Industry Trends and Solutions in Nonlinear Component Characterization with NVNA and X-parameters

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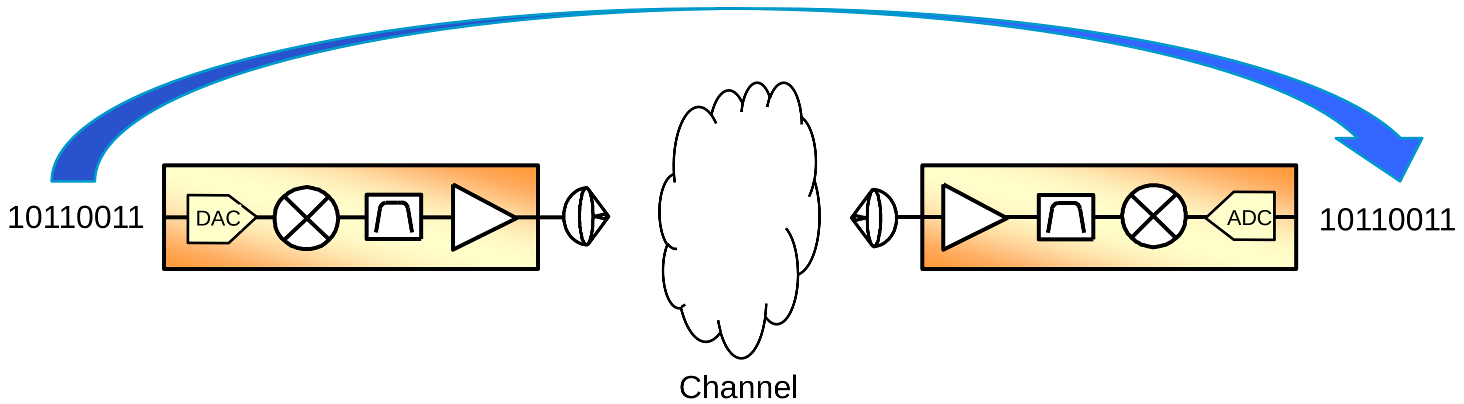
Wireless Information Transfer



Transmitter

Typical Characteristics

- Output Power and Gain
- Output Linearity/Distortion
- Efficiency

Receiver

Typical Characteristics

- Low Noise (Sensitivity)
- Input Linearity/Distortion
- Gain

Goal: ***Efficiently transfer information uncorrupted from one point to another through a channel medium***

Challenge: ***Design components/system in a systematic, accurate and cost effective manner***

Communication Framework

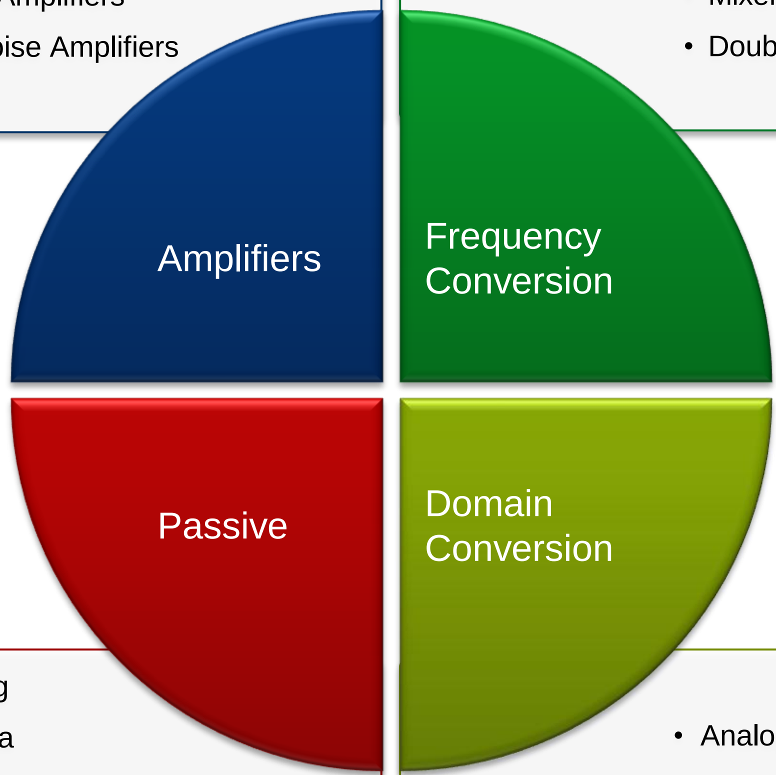
Limited number of framework components are utilized in building the information transfer channels

- Distortion (in/out band)
- Memory
- Efficiency

- Power Amplifiers
- Low Noise Amplifiers

- Mixers
- Doublers

- Conversion Linearity
- Distortion (in/out band)



- PIM/PH (very low levels)
- Memory

- Filtering
- Antenna
- Biasing

- Analog-Digital
- Digital-Analog

- Conversion Linearity
- Distortion
- Resolution/Sample Rate

All components generate nonlinear behavior

Component Characterization Space

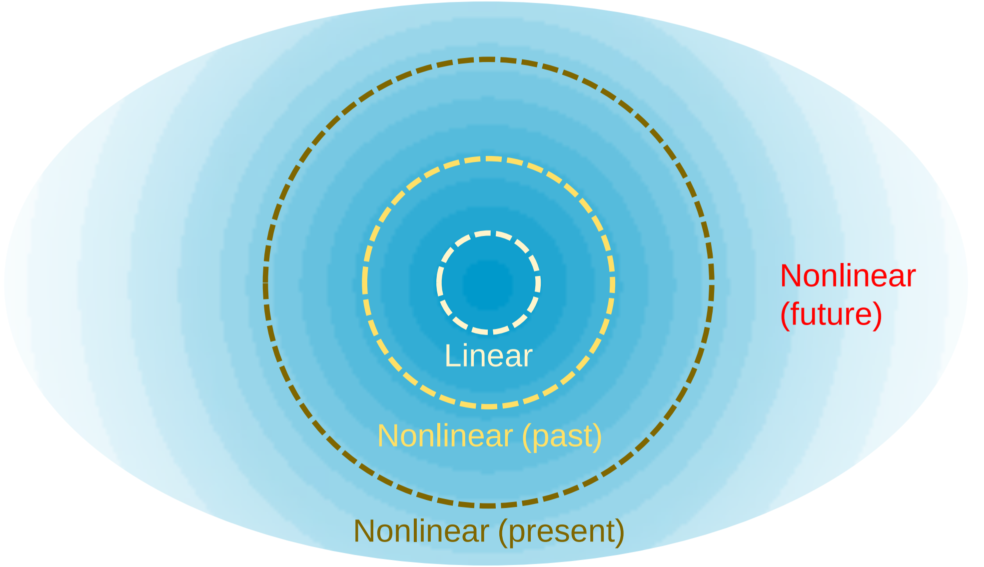
Four main aspects of linear/nonlinear measurements and modeling:

- Coverage
- Accuracy
- Usability
- Efficiency

Present advancements:

- NVNA (new measurements, frequency range, high power)
- Simulation Tools
- Models
  - Circuit
  - Compact (NVNA measurement based)
  - Blackbox/Behavioral (X-parameters)

Boundary conditions are extremely important



Measurements/modeling advancements are continuing to expand boundary conditions

System/Component Nonlinear Measurement and Modeling

Limited number of framework components are utilized in building the information transfer channels

- Distortion (in/out band)
- Memory
- Efficiency

- NVNA
- Models

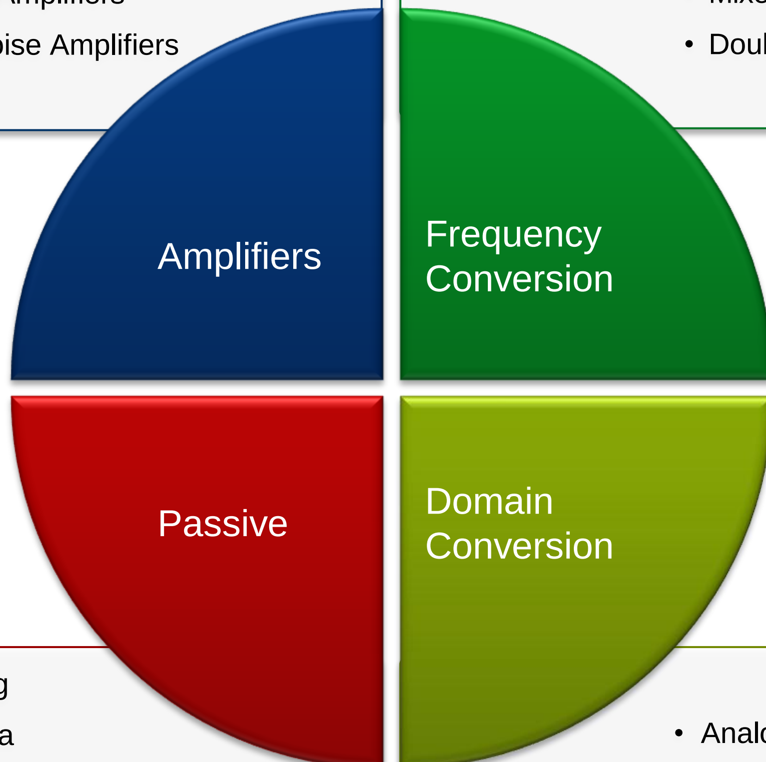
Memory

- NVNA
- Models

Distortion levels
Memory

- PIM/PH (very low levels)
- Memory

- Power Amplifiers
- Low Noise Amplifiers



- Filtering
- Antenna
- Biasing

- Mixers
- Doublers

- Analog-Digital
- Digital-Analog

- Conversion Linearity
- Distortion (in/out band)

- NVNA
- Models

Simulation-efficiency

- Nothing

- Conversion Linearity
- Distortion
- Resolution/Sample rate

All components generate nonlinear behavior

Good	Average	Limited

Future Trends

Coverage

Measurement/modeling domain conversion (ADC/DAC)
Frequency range (DC to THz)
Instantaneous bandwidth and memory (DPD)

Accuracy

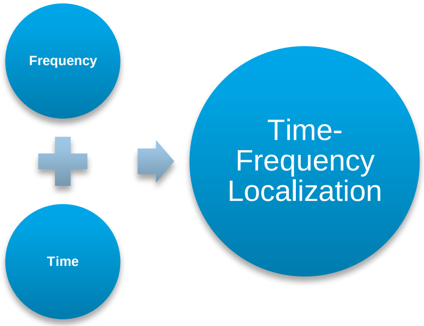
Low level distortion measurements
Model interpolation/extrapolation
Measurement accuracy/uncertainties

Usability

Simplified user experience (Hardware/Software)
Standardization
Verification

Efficiency

Hardware integration (leads to algorithm improvement)
Simulation order reduction
New science in measurement/modeling in time-frequency domain



Exciting time for RF designers and engineers

Capturing the Imagination of the Industry

Solves real-world problems now

Interoperable characterization, modeling, and design solutions

Does for nonlinear design what S-parameters do for linear design

Changing the way the industry works

Continuous wave of innovations and award-winning research

Presentation Outline

Introduction to NVNA

- Measurement Capabilities

Amplifier Design Considerations using X-parameters

- Industry Challenges
- Introduction to X-parameters

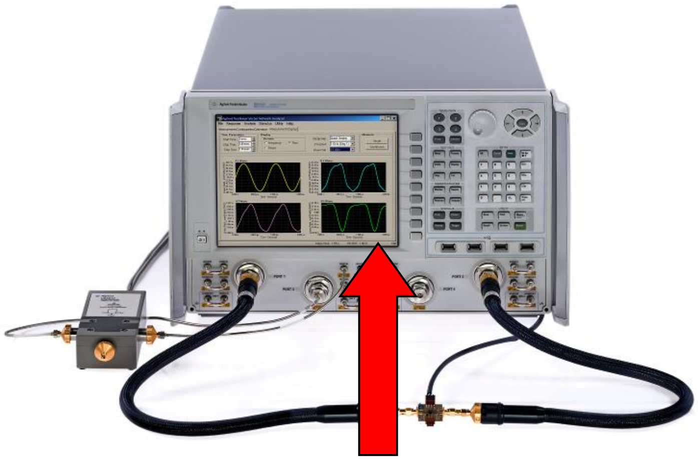
End-to-End Power Amplifier Design with X-parameters

- Load-Dependent X-parameters
- High Power X-parameter Measurement Configuration
- Final PA Results

Mixer/Converter Characterization with X-parameters

- NVNA Measurement Wizard for Mixers
- X-parameter Measurements of Mixers

Nonlinear Vector Network Analyzer (NVNA)



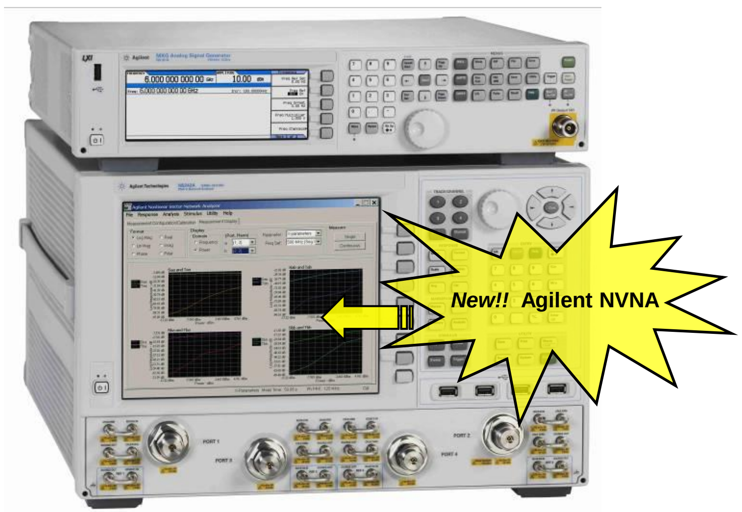
NVNA FW

New phase calibration standard

- Vector (amplitude/phase) corrected nonlinear measurements from 10 MHz to 13.5, 26.5, 43.5, 50, 67 GHz
  - Calibrated absolute amplitude and relative phase (cross-frequency relative phase) of measured spectra traceable to standards lab
  - Up to 67 GHz of vector corrected bandwidth for time domain waveforms of voltages and currents of DUT
  - Multi-Envelope domain measurements for measurement and analysis of memory effects
  - X-parameters: Extension of Scattering parameters into the nonlinear region providing unique insight into nonlinear DUT behavior
  - X-parameter extraction into ADS nonlinear simulation and design
  - NVNA can control external DC instruments (sweep and sense) during RF measurements
- Standard PNA-X with New Nonlinear features and capability

NVNA System Configuration

X-Parameter extraction/multi-tone source



Standard PNA-X Network Analyzer

Amplitude Calibration

Vector Calibration

Phase Calibration

New!! Agilent Calibrated Phase Reference

Phase Reference

Phase Reference

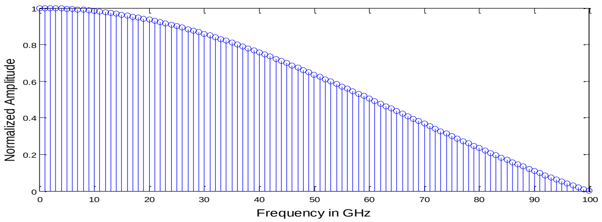
Agilent's new IC based phase reference is superior in all aspects to existing phase reference technologies.

Frequencies to 67 GHz.

New!! **Agilent Calibrated Phase Reference**

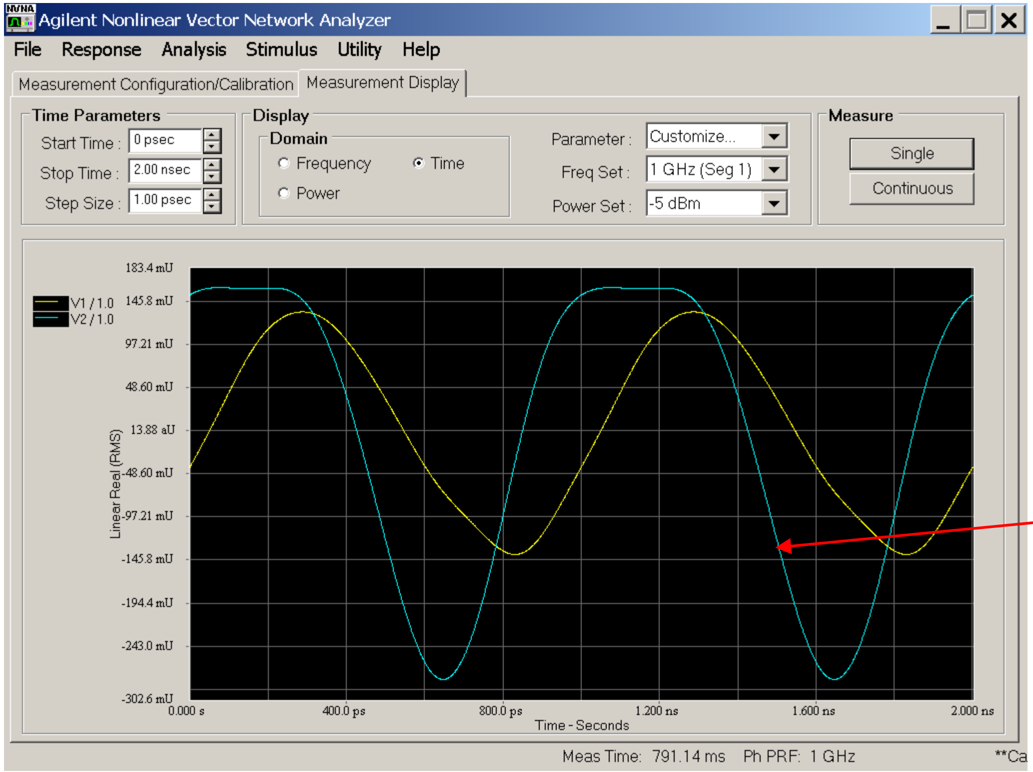
Advantages:

- Lower temperature sensitivity
- Lower sensitivity to input power
- Smaller minimum tone spacing (< 1 MHz vs 600 MHz)
- Lower frequency (< 1 MHz vs 600 MHz)
- Much wider dynamic range due to available energy vs noise



NVNA Applications (What does it do?)

Time domain oscilloscope measurements with vector error correction applied



View time domain (and frequency domain) waveforms (similar to an oscilloscope) but with vector correction applied (measurement plane at DUT terminals)

Vector corrected time domain voltages (and currents) from device

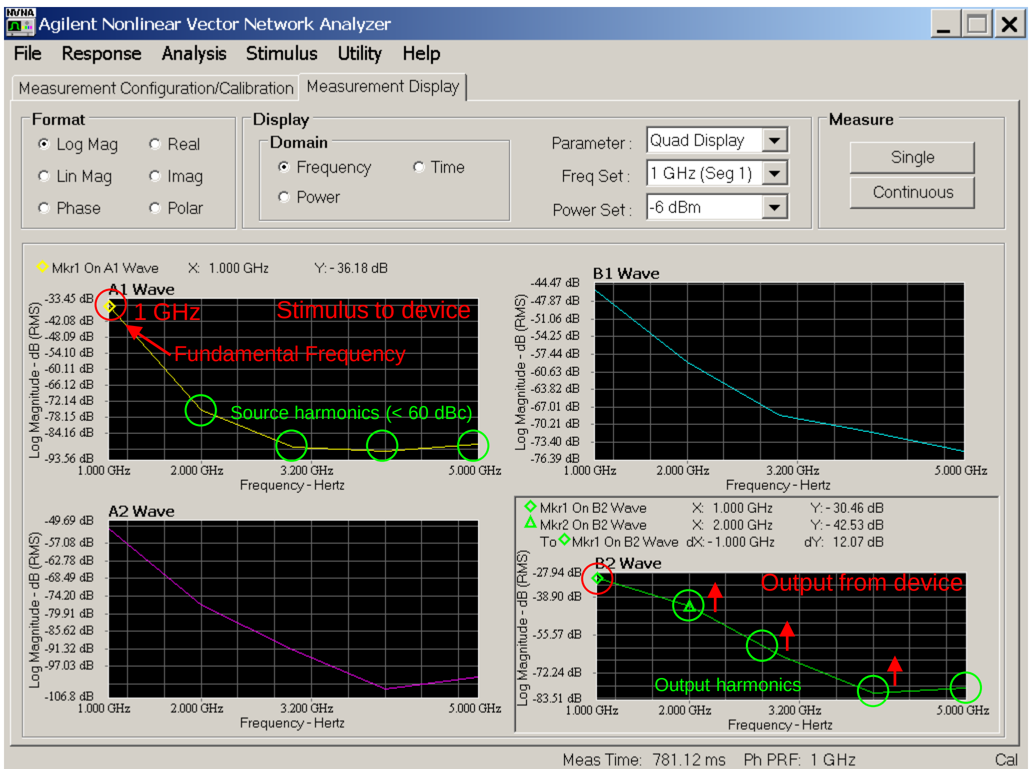
NVNA Applications (What does it do?)

Measure amplitude and cross-frequency phase of frequencies to/from device with vector error correction applied

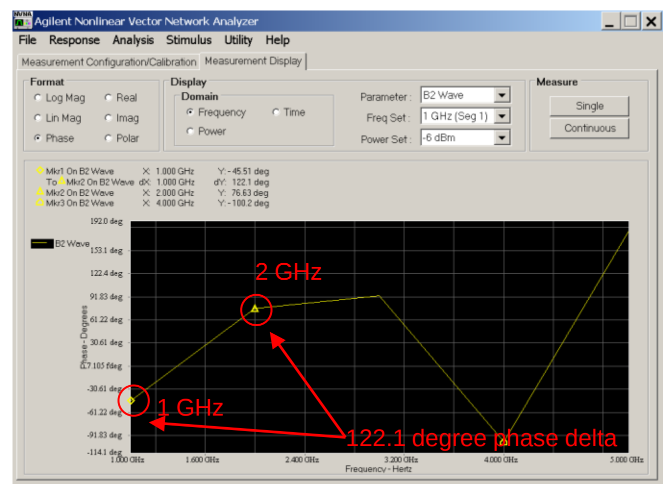
View absolute amplitude and phase relationship between frequencies to/from a device with vector correction applied (measurement plane at DUT terminals)

Useful to analyze/design high efficiency amplifiers such as class E/F

Can also measure frequency multipliers



Input output frequencies at device terminals



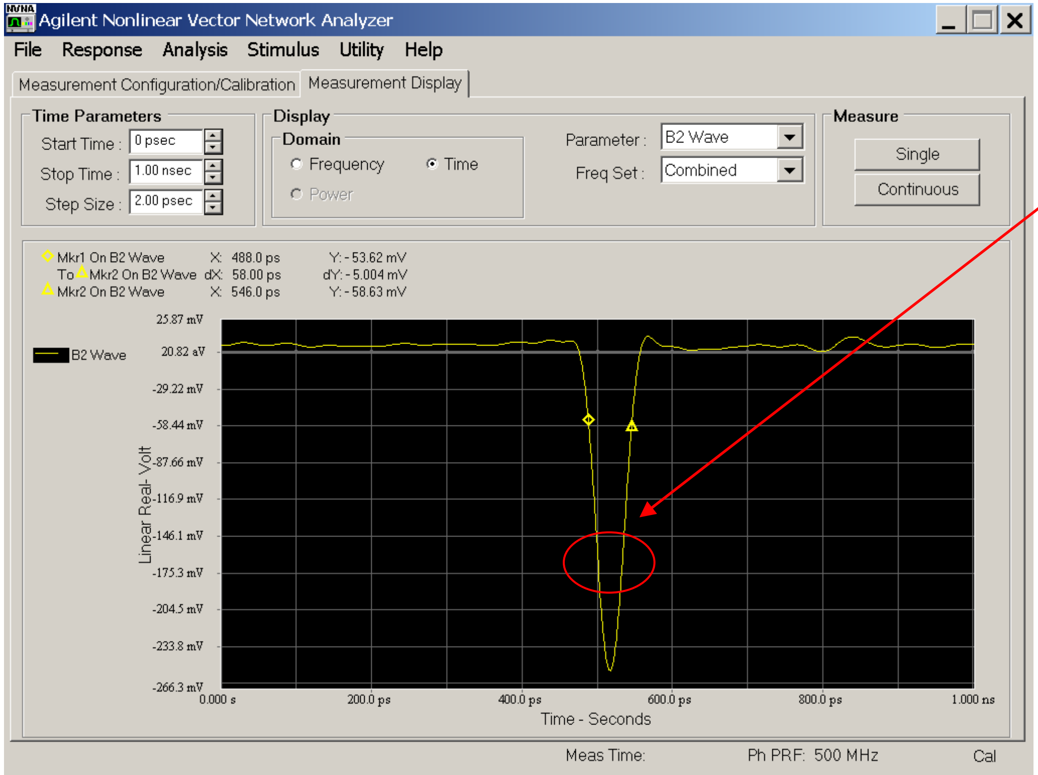
Phase relationship between frequencies at output of device

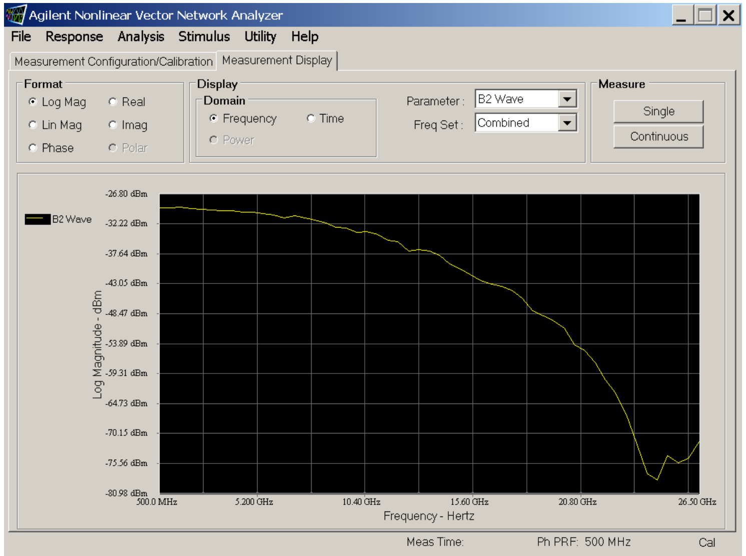
NVNA Applications (What does it do?)

Measurement of narrow (fast) DC pulses with vector error correction applied

View time domain (and frequency domain) representations of narrow DC pulses with vector correction applied (measurement plane at DUT terminals)

Less than 50 ps





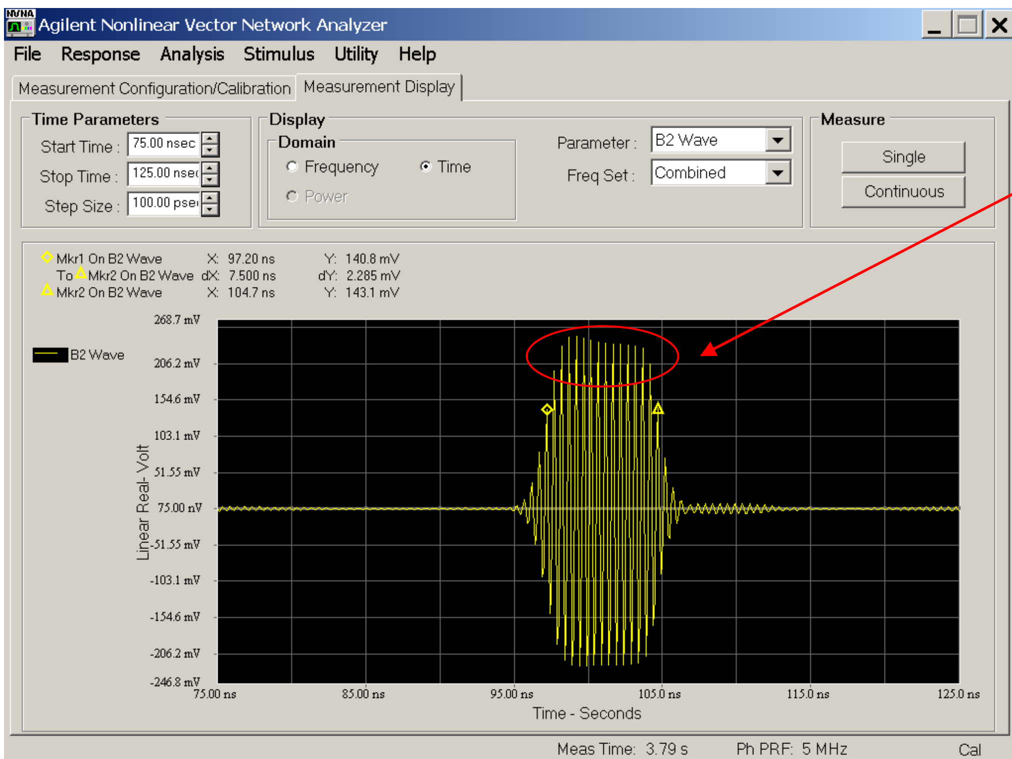
NVNA Applications (What does it do?)

