Time and frequency domain transistor modeling based on Nonlinear Vector Network Analyzer data

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Agilent Technologies Inc.

MOS-AK/GSA Workshop
San Francisco, CA
December 8, 2010

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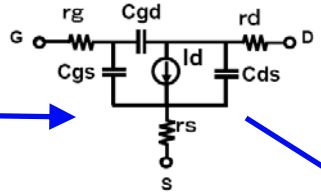
Three Modeling Flows based on Nonlinear Data

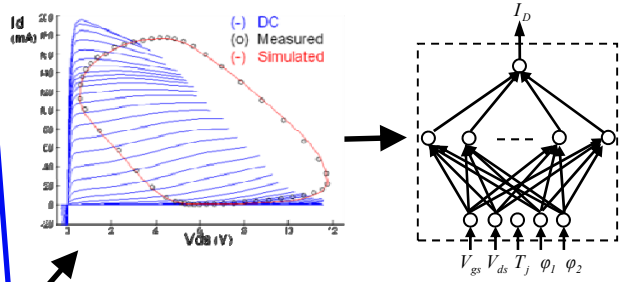
IC-CAP



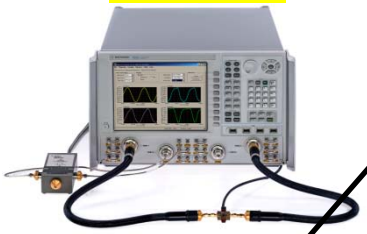
parameter extraction from NVNA data

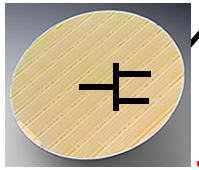
Measurement, Modeling, & Design Capabilities

Adv. Dynamic Model



NVNA

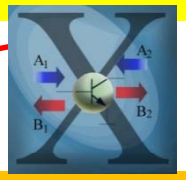




NVNA-based device characterization

Measurement-based compact model

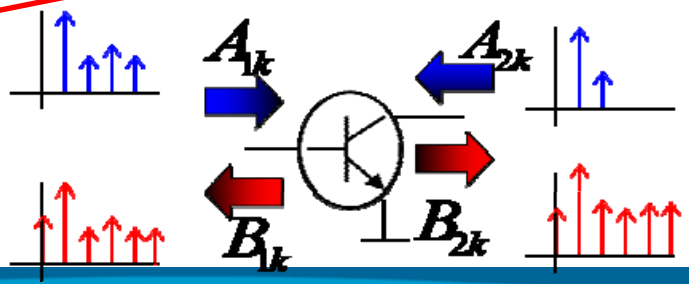
X-parameters



Measurement-based behavioral model

ADS

IC design



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Outline

- Introduction:
  - NVNA Measurements – complex spectra & waveforms
- Compact Models
  - Compact model validation and parameter extraction
  - GaAs transistor model identification and validation
- Load-dependent X-parameter model of packaged GaN transistor & validation with harmonic load-pull
- Discussion and Comparison
- Conclusions

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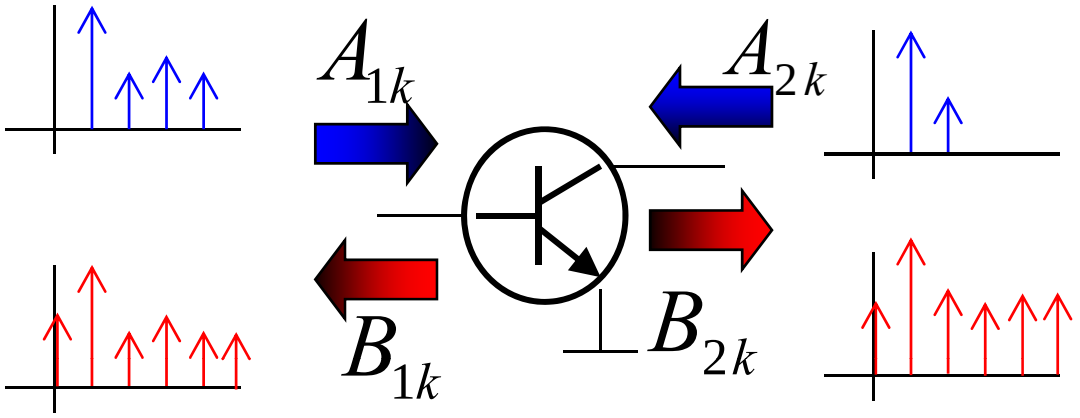
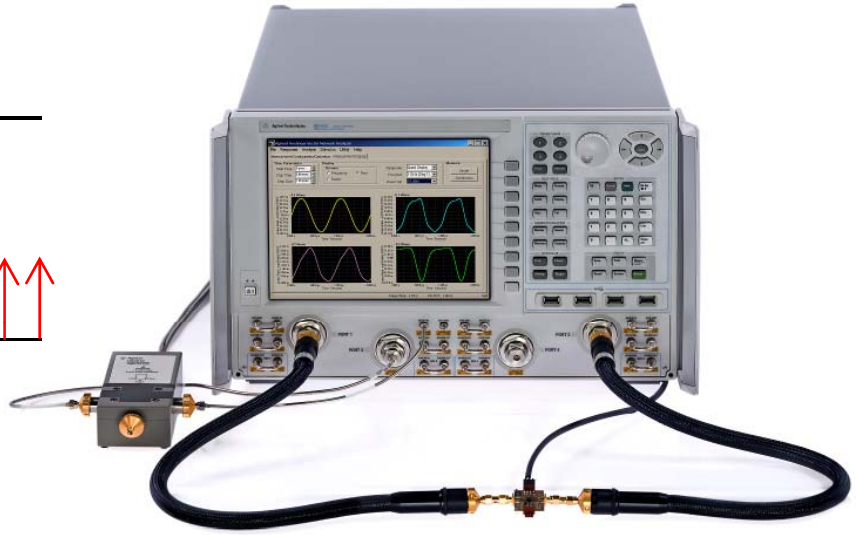
Introduction: NVNA measurements complex spectra and waveforms [1]

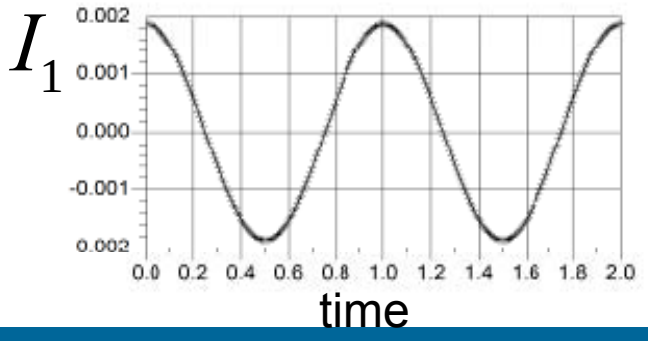


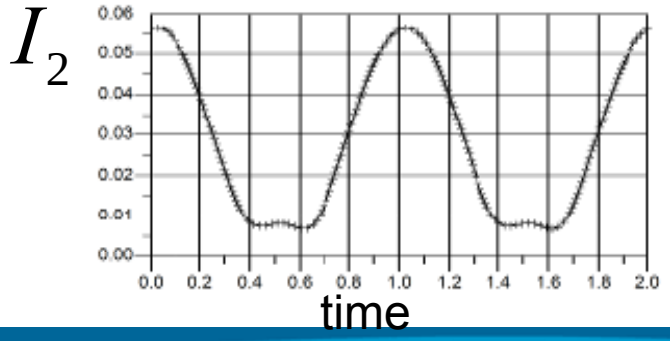


A_{pk} B_{pk}

Harmonic Index

Port Index





Includes:
S-params
Waveforms
Load-lines
X-params

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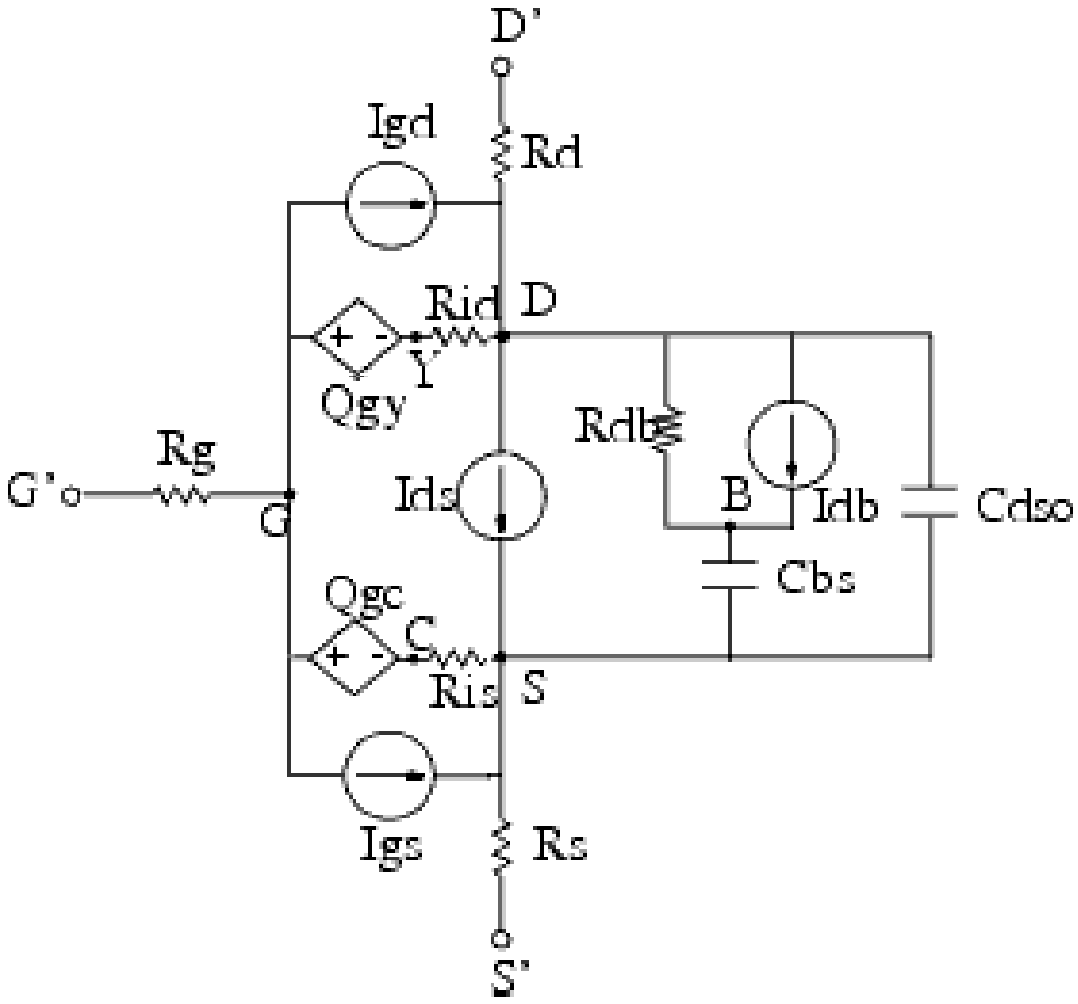
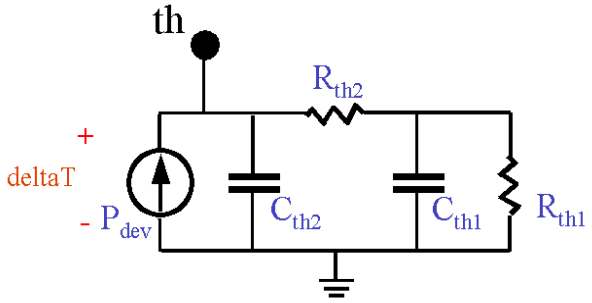
Compact Transistor Models: *time domain*





Thermal Subcircuit (Two-Poles)

Standard GaAs FET Model

Model: Coupled nonlinear ordinary differential equations

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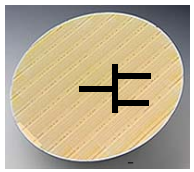
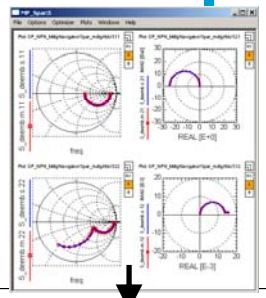
Conventional Empirical Device Modeling Flow

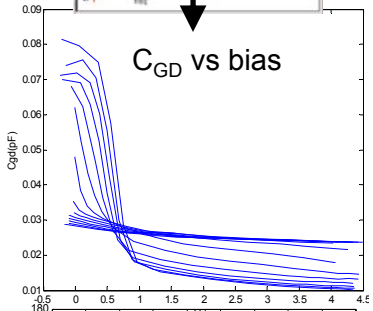
VNA

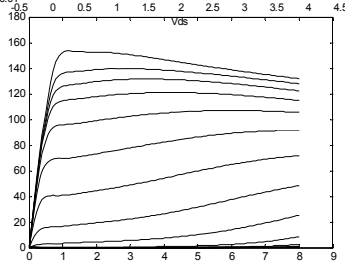
Parameter Analyzer



NVNA-based device characterization

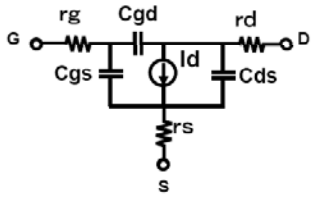






DC + S-parameter (or C-V data)

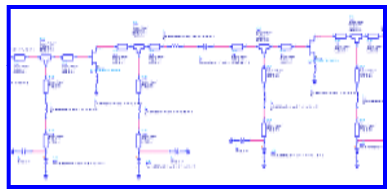
IC-CAP



Your Compact Model Here

Parameter extraction for std. compact model

ADS



Does it actually work in NL?

