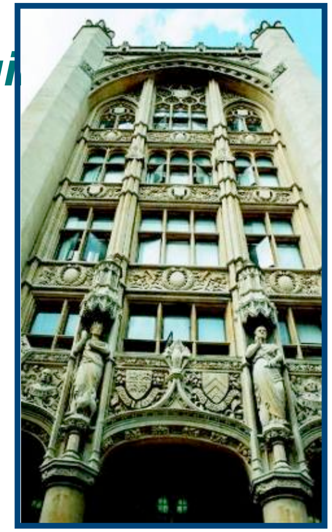
The Large Signal Microwave Characterization and Design Challenge

Centre for High Frequency Engi

School of Engineering
Cardiff University
Cardiff, Wales, UK
Website: www.engin.cf.ac.uk/chfe



Prof. Paul J Tasker
tasker@cf.ac.uk

IEEE MTT-S Distinguished Microwave Lecturer 2008-2010

- RF I-V Waveform Measurement & Engineering

Centre for High Frequency Engineering

- Who are we?

- Founded in 1997
- Significant funding from Government and Industry
- Staff & Students
  - 4 academics
  - 1 professorial fellow
  - 2 research associates
  - 20+ research Students
  - dedicated Technical Support
- Strong industrial links
  - Tektronix, Agilent, Freescale, CREE, RFMD, Nokia, Ericsson, EADS, Astrium, …
  - Research is 50% funded by industry
- Also EPSRC, DTC, FP7, EUREKA

Prof. P Tasker

Prof. A Belcher

Prof. A Porch

Prof. S Cripps

Dr. J Benedikt

Cardiff Team

Centre for High Frequency Engineering
- *What do we do?*

Mission statement: *to innovate and establish scientifically robust nonlinear characterisation, analysis and design methodologies at high-frequencies*

- *Motivation behind lectures*

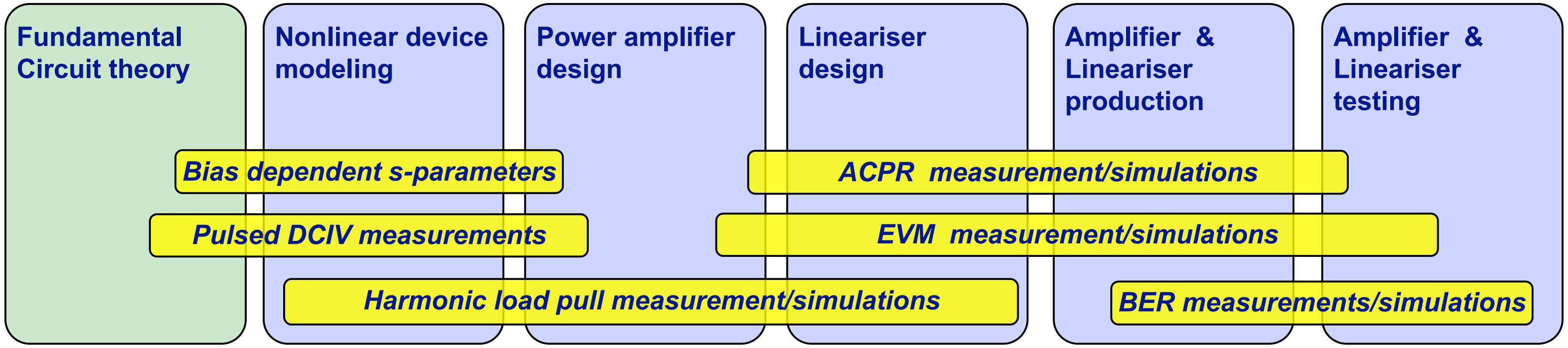
Core capability and development: *RF Waveform Measurement and Engineering*

- *Topic of the lectures*

- ***Measurement:*** *The ability to observe and quantify the time varying voltage $V_n(t)$ and current $I_n(t)$ present at all terminals of the Device Under Test (DUT): thus involves all frequencies including DC, IF and RF.*
- ***Engineering:*** *The ability to modify in a quantified manner the time varying voltage $V_n(t)$ and current $I_n(t)$ present at the terminals of the Device Under Test (DUT): thus involves all frequencies including DC, IF and RF.*

Motivation and Background

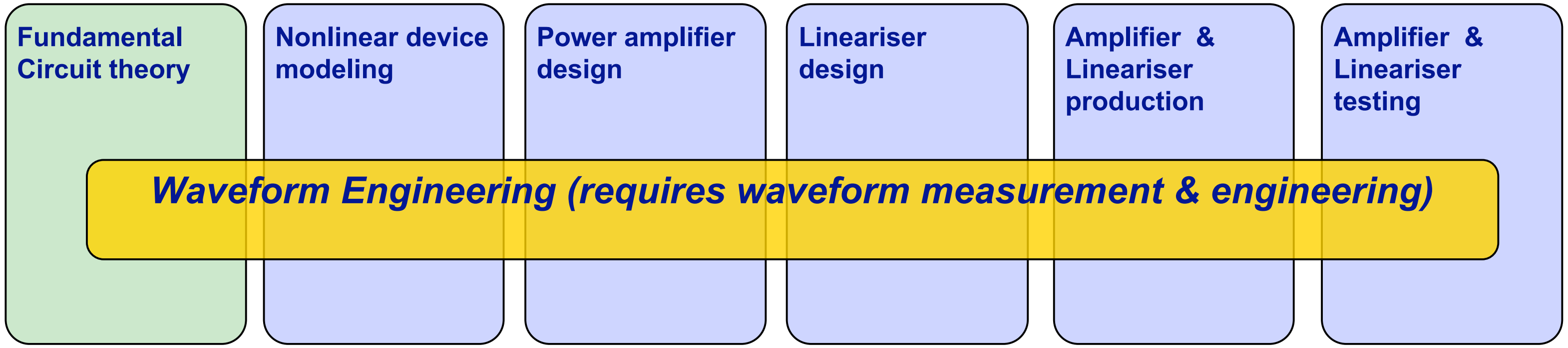
Consider the Design and Optimization of the Highly Efficient Linear RF Power Amplifier



Lack of single measurement techniques that can successfully tackle all relevant technology areas!

In coherent links between the area resulting in significant and relevant loss of information when moving from one area to another

Motivation and Background



Current and voltage waveforms have the potential to interlink the entire design and development chain!

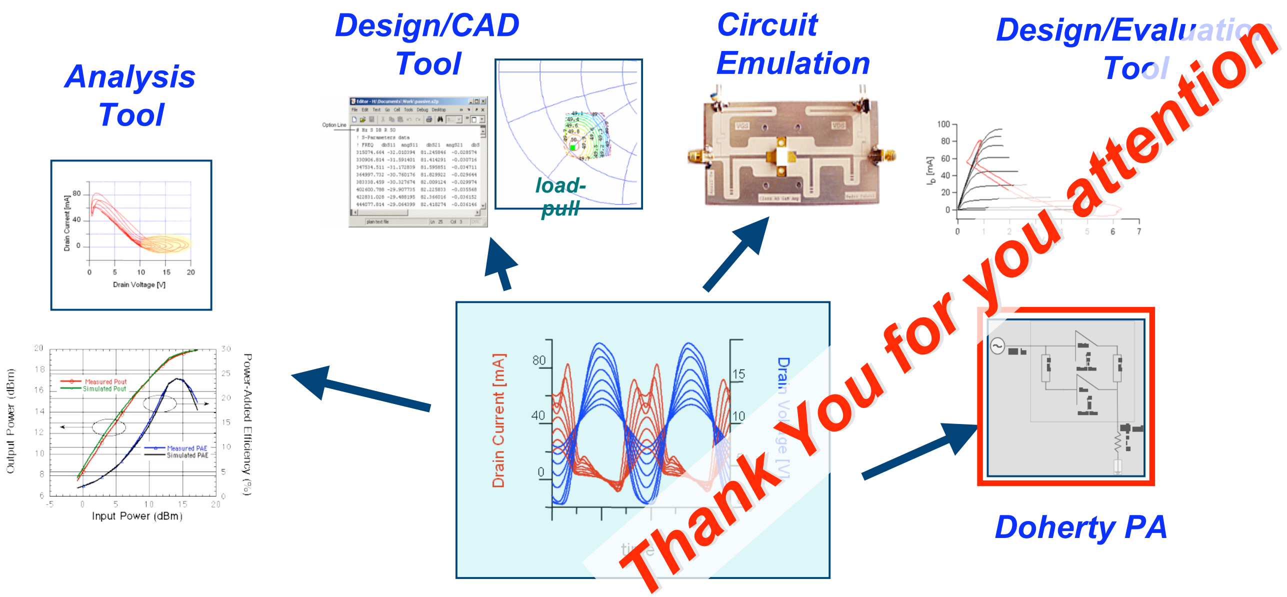
However, it is a new approach and as such requires (1) new measurement systems, (2) new data analysis tools, and (3) design techniques

RF I-V Waveform Measurement & Engineering

- Lecture : 10.00am - 11.00am
  - CW Measurement System Realization
- Lecture 2: 11.00am - 12.00pm
  - Role in Supporting Non-Linear CAD Design
- Lecture 3: 1.00pm - 2.15pm
  - Role in Transistor Characterization and Amplifier Design
- Lecture 4: 3.00pm - 4.00pm
  - Emerging Multi-Tone Systems

RF Waveform Measurements and Engineering

– a powerful tool and concept

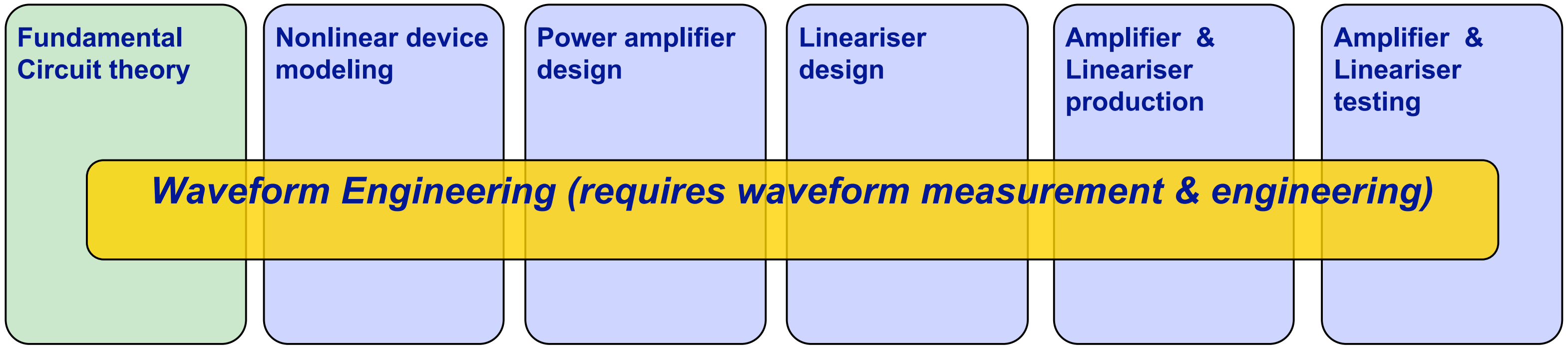


unifying link between device technology, circuit design & system performance

- **Fundamental Circuit theory**
- **Nonlinear device modeling**
- **Power amplifier design**
- **Lineariser design**
- **Amplifier & Lineariser production**
- **Amplifier & Lineariser testing**

Waveform Engineering

Summary



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Thank You

RF IV Waveform Measurement and Engineering

- CW Measurement System Realization -

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History of RF I-V Measurements

- Development of the Non-Linear Network Analyzer

- Historically has had many names;
  - NLVNA: Non-Linear Vector Network Analyser
  - LSNA: Large Signal Network Analyser
  - ANA: Absolute Network Analyser
  - Vector(ial) Component Analyser

Era of the MTA (Microwave Transition Analyser)
- **Kompa et al (1990)**
- **Tasker et al (1994)**
- **Verspecht et al**

Return of the DSO
- **Tektronix DSA**
- **Williams et al**

1990

2010

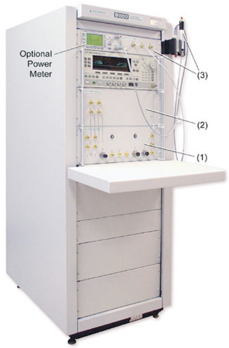
Waveform Measurement

1980

2000

First realization of calibrated waveform measurement solutions
- **Time Domain Sipila et al (1988)**
- **Frequency Domain: Lott U (1989)**

First wave of Commericalization (LNSA)
- **Agilent & Maury Microwave Corporation**



History of RF I-V Measurements
- Era of commercialization and industrial acceptance

- Second Wave of Commercialization
  - Agilent: PNA-X
  - NMDG/Rohde & Schwarz
  - VTD (Verspecht-Teyssier-DeGroot)
  - Mesuro/Tektronix

Return of the DSO
- Tektronix DSA

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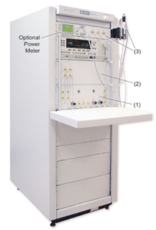
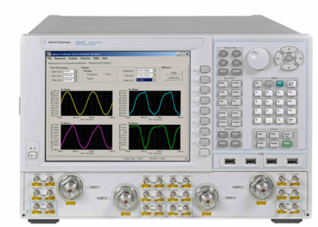


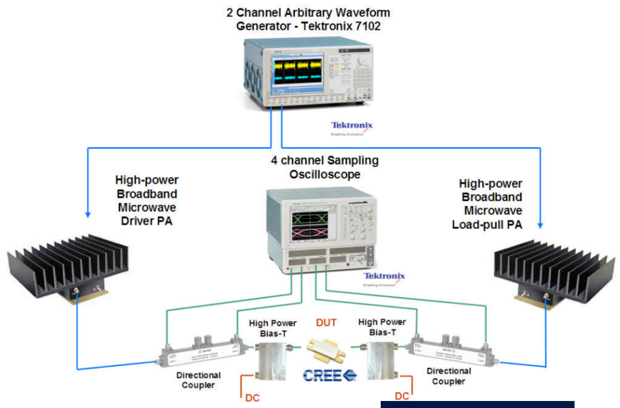
Agilent PNA-X: Frequency Domain



Mesuro/Tektronix: Time Domain

Waveform Measurement System

Simplified Architecture with active harmonic load pull



mesuro
advanced RF testing and measurement systems

Tektronix
Enabling Innovation

- Key Parallel Development

Waveform Engineering

Objective of RF I-V Measurement Systems
- has to enable Waveform Engineering in Design

