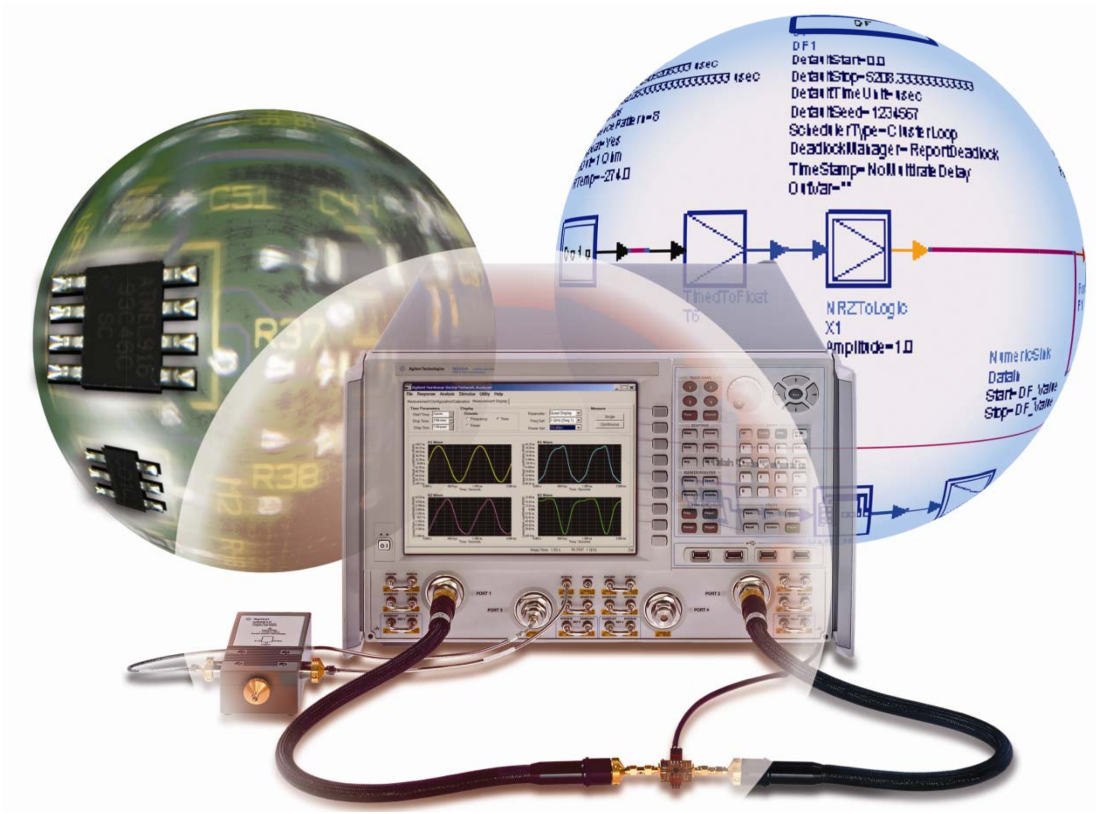
X-parameters*:
A new paradigm for measurement, modeling, and design of nonlinear microwave & RF components



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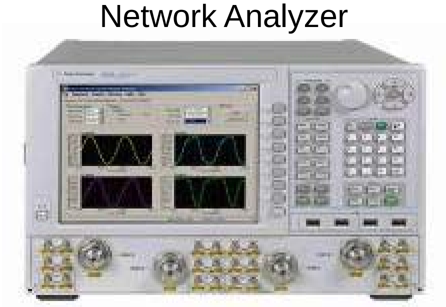
Outline

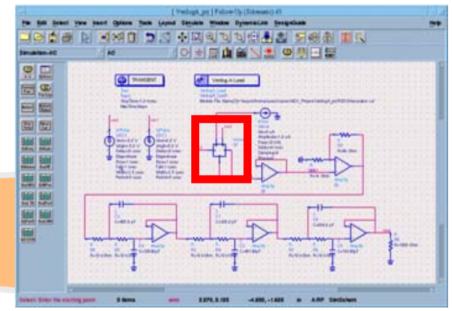
- Introduction: X-parameter Basics
- Survey of X-parameter benefits and applications
- Summary
- References and Links

X-Parameters: Mainstream Nonlinear Interoperable Technology

Agilent Nonlinear Vector Network Analyzer



Electronic design automation software

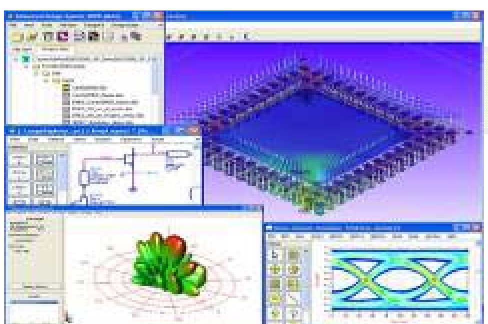


Nonlinear Measurements

Nonlinear Simulation & Design

Nonlinear Modeling

Customer Applications



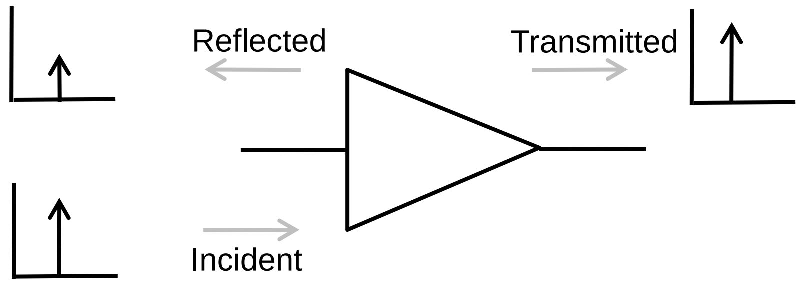
$$B_{pm} = X^{F}_{pm}(|A_{11}|) + X^{S}_{pm,qn}(|A_{11}|)P^{m-n}A_{qn} + X^{T}_{pm,qn}(|A_{11}|)P^{m+n}A^{*}_{qn}$$

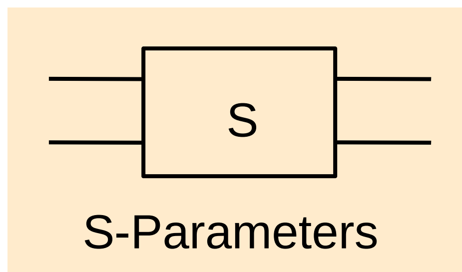
S-parameters Solve All Small-Signal Problems

But devices must operate linearly

Measure

Agilent Vector Network Analyzer

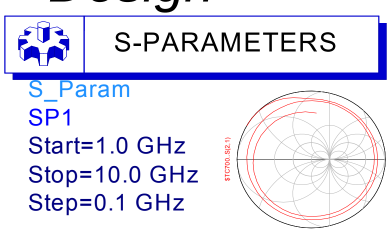


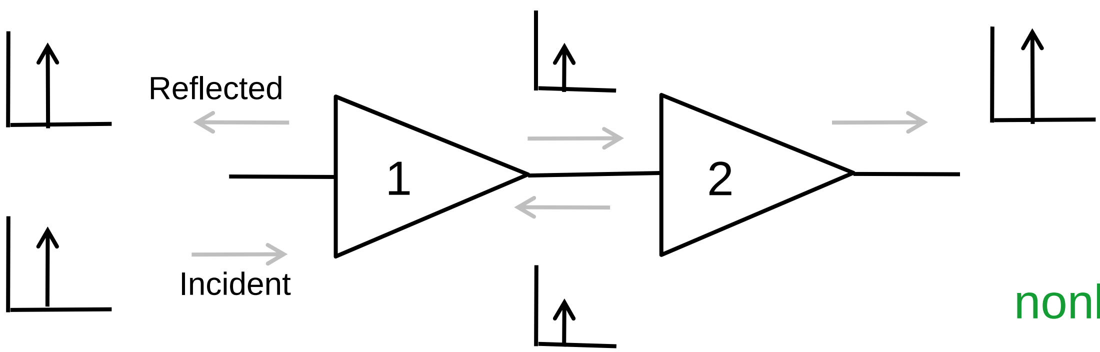


Model

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

Design

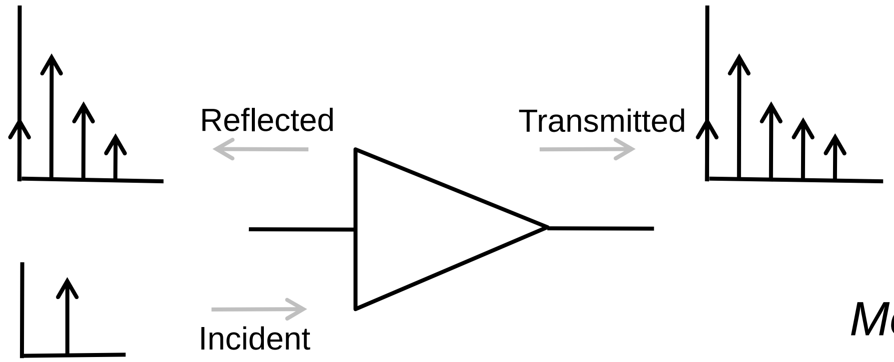




What about large-signal nonlinear problems?

X-parameters Solve Nonlinear Problems

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

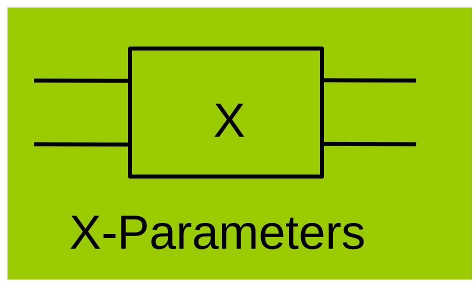


Measure

Nonlinear Vector
Network Analyzer

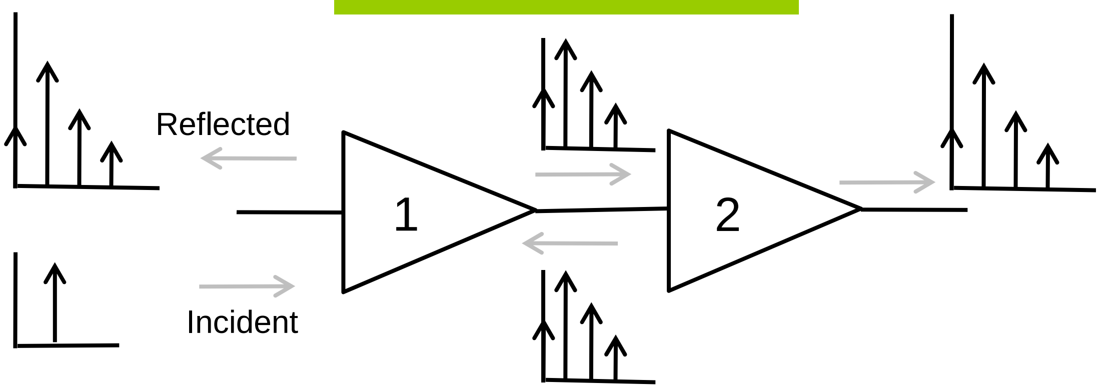
Model

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



Design

EDA Software



Capturing the imagination of the industry

Solves real-world problems now

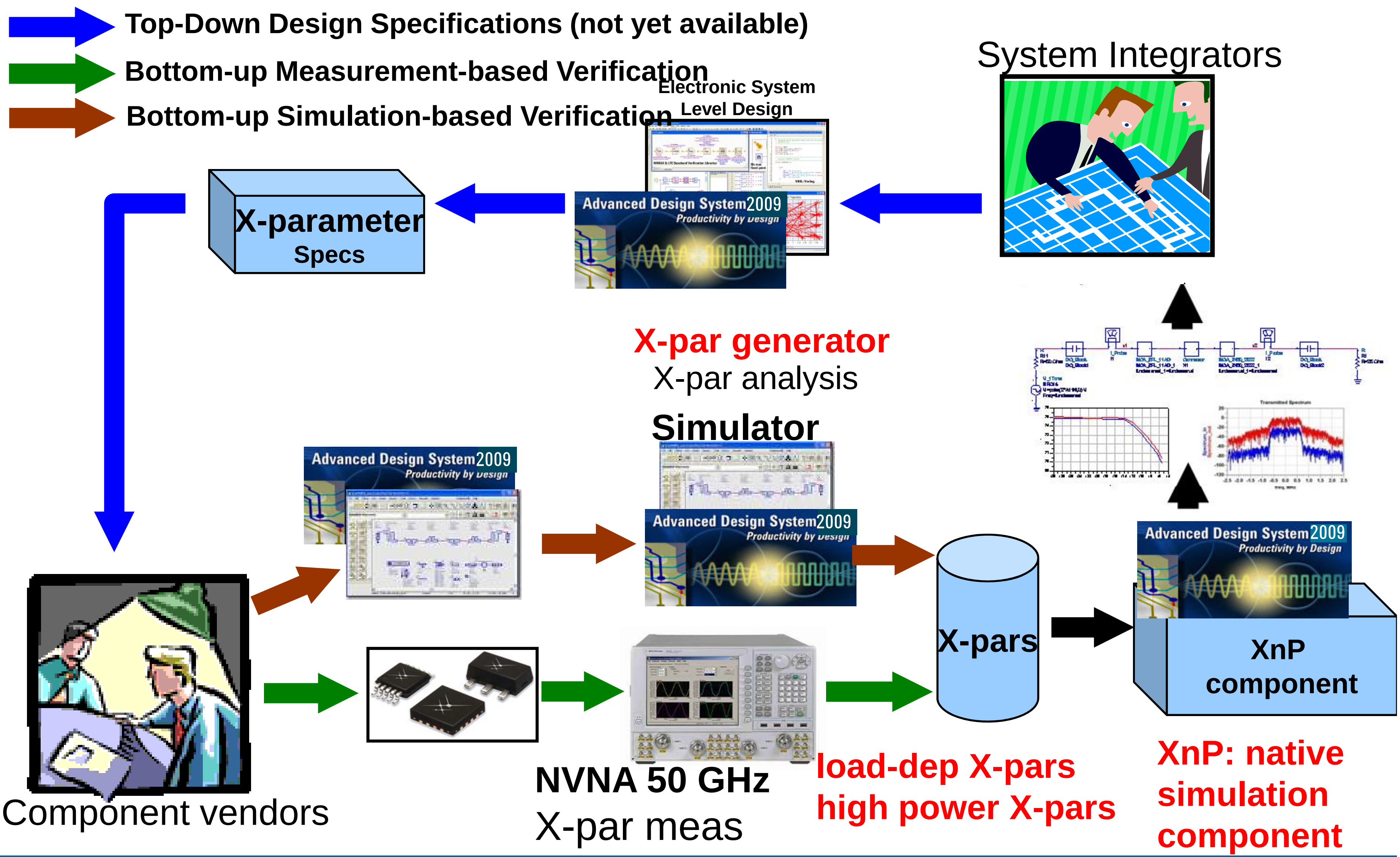
Interoperable characterization, modeling, and design solutions

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

Changing the way the industry works

Continuous wave of innovations and award-winning research

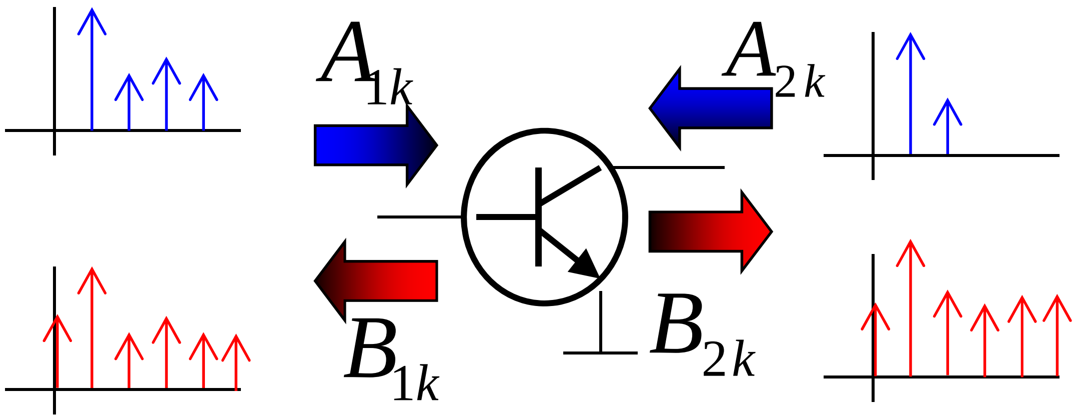
X-parameters: Hierarchical Design and Validation

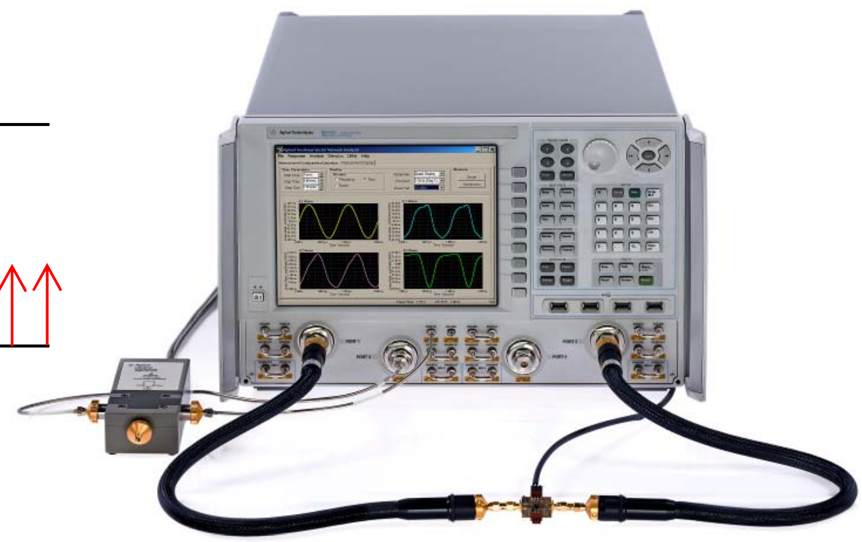


MTTS IEEE

Agilent Technologies

Introduction: NVNA measurements complex spectra and waveforms

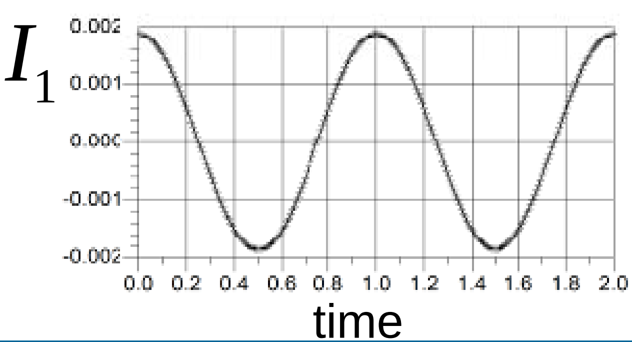


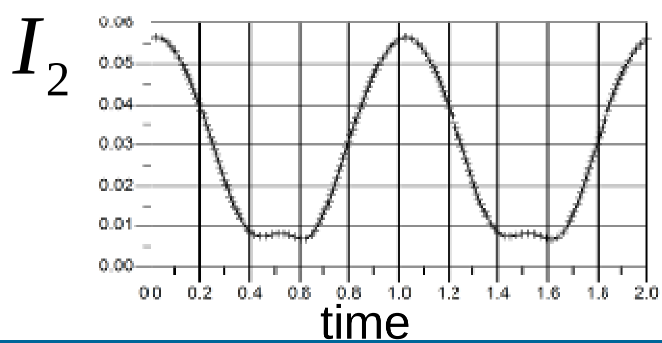


A_{pk} B_{pk}

Harmonic Index

Port Index



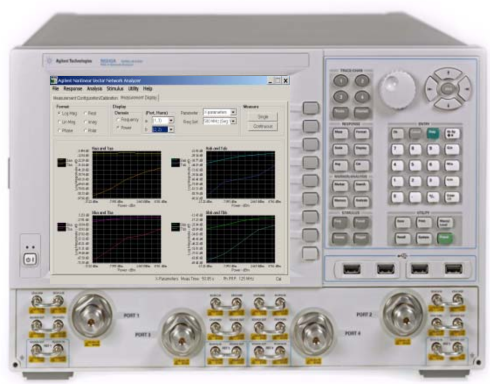


Measurement-Based Modeling & Design Flow

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

NVNA

Nonlinear Measurements

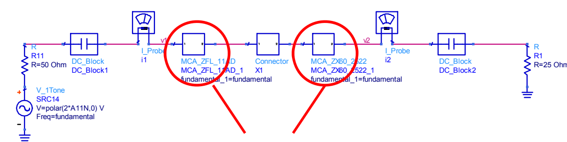


Data File

Drag and drop

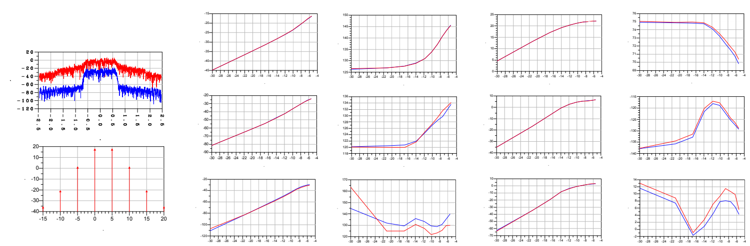
ADS

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.