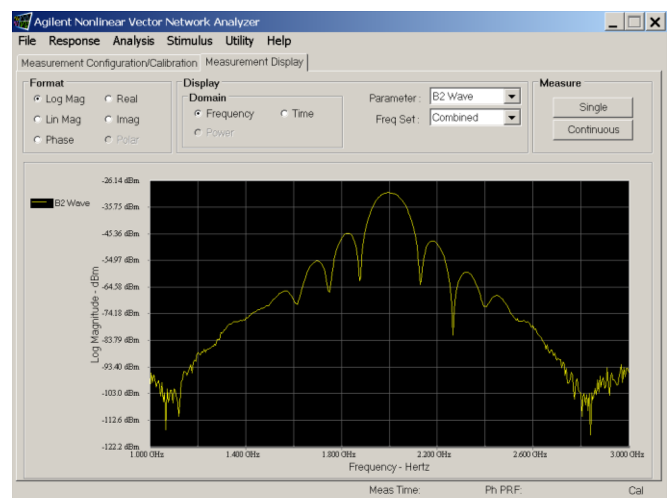
Measurement of narrow (fast) RF pulses with vector error correction applied

View time domain (and frequency domain) representations of narrow RF pulses with vector correction applied (measurement plane at DUT terminals)

Using wideband mode (resolution ~ 1/BW ~ 1/26 GHz ~ 40 ps)

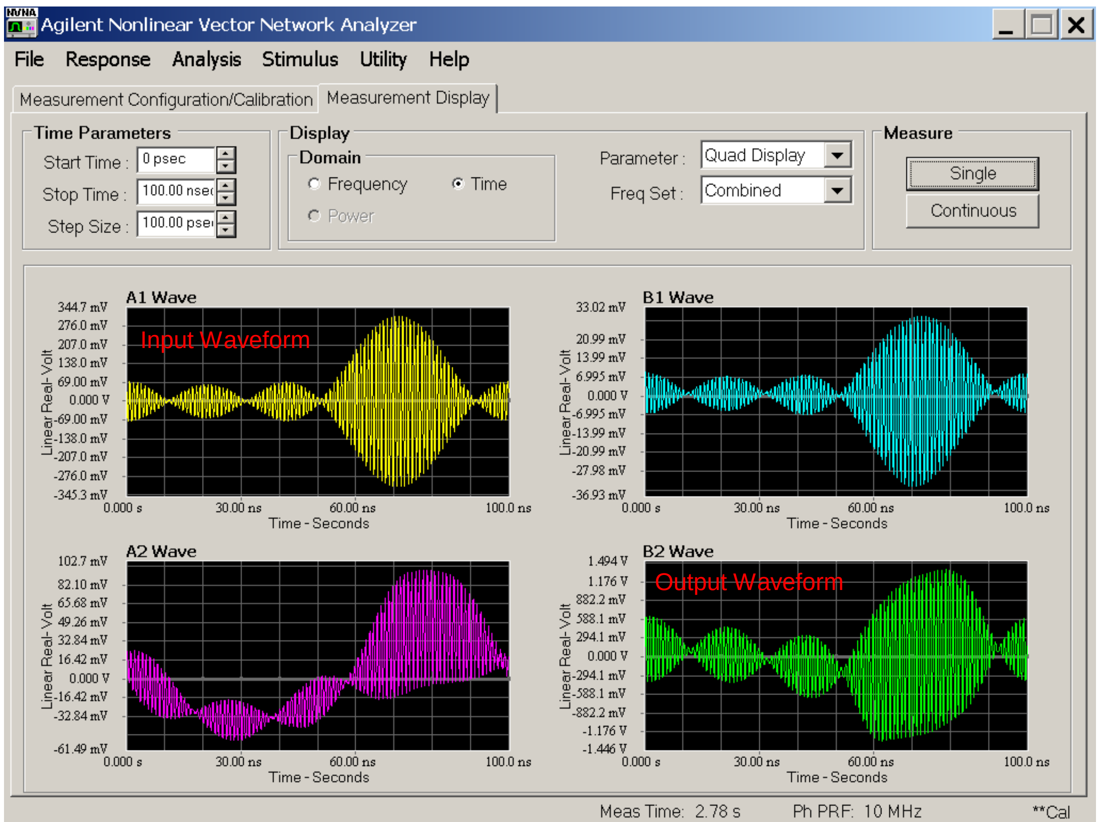
Example: 10 ns pulse width at a 2 GHz carrier frequency. Limited by external source not NVNA. Can measure down into the picosecond pulse widths





NVNA Applications (What does it do?)

Measurements of multi-tone stimulus/response with vector error correction applied



View time and frequency domain representations of a multi-tone stimulus to/from a device with vector correction applied (measurement plane at DUT terminals)

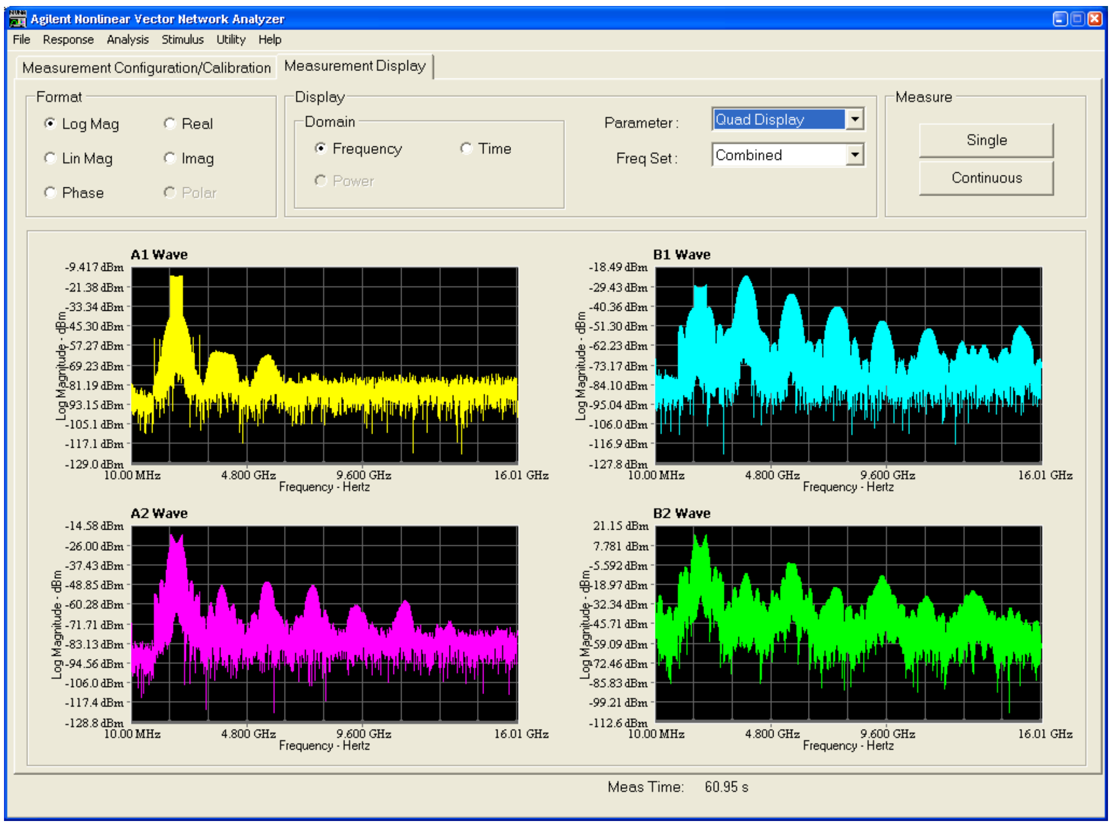
Stimulus is 5 frequencies spaced 10 MHz apart centered at 1 GHz measuring all spectrum to 20 GHz

Measure amplitude AND PHASE of intermodulation products

Generated using external source (PSG/ESG/MXG) using NVNA and vector calibrated receiver

NVNA Applications (What does it do?)

Calibrated measurements of multi-tone stimulus/response with narrow tone spacing



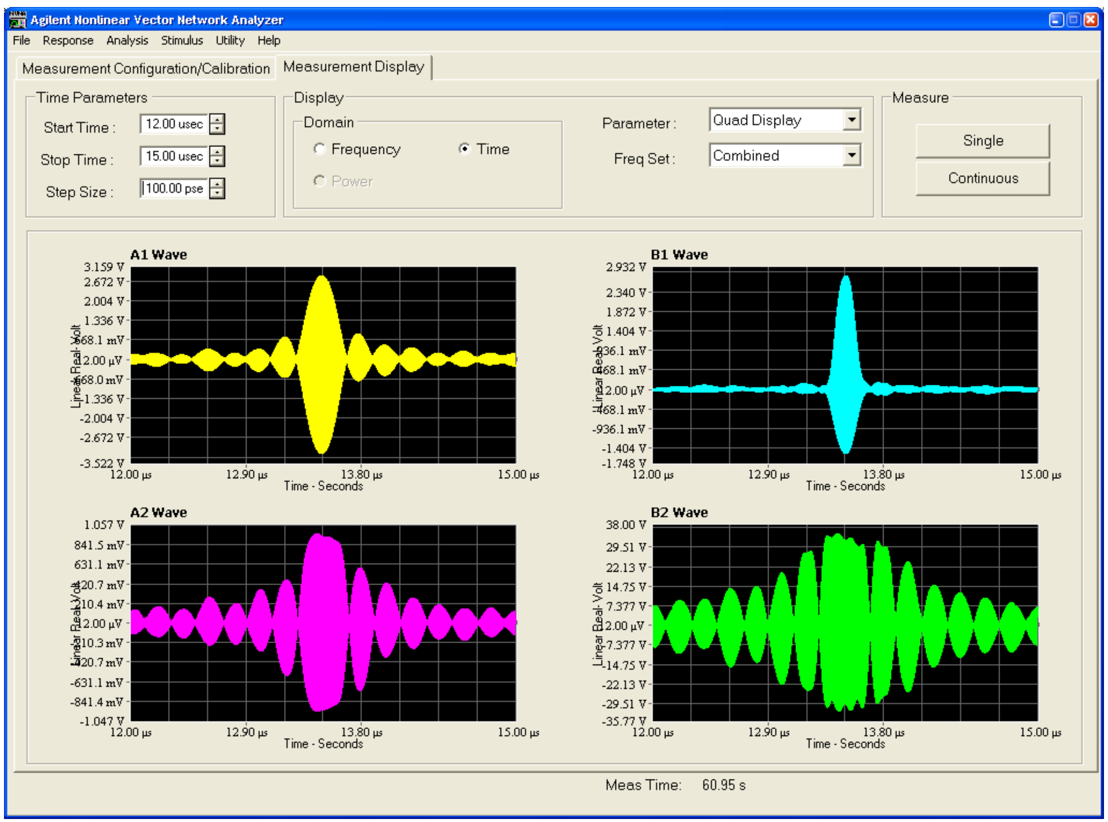
View time and frequency domain representations of a multi-tone stimulus to/from a device with vector correction applied (measurement plane at DUT terminals)

Stimulus is 64 frequencies spaced ~80 kHz apart centered at 2 GHz. The NVNA is measuring harmonics to 16 GHz (8^{th} harmonic)

Multi-tone often used to mimic more complex modulation (i.e. CDMA) by matching complementary cumulative distribution function (CCDF). Multi-tone can be measured very accurately.

NVNA Applications (What does it do?)

Calibrated measurements of multi-tone stimulus/response with narrow tone spacing

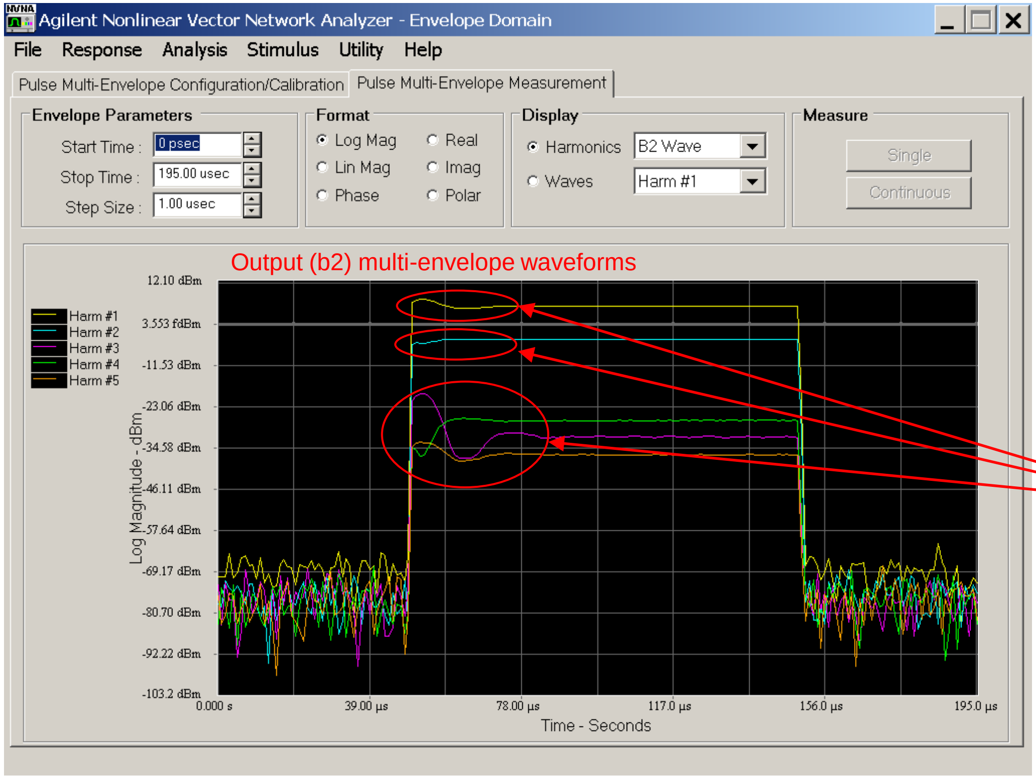


View time and frequency domain representations of a multi-tone stimulus to/from a device with vector correction applied (measurement plane at DUT terminals)

Stimulus is 64 frequencies spaced ~80 kHz apart centered at 2 GHz. The NVNA is measuring harmonics to 16 GHz (8th harmonic)

NVNA Applications (What does it do?)

Measure memory effects in nonlinear devices with vector error correction applied



View and analyze dynamic memory signatures using the vector error corrected envelope amplitude and phase at the fundamental and harmonics with a pulsed (RF/DC) stimulus

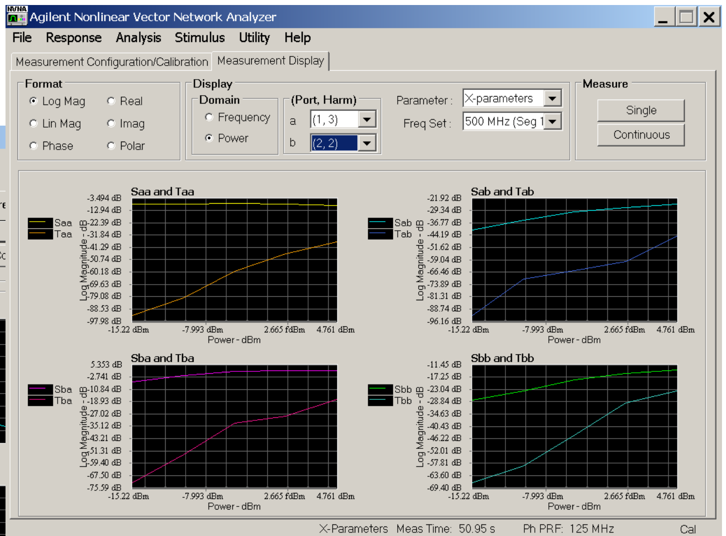
Each harmonic has a unique time varying envelope signature

NVNA Applications (What does it do?)

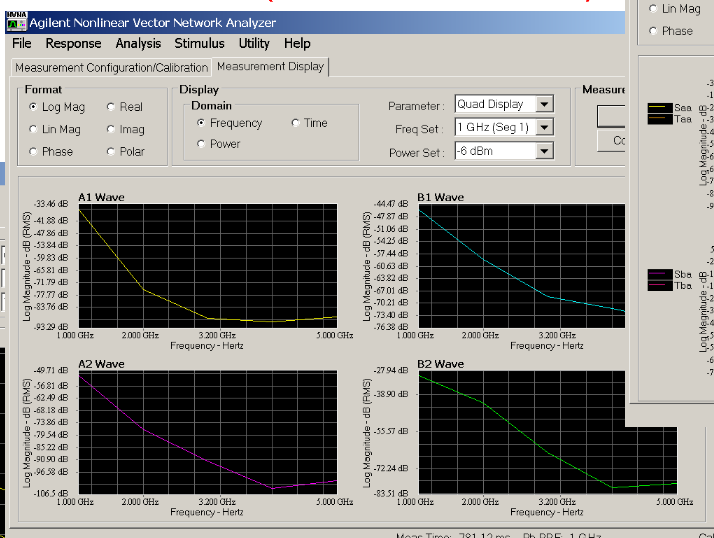
Measure modeling coefficients and other nonlinear device parameters

… More

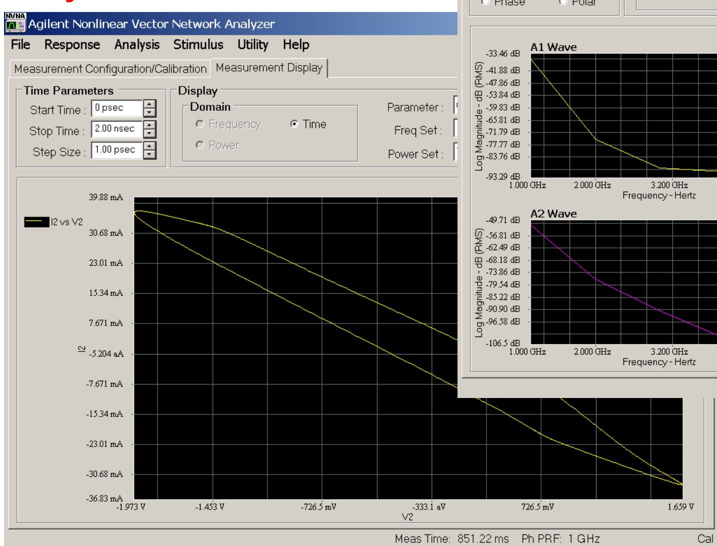
X-parameters



Waveforms ('a' and 'b' waves)



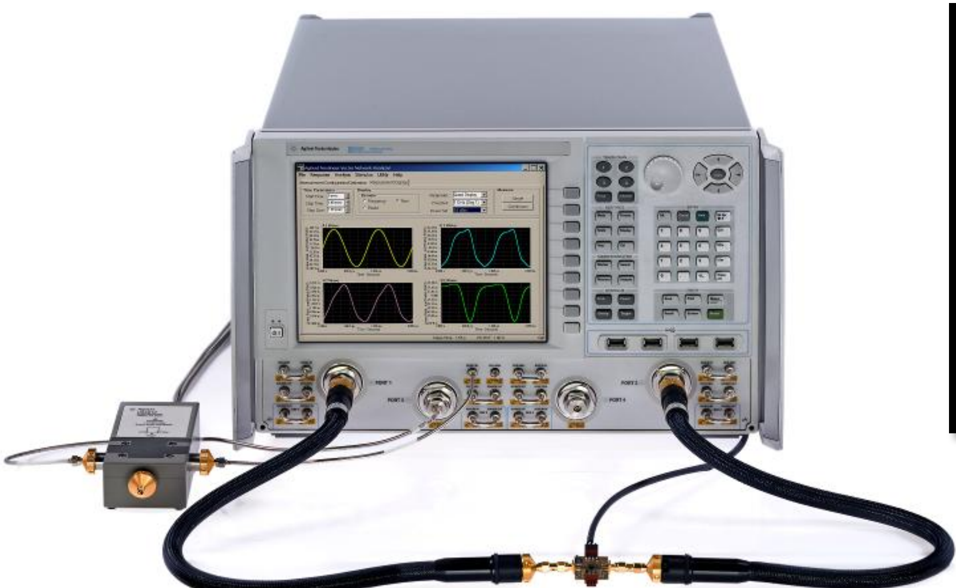
Dynamic Load Line



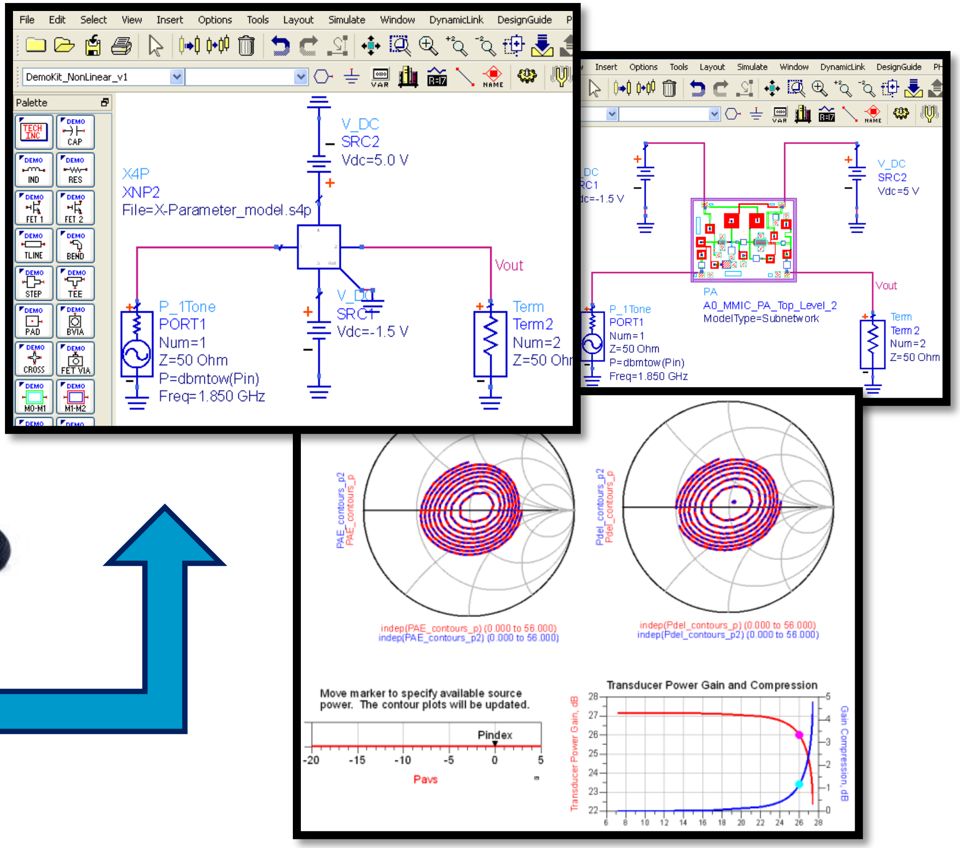
Measure, view and simulate actual nonlinear data from your device

NVNA and X-parameters

Measure X-parameters with Agilent’s NVNA

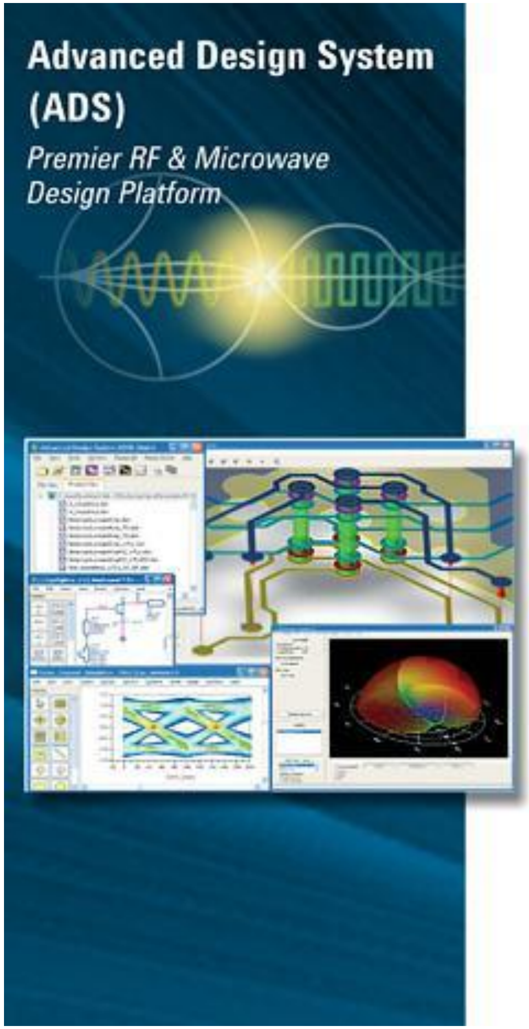


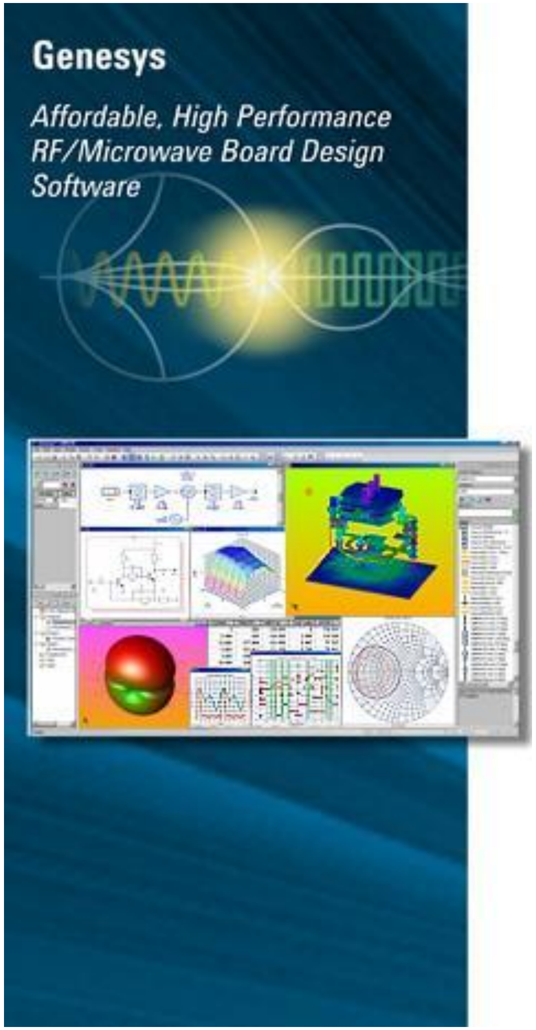
Design and simulate with measured or generated X-parameters in ADS

