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

D. E. Root, J. Horn, J. Xu, M. Iwamoto, F. Sischka, and Y. Yanagimoto

Agilent Technologies Inc.

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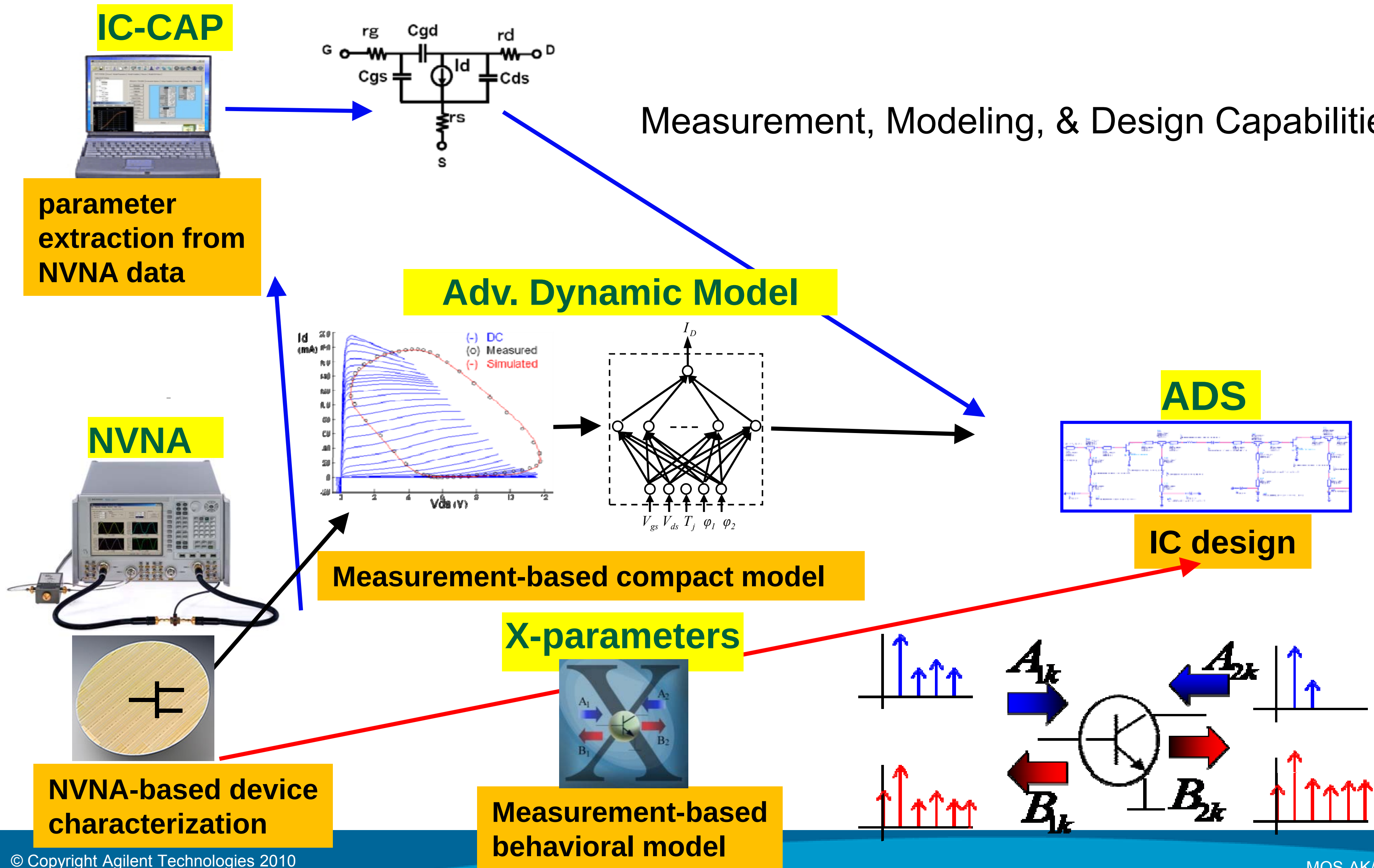
San Francisco, CA
December 8, 2010

Three Modeling Flows based on Nonlinear Data



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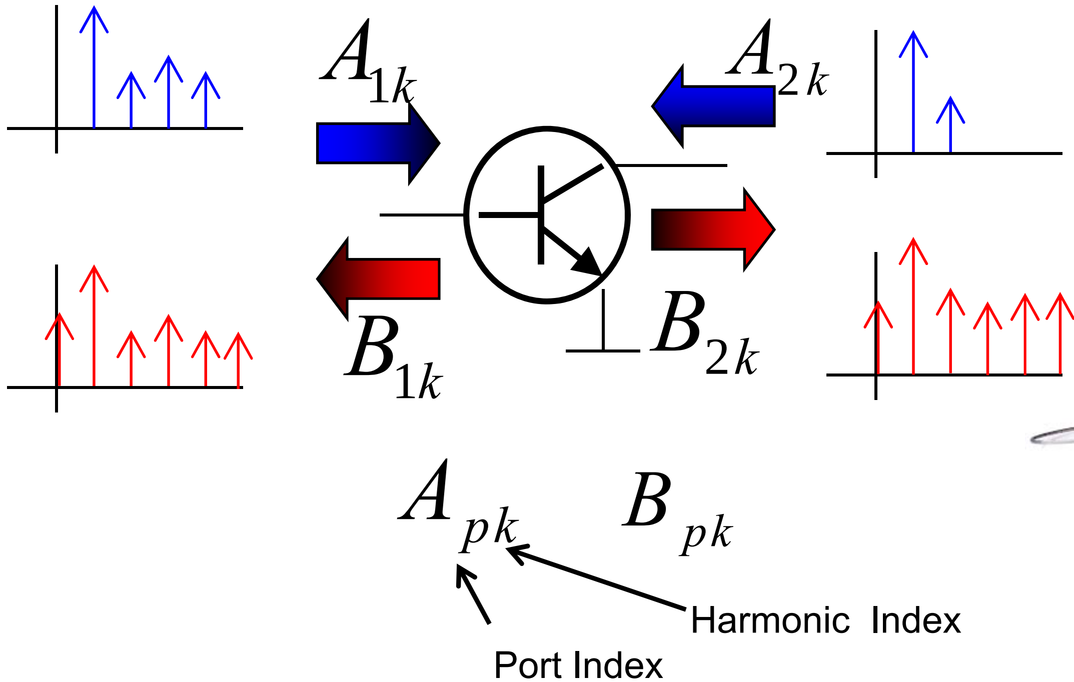
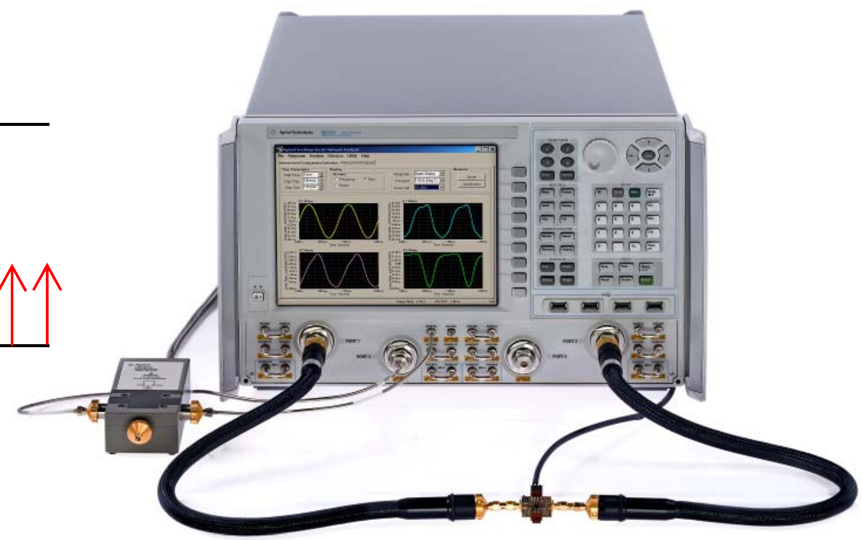
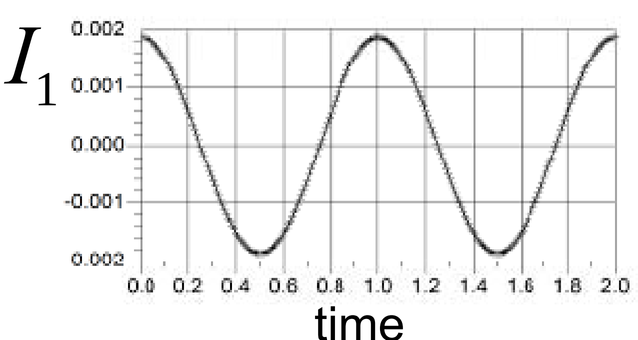
Outline

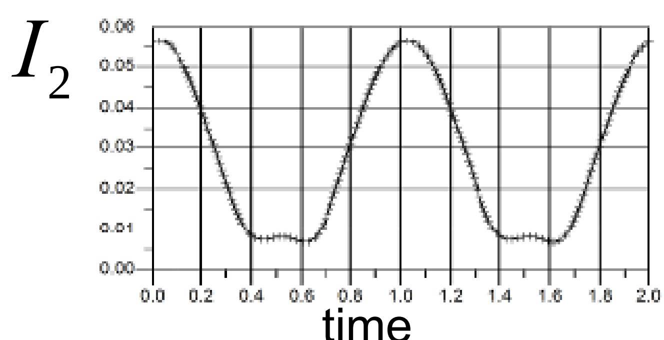
- Introduction:
  NVNA Measurements – complex spectra & waveforms
- Compact Models
  Compact model validation and parameter extraction
  GaAs transistor model identification and validation
- Load-dependent X-parameter model of packaged GaN transistor & validation with harmonic load-pull
- Discussion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

Introduction: NVNA measurements complex spectra and waveforms [1]









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

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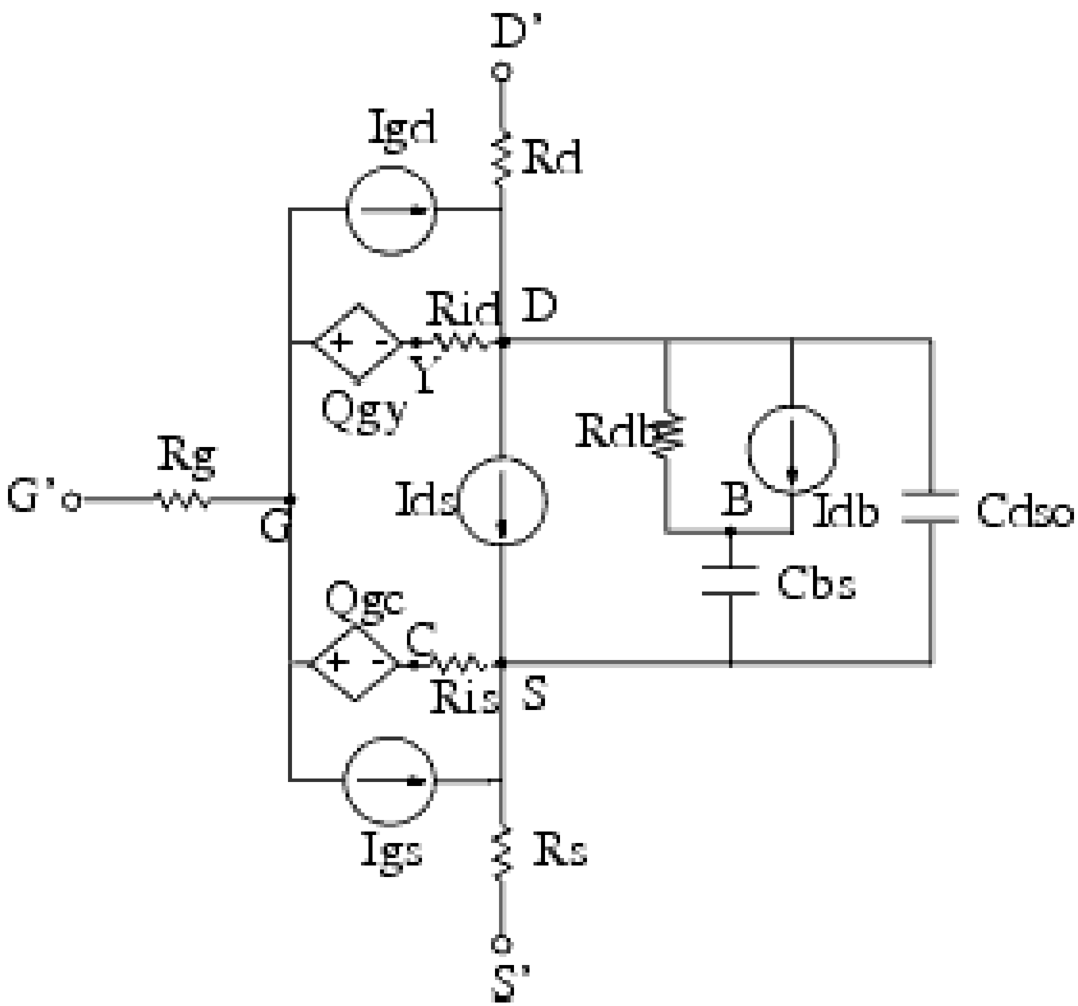
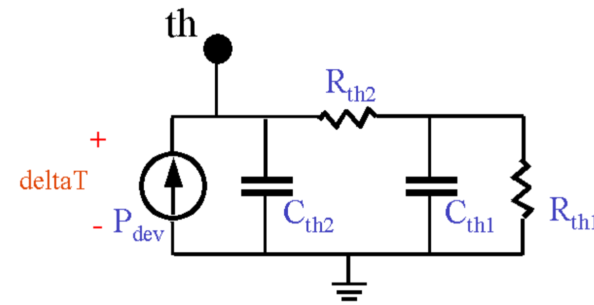
Compact Transistor Models: *time domain*





Thermal Subcircuit (Two-Poles)

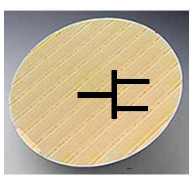
Standard GaAs FET Model

Model: Coupled nonlinear ordinary differential equations

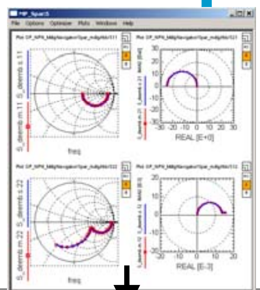
Conventional Empirical Device Modeling Flow

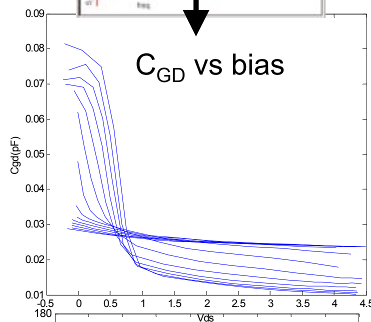
VNA

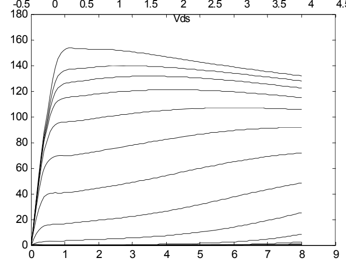
Parameter Analyzer



NVNA-based device characterization

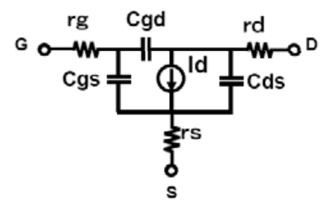






DC + S-parameter (or C-V data)

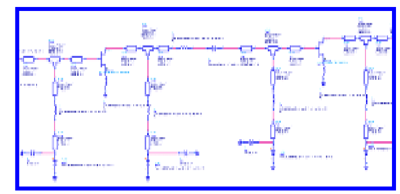
IC-CAP



Your Compact Model Here

Parameter extraction for std. compact model

ADS



Does it actually work in NL?