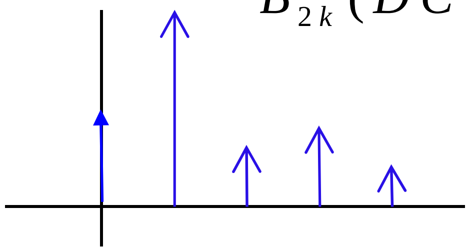
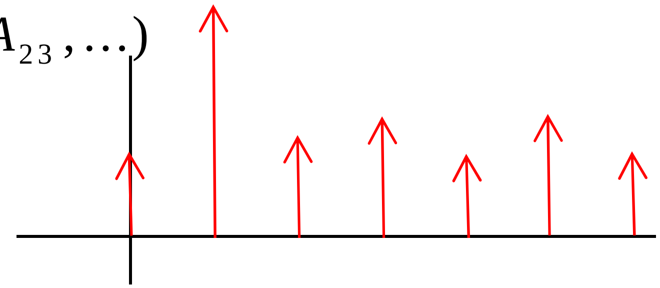
IMD / ACPR exact in narrow-band limit

"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

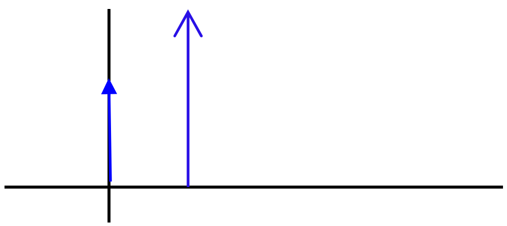
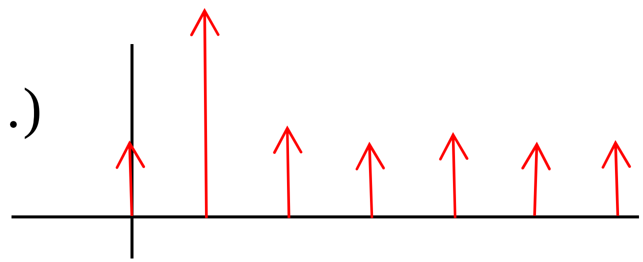
$$B_{2k}(DC, A_{11}, A_{12}, A_{13}, \ldots A_{21}, A_{22}, A_{23}, \ldots)$$

Multi-variate NL map

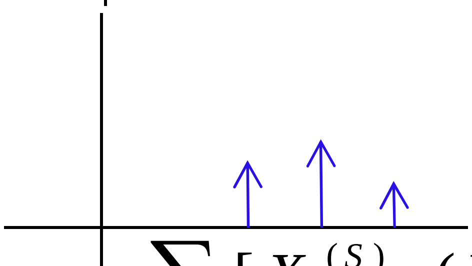
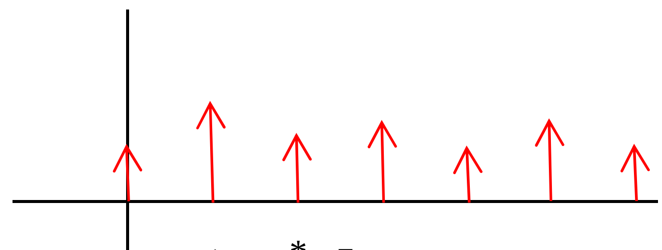
$$\approx$$

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

Simpler NL map

$$+$$

Linear non-analytic map

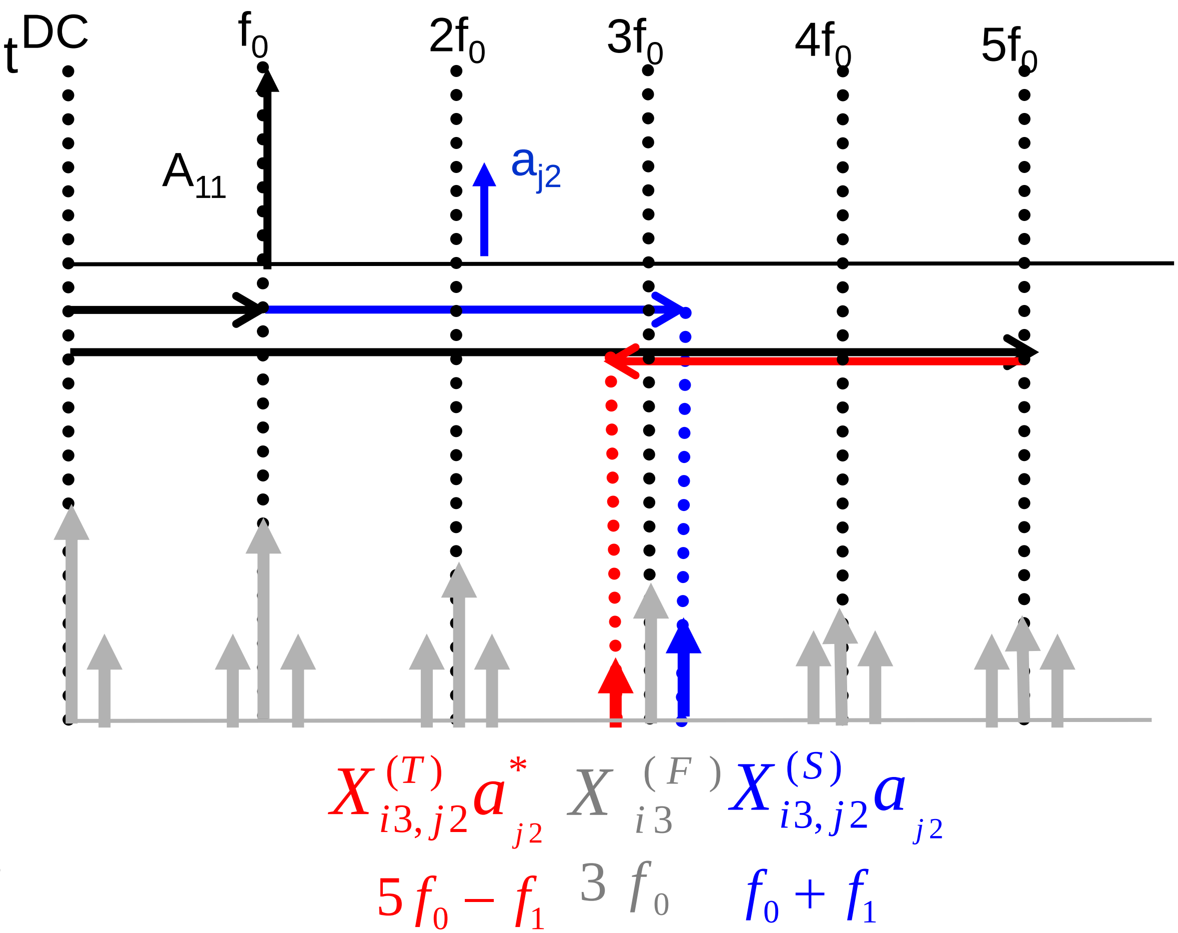
$$\sum [X_{2k,pj}^{(S)}(DC, A_{11}) A_{pj} + X_{2k,pj}^{(T)}(DC, A_{11}) A_{pj}^{*}]$$

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



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

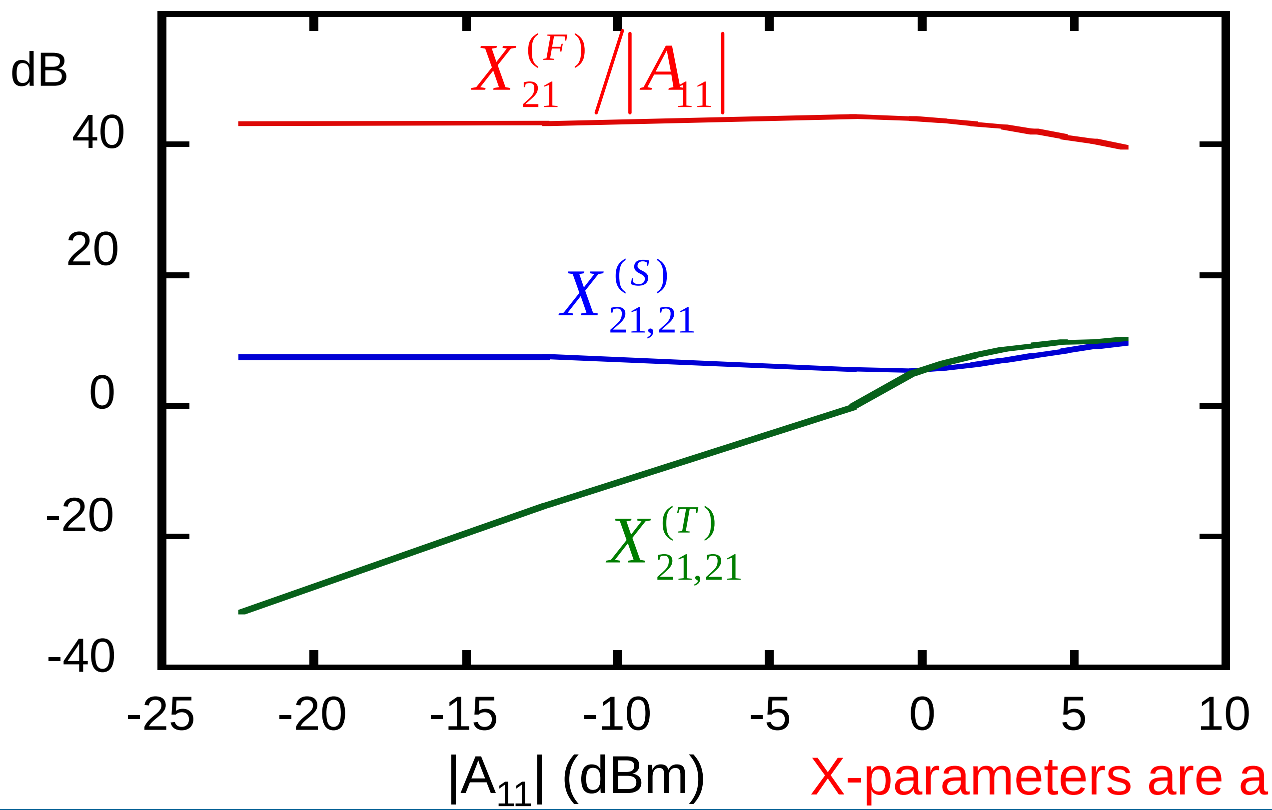
$$P = e^{j\varphi(A_{11})}$$

Simplest X-parameters for a Power Amplifier

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

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

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



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

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

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

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

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

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

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

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

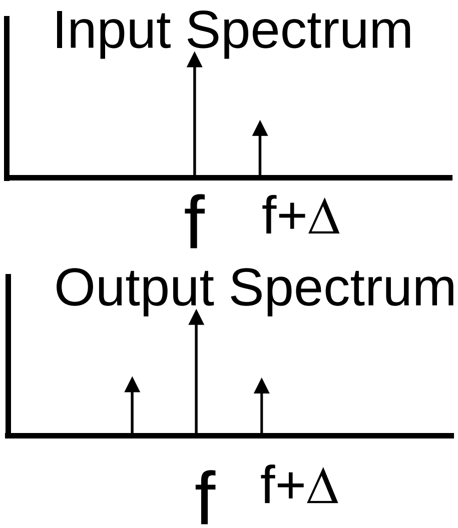
Stimulate port 1 with large tone at freq. *f*
Stimulate port 2 with small tone at freq. $f+\Delta$
Measure response at three different frequencies
Take limit as Δ goes to zero

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

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

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

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 $X_{pm}^{(F)}(|A_{11}|) = B_{pm}P^{-m}$

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

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*

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

X-Parameter: How they are measured:

Experiment Design & Identification (2): Ideal Case

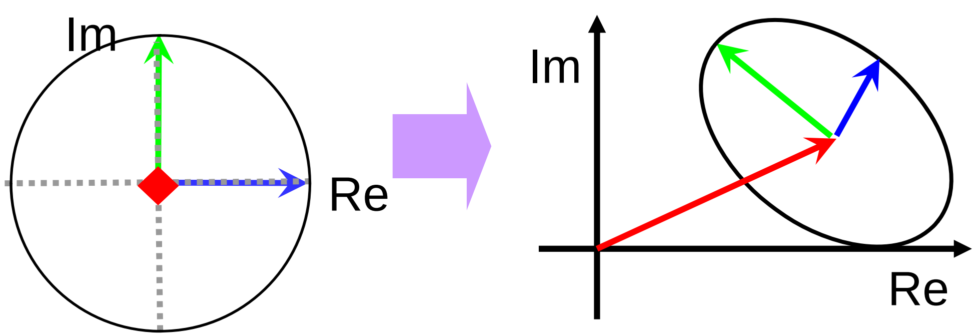
E.g. functions for B_{pm} (port p, harmonic m) given small extraction tones A_{qn} (port q, harmonic n)

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

Perform 3 independent experiments with fixed A_{11}

input A_{qn}

output B_{pm}



$$B^{(0)}_{pm} = X^{(F)}_{pm}(|A_{11}|)P^{m}$$

$$B^{(1)}_{pm} = X^{(F)}_{pm}(|A_{11}|)P^{m} + X^{(S)}_{pm,qn}(|A_{11}|)P^{m-n}A^{(1)}_{qn} + X^{(T)}_{pm,qn}(|A_{11}|)P^{m+n}A^{(1)}_{qn}$$

$$B^{(2)}_{pm} = X^{(F)}_{pm}(|A_{11}|)P^{m} + X^{(S)}_{pm,qn}(|A_{11}|)P^{m-n}A^{(2)}_{qn} + X^{(T)}_{pm,qn}(|A_{11}|)P^{m+n}A^{(2)*}_{qn}$$

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

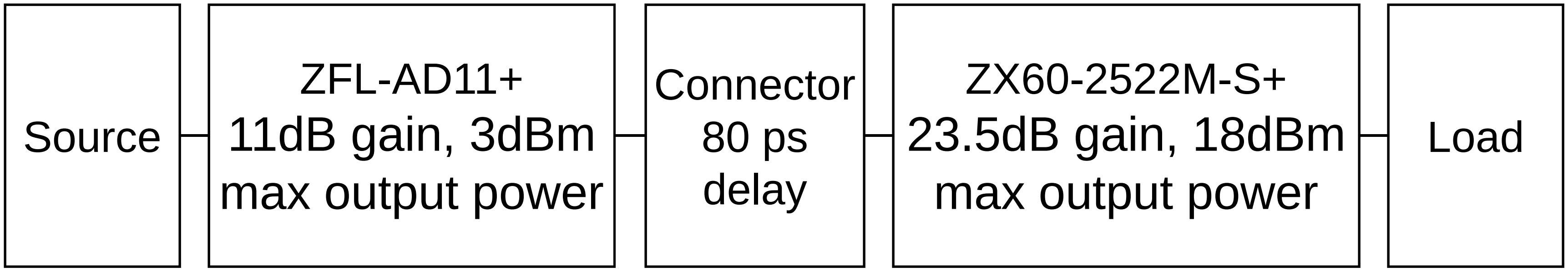
Can be *generated from Simulation and Measurement*

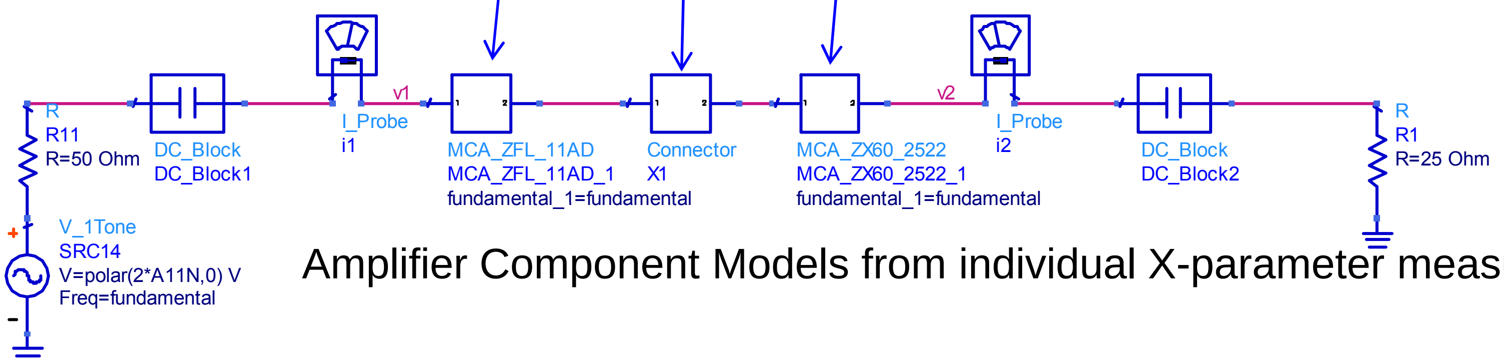
Highly automated experiment design & model identification

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



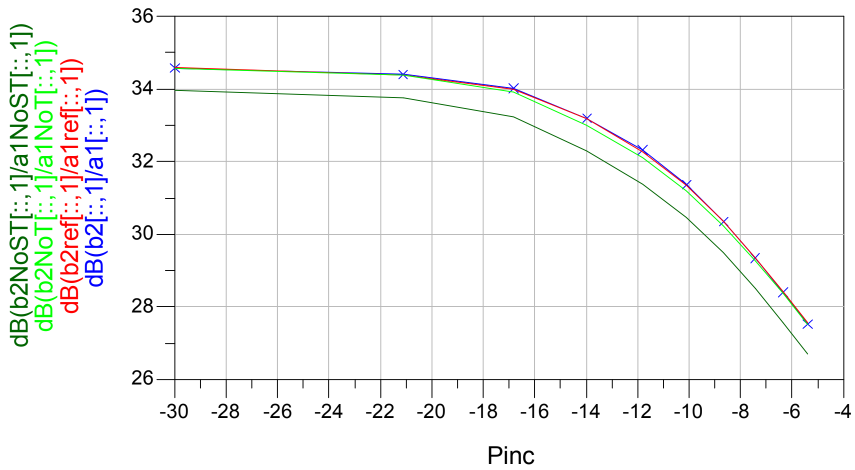


Amplifier Component Models from individual X-parameter measurements

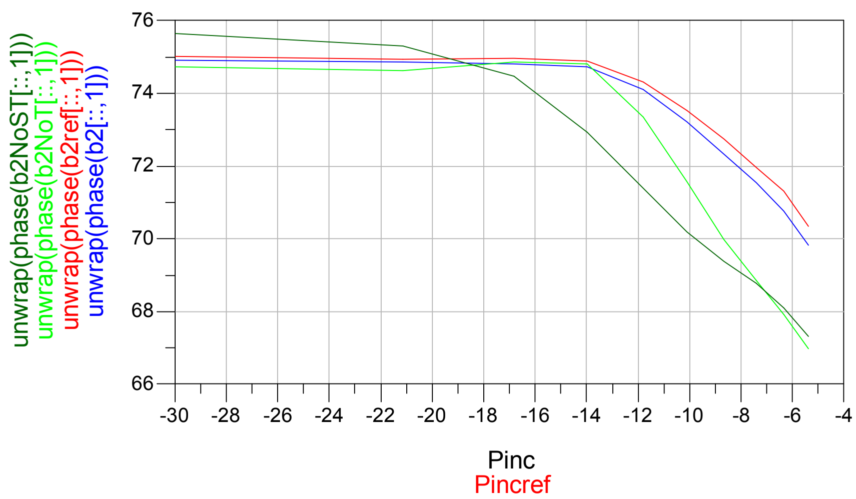
Results
Cascaded Simulation vs. Measurement

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

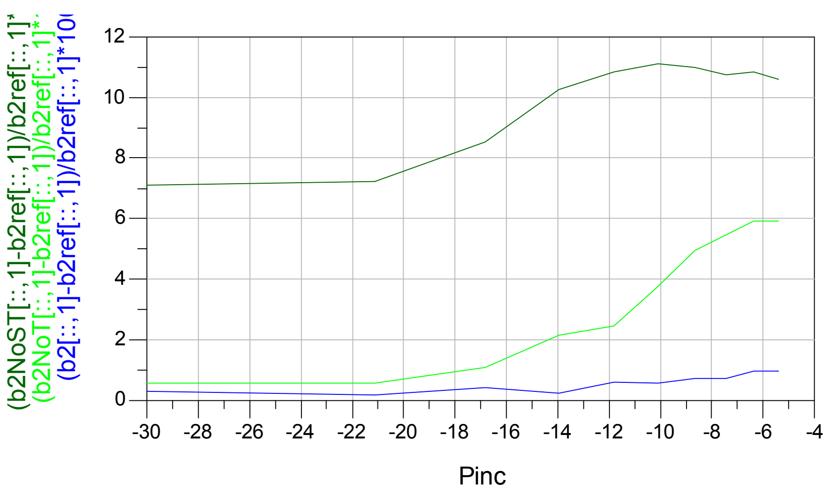
Red: Cascade Measurement

Blue: Cascaded X-parameter Simulation

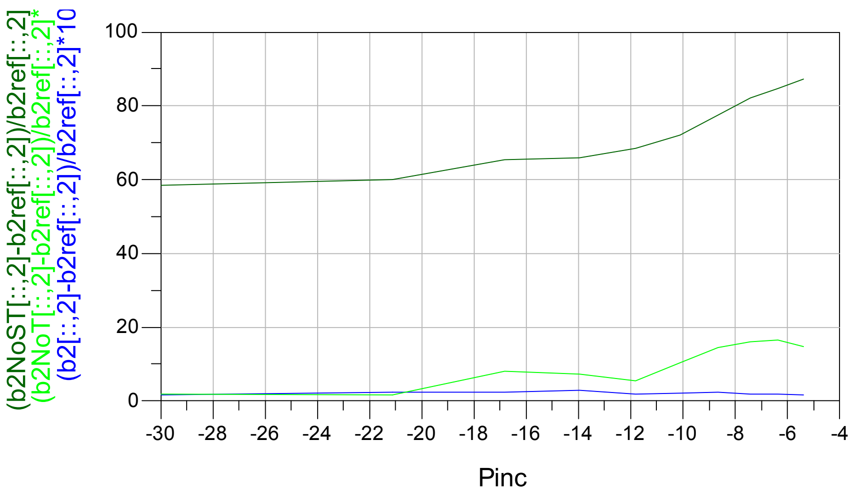
Light Green: Cascaded Simulation, No $X^{(T)}$ terms