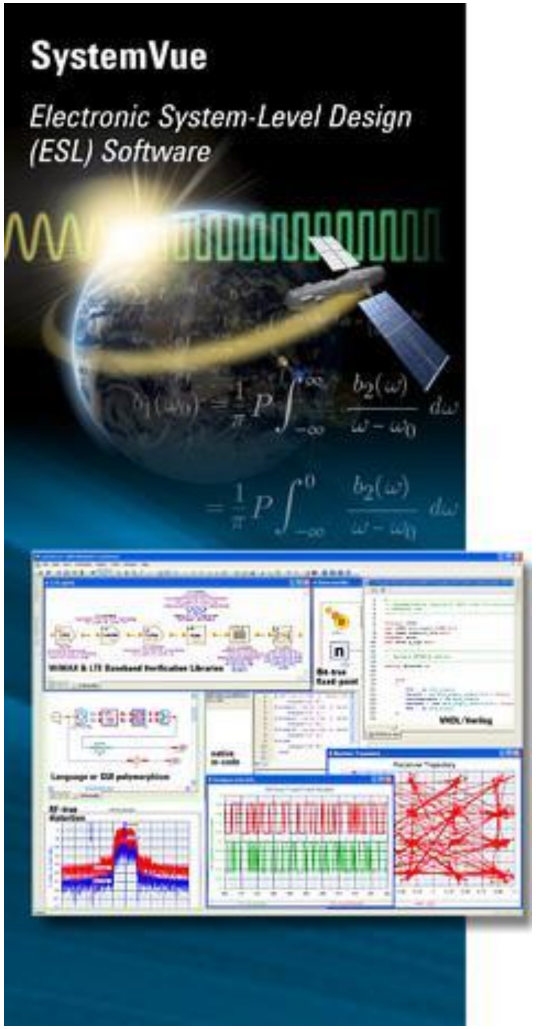


Design with measured X-parameters in ADS

X-Parameter Technology in Agilent EEsof EDA’s Platforms

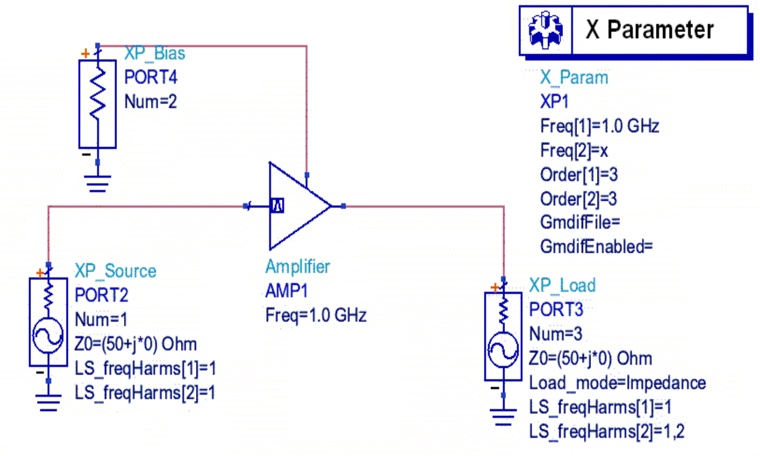






ADS X-Parameter Generator
Available in ADS 2009 Update 1

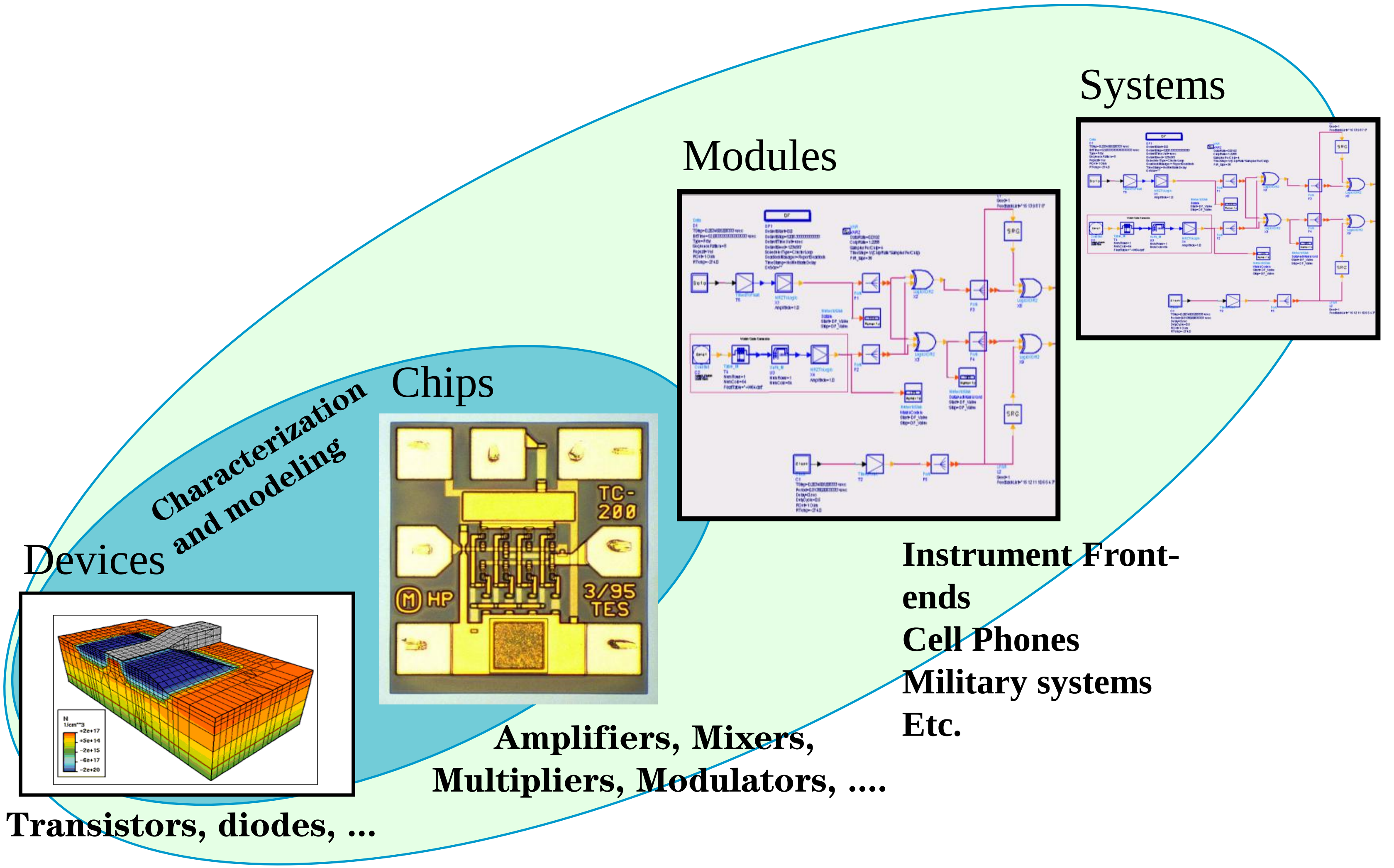
Generate nonlinear X-parameter models in ADS



- Augments Agilent’s measurement-based X-parameter generation (PNA-X Series Nonlinear Vector Network Analyzer)
- Easy to setup and run
- Multi-tone
- Multi-port: No limits on the number of ports, frequency or power
- Models amplifiers, mixers, and transceivers with frequency conversion

Linear and Nonlinear Device Characteristics

Nonlinear Hierarchy from Device to System



Presentation Outline

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- Industry Challenges
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End-to-End Power Amplifier Design with X-parameters

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Solutions: Next Generation Communication Systems

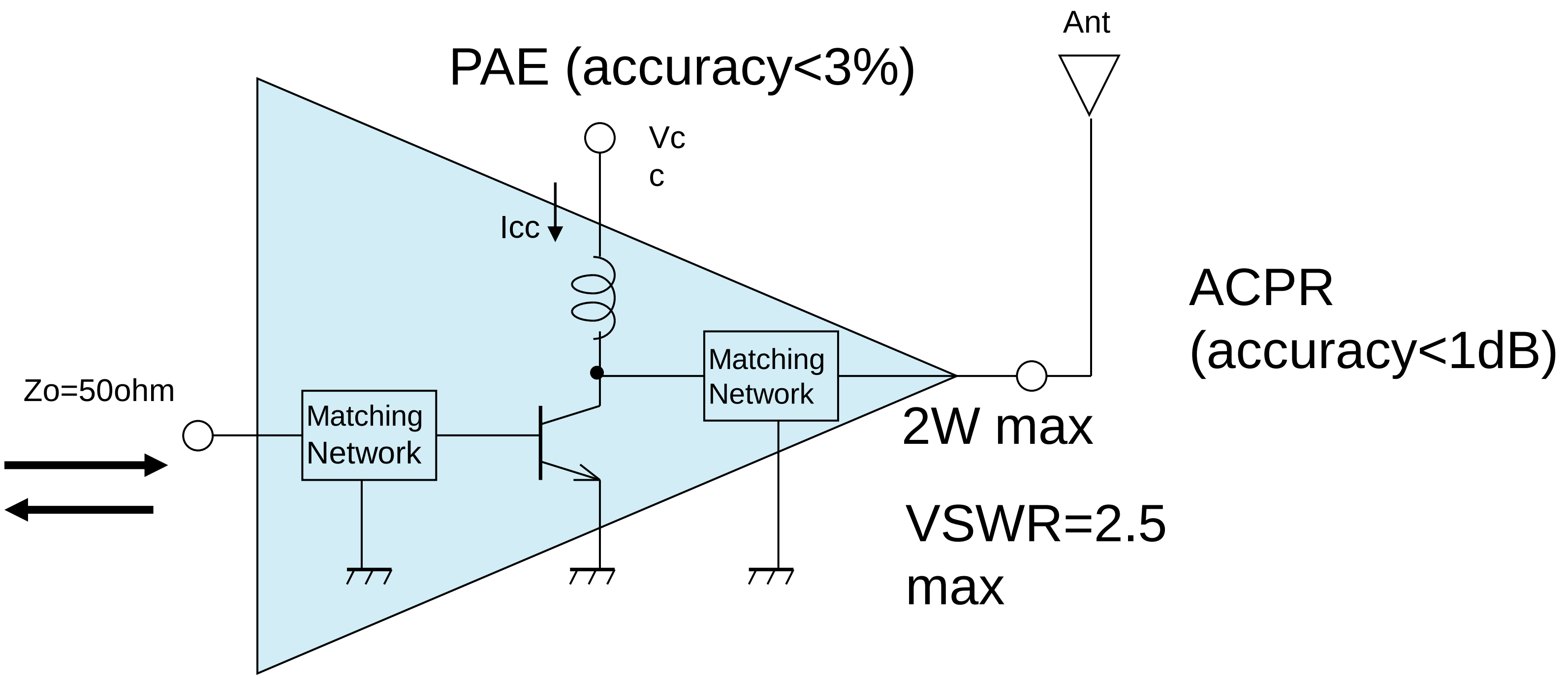
Power Amplifier Industry Challenges:

- Research & development of new semiconductor processes for next generation components
- Develop smaller, higher power, more efficient active device designs
- Reduce cost and the development time to bring product to market

Issues:

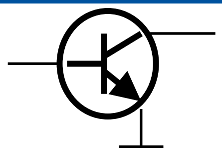
- Components are exhibiting more & more nonlinear behavior (often by design to increase efficiency)
- Models of newer technologies (such as GaN) may not exist or may not provide an accurate description of all the component behavior.

How do I Optimize Desired Amplifier Specifications?



PAE= Power Added Efficiency
ACPR= Adjacent Channel Power Ratio
VSWR= Voltage Standing Wave Ratio

Evolution of the Tools & Measurements



Patchwork → **S-Parameters** → **S-Parameters + Figures of Merit** → **NVNA X-Parameters**

TOOLS:
SS & Oscilloscope
Grease pens and
Polaroid cameras
Slotted line
Power meter

MEASUREMENTS:
Bode plots
Gain
SWR
Scalar network analyzers
Y & Z parameters

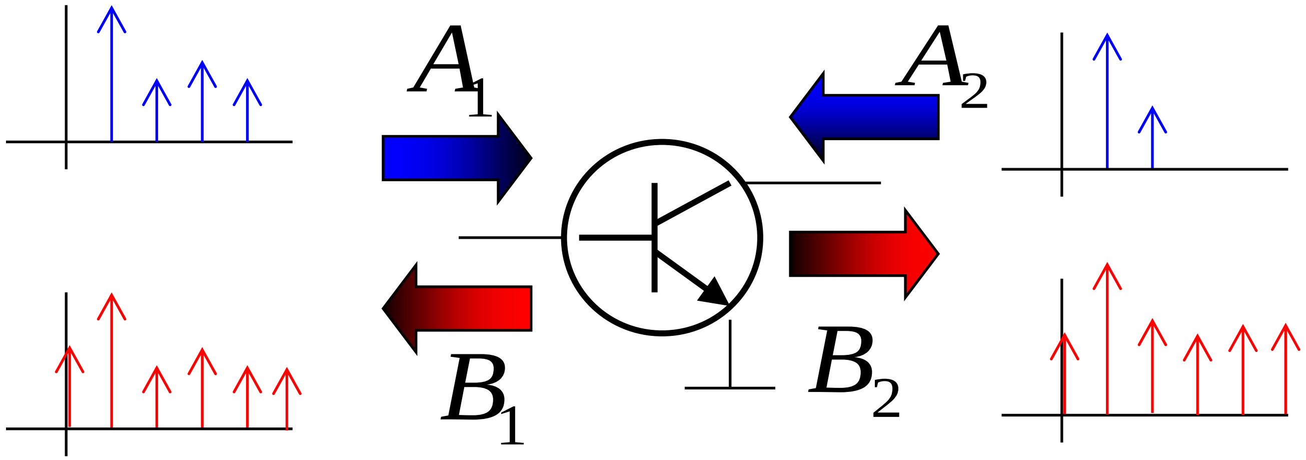
TOOLS:
Vector Network
Analyzer

MEASUREMENTS:
Gain
Input match
Output match
Isolation
Transconductance
Input capacitance

TOOLS:
NA
SA/SS/NFA
Power meter
Oscilloscope
DC Parametric Analyzer

MEASUREMENTS:
Gain compression, IP3, IMD
PAE, ACPR, AM-PM, BER
Constellation Diagram, EVM
GD, NF, Spectral Re-growth
ACLR, Hot “S22”
Source and Load-Pull

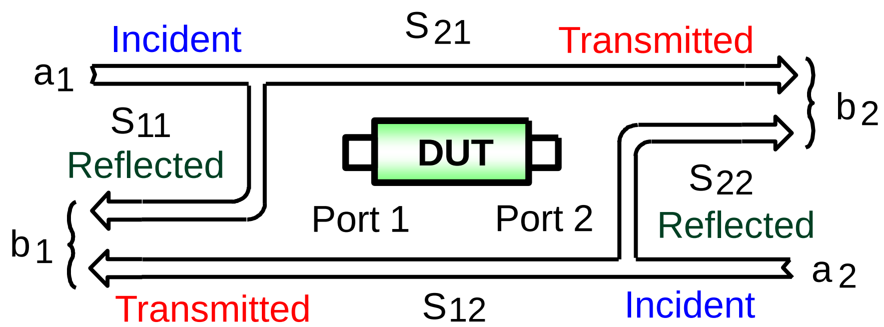
Nonlinear Component Behavior



…and you want to build a system by cascading components together.

S-parameters:
Linear Measurement, Modeling & Simulation

Measure with linear VNA:
Small amplitude sinusoids



Model Parameters:
Simple algebra

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

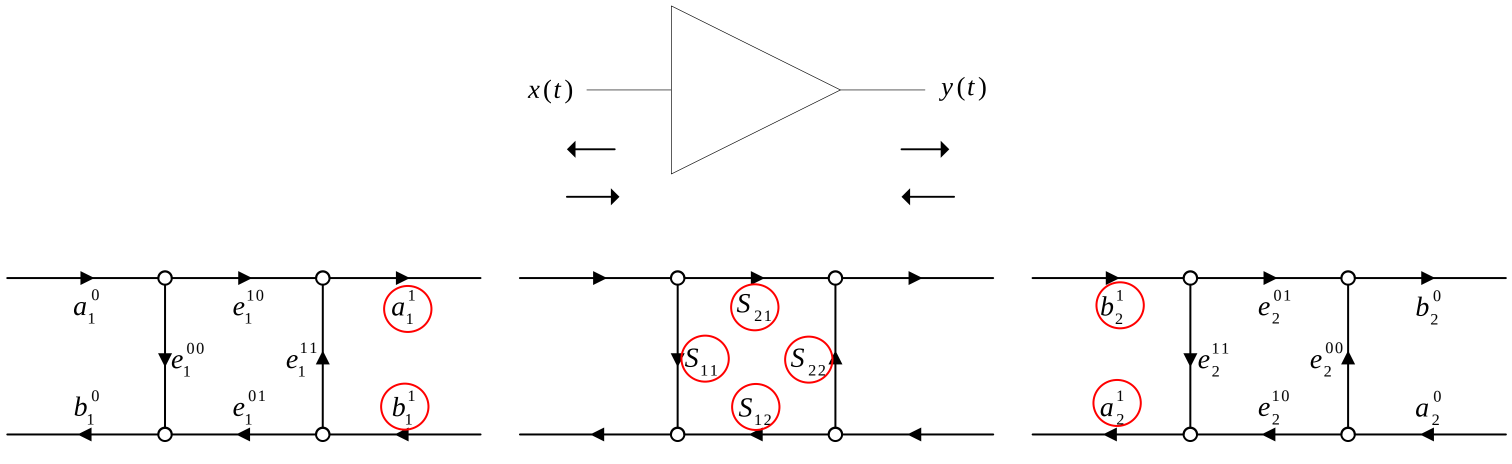
Linear Simulation:
Matrix Multiplication

S-parameters

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

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

S-parameter measurements require that the S-parameters of the device do not change during measurement



$$b_i = \sum_k S_{ik} \cdot a_k$$

S-Parameter Definition

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

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

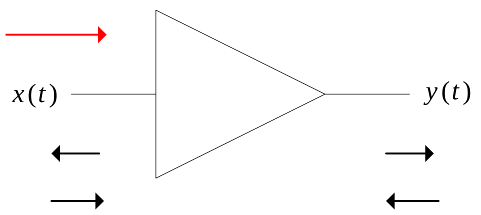
$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

To solve, VNA’s traditionally use a forward and reverse sweep (2 port error correction).

If the S-parameters change ….

(when sweeping in the forward and reverse directions when performing 2 port error correction)

… then the resulting computation of the S-parameters are invalid



$$b_1 = S_{11}a_1 + S_{12}a_2$$
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$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$\begin{bmatrix} b_1^{fwd} & b_1^{rev} \\ b_2^{fwd} & b_2^{rev} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1^{fwd} & a_1^{rev} \\ a_2^{fwd} & a_2^{rev} \end{bmatrix}$$

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} b_1^{fwd} & b_1^{rev} \\ b_2^{fwd} & b_2^{rev} \end{bmatrix} \begin{bmatrix} a_1^{fwd} & a_1^{rev} \\ a_2^{fwd} & a_2^{rev} \end{bmatrix}^{-1}$$

Hot S22

This is often why customers are asking for Hot S22 because the match is changing versus <u>input drive power</u> and frequency (Nonlinear phenomena). Hot S22 traditionally measured at a frequency slightly offset from the large input drive signal.

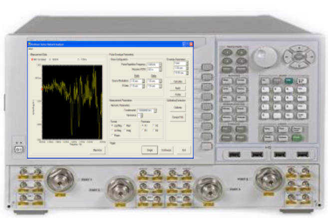
This still does not provide the complete picture. X-parameters are the solution.

X-parameters revolutionize the Characterization, Design, and Modeling of nonlinear components and systems

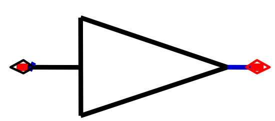
X-parameters are the mathematically correct extension of S-parameters to large-signal conditions.

- Measurement and simulation based, device independent, identifiable from a simple set of automated NVNA measurements or directly from ADS circuit-level designs
- Fully nonlinear (Magnitude *and* phase of distortion)
- Cascadable (correct behavior in even highly mismatched environment)
- Extremely accurate for high-frequency, distributed nonlinear devices

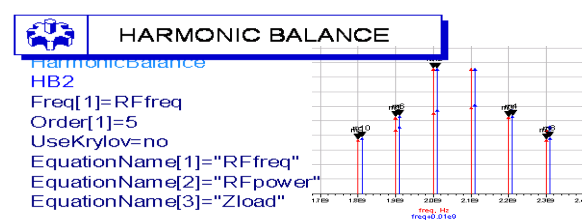
Measure X-parameters
-or-
Generate X-parameters from circuit-level designs



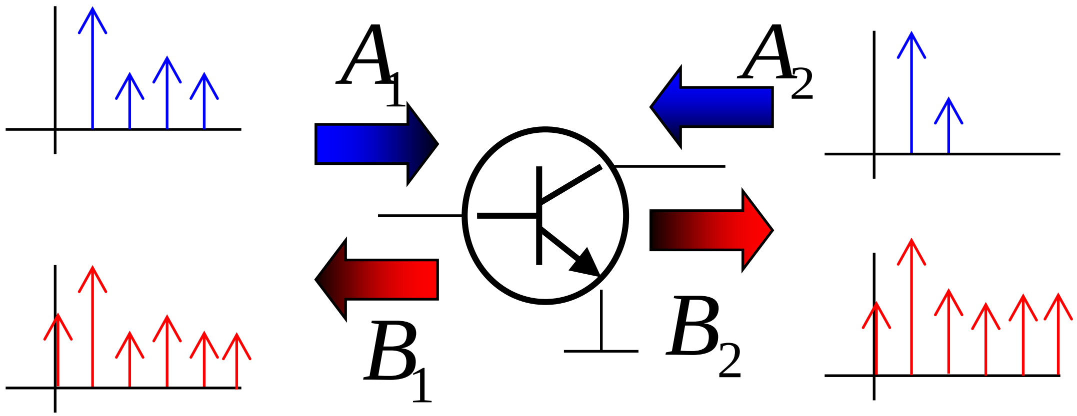
X-parameter Component :
Simulate using X-parameters



ADS, SystemVue & Genesys:
Design using X-parameters



X-parameters

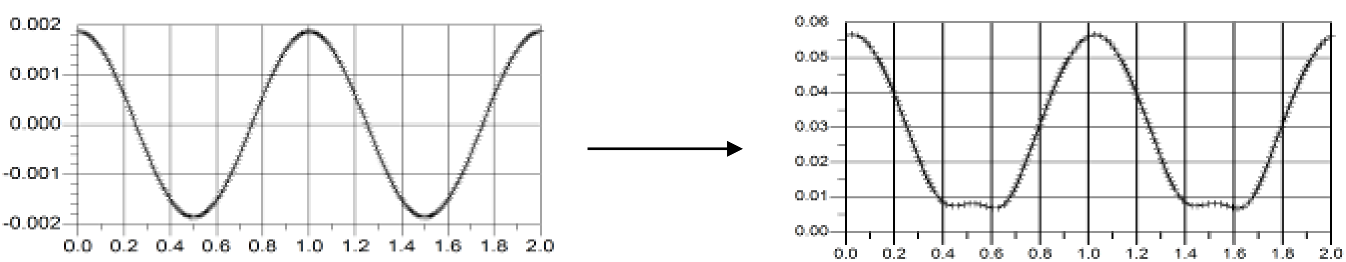


$$B_{1k} = F_{1k}(DC, A_{11}, A_{12}, \ldots, A_{21}, A_{22}, \ldots)$$

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

Harmonic (or carrier) Index

Port Index



Unifies
S-parameters
Load-Pull,
Time-domain
load-pull

The X-parameters provide a mathematically correct mapping of the ‘A’ and ‘B’ waves at ports, input powers, harmonics, DC bias, etc, etc.

Scattering Parameters

S-Parameters – Linear System Description

$$b_i = \sum_k S_{ik} \cdot a_k$$

$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2$$

X-Parameters – Linear and Nonlinear System Description

$$b_{ij} = X_{ij}^{(F)}(|A_{11}|)P^{j} + \sum_{k,l\neq(1,1)} X_{ij,kl}^{(S)}(|A_{11}|)P^{j-l} \cdot a_{kl} + X_{ij,kl}^{(T)}(|A_{11}|) \quad P^{j+l} \cdot a_{kl}^{*}$$

$|A_{11}| =$ Large signal drive to the amplifier input port (port #1) at the fundamental frequency (#1)

Definitions

- **i = output port index**
- **j = output frequency index**
- **k = input port index**
- **l = input frequency index**

For example: $X_{21,21}^{T}$

Means: output port = 2
output frequency = 1 (fundamental)
input port = 2
input frequency = 1 (fundamental)

Measurement-Based Modeling & Design Flow

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

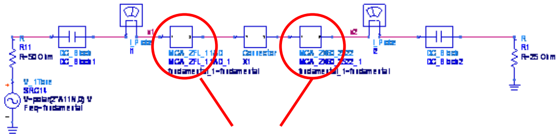
NVNA

Nonlinear Measurements

Data File

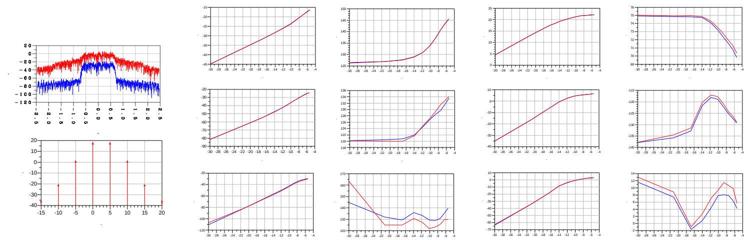
ADS

Design and Simulation



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*"

Presentation Outline

Introduction to NVNA

- Measurement Capabilities

Amplifier Design Considerations using X-parameters

- Industry Challenges
- Introduction to X-parameters

End-to-End Power Amplifier Design with X-parameters

- Load-Dependent X-parameters
- High Power X-parameter Measurement Configuration
- Final PA Results

Mixer/Converter Characterization with X-parameters

- NVNA Measurement Wizard for Mixers
- X-parameter Measurements of Mixers

Load-Dependent X-parameters

Some components (un-matched transistors) may require input and output tuners because their match is far from 50 ohm.

This requires an X-parameter model that also includes dependence on the load impedance supplied to the output of the component. This is accomplished by adding an impedance tuner to the output of the component.

Depending on the component, and the class of operation, a multi-harmonic tuner may not be required.

The source tuner can be fixed at a single impedance that is close to the conjugate match point and a power sweep performed to vary the available power to the component.

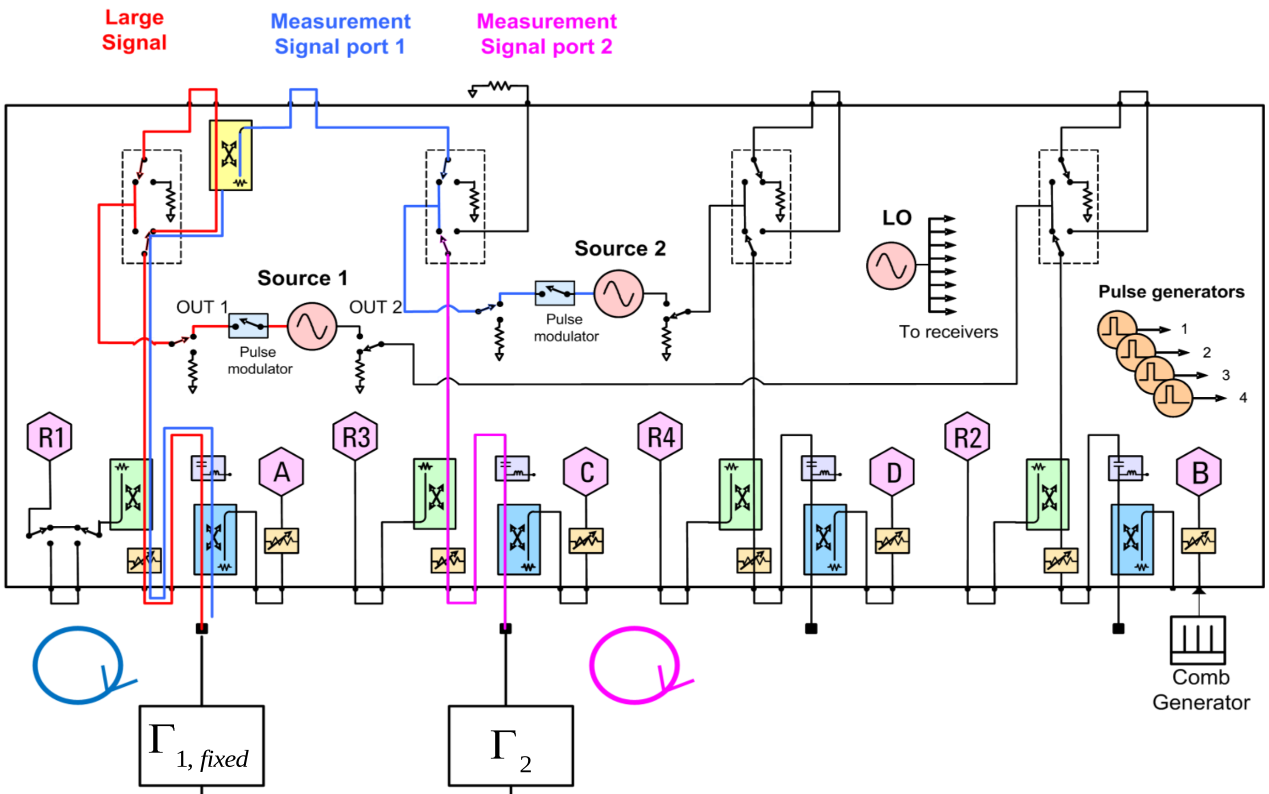
X-Parameters definition with port 2 gamma dependence

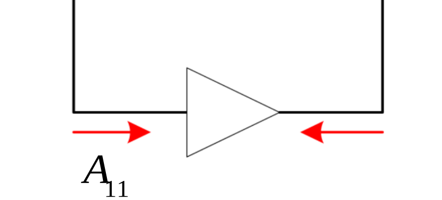
$$b_{ij} = X_{ij}^{(F)}(DC,|A_{11}|,\Gamma_2)P^{j} + \sum_{k,l\neq(1,1)} \left(X_{ij,kl}^{(S)}(DC,|A_{11}|,\Gamma_2)P^{j-l} \cdot a_{kl} + X_{ij,kl}^{(T)}(DC,|A_{11}|,\Gamma_2)P^{j+l} \cdot a_{kl}^{*} \right)$$

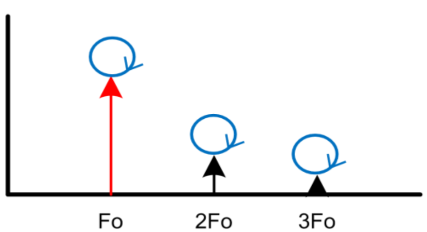
Load-Dependent X-parameter Measurements

$|A_{11}|$ is swept through a power sweep

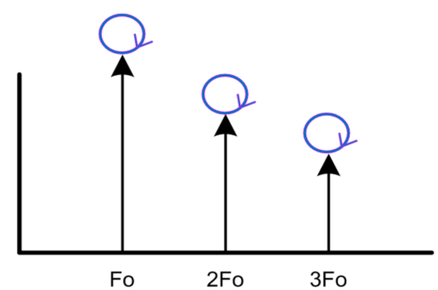
Γ_2 is swept through a set of fundamental frequency impedances supplied by tuner. All other harmonic impedances are uncontrolled