Circuit design

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Issues with compact device models

- Parameters typically extracted from DC and *linear* 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 measurement-based models may not be identifiable from only DC and S-parameter data.
  - No direct evidence that these nonlinear models will reproduce large-signal behavior under actual conditions of use!
- Large-signal data from Nonlinear Vector Network Analyzer (with additional advanced modeling techniques) can solve all these problems

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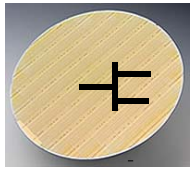
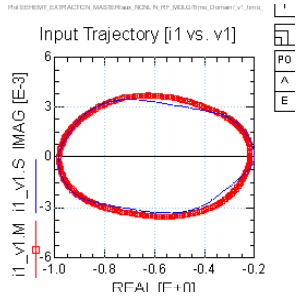
Nonlinear Modeling Flow with NVNA data (1)

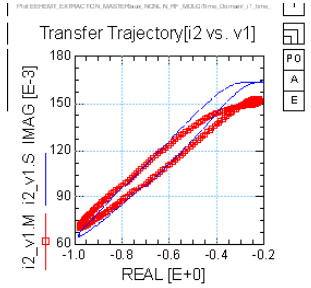
NVNA

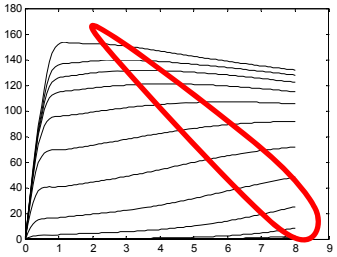
Sync. Bias Supply



NVNA-based device characterization



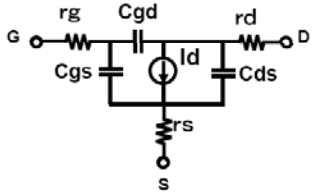




Dynamic Load-line Waveform meas.
DC-IV, S-pars

↔

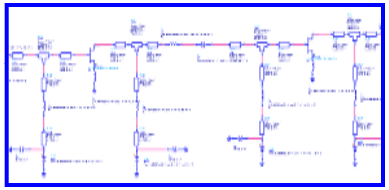
IC-CAP



Your Compact Model Here

Parameter extraction for std. compact model using NVNA data as target

ADS



Circuit design

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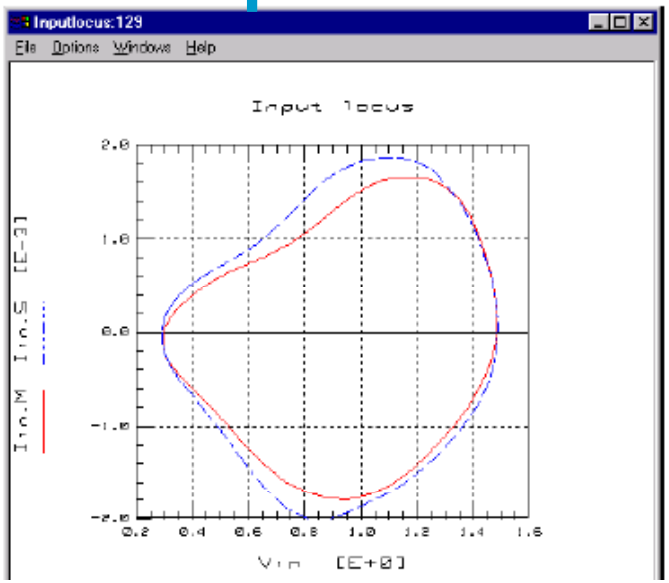
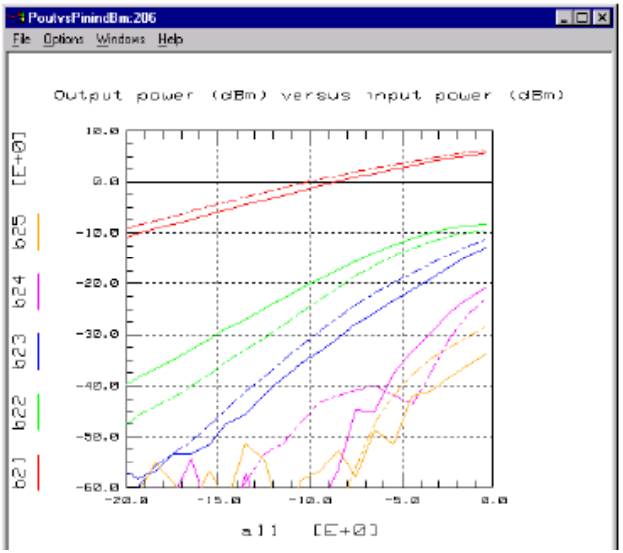
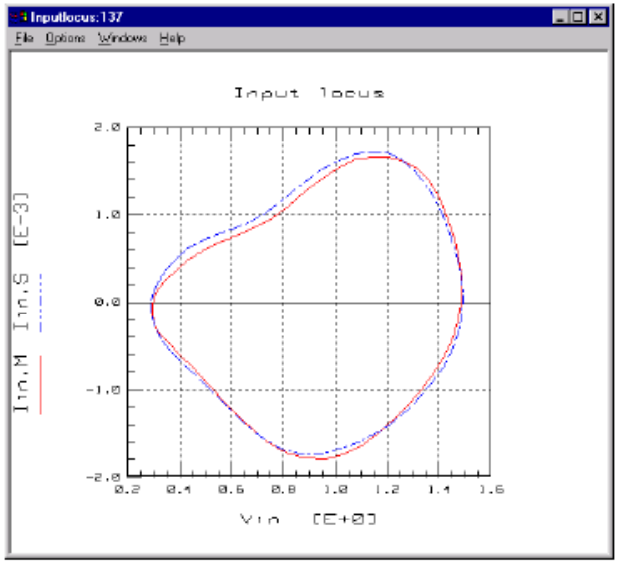
Model parameter extraction from Nonlinear Data (1)



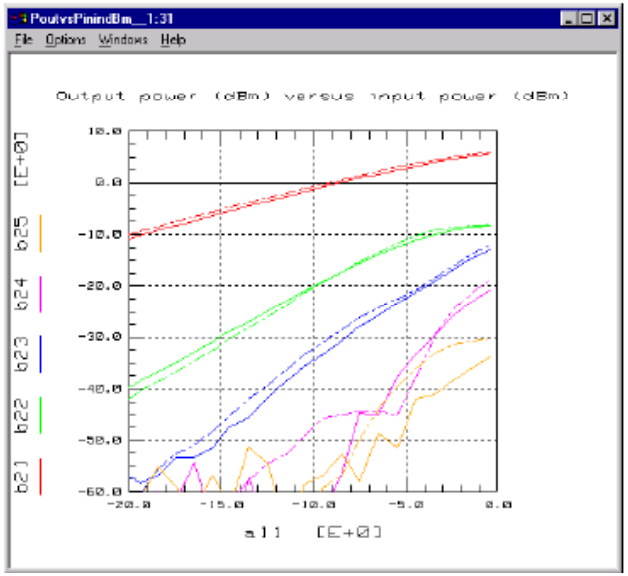
NVNA data vs HB simulation using initial parameter values extracted from DC + CV





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
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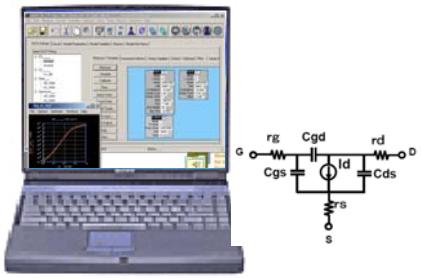
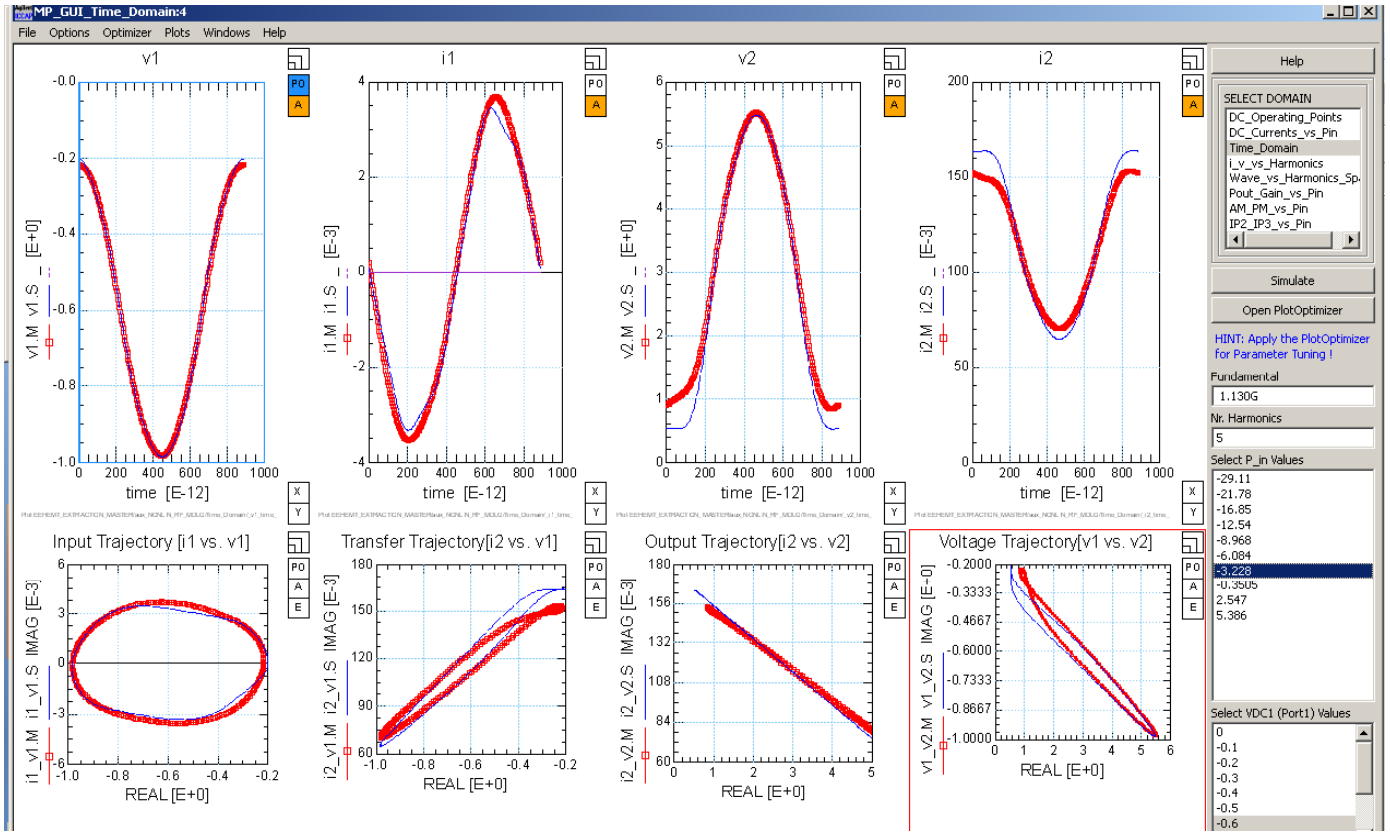
Ref. [10]

ICCAP comparison of simulated & NVNA measured results





Extract or Tune parameters with this capability
Based on NVNA data
Details are model-dependent

Large-signal Validation for free!
Evaluate model under realistic operation
See where it needs improvement

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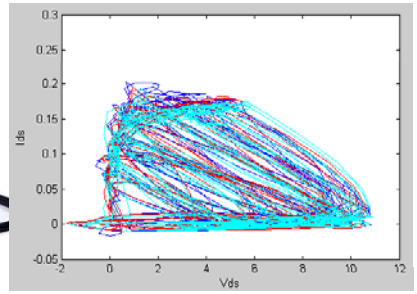
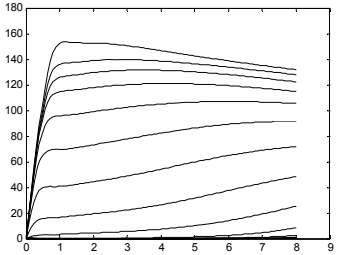
Nonlinear Modeling Flow with NVNA data (2)

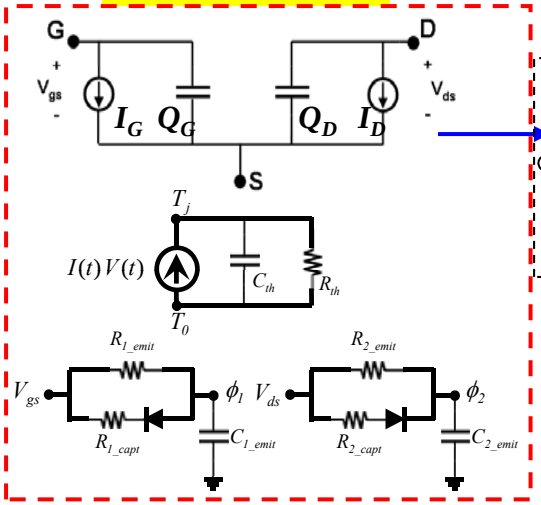
[4] J. Xu, M. Iwamoto, J. Horn, D. E. Root, *IEEE MTT-S International Microwave Symposium Digest,* May, 2010.

NVNA

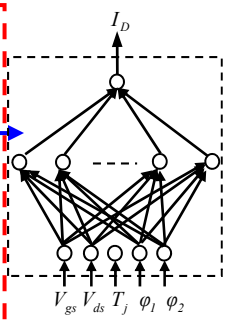




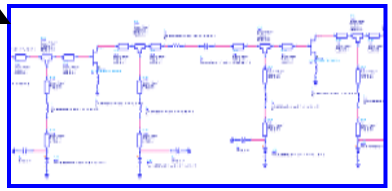
Advanced Non-parametric Dynamic Model

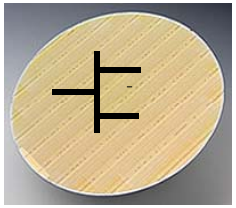


ANN



ADS





NVNA-based device characterization

Dynamic Load-line Waveform meas.
DC + Spars

Direct construction of complicated constitutive relations
Not really parameter extraction!

Circuit design

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Motivations

Modeling modern III-V FETs requires the identification and self-consistent coupling of

(1) **slowly** varying dynamical variables

e.g., temperature, slow emission of traps

(2) **rapidly** varying dynamical variables

e.g., the instantaneous intrinsic terminal voltages and fast capture processes.