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

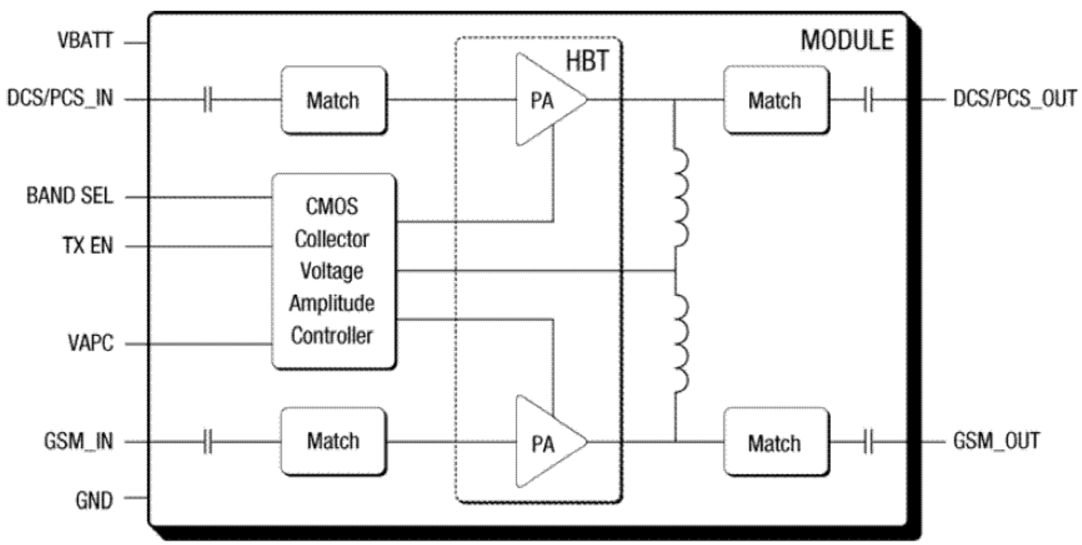
Horn et al *IEEE European Microwave Conference,* Amsterdam, October 2008

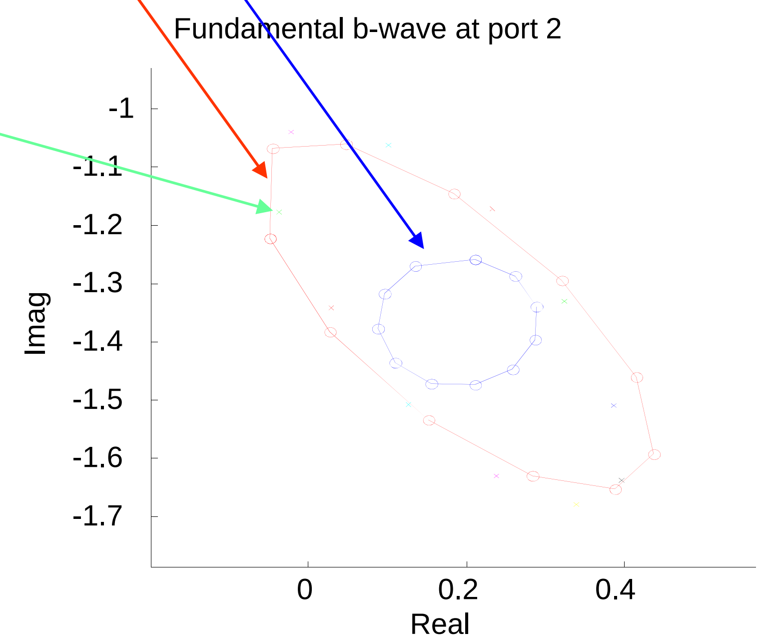
Blue circular shape Hot S_{22} prediction

Red Elliptical shape: X-parameter prediction

Measurements
small colored crosses

Skyworks amp

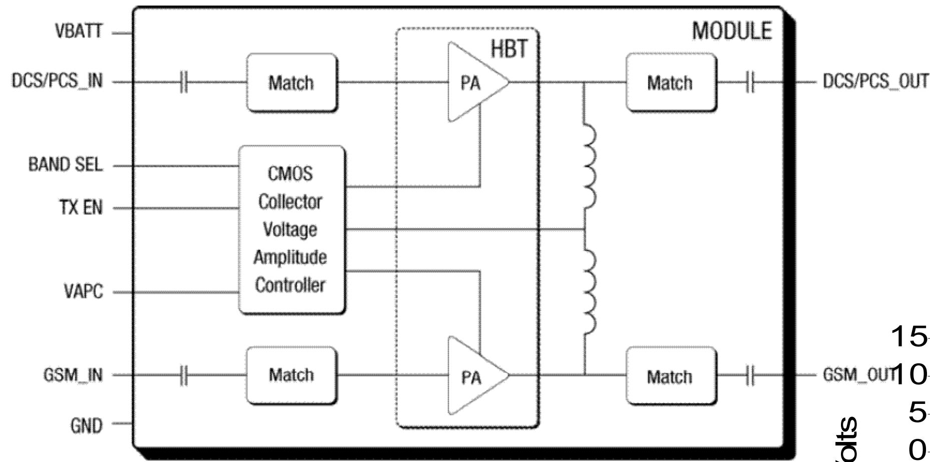




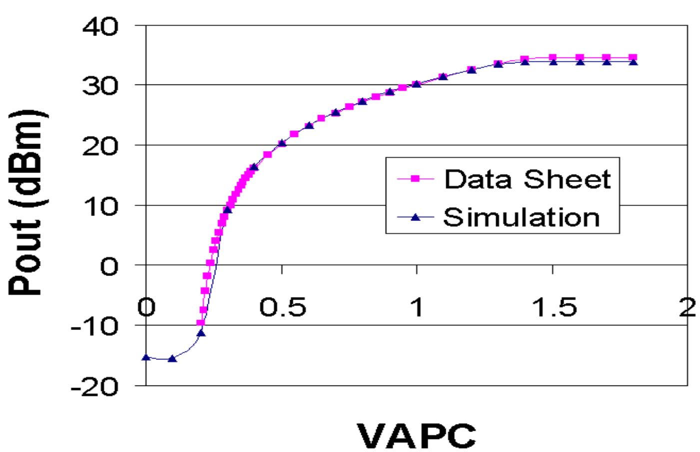
Allowed *Sony-Ericsson* to take into account second-harmonic mismatch on amp in system integration

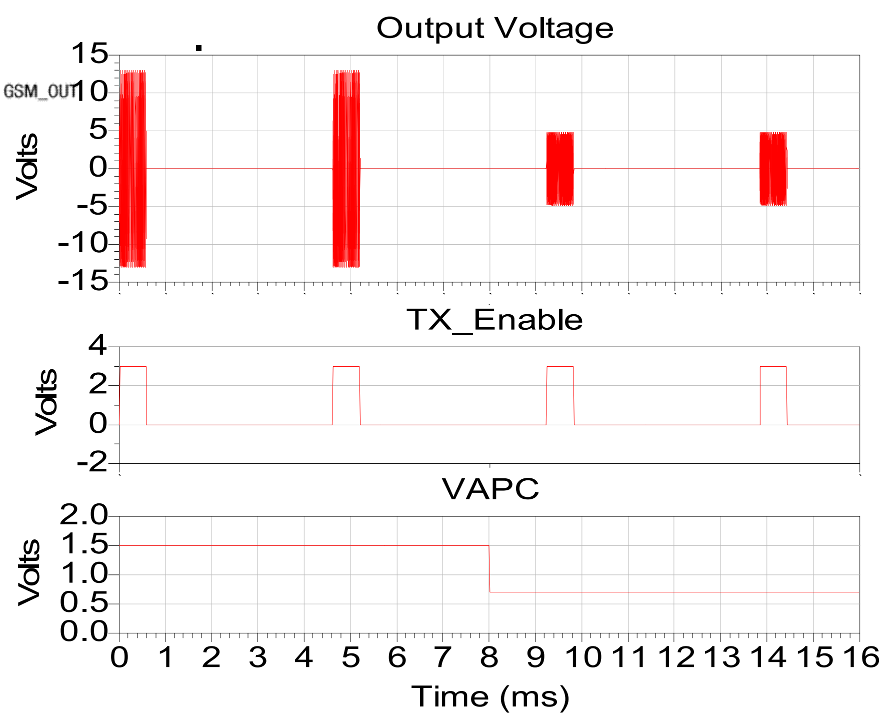
"X-parameters predict output match under large input drive *Hot* S_{22} does not"

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





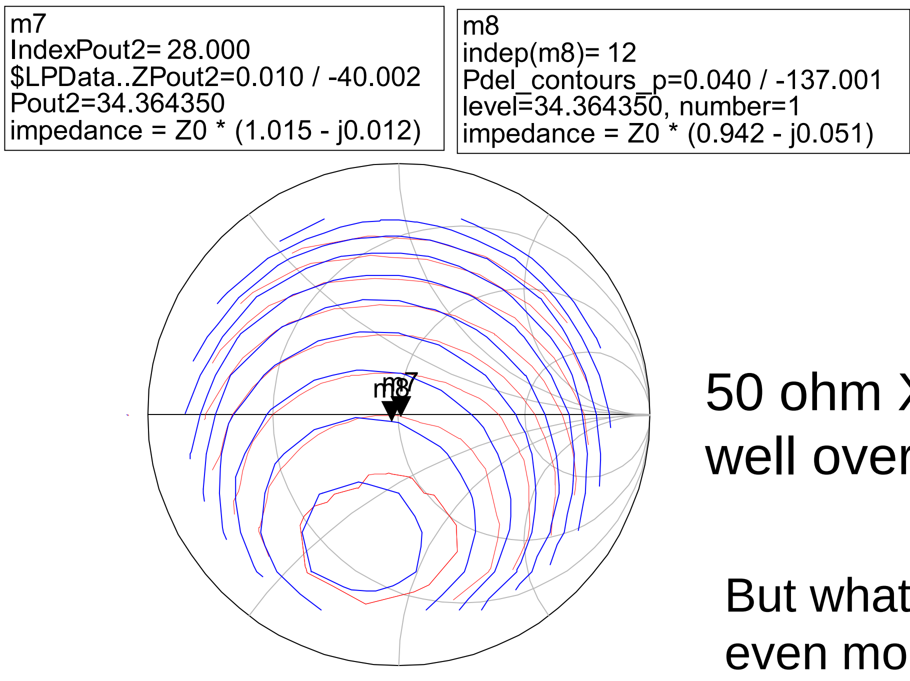
“X-parameters provide a nonlinear electronic interactive datasheet based on data”

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

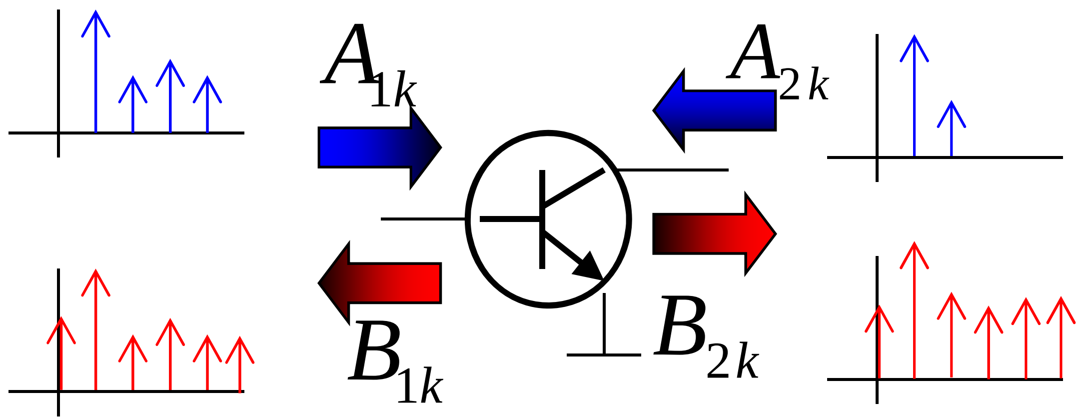


Red: LoadPull measurements
Blue: Simulations using X-parameters *extracted in 50 ohms*

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



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

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

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

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

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

$$B_{e,f} = X_{ef}^{(F)}(DC, |A_{11}|, \Gamma_2)P^{f} + \sum_{g,h} X_{ef,gh}^{(S)}(DC, |A_{11}|, \Gamma_2)P^{f-h} \cdot A_{gh} + \sum_{g,h} X_{ef,gh}^{(T)}(DC, |A_{11}|, \Gamma_2) \; P^{f+h} \cdot A_{gh}^{*}$$

"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

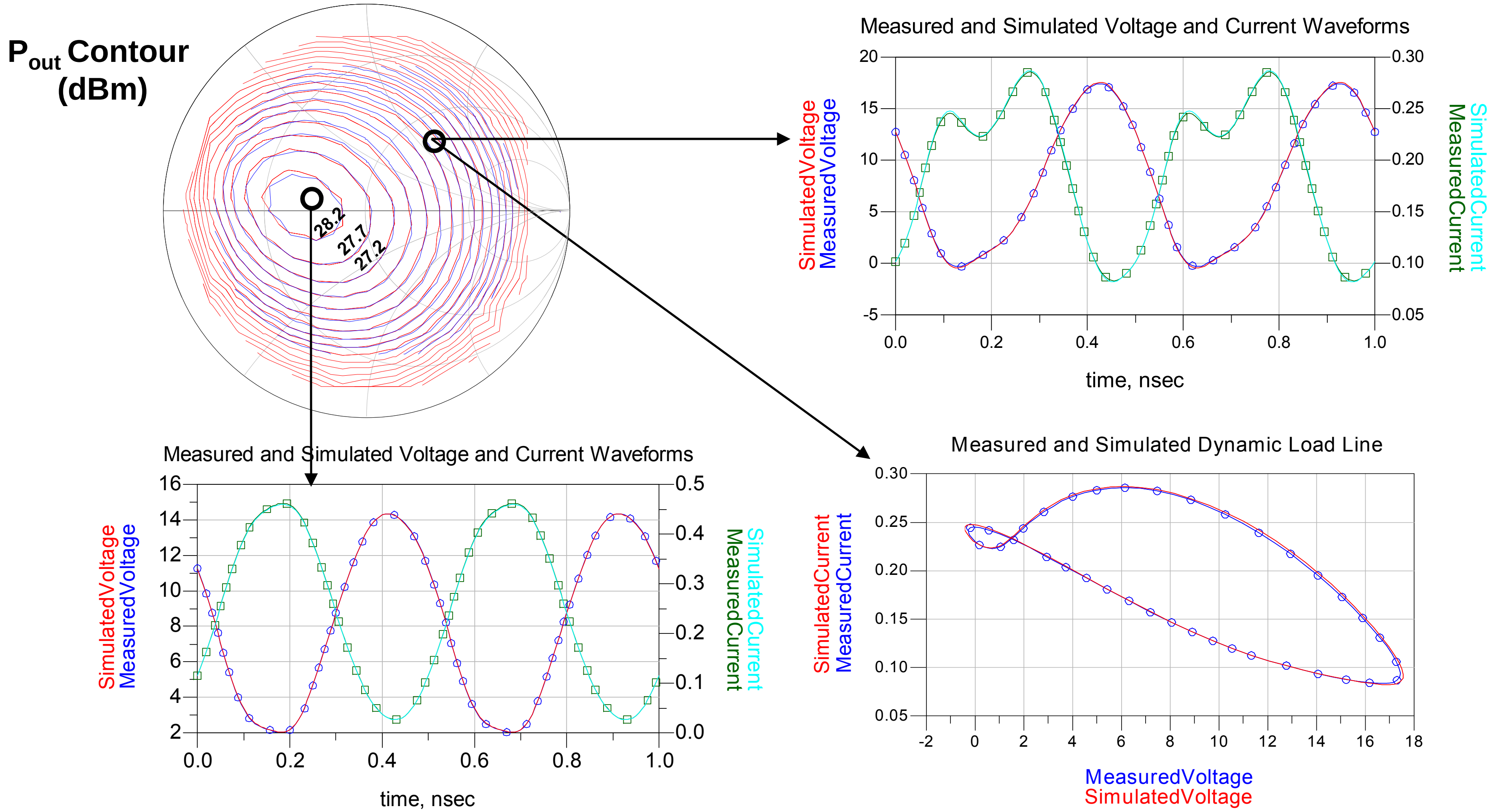
NVNA + Load-Pull

Load-Dependent X-Parameters of a FET

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

Measurements X-par Simulation

WJ FP2189 1W HFET



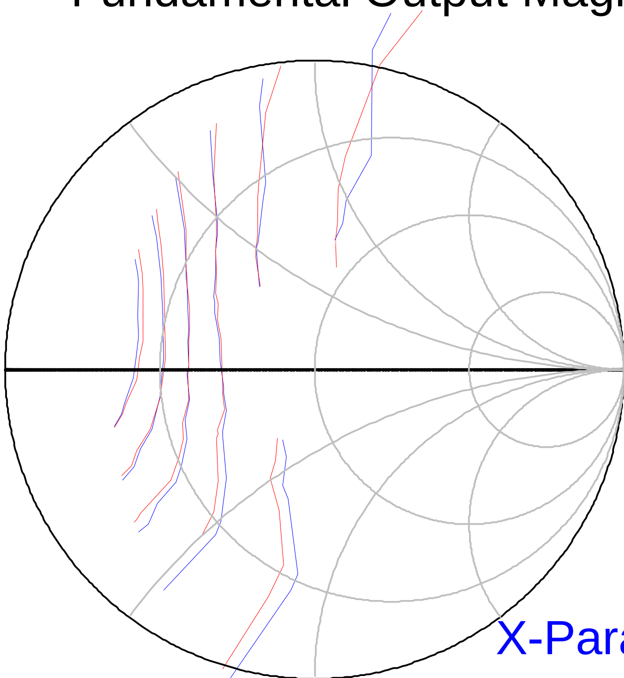
Experimental Harmonic Balance

X-parameters unify S-parameters and load-pull

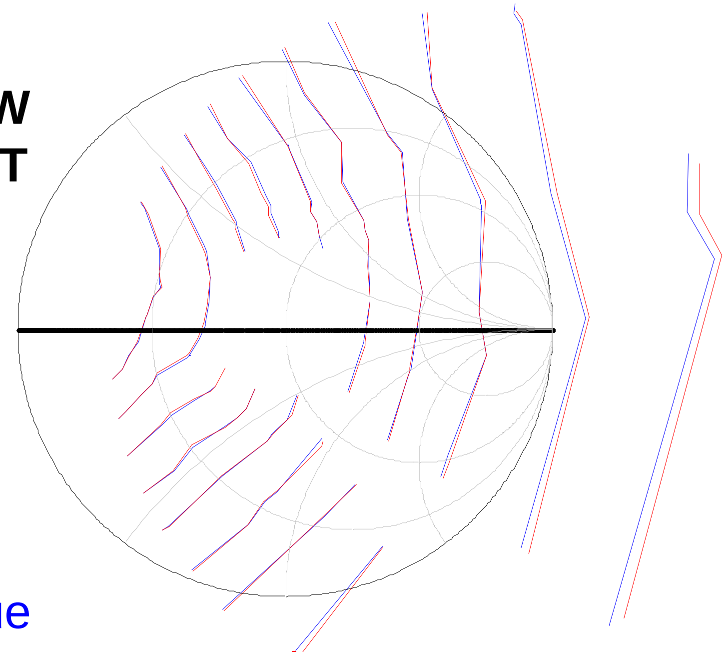
Harmonic Load-Tuning Predictions from X-parameters