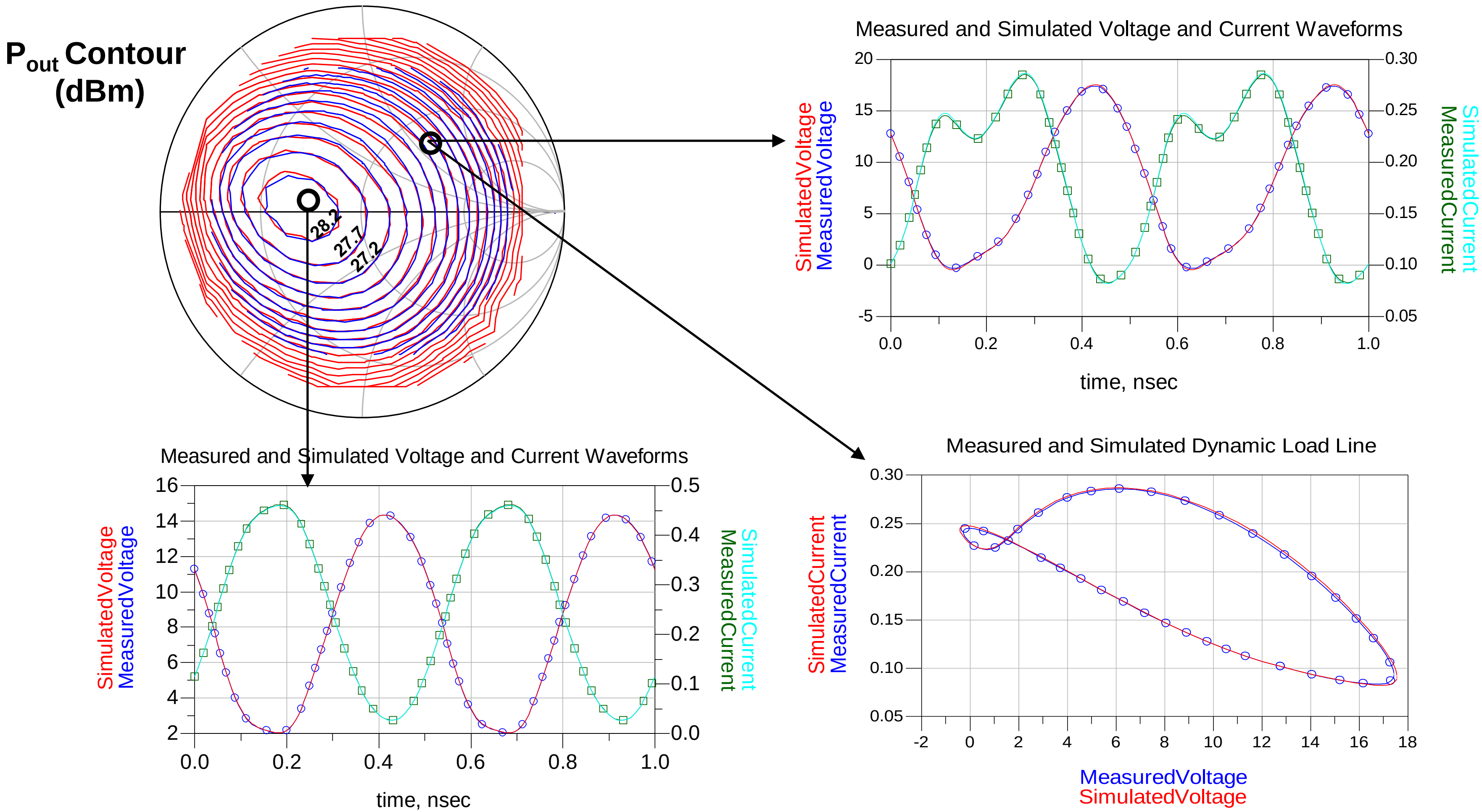
Input Frequency Spectrum



Output Frequency Spectrum

Load-Dependent X-Parameters of a FET

Measurements X-par Simulation



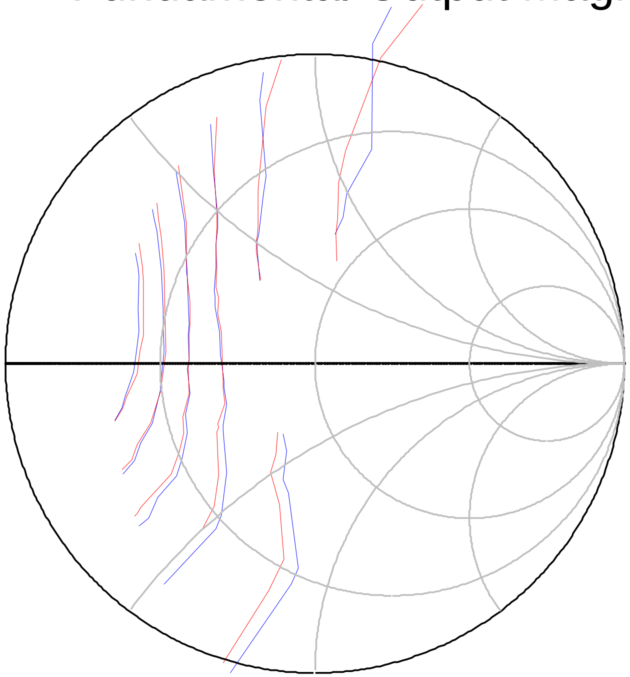
Experimental Harmonic Balance

X-parameters unify S-parameters and load-pull

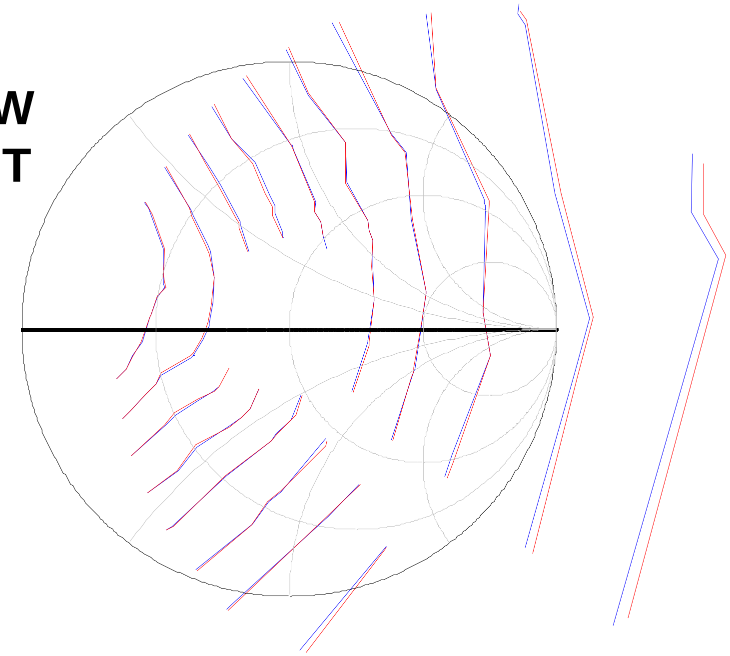
G. Simpson et al IEEE ARFTG Conference, December, 2008

X-parameter Harmonic Load-Tuning Predictions

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)

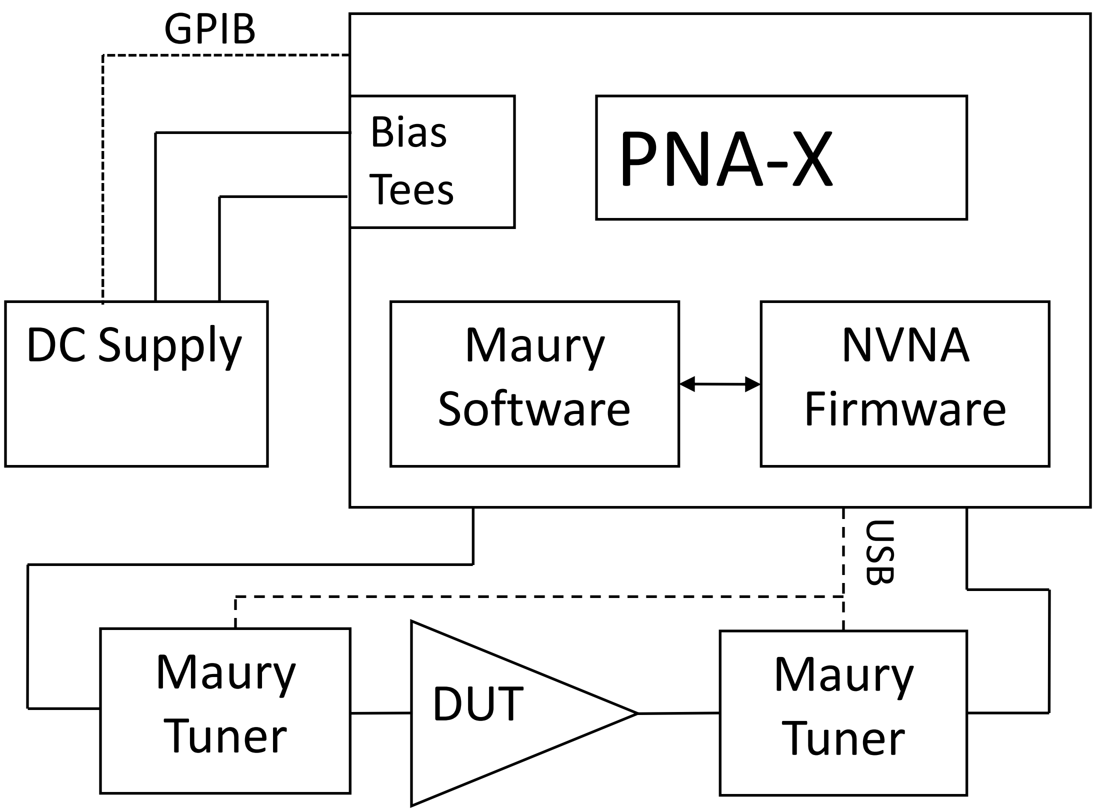
X-Parameter Prediction: Blue

Measured with Harmonic Load Pull System: Red

Harmonic load-pull <u>may</u> be unnecessary! Simpler, cheaper, faster alternatives exist

J. Horn et al, IEEE Power Amplifier Symposium, September, 2009

GaN HEMT Load-Dependent X-parameter Model



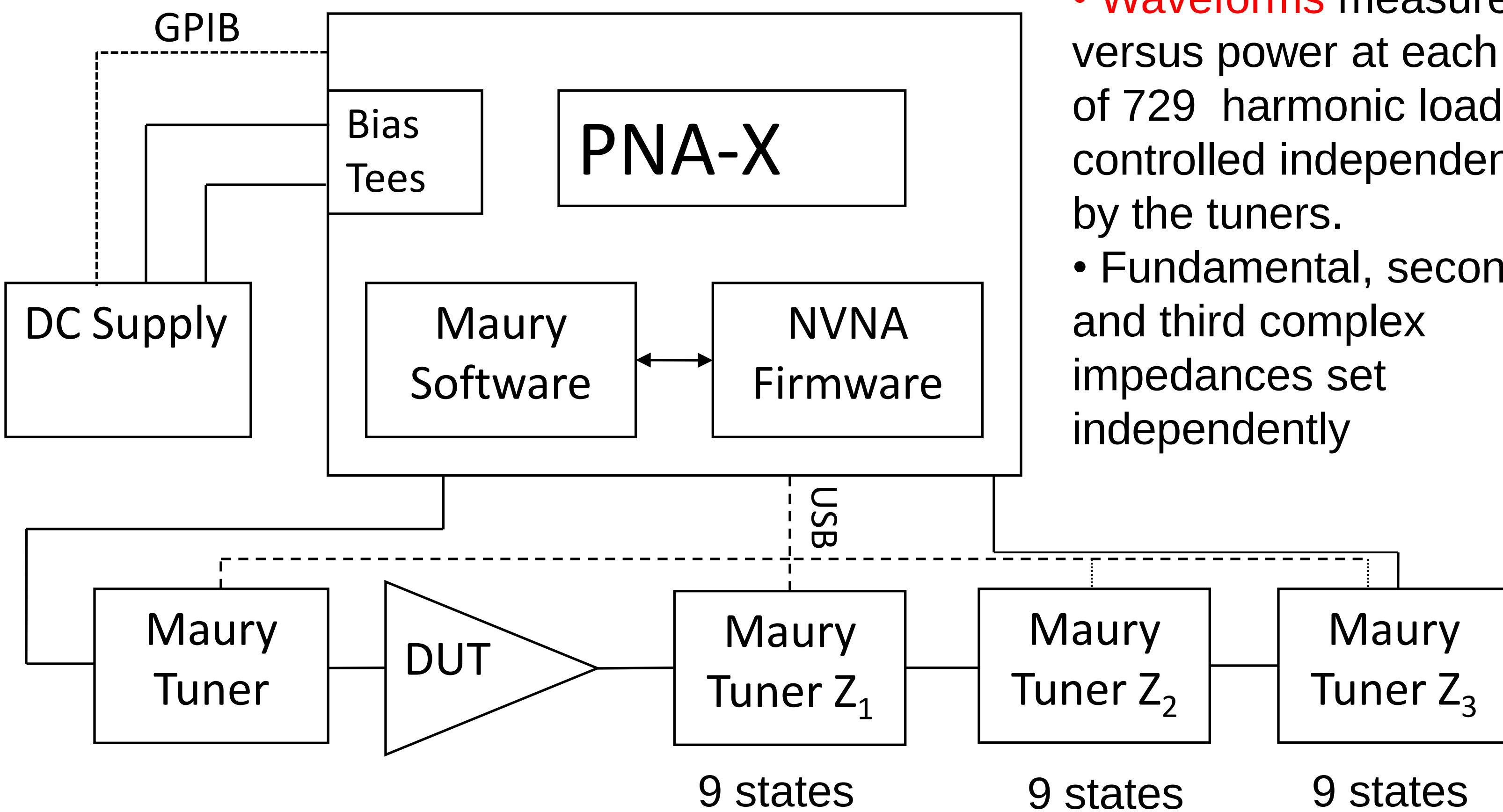
9 load states at f_1

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



- 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

J. Horn et al CSICS2010, Oct. 2010

Load-Dependent X-parameters Vs. Harmonic Load-pull

Load-dependent X-parameters

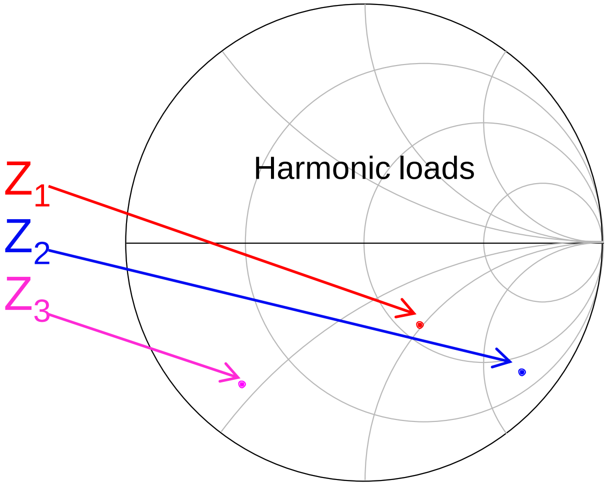
- *One output tuner* to vary load at fundamental frequency. At each load inject small tones at 2^{nd} and 3^{rd} harmonic frequencies (9x(1+2x2) = 45 measurements, actually ~125 measurements)
- Measured DC – 4^{th} harmonic
- Take into ADS. Present 729 independent loads to model

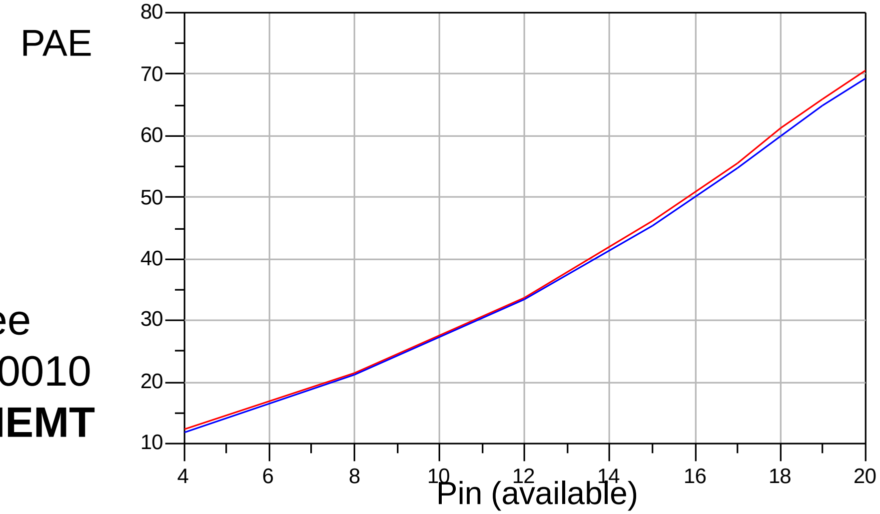
Harmonic load-pull measurements

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

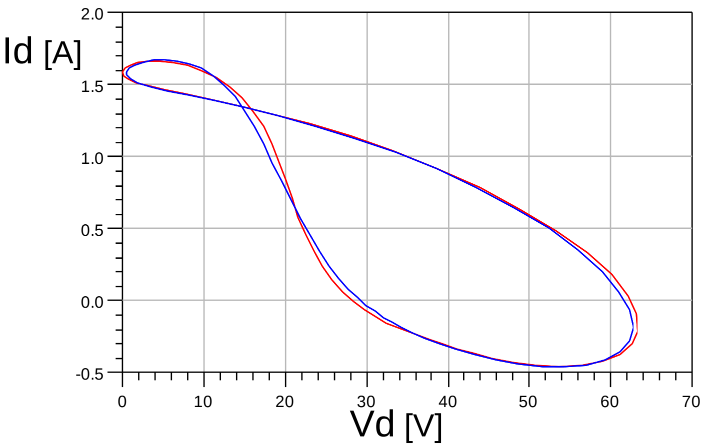
Compare waveforms, PAE, dynamic load-lines, etc.

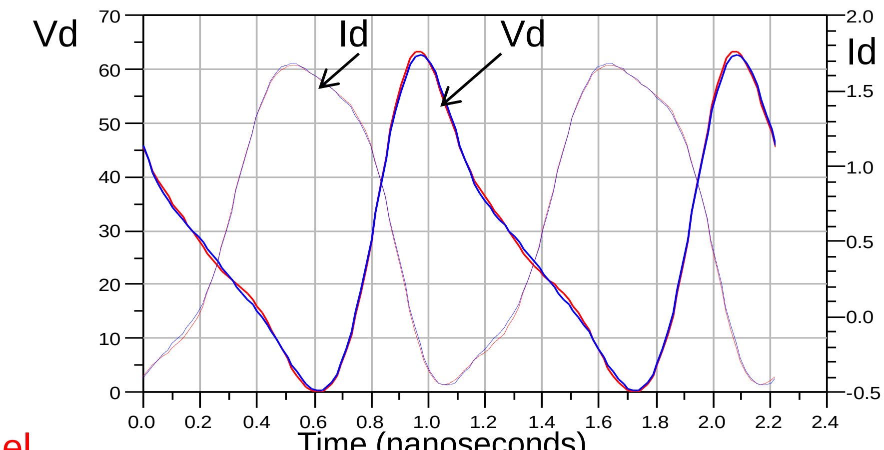
Prediction of GaN HEMT Harmonic Load-dependence from Fundamental-only Load-dependent X-parameters





Cree
CGH40010
GaN HEMT

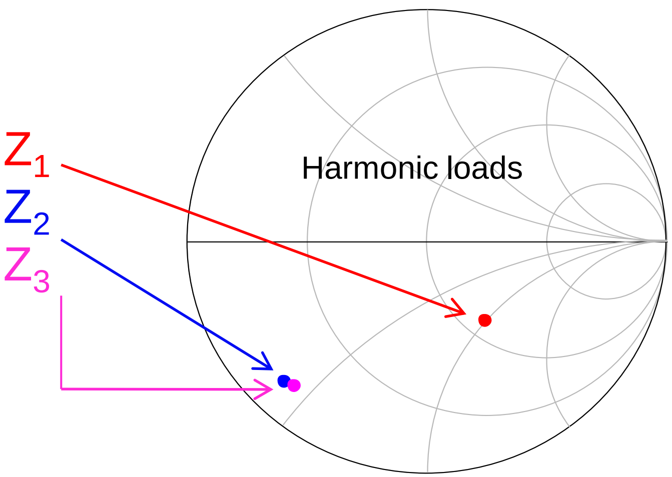




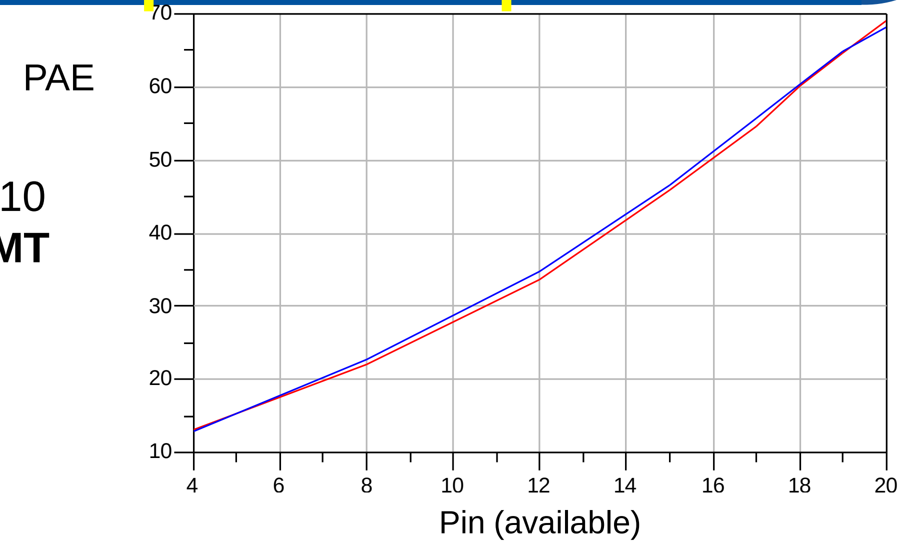
Courtesy of J. Horn

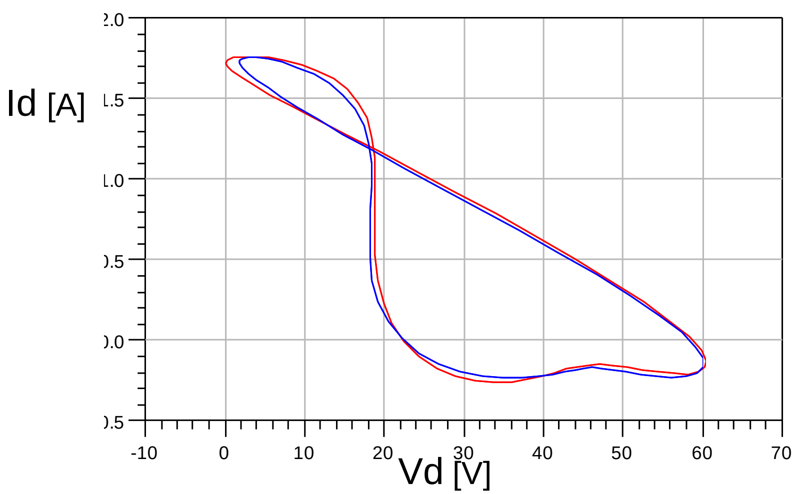
X-parameter model
Harmonic time-domain load-pull measurements

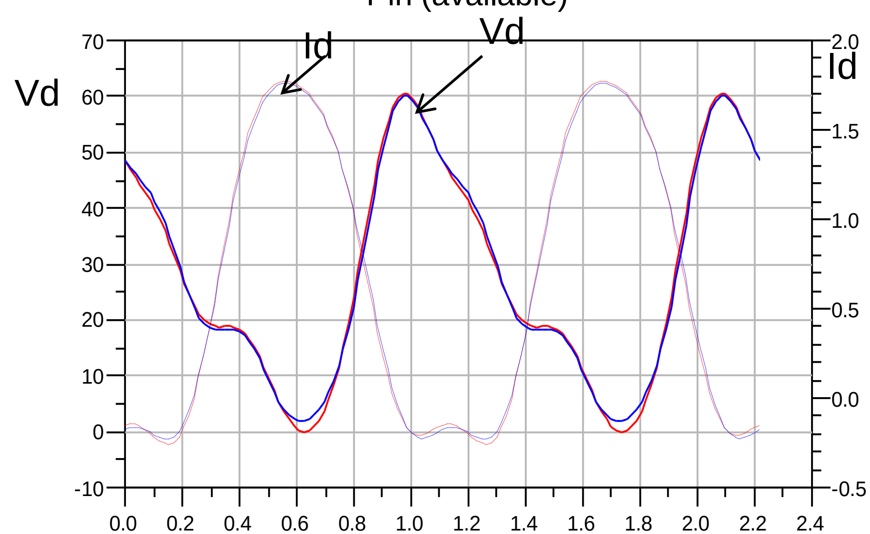
Prediction of GaN HEMT Harmonic Load-dependence from Fundamental-only Load-dependent X-parameters



Cree
CGH40010
GaN HEMT

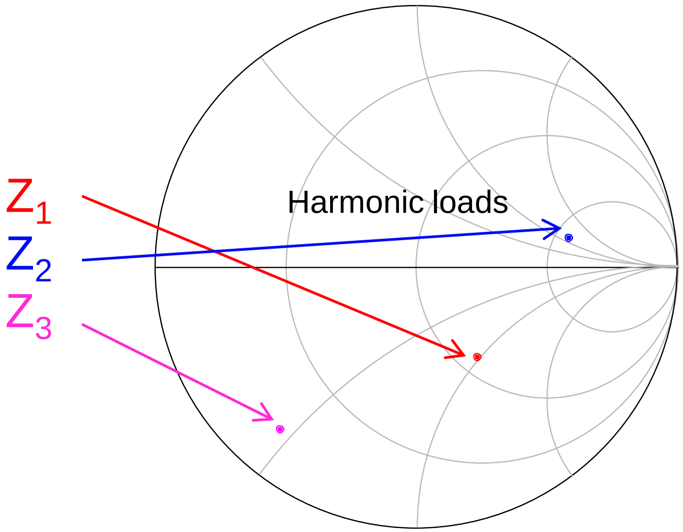




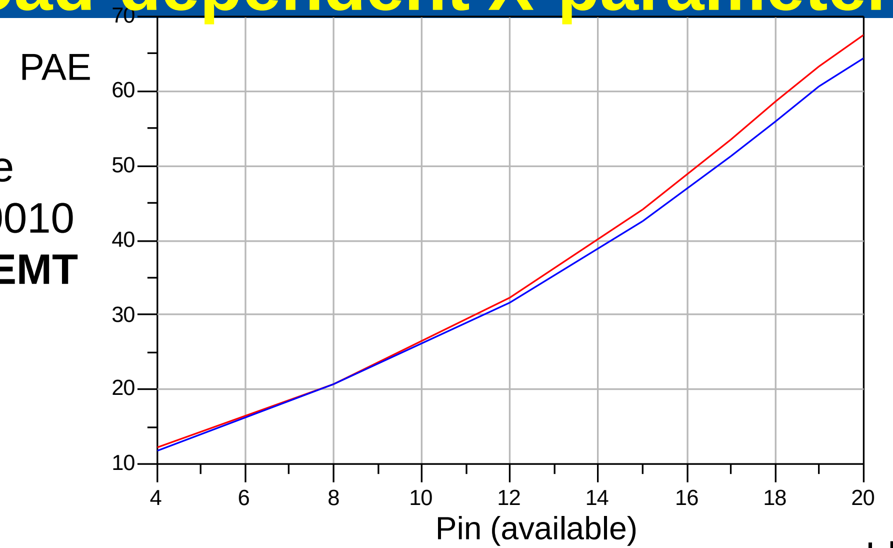


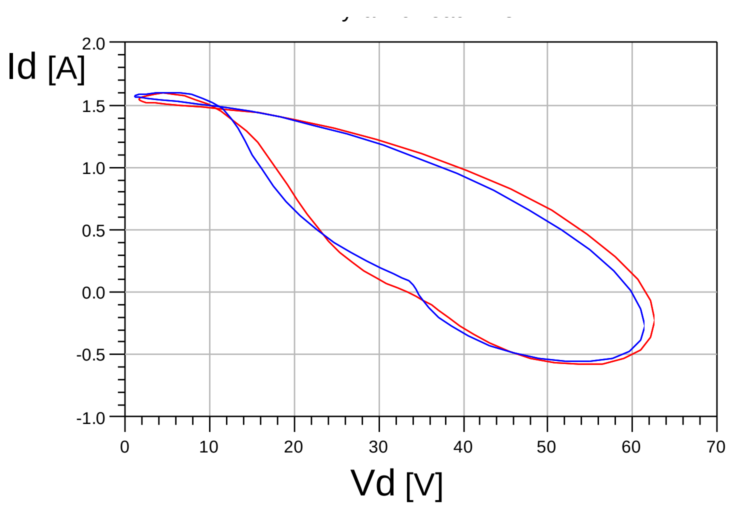
Vary second harmonic output impedance (keep others fixed)

