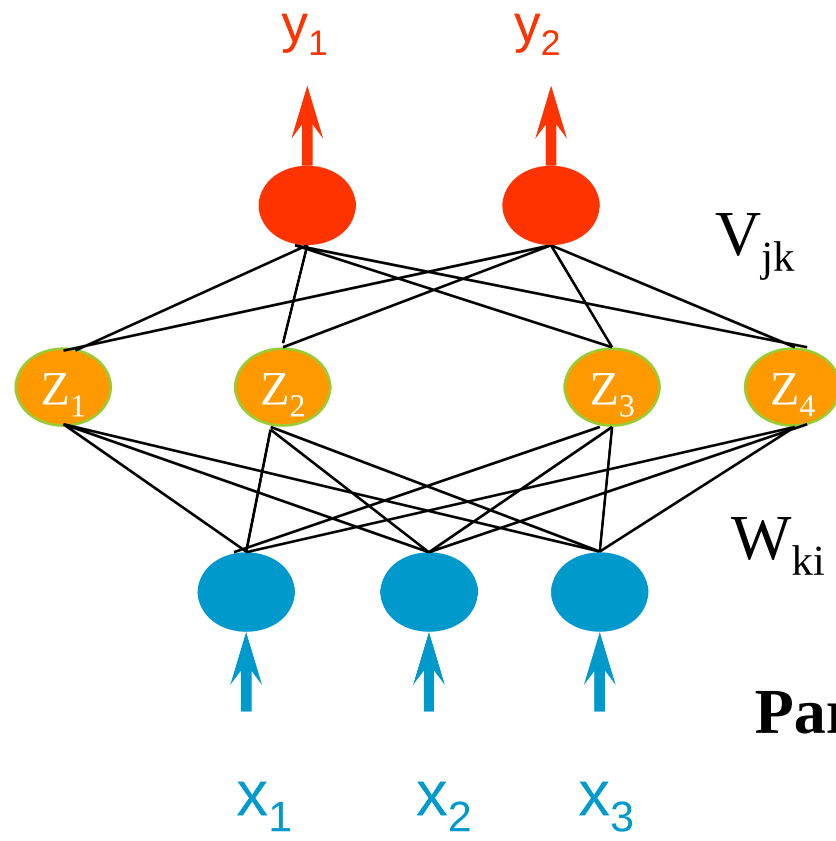


**Simple Cubic Splines**

- Third order derivative vanishes at symmetry points
- Low order polynomial can't predict high-order distortion at low amplitudes
  interpolation model is better when signal size ~ data spacing

# Spline Alternatives: Artificial Neural Networks

$$y_i = F_i(x_1, x_1, x_3)$$



**Outputs**

↑

$$y_j = \sum_k V_{jk} Z_k$$

**Hidden Neuron Output**

$$Z_k = \tanh\left(\sum W_{ki}\, x_i\right)$$

↑

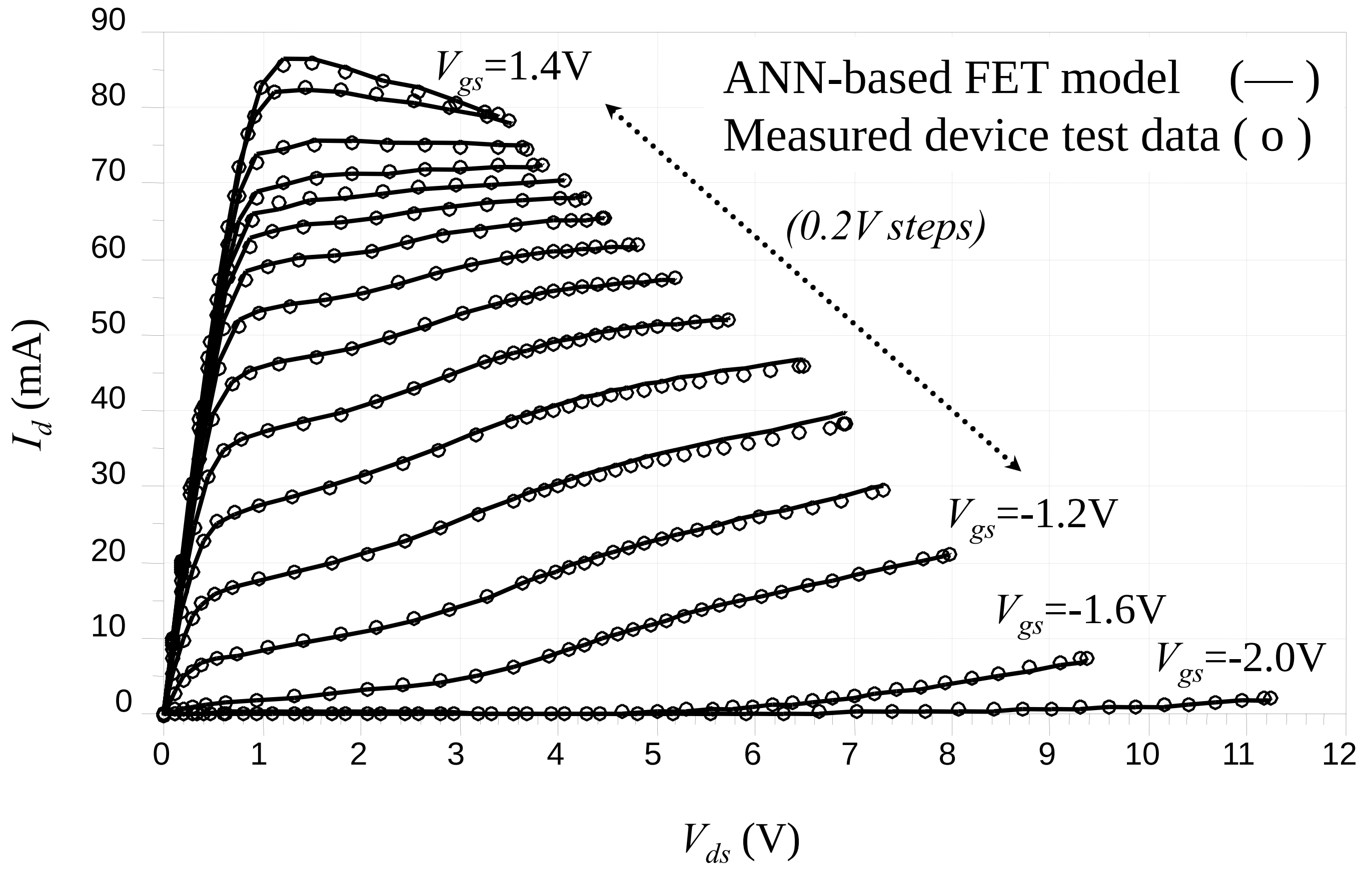
**Parameters** $\boldsymbol{w} = [W_{ki}, V_{jk}]$

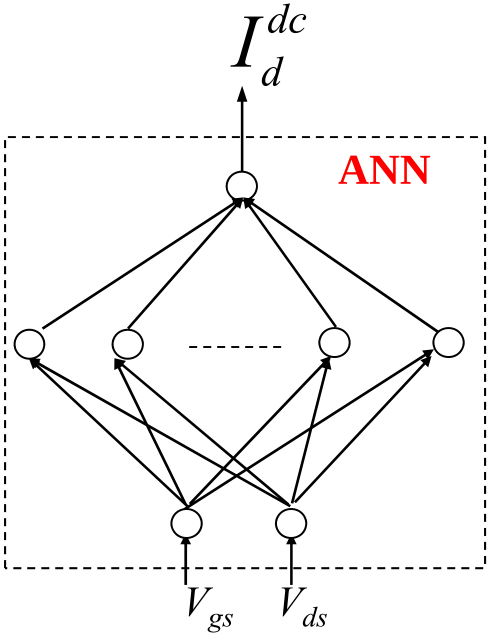
**Inputs**

- Universal Approx. Thm: Can fit any nonlinear function of many variables
- Infinitely differentiable: *better for distortion* than naïve splines
- Easy to train (identify) using standard third-party tools (MATLAB)

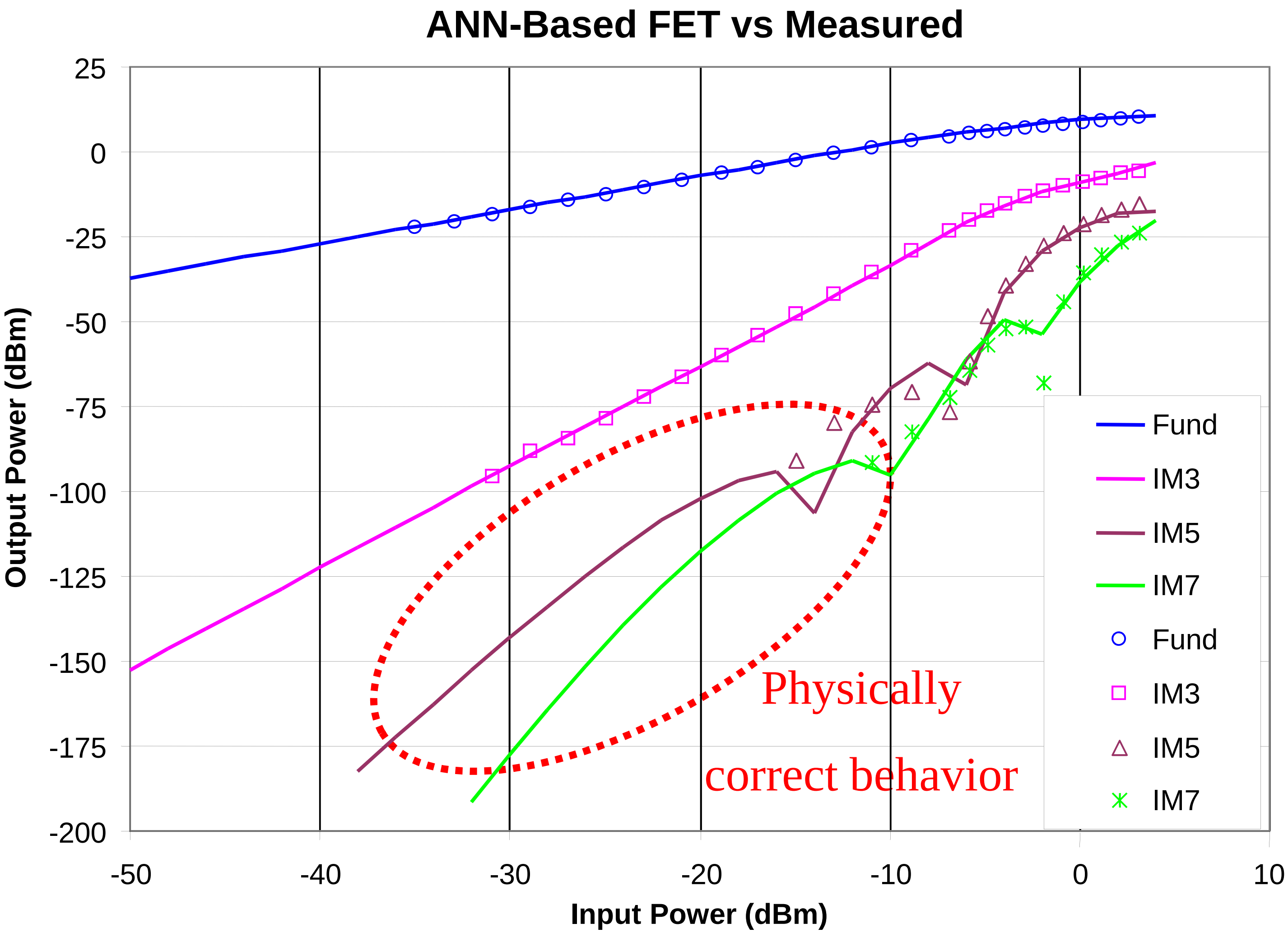
# NeuroFET: FET Model using ANNs [43]

Constitutive Relations are ANNs!