- Their measurement domain is to go **beyond s-parameters**

⇒ RF I(I) & V(t) Waveform Measurement

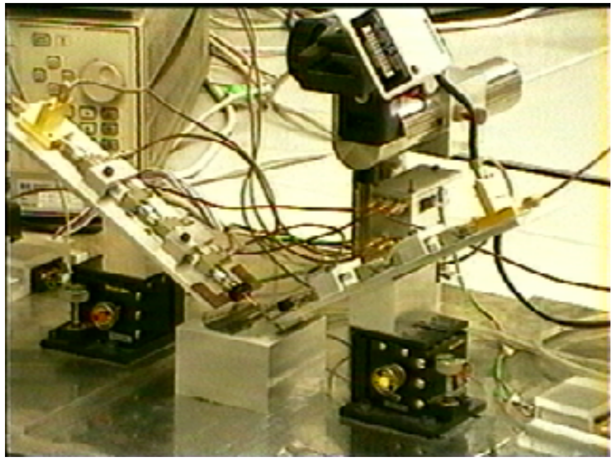
- Their application domain is to go **beyond linear design**

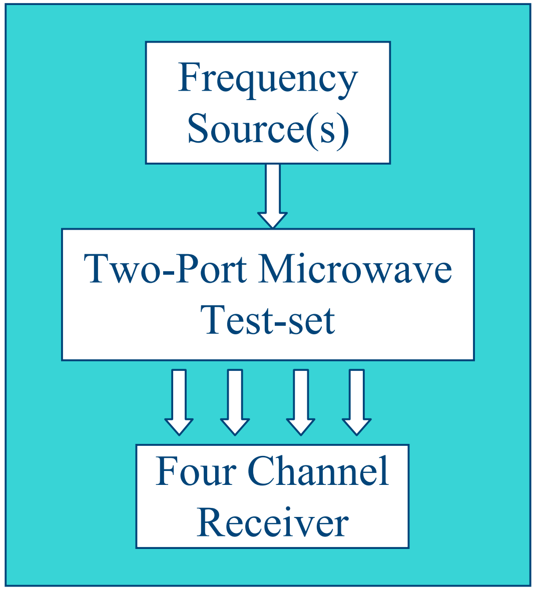
⇒ RF I(I) & V(t) Waveform Engineering

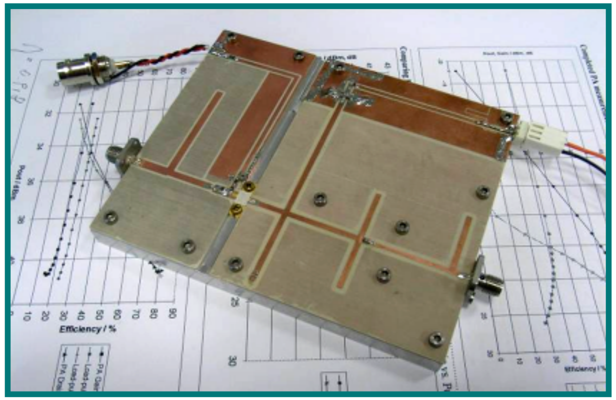
Outline:
- CW Measurement System Realization

- RF I-V Measurement Solution
  - Architecture and Receivers
  - Error Models and Calibration

- RF I-V Engineering Solutions
  - Active Open Loop Architecture
  - ELP Concept







Non-Linear Vector Network Analyzer

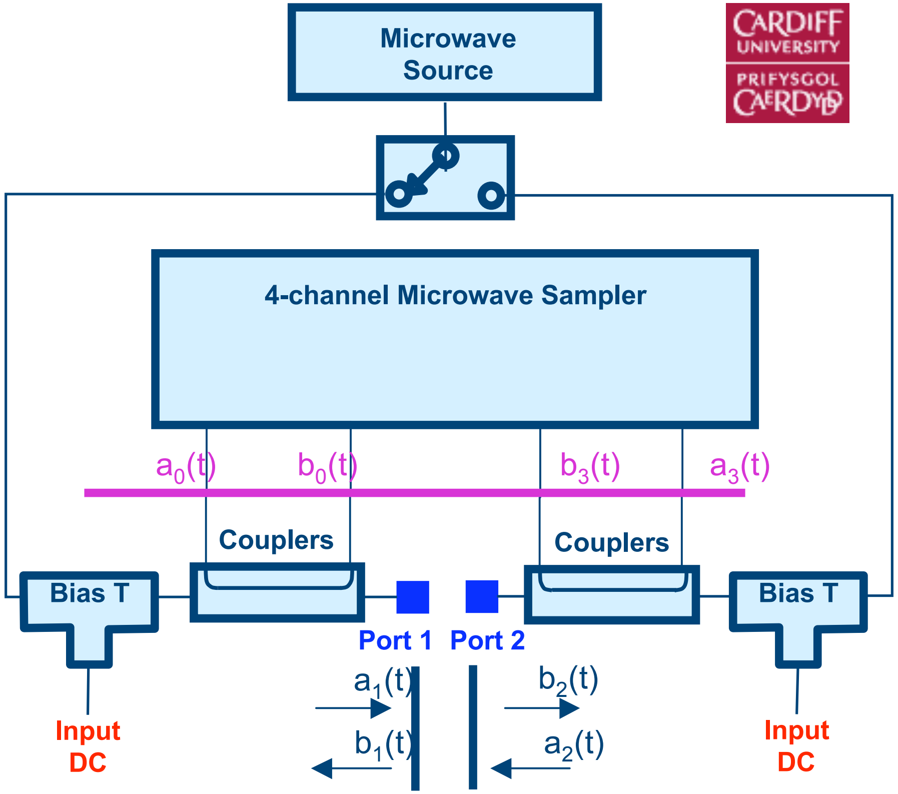
- Basic Architecture with RF Test-set

- Time domain variant requires a four channel receiver with each channel receiving either incident or scattered travelling voltage signals.
  - *Frequency domain, PNA-X, variant requires a five channel receiver and a reference signal.*

- Utilized directional couplers for detection/separation of travelling voltage signals.

- Source switch for redirection of stimulus signal.
  - *Alternatively utilize two sources, PNA-X or Tektronix AWG.*

- All instruments and components are computer controlled allowing for automated measurements



Measures RF $a_n(t)$ and $b_n(t)$ time varying Voltage Travelling Signal Waveforms

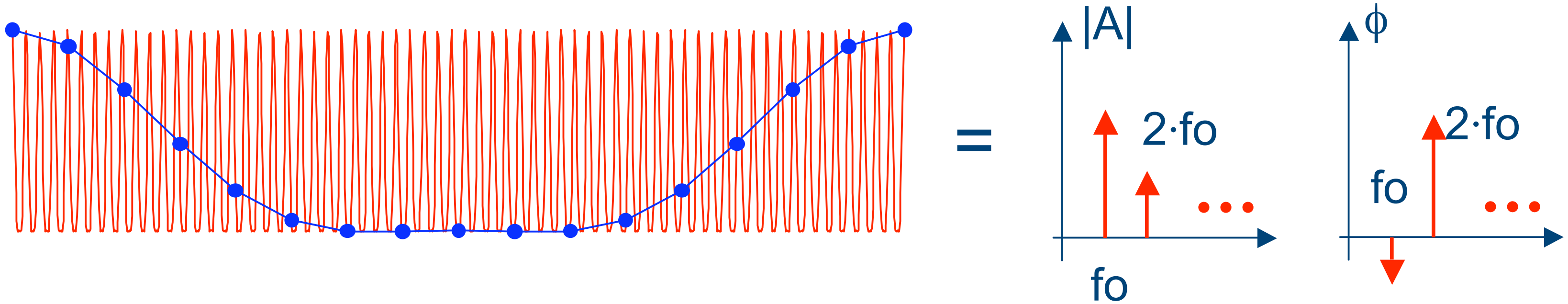
Time Domain Systems:
- Sampling Receivers

- Key component is a broadband receiver
  - ***Time domain sampling based***

Agilent: Microwave Transition Analyzer (MTA)

Tektronix: Digital Serial Analyzer (DSA)

- Principle is based on sampling over many cycles

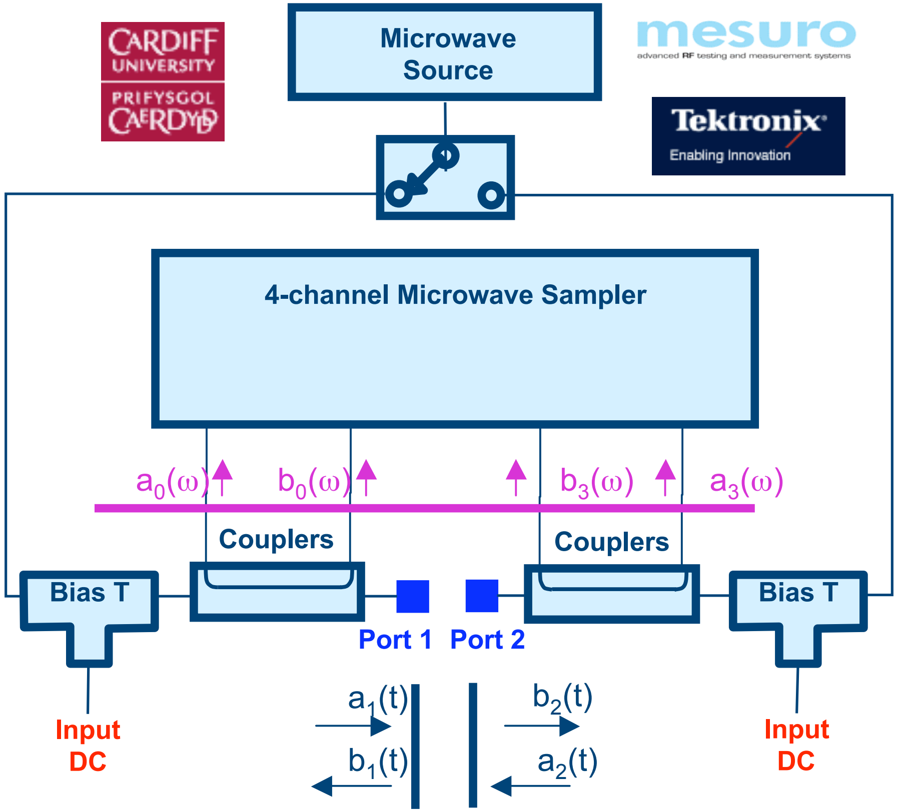


- Signals must be repetitive and on a specific frequency grid

Samples RF Voltage Waveforms $v_n(t)$

Non-Linear Vector Network Analyzer:
- Sampling based Architecture

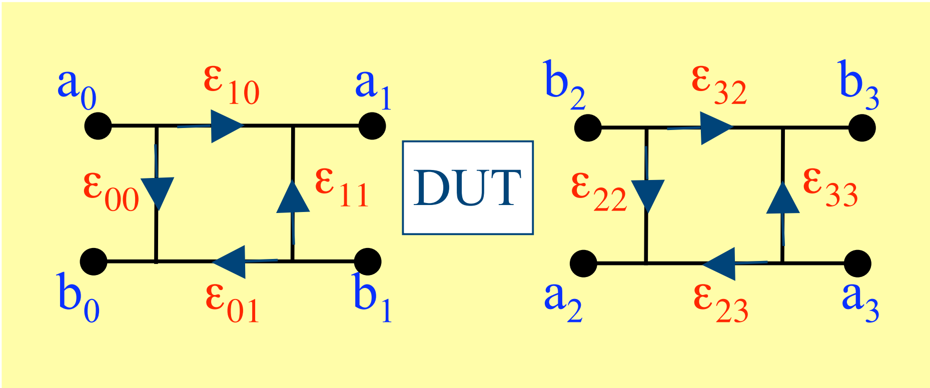
- Measurement architecture is almost identical to conventional Network Analyzer
- RF hardware between DUT and the sampling receivers.
  - Introduces Systematic Errors
- Measured $a_n(t)$ and $b_n(t)$ time varying voltage travelling signal waveforms will be erroneous.
  - Error Correction Model
  - Vector Calibration



Measurements System needs to be vector calibrated

Non-Linear Vector Network Analyzer:
- Error Model

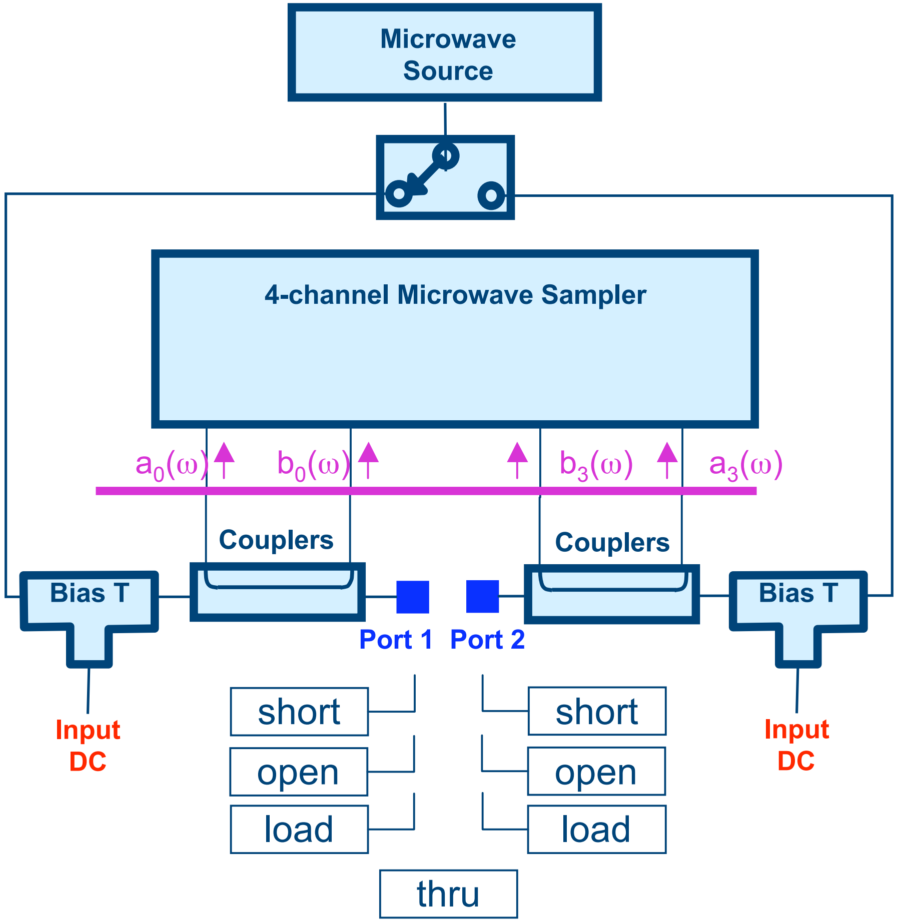
- Error Correction Flow Graph
  - 8 Term Error Model
    - Similar to that utilized by VNA
  - **All terms required**
  - **Independent of switch match**
    - *no transformation to a reference impedance*
  - Independent of direction of energy flow