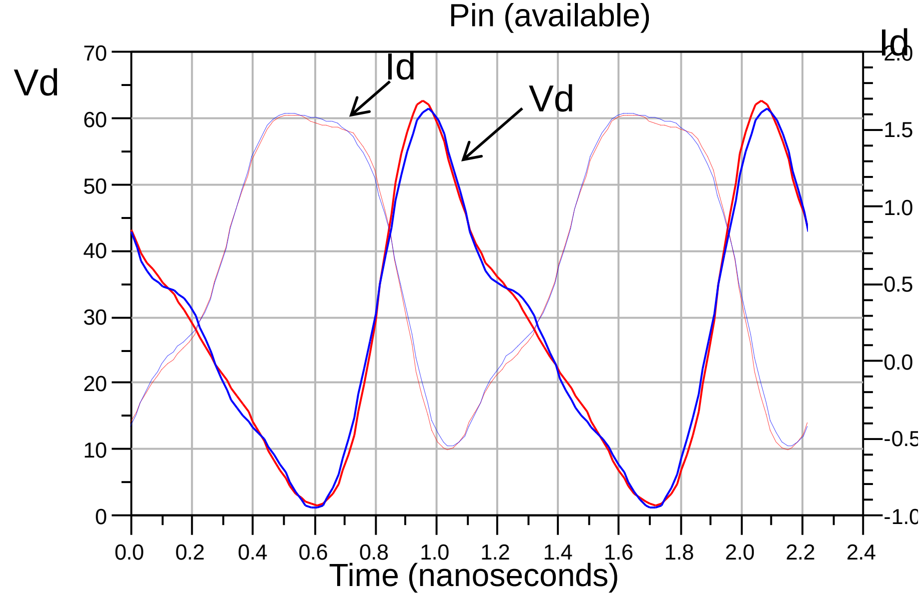
Prediction of GaN HEMT Harmonic Load-dependence from Fundamental-only Load-dependent X-parameters



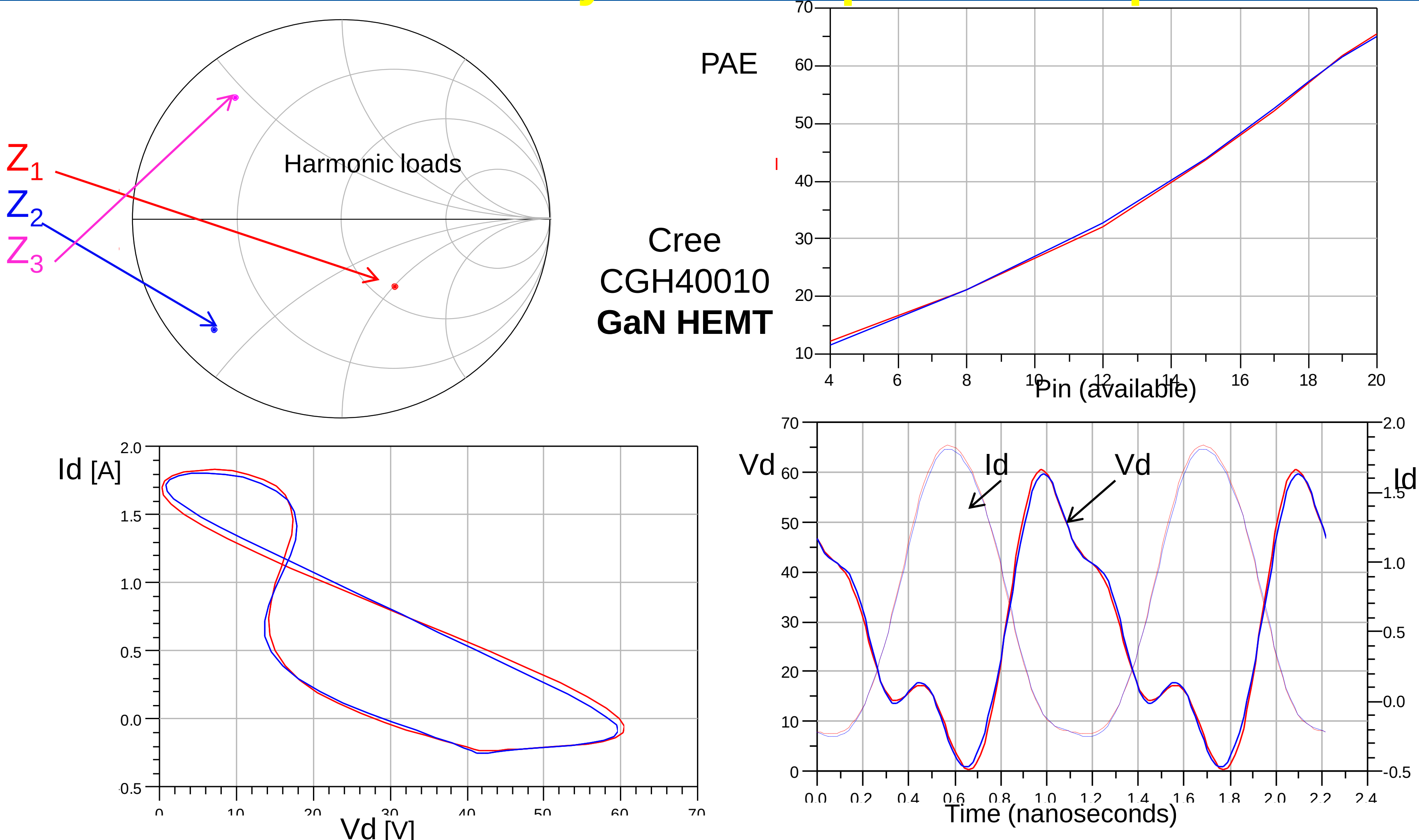
Cree
CGH40010
GaN HEMT







Prediction of GaN HEMT Harmonic Load-dependence from Fundamental-only Load-dependent X-parameters



Vary third harmonic output impedance (keep others fixed)

Implications of Arbitrary Load-dependent X-parameters

- Input and output harmonic load tuning dependence predictable
- Harmonic load-pull <u>may</u> be unnecessary for many apps.
- Source pull may be unnecessary (apart from power transfer)
- Complementary approach to “compact” nonlinear device models

Power Amplifier Design

Goal: Design a power amplifier using X-parameter measurements of a transistor.

X-parameter model measured of a Cree CGH40045F GaN transistor using NVNA.

Desired Design Goals:

- Frequency = 1.2 GHz
- Output power > 45 dBm
- PAE > 60%
- Class AB

Linearity and other performance parameters were not part of this first phase design.

Note: Cree transistor is capable of higher performance than ‘Desired Design Specifications’. Refer to Cree datasheet for more information.

CREE

CGH40045

45 W, RF Power GaN HEMT

Cree’s CGH40045 is an unmatched, gallium nitride (GaN) high electron mobility transistor (HEMT). The CGH40045, operating from a 28 volt rail, offers a general purpose, broadband solution to a variety of RF and microwave applications. GaN HEMTs offer high efficiency, high gain and wide bandwidth capabilities making the CGH40045 ideal for linear and compressed amplifier circuits. The transistor is available in a flange and pill package.

Package Types: 440193 & 440206
PN’s: CGH40045F & CGH40045P

FEATURES

- Up to 4 GHz Operation
- 16 dB Small Signal Gain at 2.0 GHz
- 12 dB Small Signal Gain at 4.0 GHz
- 55 W Typical P_{SAT}
- 55 % Efficiency at P_{SAT}
- 28 V Operation

APPLICATIONS

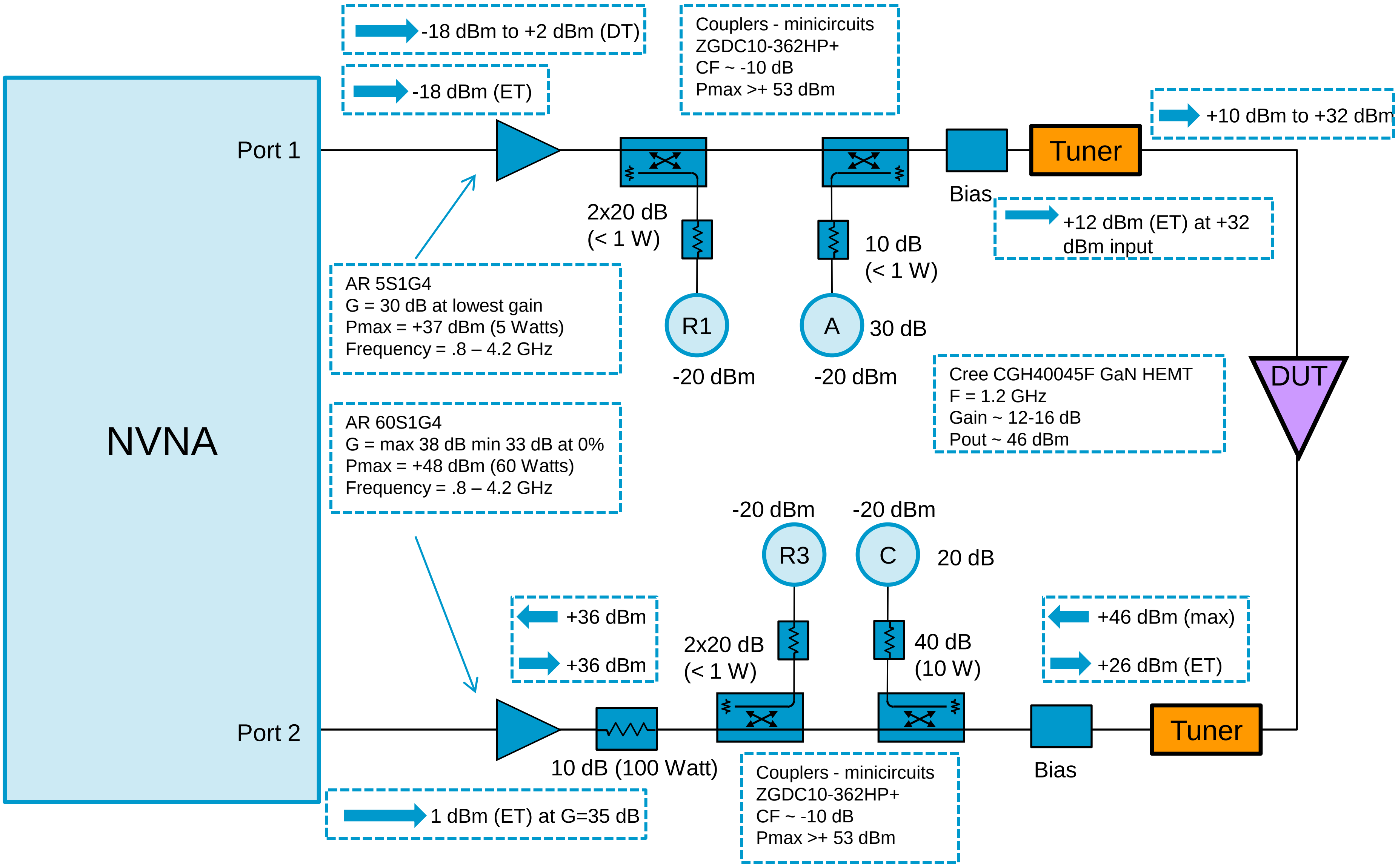
- 2-Way Private Radio
- Broadband Amplifiers
- Cellular Infrastructure
- Test Instrumentation
- Class A, AB, Linear amplifiers suitable for OFDM, W-CDMA, EDGE, CDMA waveforms

Power Amplifier Design

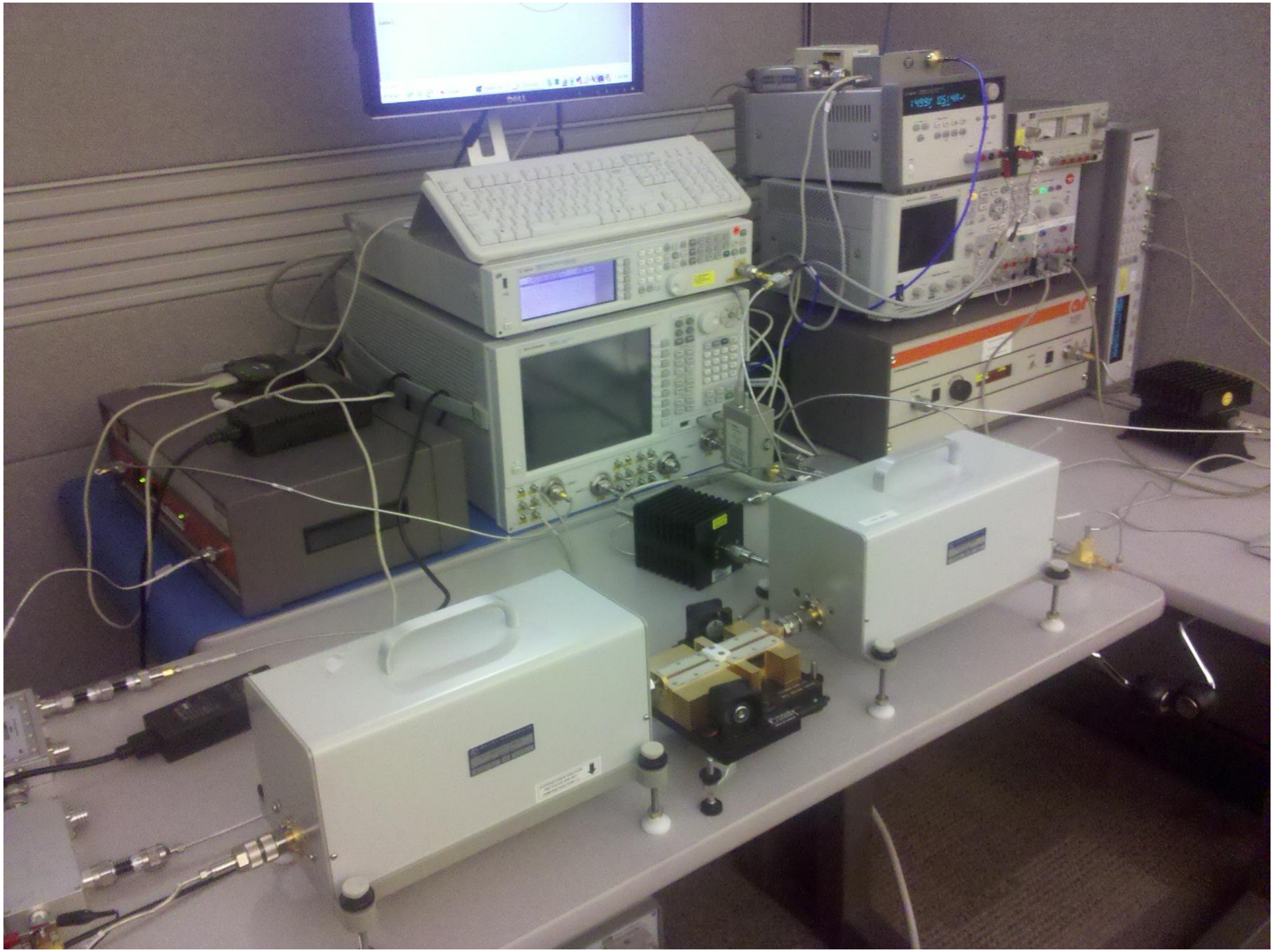
Total PA design completed in ADS:

1. Simulated impedance contours of output power and PAE at fundamental and harmonic frequencies at input (gate) and output ports (drain)
2. Simulated impedance contours used to determine appropriate termination impedances at fundamental and harmonic frequencies at input (gate) and output ports (drain) to maximize PAE and output power
3. PCB designed with appropriate matching from (2)
4. Final PA assembled and compared against simulation

NVNA X-parameter System – Power Budget (120 W)



High Power X-parameter Measurement System



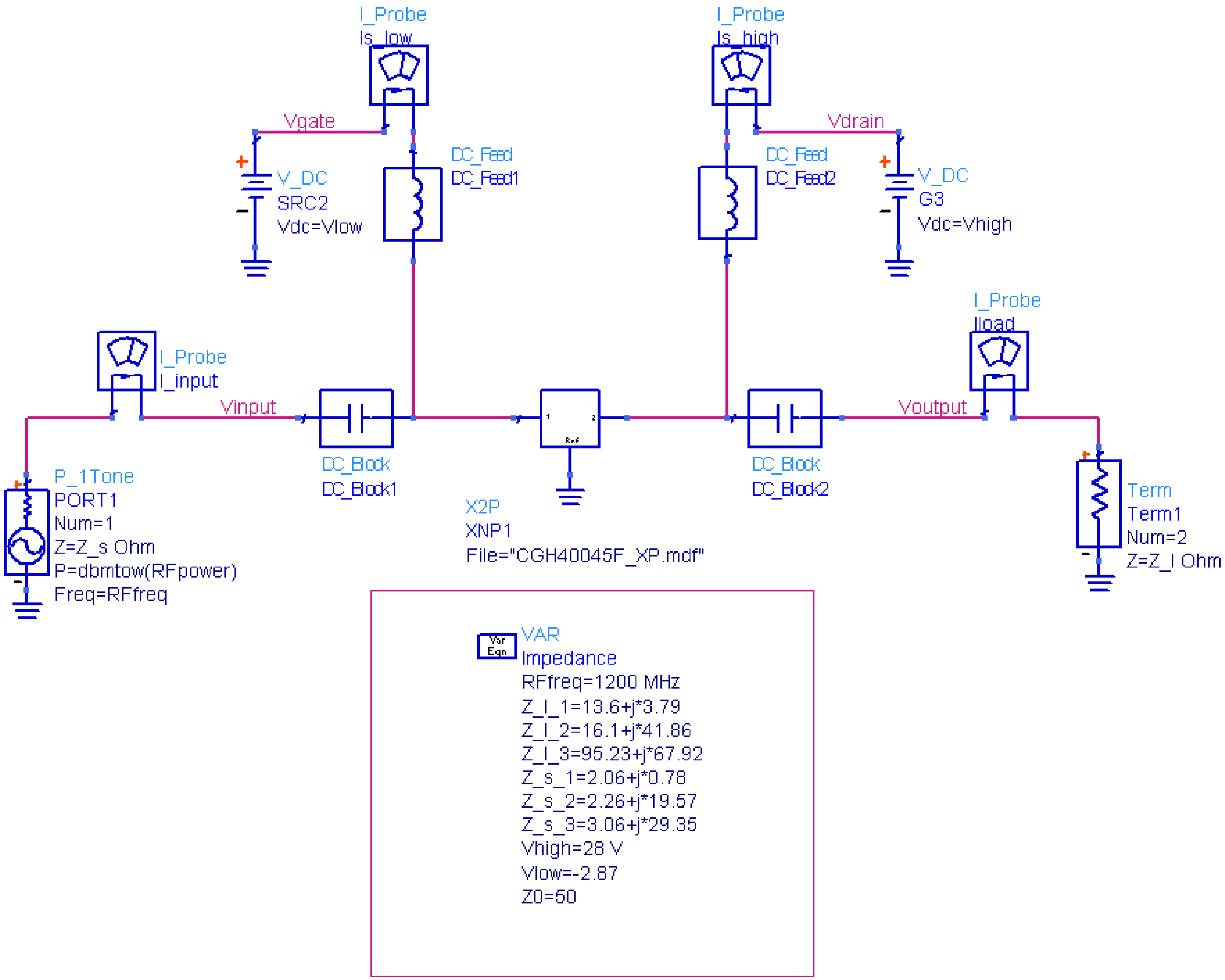
Model Verification

Verification of the measured X-parameter model:

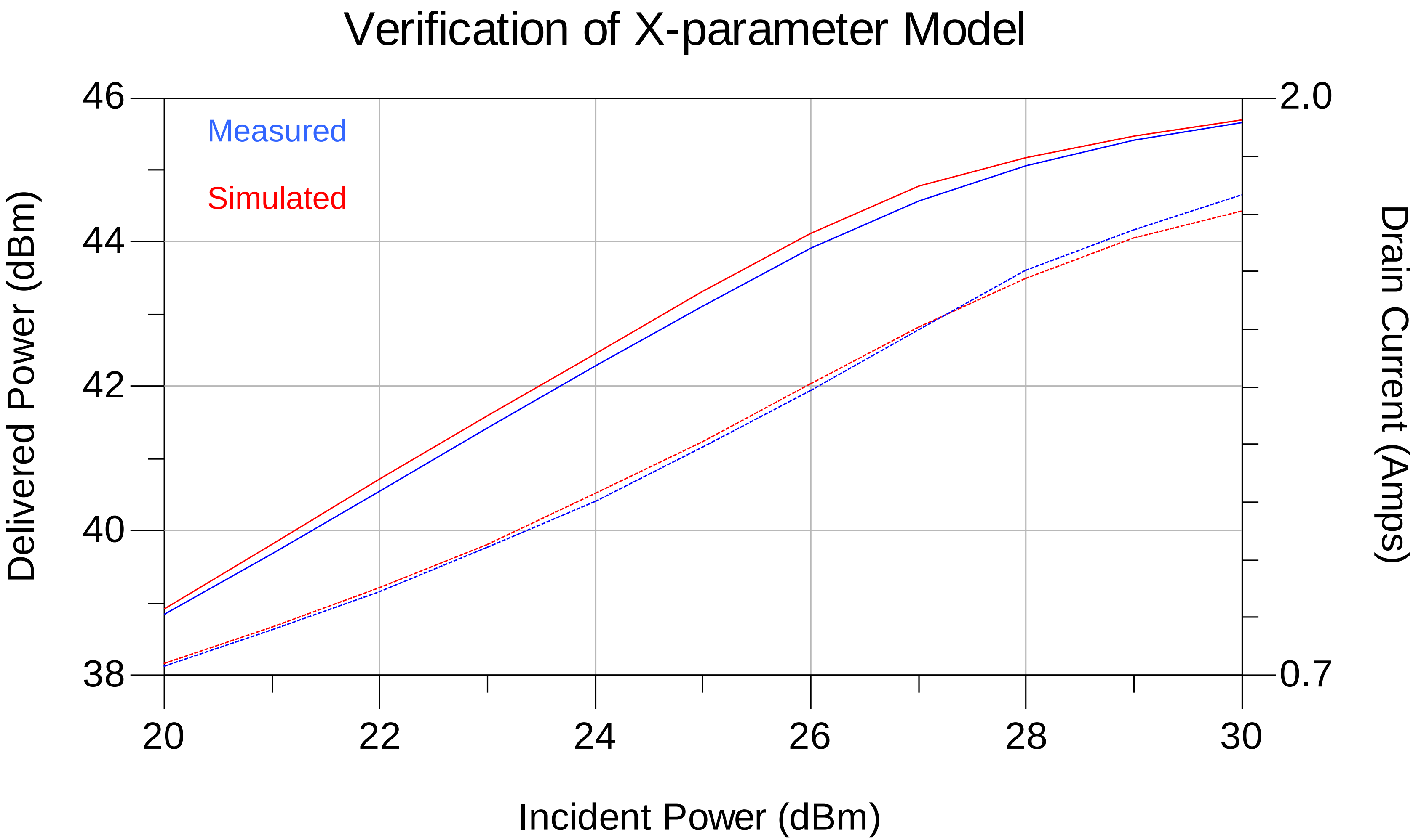
1. Make measurements of component (transistor). These are not X-parameter measurements but instead measurements of other parameters like ‘A’ and ‘B’ waves, output power, PAE or another parameter of your choice.
2. Record the input power, impedances (input and output ports, fundamental and harmonic) and bias used during the measurements in (1).
3. Place these impedances in the simulator as terminations of the X-parameter model and sweep power over that used in measurement range.

Note: Extrapolation boundaries is a topic for another day

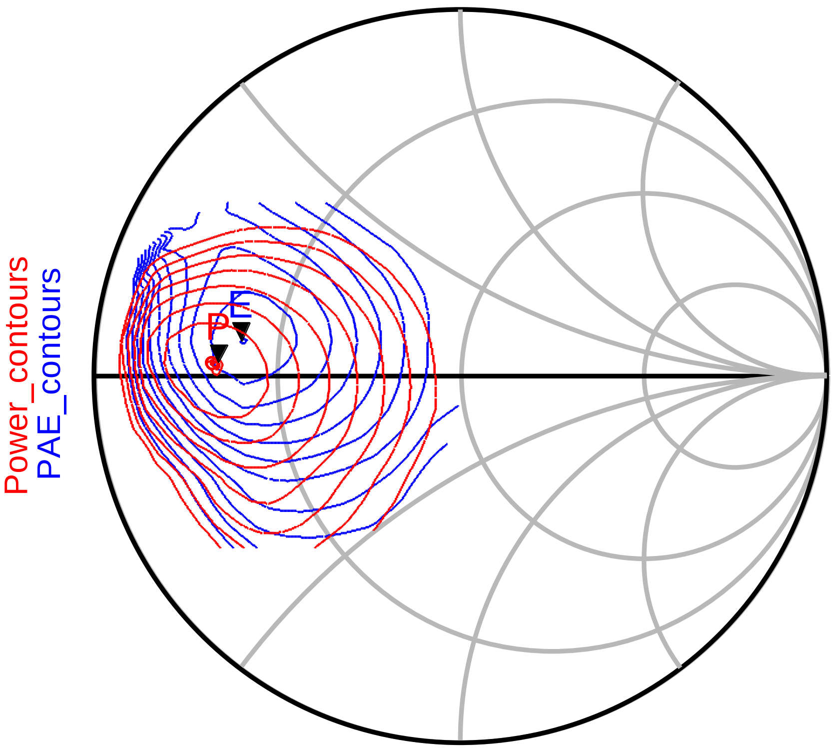
X-parameter Model Verification - Circuit Template



X-parameter Model Verification - Results



Simulated Fundamental Pout and PAE Contours



E
level=70.711610, number=65

P
level=46.029871, number=52

Maximum Power and contour levels, dBm:

46.05 ← Output Power > 45 dBm

46.00
45.50
45.00
44.50
44.00
43.50
43.00
42.50

Maximum PAE and contour levels, %:

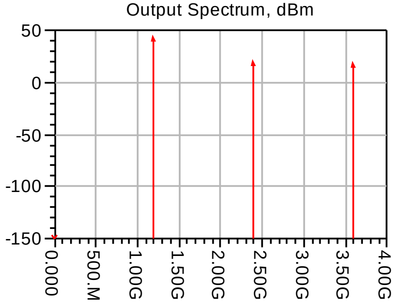
70.812 ← PAE > 70 %

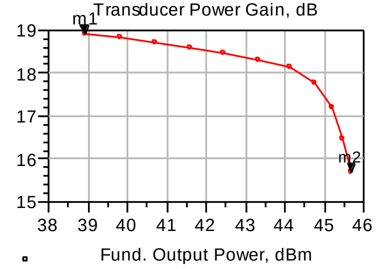
68.000
64.000
60.000
56.000
52.000
48.000
44.000
40.000

All other impedances in the simulator set to 50 ohm except fundamental input impedance (~2 ohm).