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

Fundamental Output Magnitude



Second Harmonic Output Magnitude



Cree CGH40010 10 W RF Power GaN HEMT

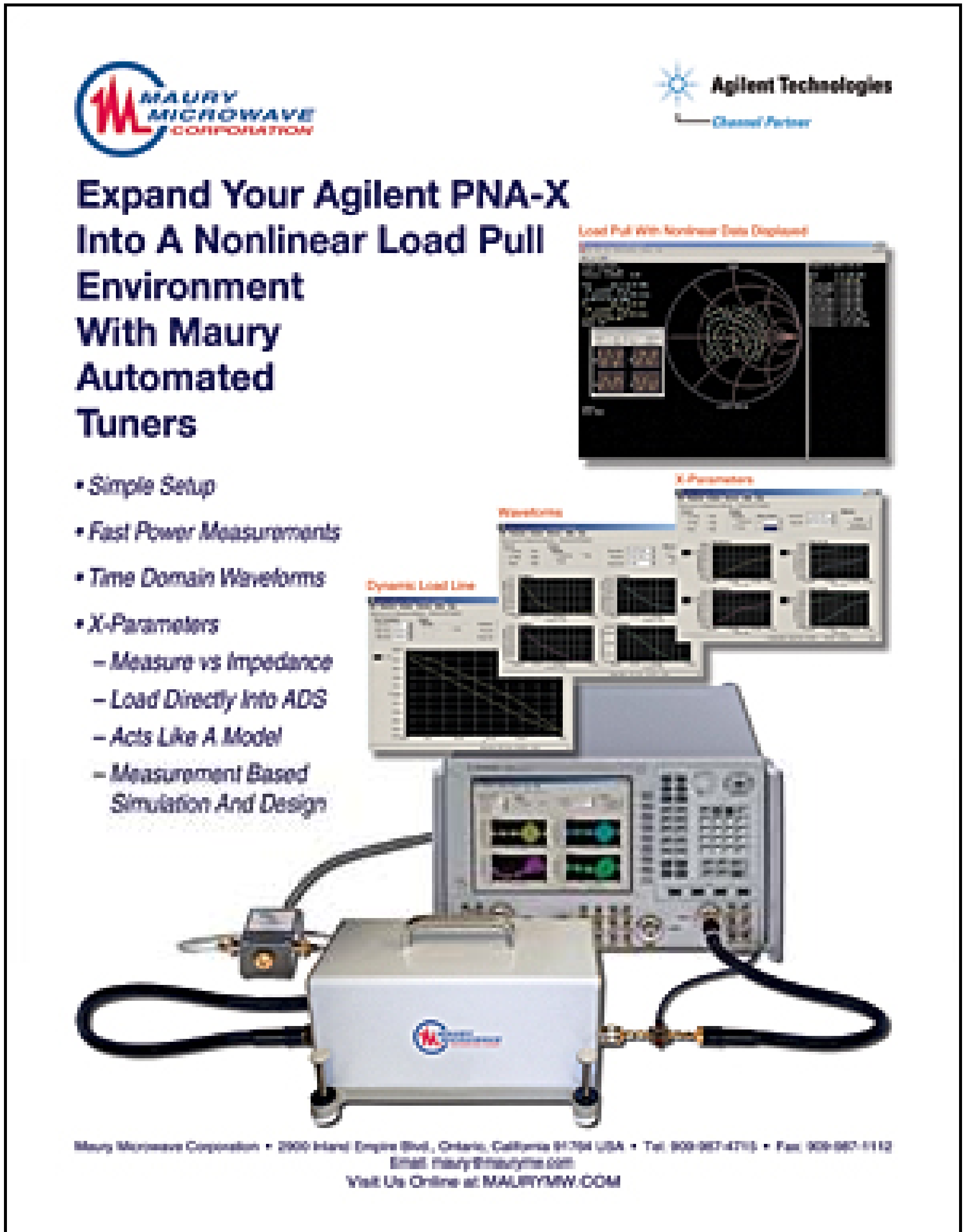
Contours vs. 2nd Harmonic Load (Fixed input power and fundamental load)

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



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

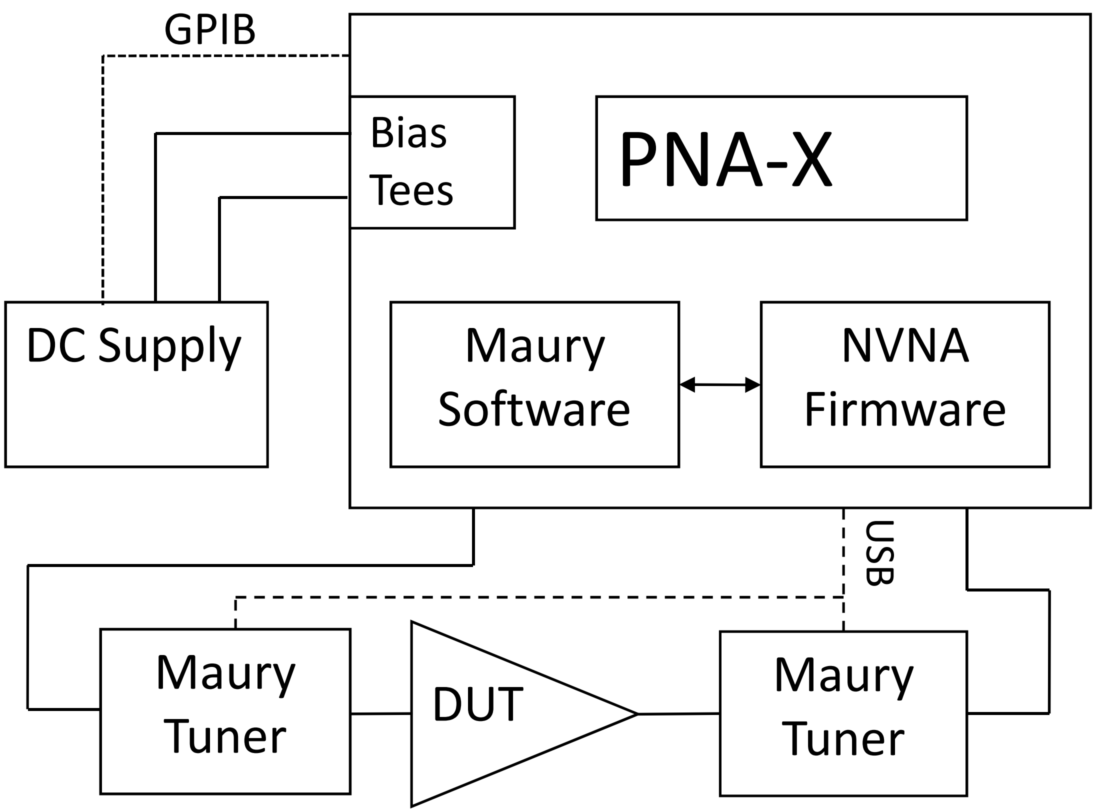
- *One output tuner* to vary load at fundamental frequency. At each load inject small tones at 2nd and 3rd harmonic freqs (9x(1+2x2) = 45 measurements, actually ~99 measurements)
- Measured DC – 4th harmonic
- Take into ADS. Present 729 independent loads to model

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

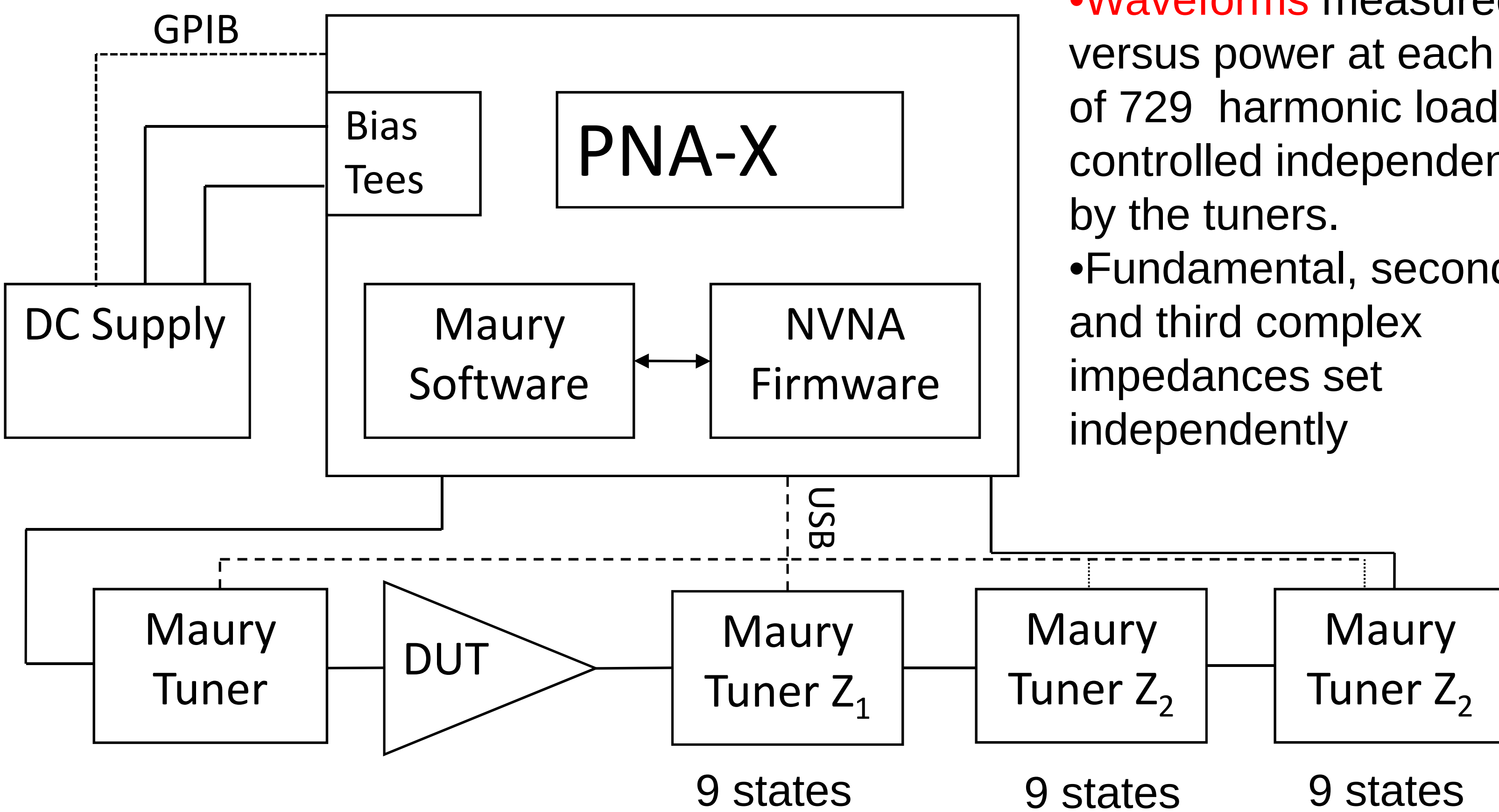
X-parameter file taken into ADS
for independent validation

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 2nd and 3rd 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

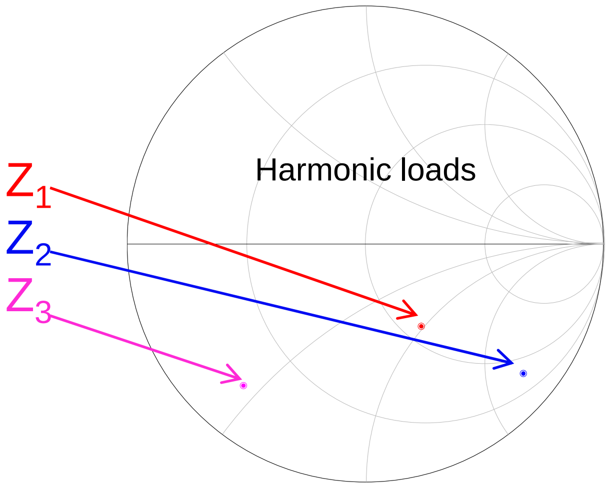
- *Three output tuners* to vary loads at fundamental, second, and third harmonics independently (9x9x9 = 729 measurements)
- Measured DC - 4th harmonic

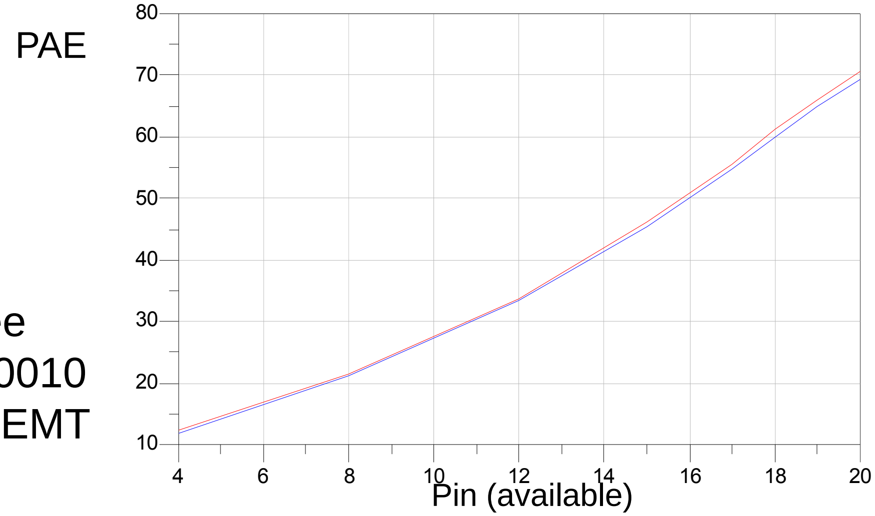
Compare waveforms, PAE, dynamic load-lines, etc.

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

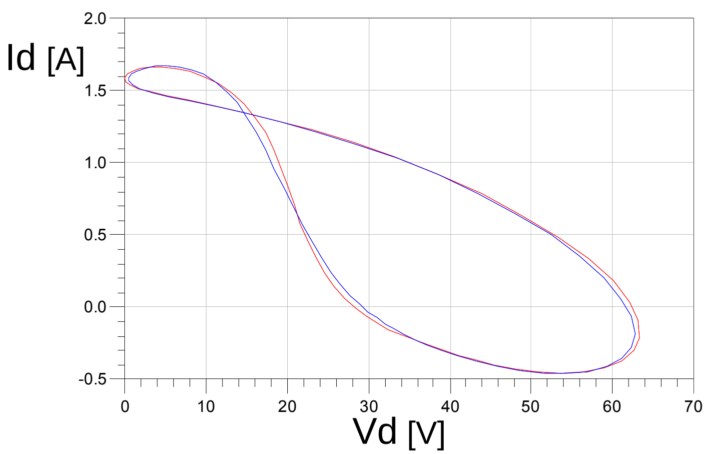
Courtesy of J. Horn

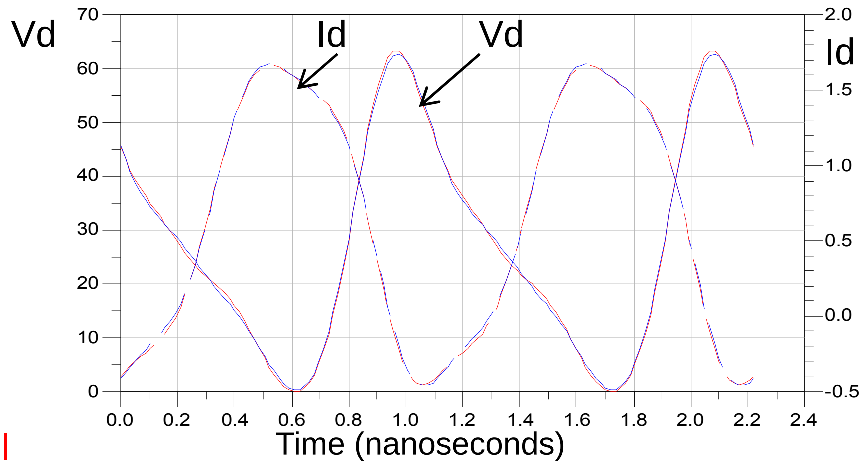
J. Horn et al, *submitted to CSICS2010*





Cree
CGH40010
GaN HEMT



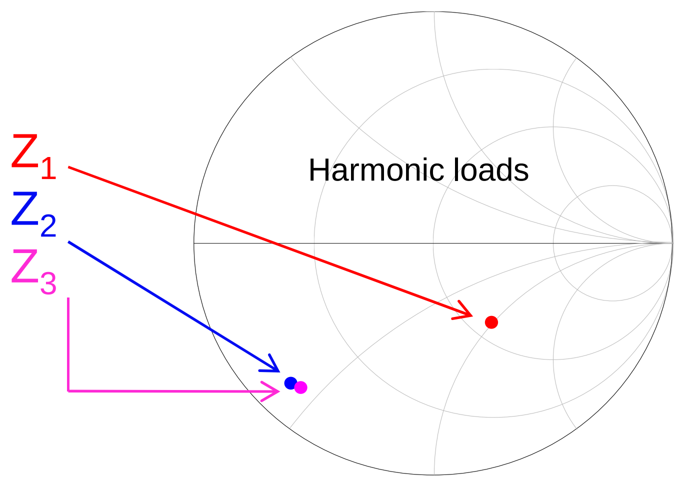


X-parameter model

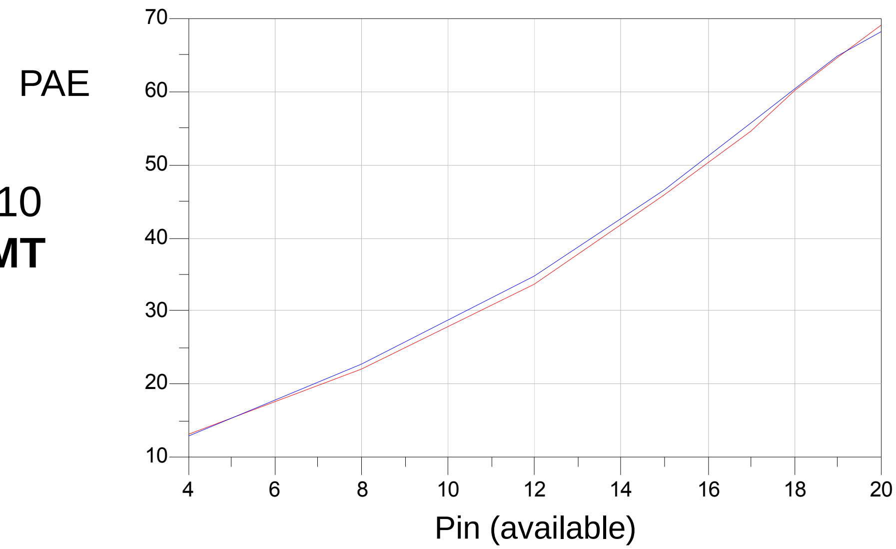
Harmonic time-domain load-pull measurements

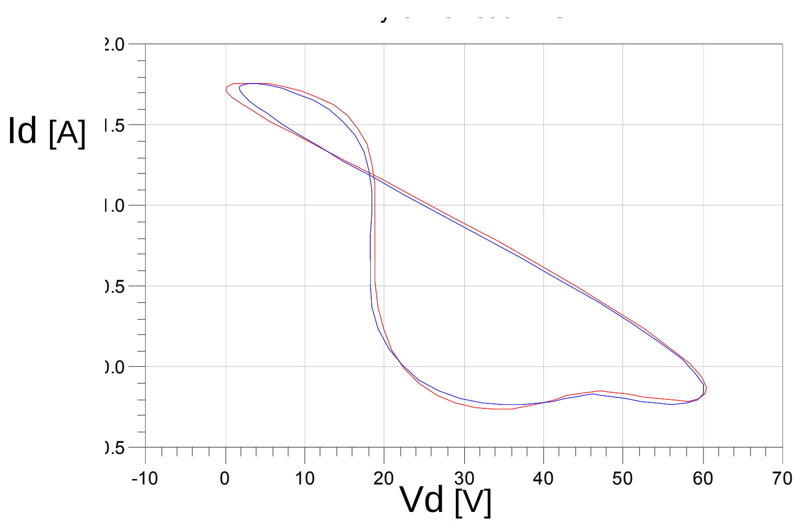
Agilent Technologies

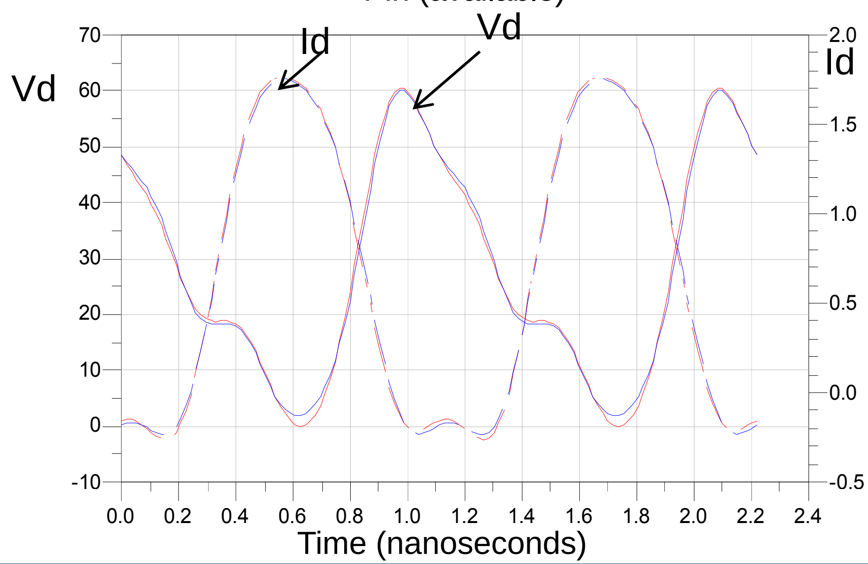
Prediction of GaN HEMT *harmonic-load dependence* from fundamental-only load-dependent X-pars