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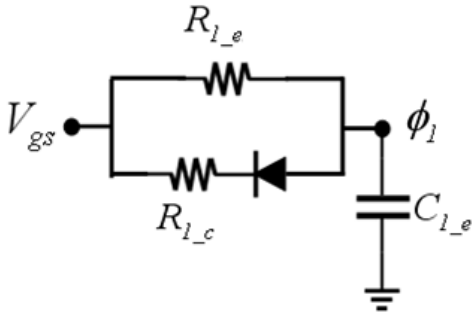
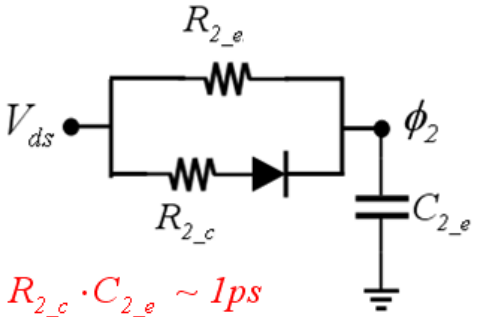
Model Formulation

[4] J. Xu, M. Iwamoto, J. Horn, D. E. Root, *IEEE MTT-S International Microwave Symposium Digest,* May, 2010.

$$\begin{cases} I_{gate}(t) = I_G(V_{gs}(t), V_{ds}(t), T_j(t)) + \dfrac{d}{dt} Q_G(V_{gs}(t), V_{ds}(t), T_j(t)) \\ I_{drain}(t) = I_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t)) + \dfrac{d}{dt} Q_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t)) \end{cases}$$

$$\dot{\phi}_1 = f_1(V_{gs}(t) - \phi_1(t)) + \frac{V_{gs}(t) - \phi_1(t)}{\tau_{1_e}} \qquad \dot{\phi}_2 = f_2(V_{ds}(t) - \phi_2(t)) + \frac{V_{ds}(t) - \phi_2(t)}{\tau_{2_e}}$$

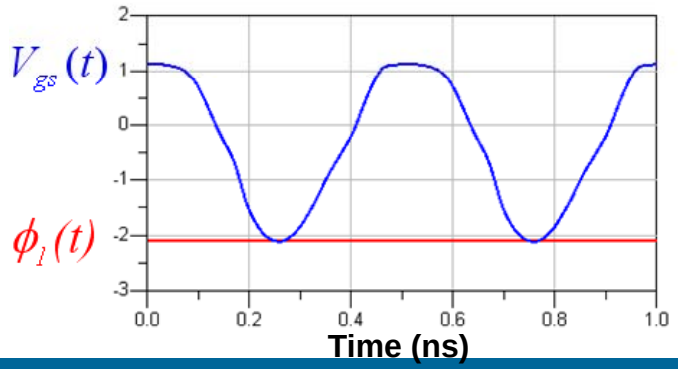


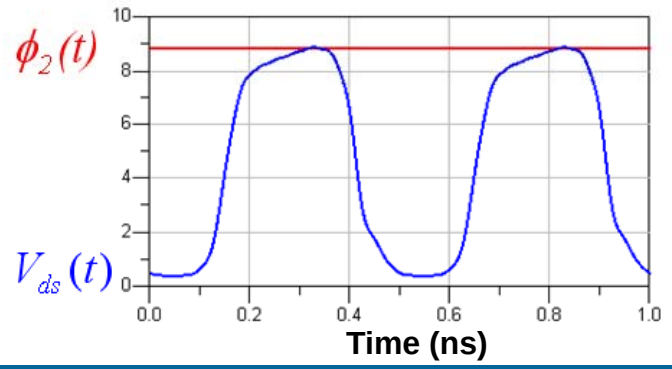


Capture Time Constant $= R_{2_c} \cdot C_{2_e} \sim 1ps$

Emission Time Constant $= R_{2_e} \cdot C_{2_e} \sim 1ms$

O. Jardel et al, *IEEE Trans. MTT.*, vol. 55, 2007.





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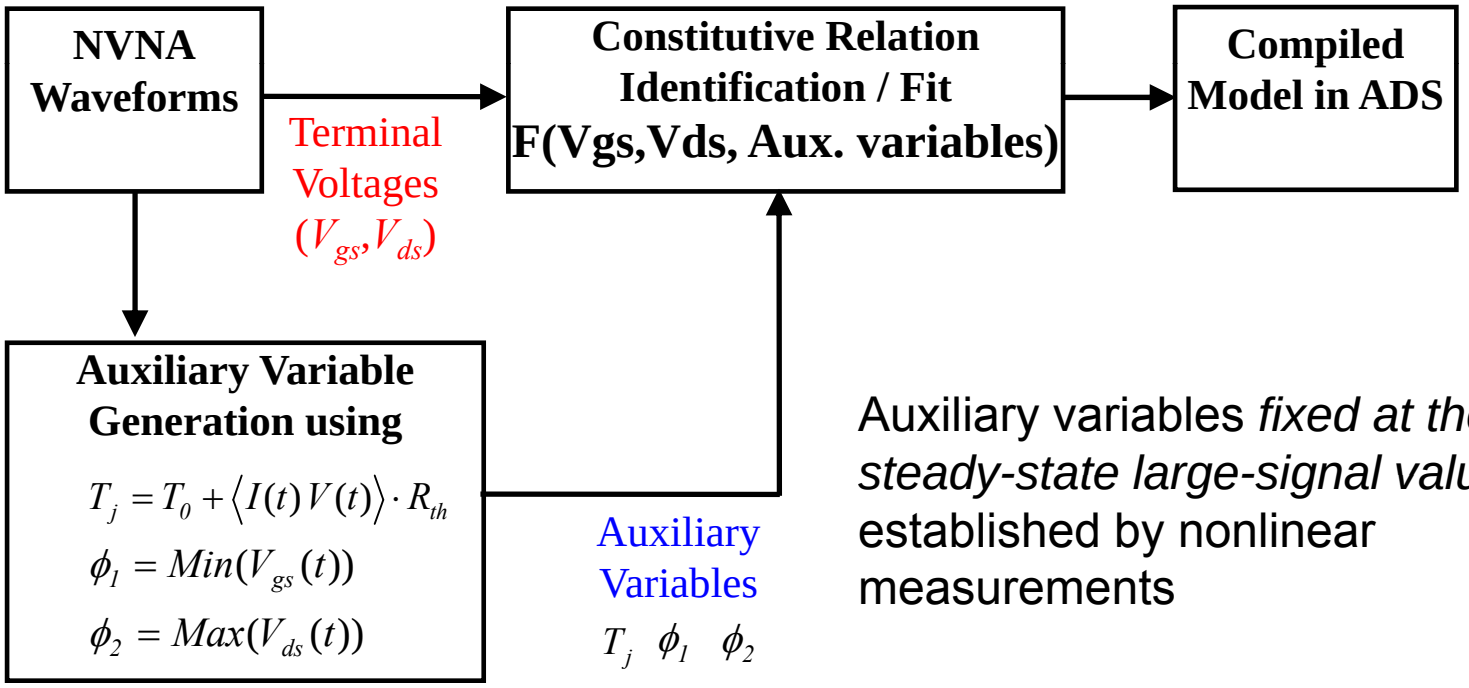
NVNA data for identification of constitutive relations

$$I_{drain}(t) = I_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t)) + \frac{d}{dt} Q_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t))$$

Terminal Voltages — Auxiliary Variables — Terminal Voltages — Auxiliary Variables



Auxiliary variables *fixed at their steady-state large-signal values* established by nonlinear measurements

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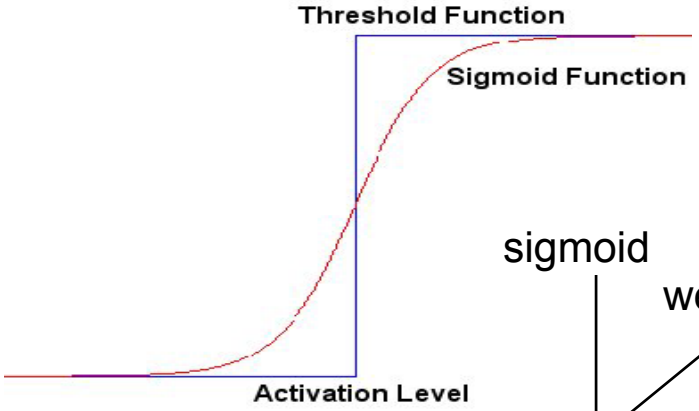
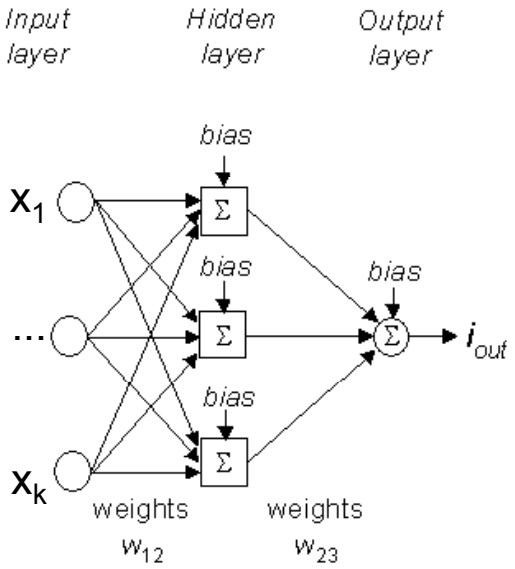
Artificial Neural Networks (ANN)

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



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

sigmoid, weights, biases



- Universal Approximation Theorem: Fit “any” nonlinear function of any # of variables
- Infinitely differentiable: good for distortion.
- Easy to train (fit) with appropriate SW
- Works well on non-gridded data and data with irregular boundaries (intrinsic FET)

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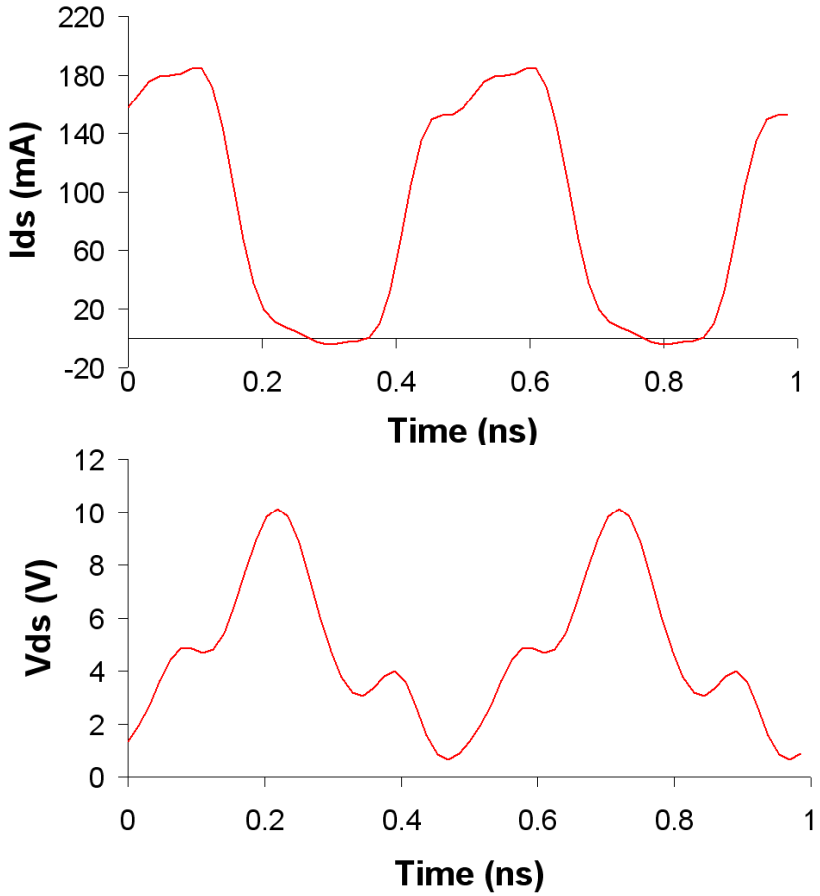
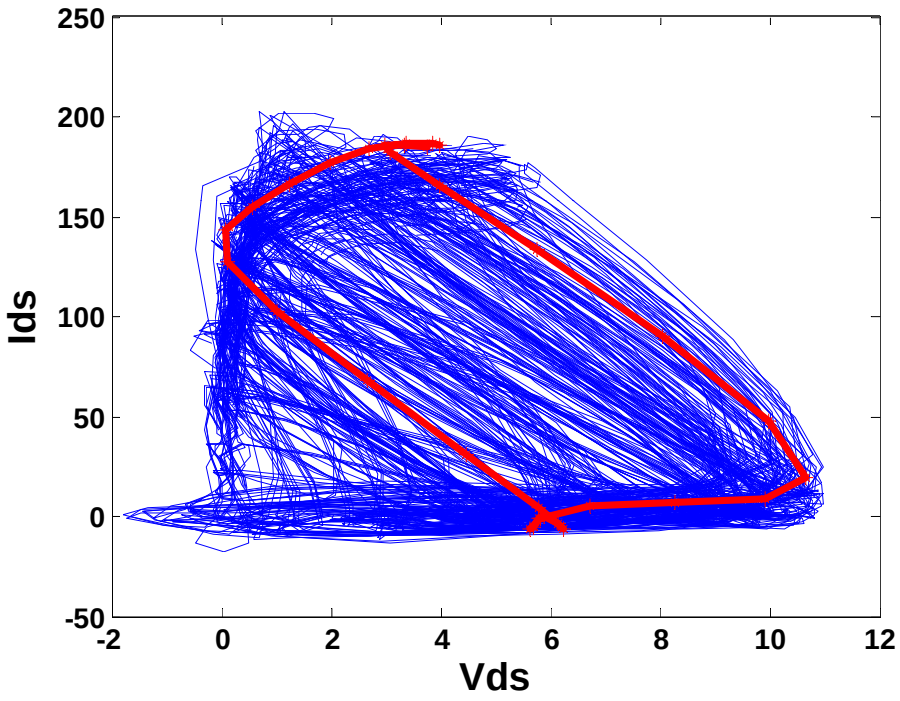
NVNA Measurements with Trap State $[\phi_1, \phi_2] \approx [-3.0, 10]$



Dynamic Load-lines



Red line is one example of the 191 waveforms for this trap state

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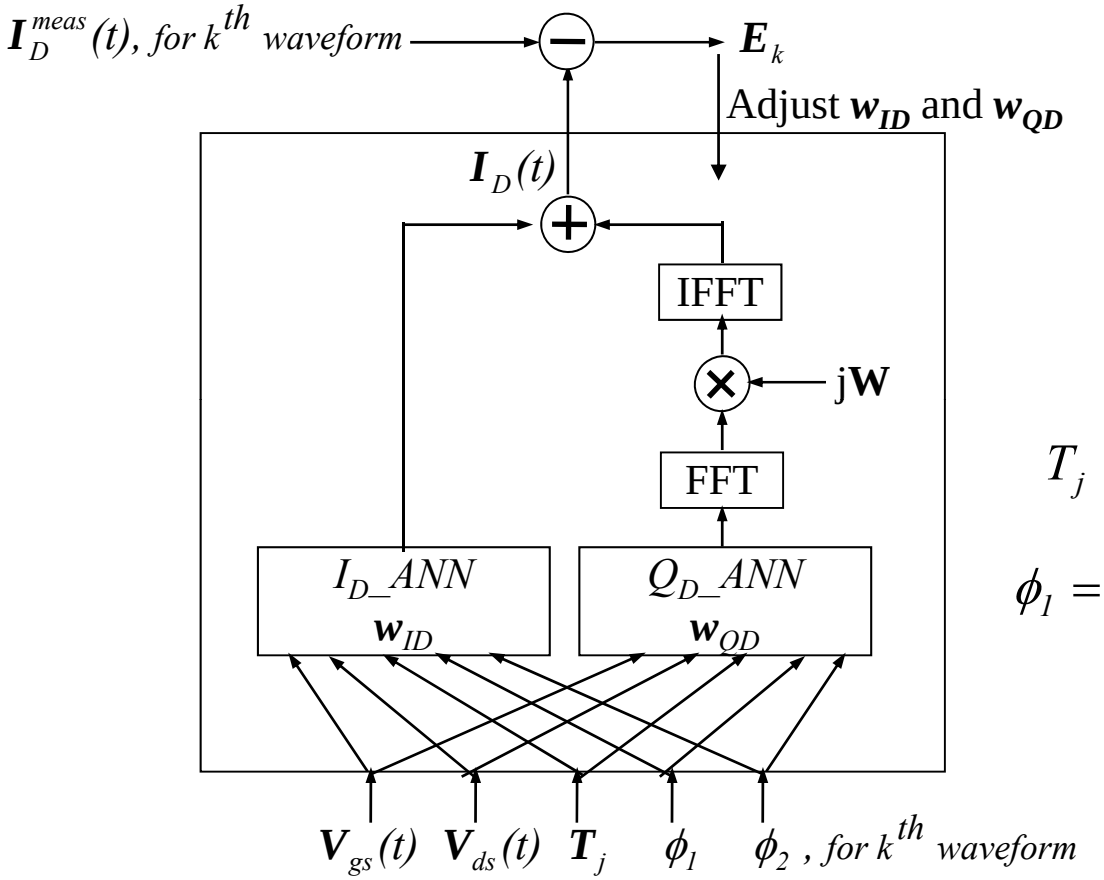
Artificial Neural Network Training Procedure



$$T_j = T_0 + \langle I(t)\,V(t)\rangle \cdot R_{th}$$

$$\phi_1 = Min(V_{gs}(t))\,,\ \phi_2 = Max(V_{ds}(t))$$

$$I_{drain}(t) = I_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t)) + \frac{d}{dt} Q_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t))$$