# NeuroFET Distortion Validation (2-tone) [43]

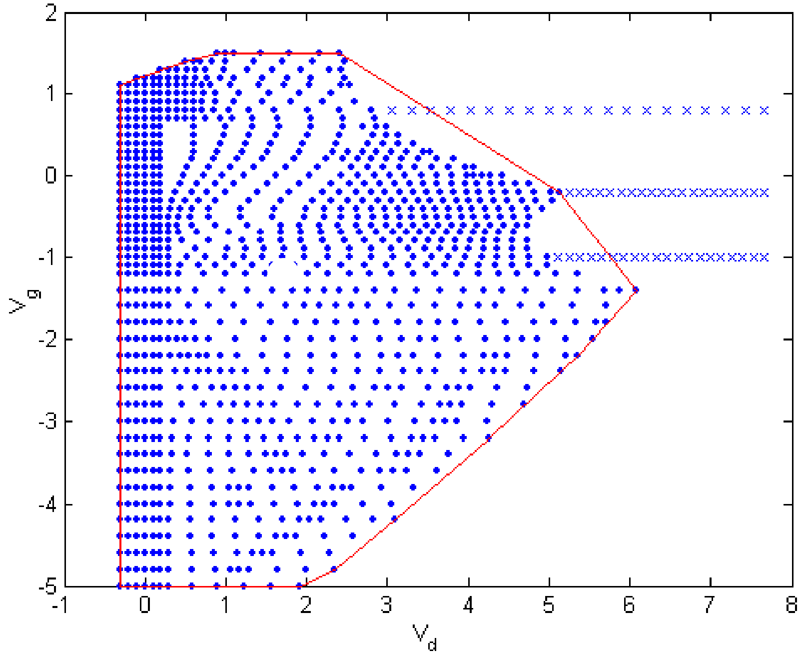


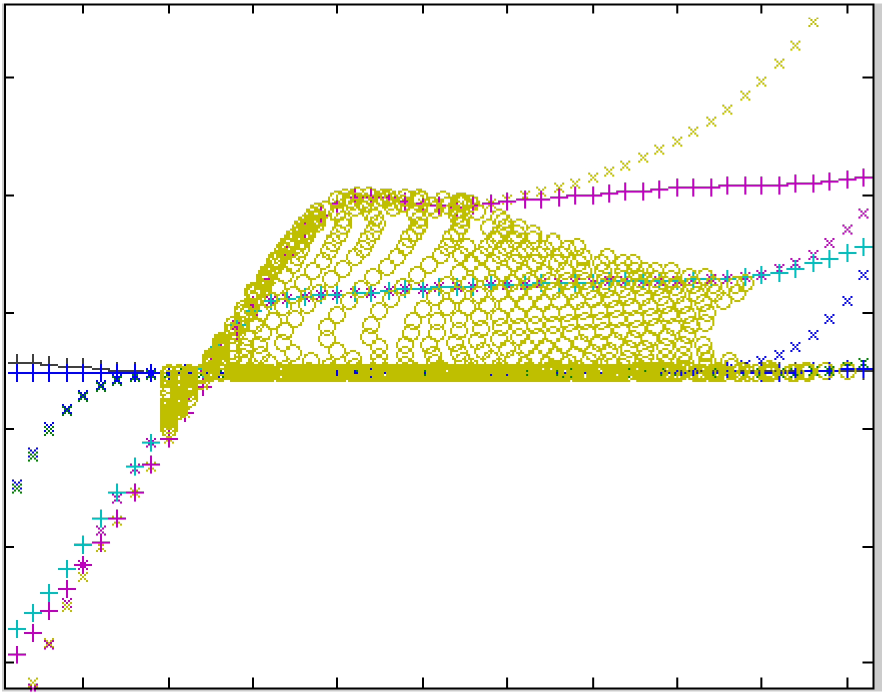
Alternatives to ANNs are “Smoothing Splines” [5]
but they don’t have all the advantages

# Global Domains for Measurement-based Models

Enables nonlinear simulation from discrete, bounded, measured data

ANNs inside, Intelligent Extrapolation outside [44]





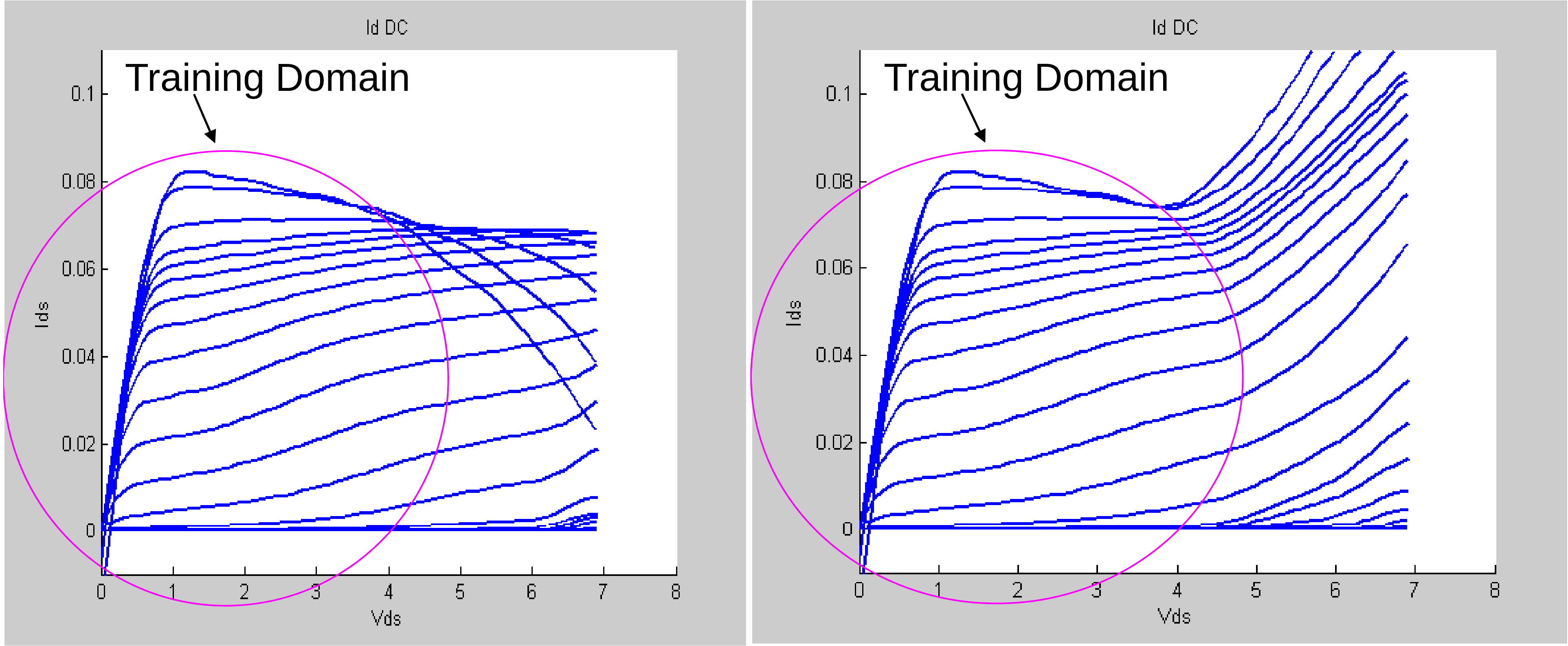
Two orders of continuity at boundary
Asymptotically ~ exponential

+ simpler algorithm
x robust algorithm

Required for robust convergence

# Guided Extrapolation Algorithm *Compiled into Model*

## Improves DC convergence, HB, TA range of use [45]

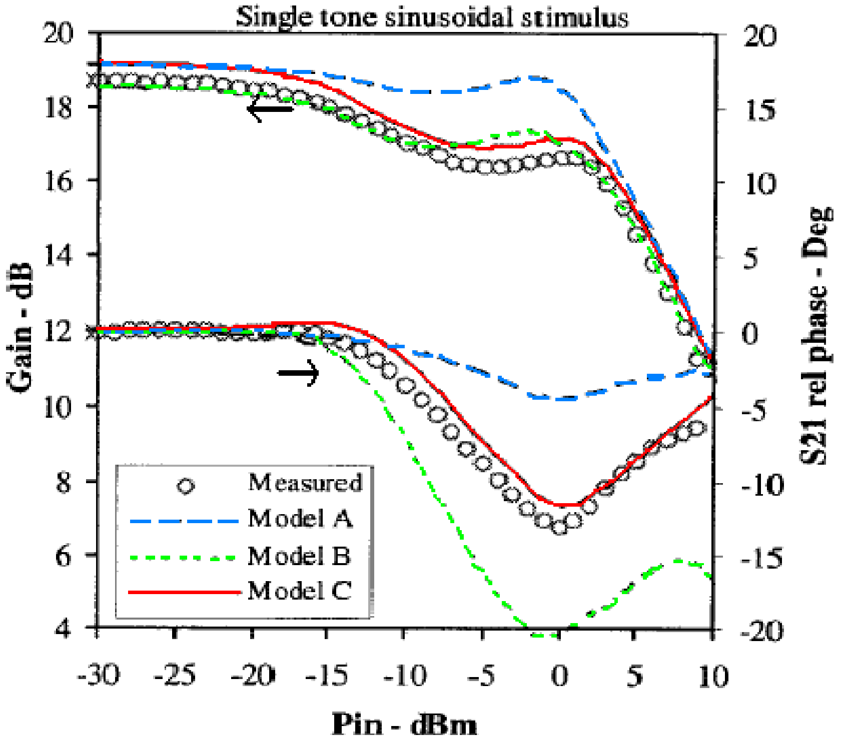


# Presentation Outline

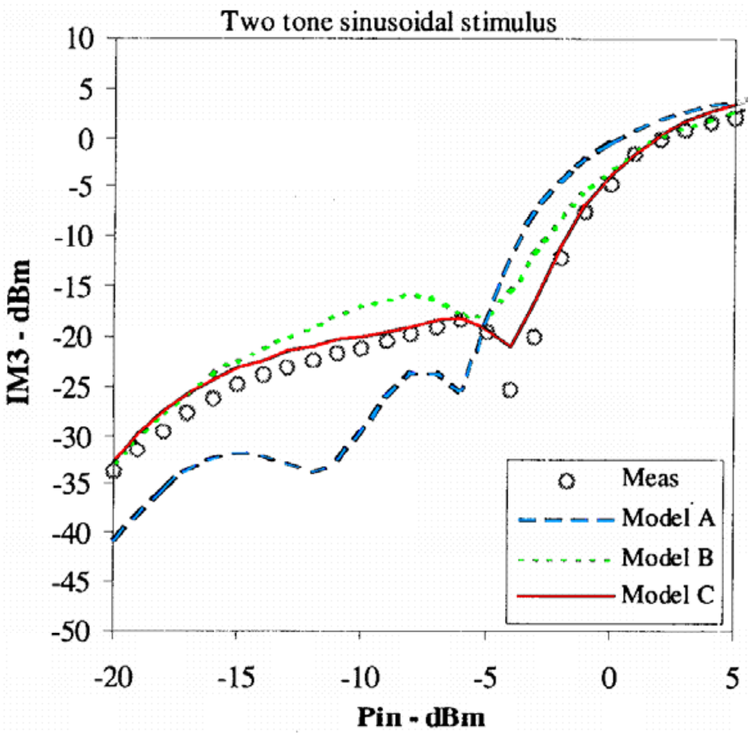
- Introduction
- I-V modeling
- Nonlinear Charge Modeling and Related Issues
- Non Quasi-Static Effects & Dispersion Modeling
- Electro-Thermal Modeling
- Advanced Measurements for Experiment Design & Model Identification
- Symmetry Considerations
- Summary & Conclusions

Artificial Neural Network applications given throughout

# Charge Modeling: Key to Distortion at high frequencies [4]



**Gain/Phase vs. $P_{in}$**



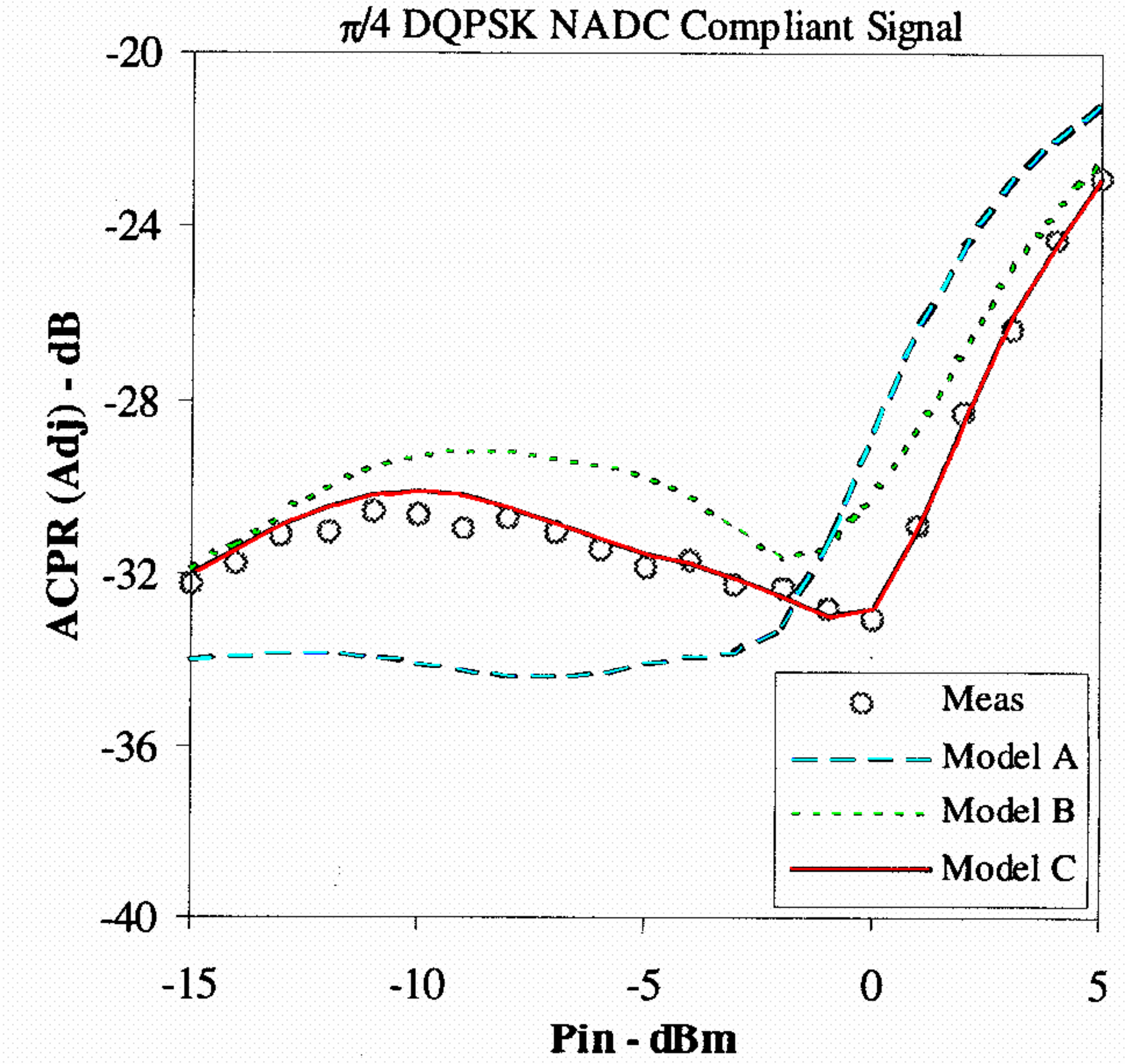
**IM3 vs. $P_{in}$**

**Model A= Shockley** **Model B = Statz[32]** **Model C =HP/AgilentFET [33]**

- All three models use the same DC analytical equations

[4] J. Staudinger, M.C. De Baca, R. Vaitkus, “An examination of several large signal capacitance models to predict GaAs HEMT linear power amplifier performance,” *Radio and Wireless Conference*, Aug. 1998 pp343-346.