Circuit design

Issues with compact device models

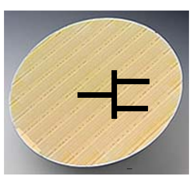
- Parameters typically extracted from DC and *linear* S-pars
  Ironic for a *nonlinear* model
  - Some devices may not be able to be characterized under DC and static operating conditions (power, temperature)
  - Advanced measurement-based models may not be identifiable from only DC and S-parameter data.
  - 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

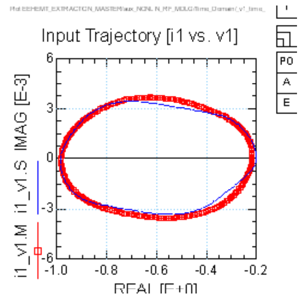
Nonlinear Modeling Flow with NVNA data (1)

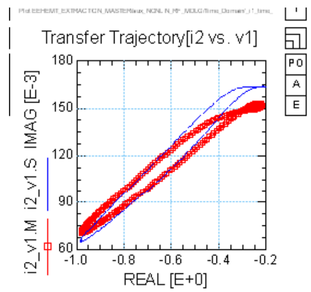
NVNA

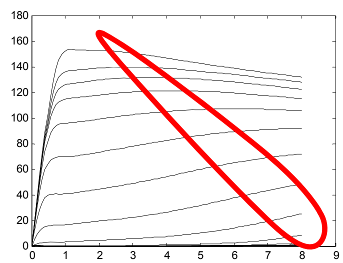
Sync. Bias Supply



NVNA-based device characterization

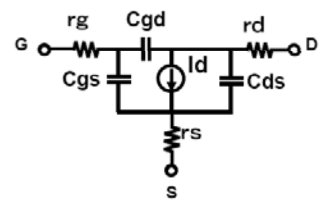






Dynamic Load-line Waveform meas.
DC-IV, S-pars

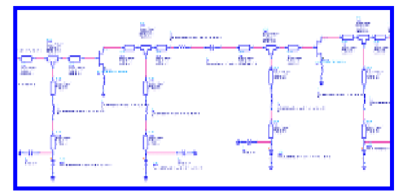
IC-CAP



Your Compact Model Here

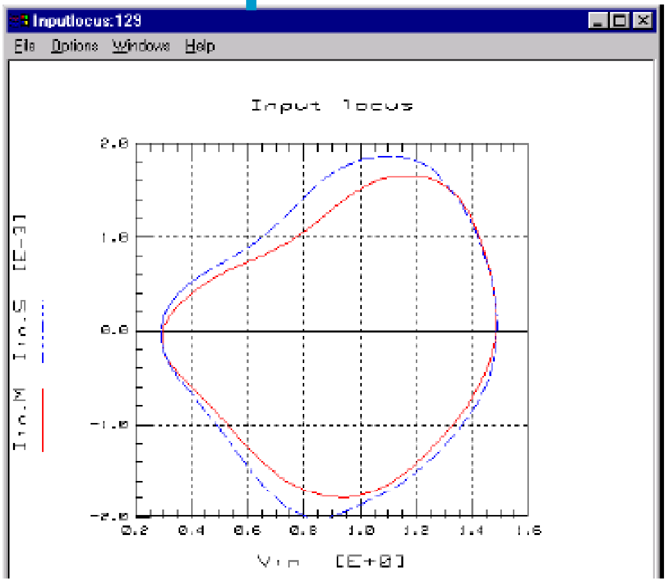
Parameter extraction for std. compact model using NVNA data as target

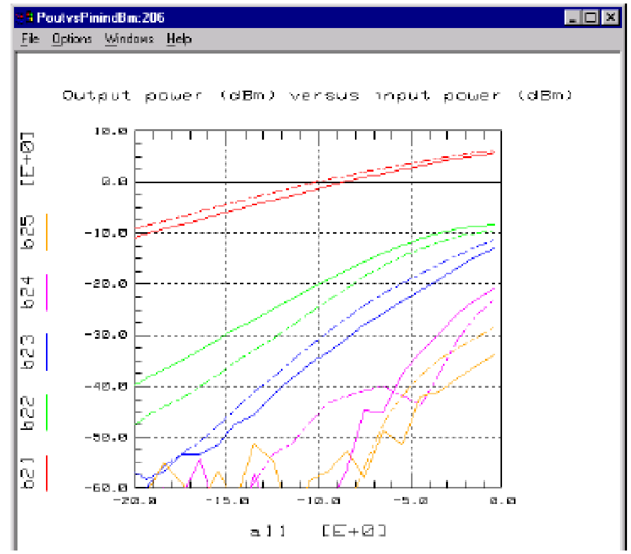
ADS



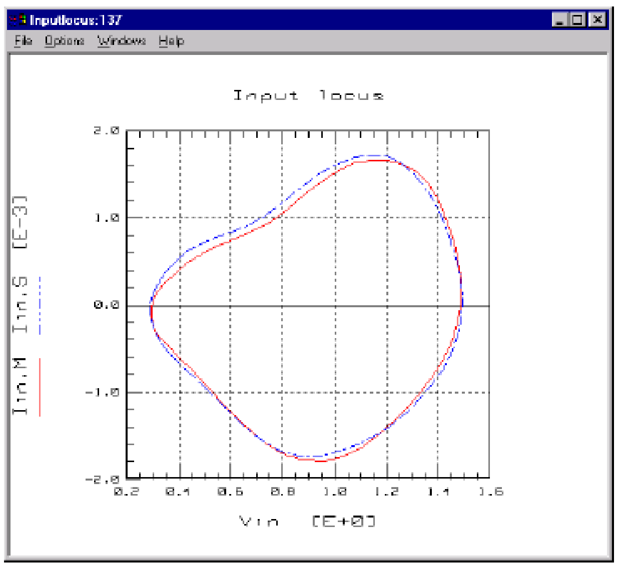
Circuit design

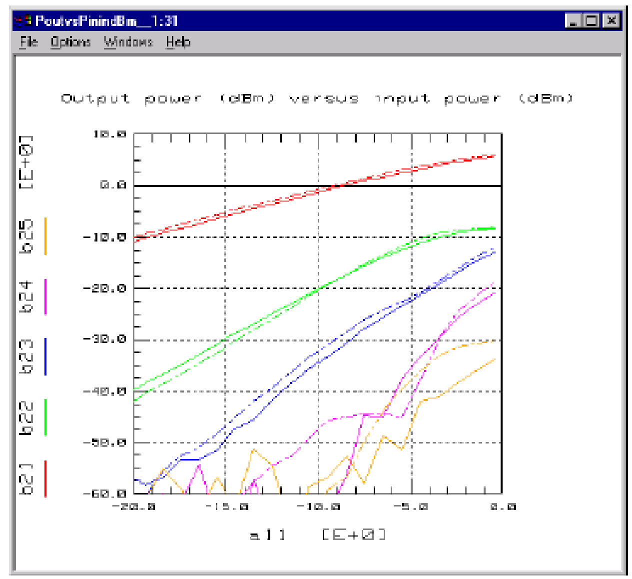
Model parameter extraction from Nonlinear Data (1)





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





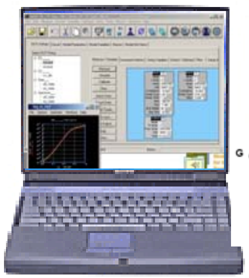
Modify parameter values (optimize) to *better fit* large-signal NVNA data

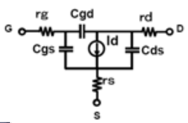
- Get optimal parameter set for given model
- trade-off DC, SP, for nonlinear performance
- App-dependent tuning
- Explore model limits

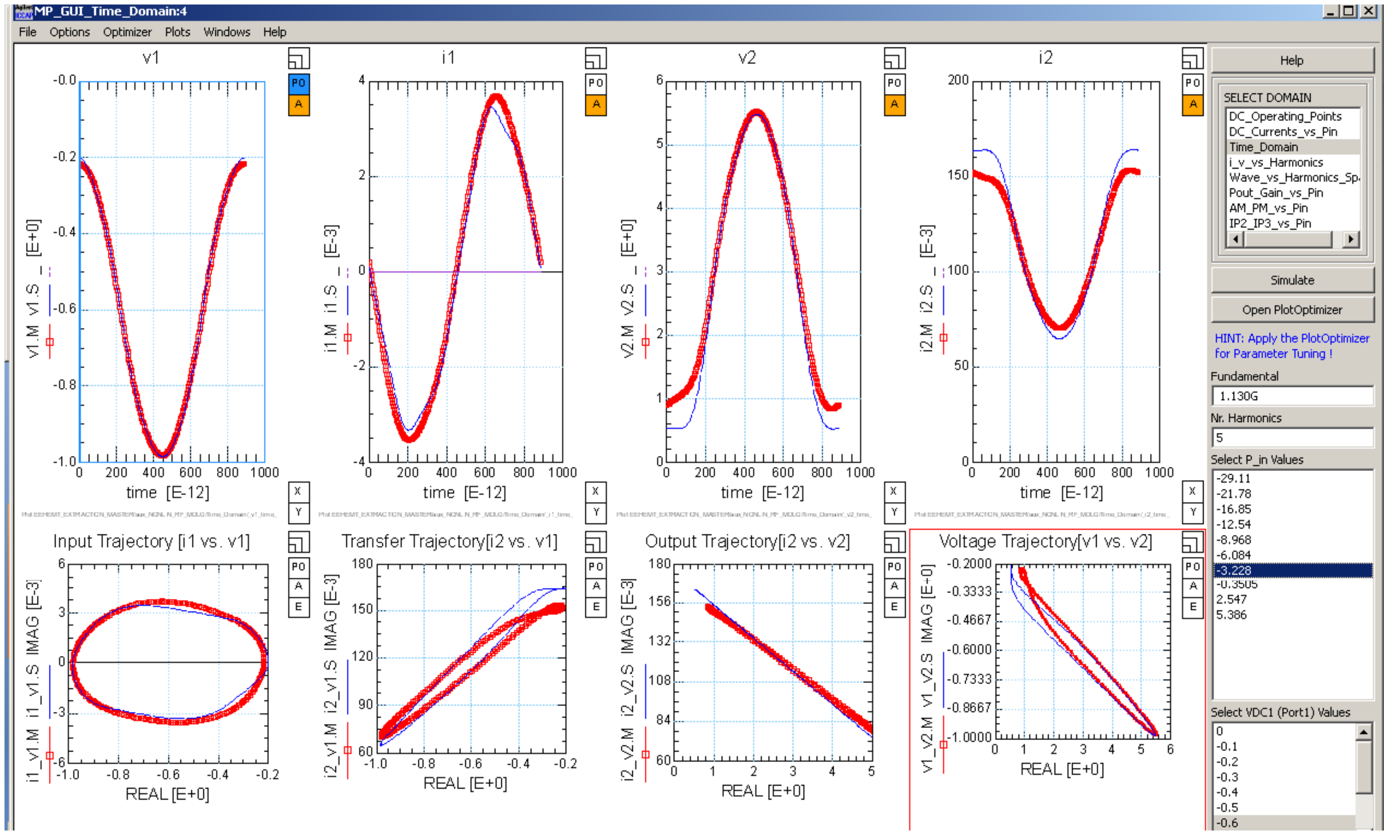
Mixdes 2002

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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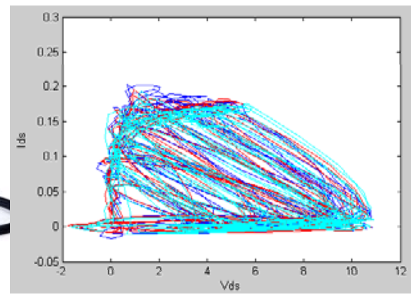
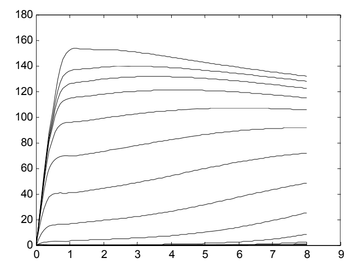
Nonlinear Modeling Flow with NVNA data (2)

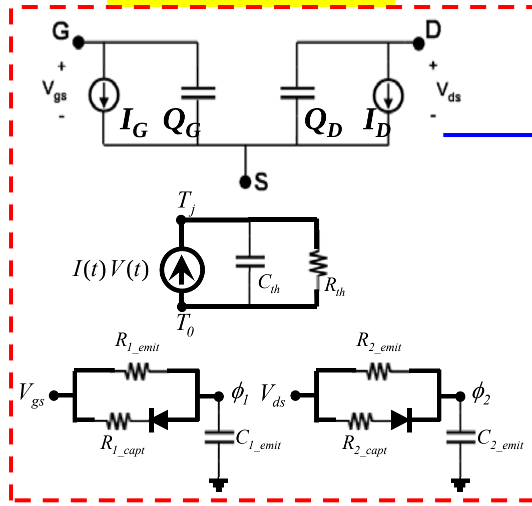
[4] J. Xu, M. Iwamoto, J. Horn, D. E. Root, *IEEE MTT-S International Microwave Symposium Digest,* May, 2010.

NVNA

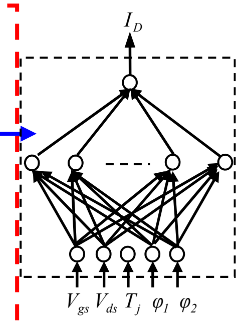




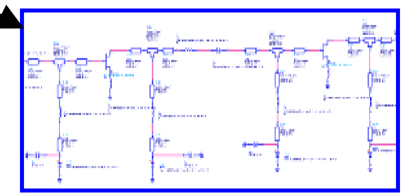
Advanced Non-parametric Dynamic Model

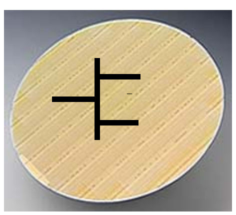


ANN



ADS





NVNA-based device characterization

Dynamic Load-line Waveform meas.
DC + Spars

Direct construction of complicated constitutive relations
Not really parameter extraction!