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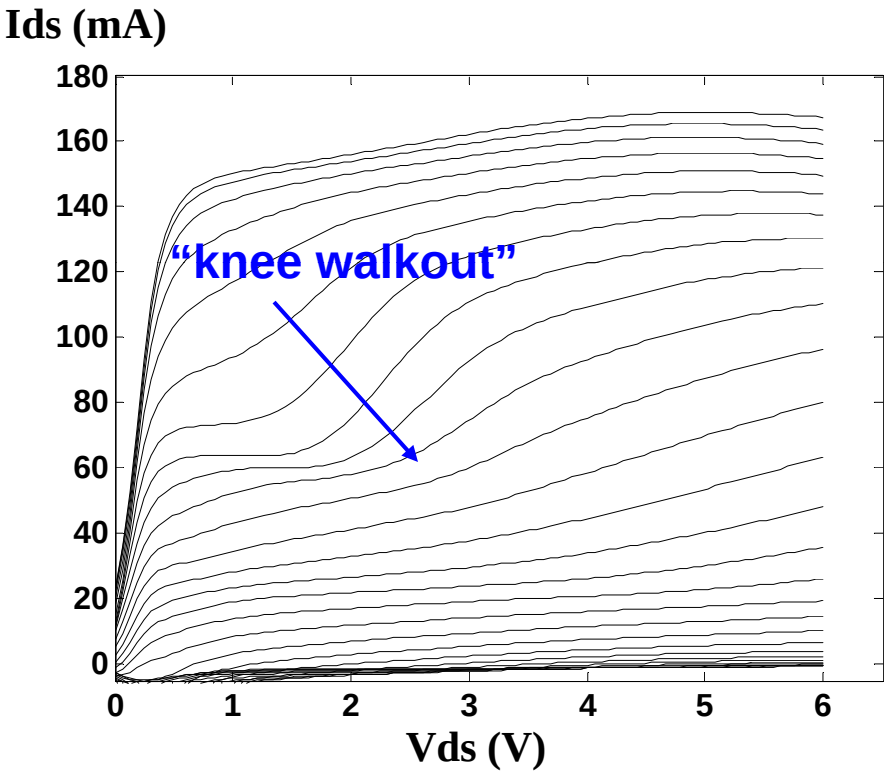
Intrinsic Model Characteristics

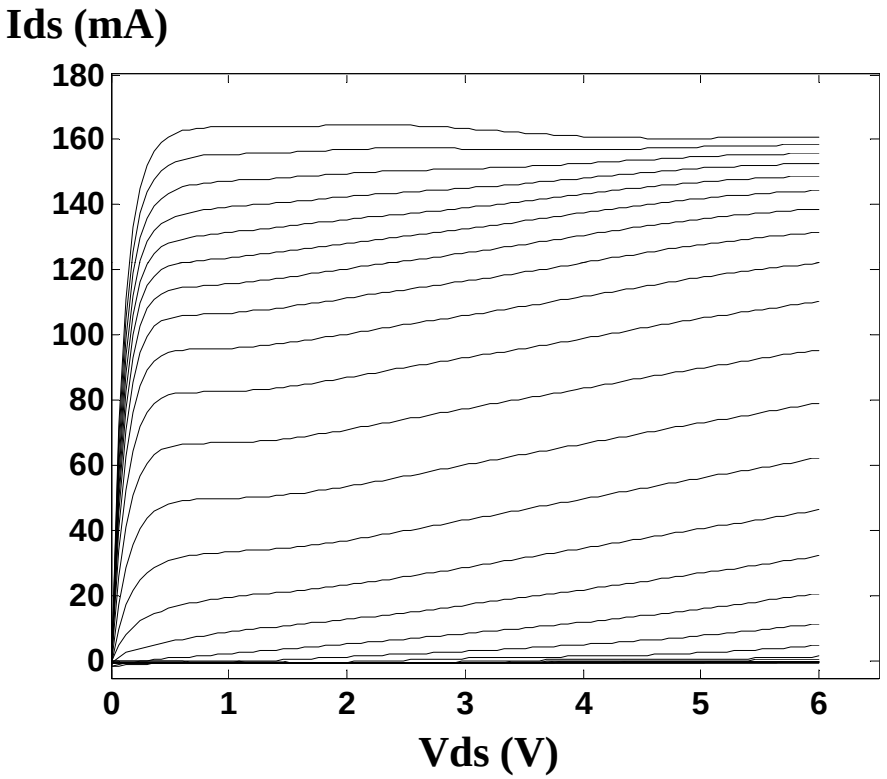
I_D @ two different trap state values

$$I_{drain}(t) = I_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t)) + \frac{d}{dt} Q_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t))$$



fixed T_j and fixed trap state = [-2.0, 8.0]

$$I_D(V_{gs}, V_{ds}, T_j = 55, \phi_1 = -2.0, \phi_2 = 8.0)$$



Isothermal DC

$$I_D(V_{gs}, V_{ds}, T_j = 55, \phi_1 = V_{gs}, \phi_2 = V_{ds})$$

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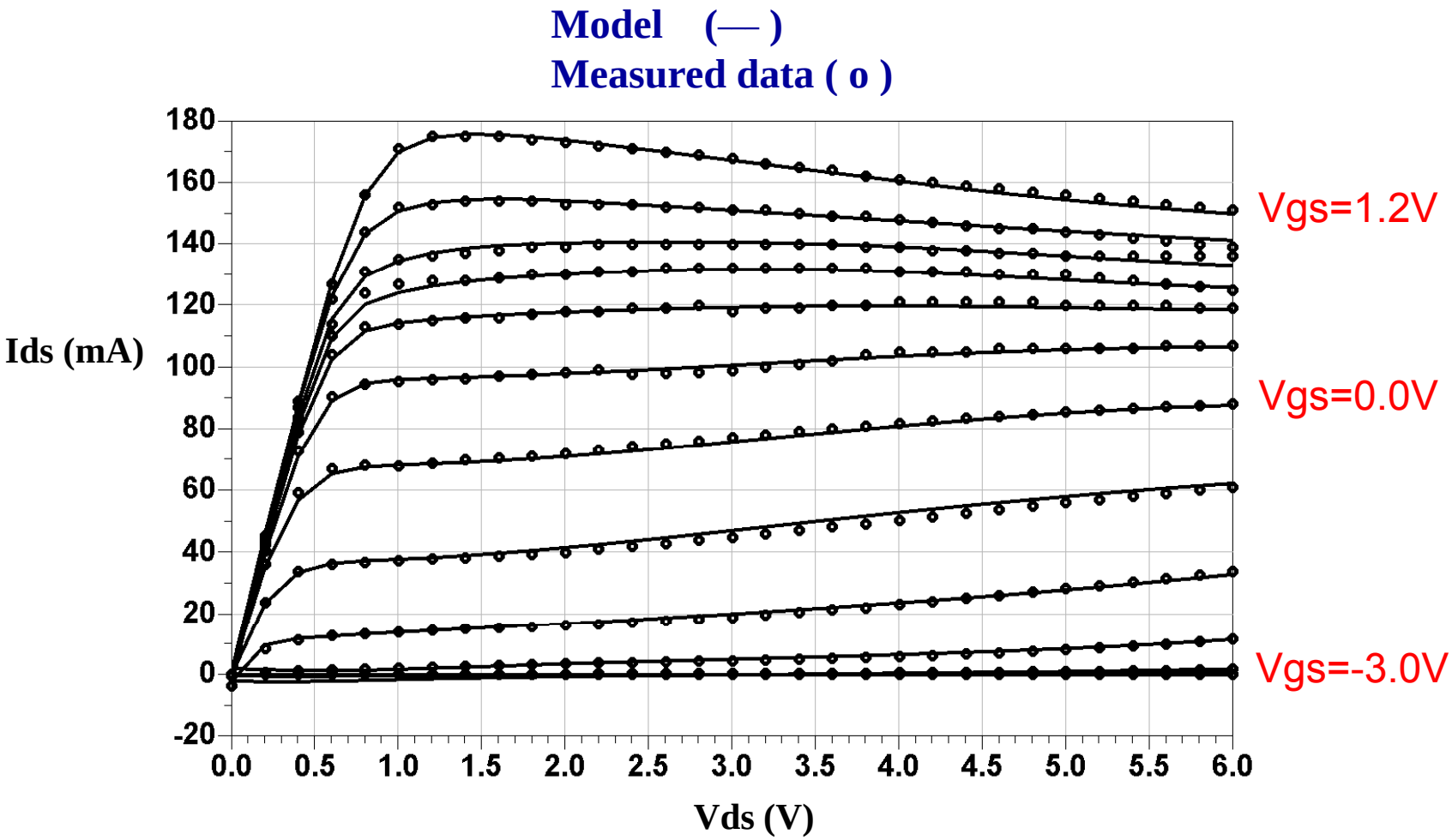
Model Validation
- DC



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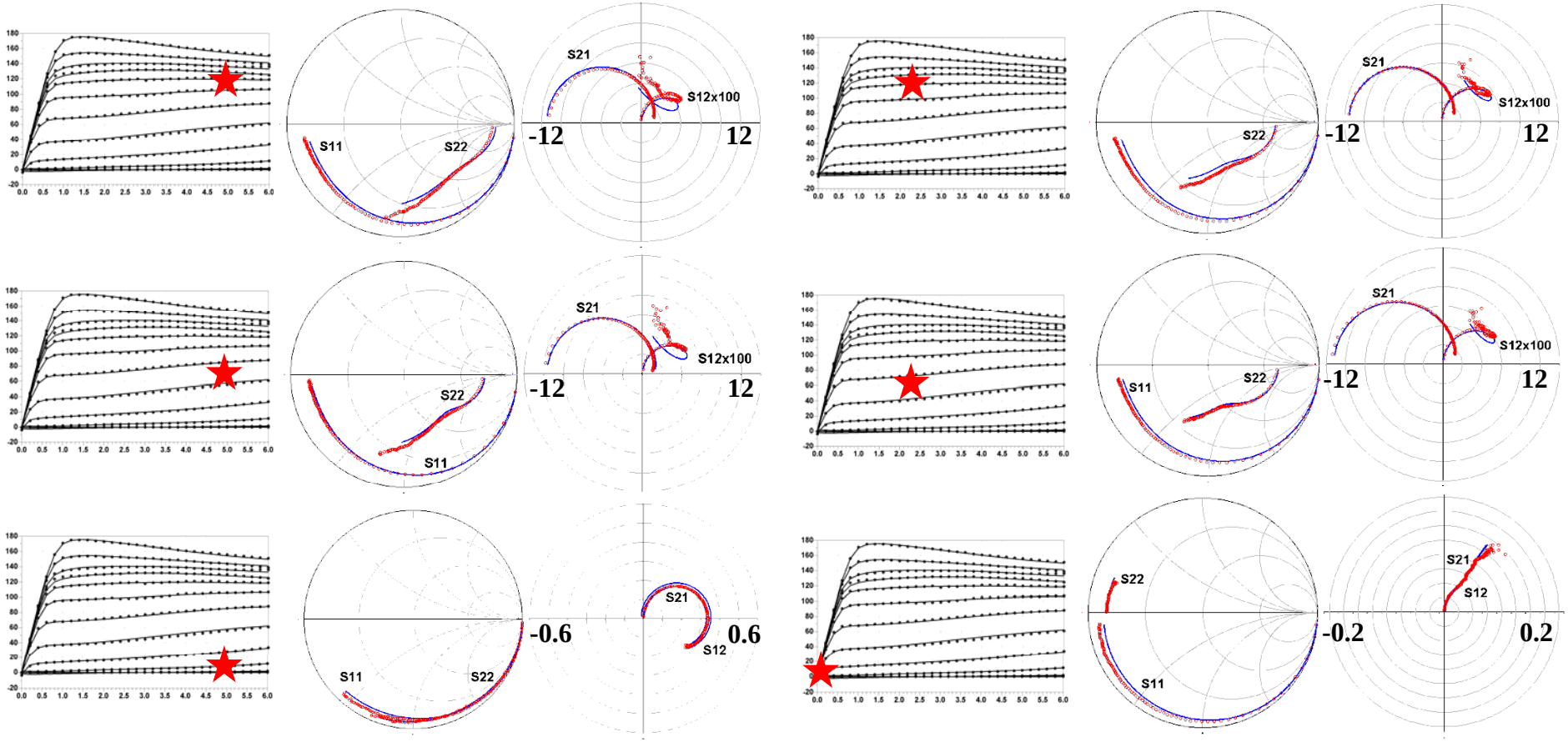
Model Validation

Frequency : 0.5 GHz to 50 GHz

- Frequency dispersion of small-signal characteristics



Excellent agreement over the entire bias range

$$I_{drain}(t) = I_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t)) + \frac{d}{dt} Q_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t))$$