# Good Charge Model Required to Predict ACPR



Model A= Shockley junction capacitances

Model B = Statz/Raytheon gate terminal charge conserving but not terminal charge conserving at drain

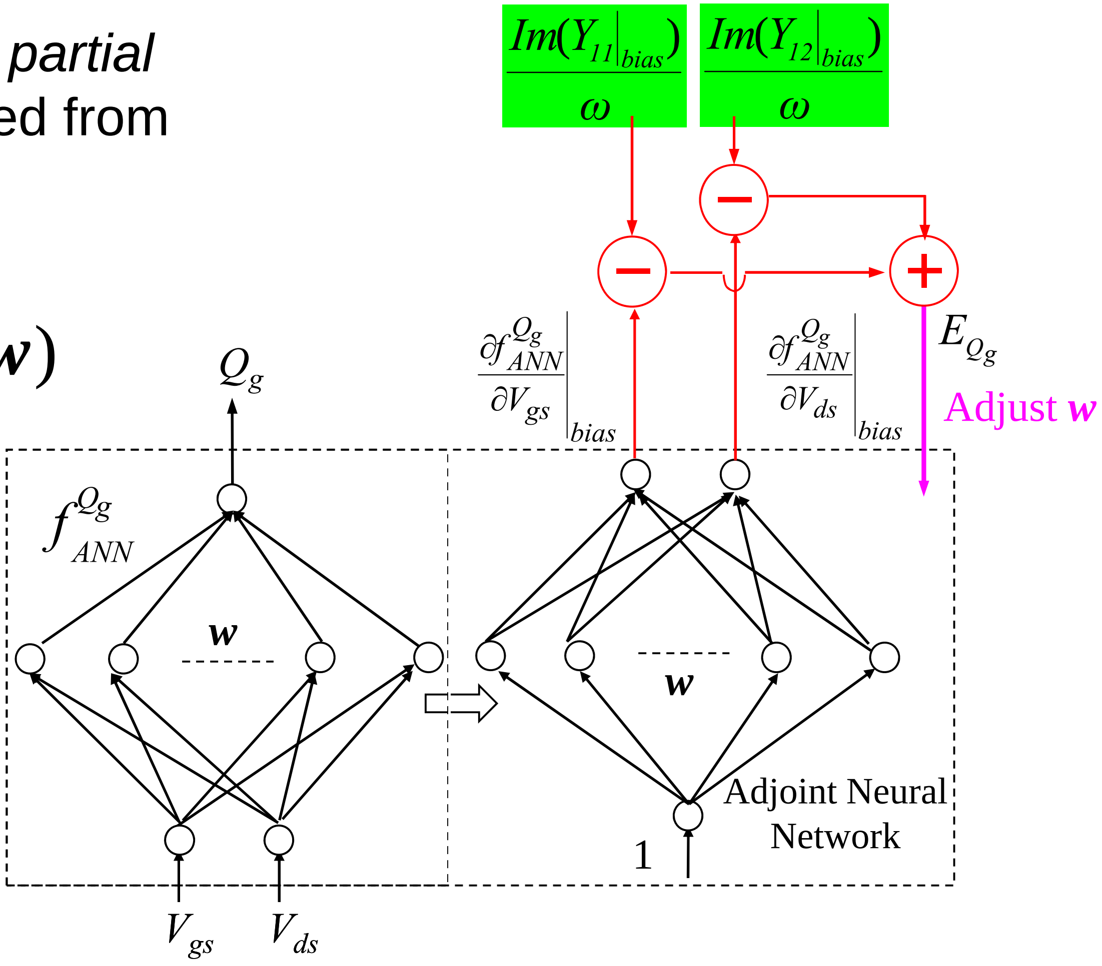
Model C =HPFET (Root model) terminal charge conserving model at both gate and drain by direct integration of measured admittances and spline interpolation

# *Adjoint Neural Network* Training for Qg

Train Adjoint network on *partial derivative data* derived from S (Y) parameters

$$Q_g = f_{ANN}^{Q_g}(V_{gs}, V_{ds}, \mathbf{w})$$

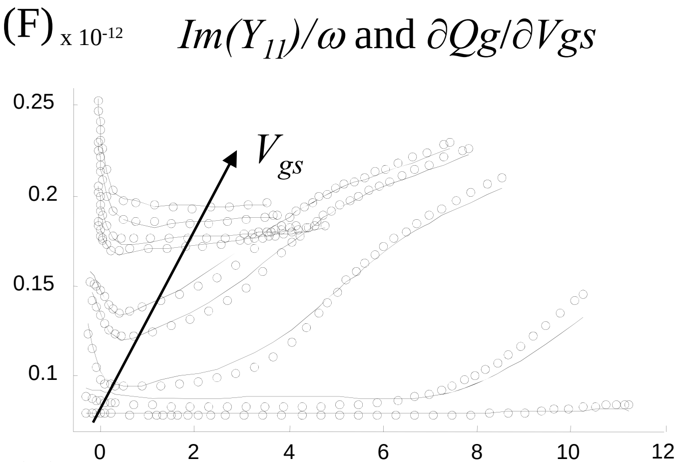
$$I_g(t) = \frac{dQ_g}{dt}$$

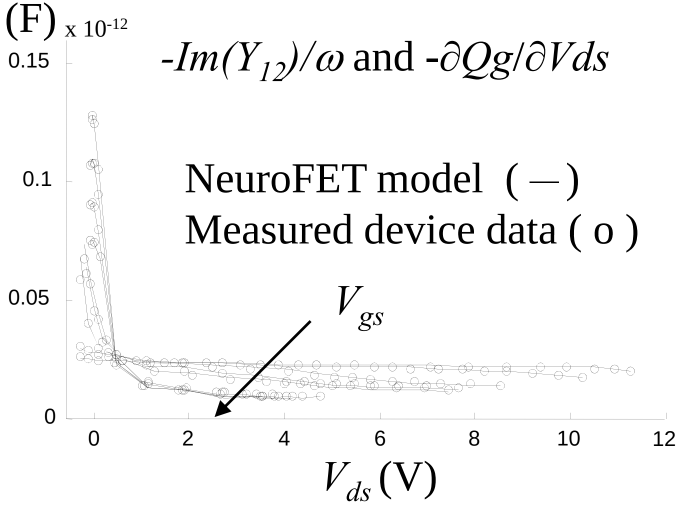


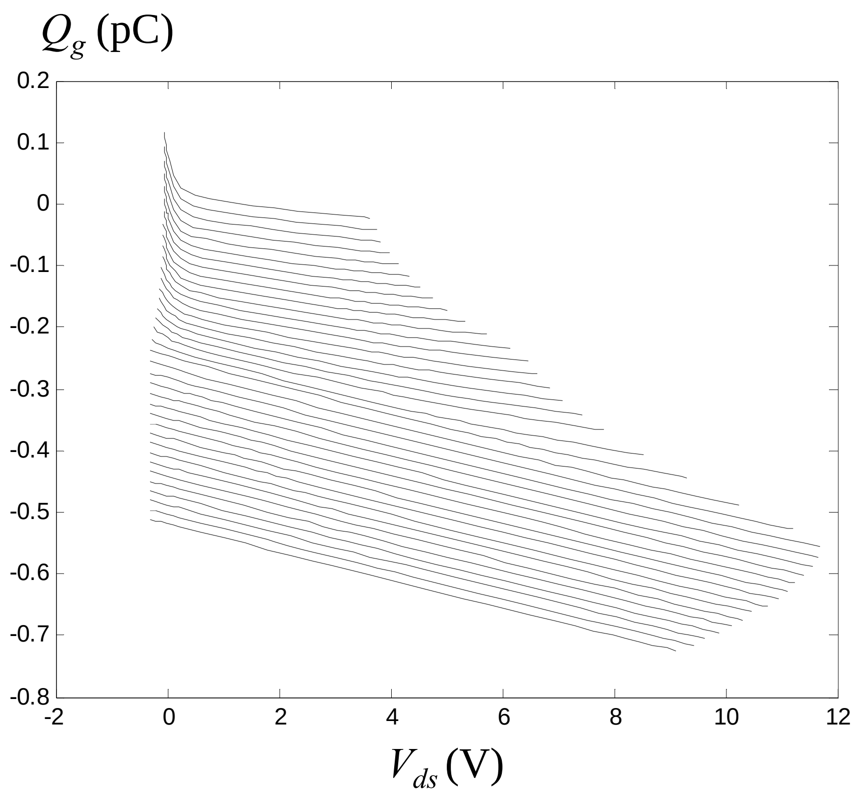
**Jianjun Xu**, M.C.E. Yagoub, Runtao Ding and Q.J. Zhang, "Exact adjoint sensitivity analysis for neural based microwave modeling and design," *IEEE Transactions on Microwave Theory and Techniques,* vol. 51, pp.226-237, 2003.

# Adjoint Neural Network Approach to Charge Modeling

## Charge $Q_g$ *obtained by Adjoint Training Methods* **[27,43]** (Generate an ANN function given *partial derivative data*)







Another experimental validation of *terminal charge conservation* at the gate for GaAs pHEMT

# Advantages of Adjoint ANN over contour Integration

- More uniform approximation of terminal charges than implementations of contour integration
- Applies to scattered data. No gridding necessary.
- Results in infinitely differentiable charge function rather than finite-order spline representation
- More easily deals with complicated boundary of data domain
- More easily generalizes to higher number of terminals

# Presentation Outline

- Introduction
- I-V modeling
- Nonlinear Charge Modeling and Related Issues
- Non Quasi-Static Effects & Dispersion Modeling
- Electro-Thermal Modeling
- Advanced Measurements for Experiment Design & Model Identification
- Symmetry Considerations
- Summary & Conclusions

Artificial Neural Network applications given throughout

# Dynamic electro-thermal (self-heating) model

$$I_d(t) = I_d(V_{ds}(t), V_{gs}(t), T(t))$$
$$Q_g(t) = Q_g(V_{ds}(t), V_{gs}(t), T(t))$$

Temperature evolution equation based on dissipated power

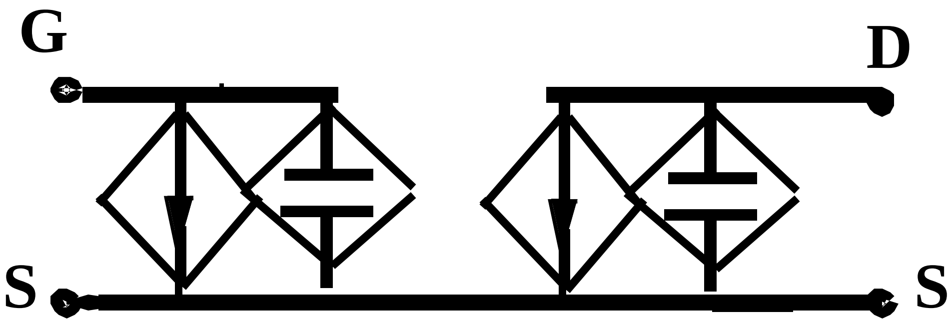
$$\tau \frac{dT}{dt} + \Delta T = R_{TH}\left(I_D(t)V_{DS}(t) + I_G(t)V_{GS}(t)\right)$$

This example is a simplified to 1st order ODE
Heat propagates via diffusion Eqn. (PDE)

. Alternatively estimate T(t) as linear filter in frequency domain [34]
Trade off "fractional pole" response for nonlinearity

# Dynamic electro-thermal (self-heating) model

Currents, Voltages, and Temperature calculated by the simulator *self-consistently* using *coupled electrical and thermal equivalent circuits*