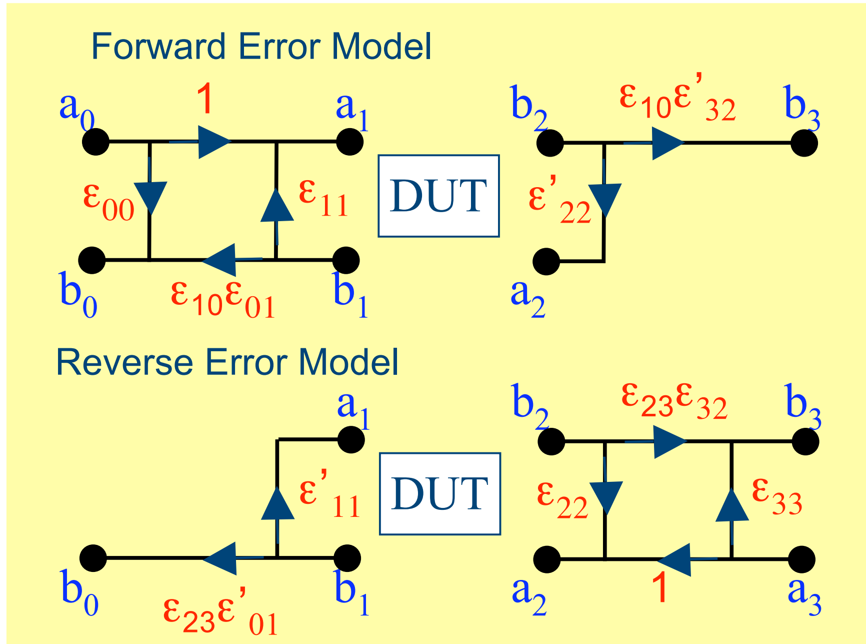
  - Simple de-embedding algorithm
    - $b_1 = (b_0 - \varepsilon_{00} a_0)/\varepsilon_{01}$
    - $a_1 = ((\varepsilon_{01}\varepsilon_{10} - \varepsilon_{00}\varepsilon_{11})a_0 + \varepsilon_{11} b_0)/\varepsilon_{01}$
    - $b_2 = (b_3 - \varepsilon_{33} a_3)/\varepsilon_{32}$
    - $a_2 = ((\varepsilon_{32}\varepsilon_{23} - \varepsilon_{33}\varepsilon_{22})a_3 + \varepsilon_{22} b_3)/\varepsilon_{32}$

Require a calibration procedure: going beyond s-parameters

Ratio Calibration:
- VNA 10 Term Error Model

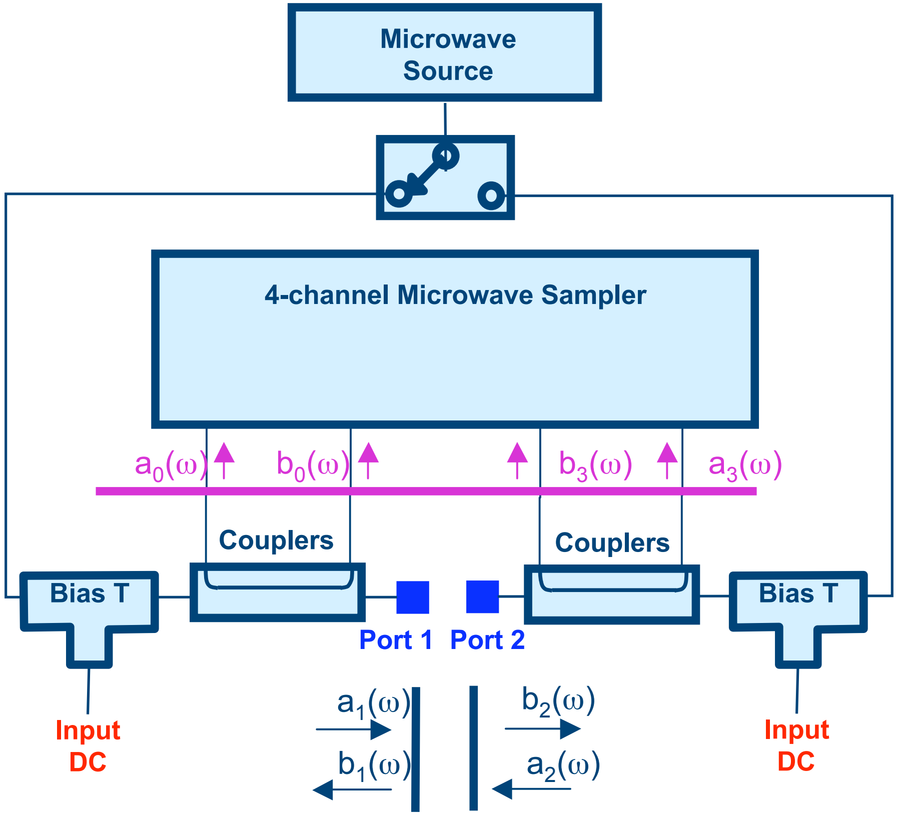


- Follow VNA Procedure
  - Determine 10 (12) Term Error Model
    - Load, Open, Short, Thru (LOST)
    - Thru, Reflect, Line (TRL)
    - Thru, Reflect, Match (TRM)

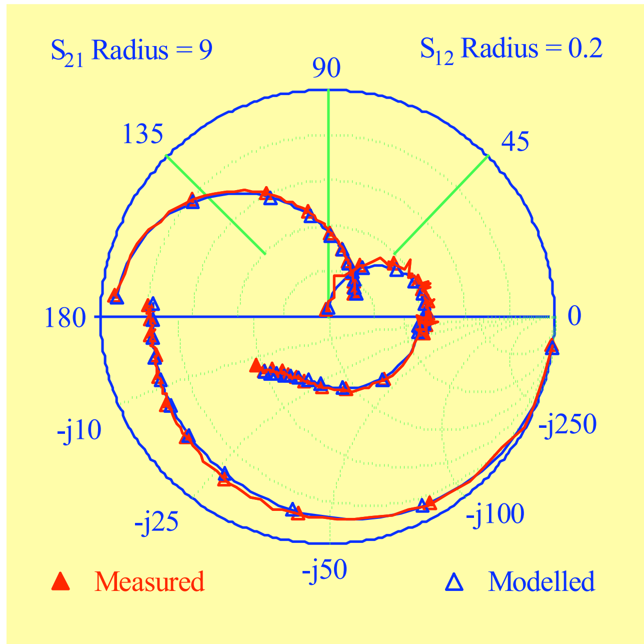


……. measure s-parameters

Ratio Calibration:
- VNA 10 Term Error Model



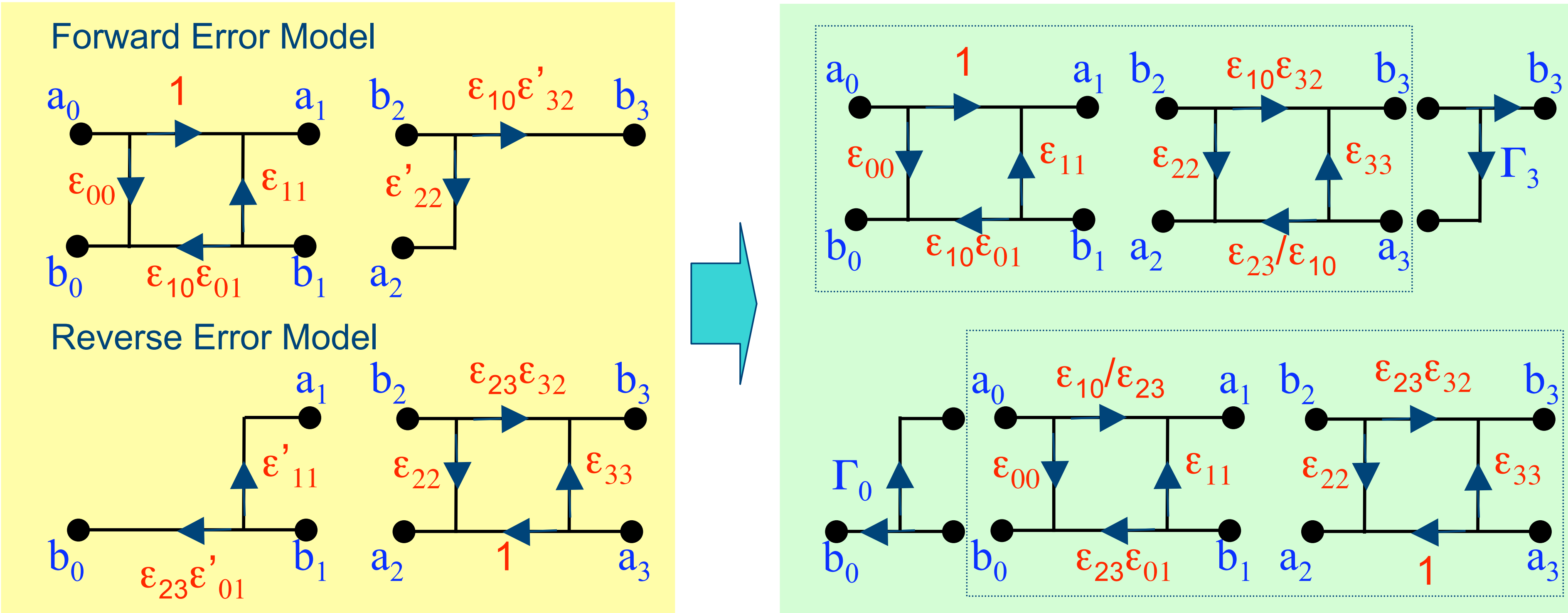
- Equivalent to VNA
  - Ratio measurements as a function of frequency



……. measure s-parameters

Relating VNA and NLVNA Error Models

- step 1



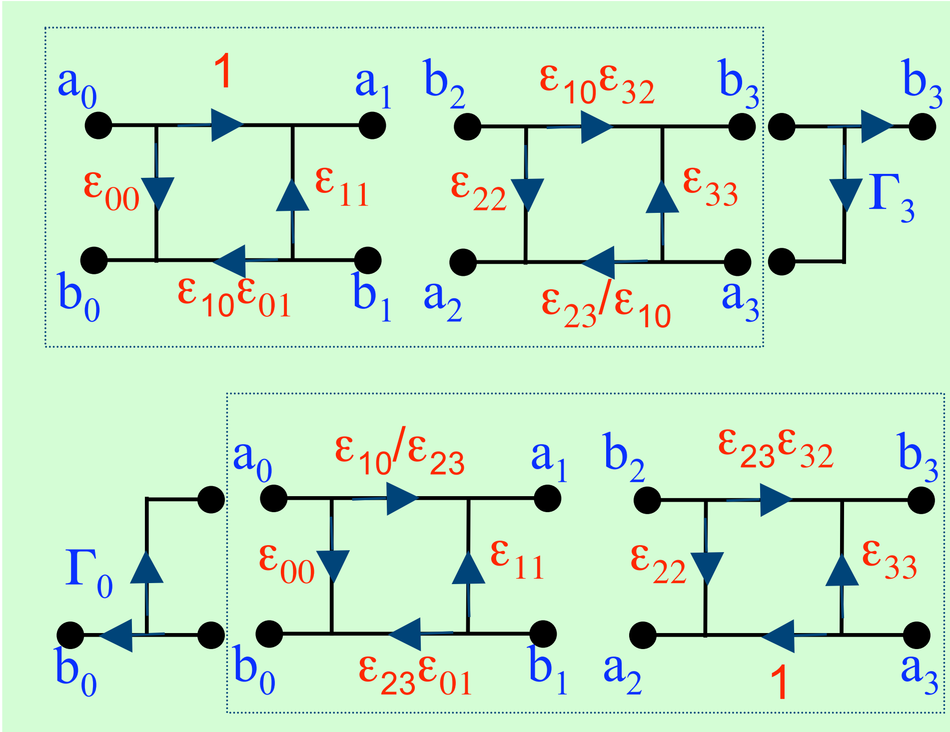
Reformulate Error Model: *Isolate correction and Impedance transformation*

Relating VNA and NLVNA Error Models

- step 1

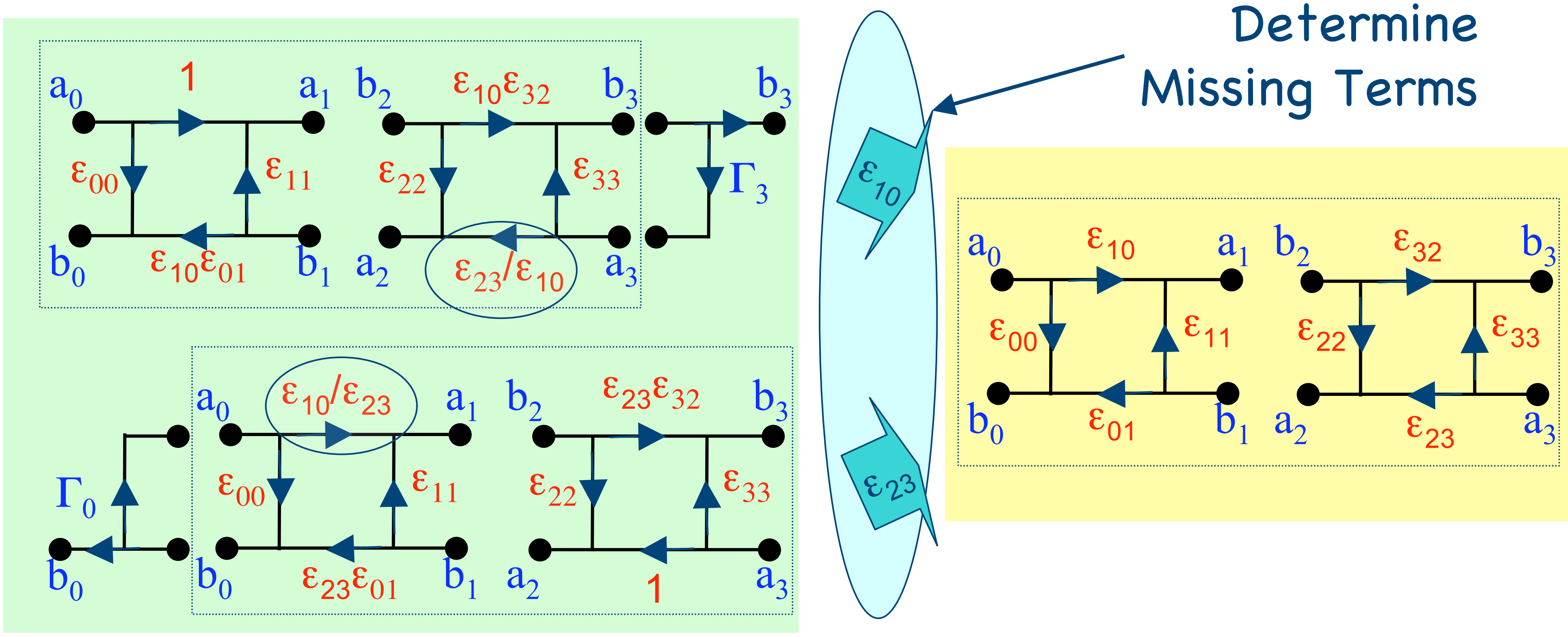
- Transformation of Error Model
  - Utilize measurement of b_3/a_3 (Γ_3) during forward THRU calibration
  - Utilize measurement of b_0/a_0 (Γ_0) during reverse THRU calibration