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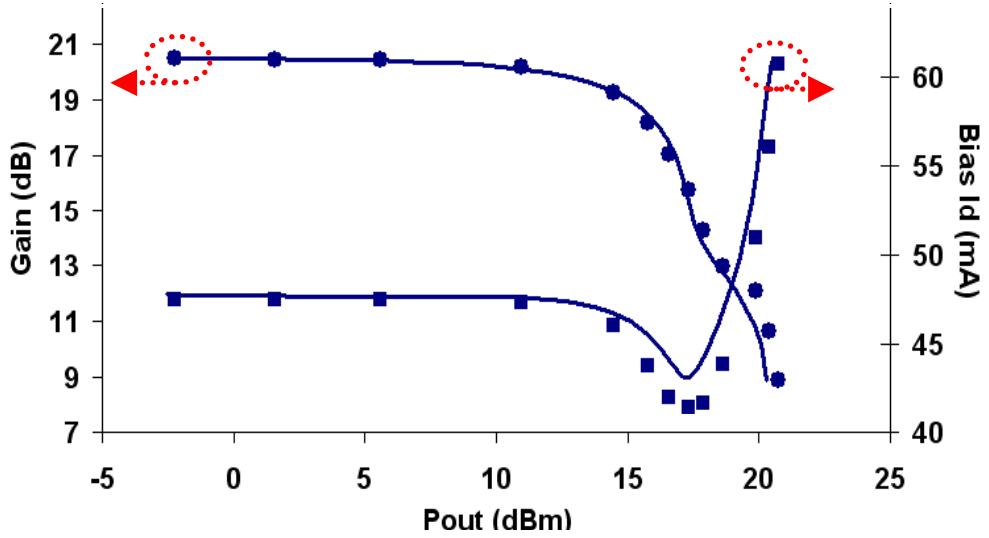
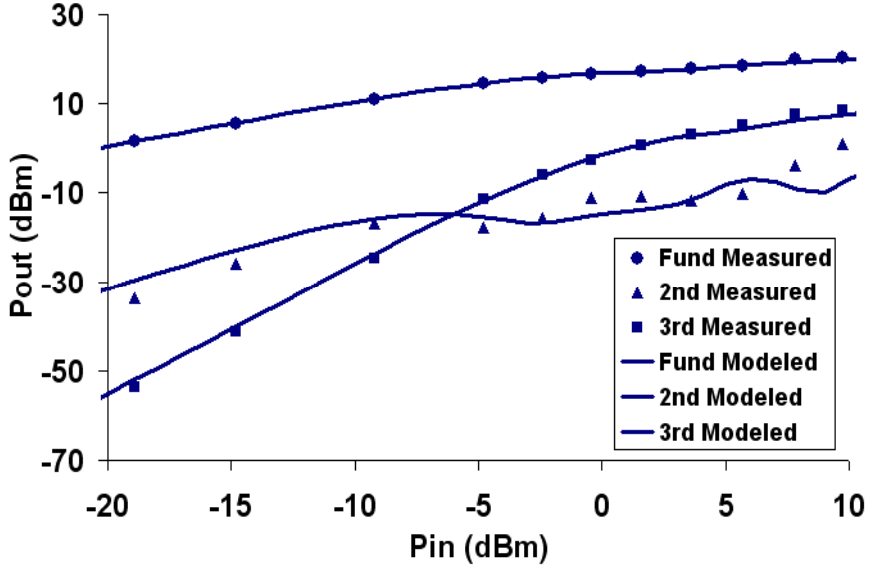
Model Validation

- Gain, Bias Current, Harmonic Distortion vs. Power

Simulated (—)
Measured data (symbols)



Simulated (—)
Measured data (symbols)



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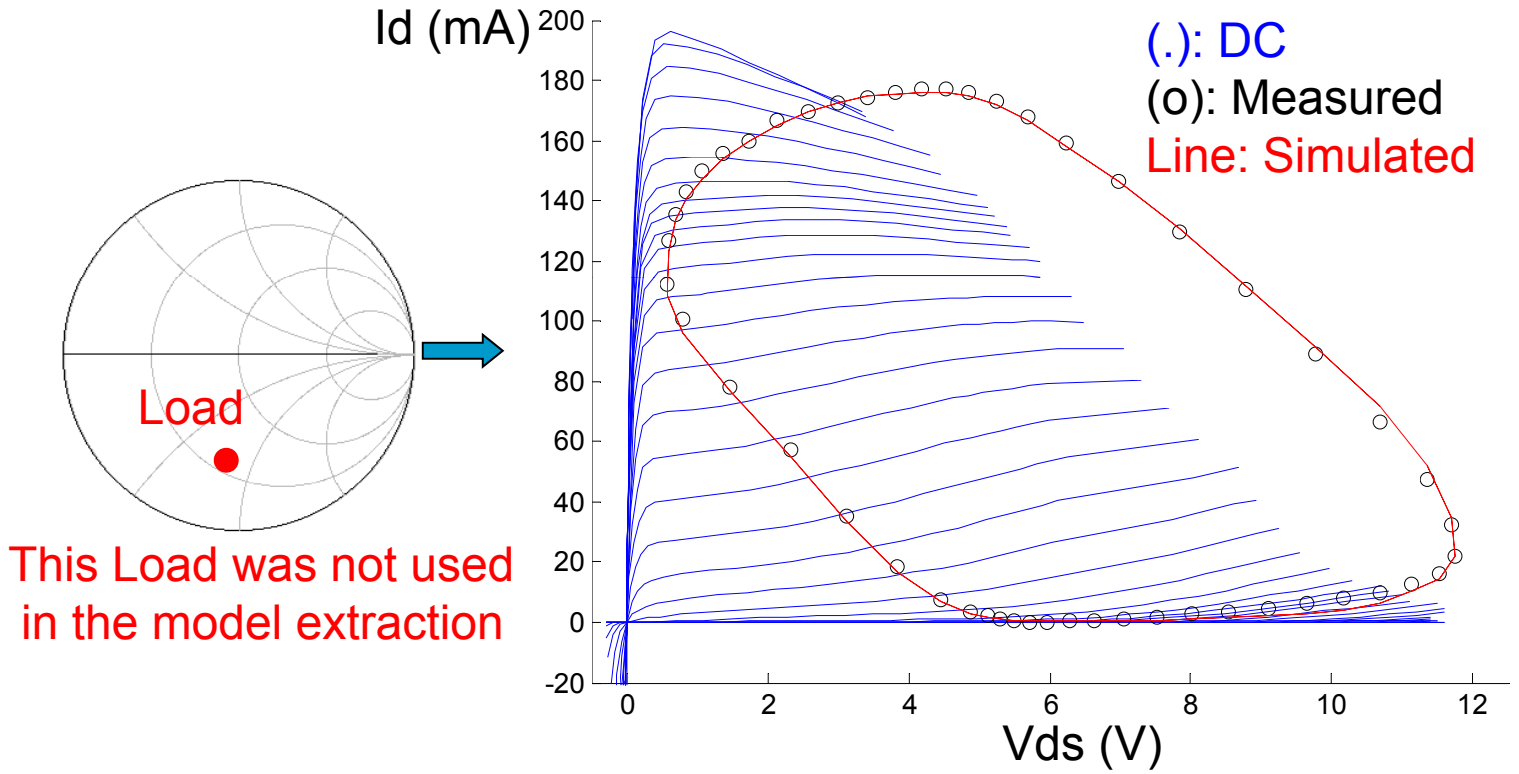
Model Validation

- Load Line (Freq=2GHz, Bias=[-0.2, 6])



Demonstrates model can go far beyond the range over which conventional DC and linear S-parameters can be taken

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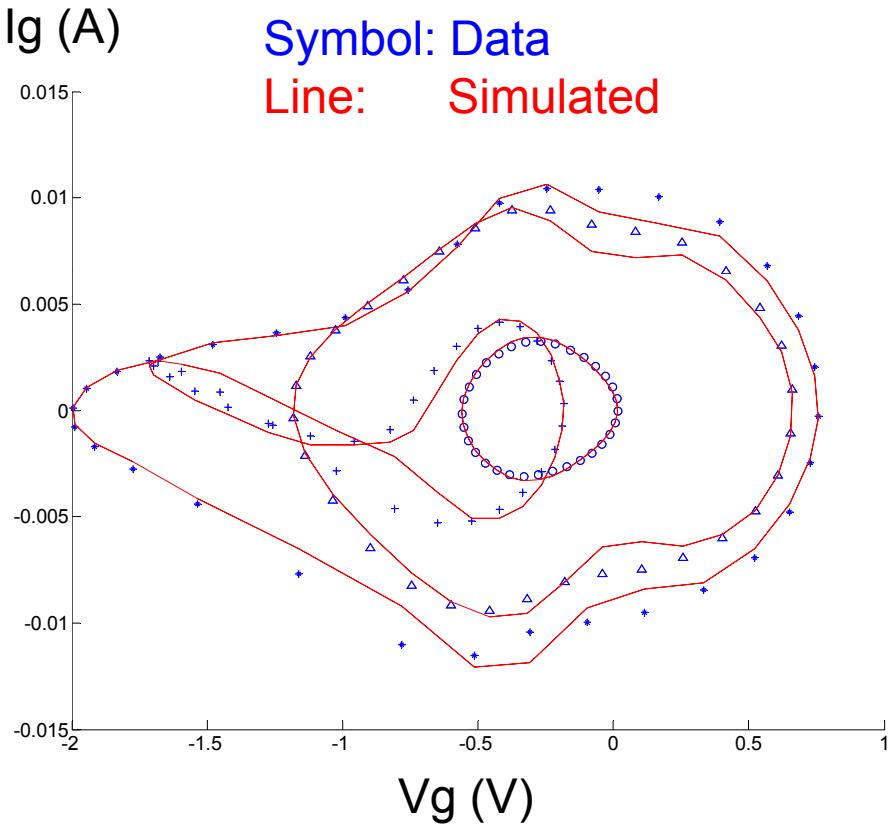
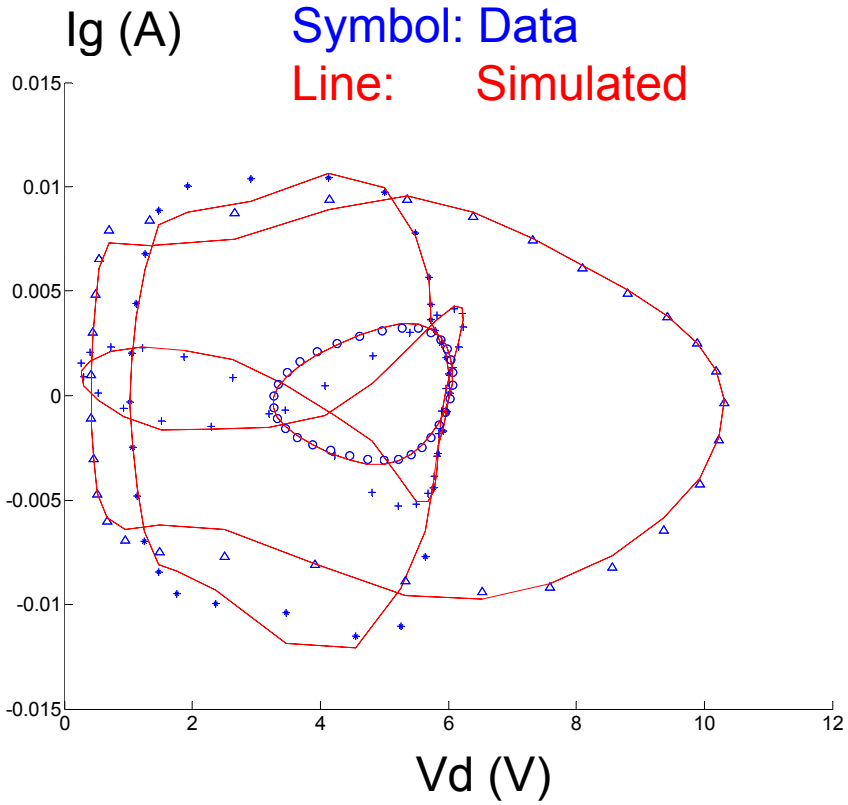
Model Validation

- Gate Current Contours

(4 contours for different powers and loads, Freq=4GHz)





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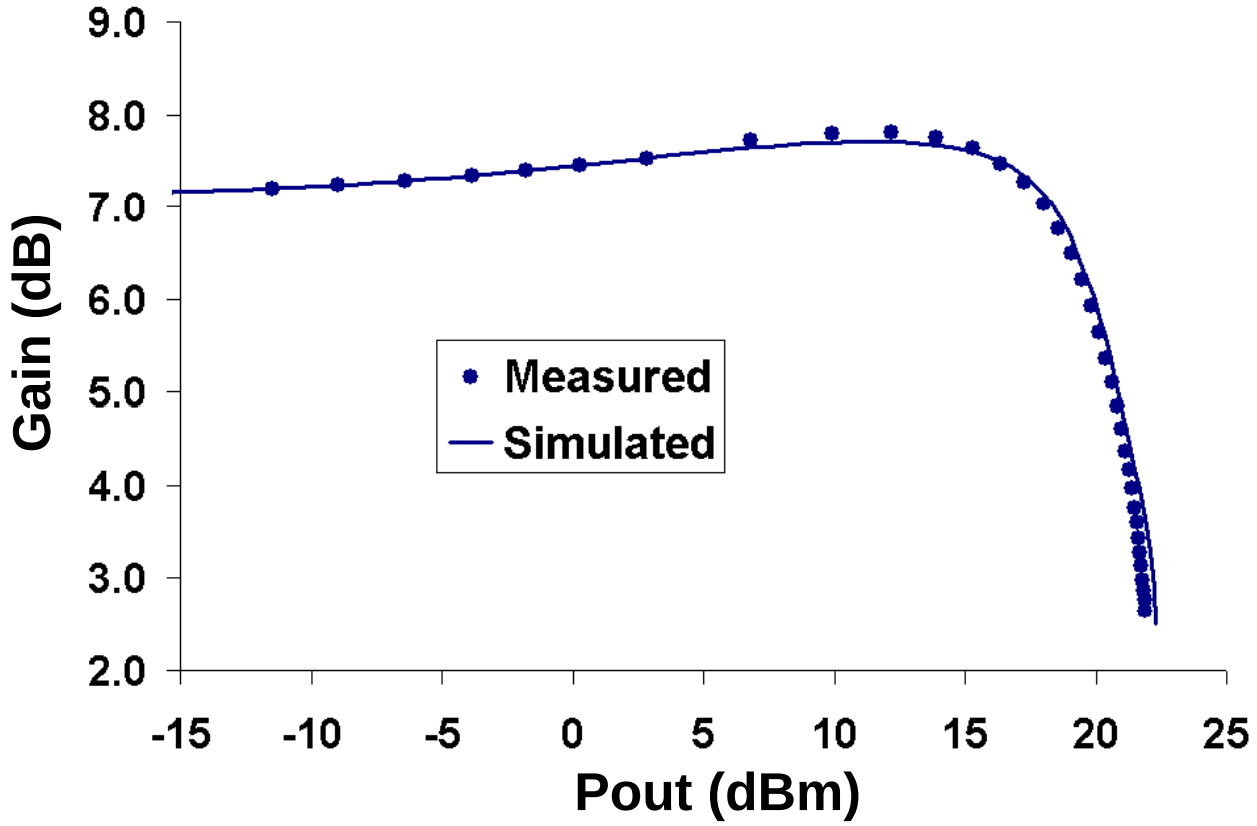
Model Validation

- Gain vs. Pout @26GHz

Model was extracted using 2GHz and 4GHz data



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Outline

- Introduction:
  - NVNA Measurements – complex spectra & waveforms
- Compact Models
  - Compact model validation
  - Parameter extraction
  - GaAs transistor model identification and validation
- Load-dependent X-parameter model of packaged GaN transistor & validation with harmonic load-pull
- Discussion and Comparison
- Conclusions