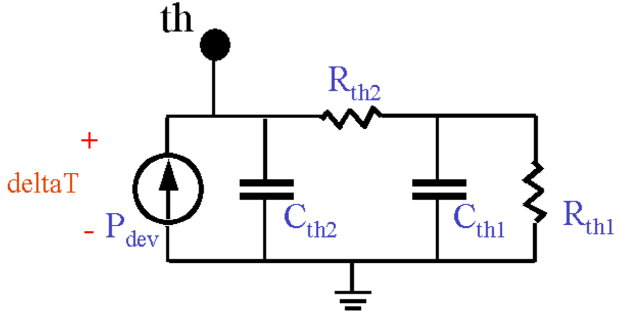
$$Q_G(V_{GS}(t),V_{DS}(t),T(t)) \qquad Q_D(V_{GS}(t),V_{DS}(t),T(t))$$

$$I_G(V_{GS}(t),V_{DS}(t),T(t)) \qquad I_D(V_{GS}(t),V_{DS}(t),T(t))$$

**Electrical Equivalent Circuit**

***T***=device junction temperature

***$T_{amb}$***=device ambient (backside) temperature



**Thermal Equivalent Circuit**

$$T = T_{amb} + deltaT$$

Can approximate distributed nature of heat propagation by many sections

External node allows coupling to other heat sources

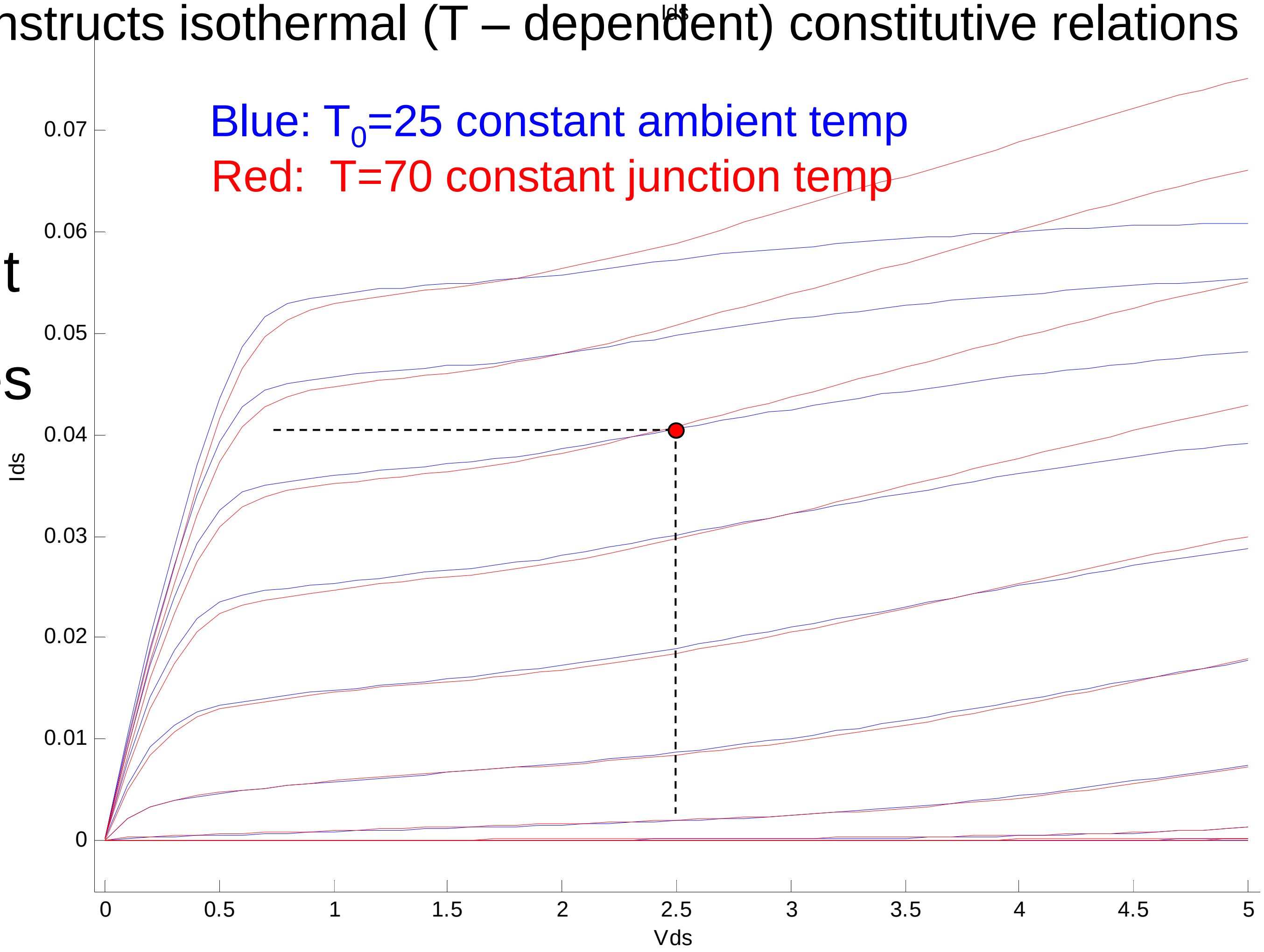
# ANN T-dependent constitutive relations

Given measured non-isothermal ambient temp. ($T_0$ – dependence), one constructs isothermal (T – dependent) constitutive relations