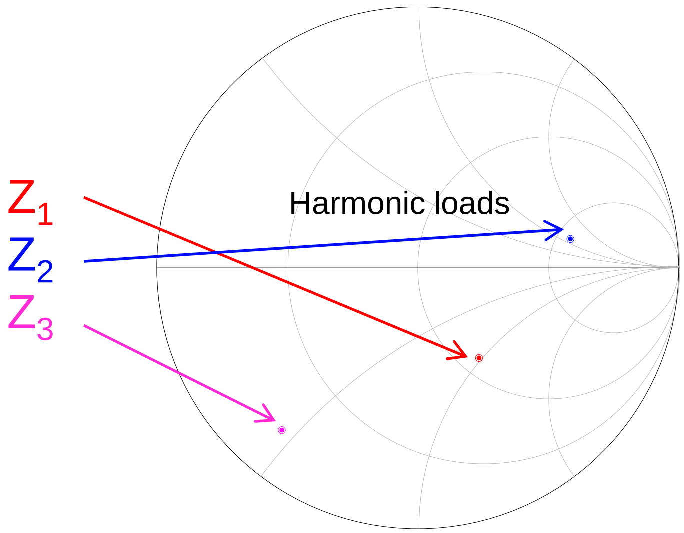
Cree
CGH40010
GaN HEMT



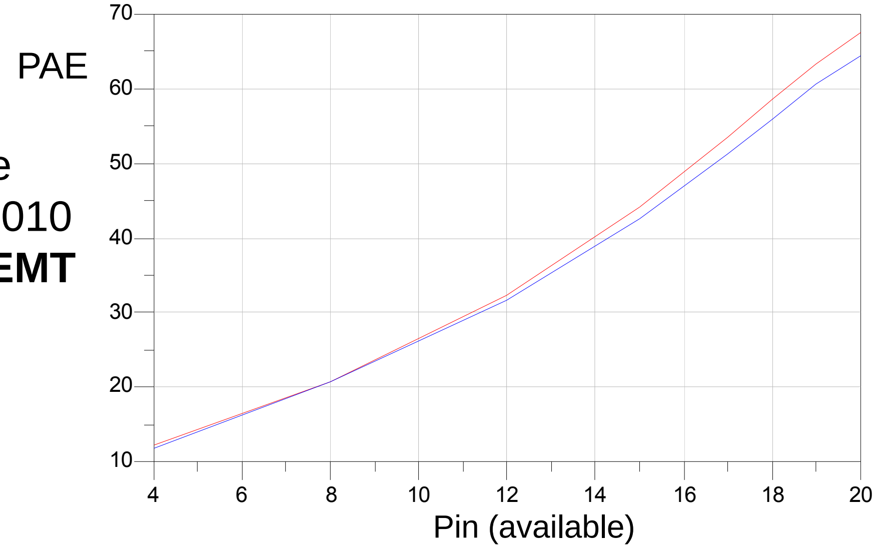


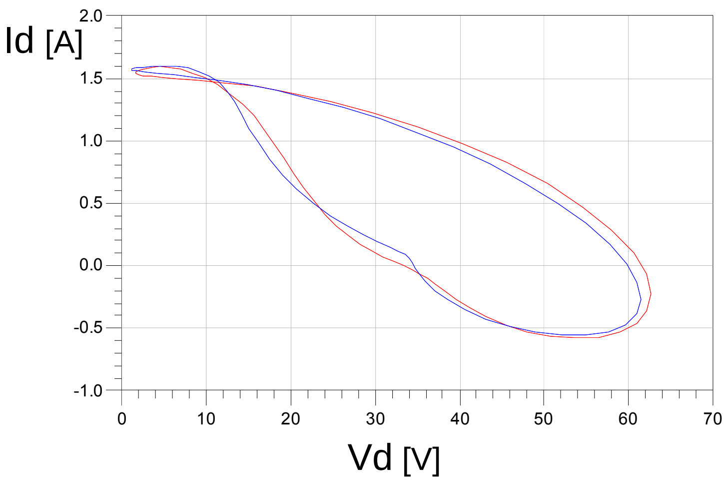


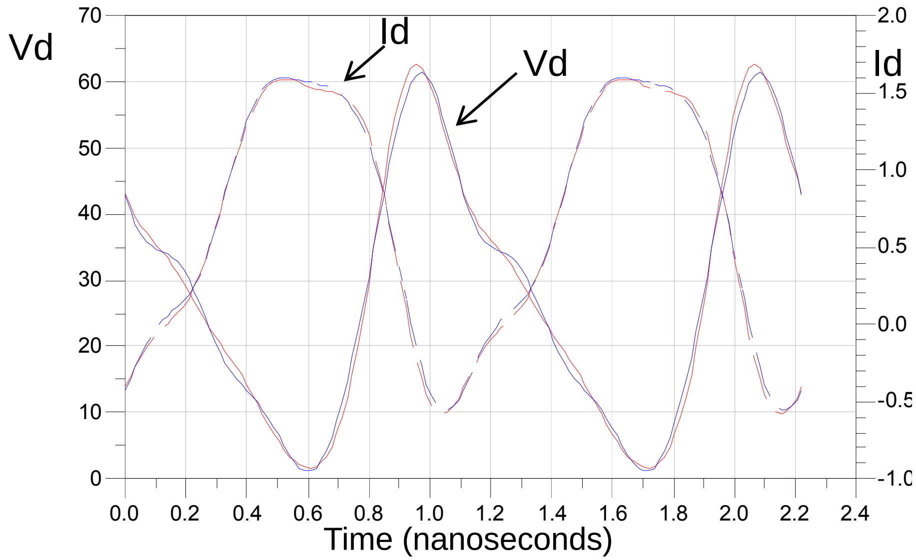
Prediction of GaN HEMT *harmonic-load dependence* from fundamental-only load-dependent X-pars



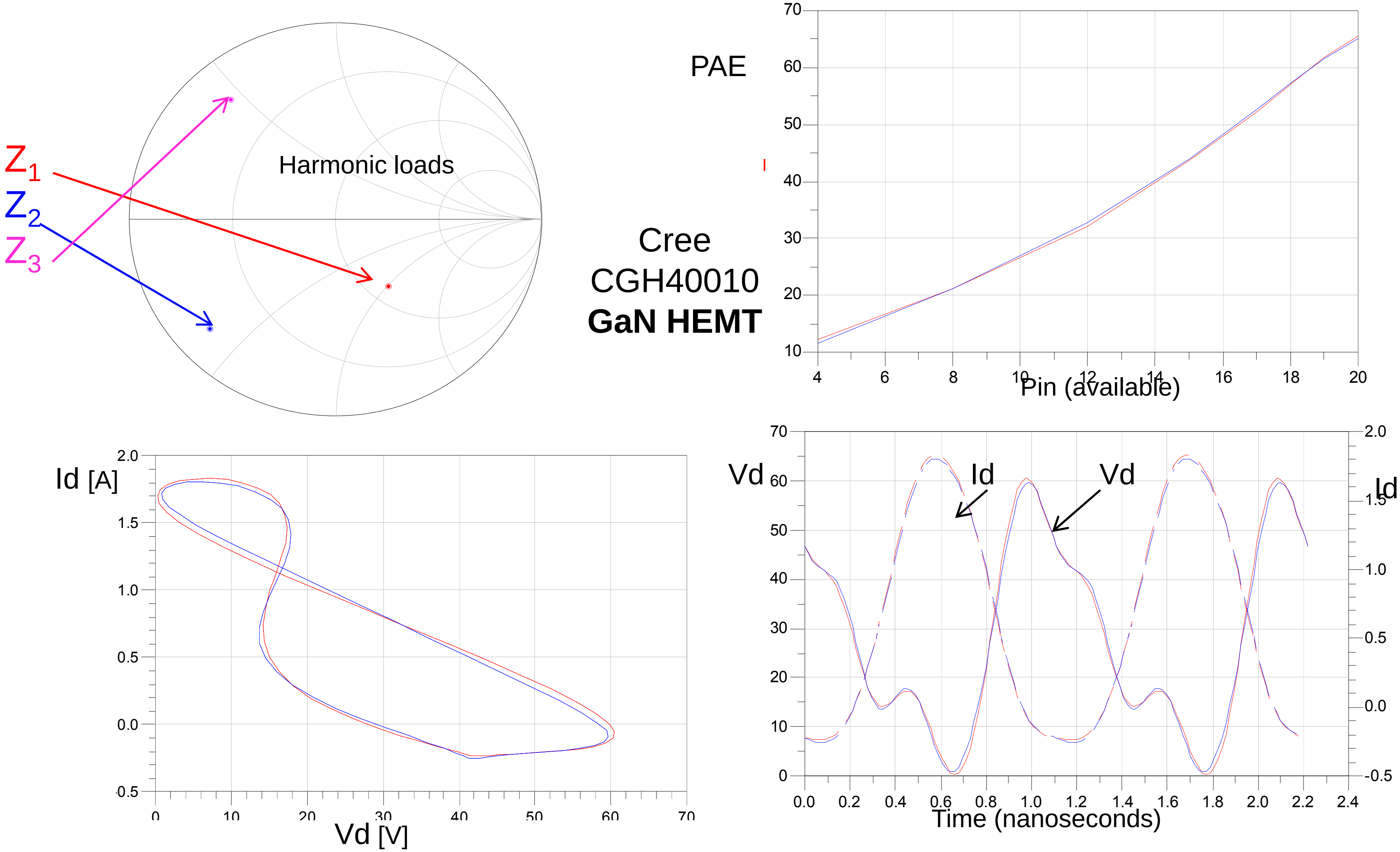
Cree
CGH40010
GaN HEMT







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



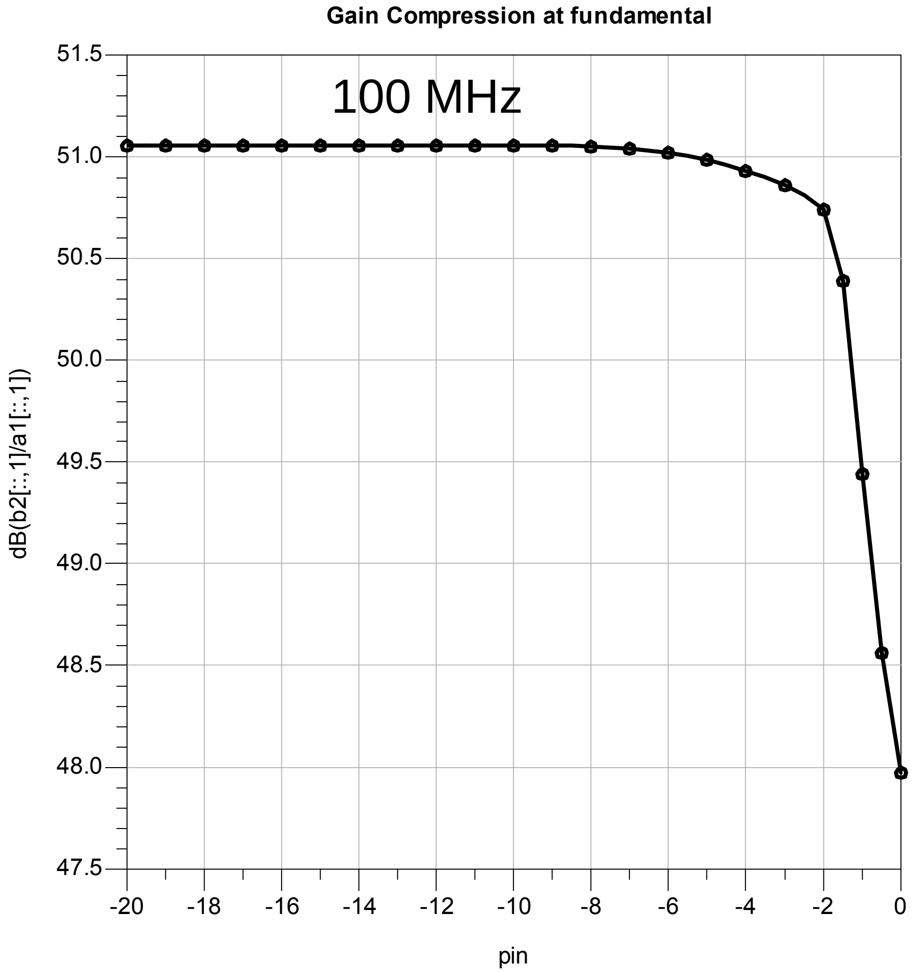
Summary:
Fundamental-only load-dependent X-parameters

- 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)

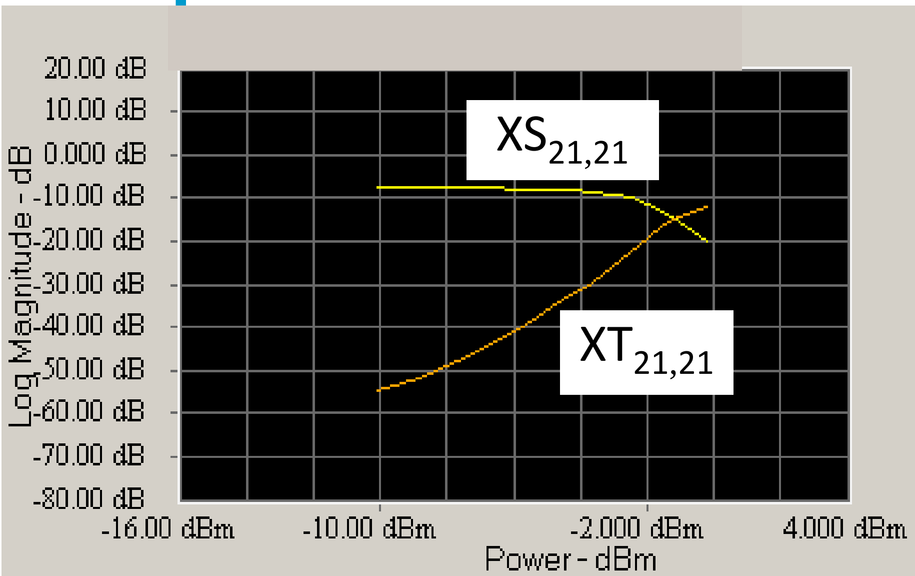
Mini-Circuits ZHL-100W-52

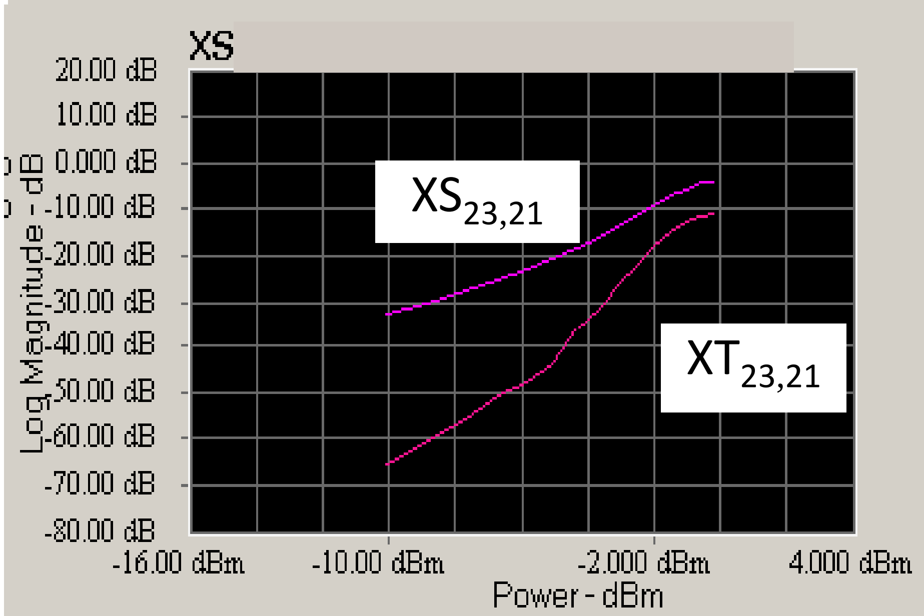
Parameter	Description
Part Number	ZHL-100W-52
Pout max (@1dB compression)	45dBm (min, 50M-500MHz) 47dBm (typ, 50M-500MHz)
Pout max (@3dB compression)	46.5dBm (min, 50M-500MHz) 48.5dBm (typ, 50M-500MHz)
Pin max (no damage)	+3dBm
Gain	48dB (min) 50dB (typ)
Input VSWR	1.45:1 (typ)
Output VSWR	2.5:1 (typ)



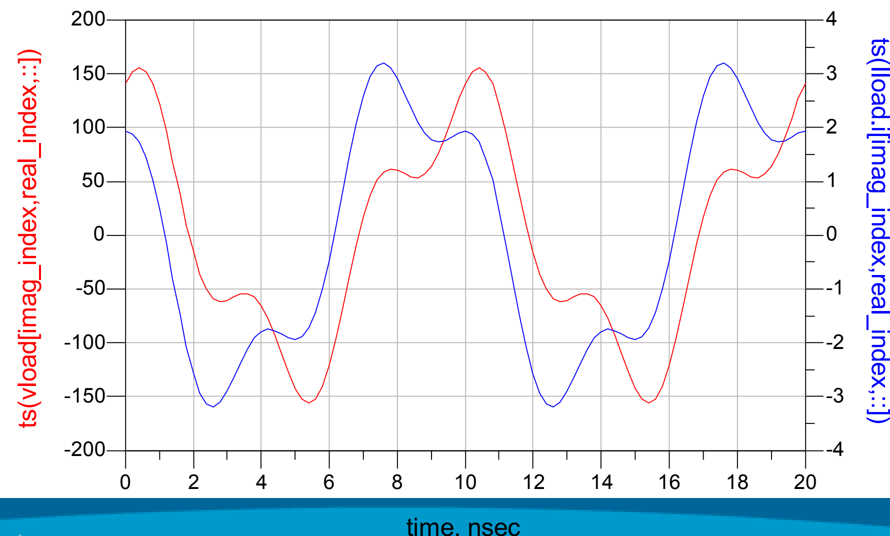
X-parameters have been measured at 250 W