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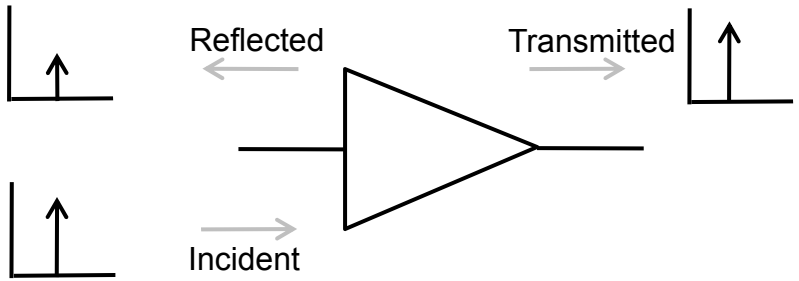
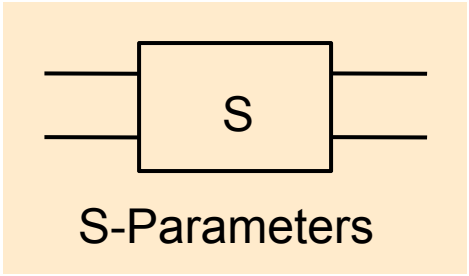
S-parameters Solve All Small-Signal Problems

But devices must operate linearly

Measure

Agilent Vector Network Analyzer

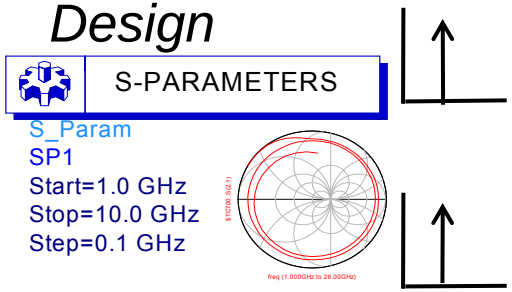


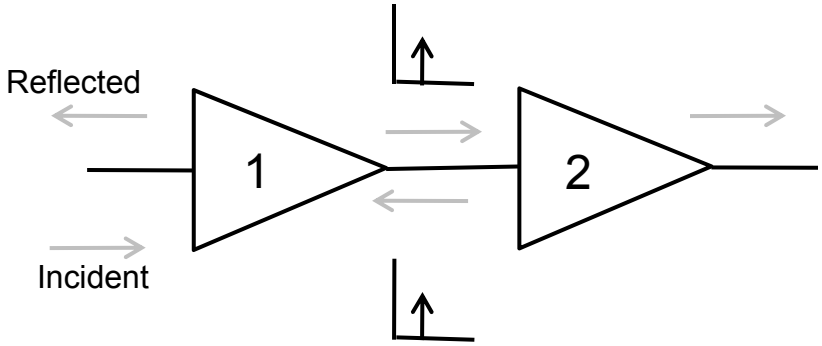


Freq. Domain Model

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

Design





What about large-signal nonlinear problems?

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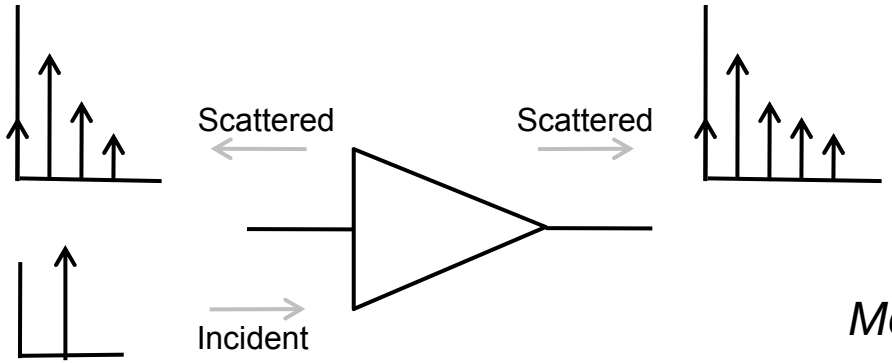
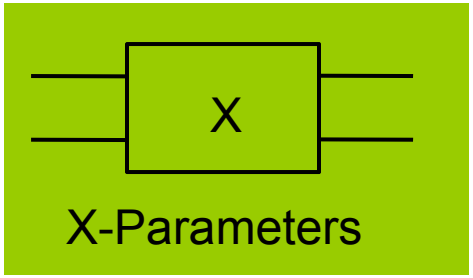
X-parameters Solve Nonlinear Problems [1,8]

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



Measure

Agilent Nonlinear Vector Network Analyzer

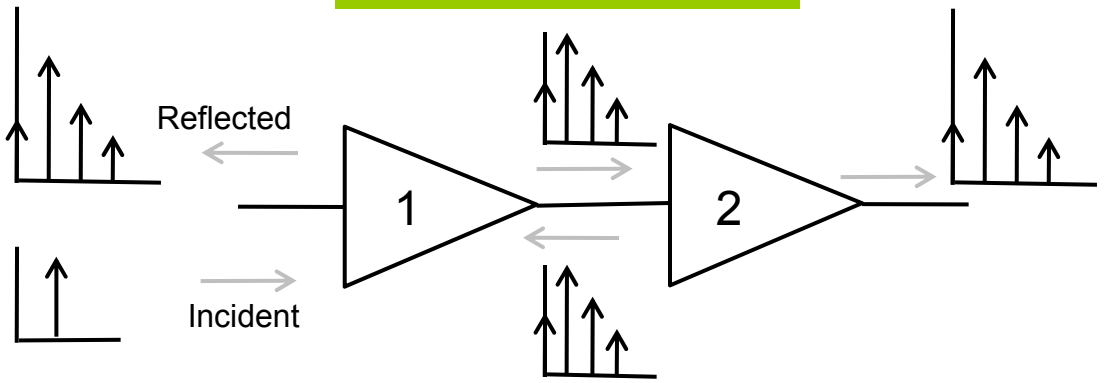


Model

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

Design

Agilent ADS EDA Software



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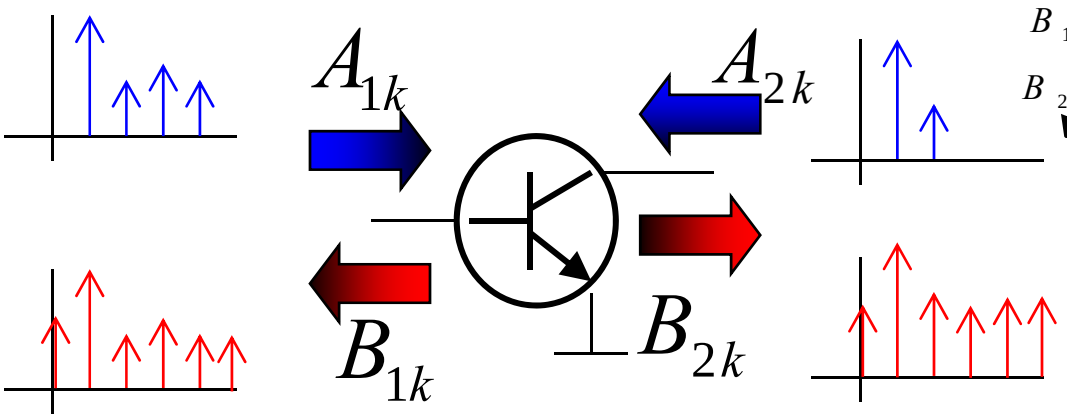
X-Parameters: Nonlinear Spectral Maps

From S-Parameters to "Harmonic Time-Domain Load-Pull"



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

Harmonic (or carrier) Index

Port Index

magnitude & cross-frequency phase

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

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

The simplest X-parameters are just linear S-parameters

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

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

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NVNA+Load-Pull = Instant Large-Signal Model

- Drag and drop measured X-parameters into ADS for immediate nonlinear circuit design based on measured X-pars

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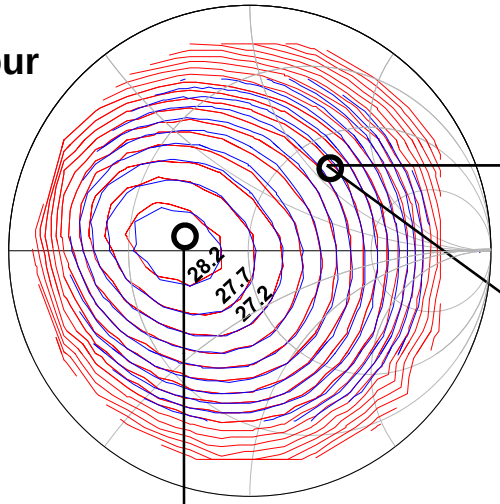
Load-Dependent X-Parameters of a FET

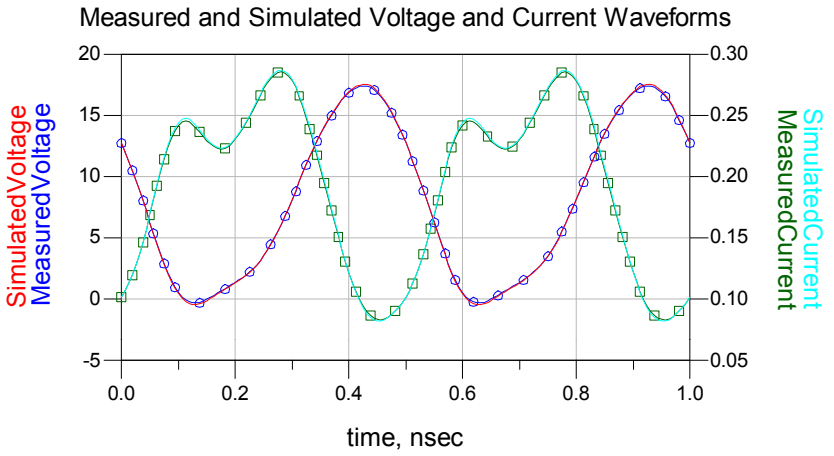
G. Simpson et al *IEEE ARFTG Conference*, December, 2008

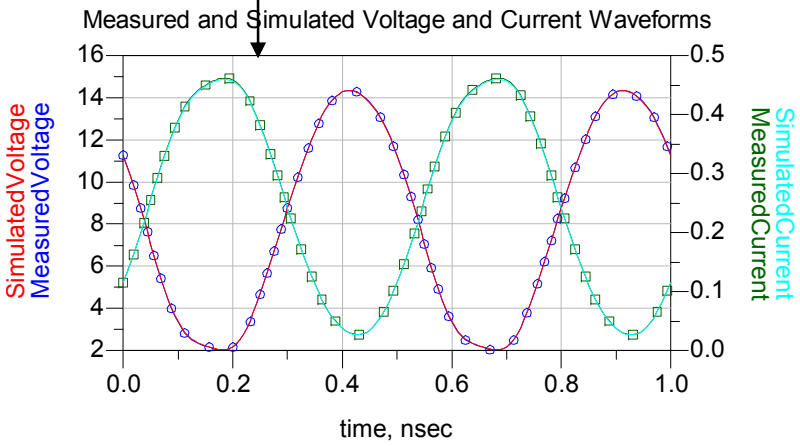
Measurements X-par Simulation

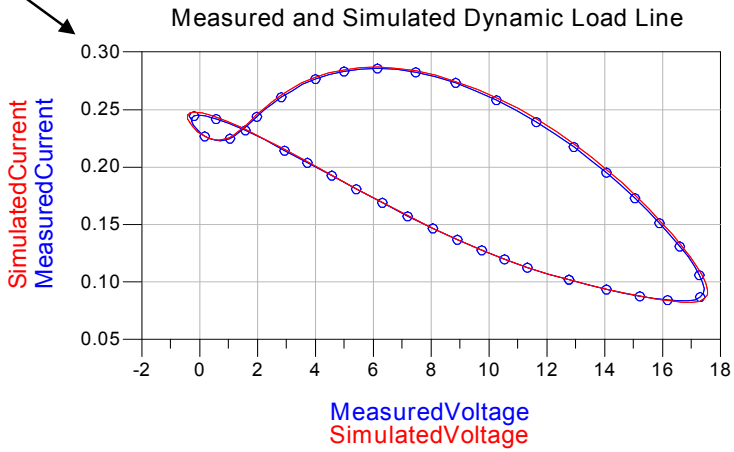
WJ FP2189 1W HFET

P_{out} Contour (dBm)









Experimental Harmonic Balance

X-parameters unify S-parameters and load-pull

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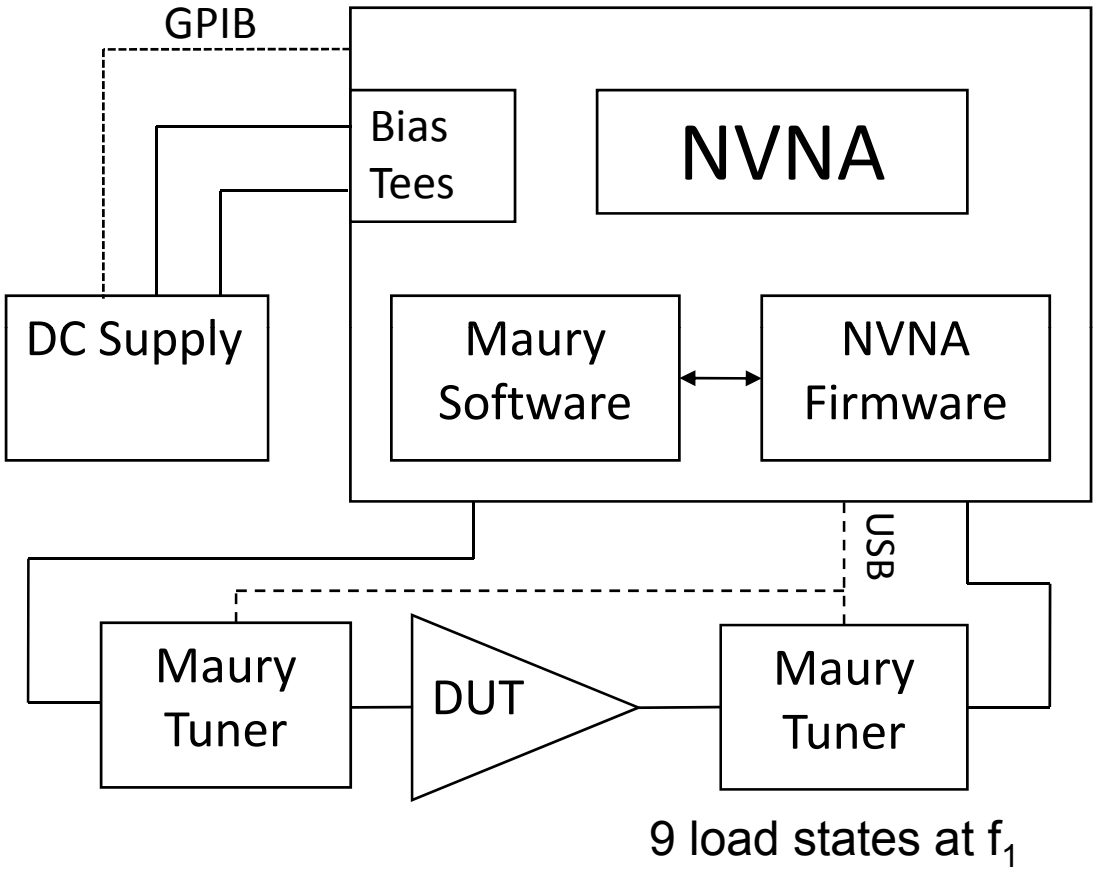
Load-Dependent X-Parameter Model for GaN HEMT:

[12] J. Horn, G. Simpson, D. E. Root
IEEE CSIC Symposium Oct. 4, 2010



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 2nd and 3rd harmonics
- harmonic impedances uncontrolled

X-parameters -> ADS for independent validation

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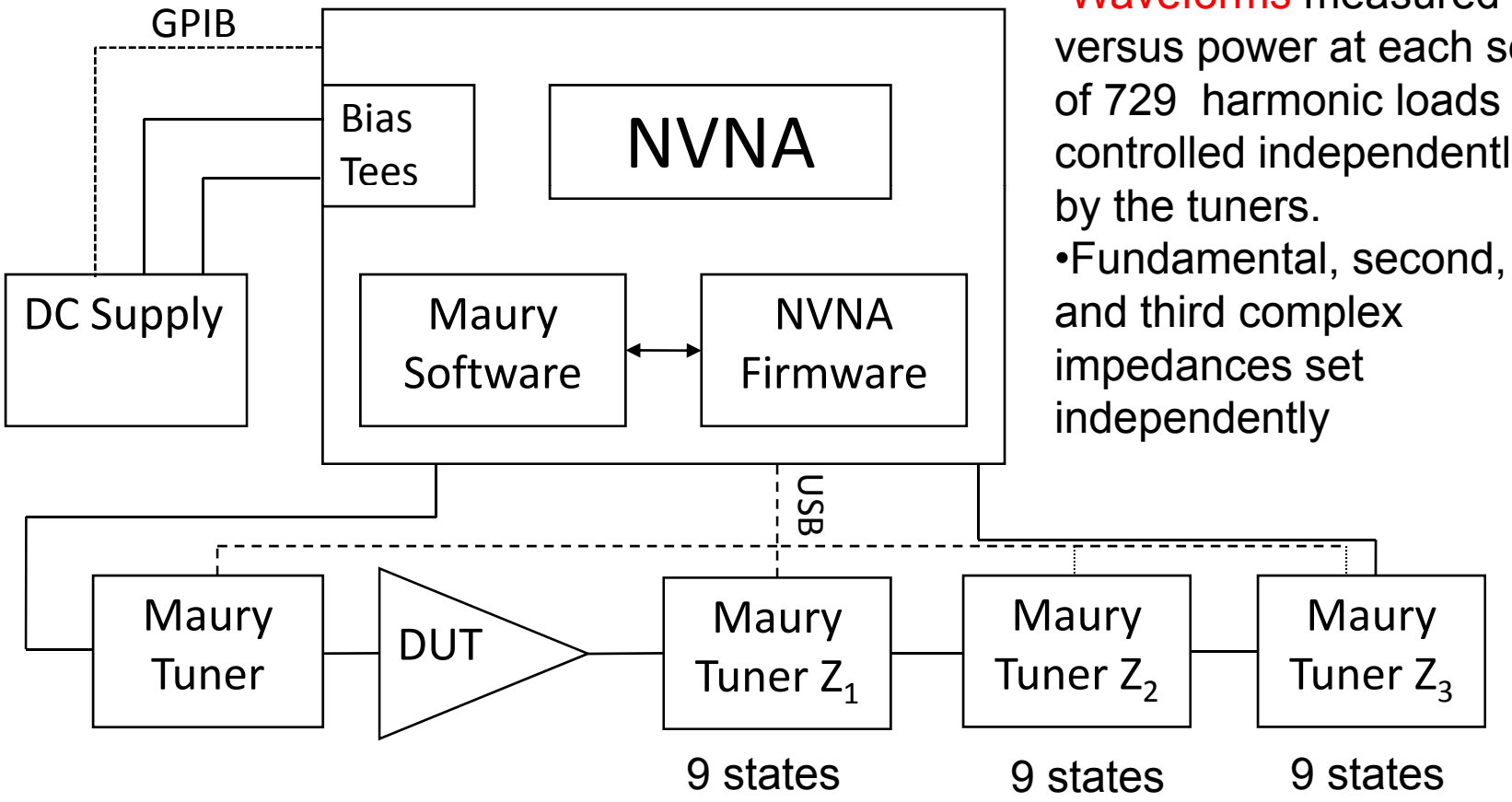
Harmonic Load-pull Setup: For Validation Only

[12] J. Horn, G. Simpson, D. E. Root *IEEE CSIC Symposium Oct. 4, 2010*



- 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

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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

ADS

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

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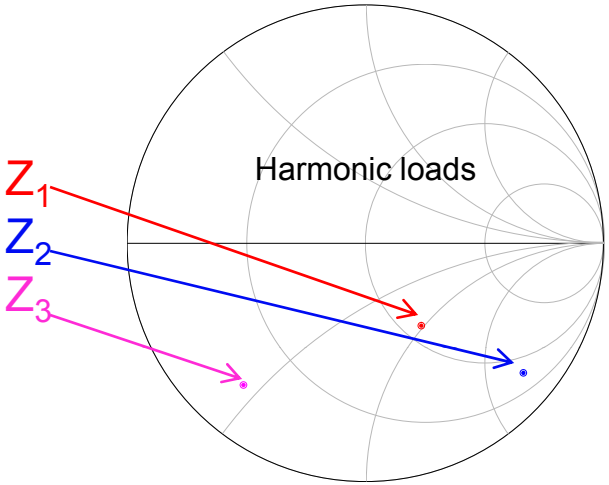
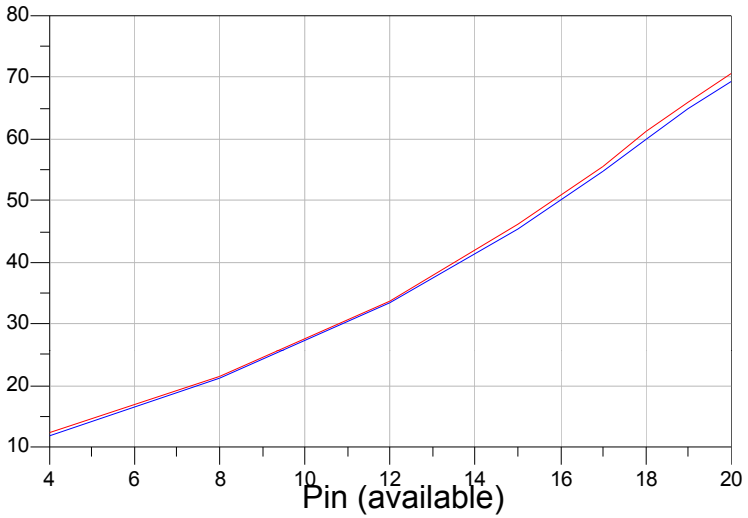
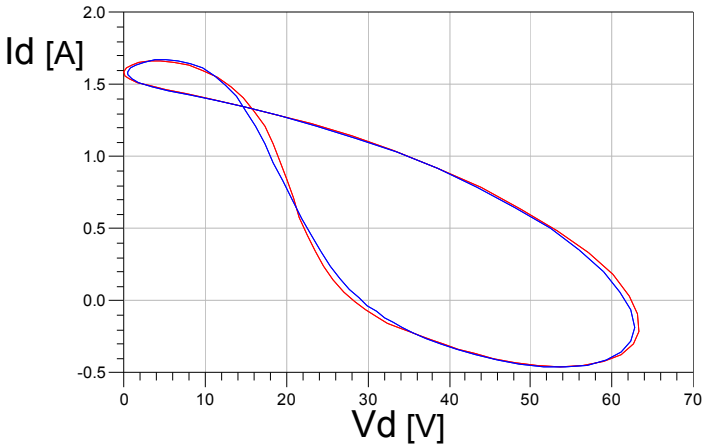
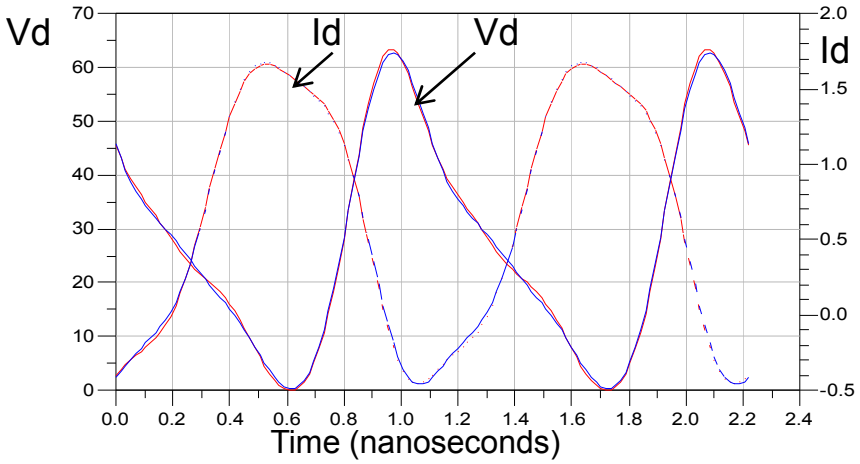
Prediction of GaN HEMT Harmonic-Load Dependence from Fundamental-Only Load-Dependent X-Parameters



Cree
CGH40010
GaN HEMT







X-parameter model

Harmonic time-domain load-pull measurements

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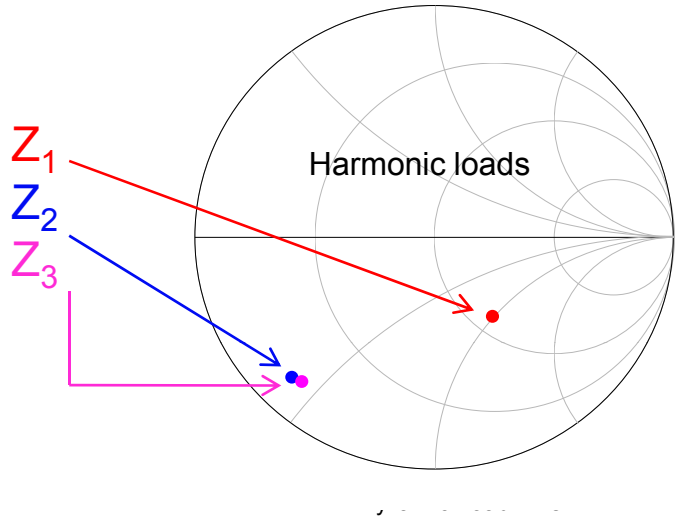
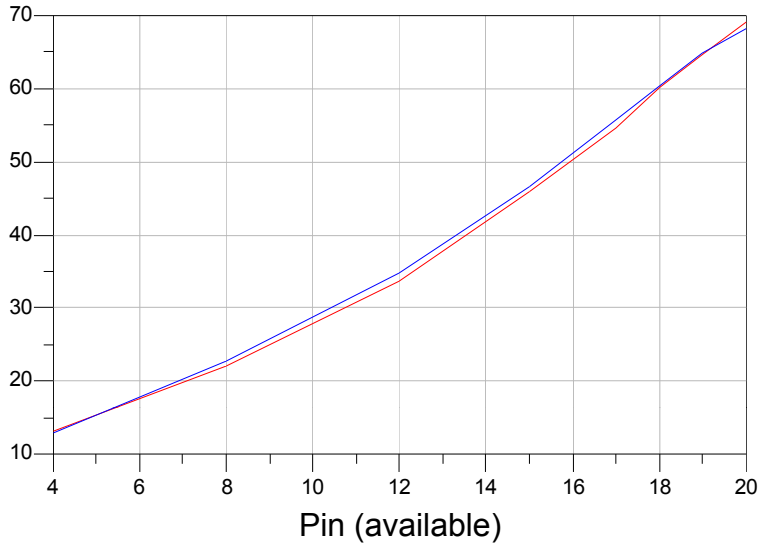
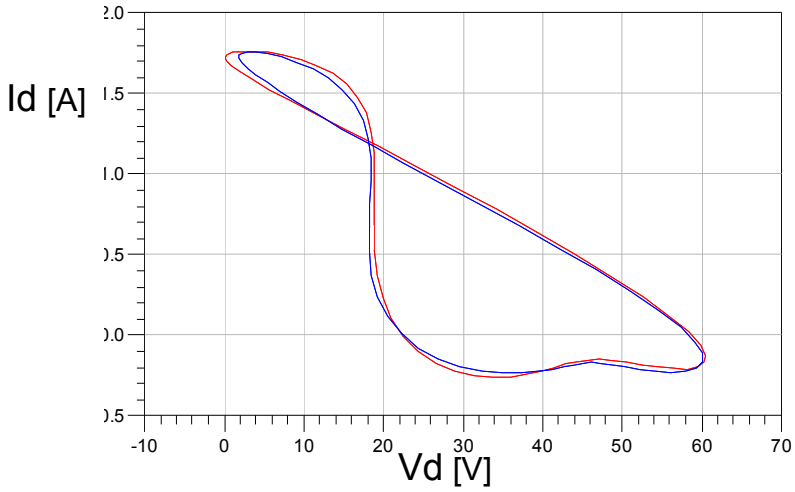
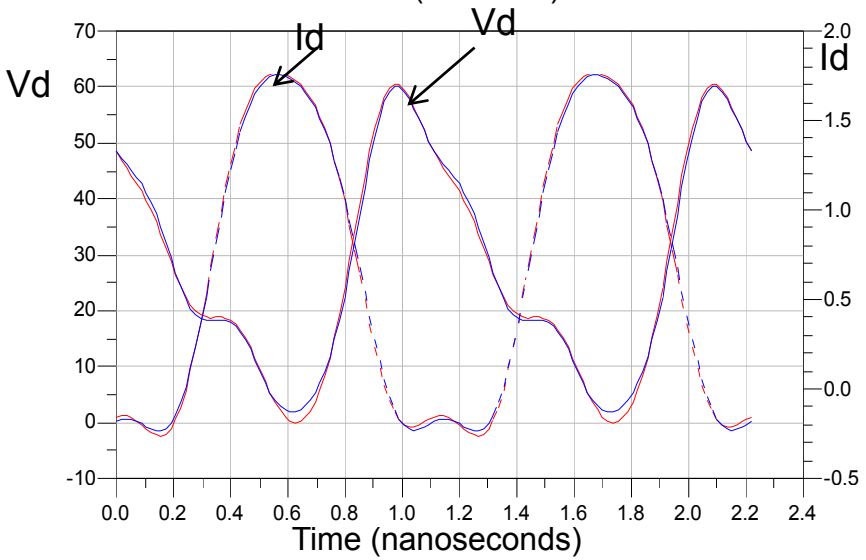
Prediction of GaN HEMT Harmonic-Load Dependence from Fundamental-Only Load-Dependent X-Parameters