Simulated Parameters

ADS Amplifier DesignGuide



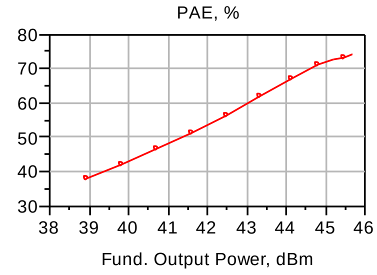


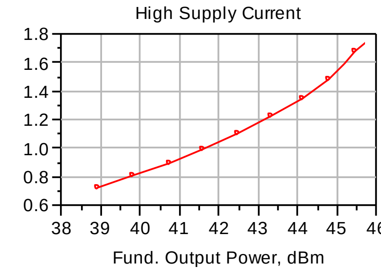
Gain Compression between markers, dB

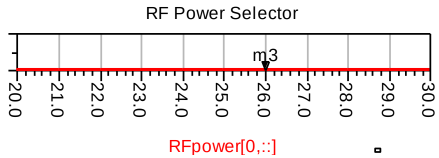
3.220

Output Power at Marker m2, dBm

45.70



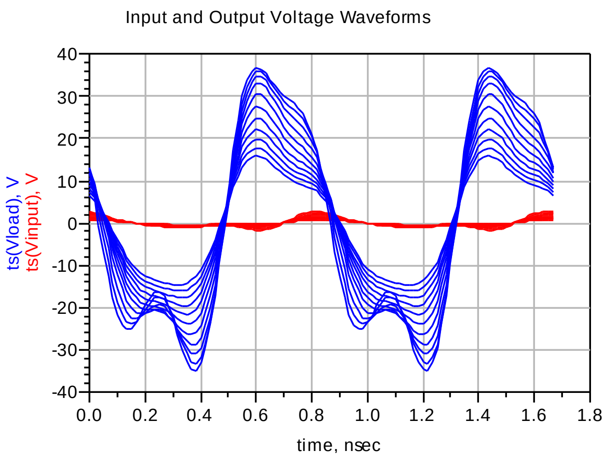


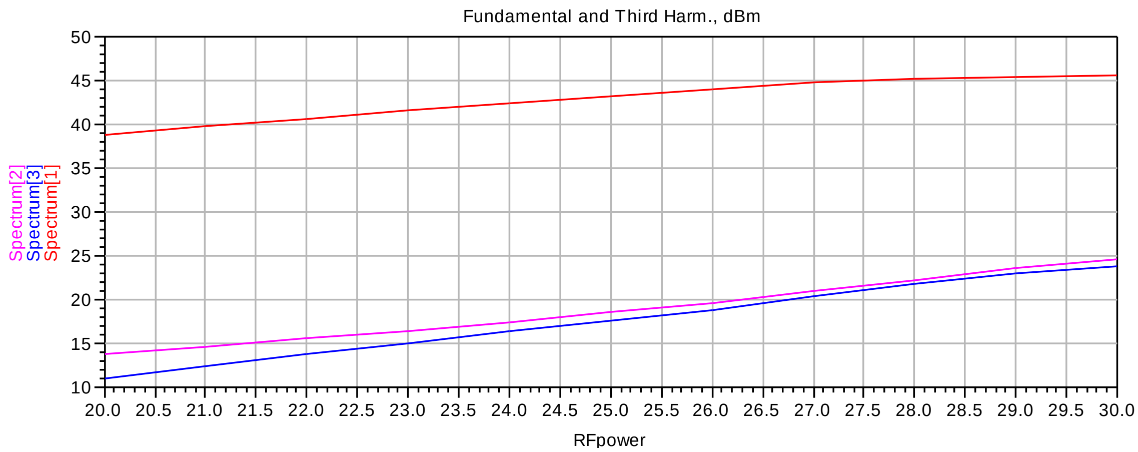


Fundamental Frequency

1.200 GHz

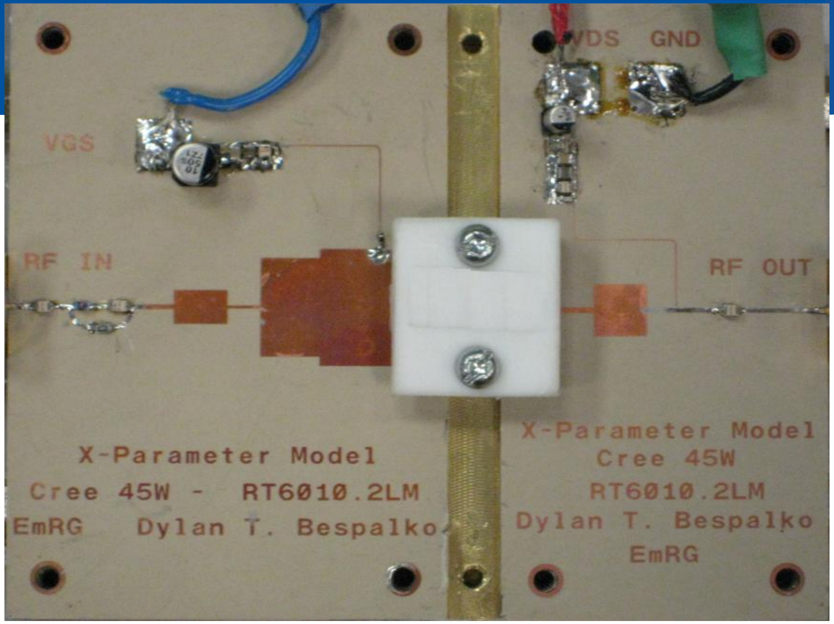
Available Source Power dBm	Fundamental Output Power dBm	Transducer Power Gain	Power- Added Efficiency, %	DC Power Consumpt. Watts	High Supply Current	Thermal Dissipation Watts
20.000	38.916	18.916	37.953	20.281	0.724	12.547
21.000	39.826	18.826	42.019	22.583	0.807	13.047
22.000	40.717	18.717	46.465	25.069	0.895	13.361
23.000	41.596	18.596	51.376	27.747	0.991	13.415
24.000	42.460	18.460	56.108	30.984	1.107	13.500
25.000	43.318	18.318	61.767	34.283	1.225	12.977
26.000	44.122	18.122	67.226	37.877	1.353	12.242
27.000	44.775	17.775	71.322	41.453	1.481	11.653
28.000	45.180	17.180	72.659	44.579	1.592	11.865
29.000	45.472	16.472	73.308	47.124	1.683	12.142
30.000	45.696	15.696	74.317	48.783	1.743	11.988





Final Power Amplifier

PAE could be improved based on a better physical termination impedance at the 2nd harmonic at the input in the next design. However, there is a tradeoff between the bandwidth of the impedance and PAE (i.e. PAE could be very peaky over a very narrow frequency bandwidth)



Courtesy of University of Waterloo

Figure of Merit	Simulation Results	Measurement Results
Input Power	30 dBm	30 dBm
Drain Efficiency	64.1%	64.6 %
PAE	62.3%	62.6 %
Output Power	45.3 dBm	44.93 dBm

X-parameter Measurements "Rules-of-Thumb"

Leave enough pre-amplifier linear gain for extraction and drive tones

- If the pre-amplifier is saturated with the drive signal then adding the extraction signal will degrade X-parameters. Generally seen during a power sweep where there is divergence between simulated and measured results at the higher end of the power sweep (watch receiver compression though).

Simulation termination impedance

- When comparing simulated a's and b's from X-parameters against measured a's and b's it is critical that the terminations in the simulation match that used during measurement. Ensure proper calibration and de-embedding techniques where applicable.

Calibration procedure using 8 term error model, tuners and pre-amplifiers

- Often pre-amplifiers are removed behind the couplers during calibration and then placed back in-line after the calibration procedure is complete. This may effect the tuner characterization and therefore the source and load impedances behind the tuners should be determined from the NVNA and accounted for to ensure proper applied impedance to the component by the tuners.

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- High Power X-parameter Measurement Configuration
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Mixer/Converter Characterization with X-parameters

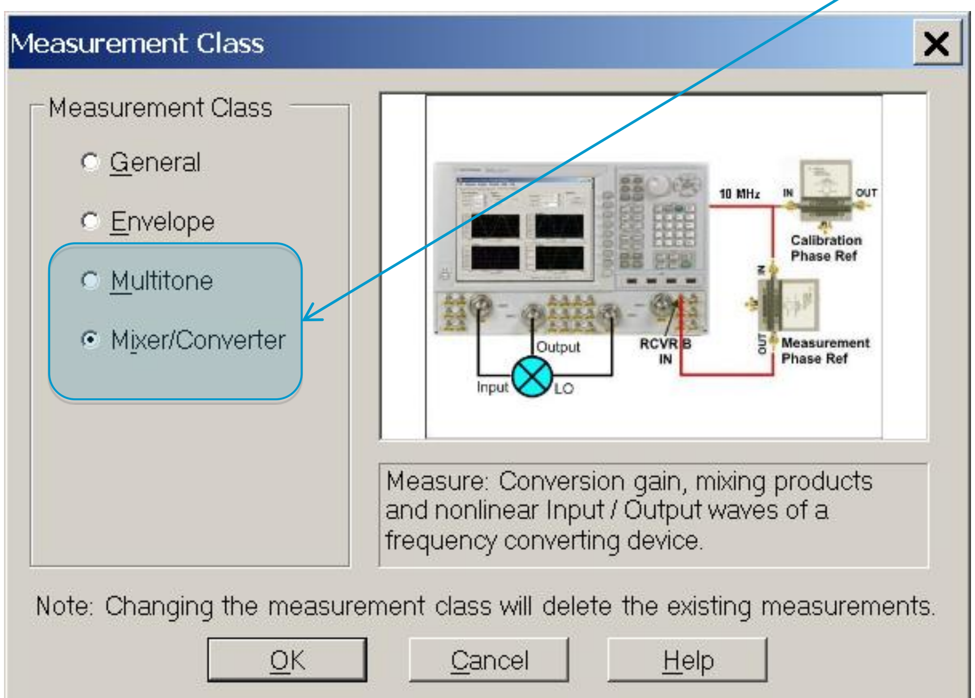
- NVNA Measurement Wizard for Mixers
- X-parameter Measurements of Mixers

New NVNA Measurement Classes

Two additional measurement classes have been added to the NVNA FW:

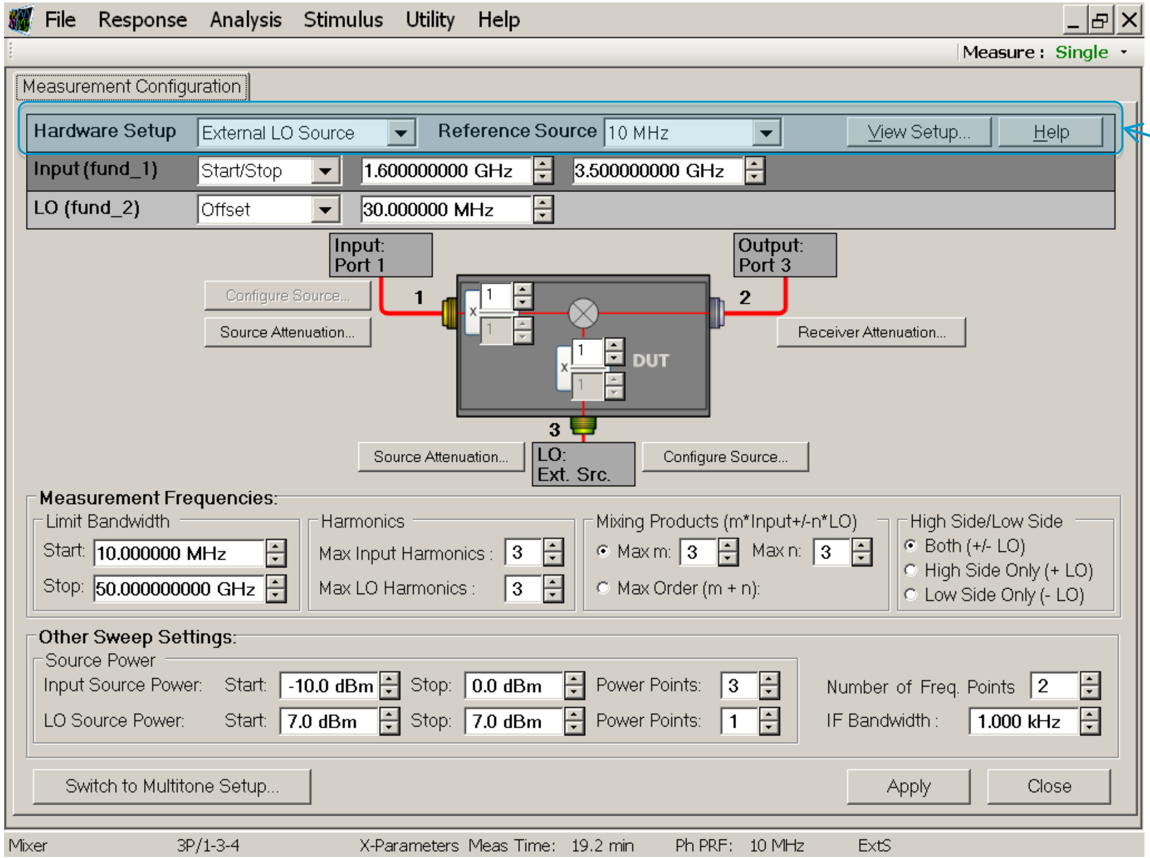
1) Multi-tone (multi-tone measurements and two-tone X-parameters).

2) Mixer/Converter (Measurements and X-parameters).



NVNA Mixer Measurement Setup Wizard

Hardware Setup



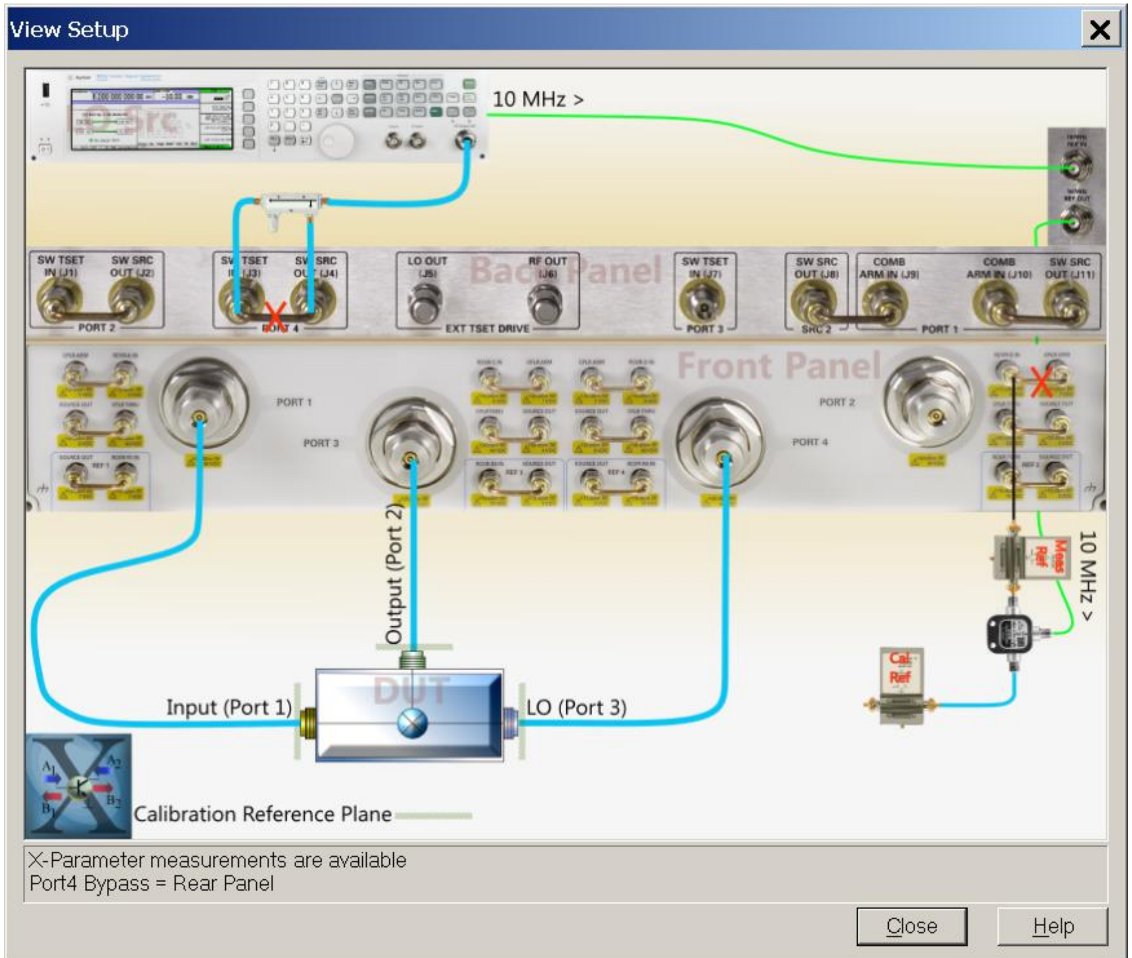
Configure:

1) External or internal LO source drive.

2) Reference source.

NVNA Mixer HW Setup Wizard

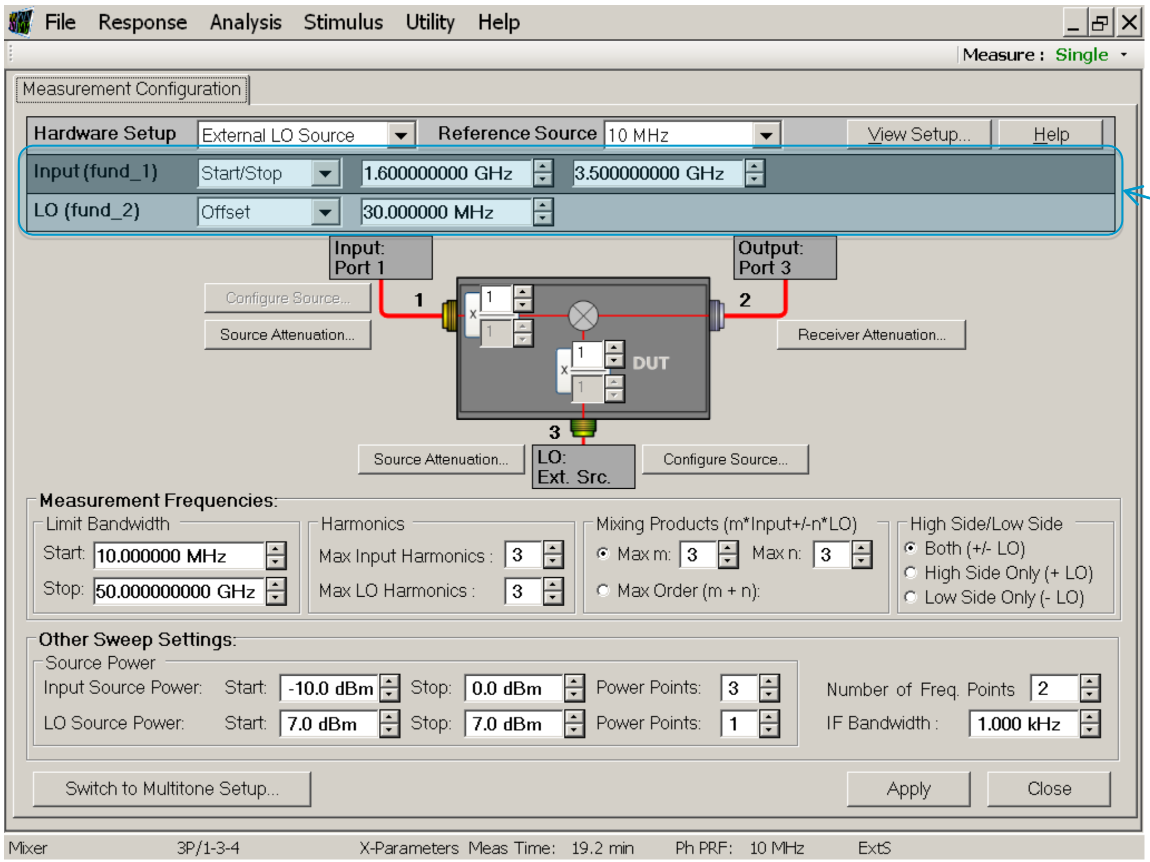
HW Setup Dialog



Illustrates connections for the HW as well as if X-parameters are available in the selected HW configuration.

NVNA Mixer Measurement Setup Wizard

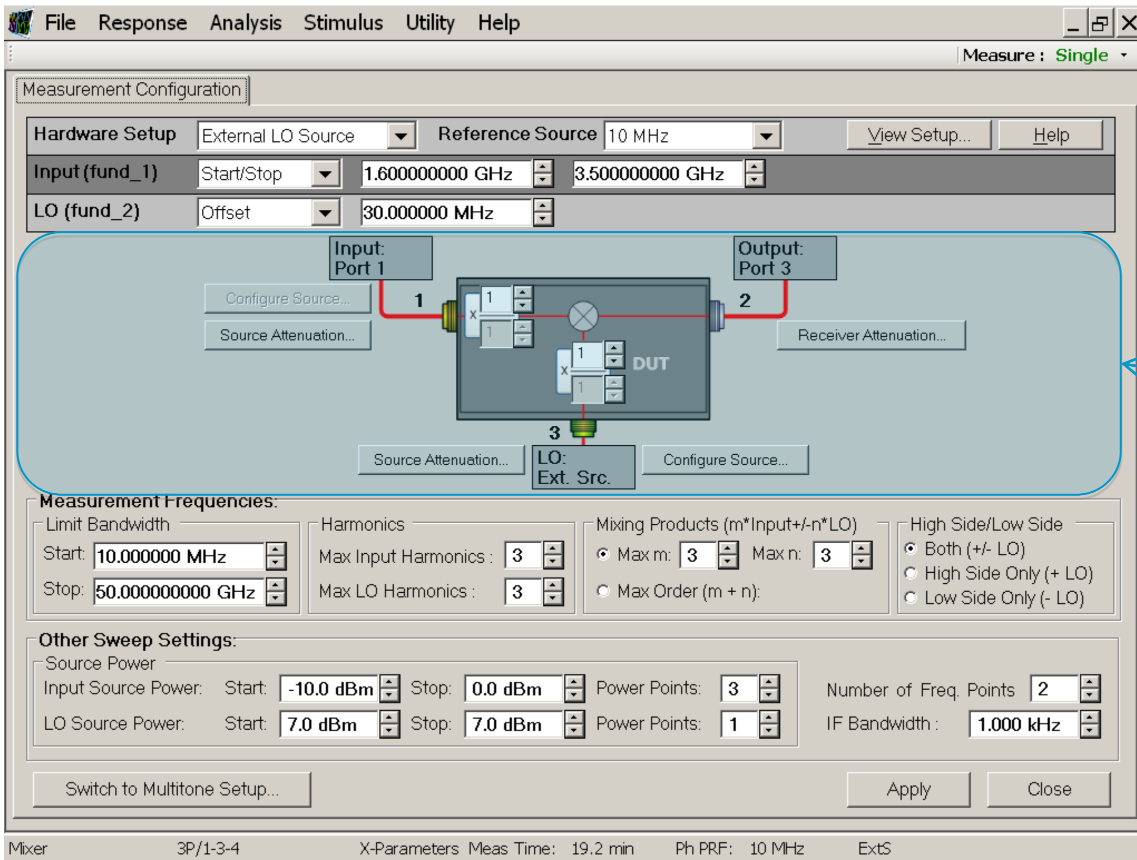
Input and LO Frequency Setup



Can configure in start/stop, center/span, offset, and fixed frequency types.

NVNA Mixer Measurement Setup Wizard

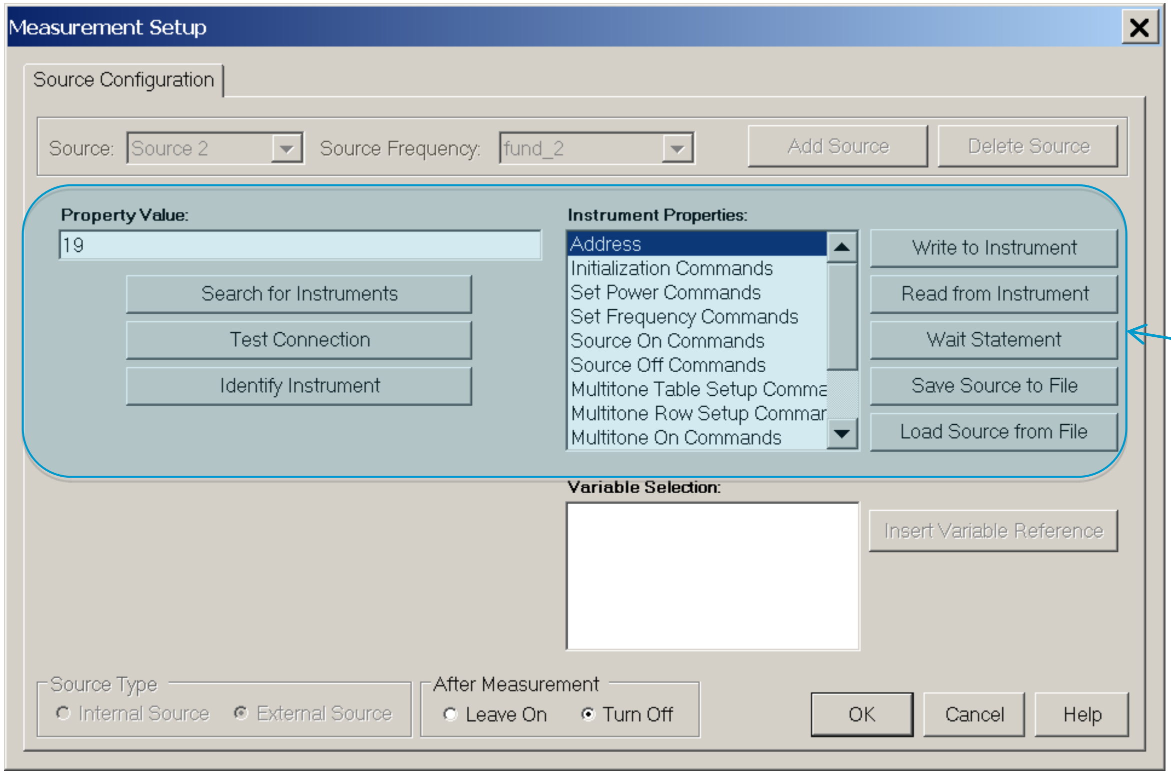
General Source Configuration



Configure internal and external sources and internal receiver attenuation.

NVNA Mixer External LO Source Setup

Configuring External LO Source for Mixer/Converter

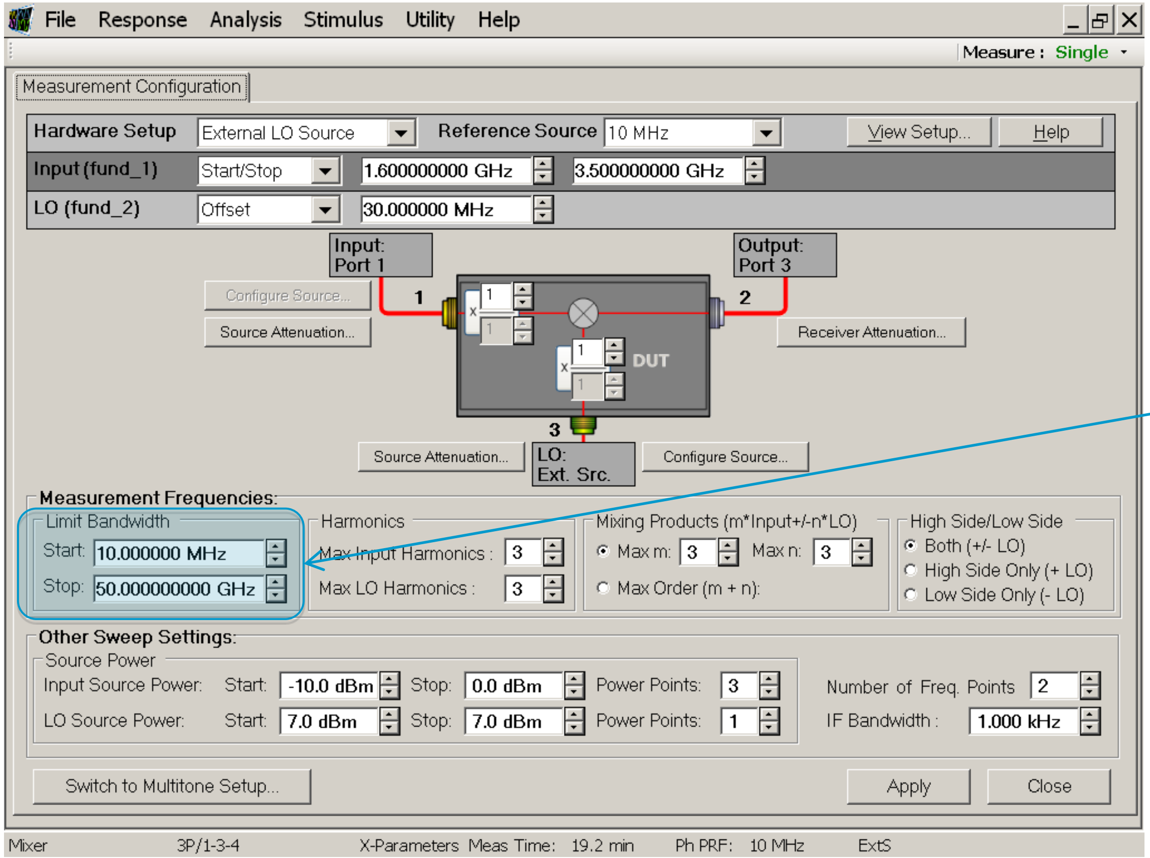


NVNA is already pre-loaded with commands to control external sources.

Can also search for instruments.