– Mathematical Conversion
  - Forward Model
    - $\varepsilon'_{22} = \varepsilon_{22}+\varepsilon_{10}\varepsilon_{32}/(1-\varepsilon_{33}.\Gamma_3)$
    - $\varepsilon_{10}\varepsilon'_{32}= \varepsilon_{10}\varepsilon_{32}/(1-\varepsilon_{33}.\Gamma_3)$
  - Reverse Model
    - $\varepsilon'_{11} = \varepsilon_{11}+\varepsilon_{01}\varepsilon_{10}/(1-\varepsilon_{00}.\Gamma_0)$
    - $\varepsilon_{01}\varepsilon'_{23}= \varepsilon_{01}\varepsilon_{23}/(1-\varepsilon_{00}.\Gamma_0)$



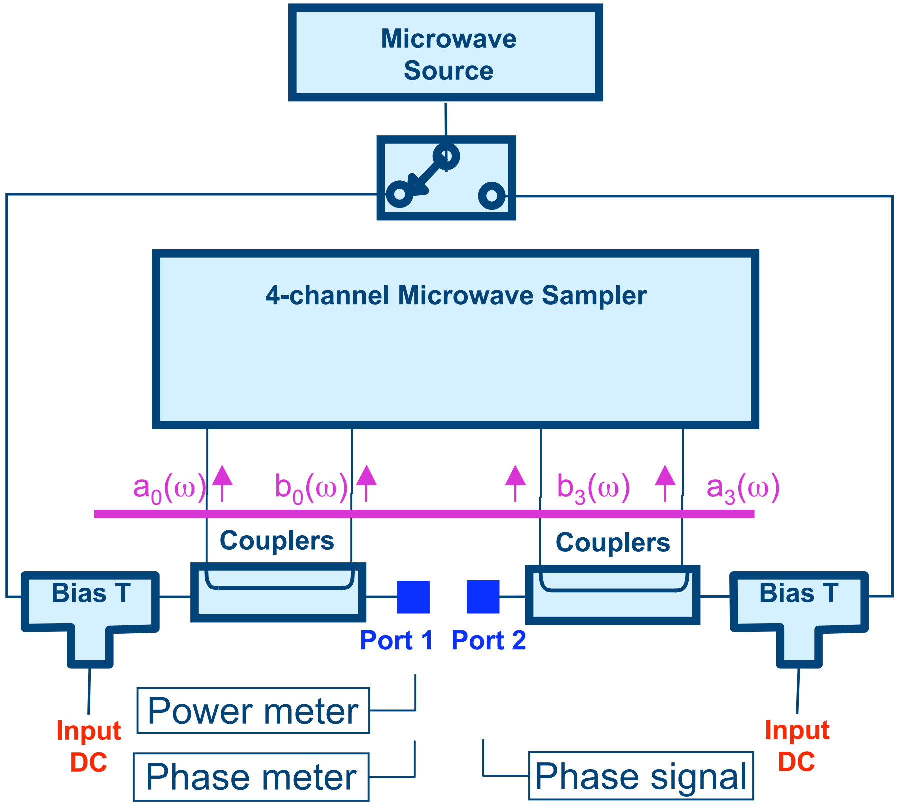
Reformulate Error Model: *Isolate correction and Impedance transformation*

Relating VNA and NLVNA Error Models
- step 2



Un-normalize and Combined Error Model

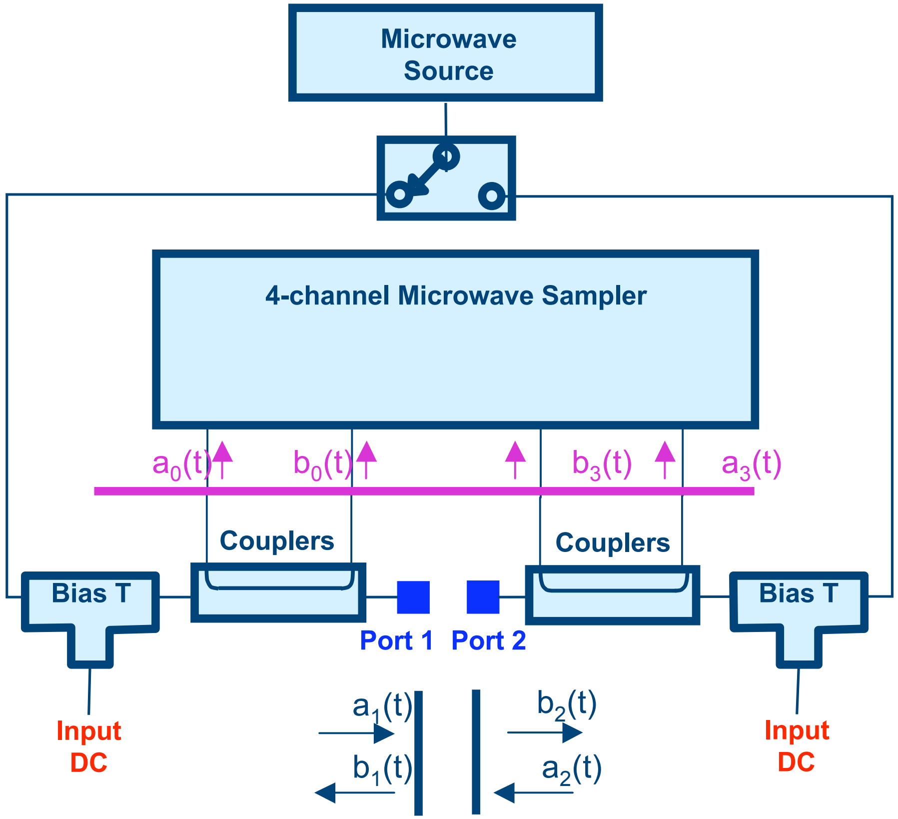
Absolute Calibration:
- Determine ε_{10} or ε_{23}

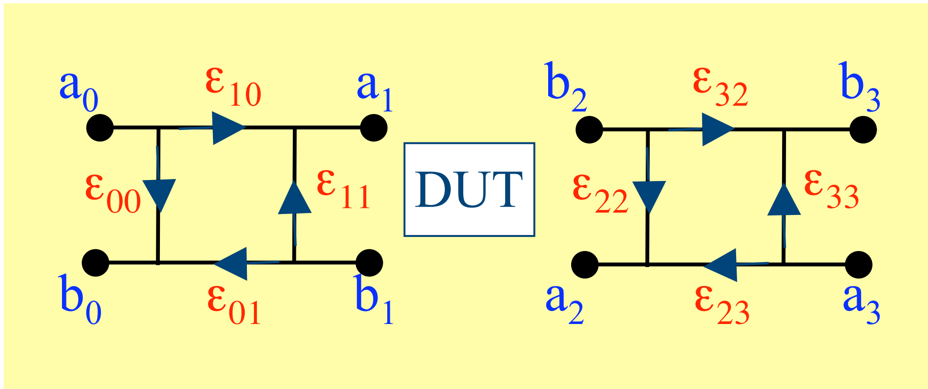


- Additional calibration steps
  - ε_{10} un-normalization
    - MAG: Attach a power meter to Port 1
    - PHASE: Attach a phase meter to Port 1
    - PHASE: Inject a known signal into Port 1
  - ε_{23} un-normalization
    - MAG: Attach a power meter to Port 2
    - PHASE: Attach a phase meter to Port 2
    - PHASE: Inject a known signal into Port 2
- Phase Meter !!!!!!!!
  - Requires the utilization one of the samplers
- Phase Signal !!!!!!!
  - Requires a spectrally rich signal with a known phase relationship

……. go beyond s-parameters

Absolute Calibration:
- NLVNA 8 Term Error Model





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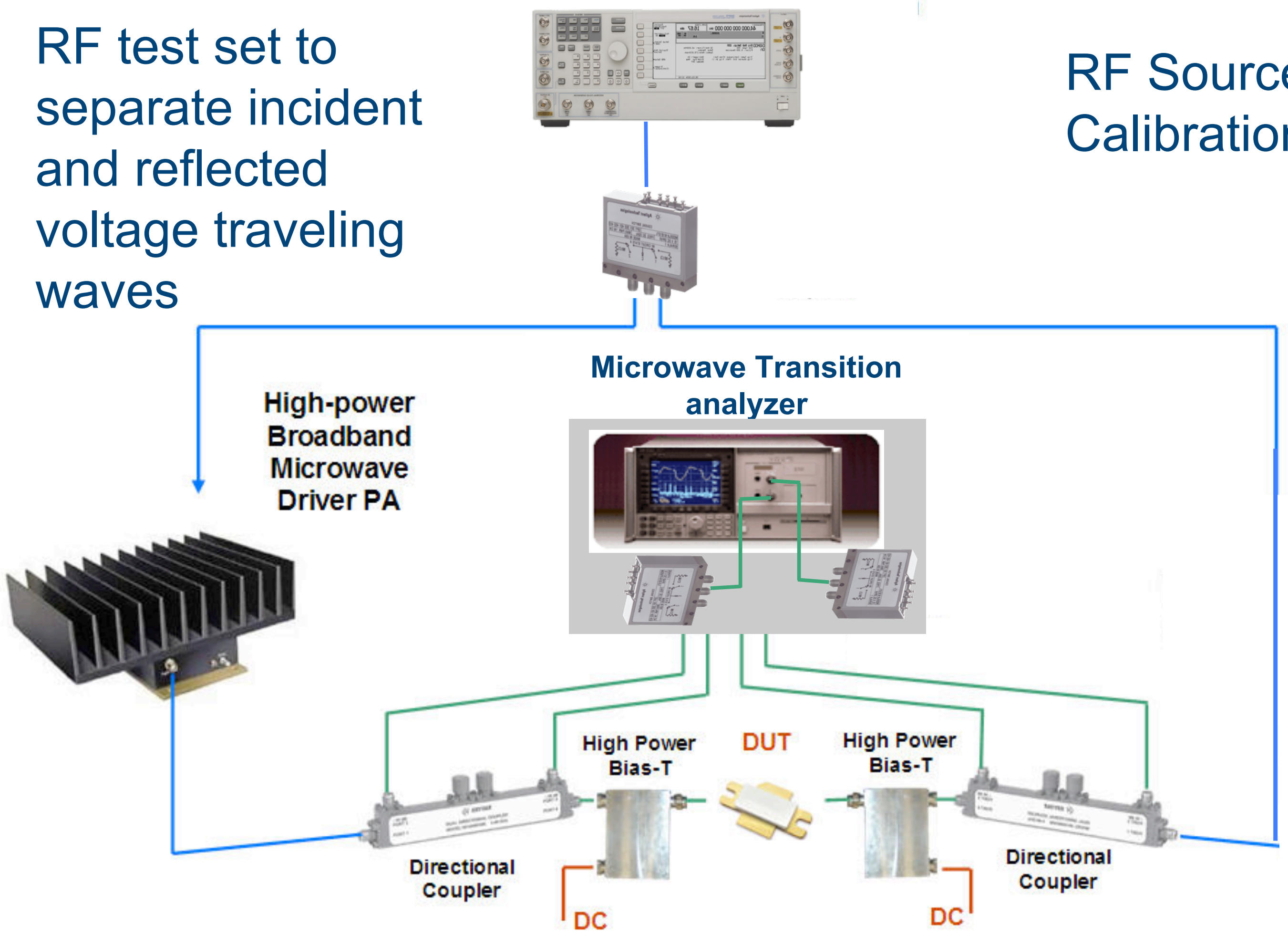
RF I-V Waveform Measurement System
- Review of Fundamental Architecture

RF test set to separate incident and reflected voltage traveling waves

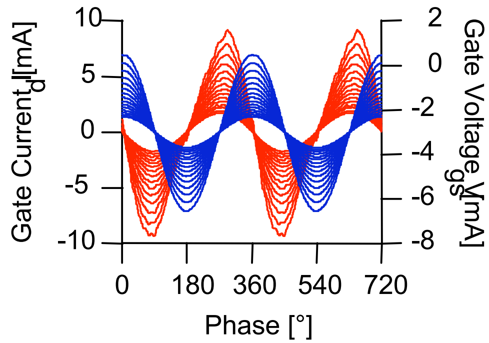
RF Source for both Calibration and Measurement

Receiver to measured voltage traveling waves
- ✓ Key Component

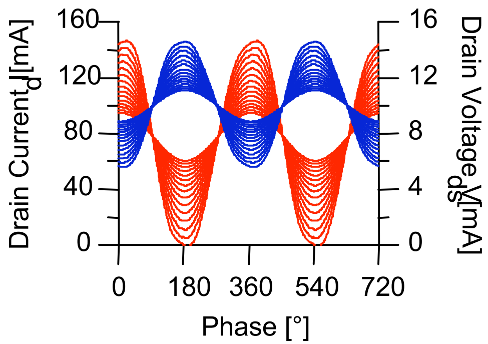


Frequencies up to 67 GHz
Power levels up to 100 Watts

NLVNA Goes Beyond S-parameter:
- Waveform Measurement

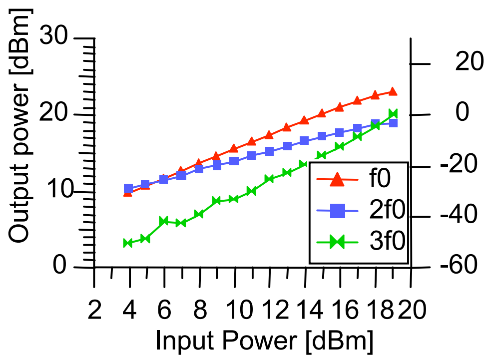


- HFET Transistor
  - Power Sweep @ 1.8 GHz



- Measures magnitude and phase of all the frequency components present in the terminal travelling waveforms
  - Power response
  - Spectral distortion
- Data Transformations
  - Frequency to Time Domain
    - Waveforms
  - *a* & *b* waves into *v* & *i* waves

NLVNA Waveform Measurement:
- Performance Extraction



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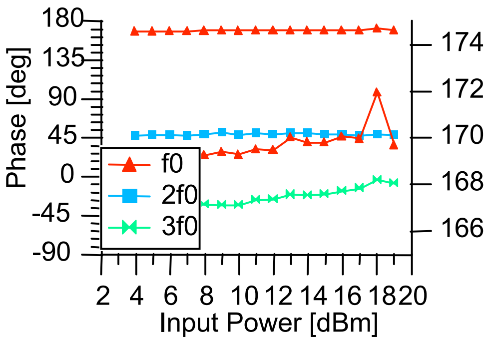


- Data Transformation. Non-Linear Performance Evaluation
  - Gain and Gain Compression AM-AM
  - Output Power
  - Phase Response AM-PM
  - Spectral growth
- Direct Observation
  - Mode of Operation
  - Breakdown/Reliability

Are Waveform Measurements Sufficient?