NeuroFET

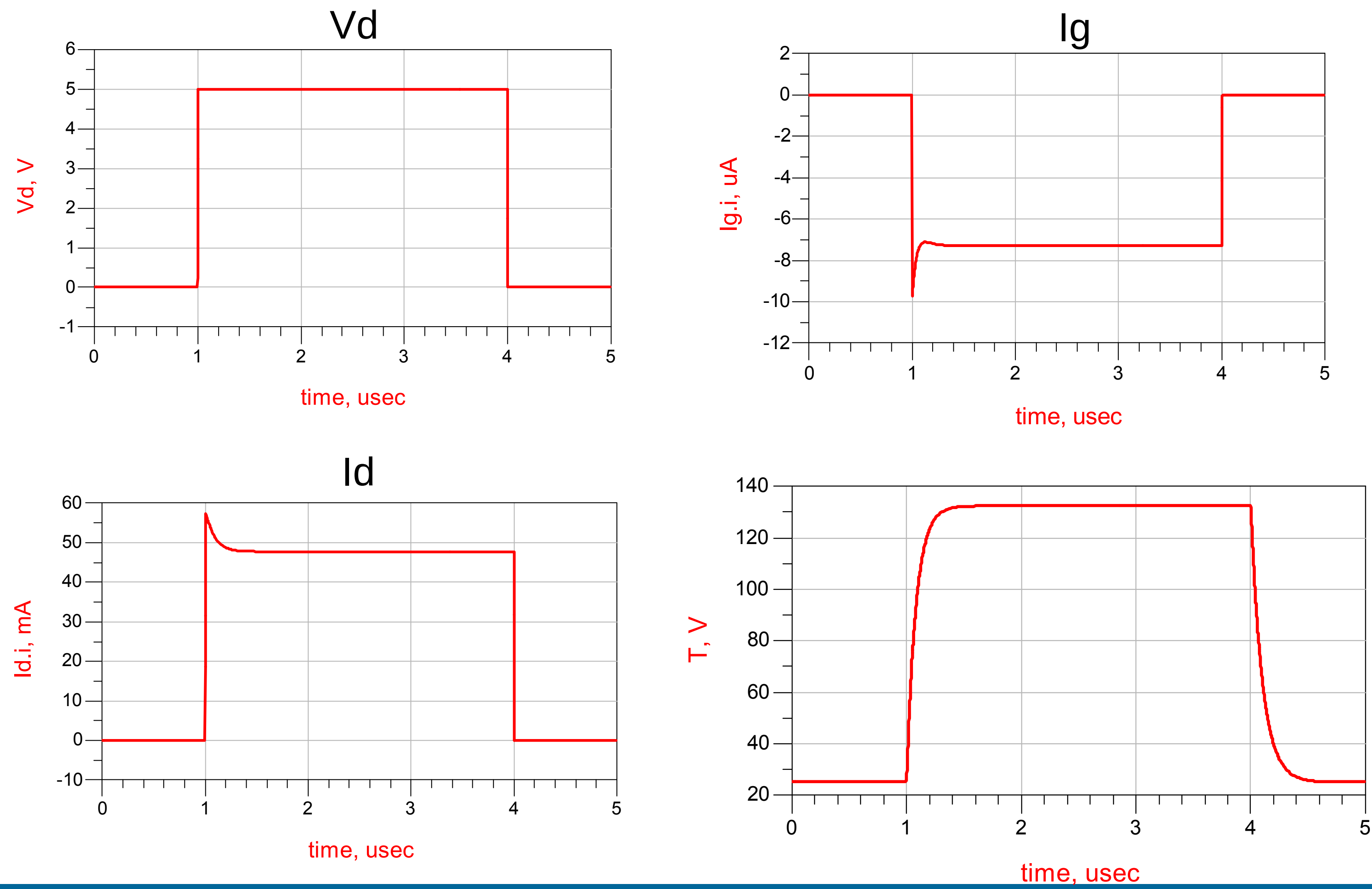
T-dependent

dc I-V curves

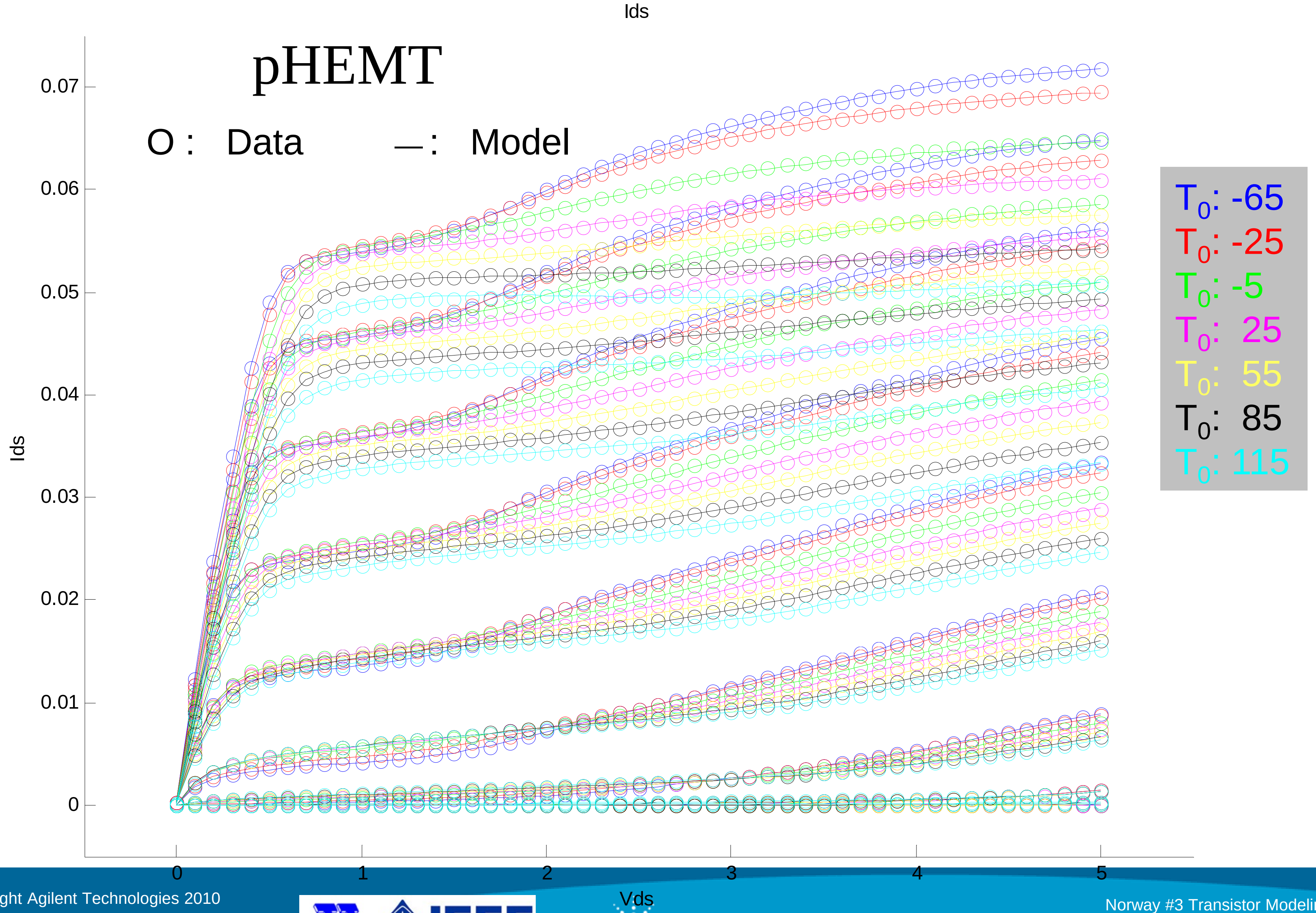


# *NeuroFET* dynamic self-heating results

## Fixed Vg



# *NeuroFET* static self-heating



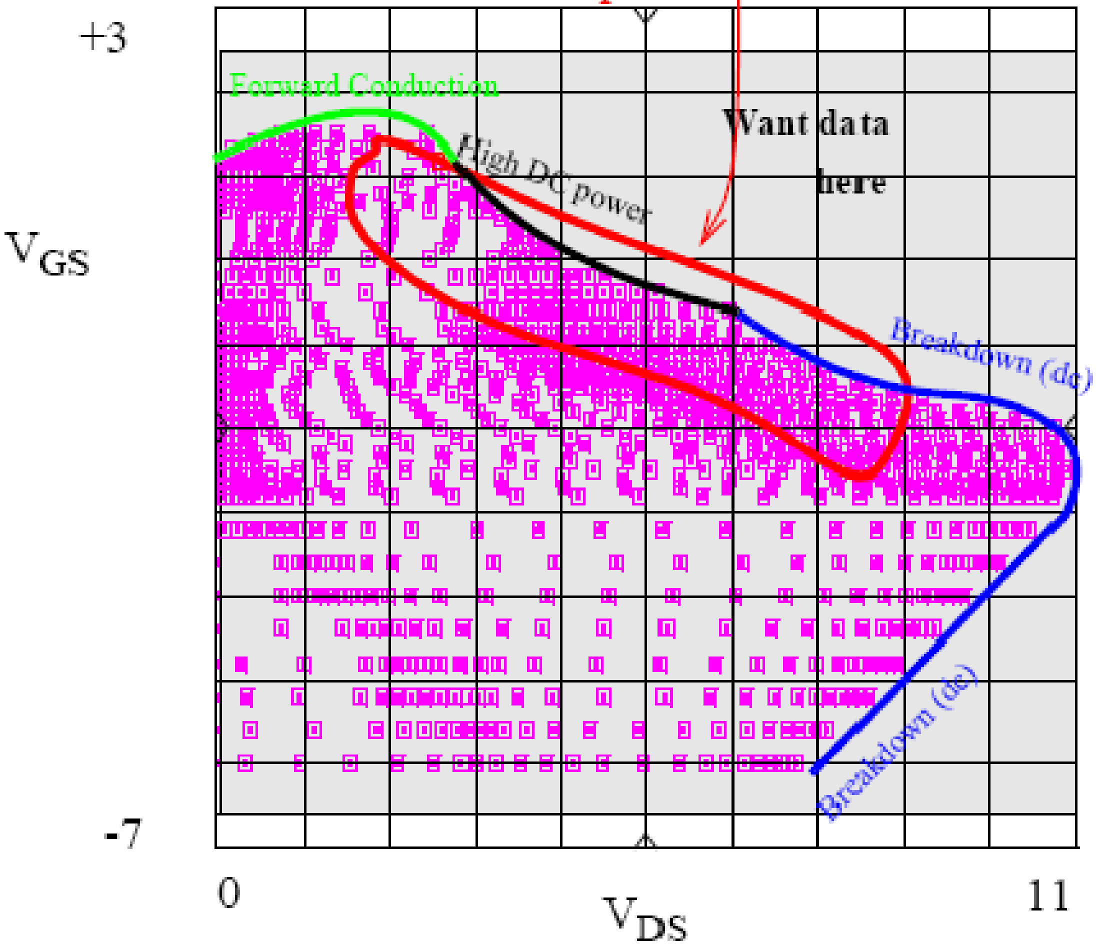
# Presentation Outline

- Introduction
- I-V modeling
- Nonlinear Charge Modeling and Related Issues
- Non Quasi-Static Effects & Dispersion Modeling
- Electro-Thermal Modeling
- Advanced Measurements for Experiment Design & Model Identification
- Symmetry Considerations
- Summary & Conclusions

Artificial Neural Network applications given throughout

# Need for Advanced Characterization for empirical Modeling [21]

Dynamic Operating Trajectory of Table-based model constructed from from dc + S-parameter data:



True for neural network model too if built from dc + S-param data

# GaN Devices

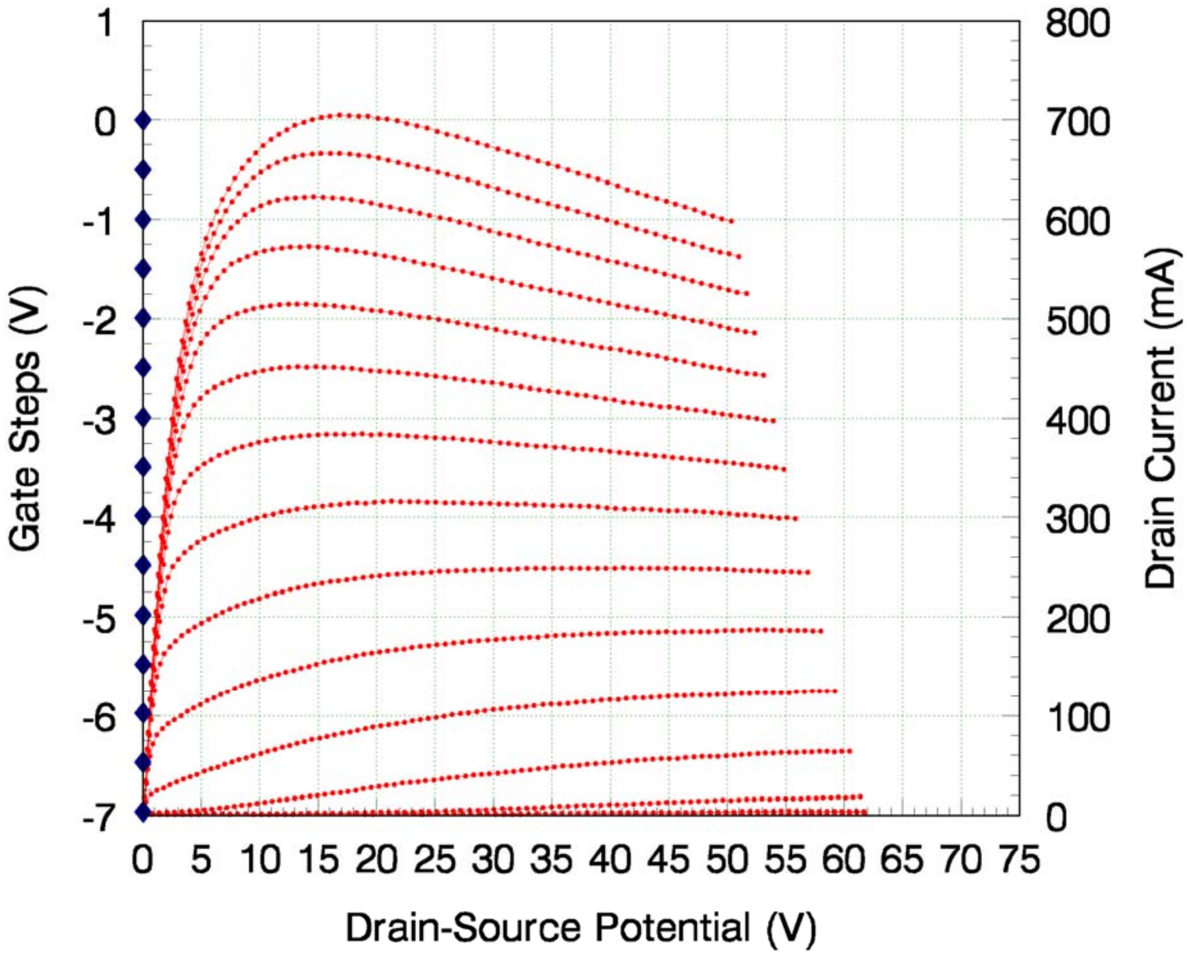
1 mm 10 fingers

GaN on Si

$f_T$ ~ 30GHz

Pulse width 2us

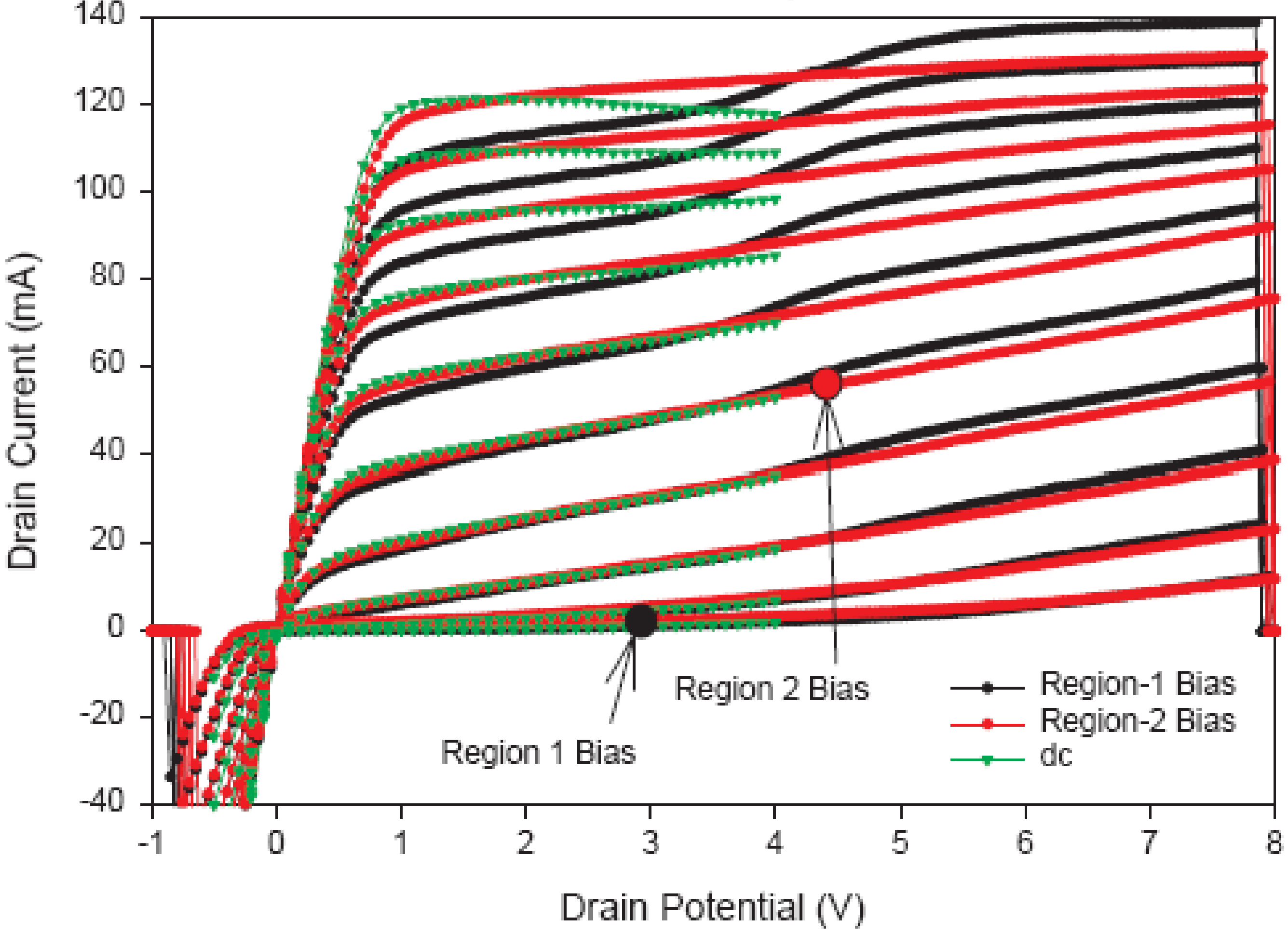
Slide courtesy J. Scott



Pulsed measurements provide much more data than can be measured under static (DC) conditions