NVNA Mixer Measurement Setup Wizard

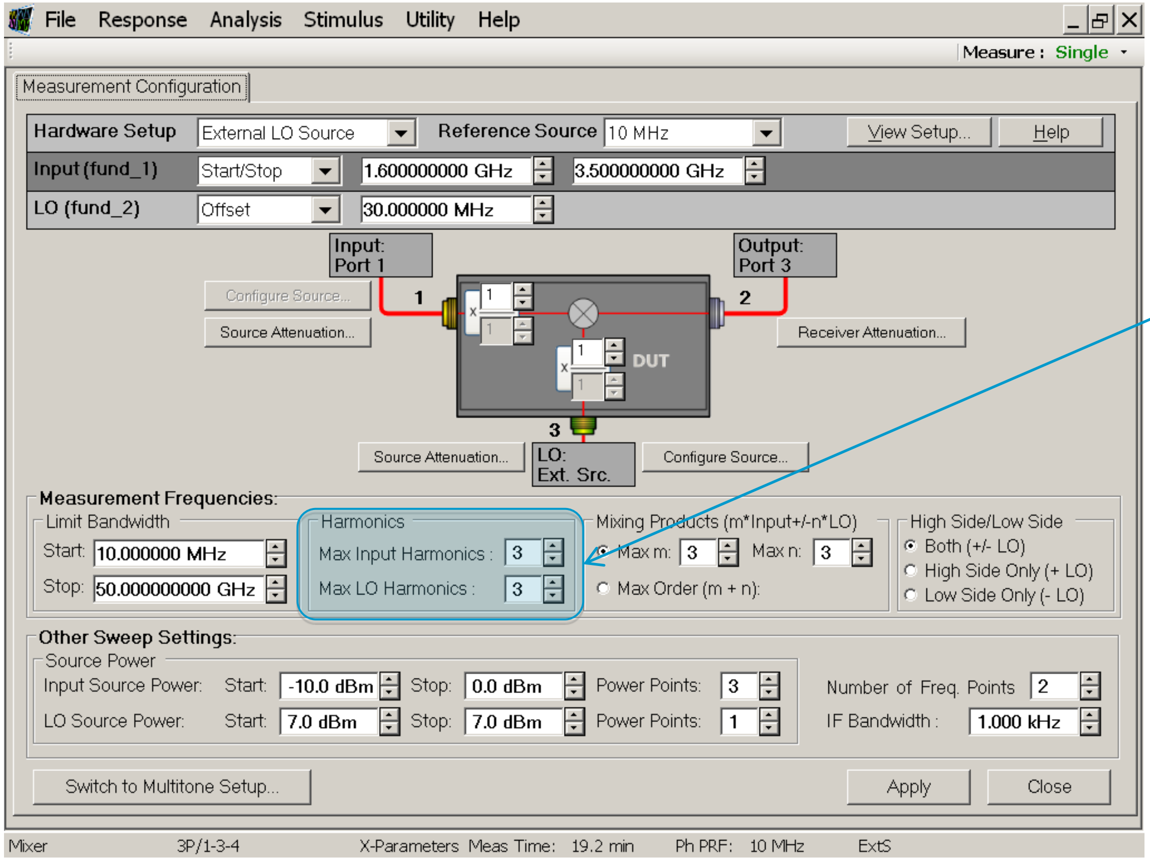
Limit Measurement Bandwidth



Reduces the total measured frequencies while still capturing the harmonic/mixing order products within the set bandwidth.

NVNA Mixer Measurement Setup Wizard

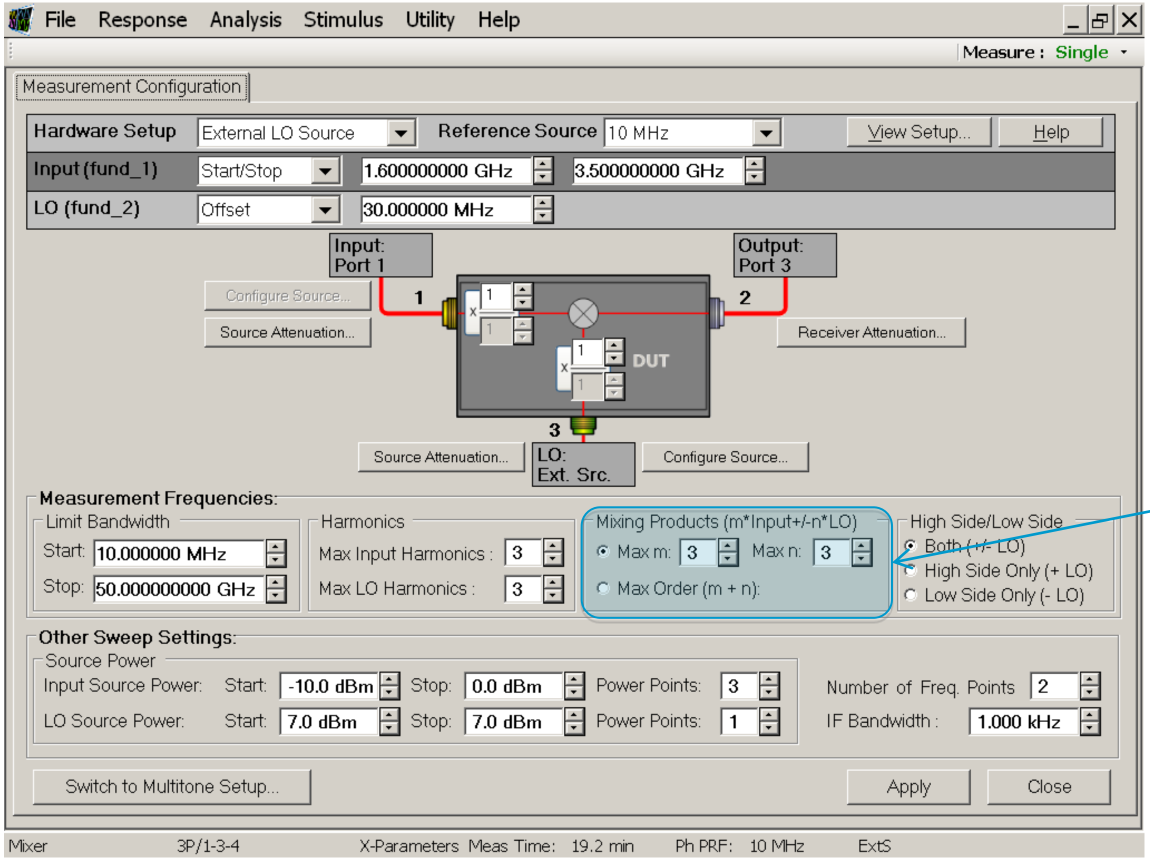
Harmonic order



The number of input/LO harmonics to measure.

NVNA Mixer Measurement Setup Wizard

Mixing Products

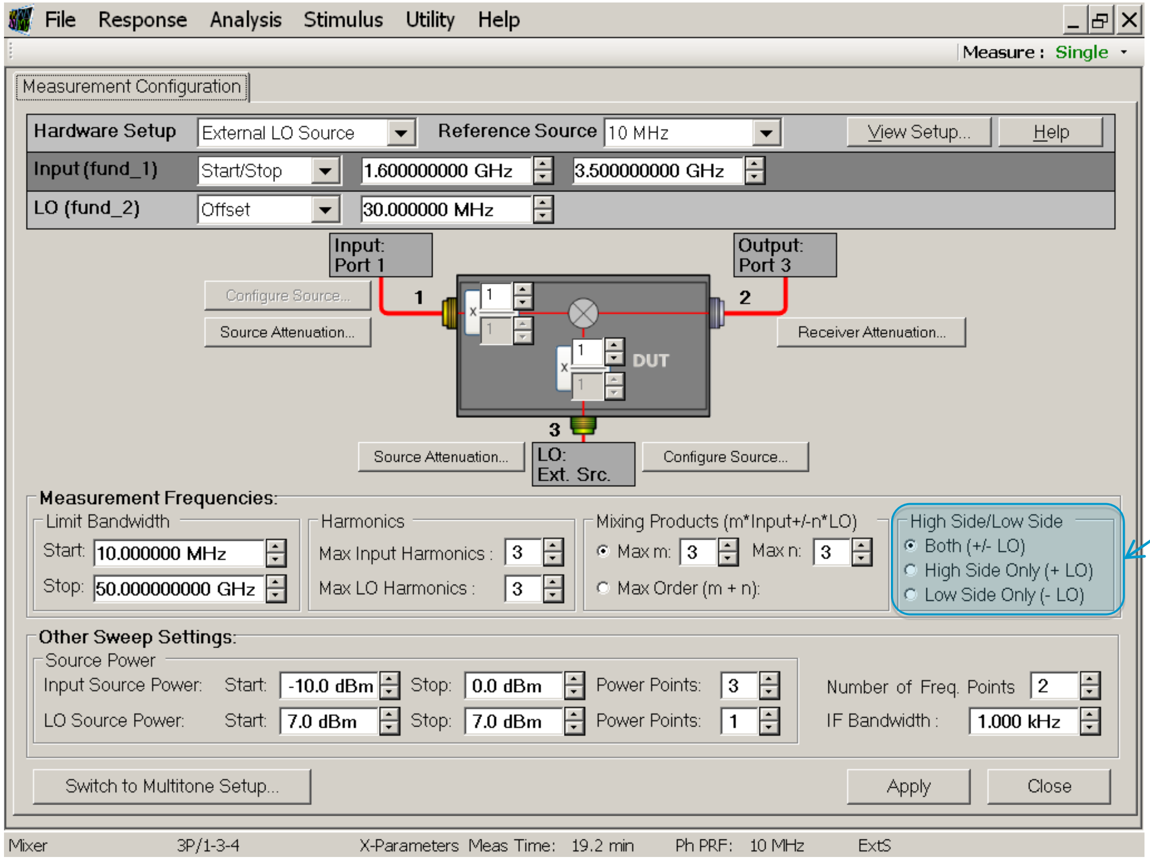


The mixing product order for the input and LO.

Harmonics and mixing products are using to determine what frequencies to measure.

NVNA Mixer Measurement Setup Wizard

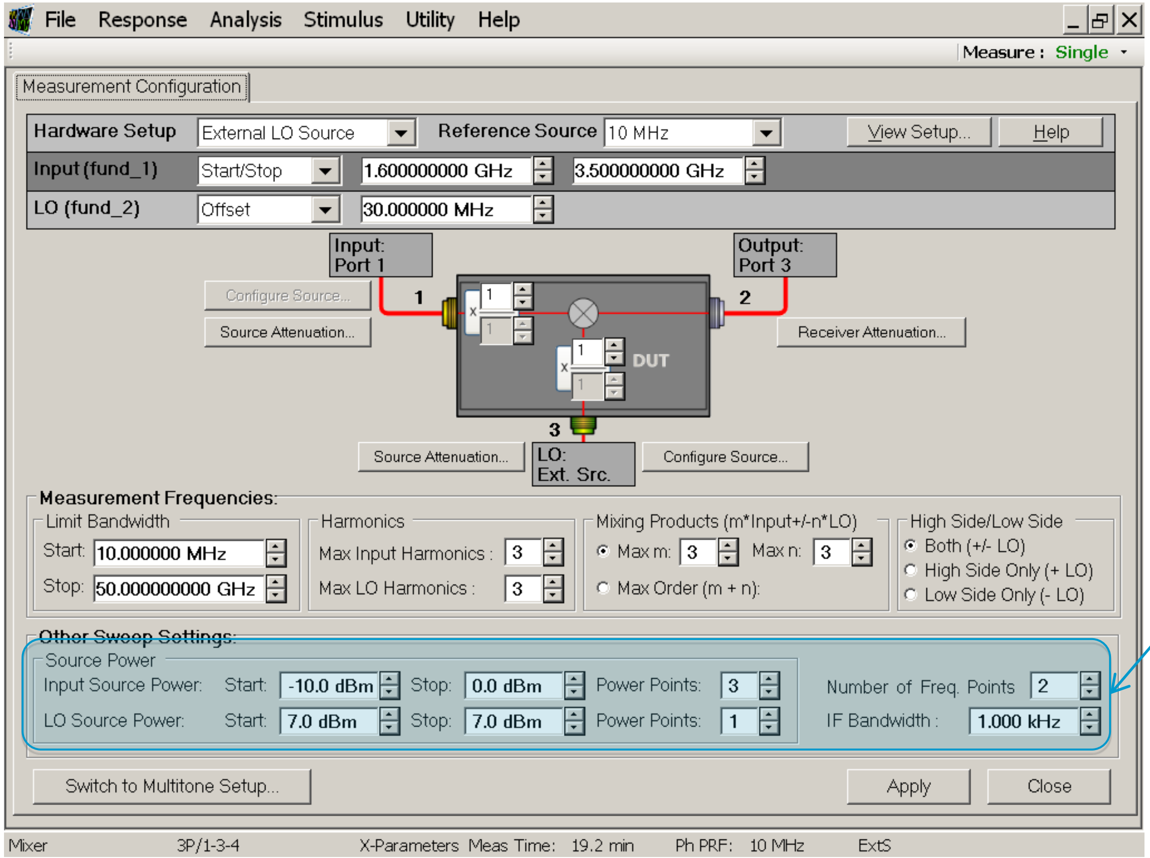
High Side and/or Low Side Mixing



Used to determine if measured frequencies should be set for high, low, or both side mixing.

NVNA Mixer Measurement Setup Wizard

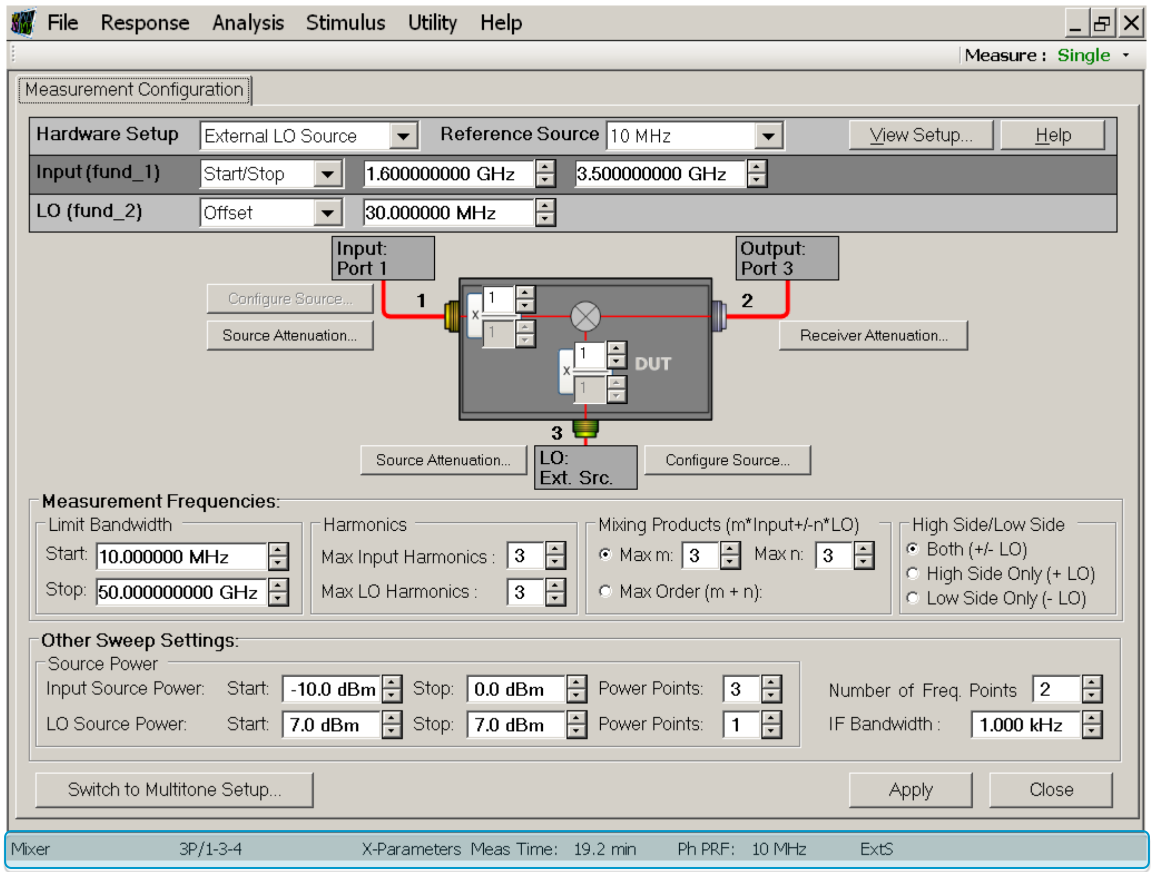
Other Sweep Settings



Configure input and LO power sweeps, frequency points and IFBW.

NVNA UI

Status Bar

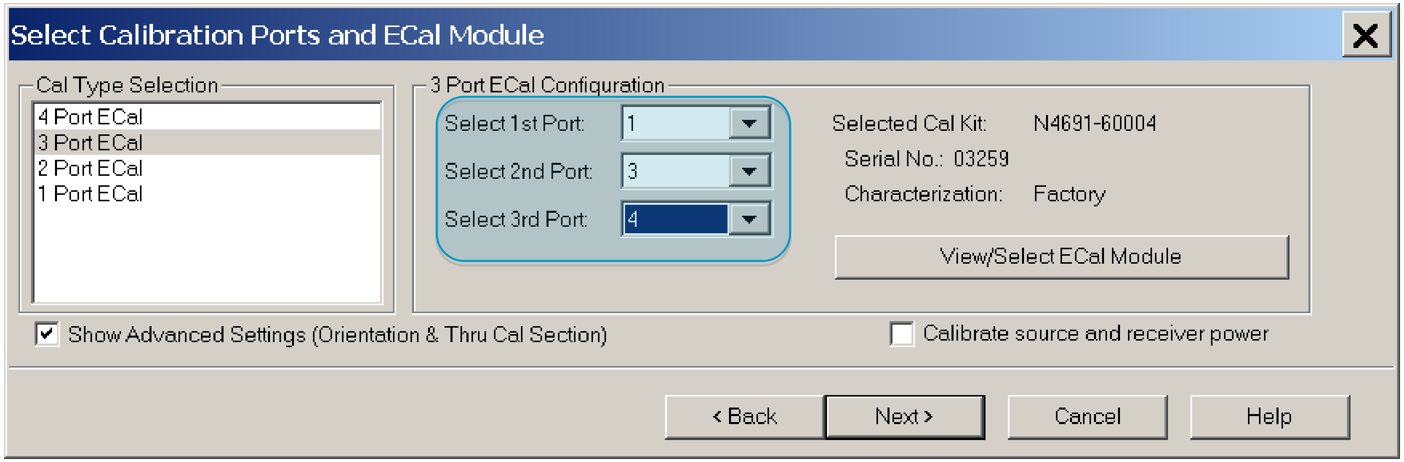


Status bar contains importance information:

1) Measurement class.
2) Number of ports configured.
3) X-parameters enabled.
4) Measurement time.
5) Phase reference source.
6) Receiver calibration.
7) Source calibration.
8) Other….

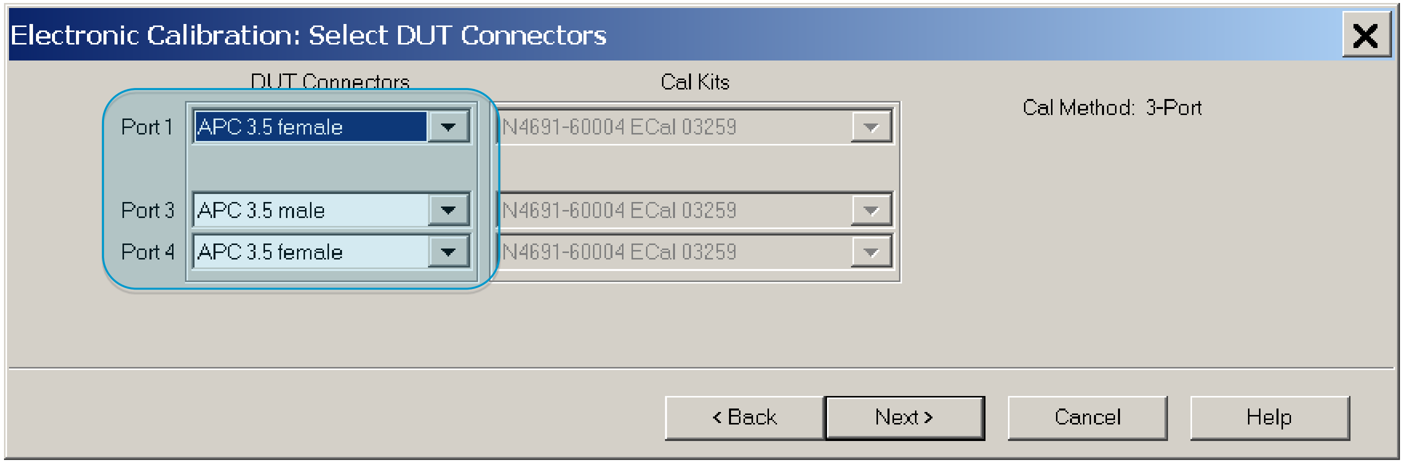
NVNA Mixer Vector Calibration – Port Selection

The mixer/converter is connected between ports 1 (Input), 3 (IF) and 4 (LO) on the NVNA. Be sure to select these ports during the vector calibration.



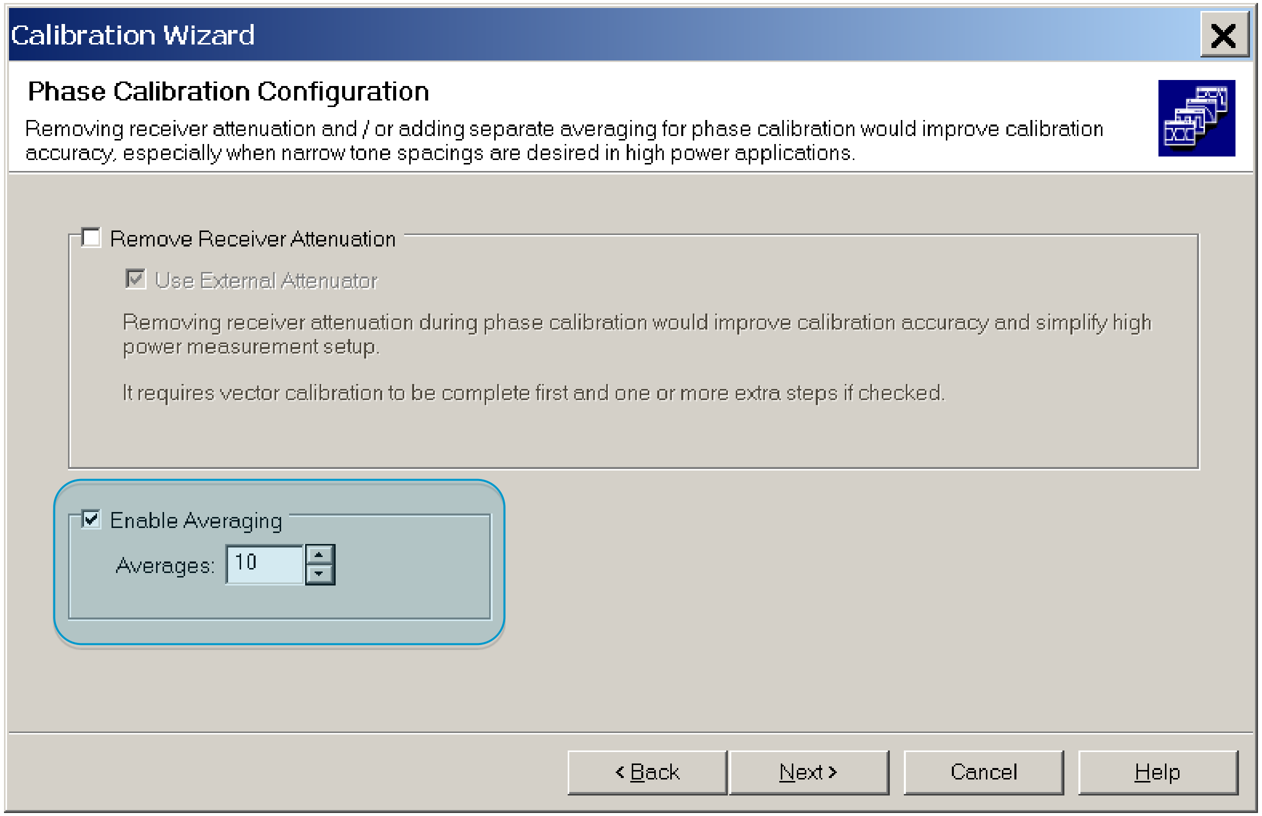
NVNA Mixer Vector Calibration – DUT Connectors

Select DUT connector types for vector calibration.



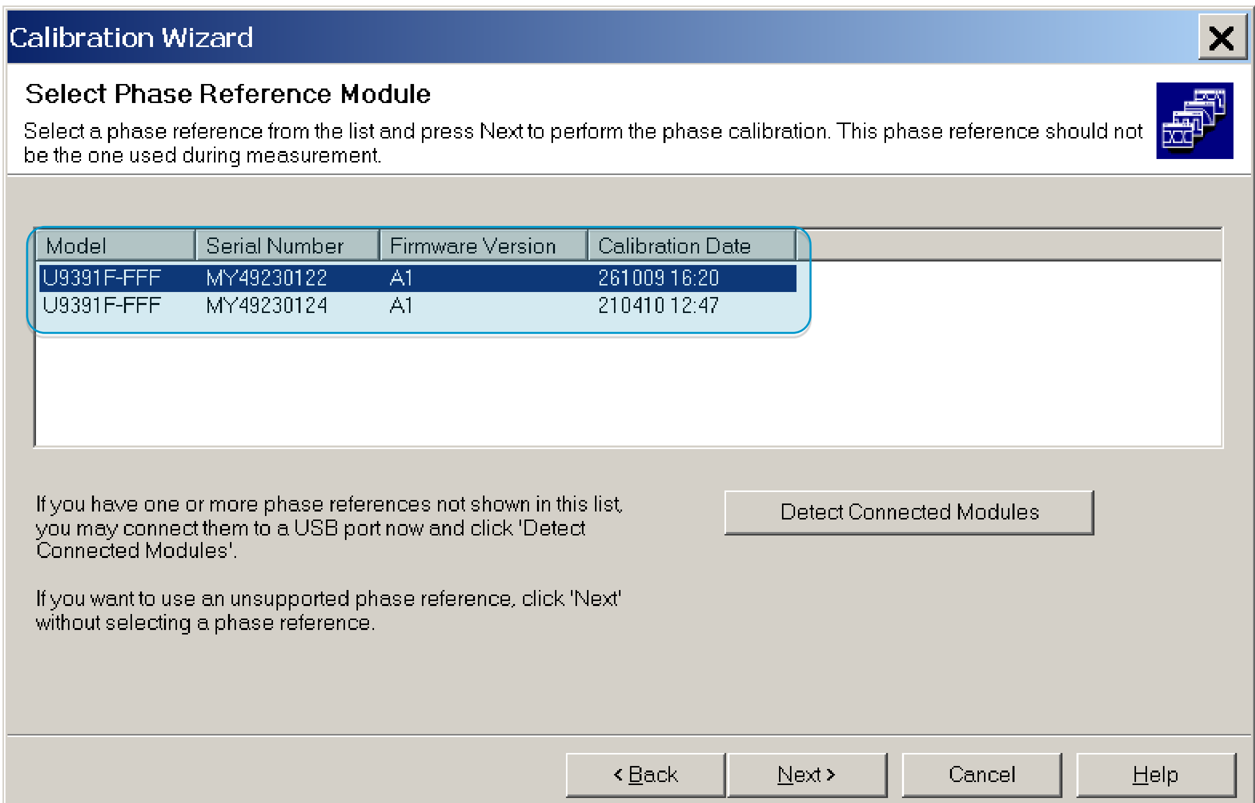
NVNA Mixer Phase Calibration - Configuration

Good practice to enabling some averaging during the phase calibration.



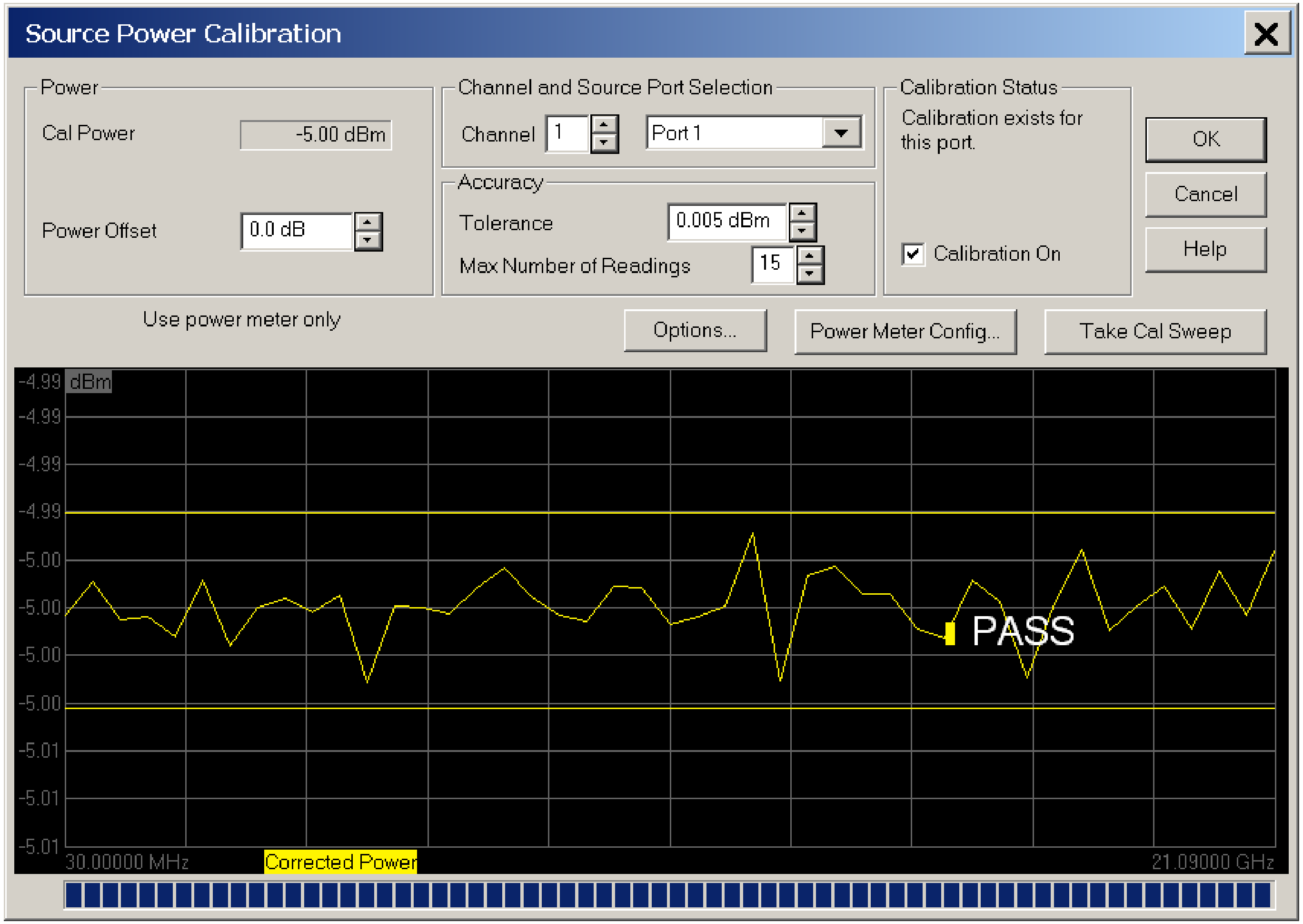
NVNA Mixer Phase Calibration – Module Selection

Select the phase reference module that will be used during calibration.