X-parameters at 100W

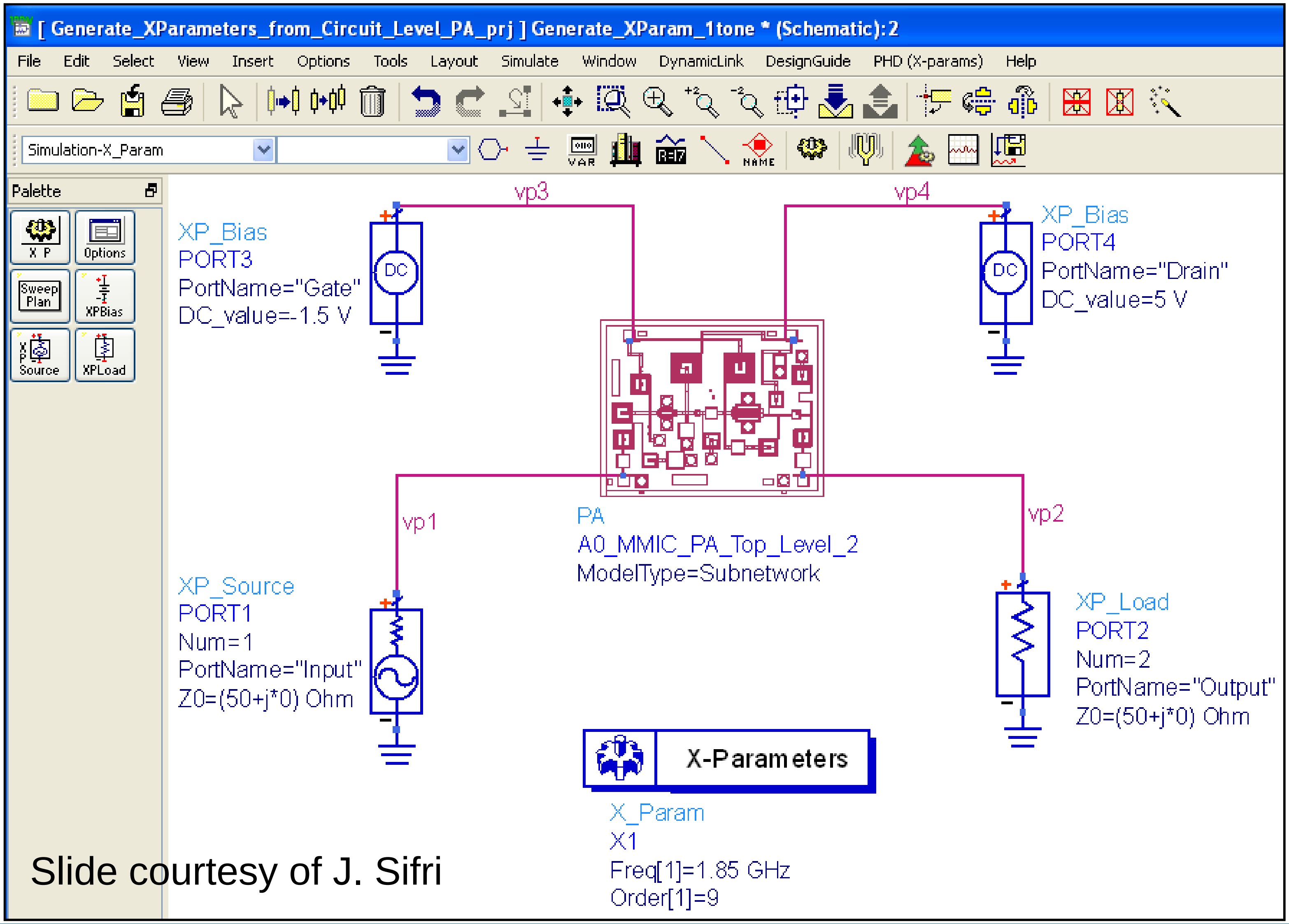




5 harmonics, magnitude and phase:
fund=150 MHz



Generate an IP-Protected X-parameter model

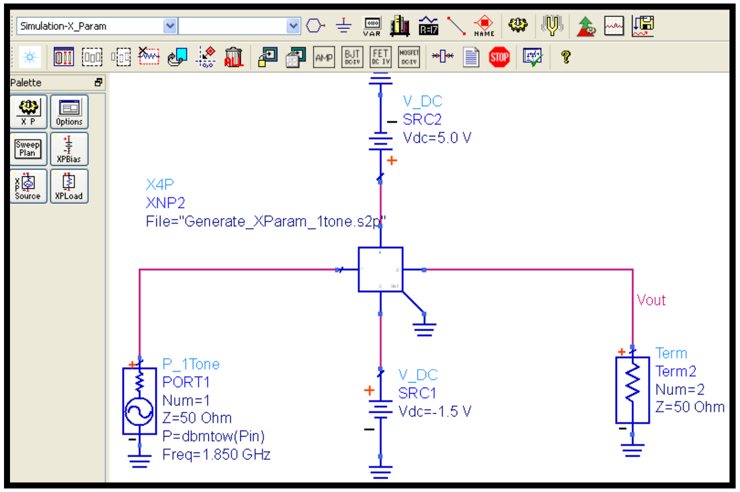


Slide courtesy of J. Sifri

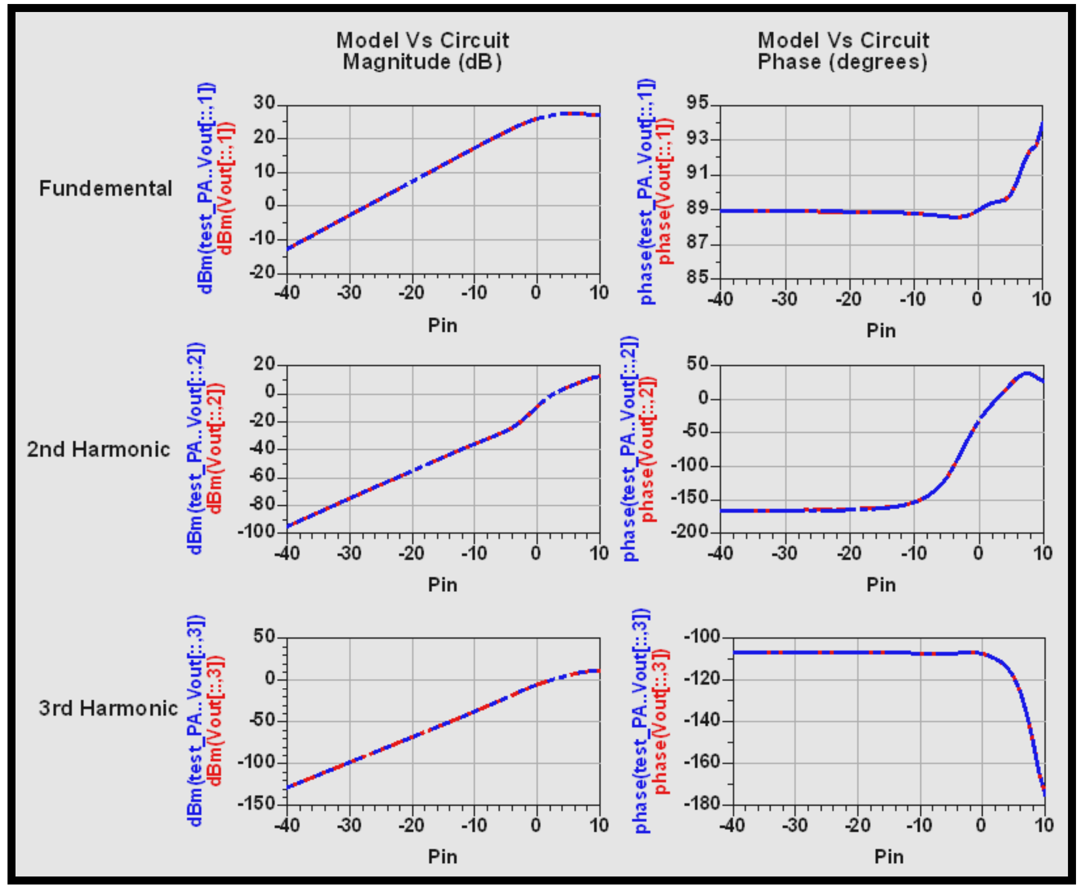
Agilent Technologies

Single Tone Amp model with 50 ohm load

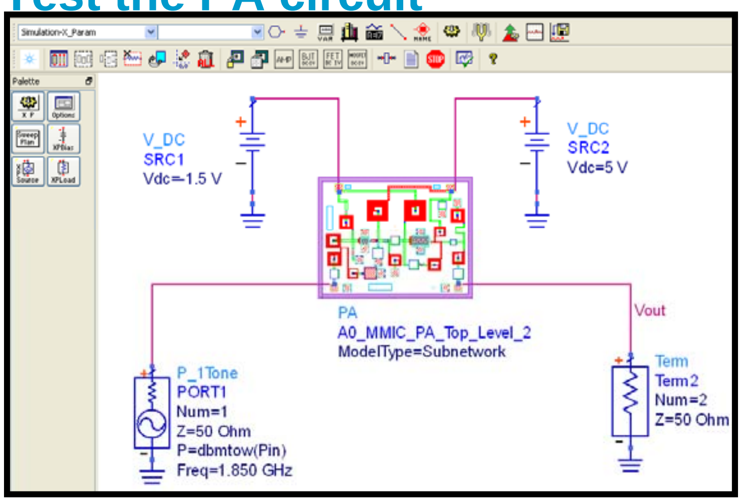
IP-protected model; Fast X-parameter simulation component (20x faster)



X-pars Vs ckt-level PA Results



Test the PA circuit



Agilent Technologies

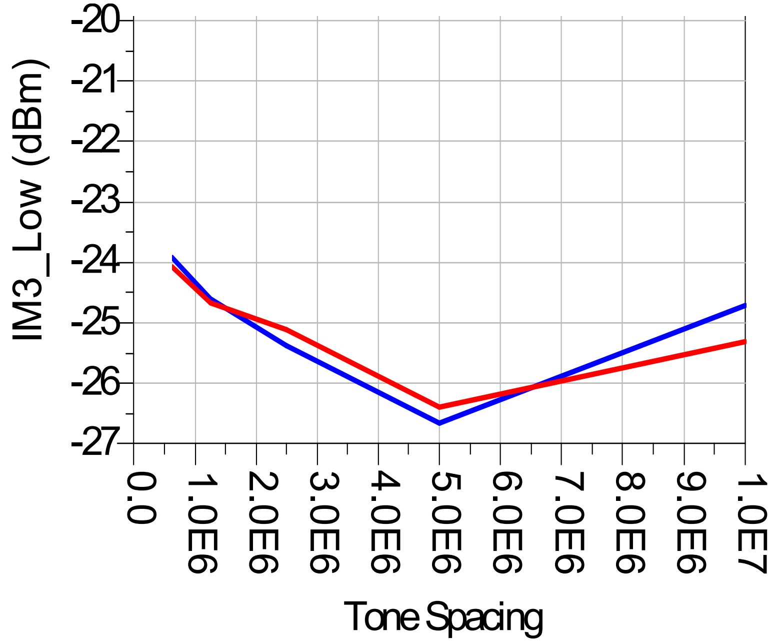
Soon: Two-tone X-parameter NVNA measurements

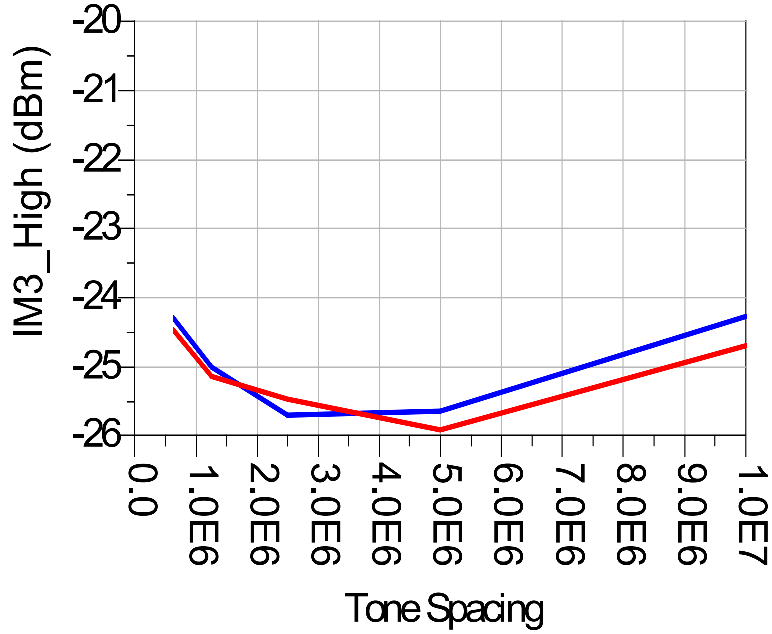
- Magnitude *and Phase* of intermod products and sensitivity to mismatch
- Measure and simulate freq-dependence & asymmetry of complex intermods
- Design nonlinear circuits that cancel distortion
- ADS X-parameter generator and XnP component can do this already

Red = 2-Tone X-parameters prediction

Blue = Independent measured data

Courtesy J. Horn

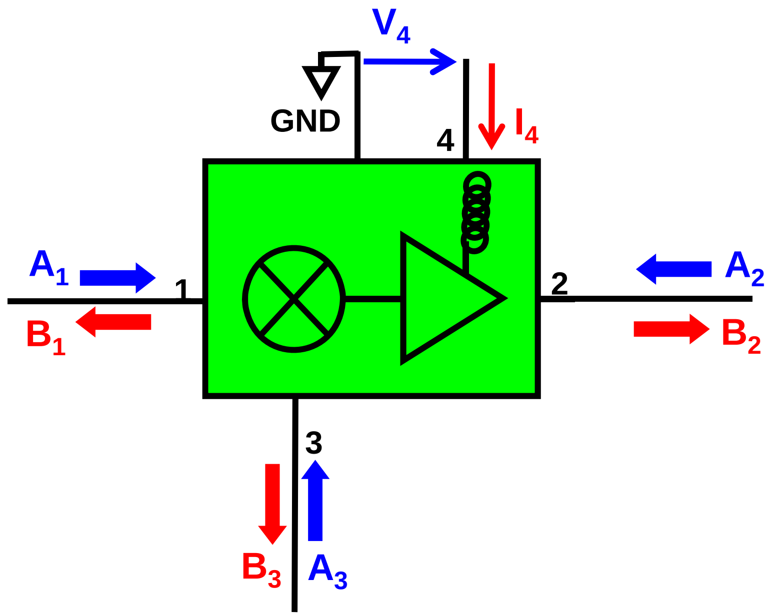




3-Port X-parameter Measurements

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

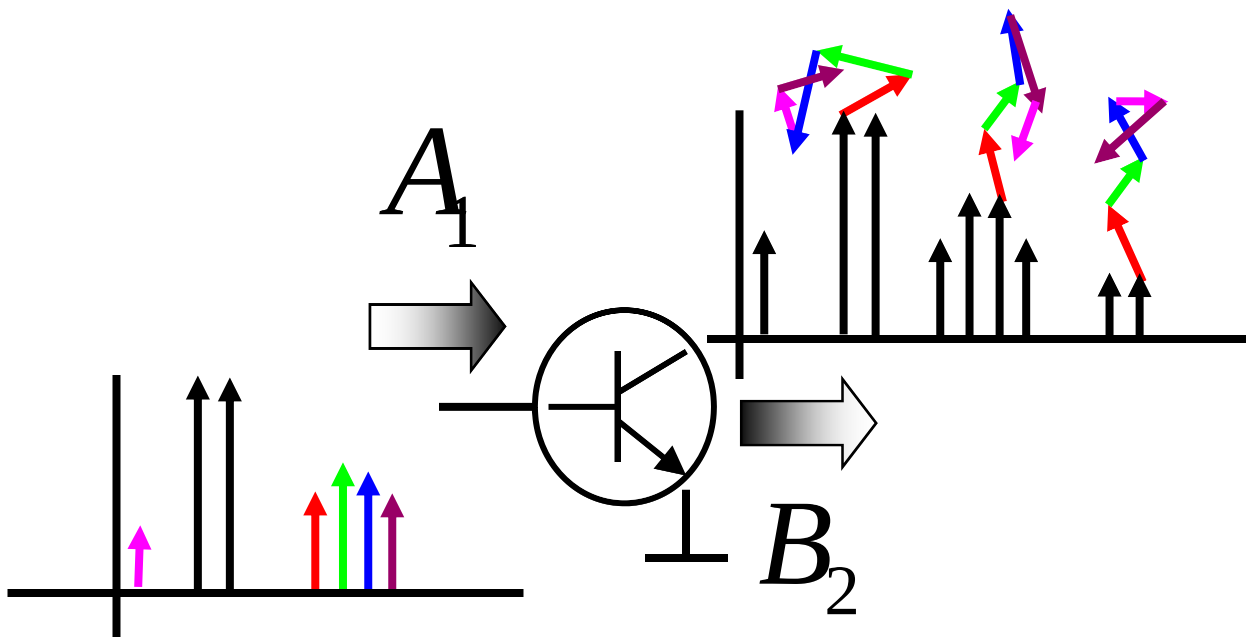
Note: ADS can already generate and simulate with multi-port, multi-tone X-parameters



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



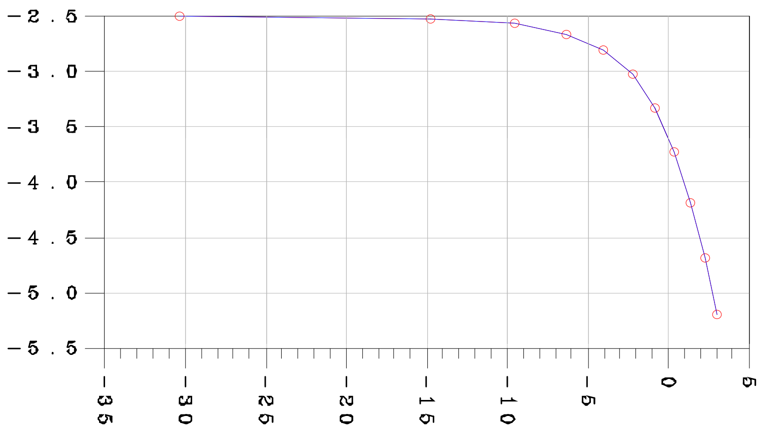
$$B_{i,kl} = X_{i,kl}^{(F)}(A_{1,10}, A_{2,01}, 0, 0, \ldots) + \text{Terms } \textit{linear} \text{ in the remaining components}$$

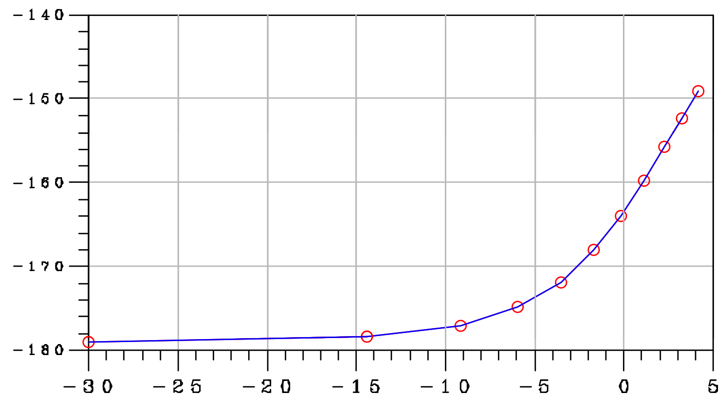
Mixers: X-parameters extracted from an Agilent DC-50 GHz InP-based Mixer 1GC1-8068: Mismatched (10 Ohms) at IF

Accurate, fast, IP-protected

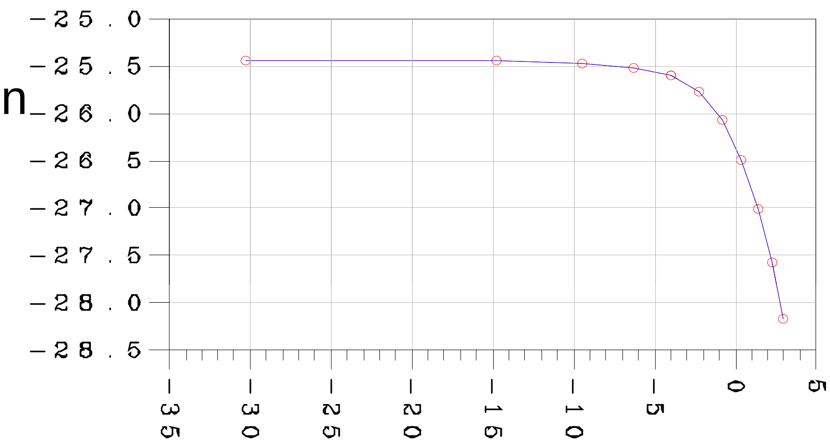
Gain (dB) | Phase (deg)

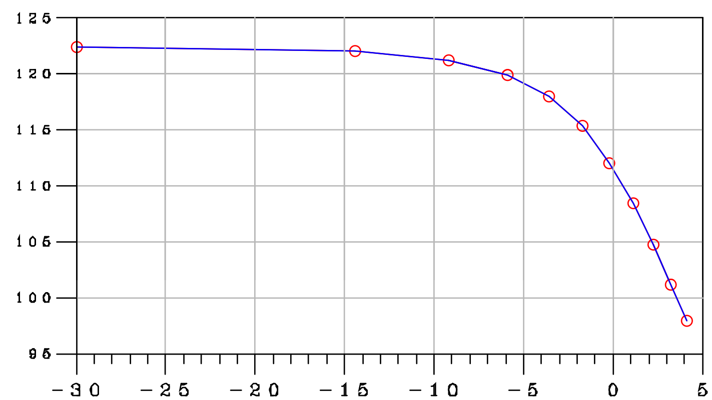
Down Conversion





Up Conversion





Simulation-based

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

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

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

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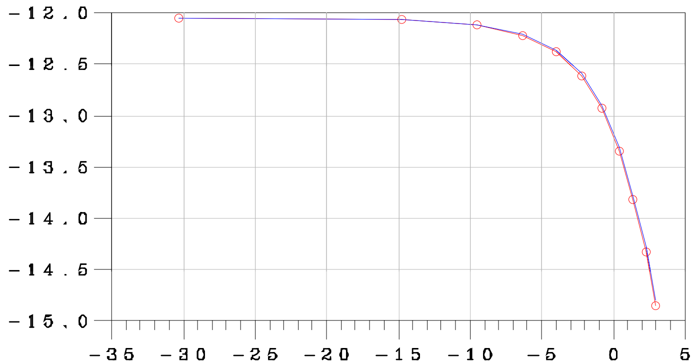
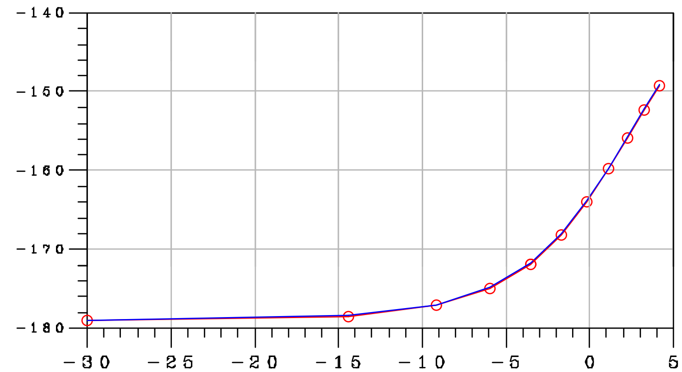
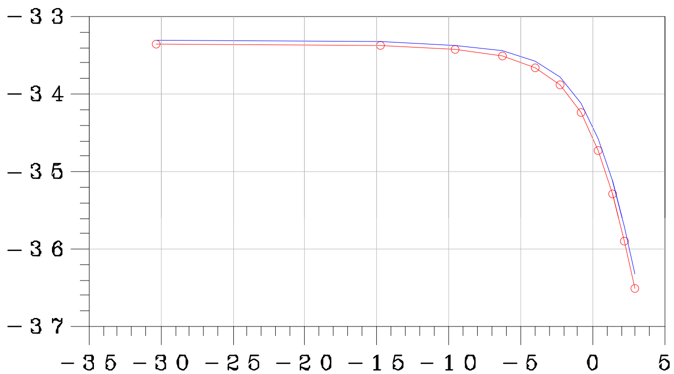
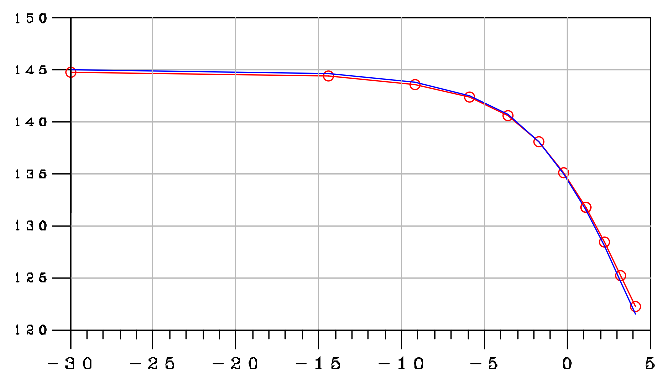