# Pulsed I-V characteristics at different quiescent points vs DC [1,21]

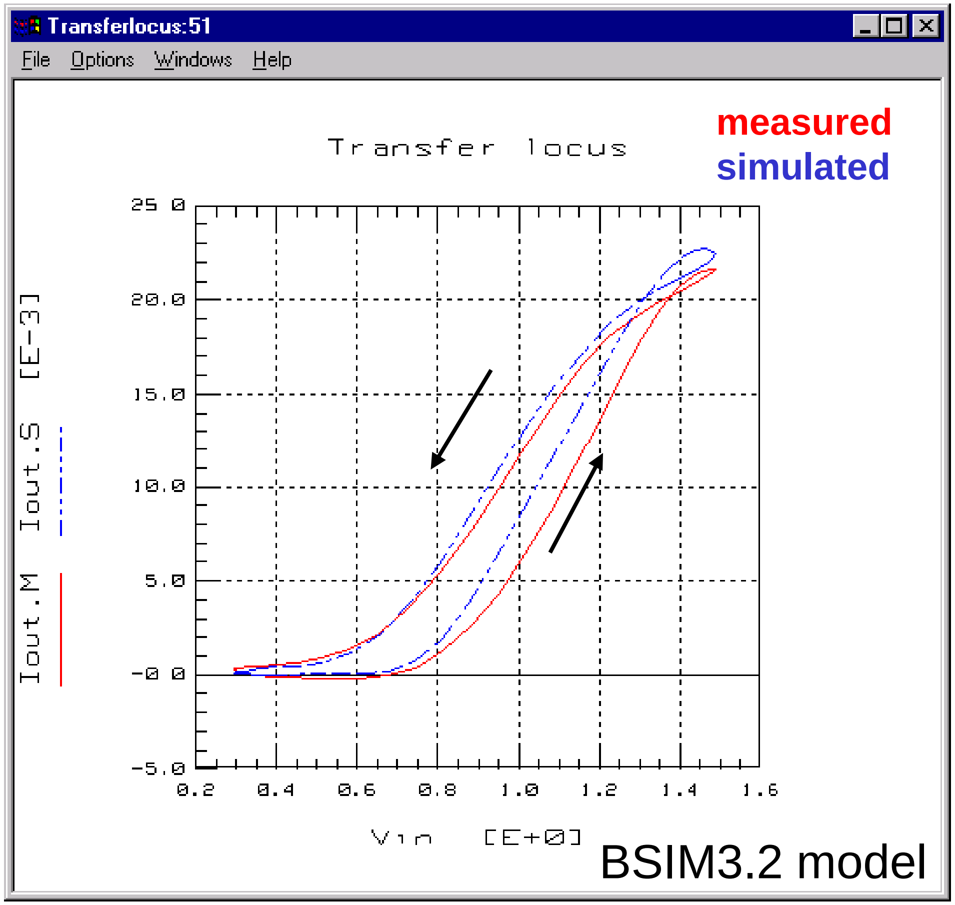
pHEMT device

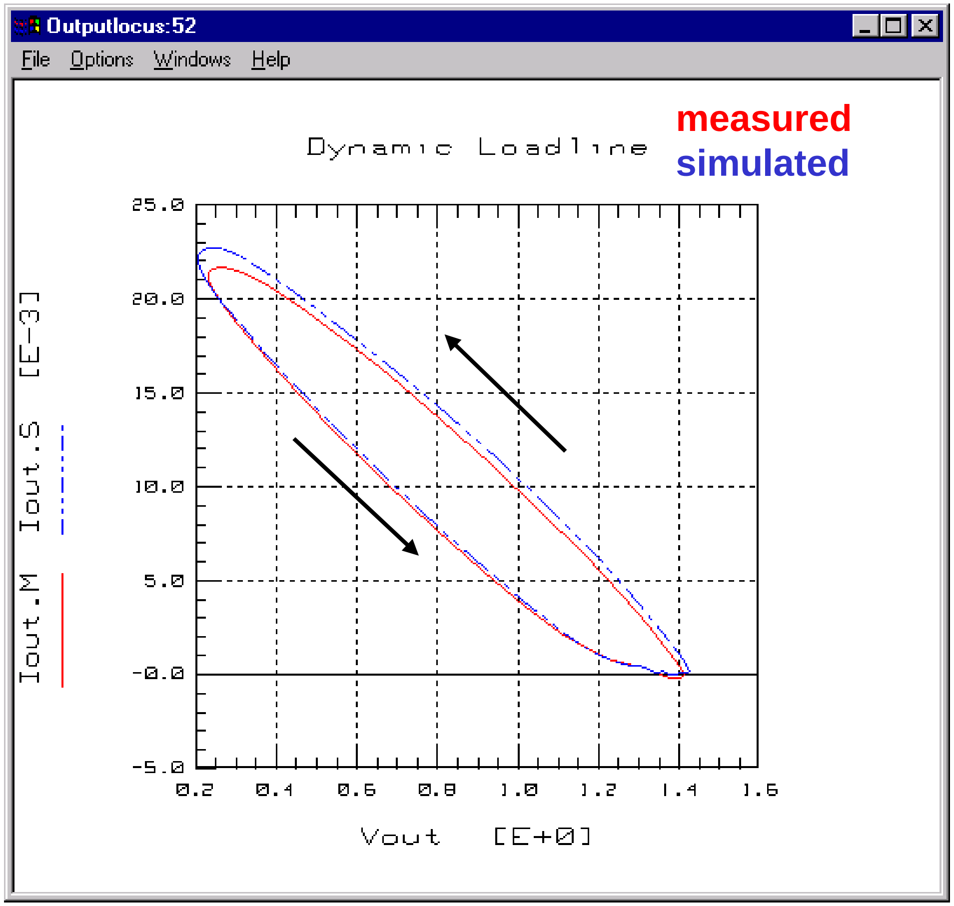


# Nonlinear Vector Network Analyzer (NVNA) Measurements for Transistor Modeling:

- These measurements will compliment and eventually totally replace small-signal measurements for large-signal device model experiment design and model identification [36-38]. Such systems are also useful for *model validation.*
  - Stimulates device with more realistic signals
  - Reduce degradation of device characteristics from static measurements
  - Less reliance on inferring large-signal dynamic behavior from *linear small- signal measurements*
  - Some device properties may very different (breakdown, Ig, …)
  - Use to identify parametric (empirical) models or even train (generate) data-based models directly

# (1a) NVNA data for compact model validation

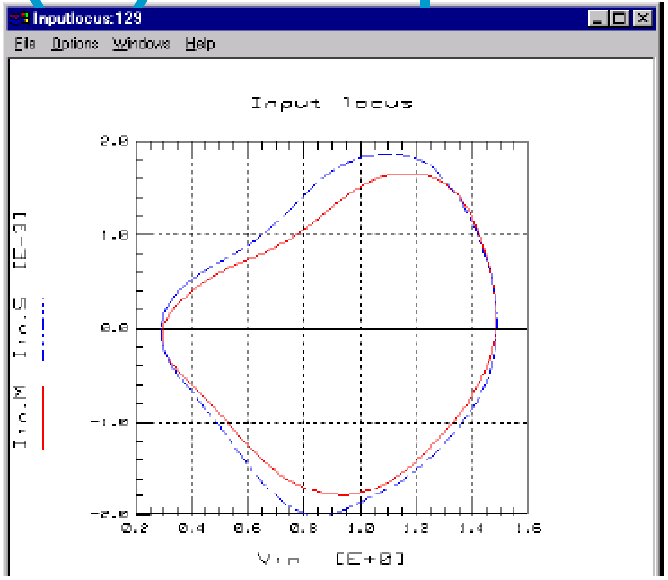




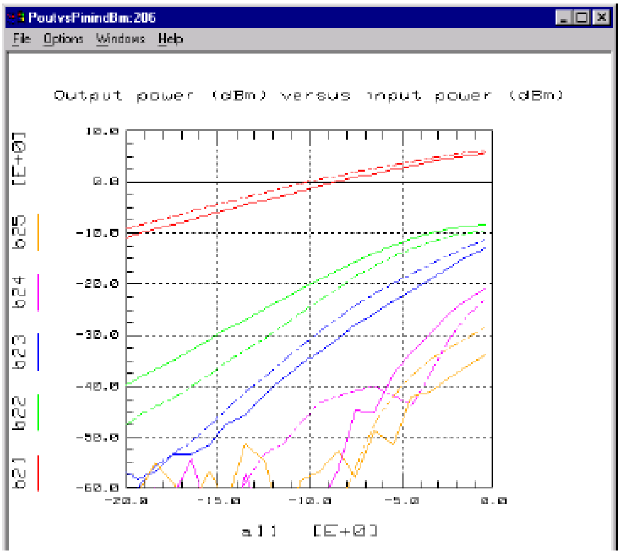
- Parameters extracted from DC and S-parameters (or CV)
- BSIM3 model simulated in Harmonic balance (HB) analysis
- Results compared with NVNA data

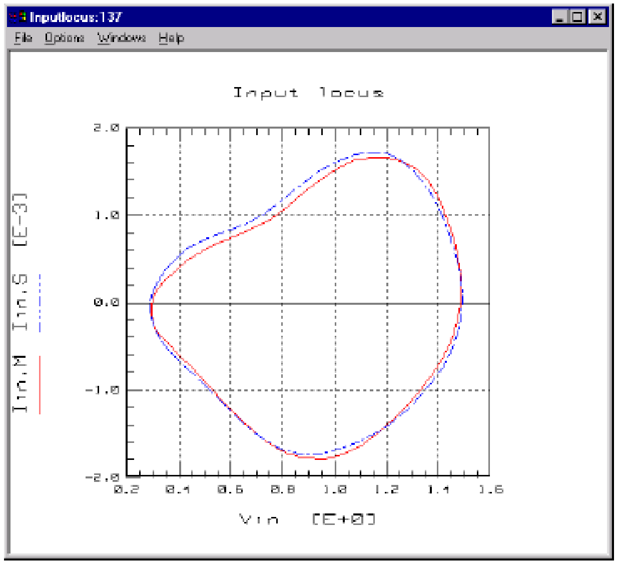
Slide courtesy of Franz Sischka, data from [51]

# (1b) Model parameter extraction from NVNA Data [51]



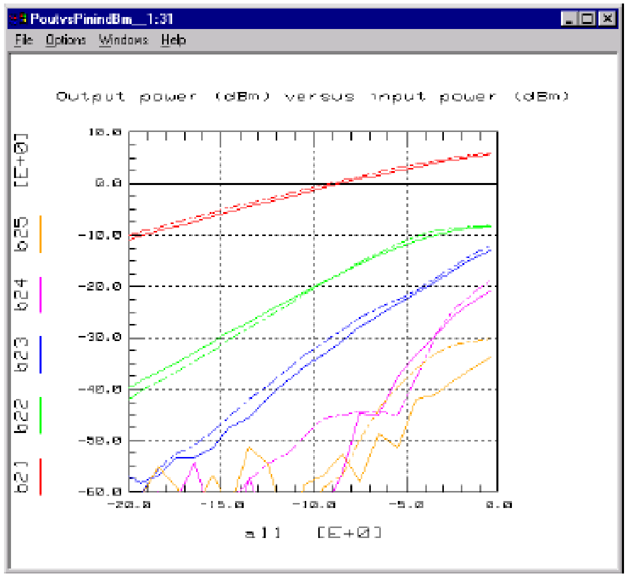
NVNA data vs HB simulation using initial parameter values extracted from DC + CV





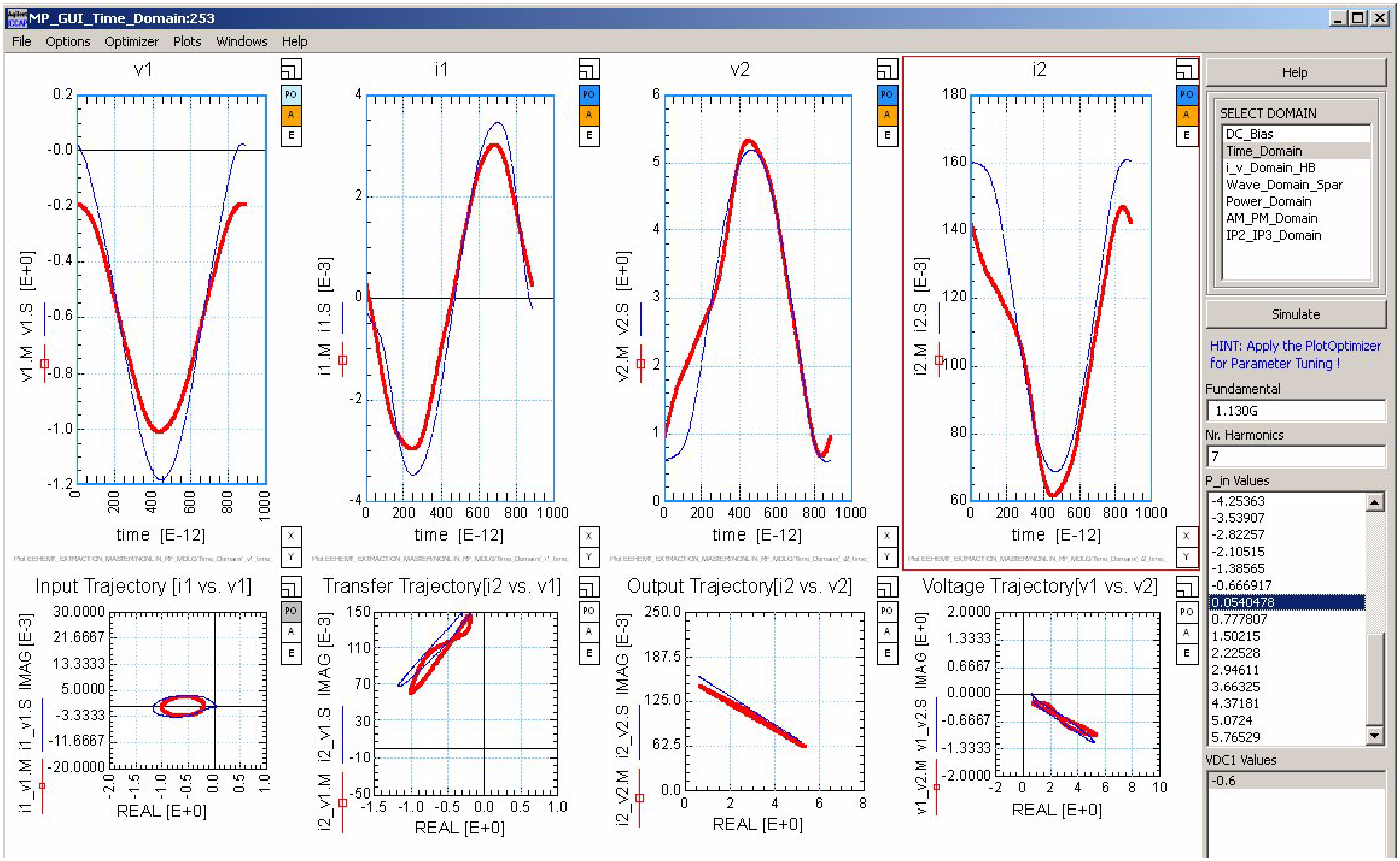
Modify parameter values (optimize) to *better fit* large-signal NVNA data

- Get optimal parameter set for given model
- trade-off DC, SP, for nonlinear performance
- App-dependent tuning
- Explore model limits



Mixdes 2002

# Parameter extraction from NVNA data



SELECT DOMAIN

- DC_Bias
- Time_Domain
- i_v_Domain_HB
- Wave_Domain_Spar
- Power_Domain
- AM_PM_Domain
- IP2_IP3_Domain

HINT: Apply the PlotOptimizer for Parameter Tuning !