Circuit design

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

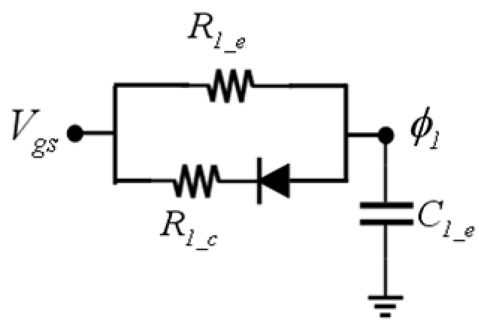
e.g., the instantaneous intrinsic terminal voltages and fast capture processes.

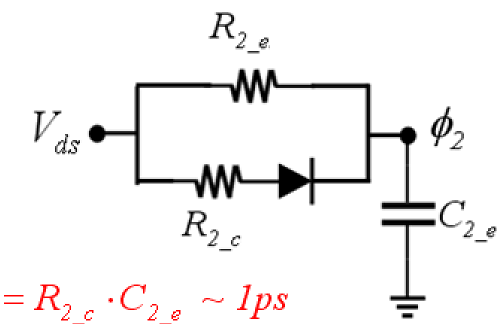
Model Formulation

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

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

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

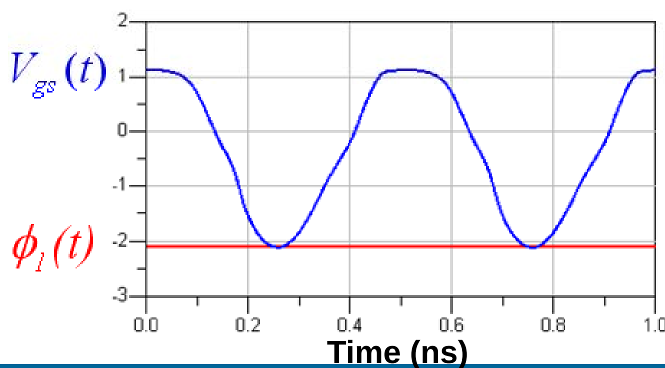


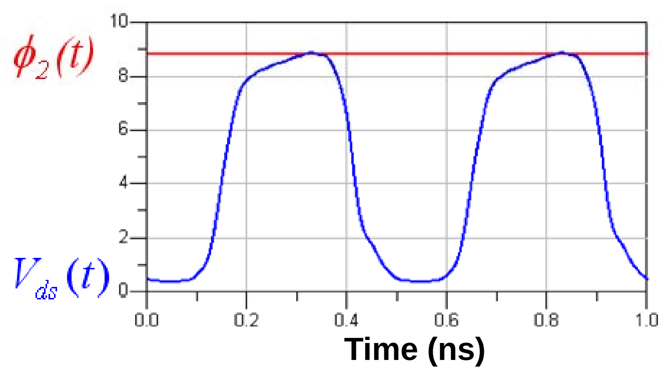


Capture Time Constant $= R_{2\_c} \cdot C_{2\_e} \sim 1ps$

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

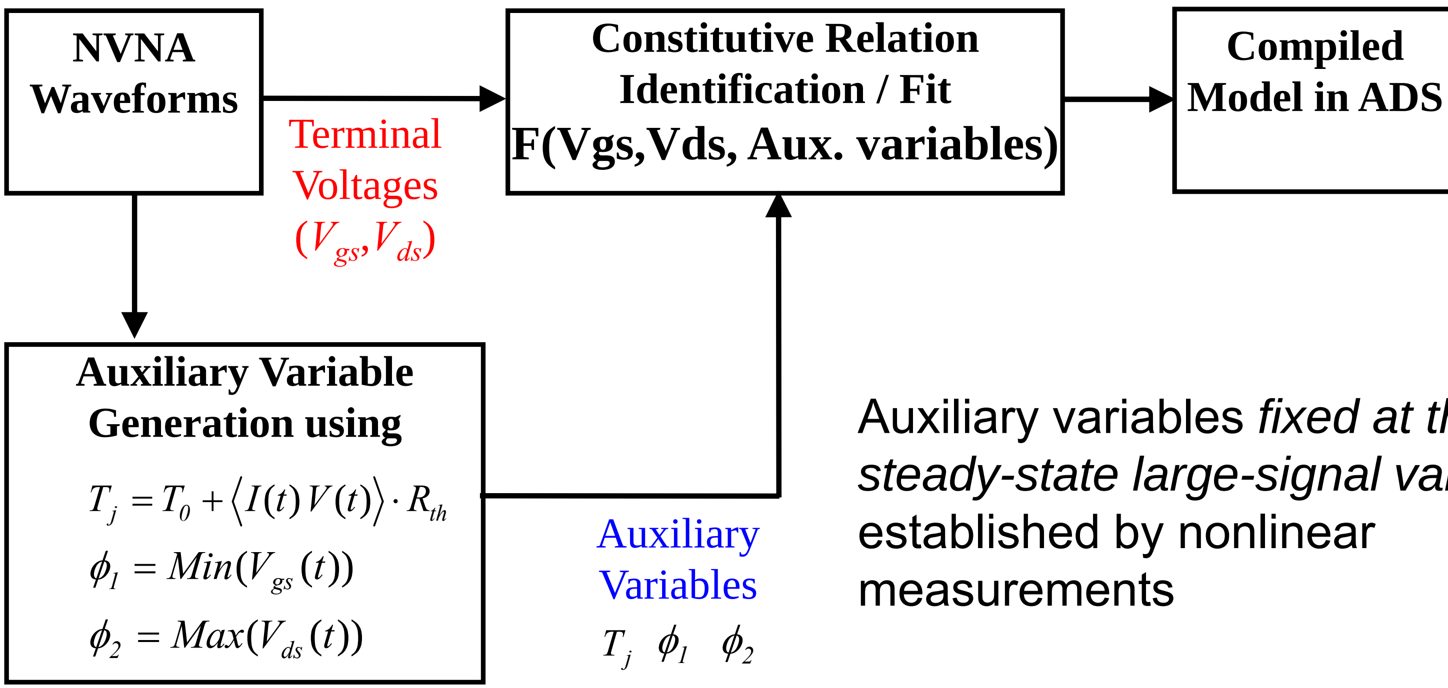
O. Jardel et al, *IEEE Trans. MTT.*, vol. 55, 2007.





NVNA data for identification of constitutive relations

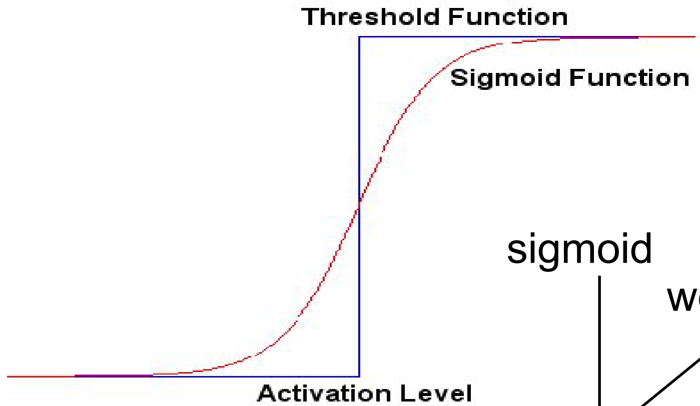
$$I_{drain}(t) = I_D(\underbrace{V_{gs}(t), V_{ds}(t)}_{\text{Terminal Voltages}}, \underbrace{T_j(t), \phi_1(t), \phi_2(t)}_{\text{Auxiliary Variables}}) + \frac{d}{dt} Q_D(\underbrace{V_{gs}(t), V_{ds}(t)}_{\text{Terminal Voltages}}, \underbrace{T_j(t), \phi_1(t), \phi_2(t)}_{\text{Auxiliary Variables}})$$



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

Artificial Neural Networks (ANN)

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

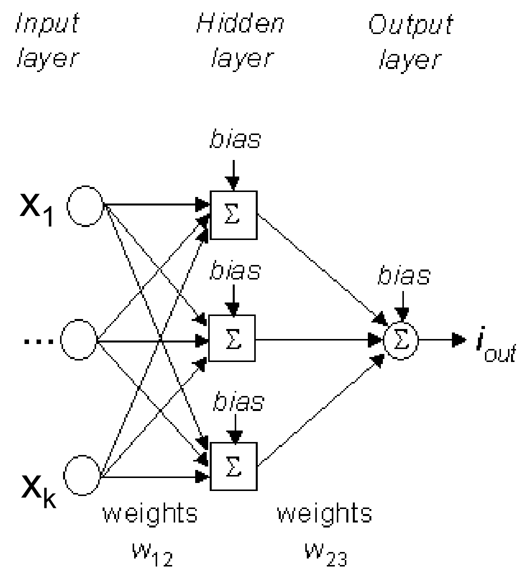


sigmoid

weights

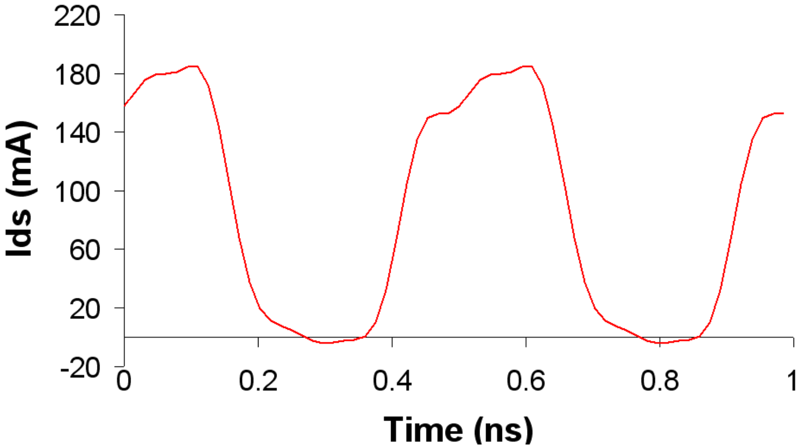
biases

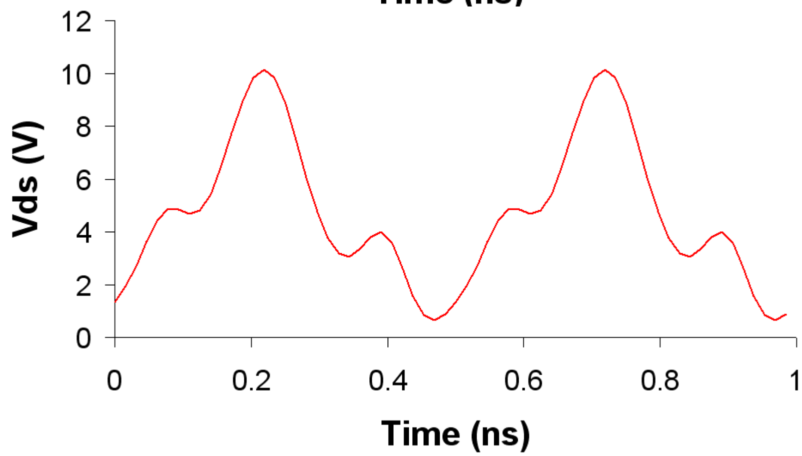
$$F(x_1,\ldots,x_K) = \sum_{i=1}^{I} v_i s\left(\sum_{k=1}^{K} w_{ki} x_k + a_i\right) + b$$



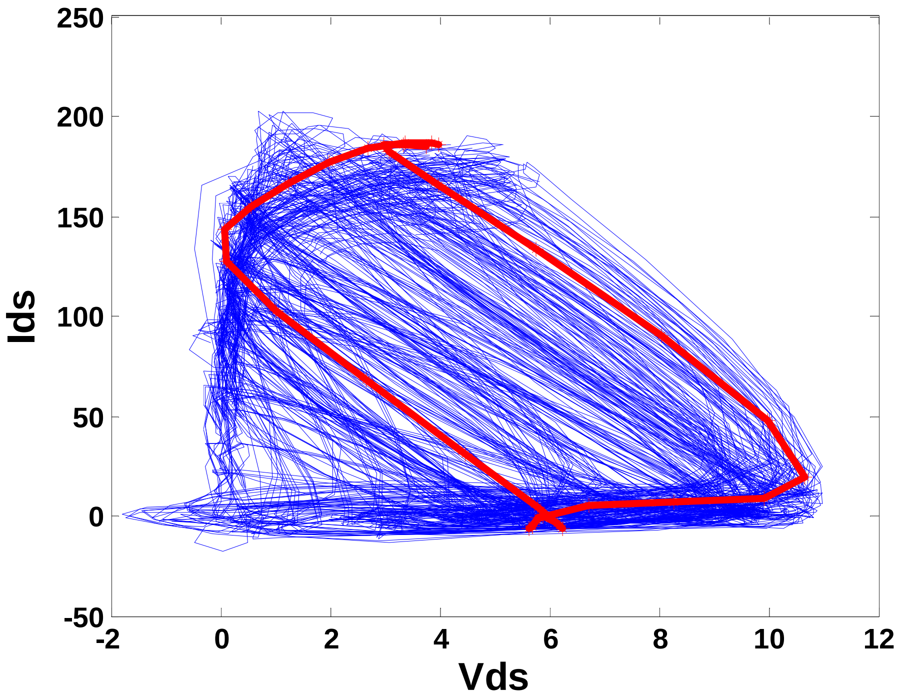
- Universal Approximation Theorem: Fit “any” nonlinear function of any # of variables
- Infinitely differentiable: good for distortion.
- Easy to train (fit) with appropriate SW
- Works well on non-gridded data and data with irregular boundaries (intrinsic FET)