Up Conversion





Simulation-based

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

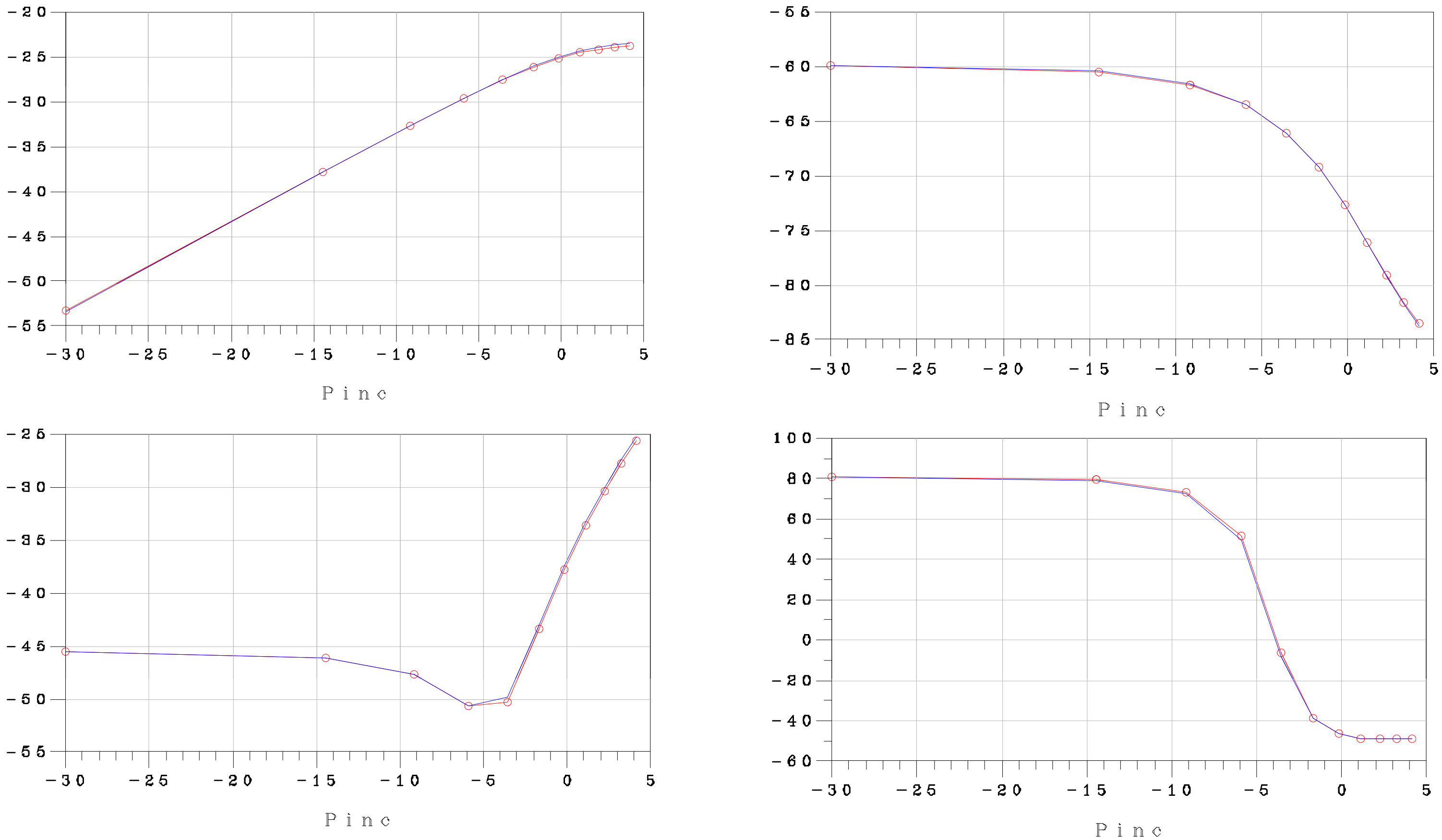
Circuit Model (solid blue) X-parameters (red points)

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

Gain (dB) | Phase (deg)

LO Leakage

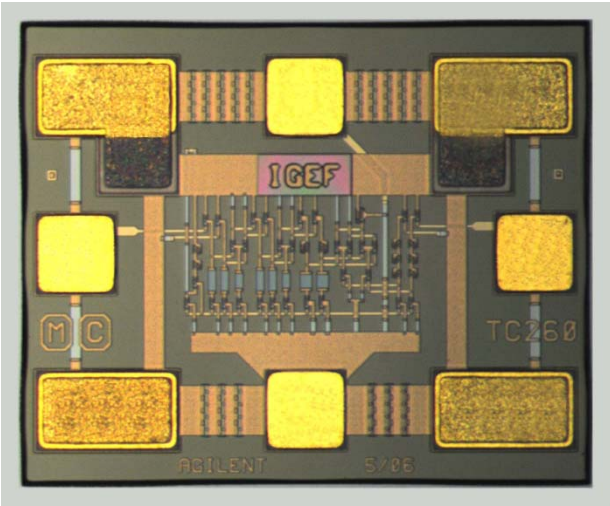
RF Leakage

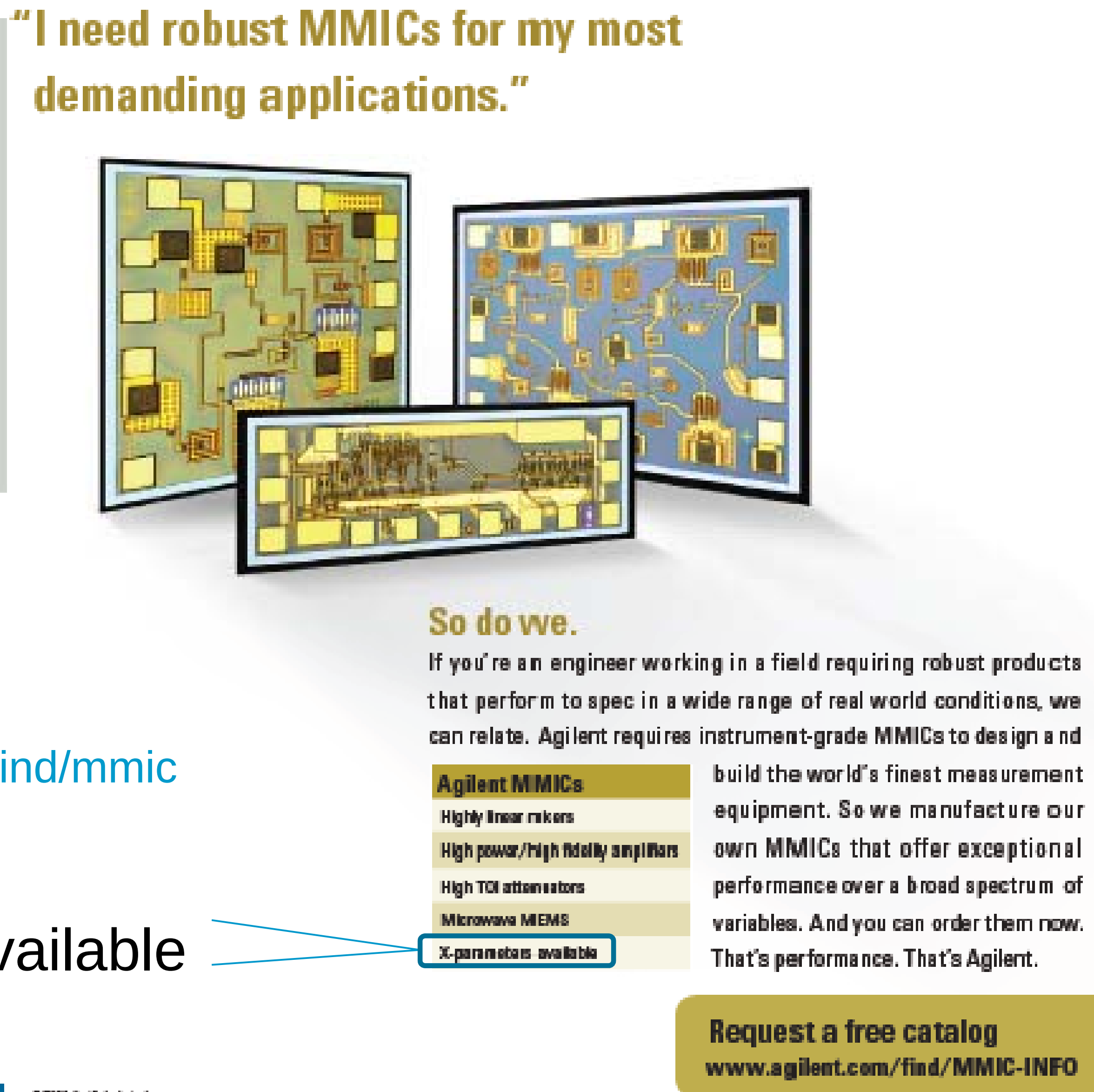


Simulation-based LO: 45 GHz RF: 45.1 GHz LO power = 3.5 dBm

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

Agilent MMICs: Available for purchase



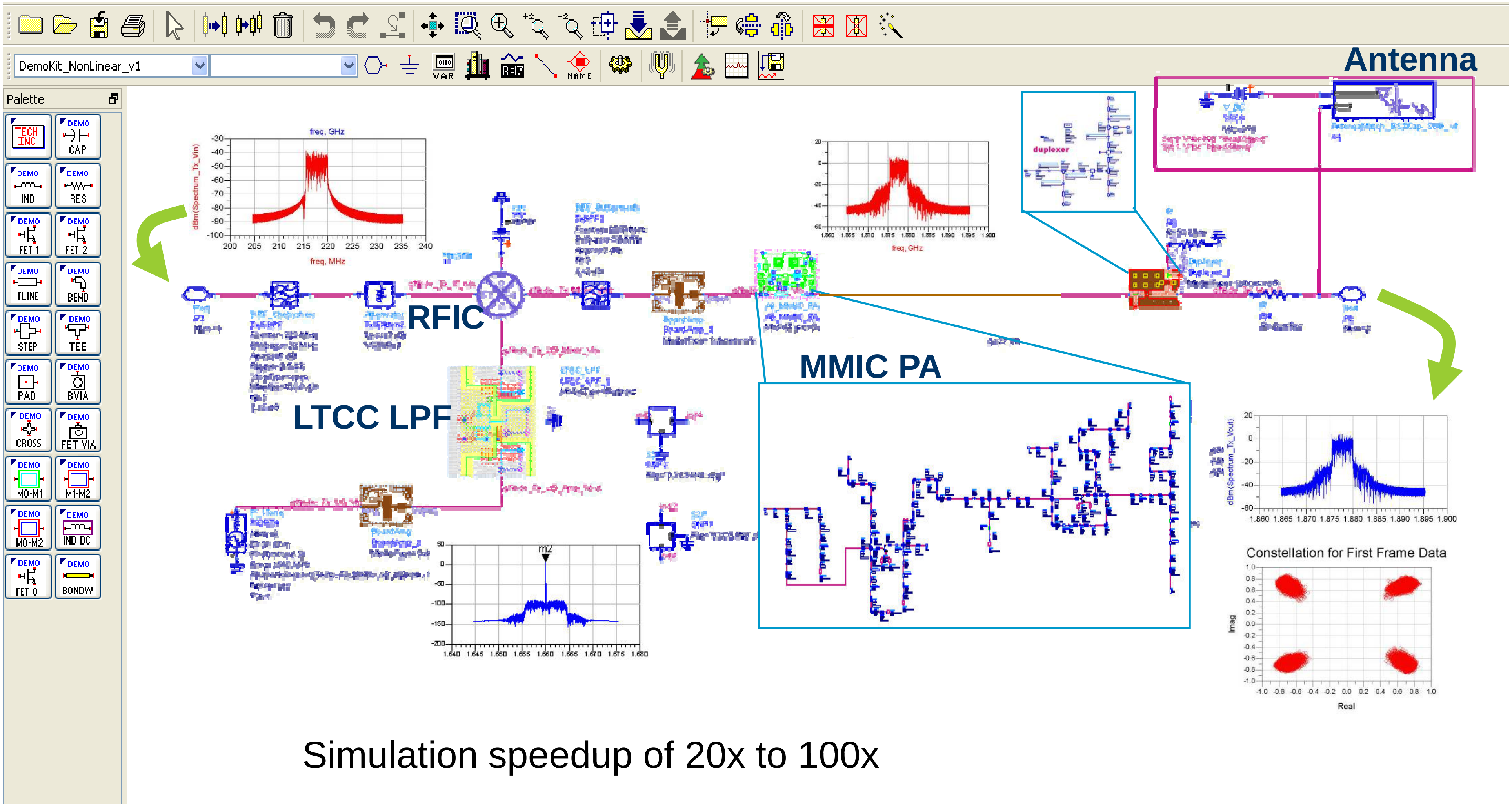


50 GHz InP-based Mixer
Part number: 1GC1-8068

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

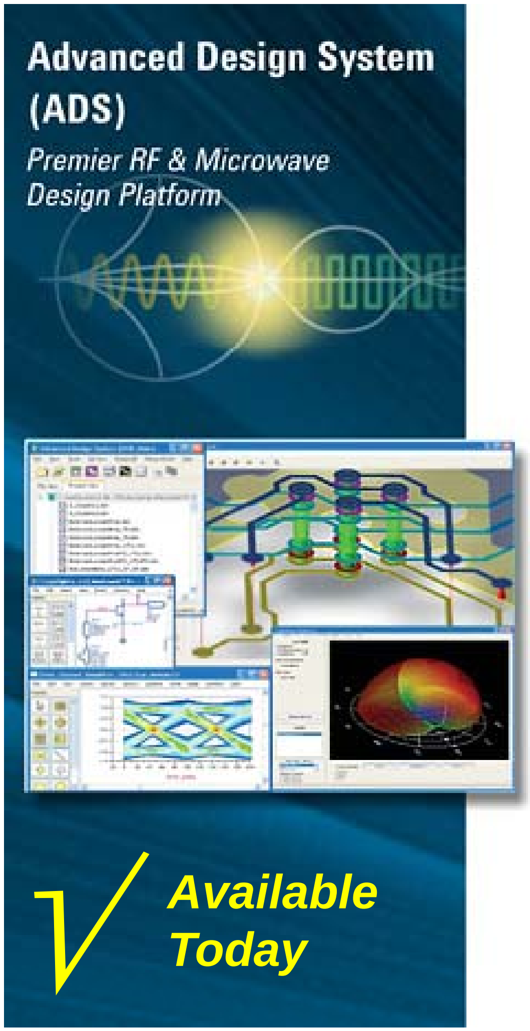
X-parameters available

Design Nonlinear RF Systems

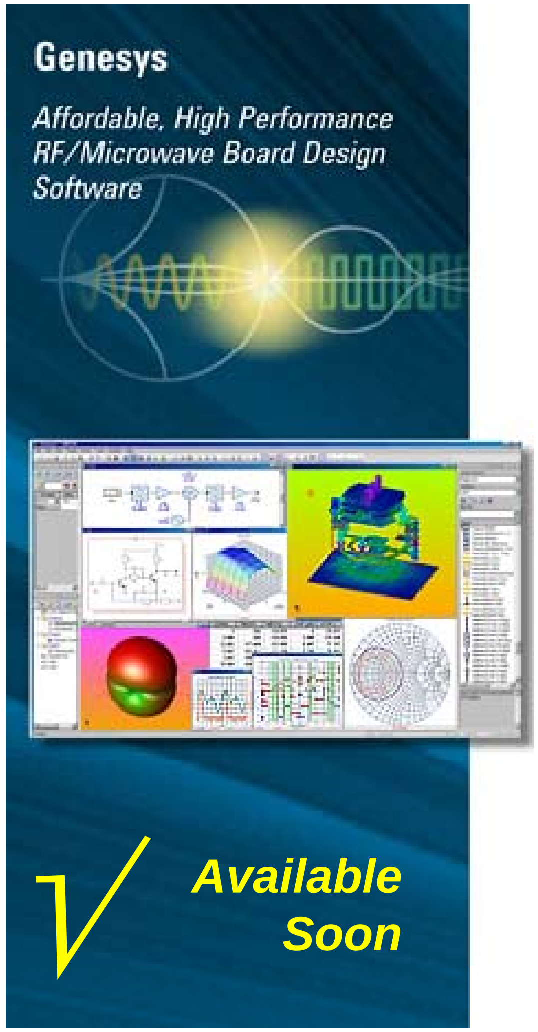


Simulation speedup of 20x to 100x

X-Parameter technology available in commercial EDA SW



√ ***Available Today***



√ ***Available Soon***

√ ***Available Soon***

MTTS IEEE

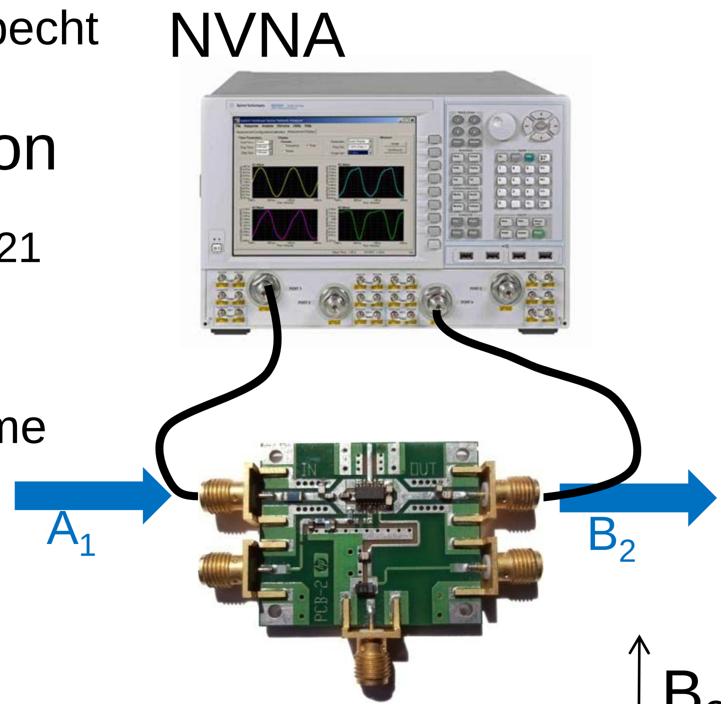
Agilent Technologies

Extending X-parameters to long-term memory

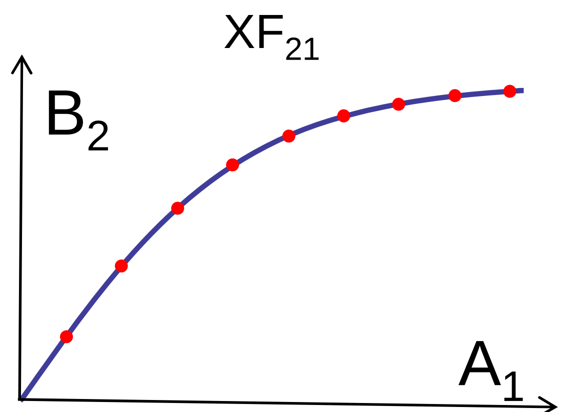
Original X-parameters are Static Spectral Mappings

Slides courtesy J. Verspecht

Static transmission X-parameter: XF_{21}



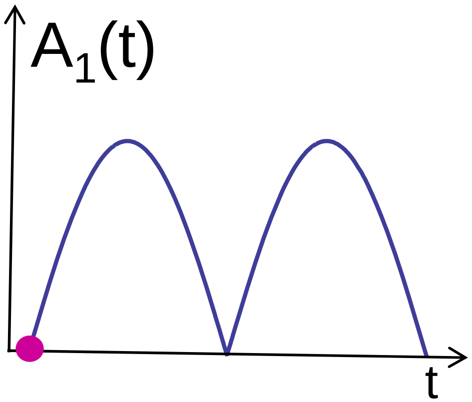
Can be measured under True CW, pulsed DC or Pulsed RF conditions