Linear versus Non-Linear Circuit Design
- the need for waveform engineering

- Linear System
  - characterized by s-parameters
    - allow impedance transformation
    - cascading of networks

→ S-parameters are also a design tool in Linear CAD

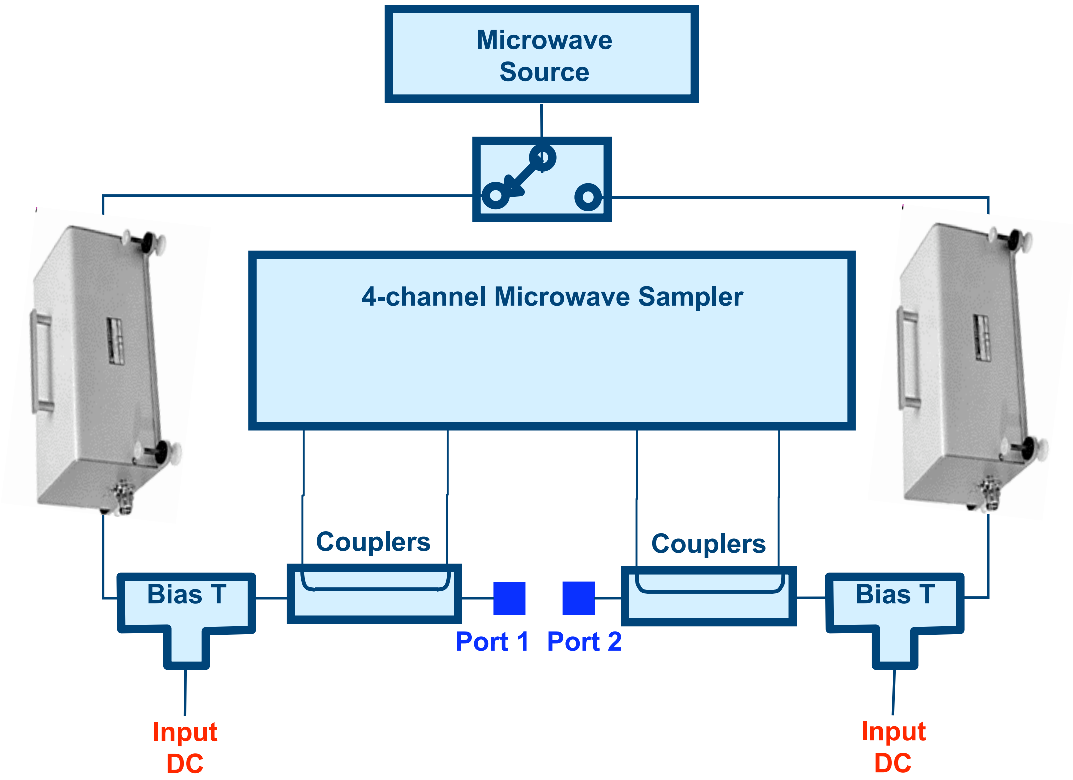
- Non-Linear System
  - characterized by waveforms
      - includes spectra growth (harmonics & inter-modulation)
    - cannot perform impedance transformation
      - Performance is influenced by measurement environment

Need to Engineer as well as Measure Waveforms

NLVNA needs a waveform engineering extension to become a productive design tool

- Non-Linear Vector Network Analyzer Limitations
  - Determines non-linear behaviour only into its fixed “nominal 50 ohms” impedance environment
  - Circuit design requires knowledge of on-linear behaviours into an arbitrary impedance environment

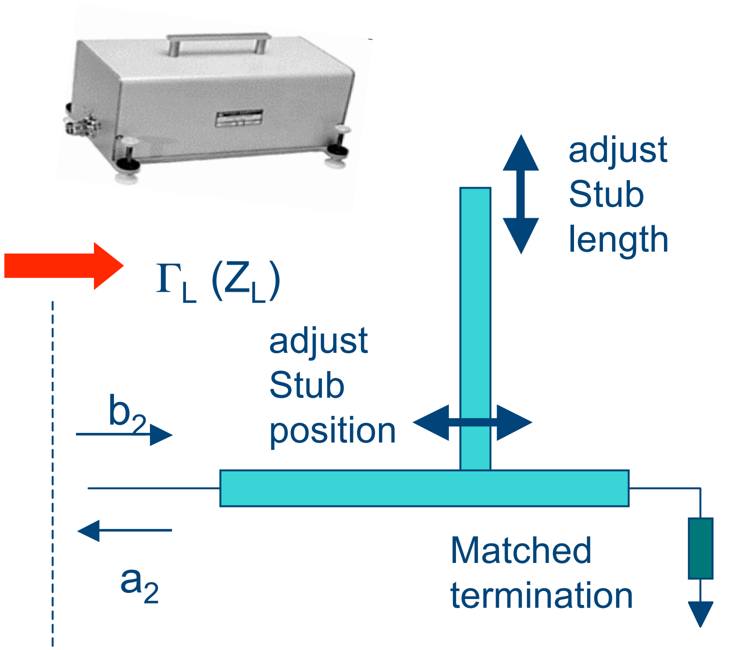
- Waveform Engineering Extension
  - Valid calibration despite changing impedance states
- Passive Impedance Variation
  - Manual stub tuners
  - Automated source- and load-pull systems
- Active Impedance Variation
  - Requires multiple microwave sources.
  - Allows for compensation for losses



Engineering the Stimulus Voltage Waveform

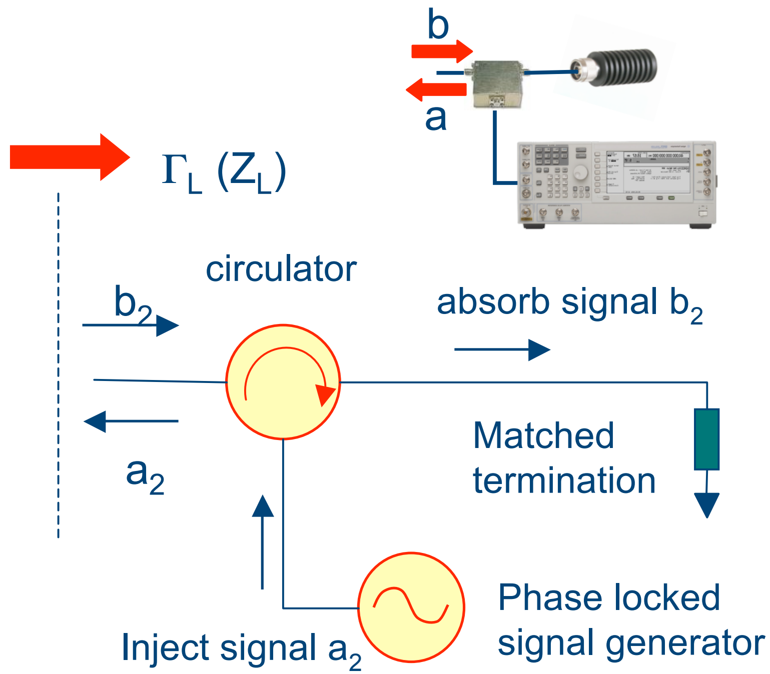
- The concept of open-loop active "load-pull"

- "load-pull" requirement: Modify Reflected Travelling Wave



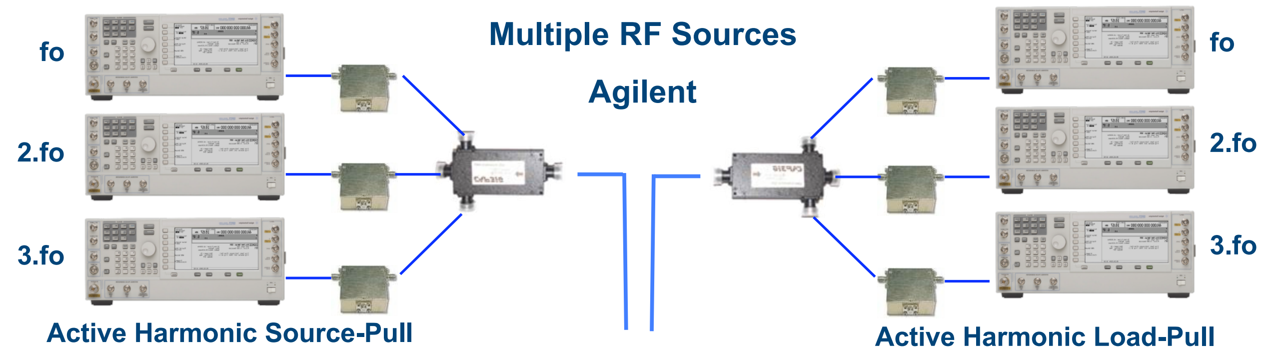
- Passive System
  - Performance limited by losses in measurement system
    - Couplers, bias-tees, fixture

- Active System
  - Amplify signal to overcome losses
    - Closed loop stability issues



Engineering the Stimulus Voltage Waveform

- multi-harmonic open-loop active "load-pull"



Microwave Sources

Frequency domain

Arbitrary Waveform Generator

Tektronix

Time domain

Digital World reaches RF

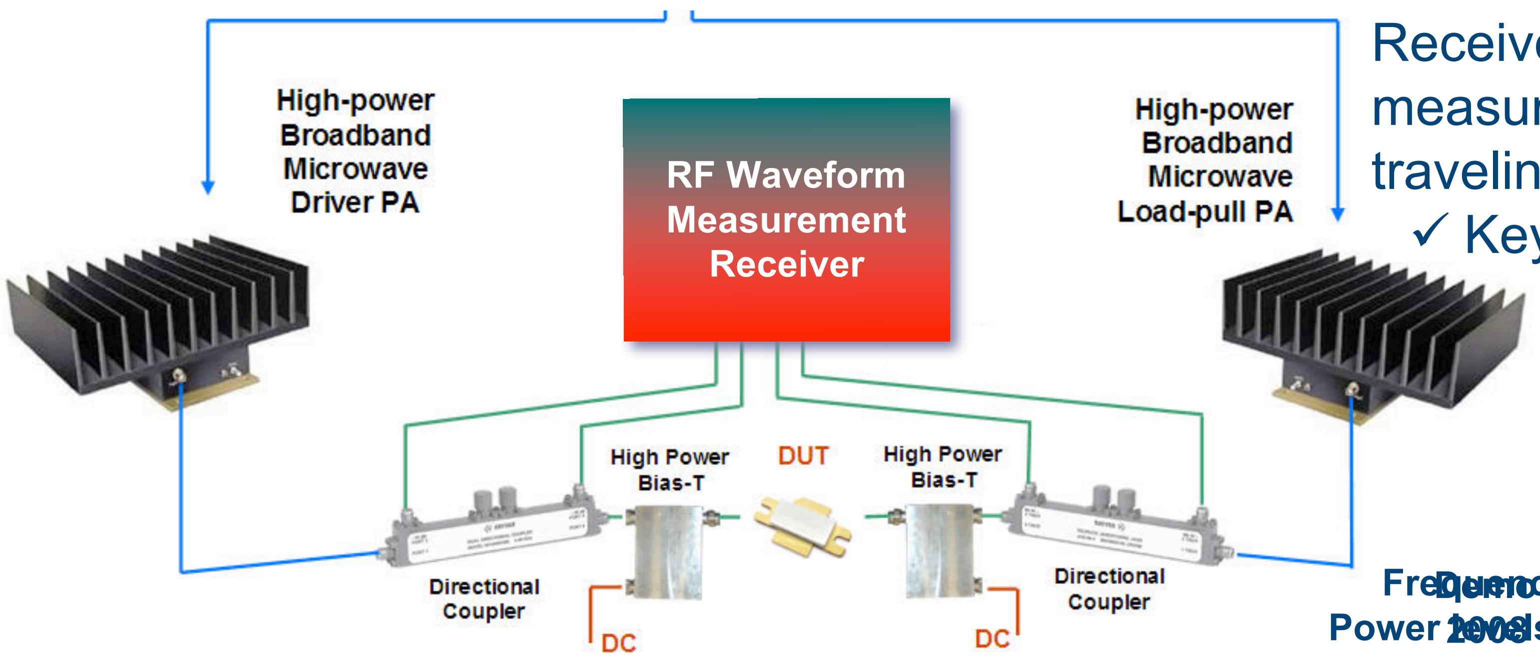
RF I-V Waveform Measurement & Engineering System

- Review Fundamental Architecture

RF Waveform Engineering Stimulus

Stimulus to engineer voltage traveling waves

- ✓ Key Component



Receiver to measured voltage traveling waves

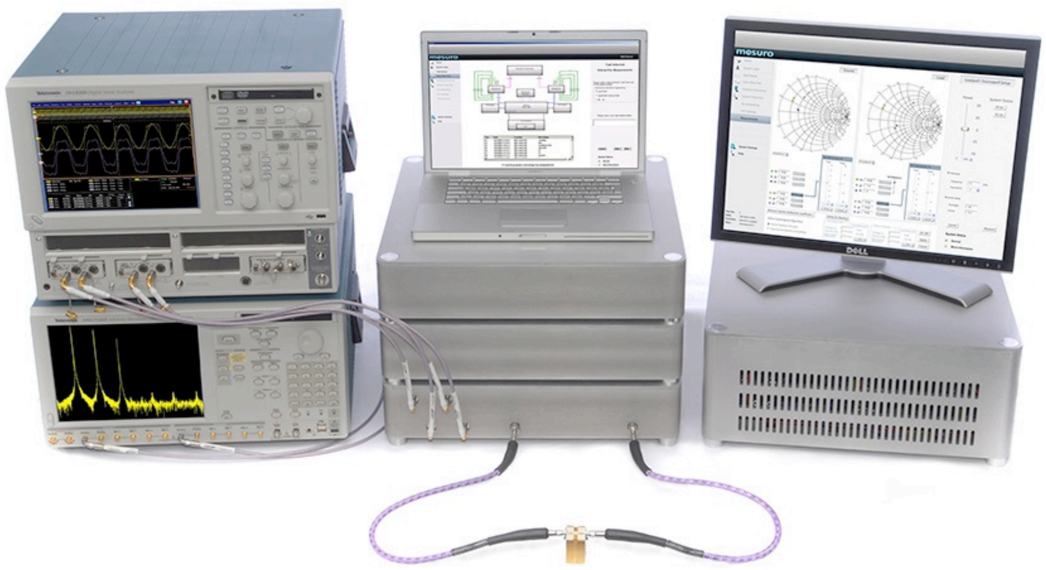
- ✓ Key Component

Frequencies up to 67 GHz
Power levels up to 100 Watts

Demonstrated at IMS 2008 with Tektronix

RF I-V Waveform Measurement & Engineering System

- Emerging Commercial Architectures



Time Domain Based

Demonstrated at IMS 2009 with Tektronix

Further Considerations and Developments

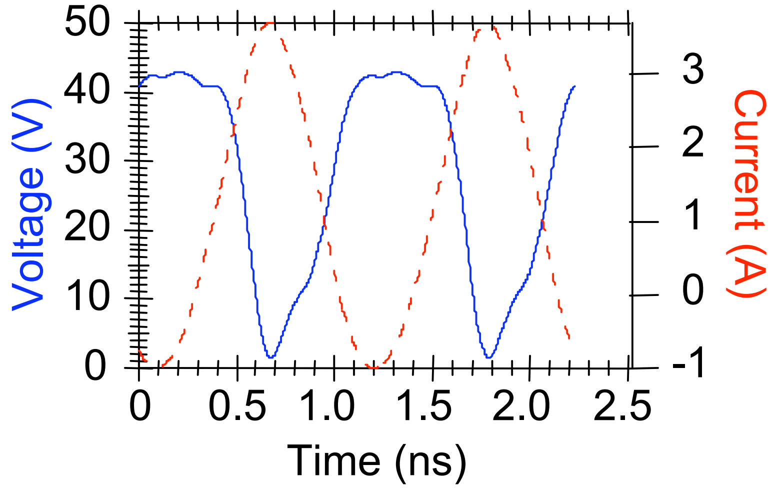
- higher power and/or higher thru-put

- Packaged Devices
  - Requirement for waveform de-embedding
- High Power Devices
  - Requirement for impedance transformation
- High Thru-put
  - Requirement for “closed loop” active load-pull