Fundamental: 1.130G

Nr. Harmonics: 7

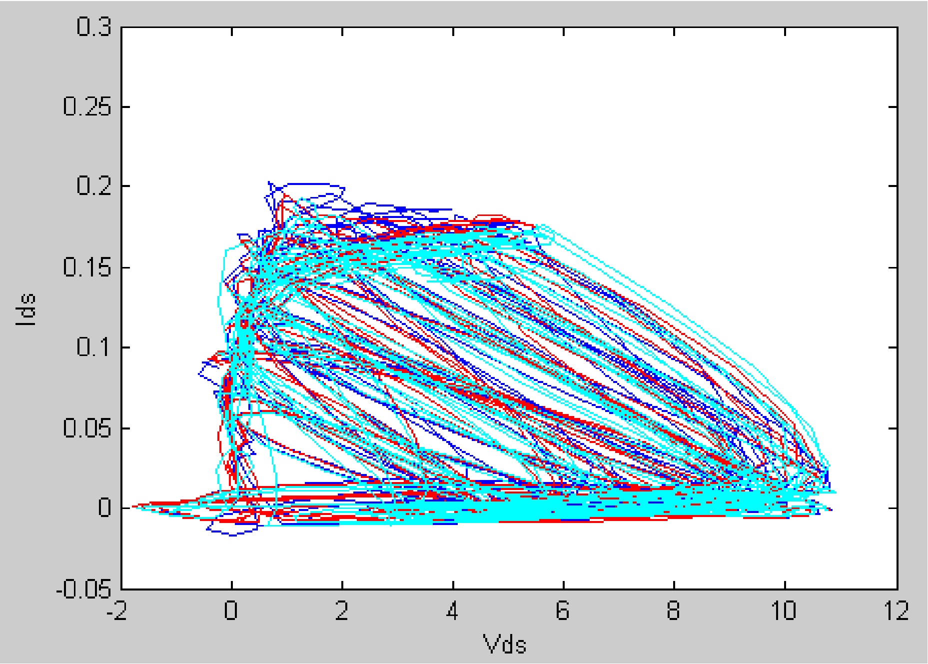
P_in Values

-4.25363
-3.53907
-2.82257
-2.10515
-1.38565
-0.666917
0.0540478
0.777807
1.50215
2.22528
2.94611
3.66325
4.37181
5.0724
5.76529

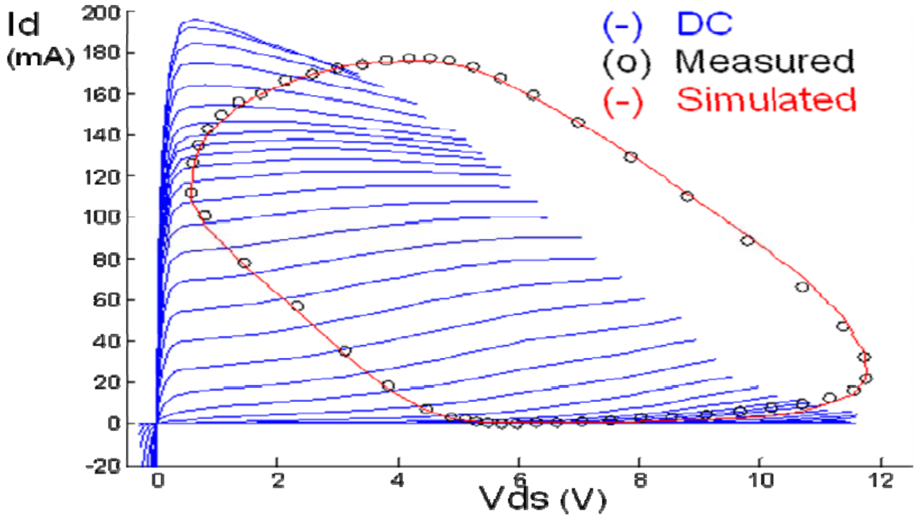
VDC1 Values: -0.6

Slide courtesy Franz Sischka

# Examples of measured dynamic load-lines using NVNA for advanced FET model construction



Root et al INMMiC2010 [52]
Xu et al IMS2010 [53]

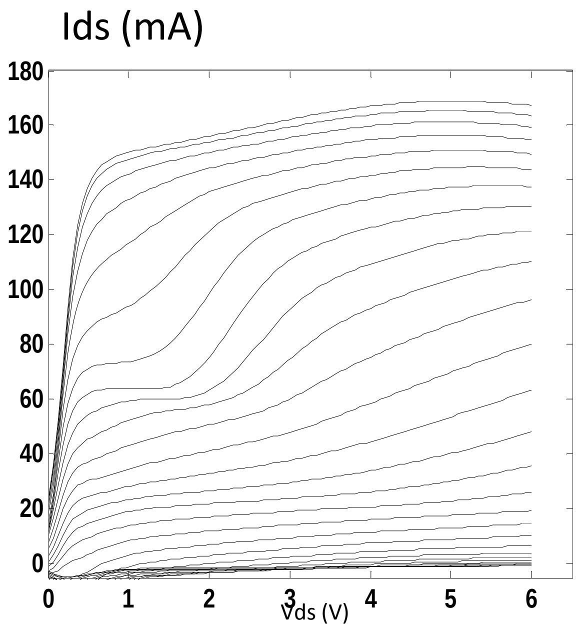


- Entire operating range covered
- Can measure into limiting operating regions
- Get data under realistic operating conditions

# Model I-V characteristics at different trap-states

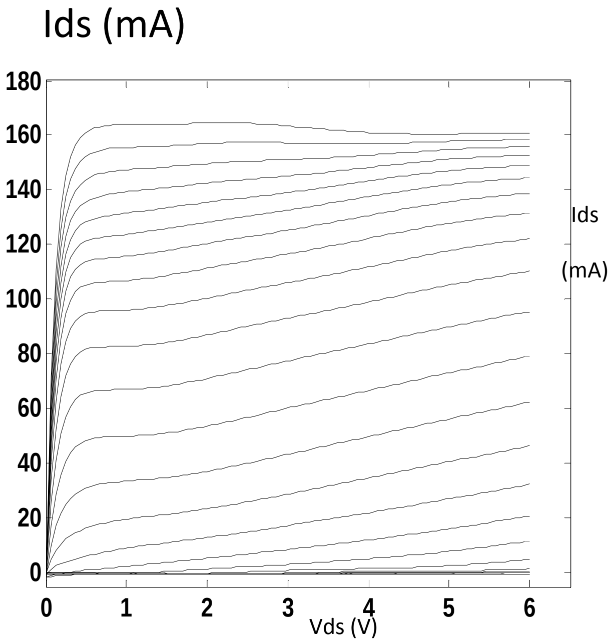
$$I_D(V_{gs}(t), V_{ds}(t), T_j, \varphi_1, \varphi_2)$$

Xu et al IMS2010 [53]



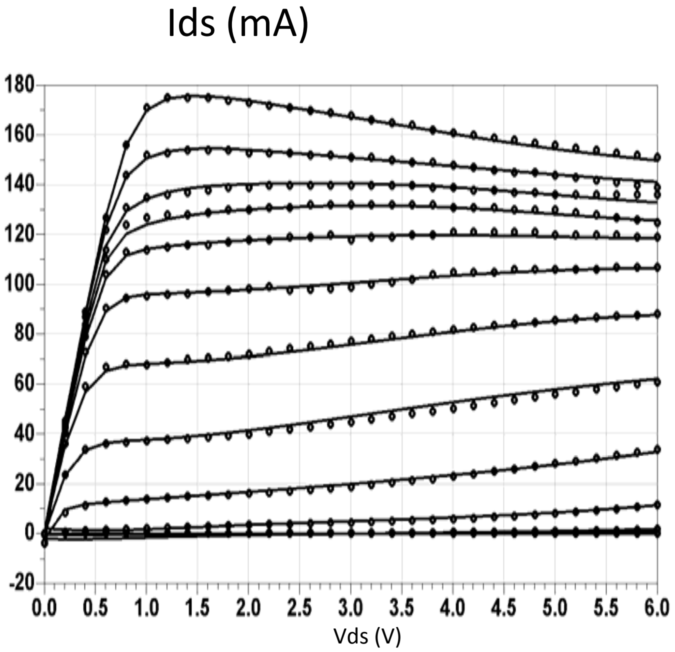
Corresponds to *drain-lag* (knee walk-out) (intrinsic)

Trap state $\varphi_1 = -2 \quad \varphi_2 = 8$



Static “Iso-thermal” intrinsic I-V

$\varphi_1 = Vgs \quad \varphi_2 = Vds \;\; T_j = 65$

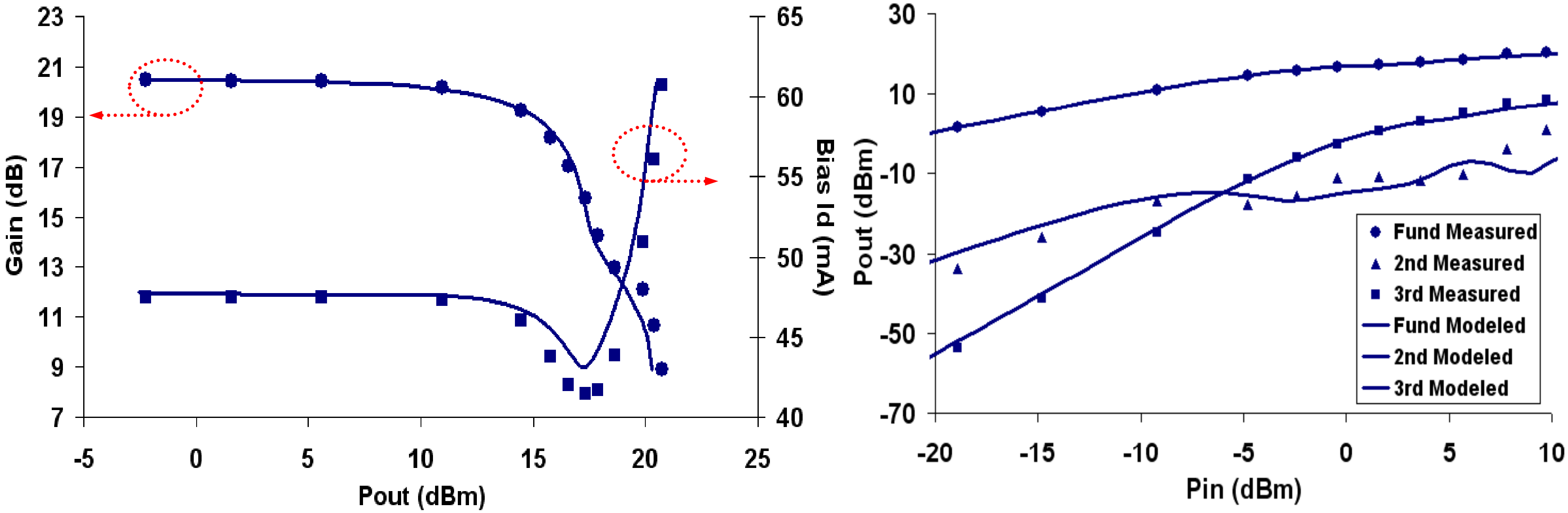


Measured and simulated extrinsic DC - IV

Bias-dependent small-signal admittances fit better everywhere

# Nonlinear validation of advanced GaAs FET model (using NVNA data)

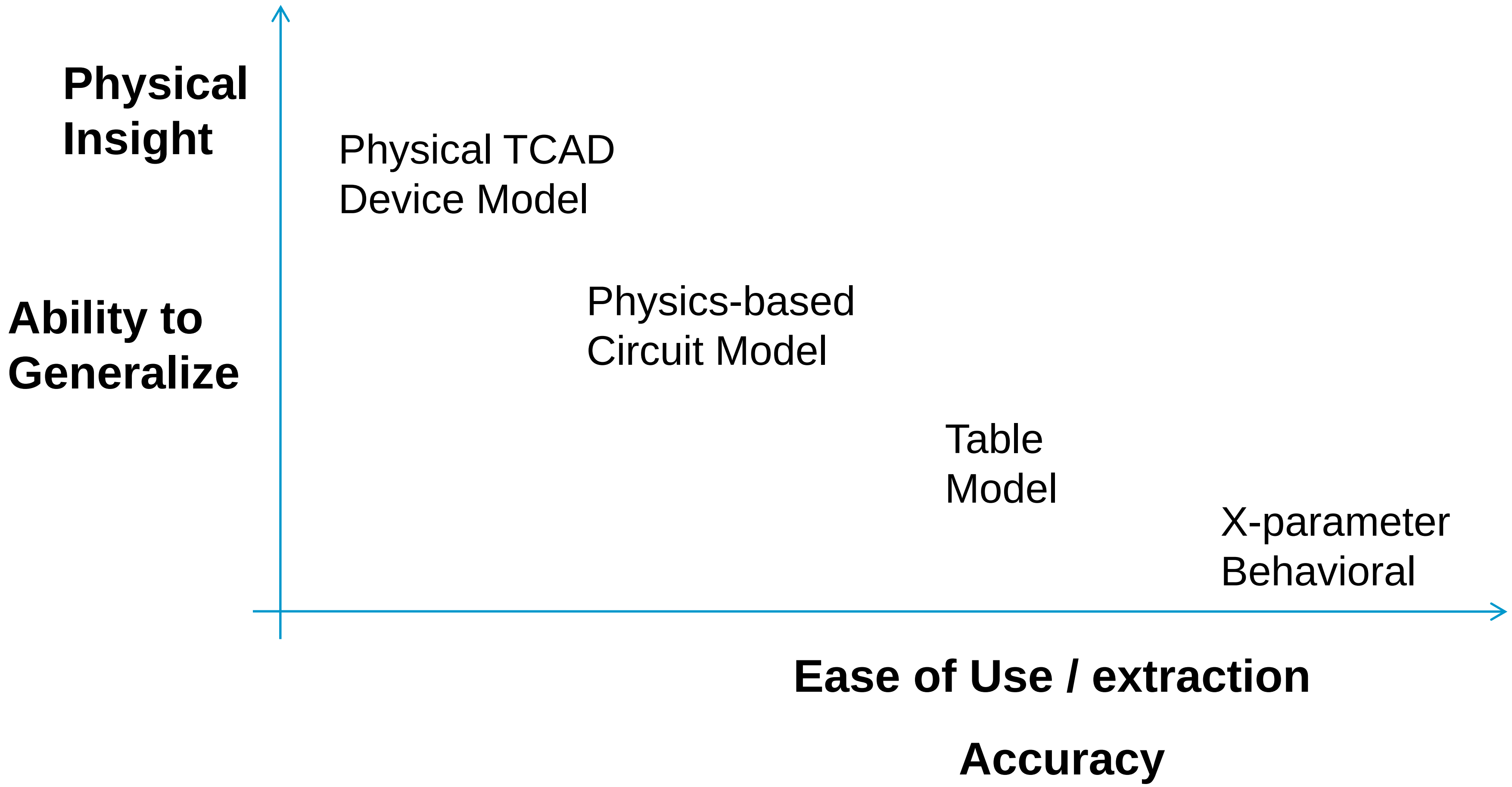
Xu et al IMS2010 [53]



**Simulated (— )**
**Measured data (symbols)**

With NVNA, Nonlinear validation ***comes for free***

# Tradeoffs



**Physical Insight**

**Ability to Generalize**

Physical TCAD Device Model

Physics-based Circuit Model

Table Model

X-parameter Behavioral

**Ease of Use / extraction**

**Accuracy**

# Conclusions

- Physical, Empirical, Table-based, and Behavioral models (e.g. X-parameters) of transistors all have their place in device modeling
- Advanced characterization techniques and instruments (e.g. NVNA) will change the paradigm for nonlinear device modeling and validation. This is a key industry trend.
- Modeling is a rigorous and complex process. Good results take time, expertise, good measurements, and care.