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



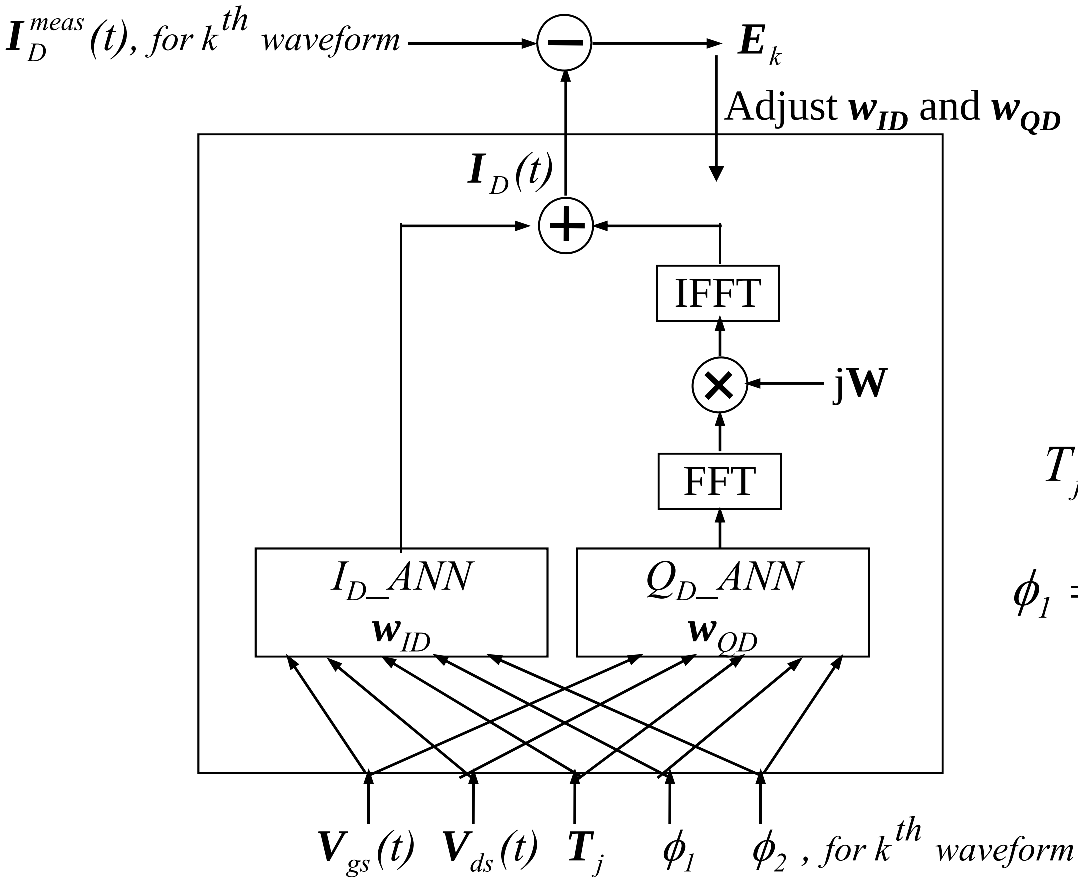


Dynamic Load-lines



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

Artificial Neural Network Training Procedure



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

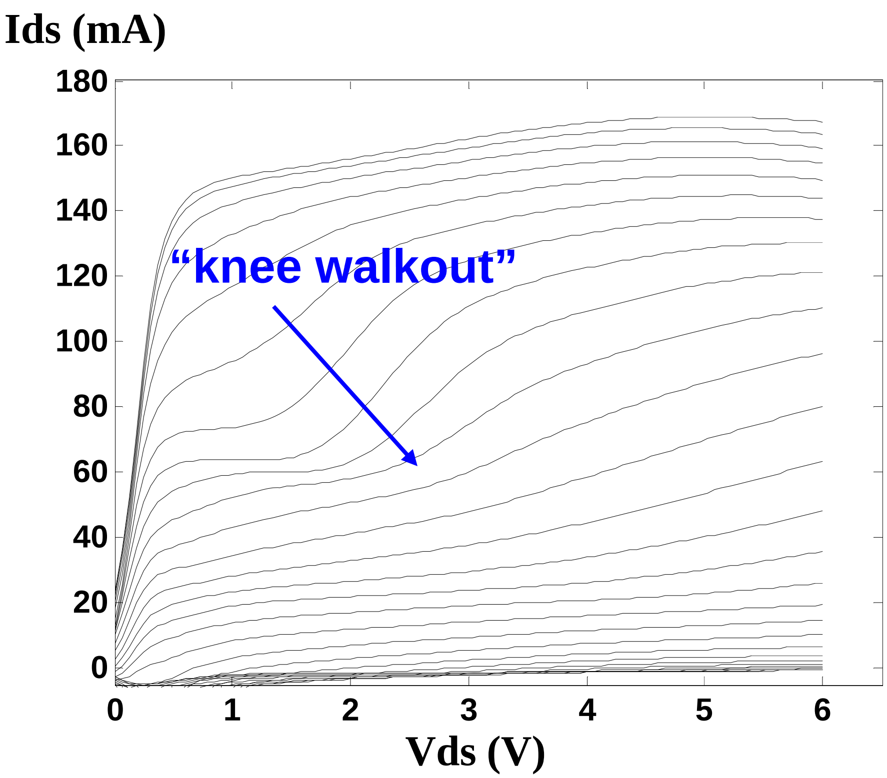
$$\phi_1 = Min(V_{gs}(t))\,,\,\phi_2 = Max(V_{ds}(t))$$

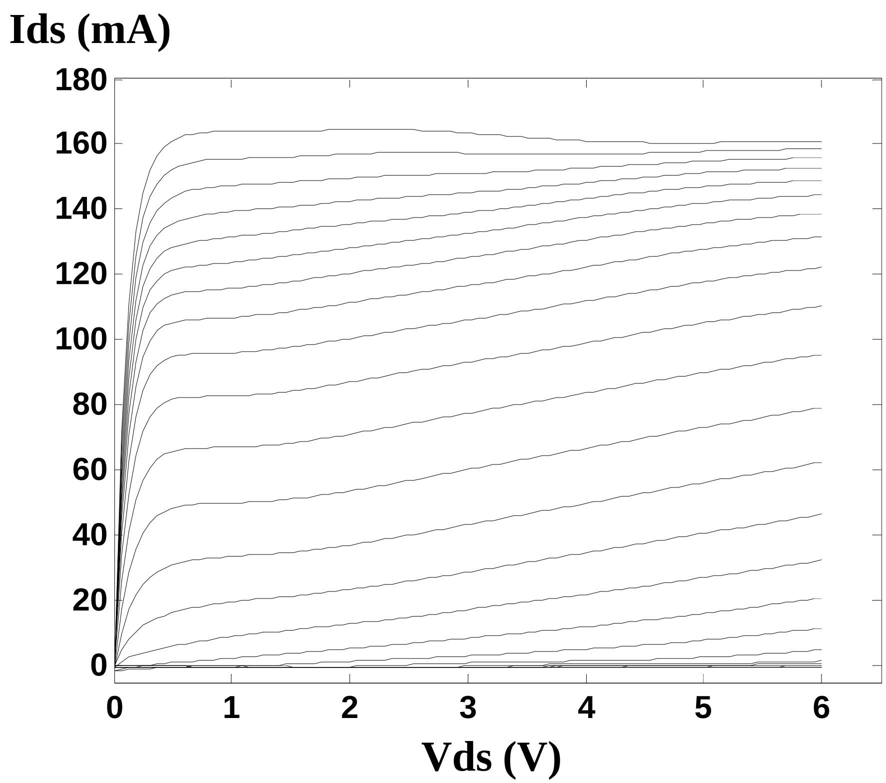
$$I_{drain}(t) = I_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t)) + \frac{d}{dt} Q_D(V_{gs}(t), V_{ds}(t), T_j(t), \phi_1(t), \phi_2(t))$$

Intrinsic Model Characteristics

I_D @ two different trap state values

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





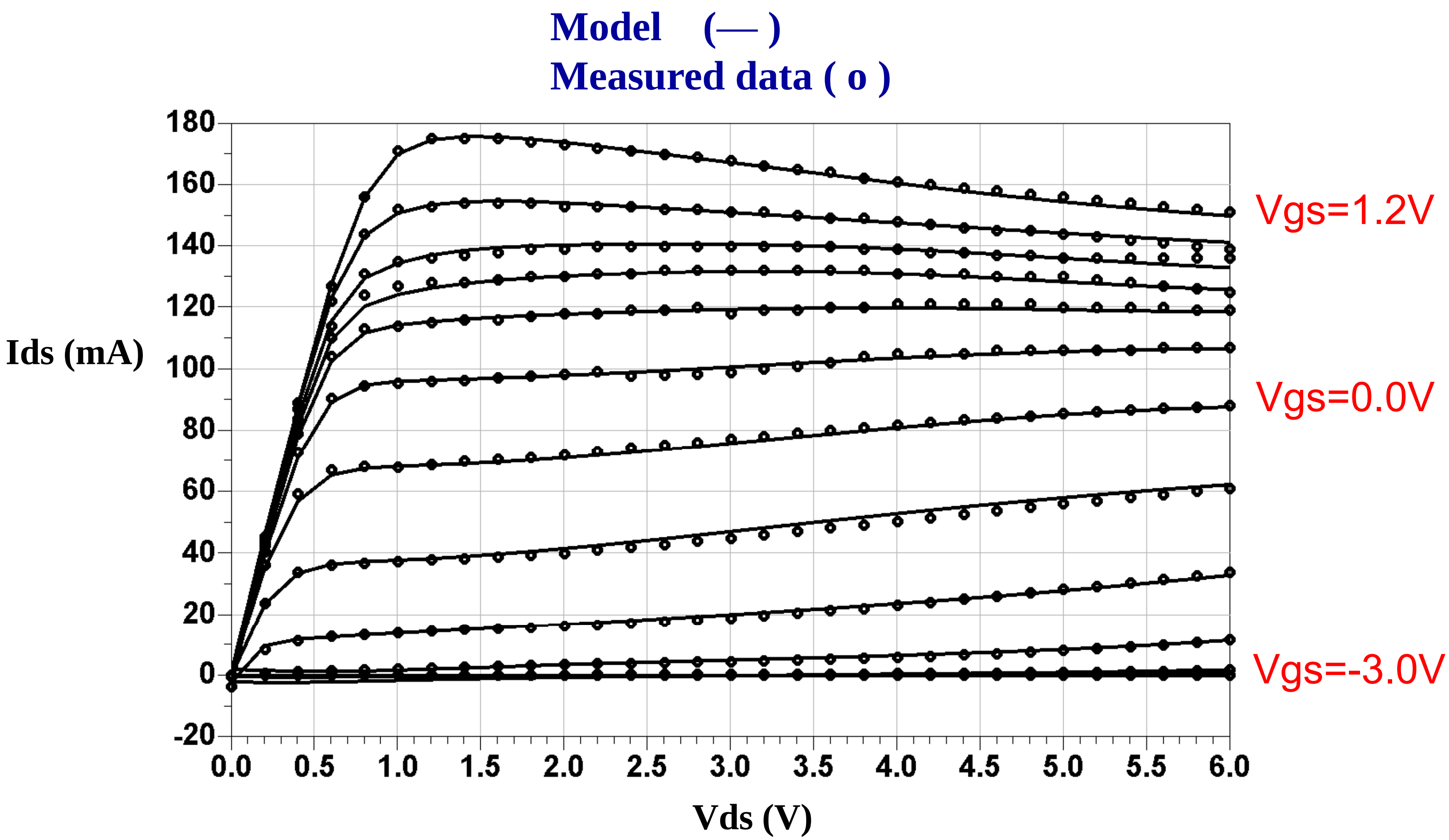
fixed T_j and fixed trap state = [-2.0, 8.0]

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

Isothermal DC

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

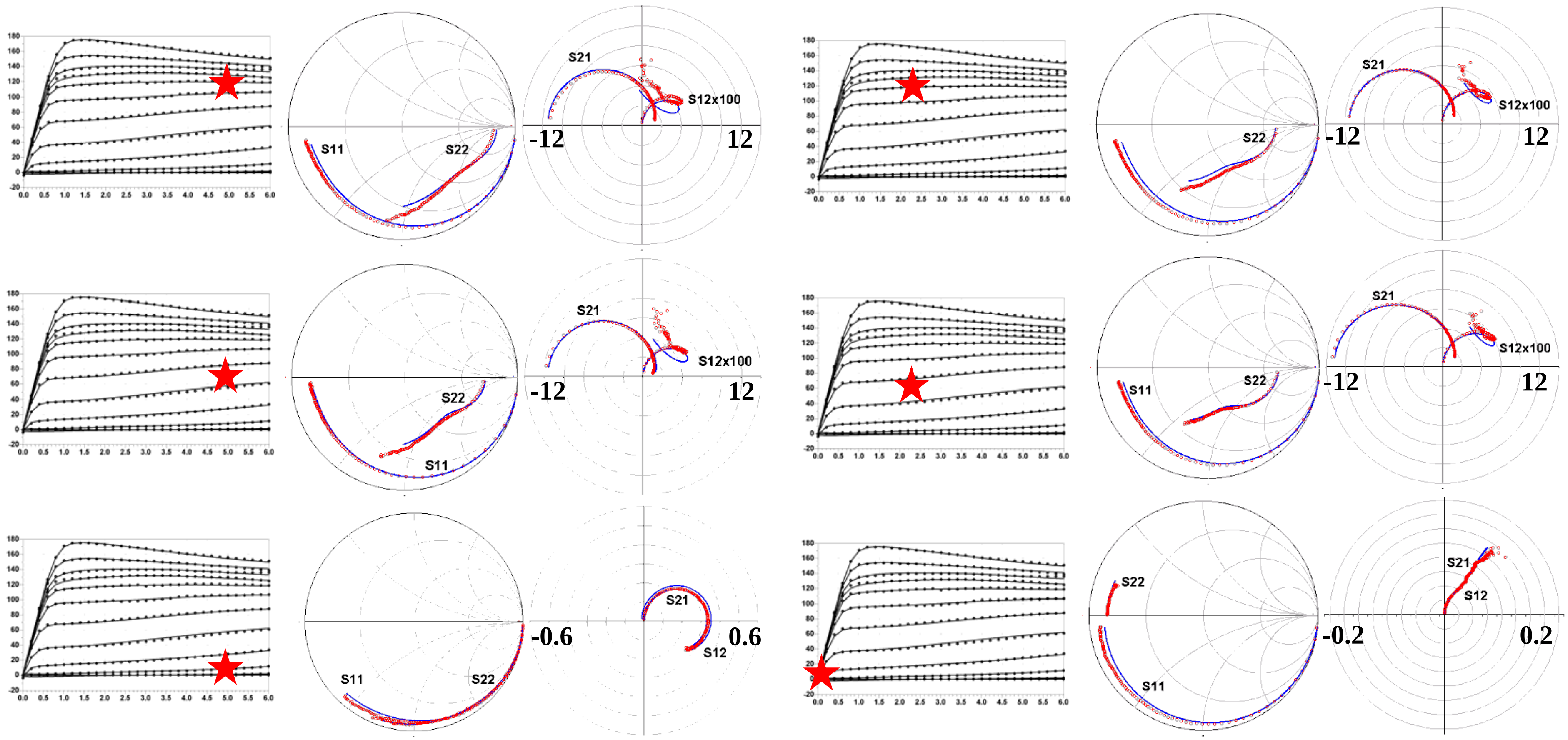
Model Validation
- DC



Model Validation

Frequency : 0.5 GHz to 50 GHz

- Frequency dispersion of small-signal characteristics



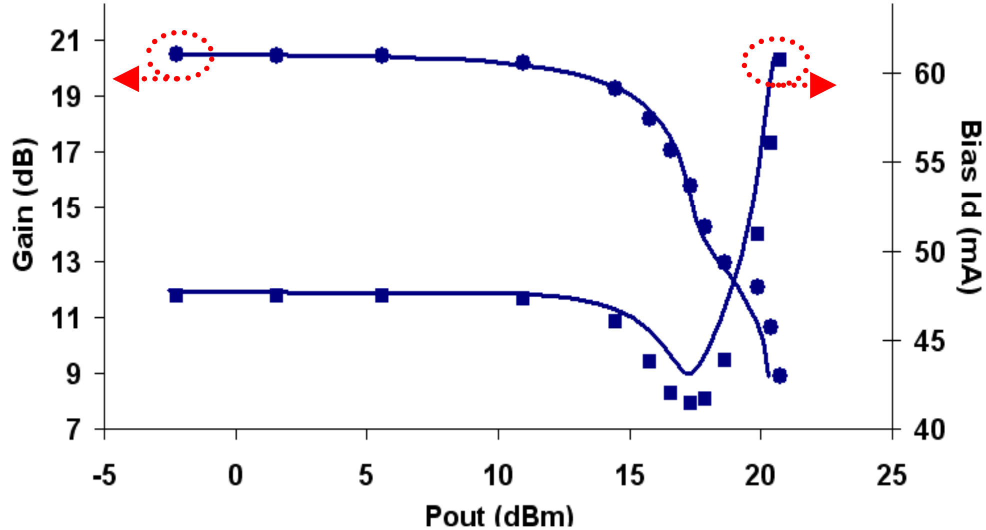
Excellent agreement over the entire bias range