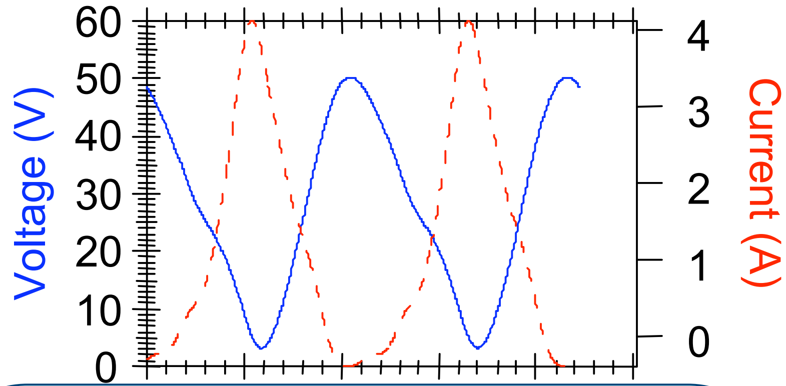
De-embedding Requirements:

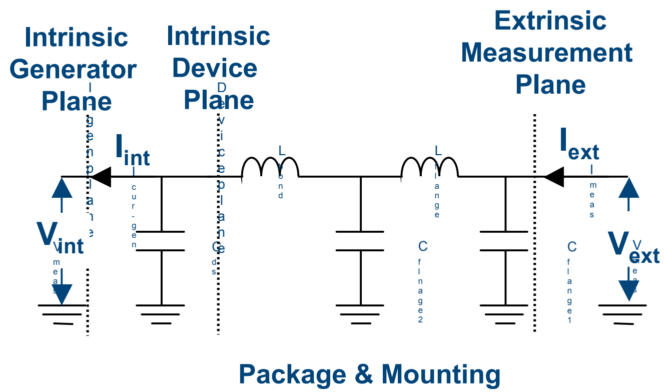
- Packaged 20W Si LDMOS Device

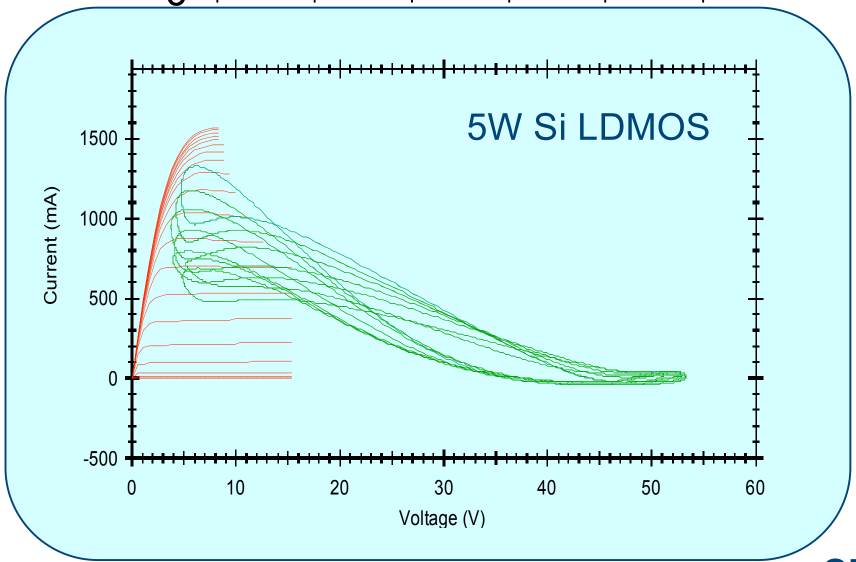
Extrinsic Waveforms: Meaningless



Intrinsic Waveforms: Design Aid

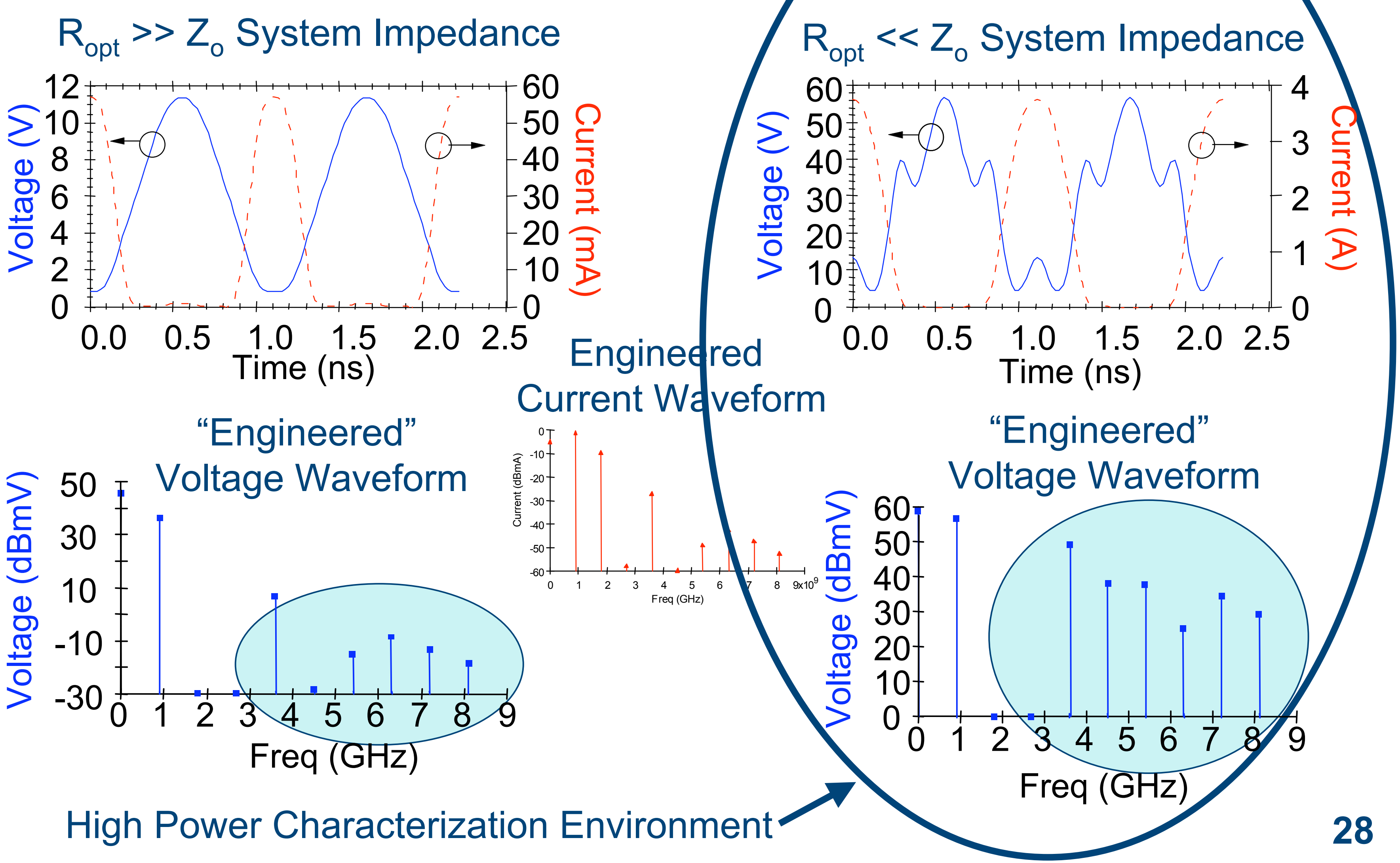






System Impedance Issue:

- Band Limited Waveform Engineering



Waveform Engineering Issues

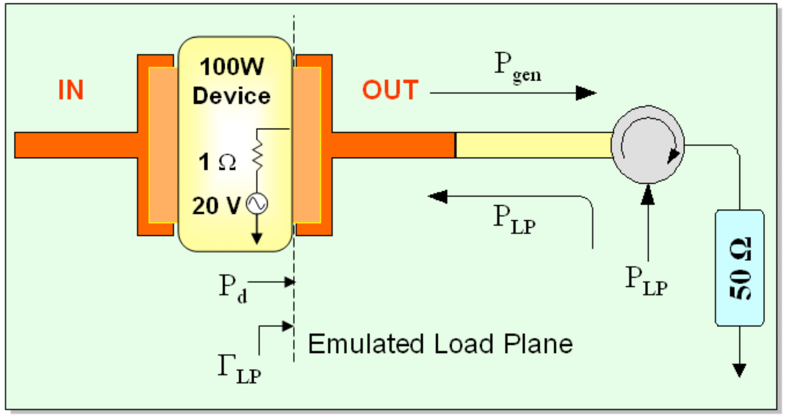
- Active load pull at high powers?

- High $|\Gamma| = \sqrt{P_{LP}/P_{Gen}}$ requires both values to be almost equal
- High dissipated power $P_{Dis} = P_{Gen} - P_{LP}$ requires a difference
- Both requirements can be only satisfied by a rise of P_{LP} and P_{Gen}

Example:
Load-pull of a 100 Watt device with 1Ω output impedance in a 50Ω system results in the following signal levels:

$$P_{LP} = 1.2\,\mathrm{kW} \quad P_{Gen} = 1.3\,\mathrm{kW}$$
$$VSWR = 50 \quad V_{Max} = 1.4\,\mathrm{kV}$$

➔ Prohibitive!

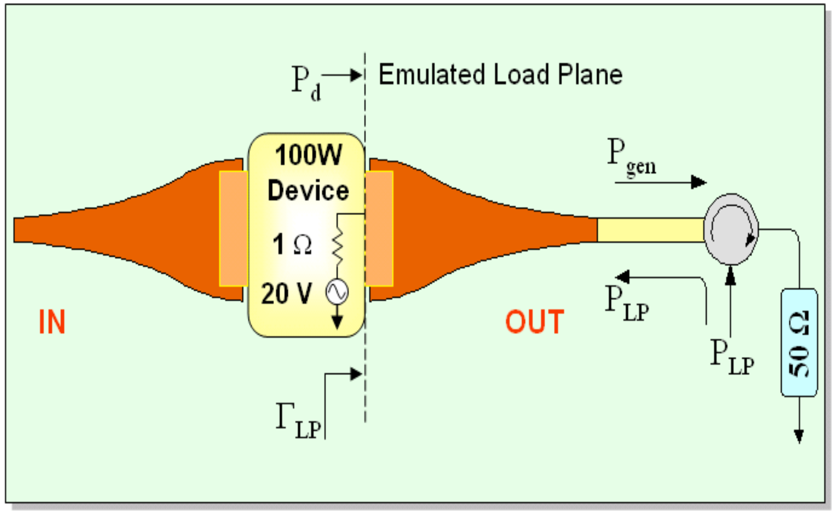


Abbreviation

- P_{Lp}: Load-Pull Power (Watt)
- P_d: Power delivered by the DUT
- P_{gen}: P_{LP} + P_d
- VSWR: Voltage Standing Wave Ratio

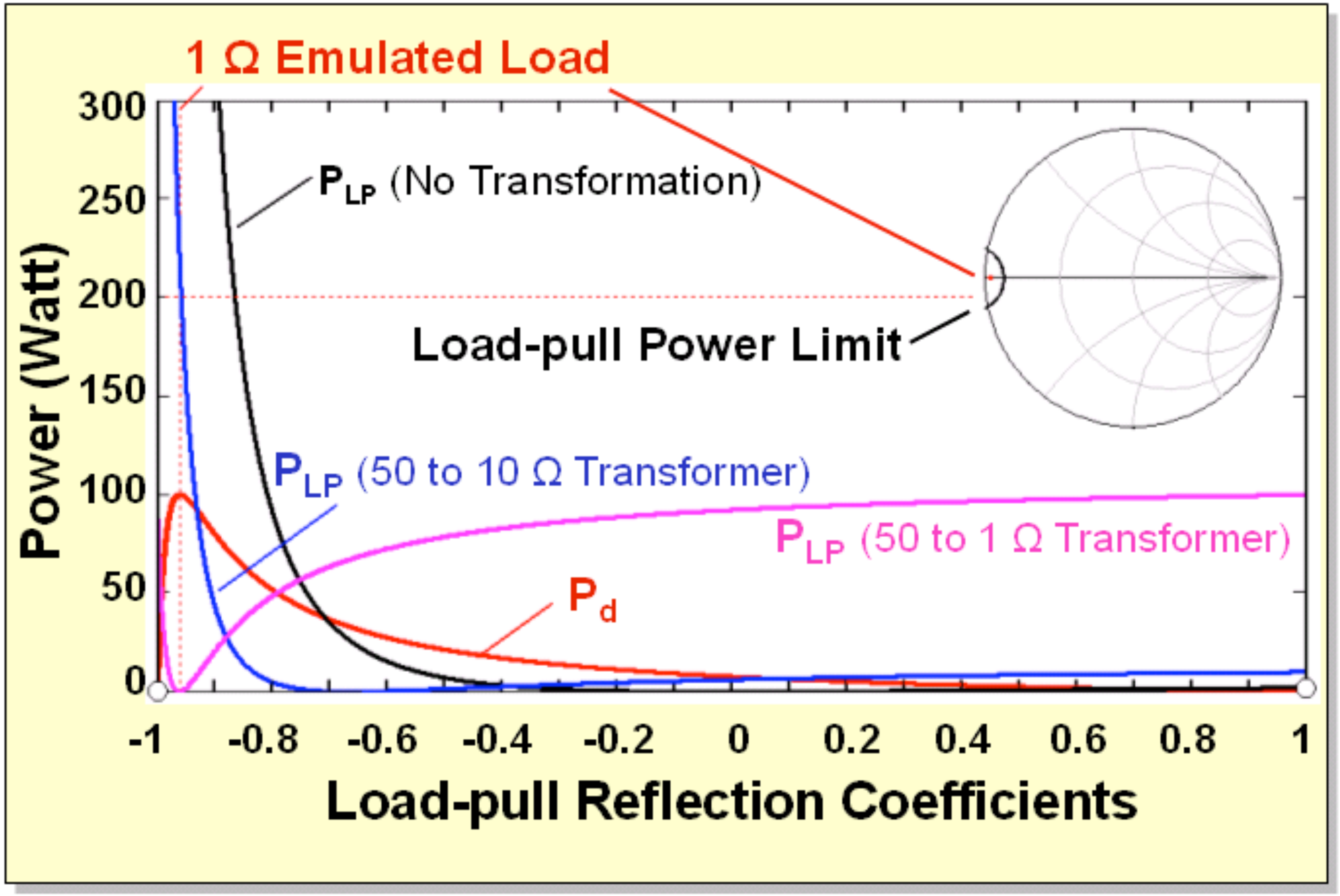
High Power Waveform Engineering:
- Solution is a low impedance measurement system

- Build a low-impedance measurement system
  - This is the preferable option but is impractical
- Use of broad impedance transformers
  - Significantly reduced VSWR
  - Maintain integrity of waveforms
  - Resonance free environment over large bandwidth
  - Can employ well established TRL calibration techniques.