# References

[1] A.E.Paker and D.E.Root “Pulse Measurements Quantify Dispersion in PHEMTs,” *1998 IRSI Symposium on Signals, Systems, and Electronics,* Pisa, Italy, Sept. 29 - Oct. 2, 1998, URSI and IEEE, pp. 444-449.

[2] Pirola,M., Root,D.E., Ghione,G., “Large-signal performance of measurement-based diode models for nonlinear circuit simula-tion: a comparison, *1995 European Microwave Conf. Technical Digest,* Italy,

[3] Root, D.E., Fan, S., Meyer, J. “Technology Independent Non Quasi-Static FET Models by Direct Construction from Automati-cally Characterized Device Data” 21st European Microwave Conf.Proceedings, Stuttgart, Germany, Sept 1991, pp 927-932.

[4] J. Staudinger, M.C. De Baca, R. Vaitkus, “An examination of several large signal capacitance models to predict GaAs HEMT linear power amplifier performance,” *Radio and Wireless Conference*, Aug. 1998 pp343-346.

[5] V. Cuoco, M.P. van den Heijden, L.C.N de Vreede, “The ‘Smoothie’ data base model for the correct modeling of non-linear distortion in FET devices,” *International Microwave Symposium Digest*, 2002, Vol. 3, pp2149 – 2152

[6] HP NMDG Group

[7] Aarts, A.C.T.; van der Hout, R.; Paasschens, J.C.J.; Scholten, A.J.; Willemsen, M.; Klaassen, D.B.M.; “Capacitance modeling of laterally non-uniform MOS devices,” *2004 IEEE IEDM Technical Digest*, 13-15 Dec. 2004 Page(s):751 - 754

[8] D.J.McGinty and D.E.Root, and J.Perdomo, “A Production FET Modeling and Library Generation System,” in *IEEE GaAs MANTECH Conference Technical Digest*, San Francisco, CA, July, 1997 pp. 145-148

[9] Root, D.E. and Fan, S., “Experimental Evaluation of Large-Signal Modeling Assumptions Based On Vector Analysis of Bias-Dependent S-Parameter Data from MESFETs and HEMTs”, *1992 IEEE MTT-S International Microwave Symposium Technical Digest*, pp.255-259

[10] *Agilent ADS* manual

[11] Parker & Rathmell *IEEE Intl. Microwave Symp. Dig.* 2004

[12] Curtice, W.R.; Ettenberg, M.; “A Nonlinear GaAs FET Model for Use in the Design of Output Circuits for Power Amplifiers” IEEE Transactions on Microwave Theory and Techniques, Volume 33, Issue 12, Dec 1985 Page(s):1383 - 1394

[13] *Agilent ADS* manual

[14] S. Maas, “Ill conditioning in self-heating FET models**,”** *IEEE Microwave & Wireless Comp. Let. 12, 3* Mar. 02 pp 88-89

[15] A. Parker, Comments on" ill conditioning in self-heating FET models"., *IEEE Microwave and Wireless Components Letters* 12:99, 351-352, 2002

[16] D.E.Root, “Nonlinear Charge Modeling for FET Large-signal Simulation and its Importance for IP3 and ACPR in Communica-tion Circuits,” *Proc. of the 44th IEEE Midwest Symposium on Circuits and Systems*, Dayton OH, August, 2001, pp 768 - 772 (contact author for corrected version)

[17] D.E. Root “Overview of Microwave FET Modeling for MMIC Design, Charge Modeling and Conservation Laws, and Advanced Topics,” *1999 Asia Pacific Microwave Conference Workshop Short Course on Modeling and Characterization of Microwave Devices and Packages*, Singapore, November, 1999

[18] AE Parker and JG Rathmell, “Bias and Frequency Dependence of FET Characteristics, *IEEE Transactions on Microwave Theory and Techniques* vol. 51, no. 2, pp. 588--592, Feb. 2003.

[19] Ouarch, Z.; Collantes, J.M.; Teyssier, J.P.; Quere, R.;
Measurement- based nonlinear electro-thermal modeling of GaAs FET with dynamical trapping effects, 1998 IEEE MTT-S International Microwave Symposium Digest Volume 2, 7-12 June 1998 pp :599 - 602

[20] Webster, D.; Darvishzadeh, M.; Haigh, D.;“Total charge capacitor model for short-channel MESFETs,” IEEE Microwave and Guided Wave Letters, Volume 6, Issue 10, Oct. 1996 Page(s):351 - 353

[21] D.E.Root, *2001International Symposium on Circuits and Systems Tutorial/Short-Course and Special Session on High-Speed Devices and Modeling*, Sydney, Australia, May, 2001, pp 2.3_1 - 2.3_7 and 2.7_1 - 2.7_8

[22] Schreurs, D.; Verspecht, J.; Vandenberghe, S.; Carchon, G.; van der Zanden, K.; Nauwelaers, B.; Easy and accurate empirical transistor model parameter estimation from vectorial large-signal measurements,” *IEEE Intl Microwave Symp. Dig*est, Volume 2, 13-19 June 1999 Page(s):753 - 756 vol.2

[23] Schreurs et al “Direct Extraction Of The Non-linear Model For Two-port Devices From Vectorial Non-linear Network Analyzer Measurements,” *27th European Microwave Conf.* Sept ’97 921-926

[24] Curras-Francos, M.C.; Tasker, P.J.; Fernandez-Barciela, M.; Campos-Roca, Y.; Sanchez, E.; “Direct extraction of nonlinear FET Q-V functions from time domain large signal measurements,” *IEEE Microwave and Guided Wave Letters* Volume 10, Issue 12, Dec. 2000 Page(s):531 - 533

# References (2)

[25] S. Haykin, Neural Networks: A Comprehensive Foundation (2nd Ed. ) Prentice Hall; 1998

[26] Q.J.Zhang &.K.C.Gupta, Neural Networks for RF and Microwave Design, Artech House, 2000

[27] Xu et al "Exact adjoint sensitivity analysis for neural-based microwave modeling and design," *IEEE Transactions on Microwave Theory and Techniques* Volume 51, Issue 1, Part 1, Jan. 2003 Page(s):226 – 237

[28] J. Verspecht & D. Schreurs, "Measuring transistor dynamic loadlines and breakdown currents under large-signal high-frequency operating conditions," in *IEEE Microwave Symposium Digest*, 1998 Vol 3, 7-12 June 1998 pages 1495-1498 vol. 3

[29] Aarts, A.C.T.; van der Hout, R.; Paasschens, J.C.J.; Scholten, A.J.; Willemsen, M.B.; Klaassen, D.B.M.; "New fundamental insights into capacitance modeling of laterally nonuniform MOS devices,"
IEEE Transactions on Electron Devices, Volume 53, Issue 2, Feb. 2006 Page(s):270 - 278

[30] S. Maas, "Fixing the Curtice FET Model" Microwave Journal, March 2001

[31] Parker, A.E.; Skellern, D.J.; "A realistic large-signal MESFET model for SPICE," *IEEE Transactions on Microwave Theory and Techniques* Volume 45, Issue 9, Sept. 1997 Page(s):1563 - 1571

[32] D.E.Root, in *1999 Asia-Pacific Microwave Conference Workshop (WS2) Modeling and Characterization of Microwave Devices and Packages*, Singapore, 1999

[33] D.E.Root "Elements of Measurement-Based Large-Signal Device Modeling," in *1998 IEEE Radio and Wireless Conference (RAWCON) Workshop on Modeling and Simulation of Devices and Circuits for Wireless Communication Systems*, Colorado Springs, August, 1998

[34] AE Parker and JG Rathmell, "Broad-band Characterization of FET Self-Heating" *IEEE Transactions on Microwave Theory and Techniques,* vol. 53, no. 7, pp. 2424--2429, Jul. 2005.

[35] Filicori, F.; Vannini, G.; Monaco, V.A.; "A nonlinear integral model of electron devices for HB circuit analysis," *IEEE Transactions on Microwave Theory and Techniques,* Volume 40, Issue 7, July 1992 Page(s):1456 - 1465

[36] HPNMDG group

[37] D.Schreurs, J.Verspecht, B.Nauwelaers, A.Van de Capelle, and M. Van Rossum, "Procedure to extract the nonlinear HEMT model from vectorial non-linear network analyzer measurements," *International IEEE Workshop on Experimentally Based FET Device Modeling and Related Nonlinear Circuit Design*, Kassel, Germany, pp. 20.1 - 20.7, July, 1997.

[38] Martín-Guerrero et al "Frequency domain-based approach for nonlinear quasi-static FET model extraction from large-signal waveform measurements," EuMICC Conf. 2006

[39] V. Cuoco, " Smoothie – A Model for Linearity Optimization of FET Devices in RF Applications," Ph.D. Thesis Technical University of Delft, 2006

[40] Lingquan Wang, "Investigation on High Frequency Terminal Current Non-conservation and its Physical Implications," University of California at San Diego Class EE283 Final Project, 2005

[41] Trew, R.J.; Yueying Liu; Bilbro, L.; Weiwei Kuang; Vetury, R.; Shealy, J.B.; "Nonlinear source resistance in high-voltage microwave AlGaN/GaN HFETs," *IEEE Transactions on Microwave Theory and Techniques* Volume 54, Issue 5, May 2006 Page(s):2061 - 2067

[42] A. Conway and P. Asbeck, To be published at *IEEE 2007 International Microwave Symposium*

[43] Xu, J.; Gunyan, D.; Iwamoto, M.; Cognata, A.; Root, D.E.; "Measurement-Based Non-Quasi-Static Large-Signal FET Model Using Artificial Neural Networks," *IEEE MTT-S International Microwave Symposium Digest* June 2006 Page(s):469 - 472

[44] D.Root and J. Wood, "Simulator Requirements for Measurement and Simulation-based Black-Box Nonlinear Models," *2004 IEEE International Microwave Symposium Workshop*

[45] Xu, J.; Gunyan, D.; Iwamoto, M, Horn, J,, Cognata, A.; Root, D.E.; "Drain-Source Symmetric Artificial Neural Network-Based FET Model with Robust Extrapolation Beyond Training Data," *IEEE MTT-S International Microwave Symposium Digest* June 2007

[46] Li, E.X.; Scheinberg, N.; Stofman, D.; Tompkins, W.; "An independently matched parameter SPICE model for GaAs MESFET's," *IEEE Journal of Solid-State Circuits*, Volume 30, Issue 8, Aug. 1995 Page(s):872 - 880

[47] F.Filicori et al "Empirical Modeling of Low-Frequency Dispersive Effects Due to Traps and Thermal Phenomena in III-V FETs," *IEEE Trans. Microwave Theory Tech*. Vol 43, No. 12, Dec., 1995, pp.2972-2981

[48] M. Iwamoto et al "Large-signal HBT model with improved collector transit time formulation for GaAs and InP technologies," in *2003 IEEE MTT-S Int. Microwave Symp. Dig.*, Philadelphia, PA, June 2003 pp.635-638

[49] M. Iwamoto, D.E. Root, "Large-Signal III-V HBT Model with Improved Collector Transit Time Formulations, Dynamic Self-Heating, and Thermal Coupling," *2004 International Workshop on Nonlinear Microwave and Millimeter Wave Integrated Circuits (INMMIC)*, Rome, Nov. 2004

[50] Blockley et al *2005 IEEE MTT-S International Microwave Symposium Digest*, Long Beach, CA, USA, June 2005.

# References (3)

[51] E. Vandamme et al, “Large-signal network analyzer measurements and their use in device modeling,” *MIXDES 2002*, Wroclaw, Poland.

[52] D. E. Root et al “Device Modeling with NVNAs and X-parameters,” *IEEE INMMiC Conference*, Gotenborg, Sweden, April, 2010

[53] J. Xu et al “Large-signal FET model with multiple time scale dynamics from nonlinear vector network analyzer data,” *IEEE MTT-S International Microwave Symposium Digest,* May, 2010