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

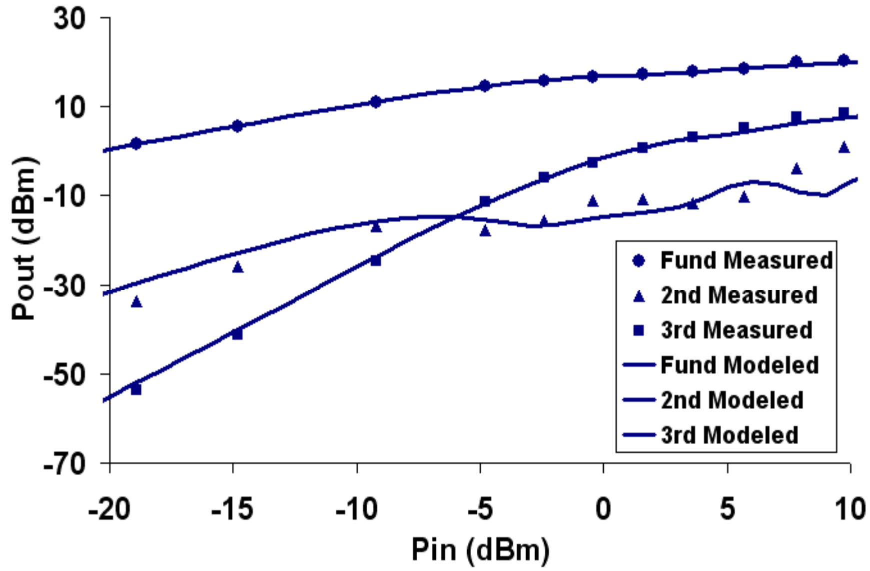
Model Validation

- Gain, Bias Current, Harmonic Distortion vs. Power

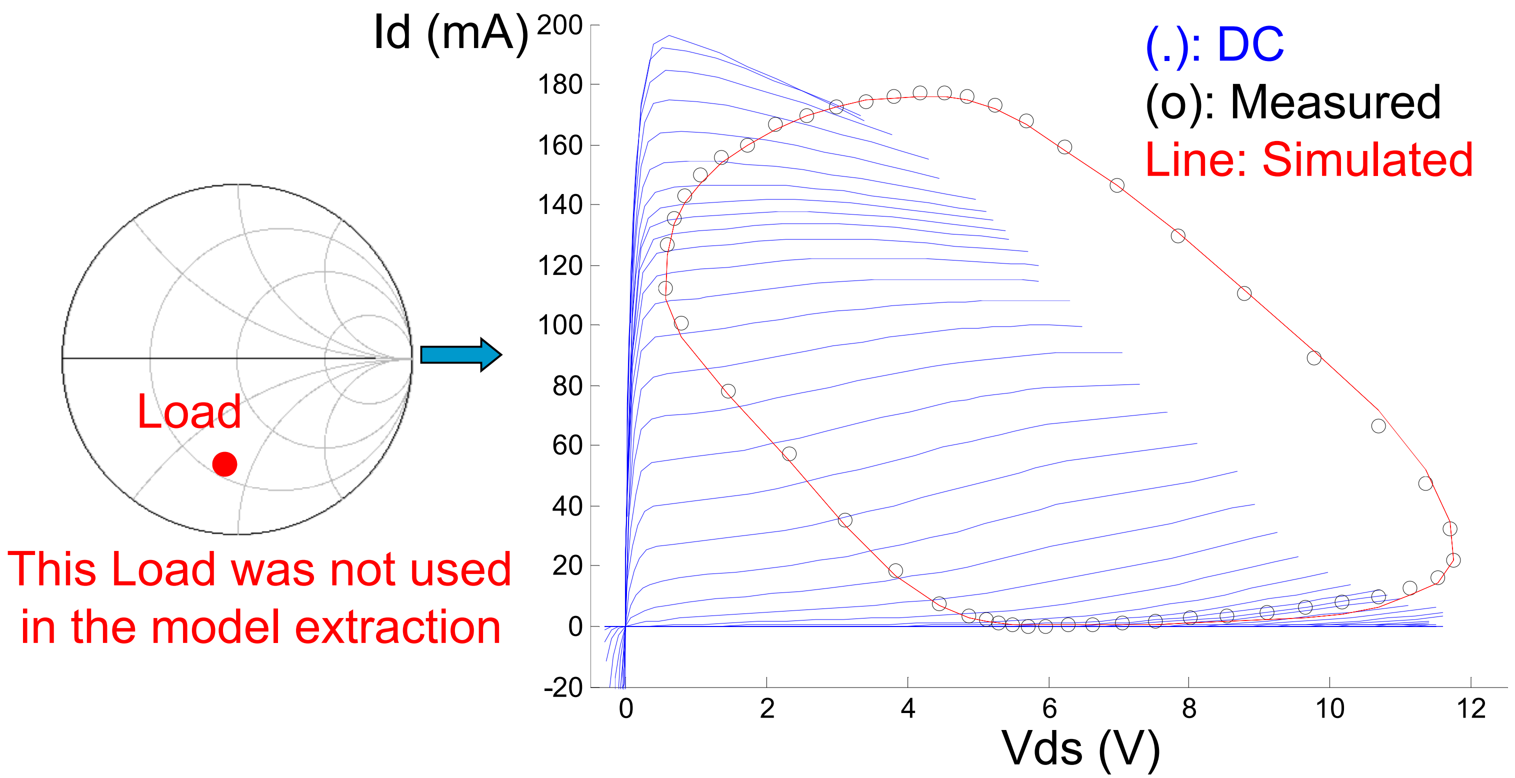
Simulated (—)
Measured data (symbols)



Simulated (—)
Measured data (symbols)



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

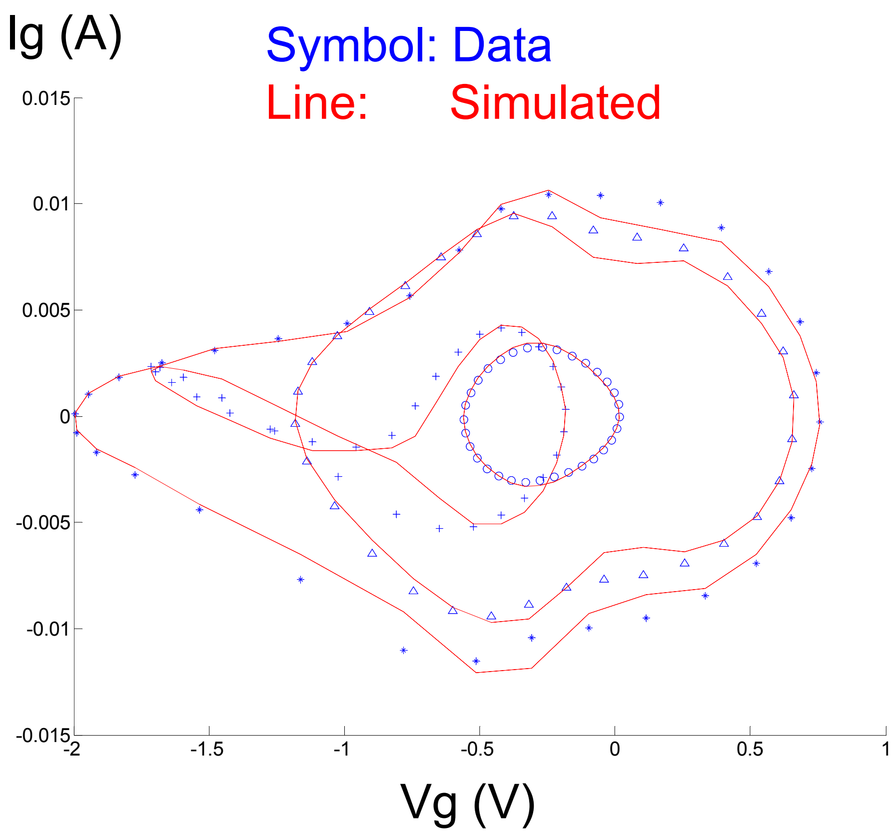


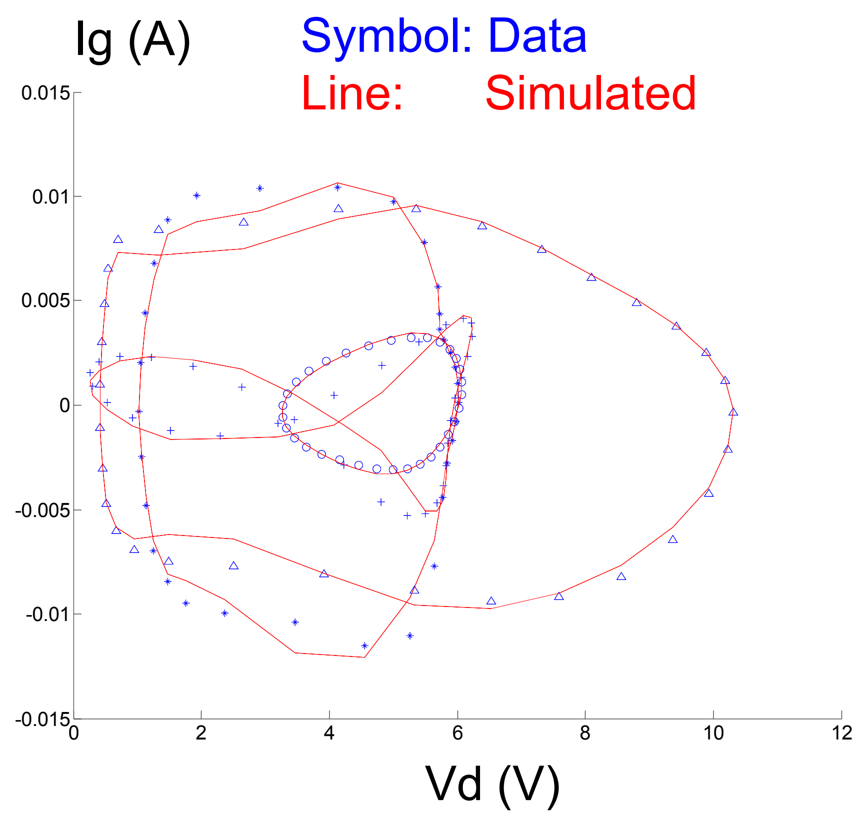
Demonstrates model can go far beyond the range over which conventional DC and linear S-parameters can be taken

Model Validation

- Gate Current Contours

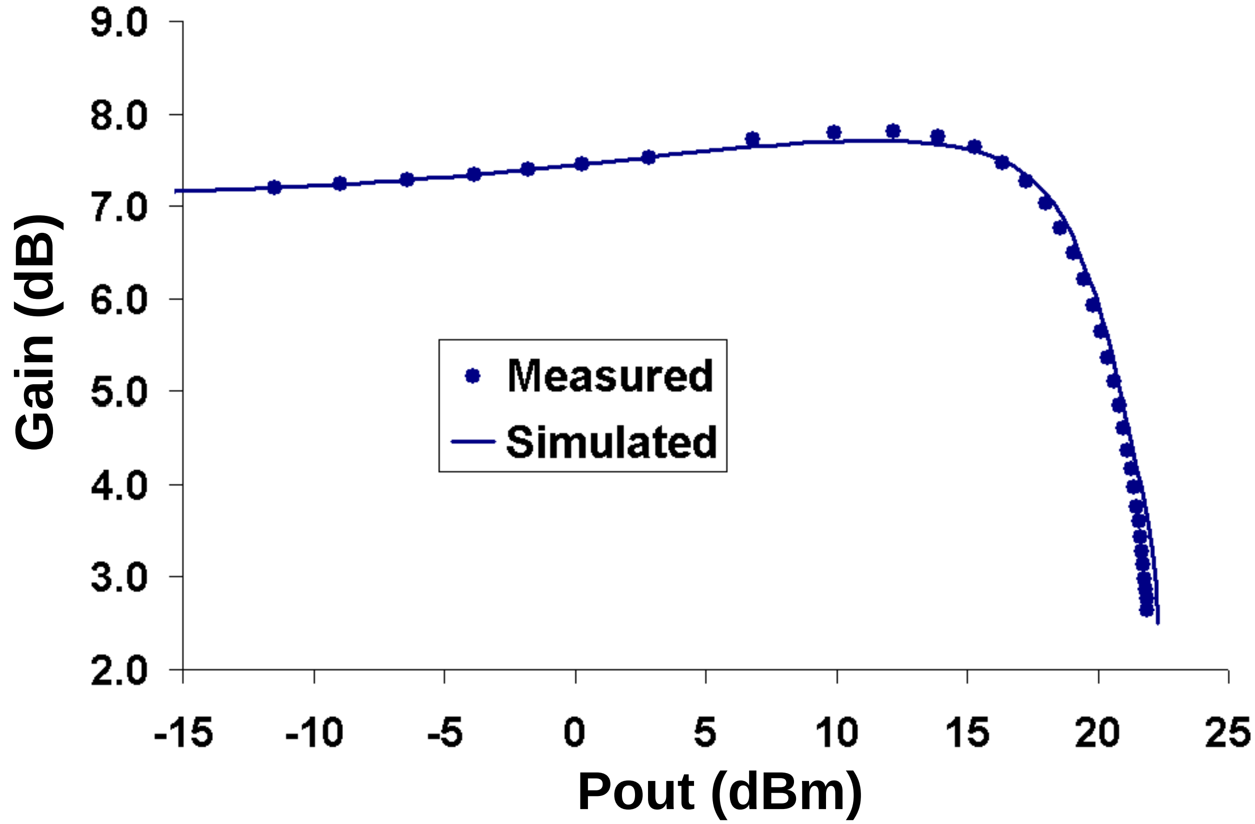
(4 contours for different powers and loads, Freq=4GHz)