Cree
CGH40010
GaN HEMT







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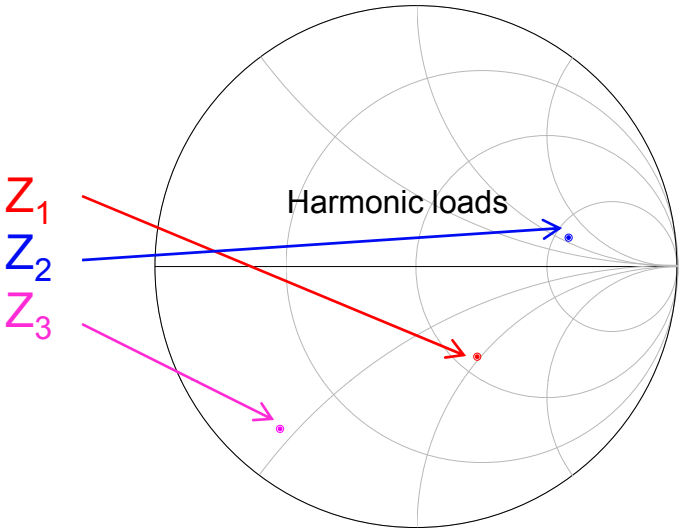
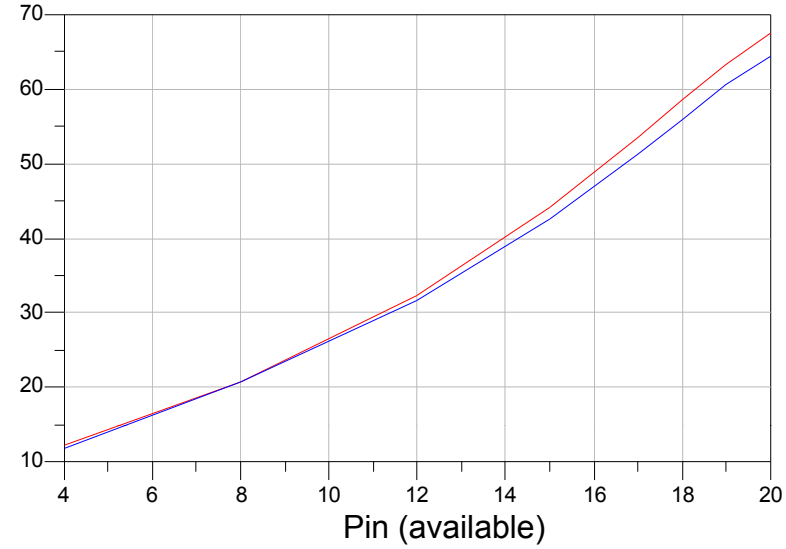
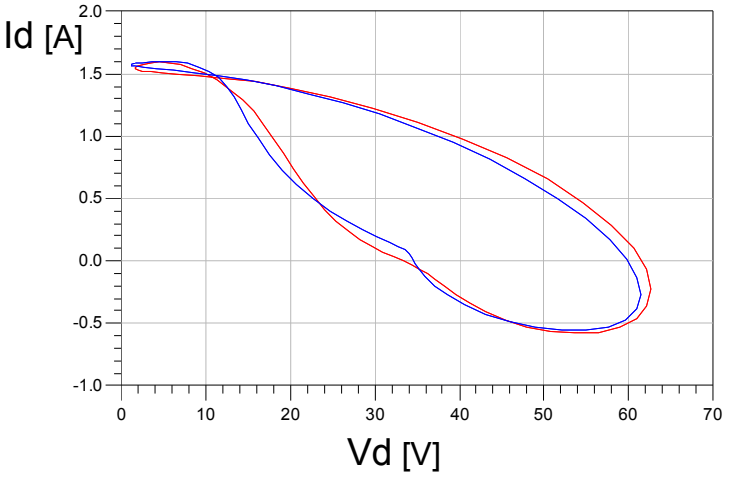
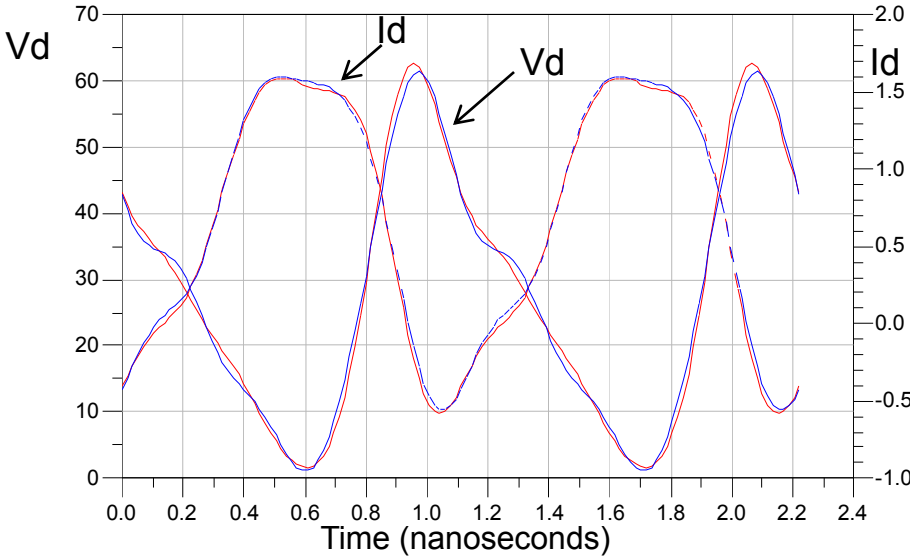
Prediction of GaN HEMT *harmonic-load dependence* from fundamental-only load-dependent X-pars



Cree
CGH40010
GaN HEMT







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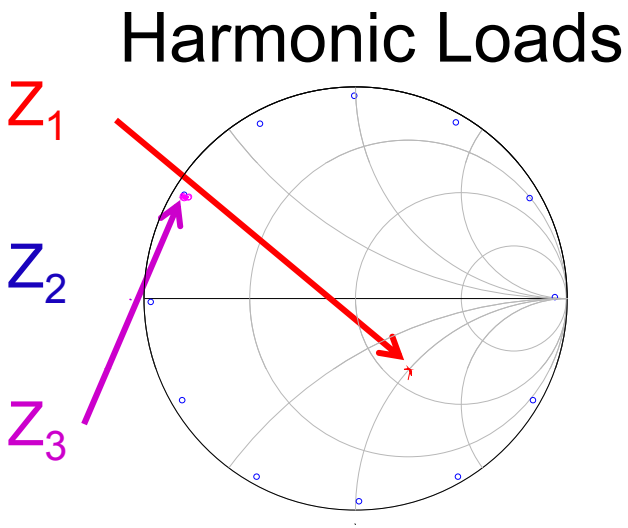
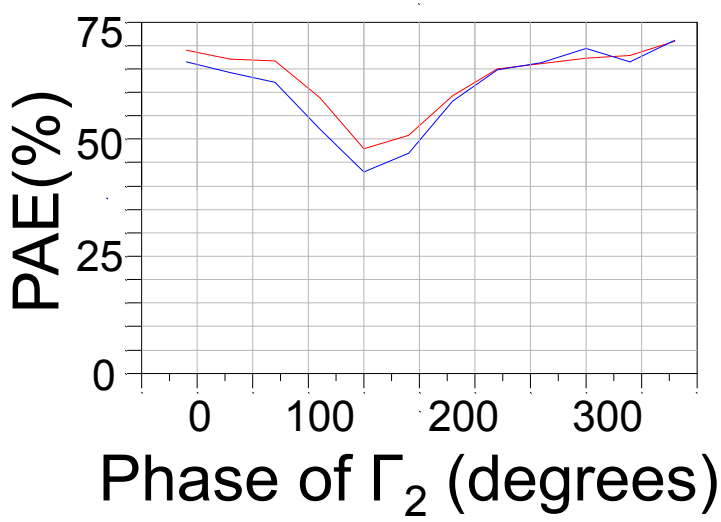
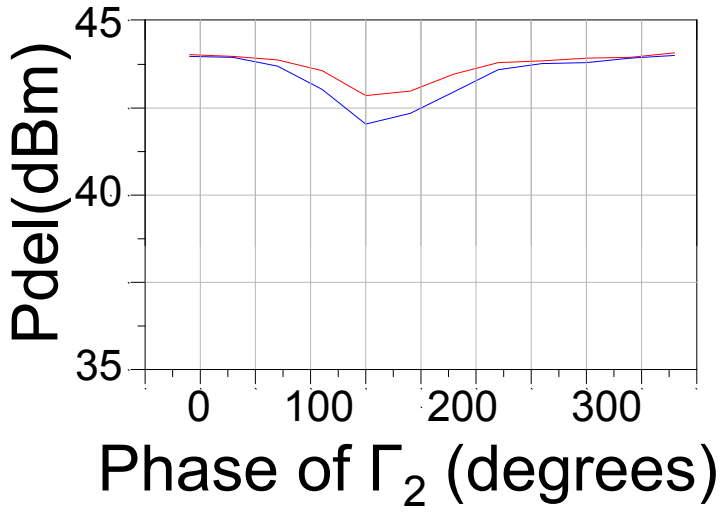
10W GaN Device Model

Comparison







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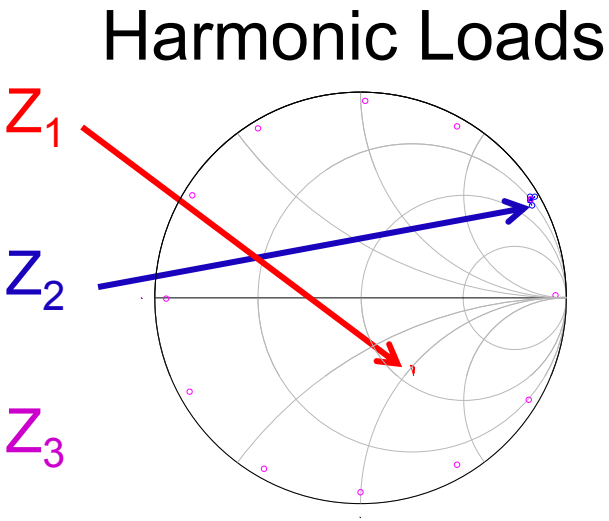
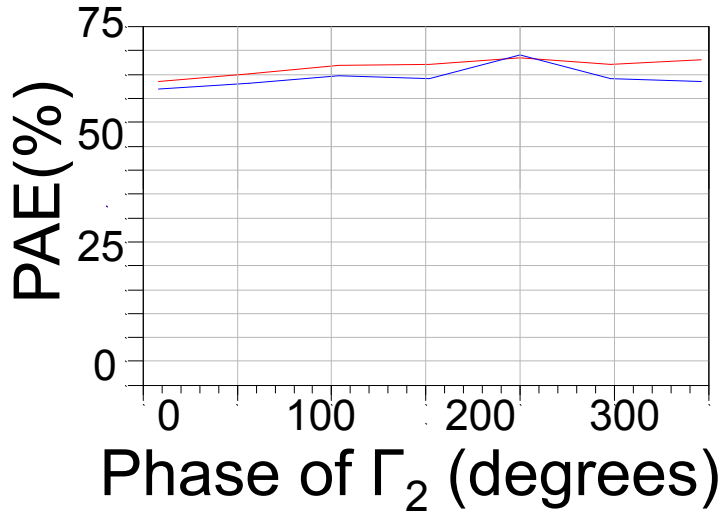
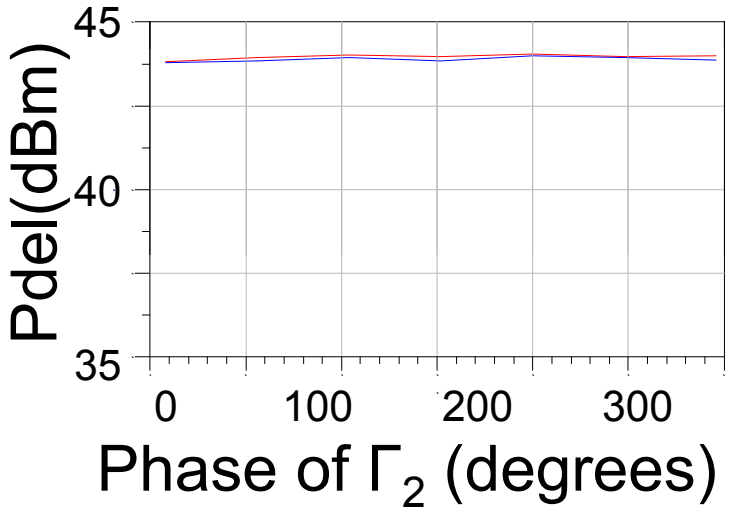
10W GaN Device Model

Comparison







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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, Dougherty amps.
  - Accurate model of GaN device demonstrated
- Large reduction of data / time compared to harmonic load-pull
- Harmonic load-pull may be unnecessary
  - Source-pull unnecessary (see [12]) except for power transfer

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Comparison of approaches presented here

Approach	Advantages	Disadvantages
Compact Device model	• Works in all simulation modes (TA, HB, CE) • More scalable • Simple statistics • Noise models; dynamic self-heating common • What-if scenarios possible	• Development time long • Extraction difficult • Technology-dependent
X-parameter Device model	• Technology independent • Extremely accurate within characterization range • Complete IP protection • Works for packaged parts • Automated extraction • Often converge better than compact models in circuits	• Limited by NVNA BW • Large file size, especially for multi-tone models • Limited memory effects in products (but demonstrated in [15])

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Conclusions

- NVNA is a powerful, valuable tool for device modeling
  1. NVNA data ("HB data") can be used to validate, tune, extract optimal parameters, explore compact model limitations & suggest improvements
  2. NVNA data can be used to identify complicated constitutive relations for advanced compact models - *not possible using conventional data*.
  3. Load-dependent X-parameters, measured on an NVNA, is a powerful, efficient, and accurate way to model important, new devices for PA and circuit design. Complementary approach to compact modeling.
- Compact models & X-parameters compared for device modeling applications
- *Every* nonlinear modeling station should use an NVNA instead of a conventional linear VNA.

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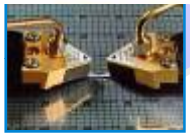
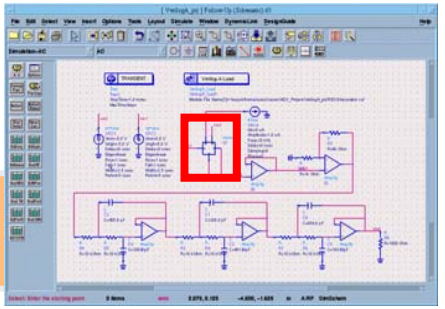
NVNA, ANNs, and X-parameters fill in nonlinear puzzle

Agilent Nonlinear Vector Network Analyzer



Electronic design automation software

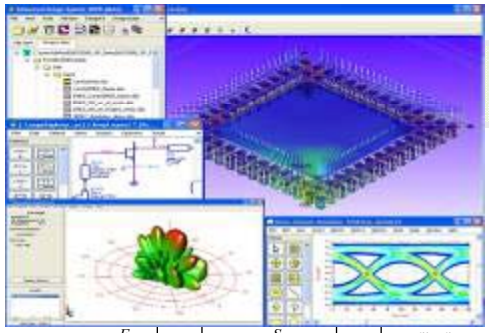


Nonlinear Measurements

Nonlinear Simulation & Design

Nonlinear Modeling

Customer Applications



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

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