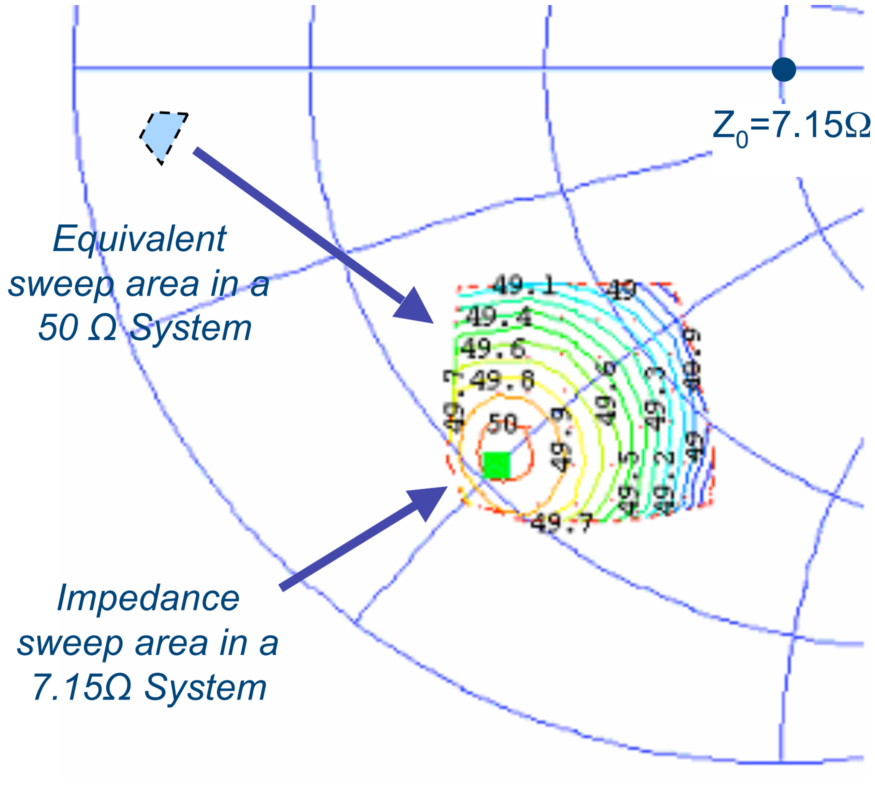
High Power Waveform Engineering:

- Solution is a low impedance measurement system



High Power Waveform Engineering:

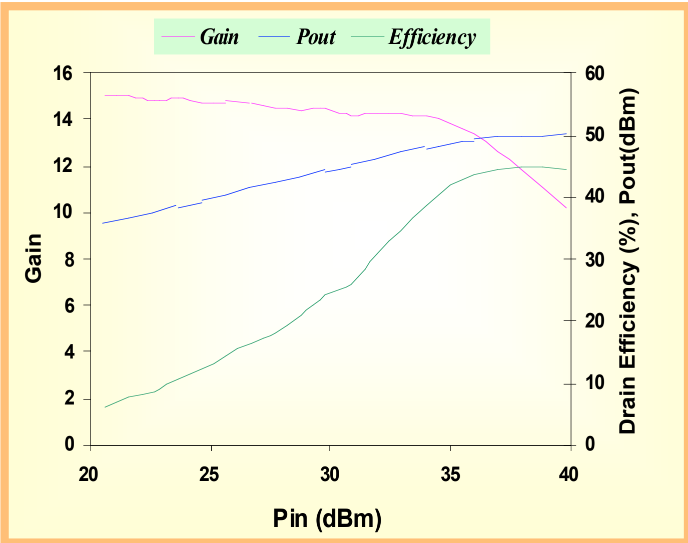
- Measurement of a Freescale 100 W LDMOS Device



Measured Optimum Load Impedance (Z_{opt})

1.643 – j3.562 Ω

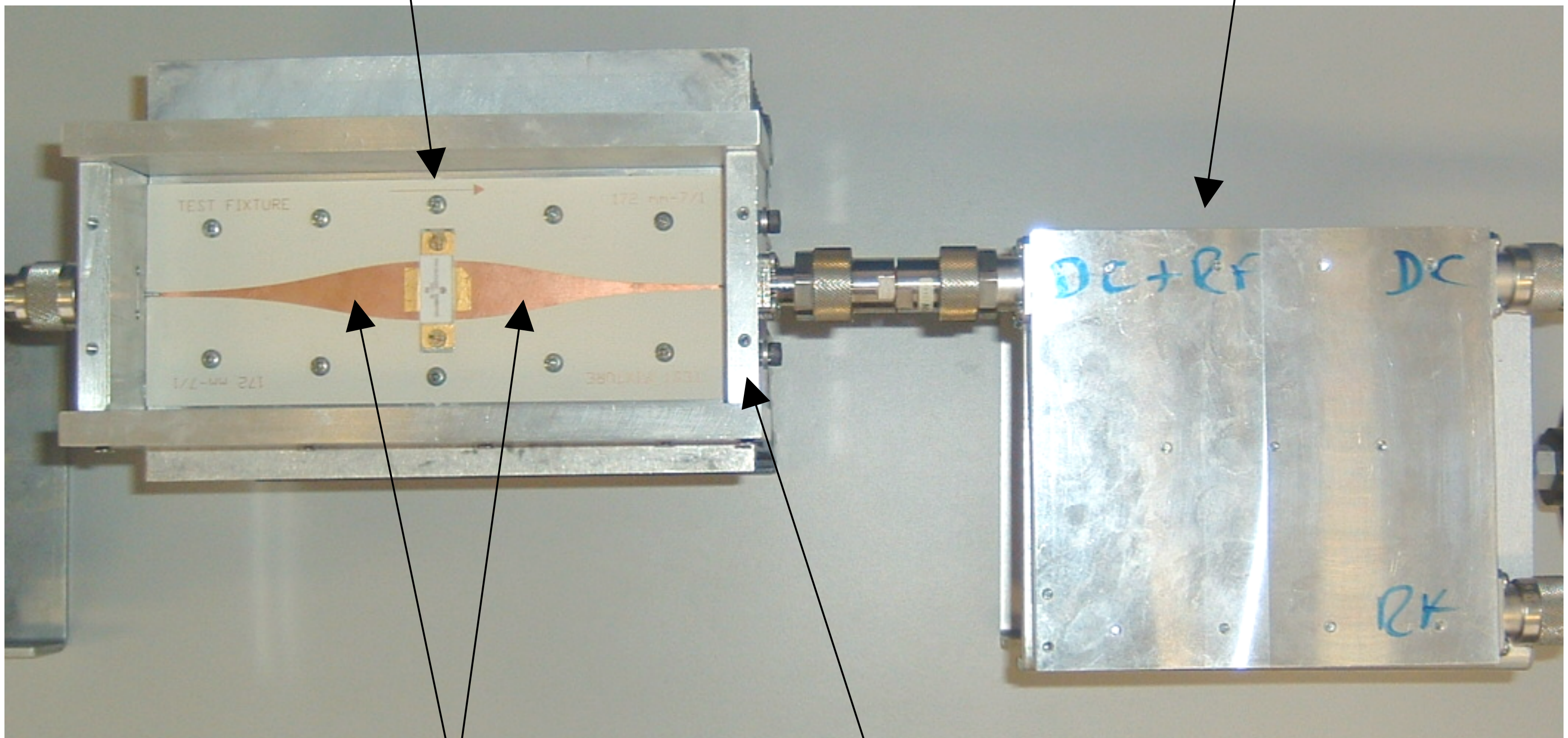
Only 120 Watts required to probe the optimum load when using 50 to 7.15 impedance transformer



High Power Waveform Engineering:
- Critical High power measurement set-up components

100 Watt LDMOS Transistor

High Power Bias-tee



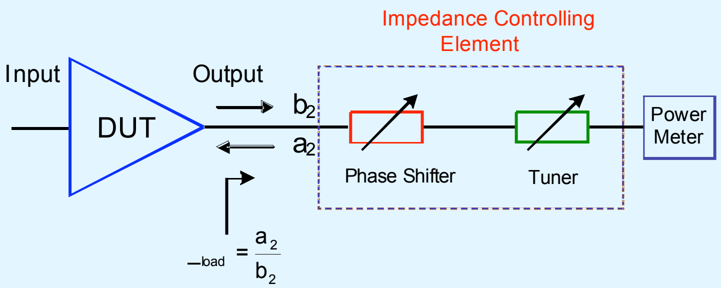
Klopfenstein Impedance Transformers

High Power Test Fixture

Alternative Active Load Pull Solutions

- address the issue of measurement thru-put

Passive Load-Pull Technique

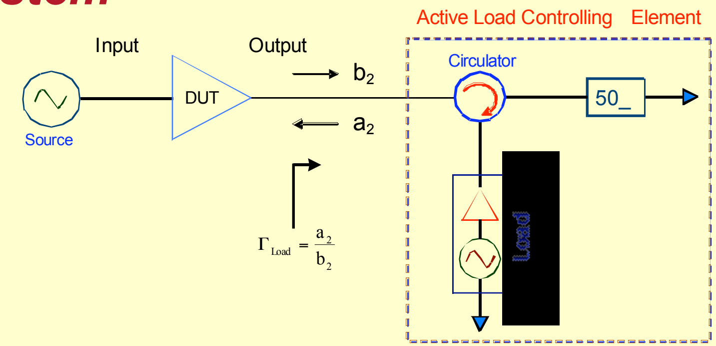


A traditional ***passive load-pull system*** can:

- …et loads independent of power output of DUT
- × …tability & measurement artefacts due to bro… …npedance variations
- × Pr… …omplex challenge to independently set harmoni…
- × Take a considerable amount of time to characterise and calibrate at different frequencies

Can we take the advantages of both of these load setting techniques?

Active Open-Loop Load-Pull System

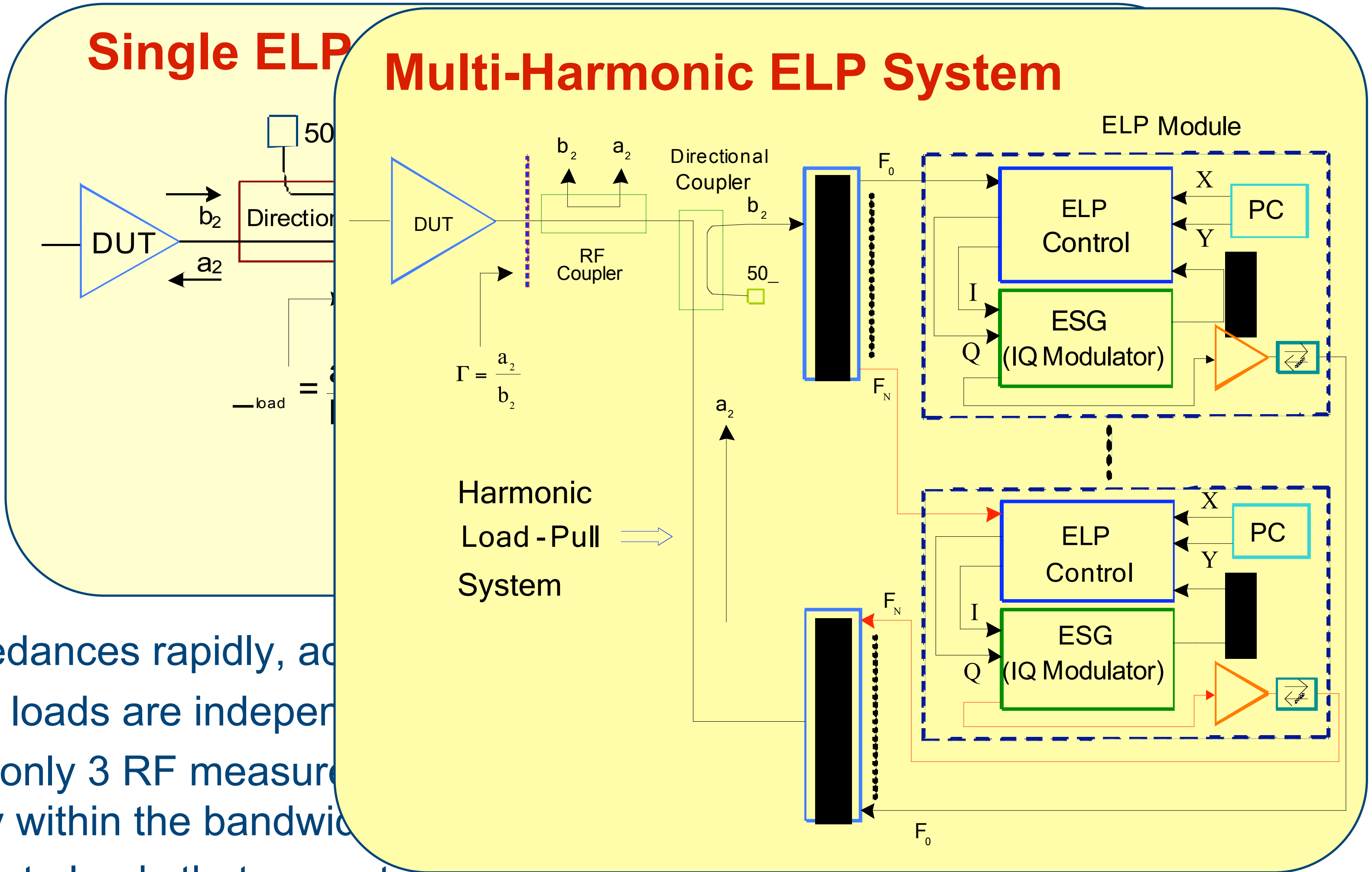


The ***active open-loop load-pull*** approach:

- ✓ Sets harmonic impedances independent of each oth…
- ✓ Of… …conditional stability
- ✓ … not require calibration or pre-…racterisation
- May take considerable time to iterate to each load