Model Validation
- Gain vs. Pout @26GHz

Model was extracted using 2GHz and 4GHz data



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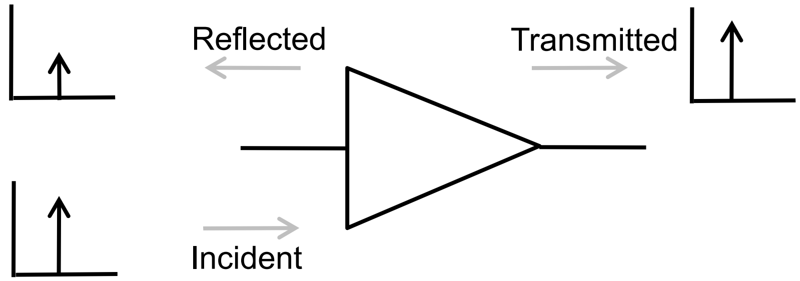
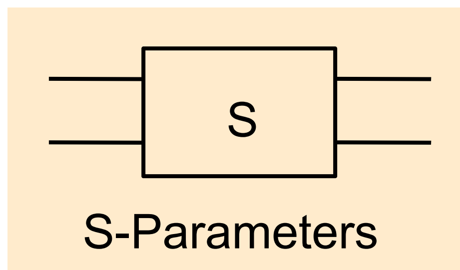
S-parameters Solve All Small-Signal Problems

But devices must operate linearly

Measure

Agilent Vector Network Analyzer





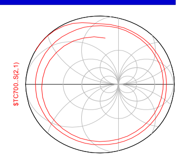
Freq. Domain Model

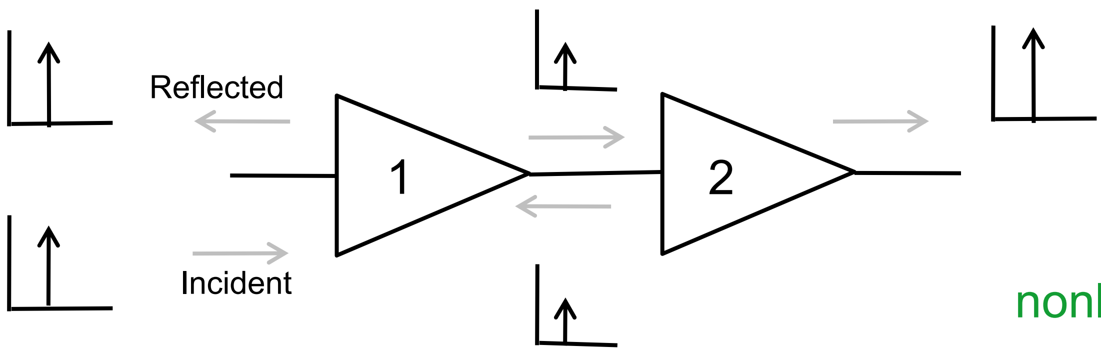
$$B_1 = S_{11}A_1 + S_{12}A_2$$
$$B_2 = S_{21}A_1 + S_{22}A_2$$

Design

S-PARAMETERS

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





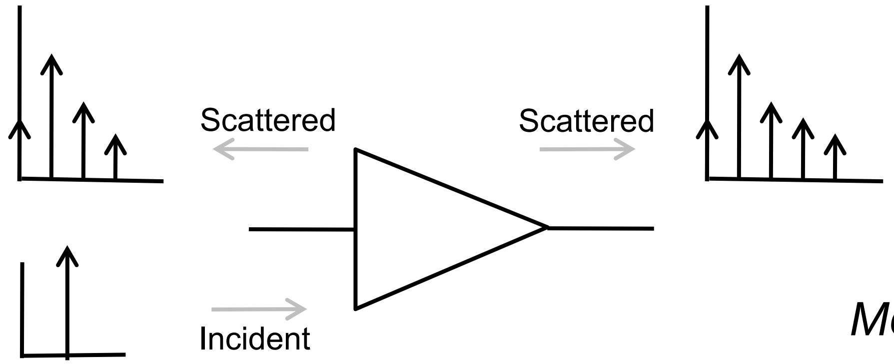
What about large-signal nonlinear problems?

X-parameters Solve Nonlinear Problems [1,8]

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

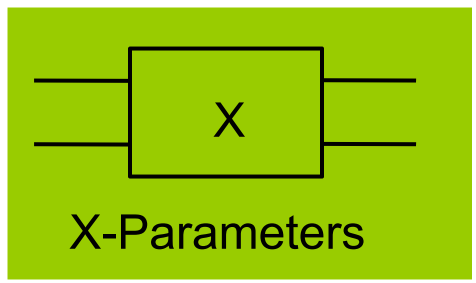
Measure

Agilent Nonlinear Vector Network Analyzer



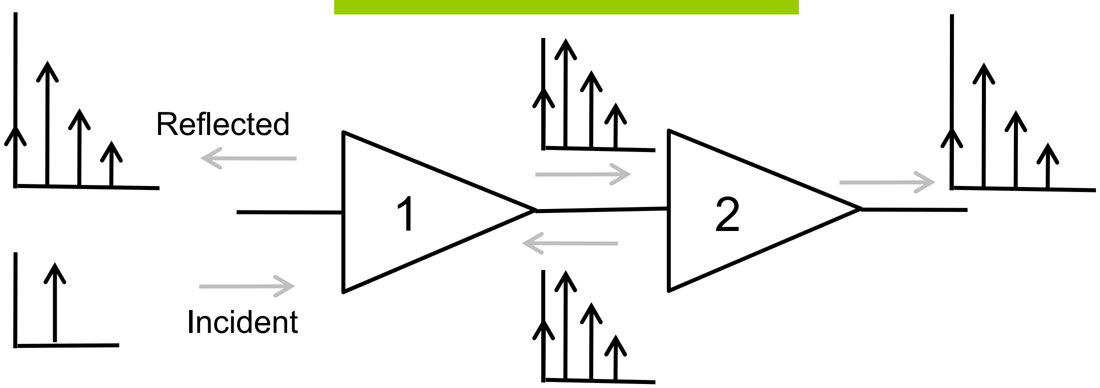
Model

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



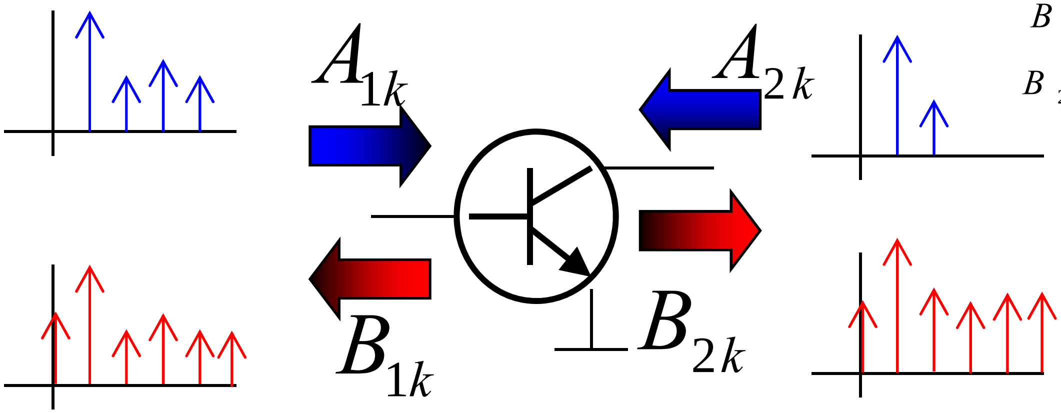
Design

Agilent ADS
EDA Software



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

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

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

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

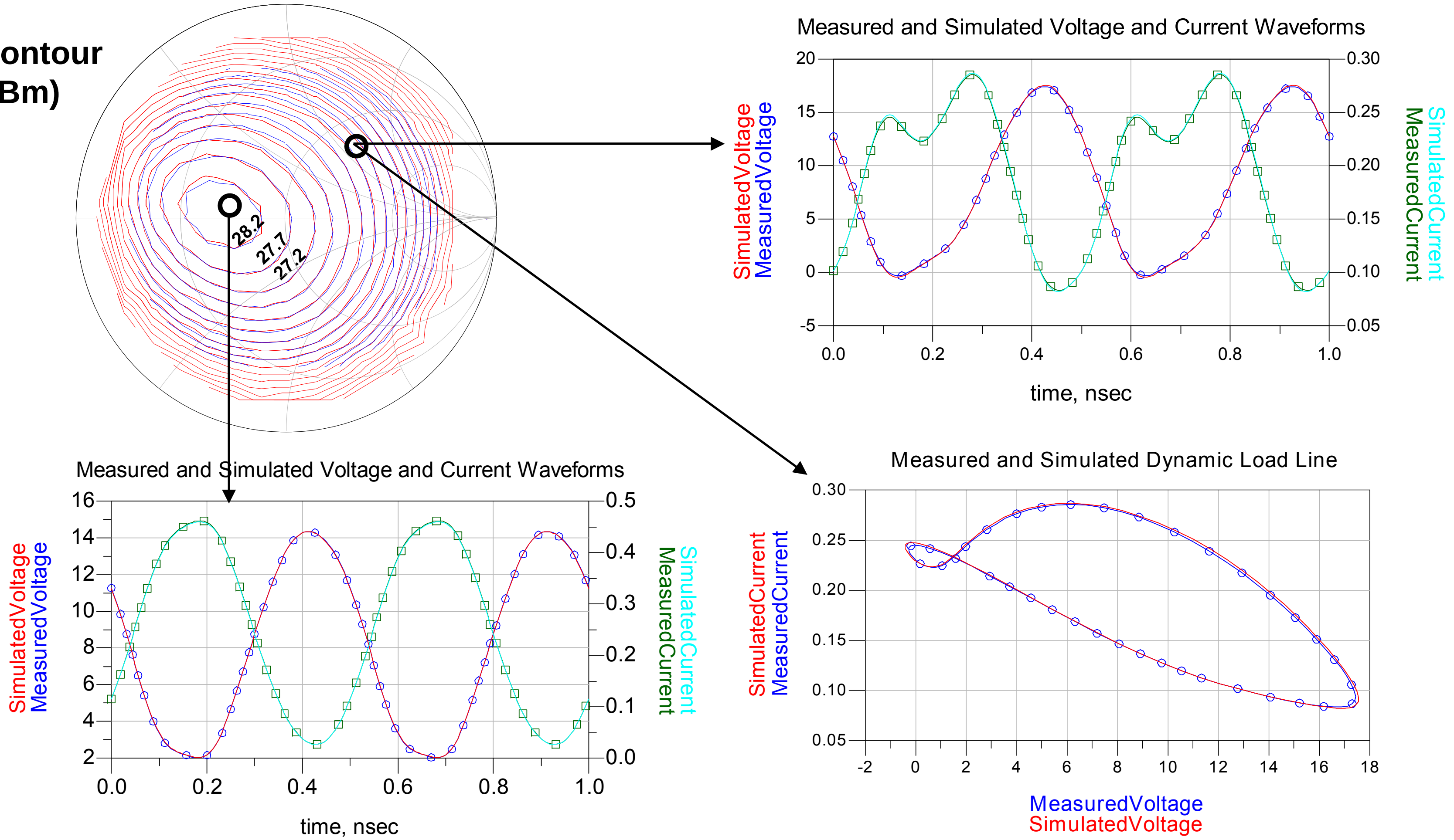
Load-Dependent X-Parameters of a FET

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

Measurements X-par Simulation

WJ FP2189 1W HFET

P_{out} Contour (dBm)

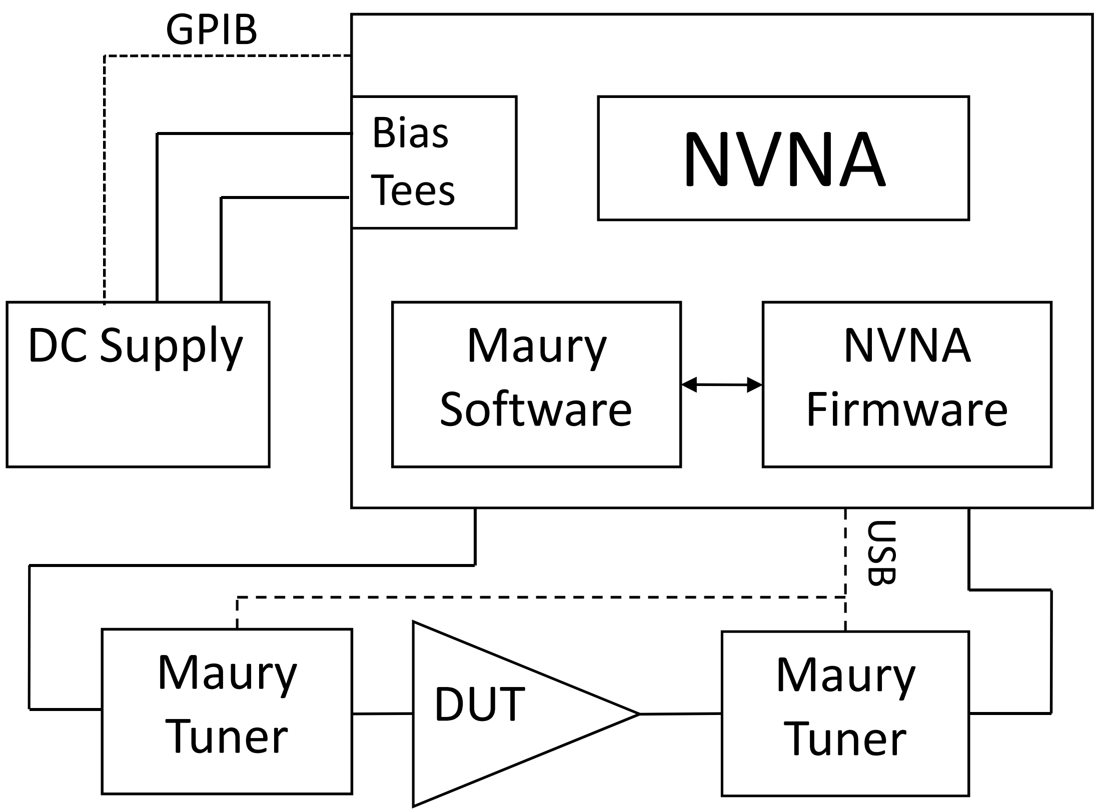


Experimental Harmonic Balance

X-parameters unify S-parameters and load-pull

Load-Dependent X-Parameter Model for GaN HEMT:

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



9 load states at f_1

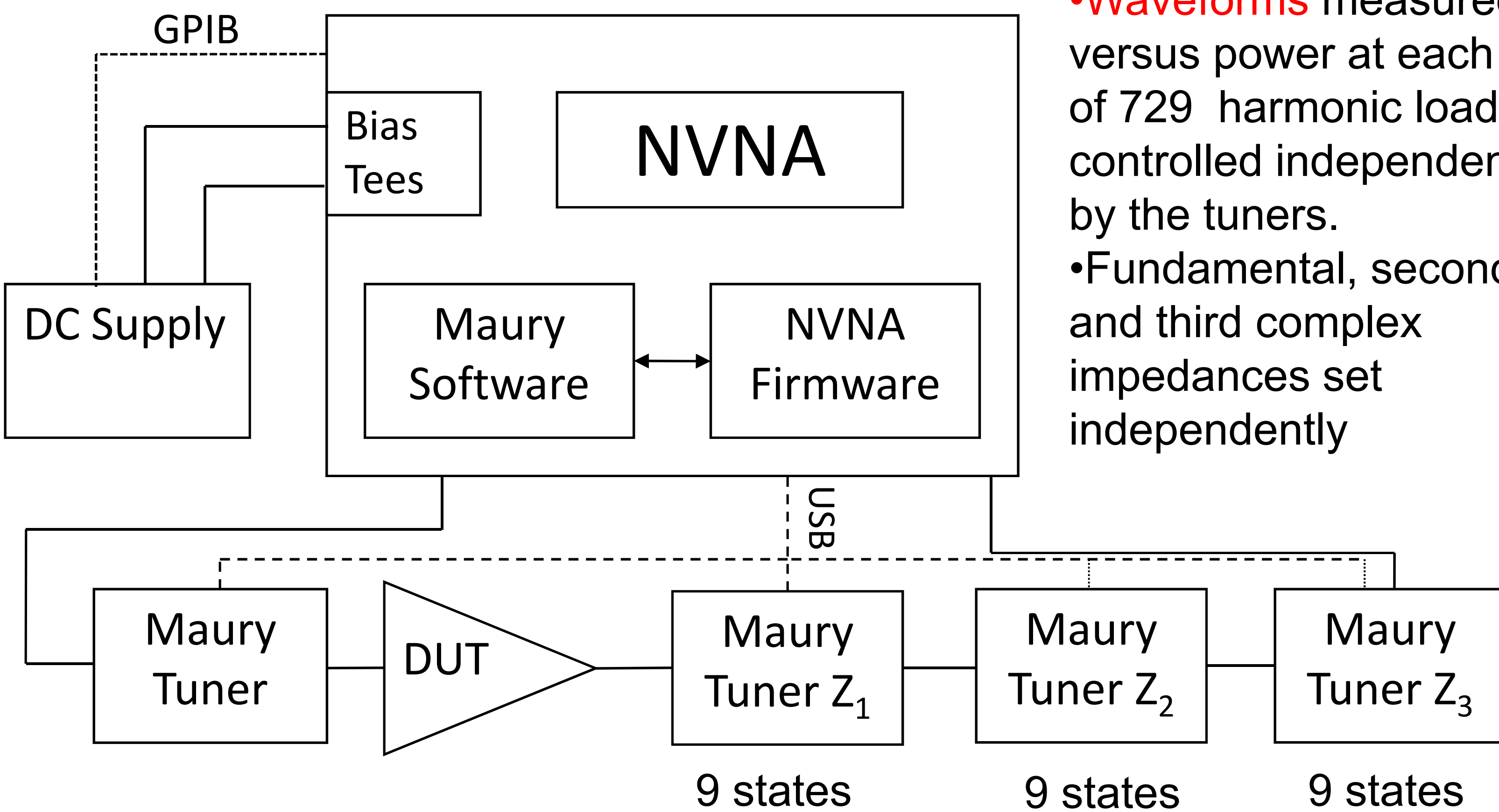
Cree
CGH40010
GaN HEMT
10 W packaged
transistor

- 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

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

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 2^{nd} and 3^{rd} harmonic freqs (9x(1+2x2) = 45 measurements, actually ~125 measurements)
- Measured DC – 4^{th} harmonic
- Take into ADS. Present 729 independent loads to model

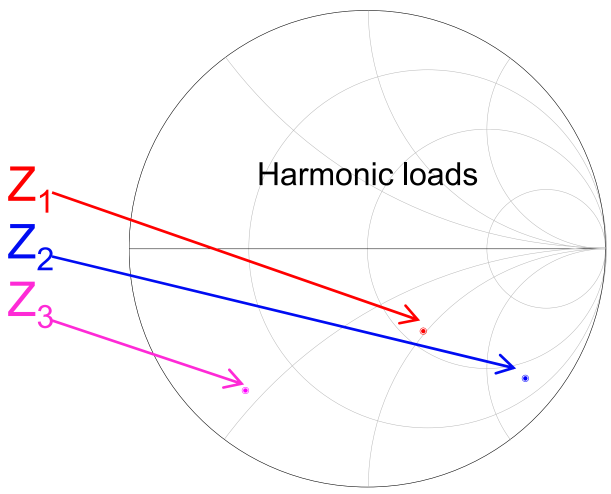
Harmonic load-pull validation

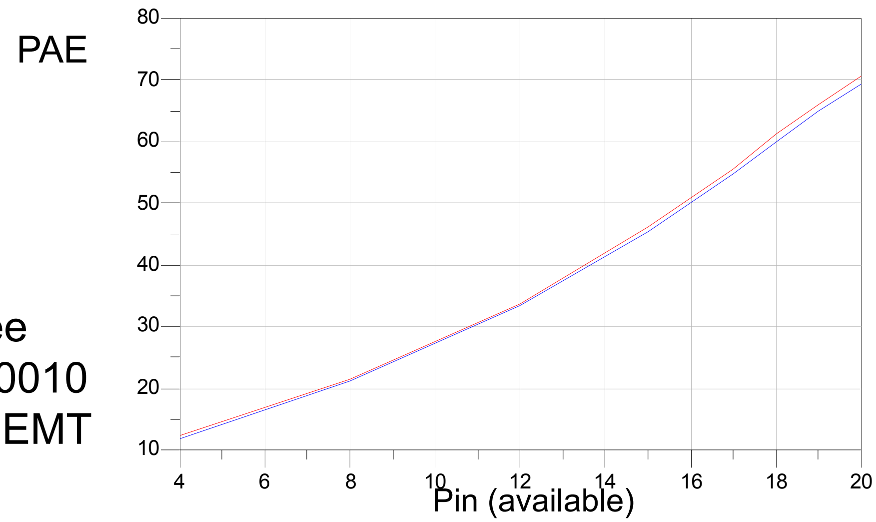
- *Three output tuners* to vary loads at fundamental, second, and third harmonics independently (9x9x9 = 729 measurements)
- Measured DC - 4^{th} harmonic

ADS

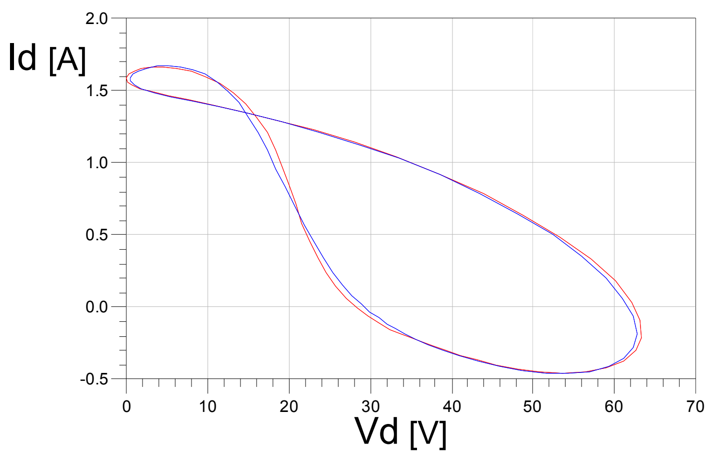
Compare waveforms, PAE, dynamic load-lines, etc.

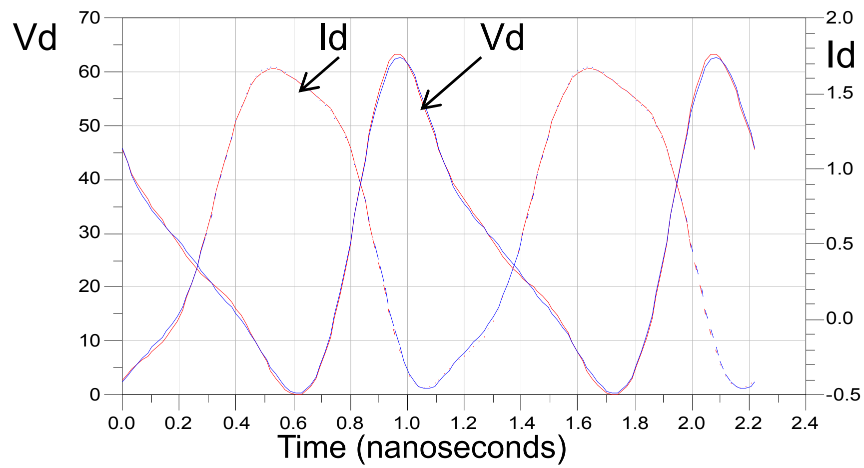
Prediction of GaN HEMT Harmonic-Load Dependence from Fundamental-Only Load-Dependent X-Parameters





Cree
CGH40010
GaN HEMT

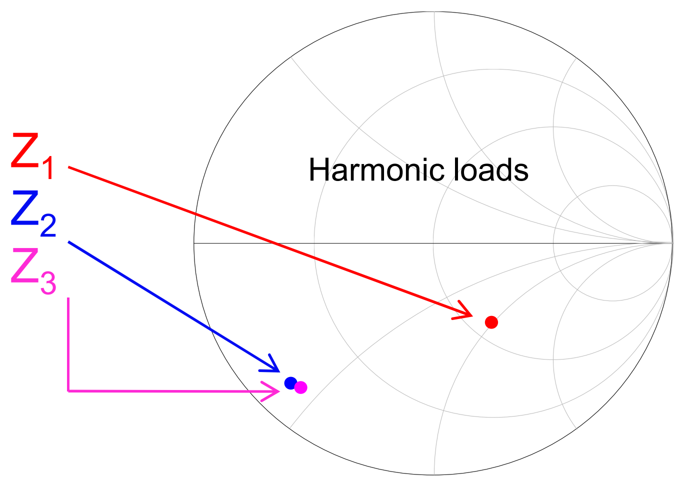




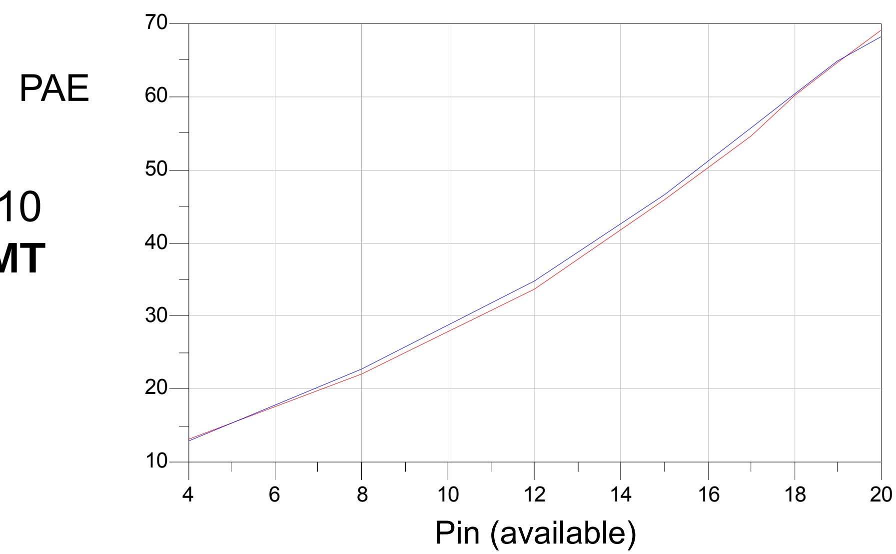
X-parameter model

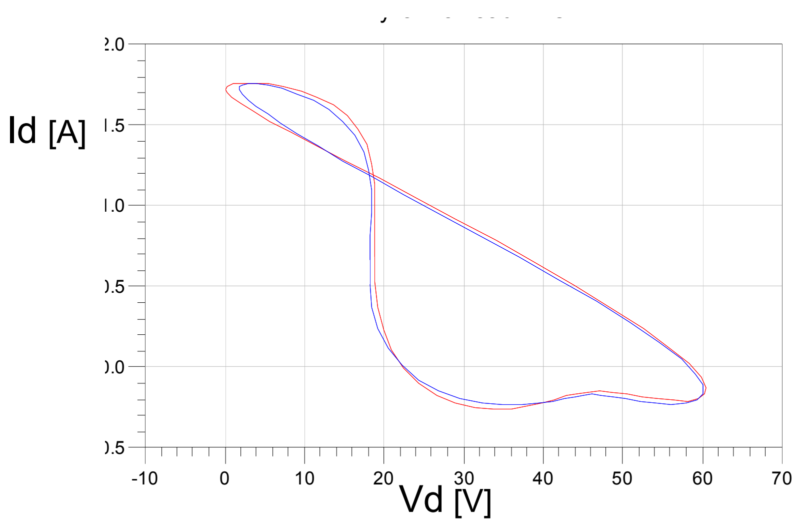
Harmonic time-domain load-pull measurements

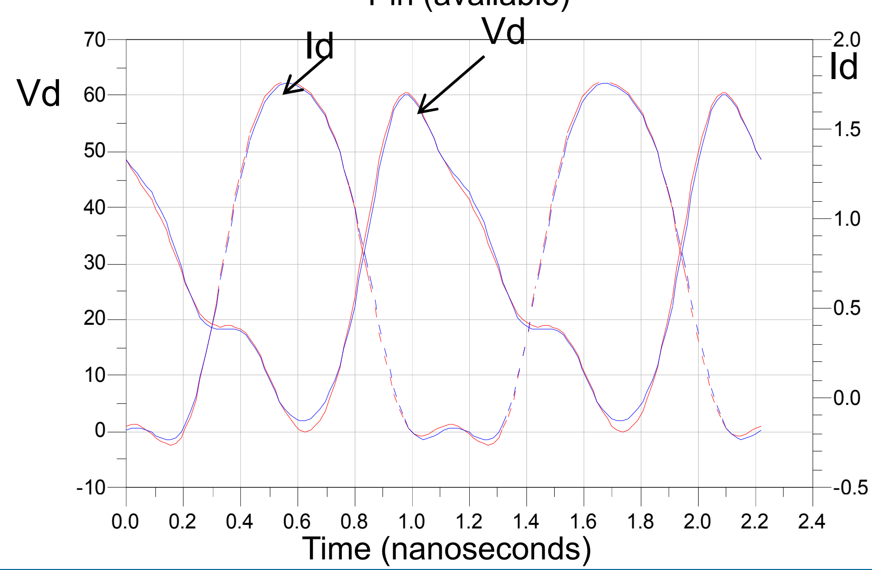
Prediction of GaN HEMT Harmonic-Load Dependence from Fundamental-Only Load-Dependent X-Parameters