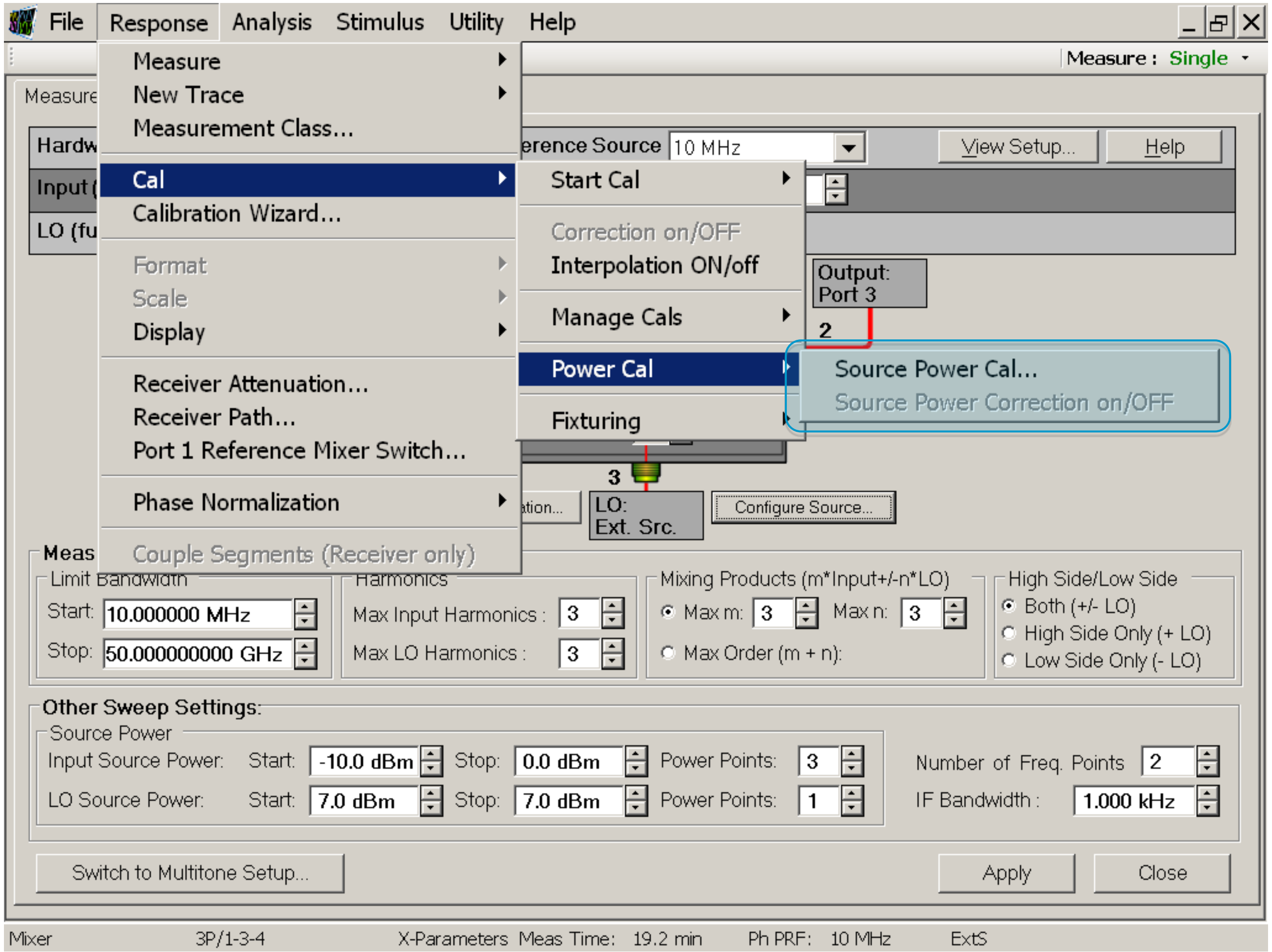
NVNA Mixer Amplitude Calibration

Amplitude calibration is calibrating the amplitude response of the receivers(This is <u>not</u> performing a source power calibration).



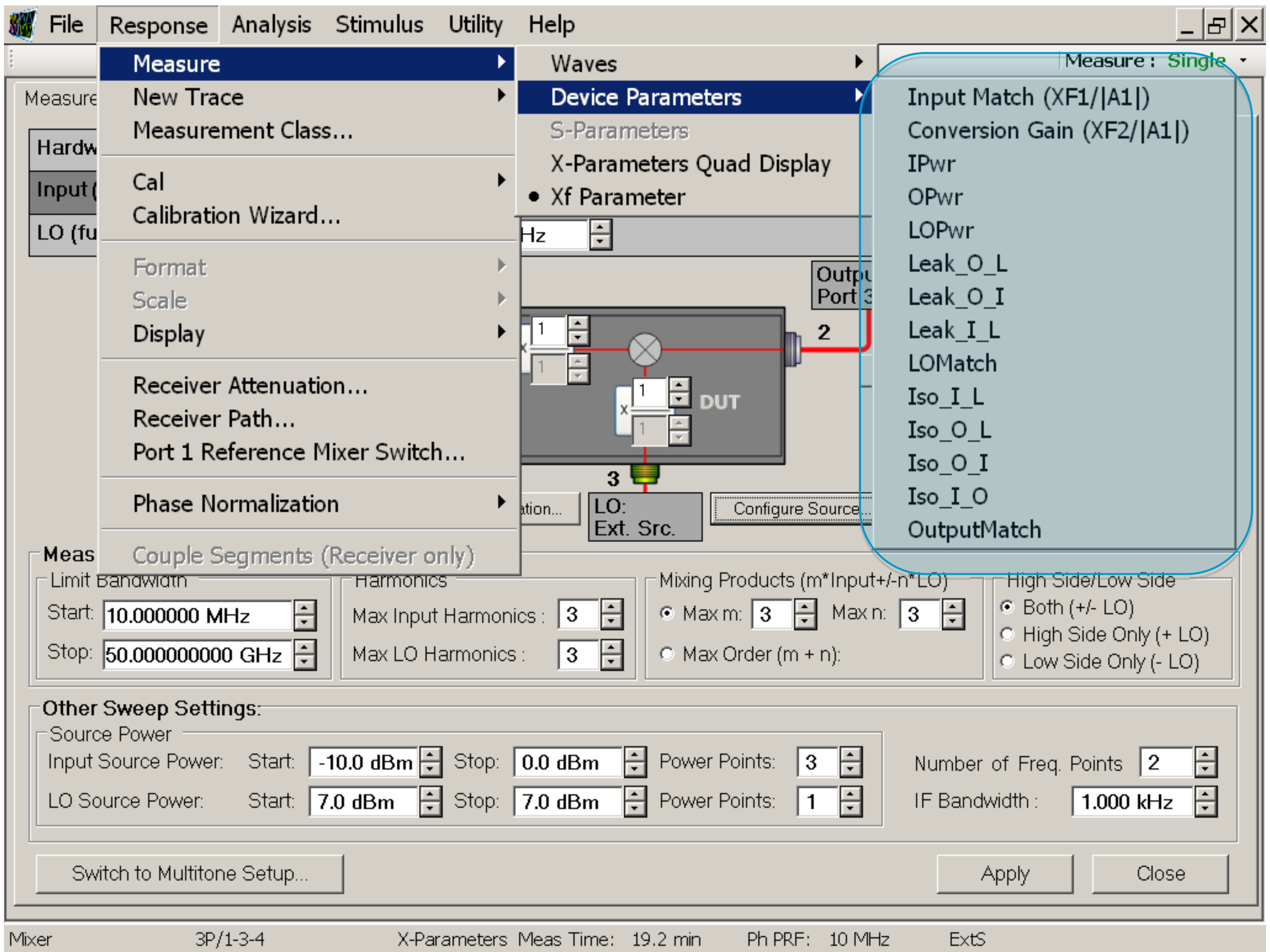
NVNA Mixer Source Power Calibration (New)

Once the NVNA receivers have been calibrated they are then used to calibrate the source(Receivers are very accurate).



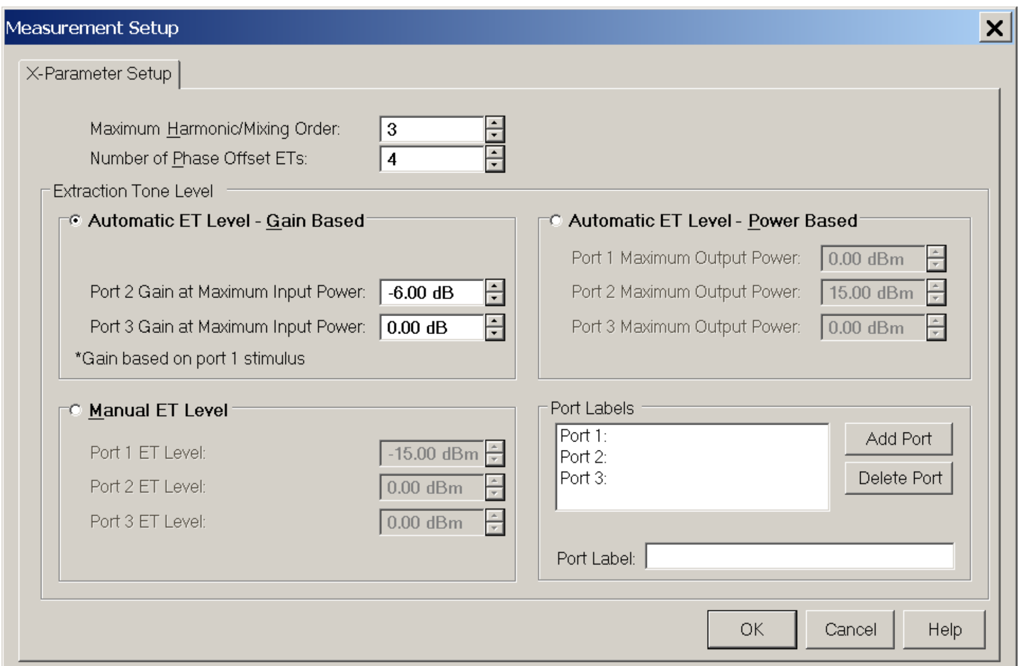
NVNA Mixer Measurement Types

Specific device parameters can be selected for display.



NVNA Mixer X-parameter Measurement Setup

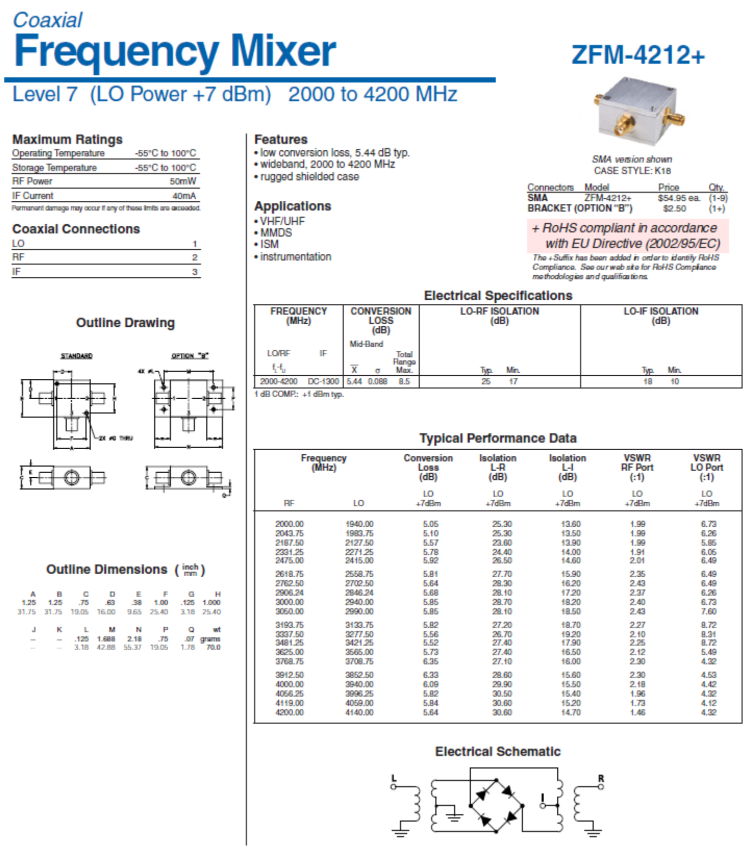
To measure X-parameters you need to specify the appropriate ET level mechanism.



Gain based is generally best if component is not hard in compression. Otherwise extraction signal may be to low at lower drive levels.

X-parameter Mixer Lab

Measure a mini-circuits mixer



Coaxial

Frequency Mixer

Level 7 (LO Power +7 dBm) 2000 to 4200 MHz

ZFM-4212+

SMA version shown
CASE STYLE: K18

Connectors	Model	Price	Qty.
SMA	ZFM-4212+	$54.95 ea.	(1-9)
BRACKET (OPTION "B")		$2.50	(1+)

+ RoHS compliant in accordance with EU Directive (2002/95/EC)

The +Suffix has been added in order to identify RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications.

Maximum Ratings

Operating Temperature	-55°C to 100°C
Storage Temperature	-55°C to 100°C
RF Power	50mW
IF Current	40mA

Permanent damage may occur if any of these limits are exceeded.

Coaxial Connections

LO	1
RF	2
IF	3

Features
- low conversion loss, 5.44 dB typ.
- wideband, 2000 to 4200 MHz
- rugged shielded case

Applications
- VHF/UHF
- MMDS
- ISM
- instrumentation

Outline Drawing

STANDARD
OPTION "B"

Outline Dimensions (inch / mm)

A	B	C	D	E	F	G	H
1.25	1.25	.75	.63	.38	1.00	.125	1.000
31.75	31.75	19.05	16.00	9.65	25.40	3.18	25.40

J	K	L	M	N	P	Q	wt
--	--	.125	1.688	2.18	.75	.07	grams
--	--	3.18	42.88	55.37	19.05	1.78	70.0

Electrical Specifications

FREQUENCY (MHz) LO/RF f_L-f_U	IF	CONVERSION LOSS (dB) Mid-Band $\overline{X}$	σ	Total Range Max.	LO-RF ISOLATION (dB) Typ.	Min.	LO-IF ISOLATION (dB) Typ.	Min.
2000-4200	DC-1300	5.44	0.088	8.5	25	17	18	10

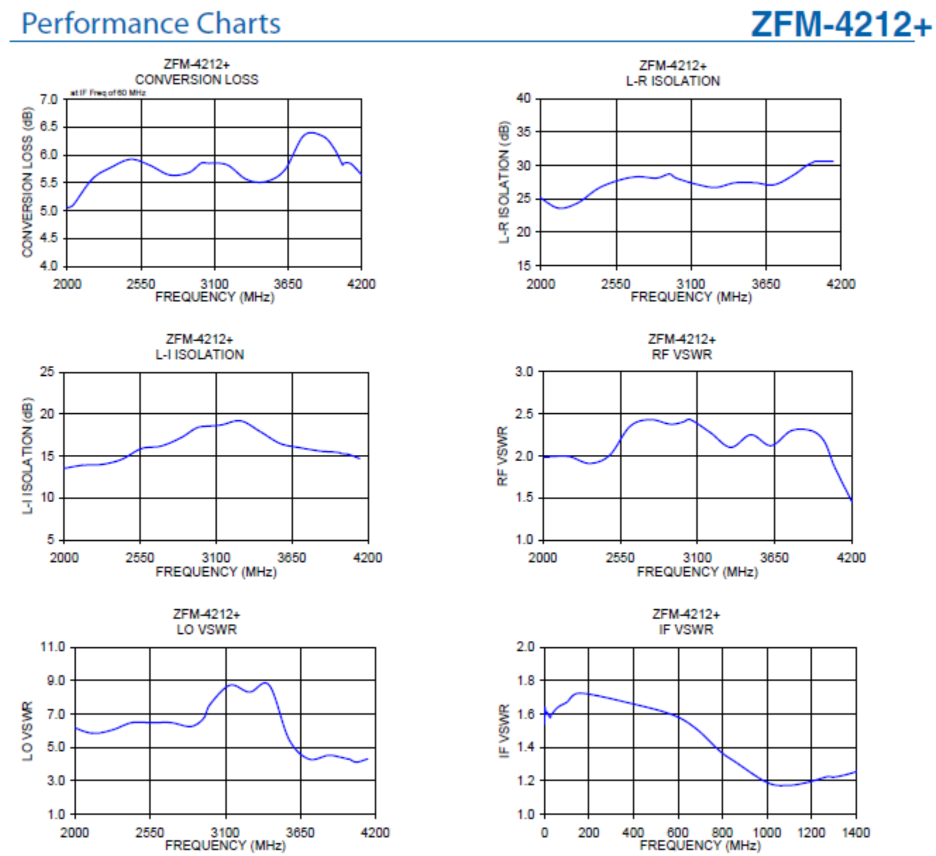
1 dB COMP.: +1 dBm typ.

Typical Performance Data

Frequency (MHz) RF	LO	Conversion Loss (dB) LO +7dBm	Isolation L-R (dB) LO +7dBm	Isolation L-I (dB) LO +7dBm	VSWR RF Port (:1) LO +7dBm	VSWR LO Port (:1) LO +7dBm
2000.00	1940.00	5.05	25.30	13.60	1.99	6.73
2043.75	1983.75	5.10	25.30	13.50	1.99	6.26
2187.50	2127.50	5.57	23.60	13.90	1.99	5.85
2331.25	2271.25	5.78	24.40	14.00	1.91	6.05
2475.00	2415.00	5.92	26.50	14.60	2.01	6.49
2618.75	2558.75	5.81	27.70	15.90	2.35	6.49
2762.50	2702.50	5.64	28.30	16.20	2.43	6.49
2906.24	2846.24	5.68	28.10	17.20	2.37	6.26
3000.00	2940.00	5.85	28.70	18.20	2.40	6.73
3050.00	2990.00	5.85	28.10	18.50	2.43	7.60
3193.75	3133.75	5.82	27.20	18.70	2.27	8.72
3337.50	3277.50	5.56	26.70	19.20	2.10	8.31
3481.25	3421.25	5.52	27.40	17.90	2.25	8.72
3625.00	3565.00	5.73	27.40	16.50	2.12	5.49
3768.75	3708.75	6.35	27.10	16.00	2.30	4.32
3912.50	3852.50	6.33	28.60	15.60	2.30	4.53
4000.00	3940.00	6.09	29.90	15.50	2.18	4.42
4056.25	3996.25	5.82	30.50	15.40	1.96	4.32
4119.00	4059.00	5.84	30.60	15.20	1.73	4.12
4200.00	4140.00	5.64	30.60	14.70	1.46	4.32

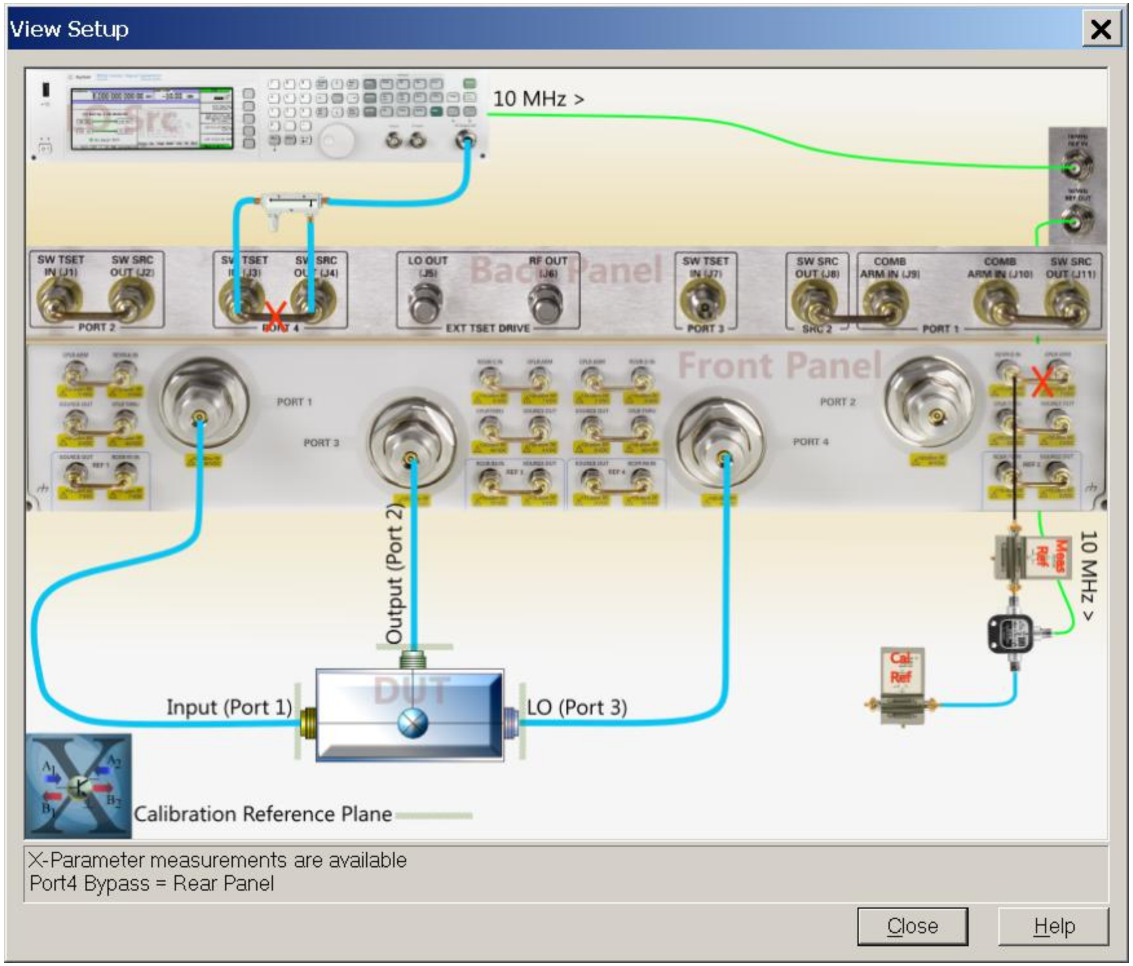
Electrical Schematic

L
R



NVNA Mixer HW Setup Wizard

Connect external HW as described in the following diagram



Mixer Measurement Setup Steps #2

Setup the following stimulus response settings in NVNA:

RF (Input)

Frequency = 2 – 4 GHz (2 points)

Power = -20 – 0 dBm (5 points)

LO

Frequency = -60 MHz offset (fixed IF measurement)

Power = +7 dBm

Harmonics

Max input and LO = 3

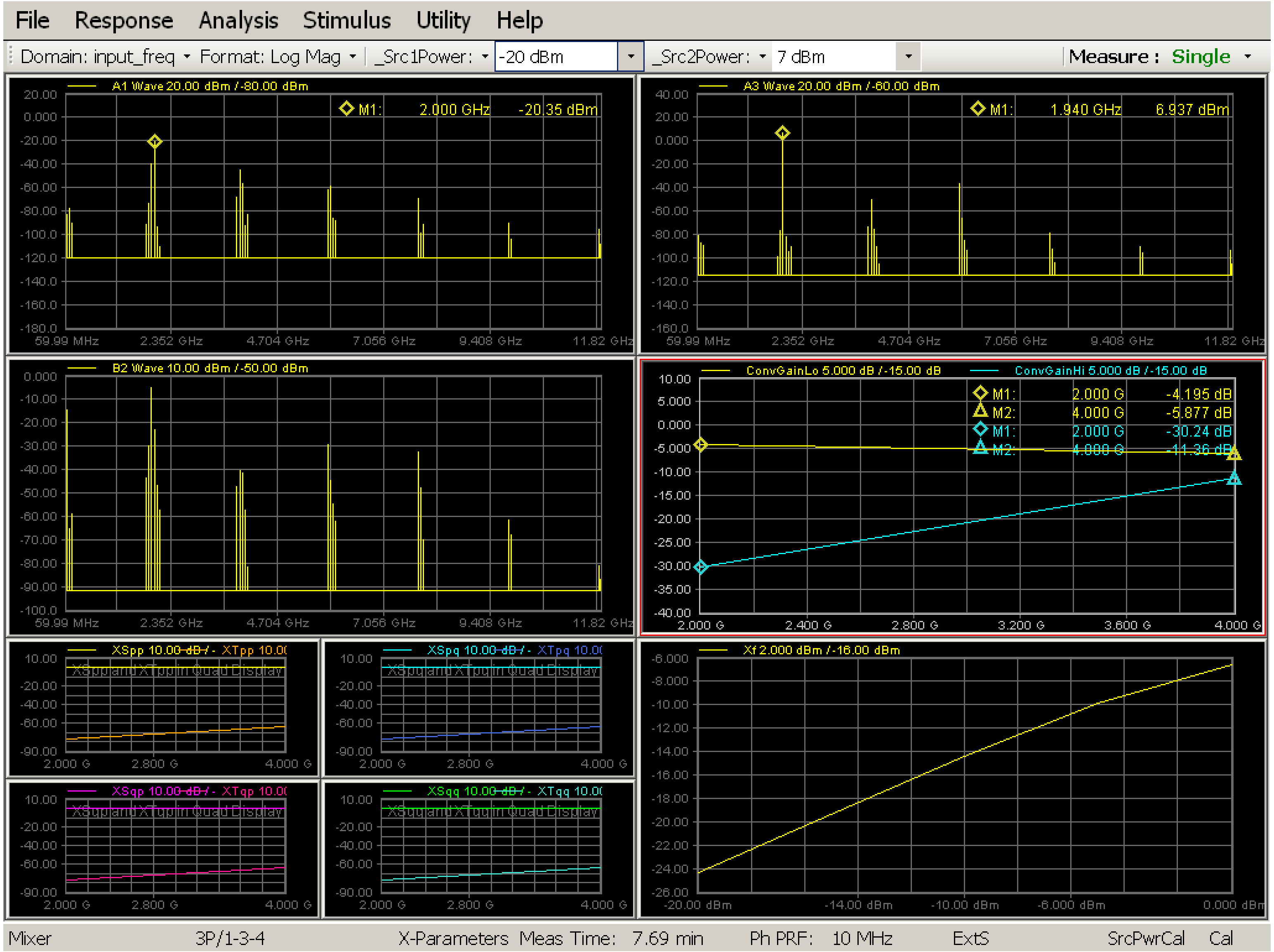
Mixing Products

Max ‘m’ and ‘n’ = 3

High Side/Low Side

Both

NVNA Mixer Measurement Results



X-parameter technology is expanding rapidly

Agilent breakthroughs:

- Load-dependent X-parameters
- 50 GHz Agilent NVNA
- High-Power X-parameter measurements
- X-parameter generator in ADS
- Simulation of XnP component in ADS, Genesys & SystemVue
- Two-tone measured X-parameters
- Three-port measured X-parameters
- Memory: Dynamic X-parameters
- Education, training, app. Notes

For More Information

X-parameters

www.agilent.com/find/x-parameters

Nonlinear Vector Network Analyzer

www.agilent.com/find/nvna

ADS MMIC design seminar (click on X-parameters link)

www.agilent.com/find/eesof-mmic-seminar

X-Parameters Aid MMIC Design
http://www.mwrf.com/Articles/Index.cfm?Ad=1&ArticleID=22811

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