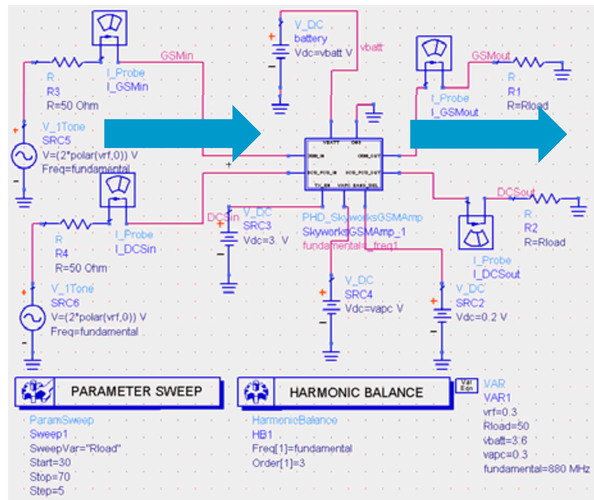
Frequency Domain:

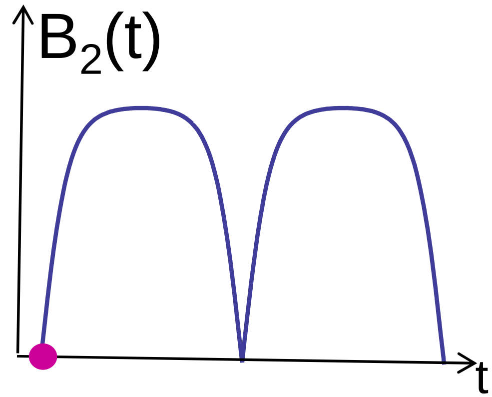
$$B_2 = XF_{21}\left(\left|A_1\right|\right)e^{j\varphi(A_1)}$$

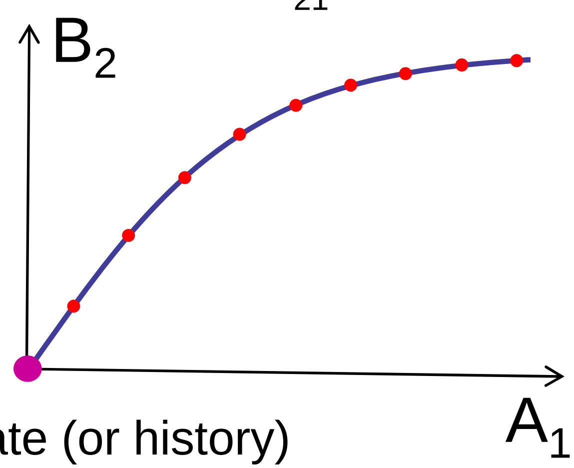
Modulation Simulated in Envelope Domain:



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

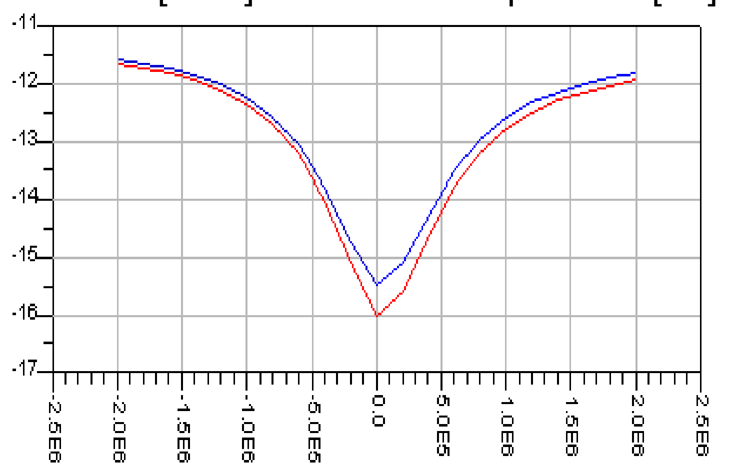
• Physical causes of memory: Dynamic self-heating, bias-line interaction, trapping effects caused by *additional dynamic variables* – multiple time-scale problem

IM3 products asymetric

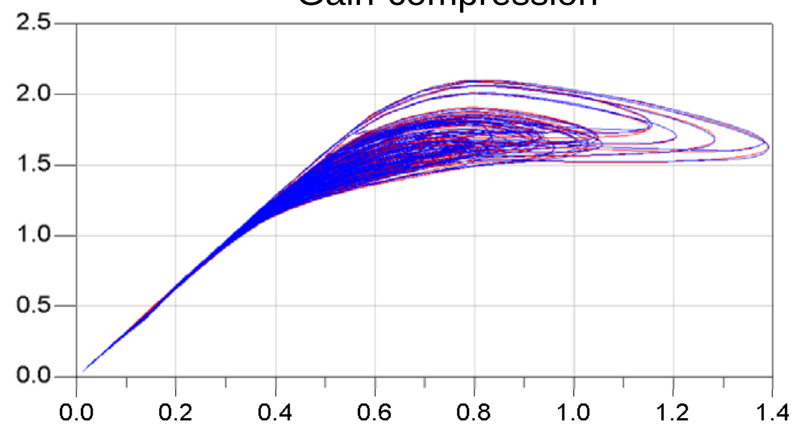
Depend on tone spacing

Hysteresis in compression plot

HBT IM3 [dBm] versus tone separation [Hz]



Gain-compression



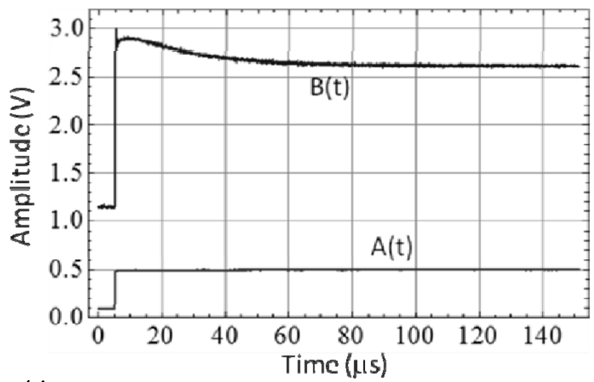
Agilent Technologies

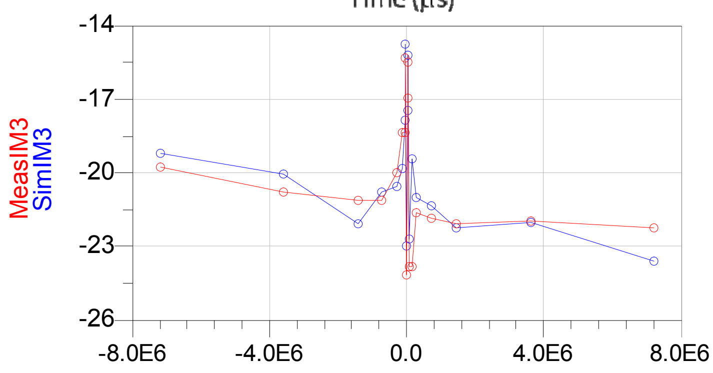
Dynamic X-parameters: Long-Term Memory

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

$$B(t) = \left\{ XF_{21}\left(\left|A(t)\right|\right) + \int_0^\infty G\left(\left|A(t)\right|, \left|A(t-u)\right|, u\right) du \right\} e^{j\varphi(A(t))}$$





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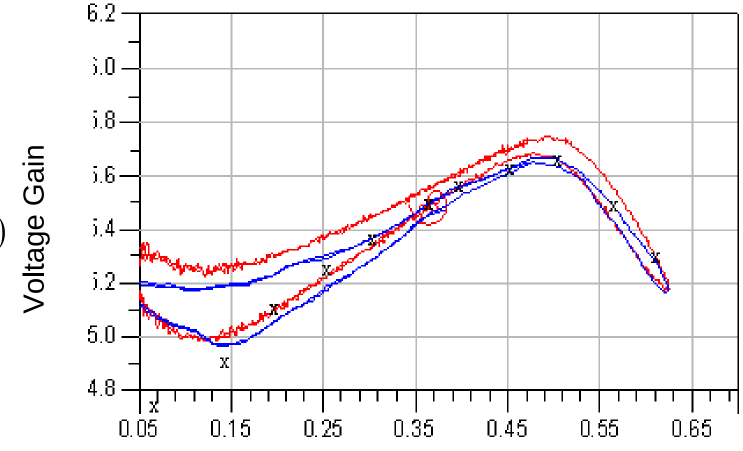
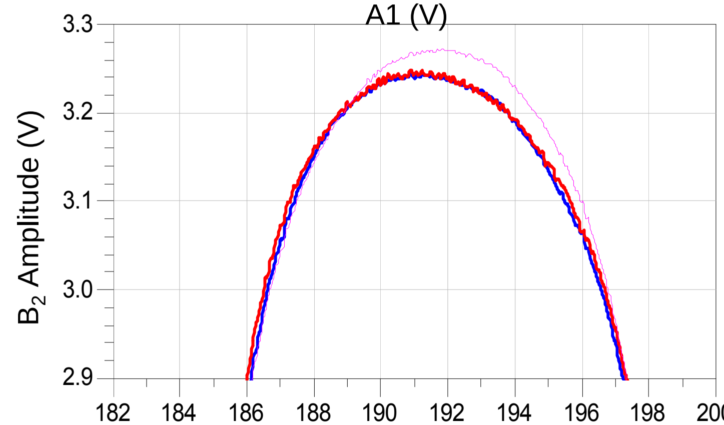




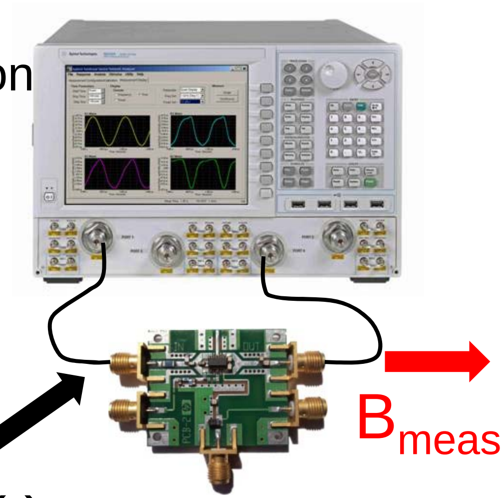
Measured Data: Red

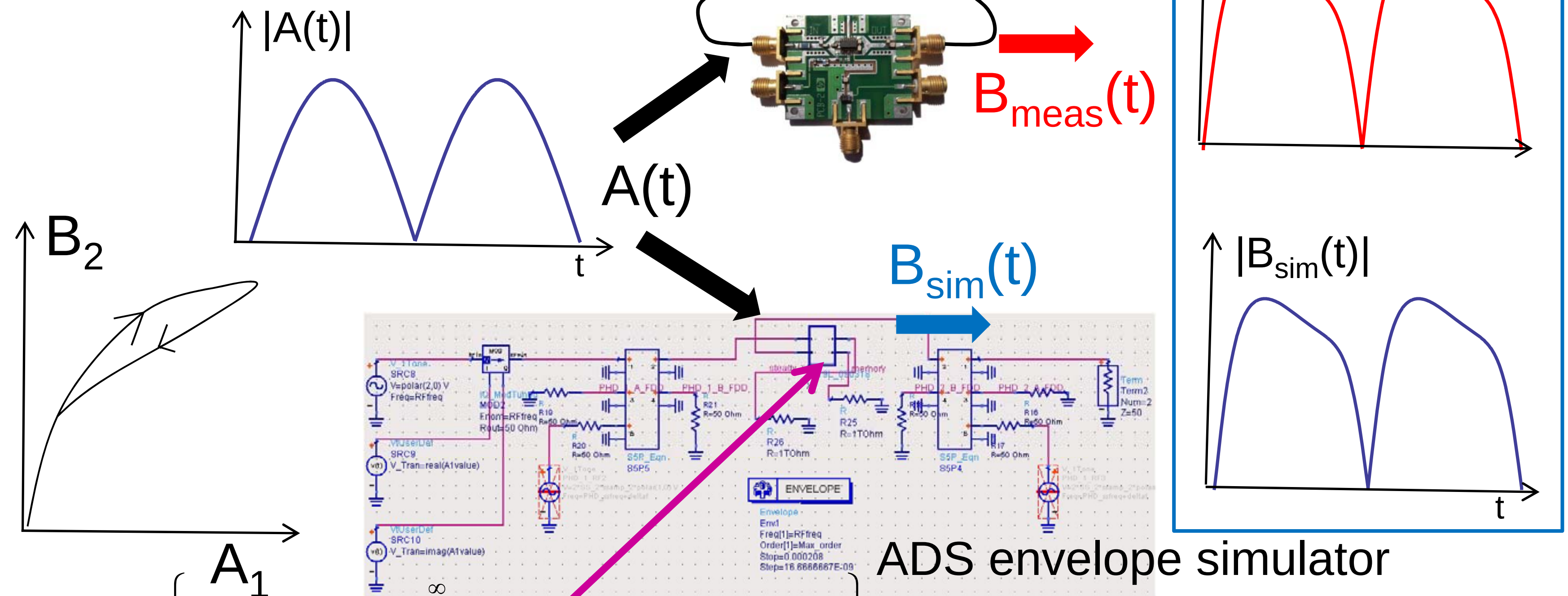
Memory model prediction: Blue

Static X-parameter prediction: Magenta

Dynamic X-parameters Beyond Quasi-Static

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

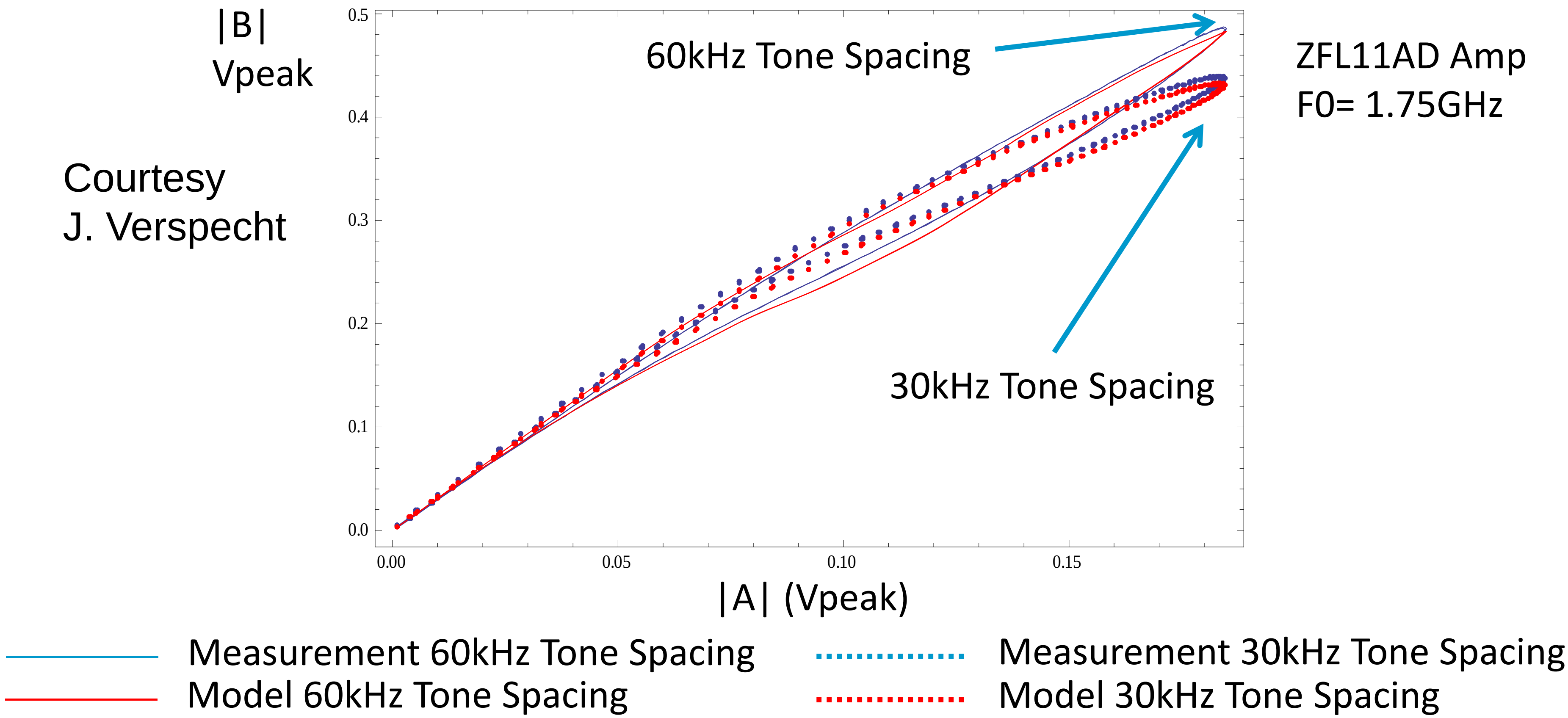




$$B(t)=\left\{XF_{21}\left(\left|A(t)\right|\right)+\int_{0}^{\infty}G\left(\left|A(t)\right|,\left|A(t-u)\right|,u\right)du\right\}e^{j\varphi(A(t))}$$

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)

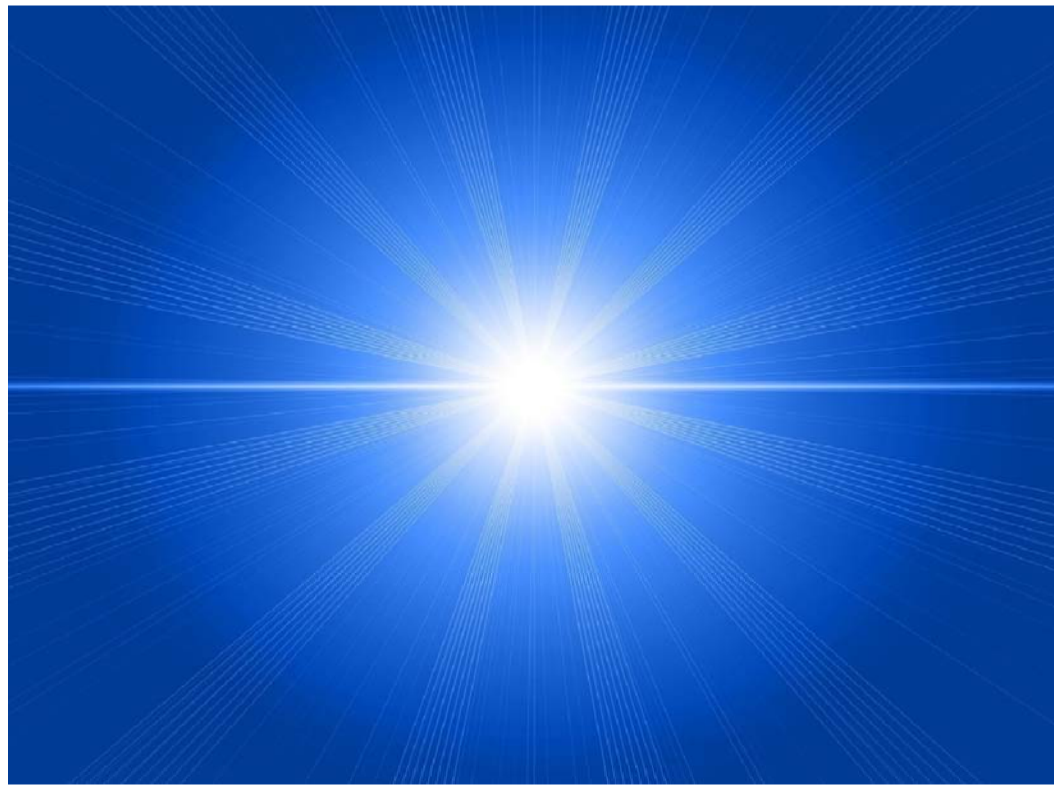
Summary: X-parameter universe is expanding rapidly

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"

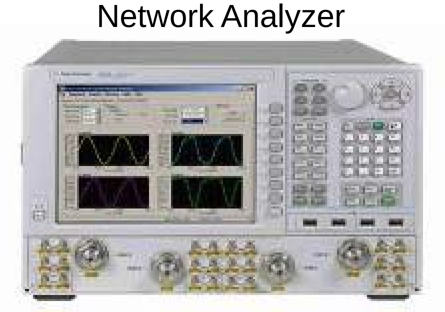
Applications

- 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**

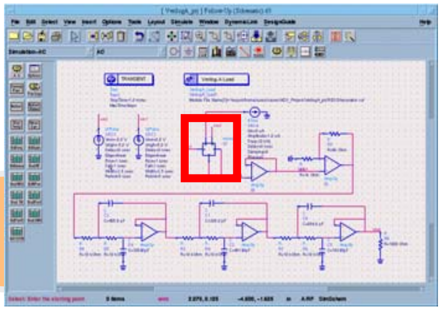


X-Parameters: Agilent Completes the Nonlinear Puzzle!

Agilent Nonlinear Vector Network Analyzer



Electronic design automation software

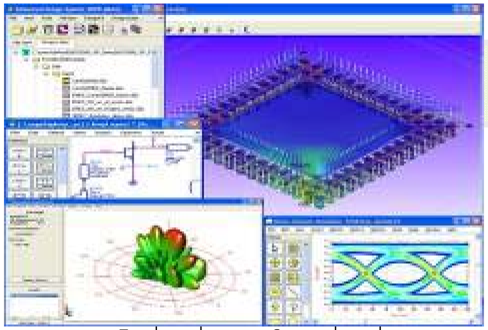


Nonlinear Measurements

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

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3. J. Verspecht and D. E. Root, "Poly-Harmonic Distortion Modeling," in *IEEE Microwave Theory and Techniques Microwave Magazine*, June, 2006.
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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
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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