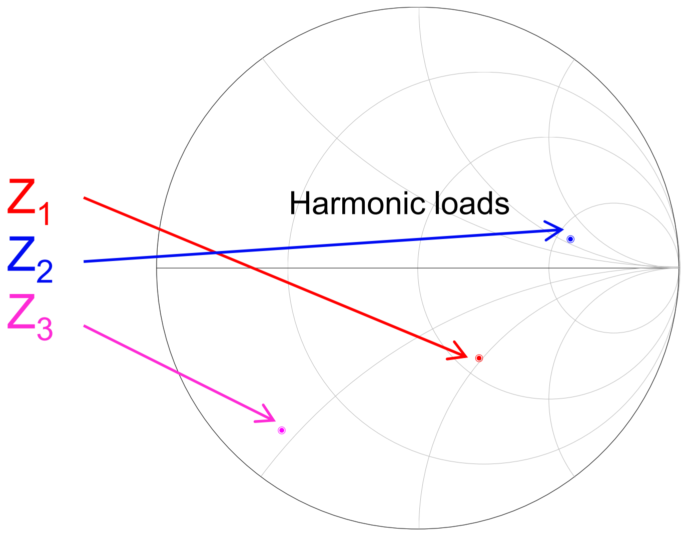
Cree
CGH40010
GaN HEMT



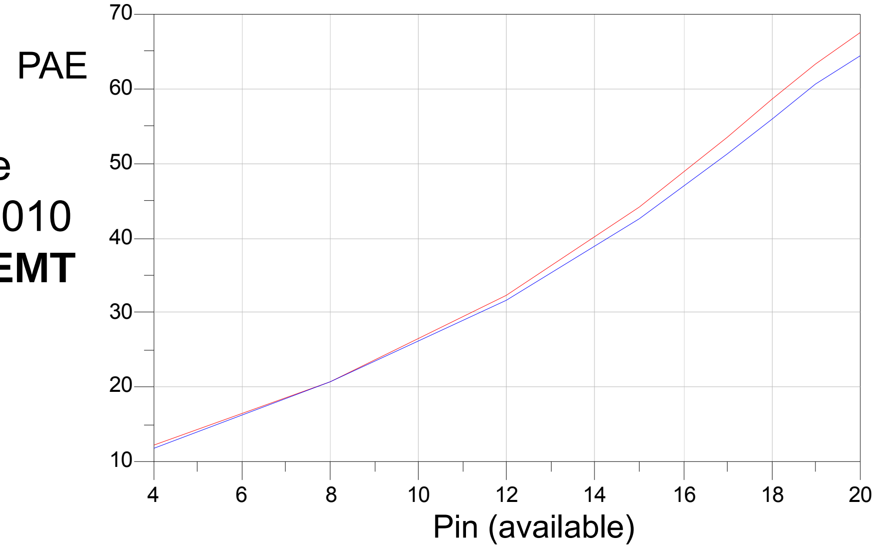


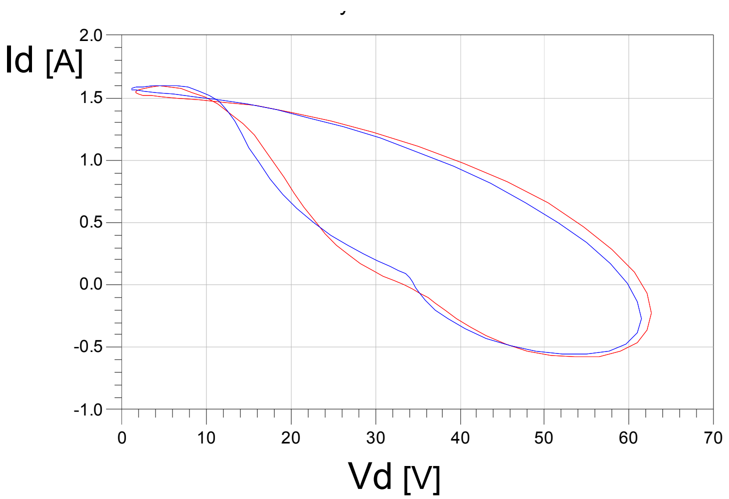


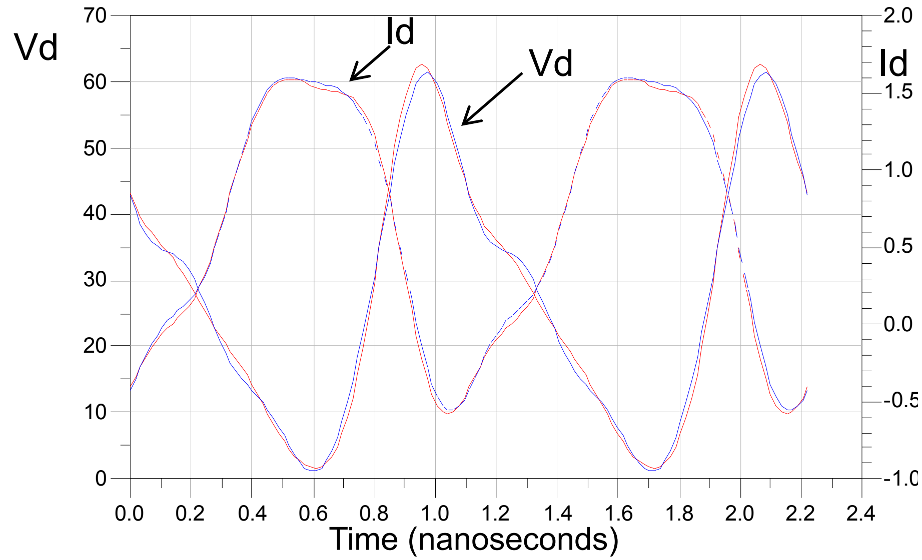
Prediction of GaN HEMT *harmonic-load dependence* from fundamental-only load-dependent X-pars



Cree
CGH40010
GaN HEMT



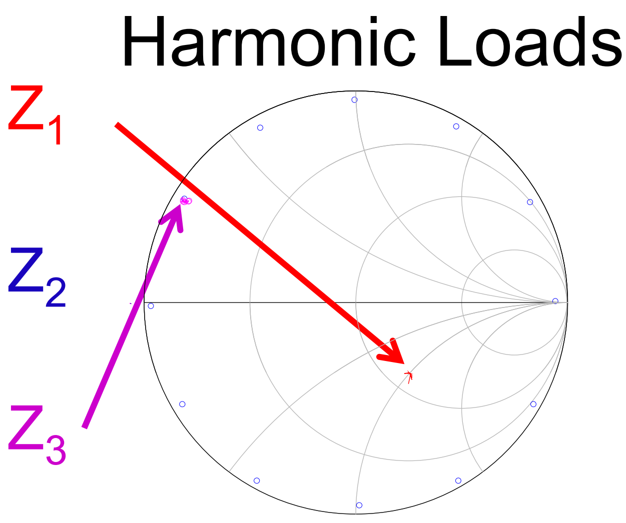


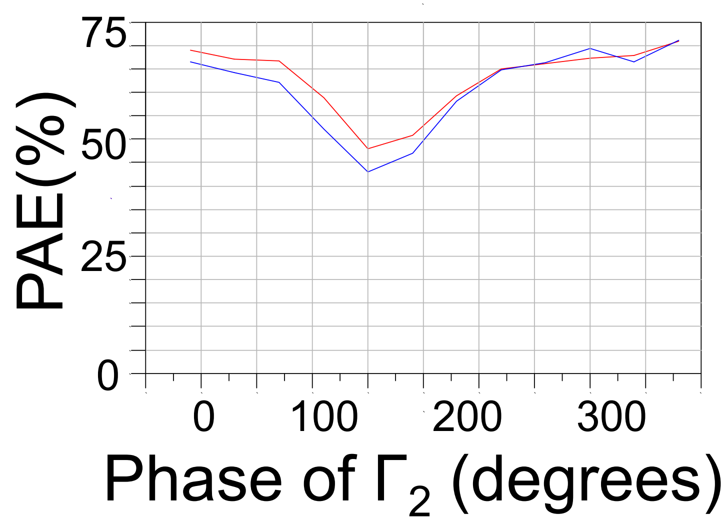


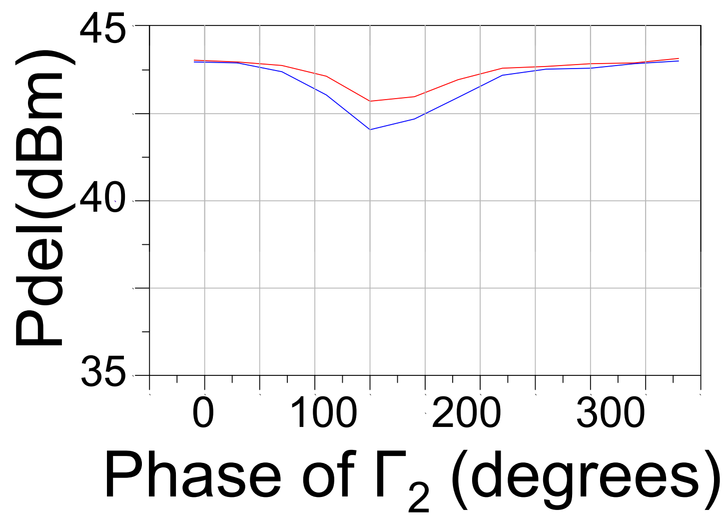
Agilent Technologies

10W GaN Device Model

Comparison

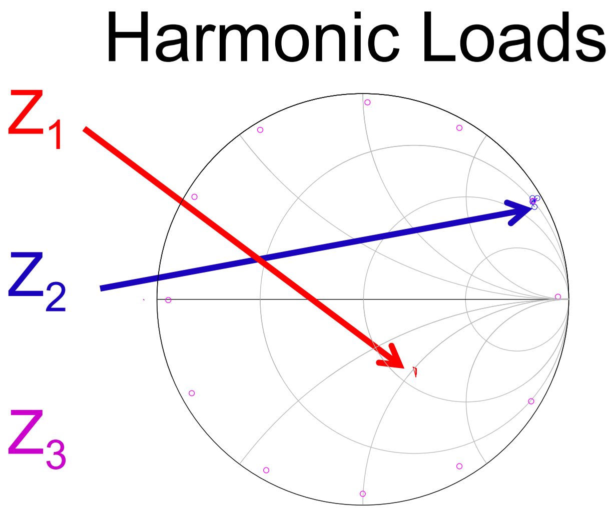


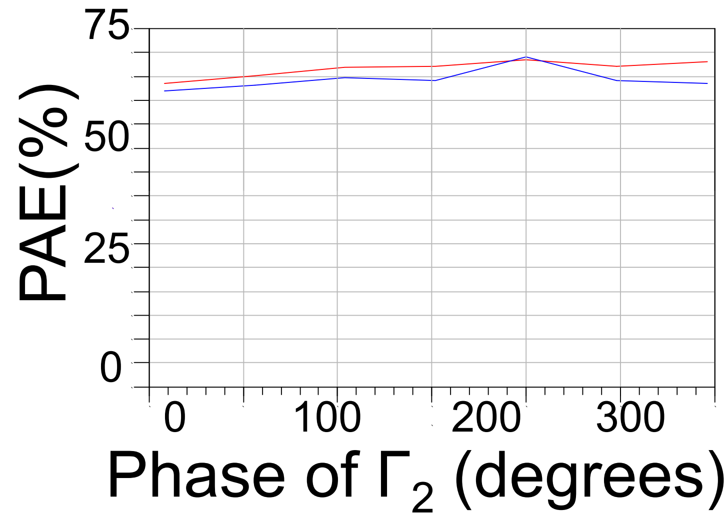


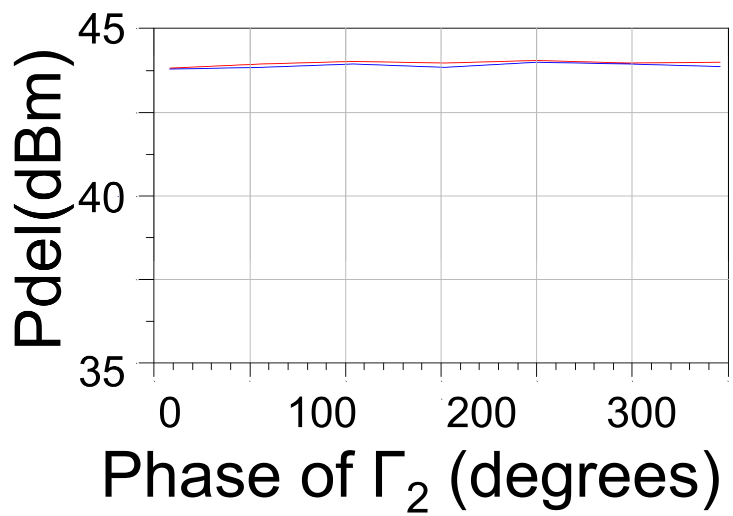


10W GaN Device Model

Comparison







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

Comparison of approaches presented here

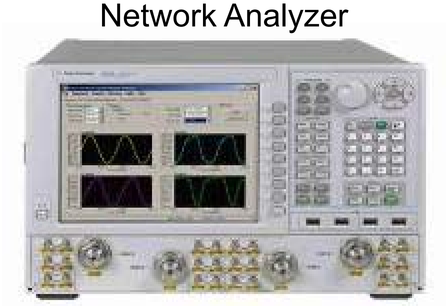
Approach	Advantages	Disadvantages
Compact Device model	• Works in all simulation modes (TA, HB, CE) • More scalable • Simple statistics • Noise models; dynamic self-heating common • What-if scenarios possible	• Development time long • Extraction difficult • Technology-dependent
X-parameter Device model	• 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])

Conclusions

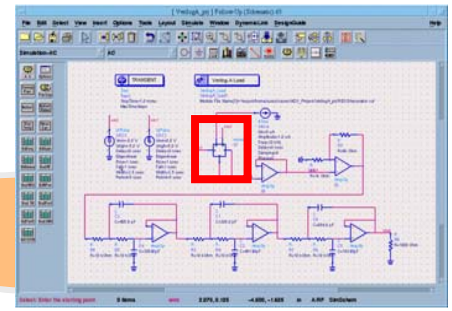
- NVNA is a powerful, valuable tool for device modeling
  1. NVNA data ("HB data") can be used to validate, tune, extract optimal parameters, explore compact model limitations & suggest improvements
  2. NVNA data can be used to identify complicated constitutive relations for advanced compact models - *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.

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

Agilent Nonlinear Vector Network Analyzer



Electronic design automation software

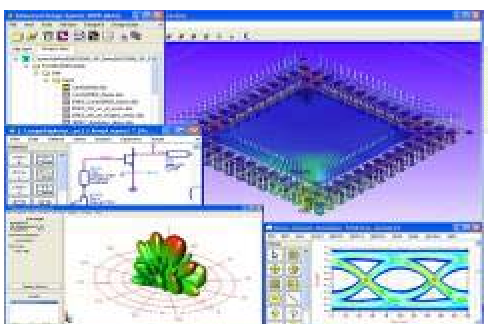


Nonlinear Measurements

Nonlinear Simulation & Design

Nonlinear Modeling

Customer Applications



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

References

[1] http://www.agilent.com/find/nvna

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[4] J. Xu, M. M. Iwamoto, J. Horn, 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.

[5] J. Horn, "Harmonic load-tuning predictions from X-parameters," *IEEE PA Symposium*, San Diego, Sept. 2009

[6] G. Simpson et al, "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.

[7] J. Verspecht and D. E. Root, "Poly-Harmonic Distortion modeling," in *IEEE Microwave Theory and Techniques Microwave Magazine*, June, 2006

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[9] Agilent Advanced Design System documentation: Nonlinear Devices

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

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[13] O. Jardel et al, "An electrothermal model for AlGaN/GaN power HEMTs including trapping effects to improve large-signal simulation results on high VSWR," *IEEE Transactions on MTT.*, vol. 55, Dec., 2007.

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