Alternative Active Load Pull Solutions

- developed Envelop Load-Pull System



- ✓ Sets impedances rapidly, ac
- ✓ Harmonic loads are indeper
- ✓ Requires only 3 RF measure frequency within the bandwic
- ✓ Can emulate loads that are outside the Smith chart

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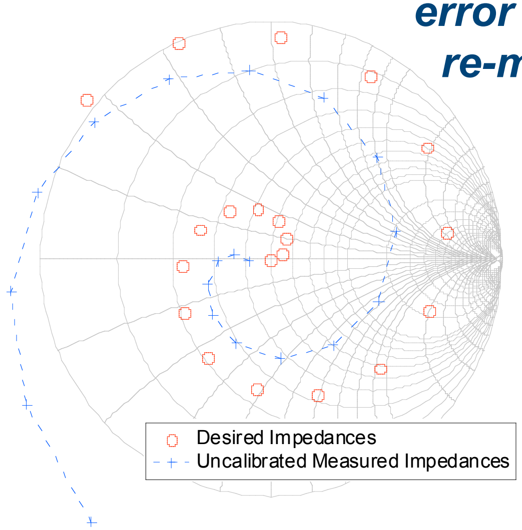
Envelope Active Load Pull Solutions

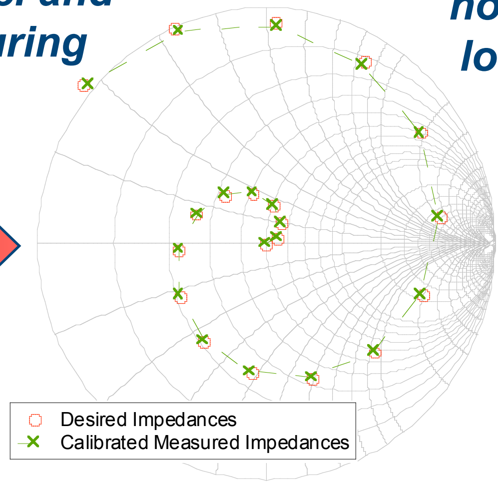
- calibrated electronic load-pull system

Applying the calibration error model and re-measuring

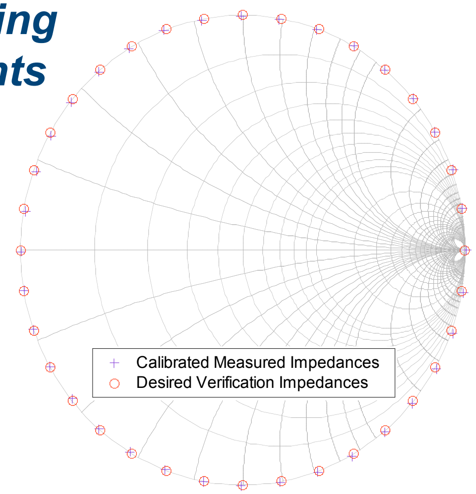
Ensure impedance setting accuracy using non-training load points



Before Calibration



After calibration



Load Setting Verification

Calibration Advantages & Assessment

- The accuracy of the loads set after calibration is independent of the number of data points captured, providing that there are at least 3 points in the set.

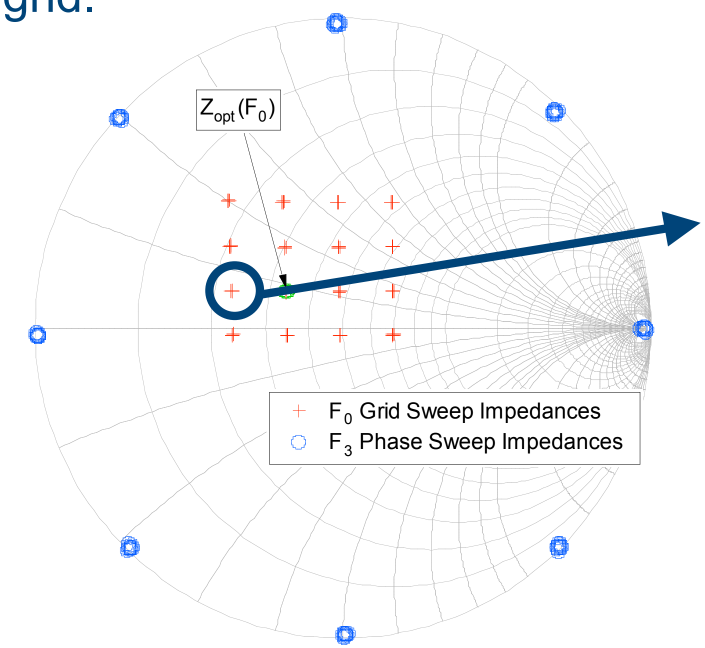
No. of Cal Points	**Percentage Difference in Loads Set**		
	Fundamental (F_0)	***Second Harmonic (F_2)***	***Third Harmonic (F_3)***
12	0.0236 %	0.0344%	0.0335%
20	0.0237 %	0.0348%	0.0338%

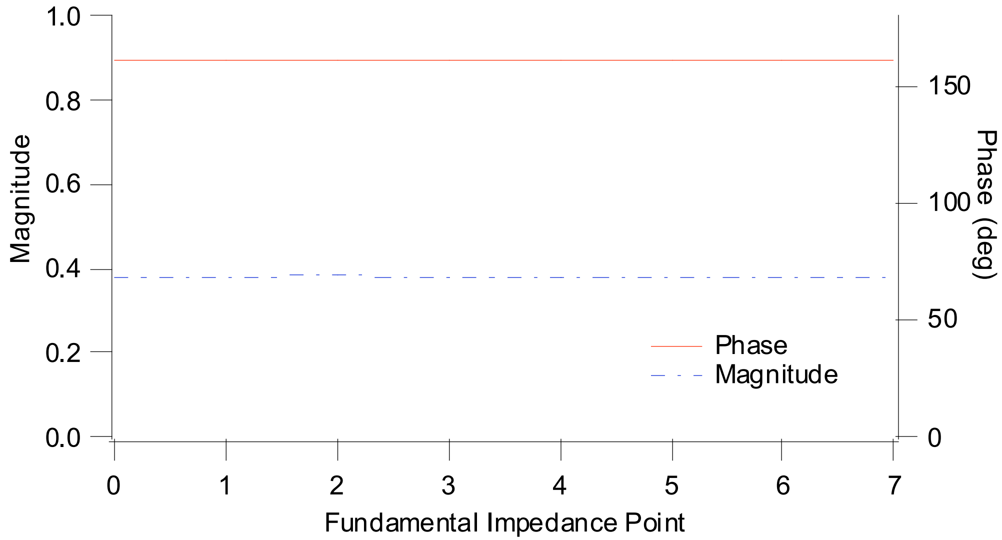
Alternative Active Load Pull Solutions
- developed Envelope Load-Pull System

Example:

The third harmonic load was swept around the edge of the Smith chart with 8 equi-spaced impedances, whilst sweeping the fundamental load in a 4x4 grid.

Viewing the variation of the fundamental magnitude and phase (at a desired load of 0.38 ∠ 160°) as the 3rd harmonic is swept around the edge of the Smith chart:





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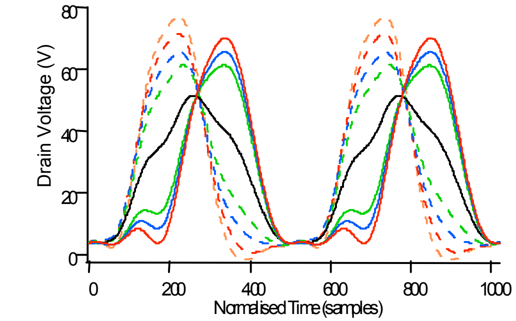
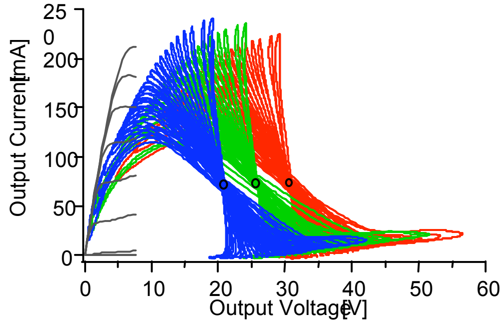
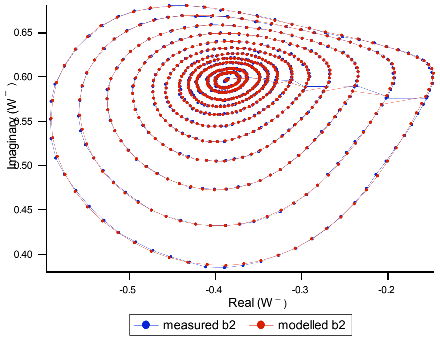
Fully Functional NLVNA: Integrated System
- Waveform Measurement and Engineering







- Investigating and optimizing amplifier modes of operation
  - Development of Class J
- Investigating and optimizing Transistor performance
  - Fan Diagrams
- Behavioural Characterization/Modelling
  - Data Lookup Models

RF IV Waveform Measurement and Engineering

- Role in Supporting Non-Linear CAD Design -

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Cardiff University

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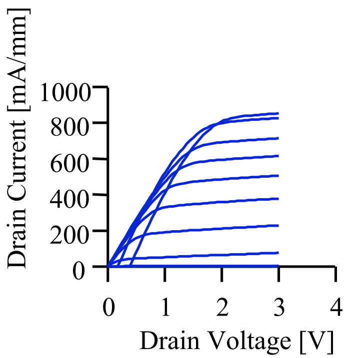
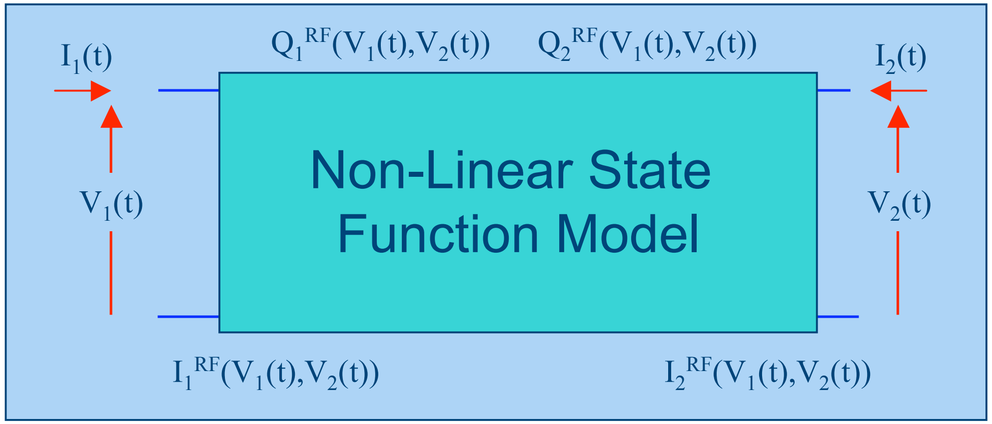
Non-Linear CAD Models:
- state function based formulation

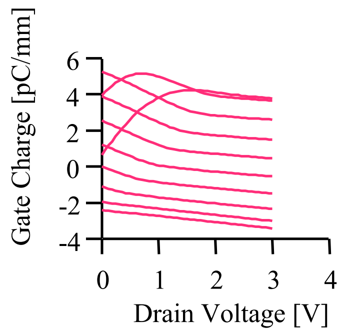
- Time domain formulations
  - Physics Based State function formulation: I & Q
    - Four quasi-static I and Q surface functions
      - Advanced formulations include time delays

$$i_{gs}(t) = I_g\left(v_{gs}(t), v_{ds}(t)\right) + \partial Q_g\left(v_{gs}(t), v_{ds}(t)\right) / \partial t$$

$$i_{ds}(t) = I_d\left(v_{gs}(t), v_{ds}(t)\right) + \partial Q_d\left(v_{gs}(t), v_{ds}(t)\right) / \partial t$$







This fundamental formulation is followed by all analytical models and the Root lookup table model

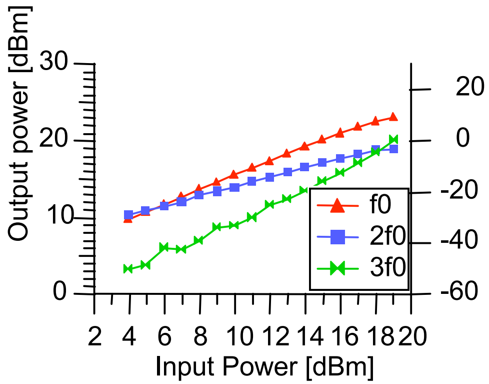
Non-Linear CAD Models:

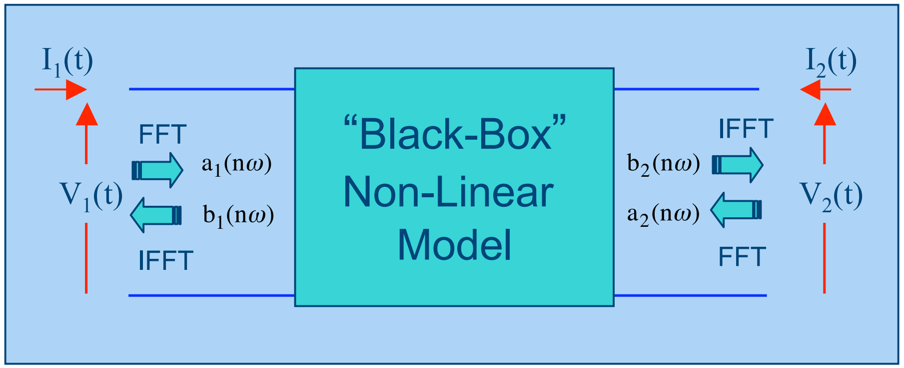
- behavioral "black box: based formulation

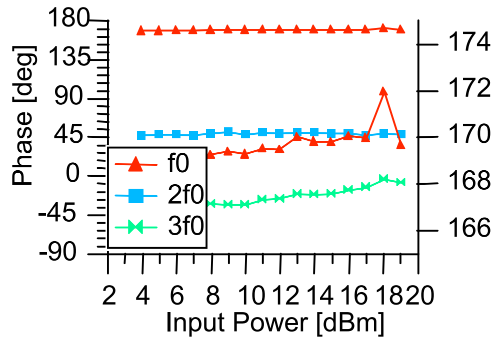
- Frequency or Time domain formulations
  - Behavioral based formulation
    - Many different formulations
      - Analytical or experimental data based

$$i_{ds}(t) = \alpha_0 + \alpha_1 v_{gs}(t-\tau_1) + \alpha_2 v_{gs}(t-\tau_2)^2 + \alpha_3 v_{gs}(t-\tau_3)^3 + ...$$

$$b_2(\omega) = f\left(a_1(\omega), a_1(2.\omega), ..., a_1(n.\omega),, a_2(\omega), a_2(2.\omega), ...a_2(n.\omega)\right)$$







Generally focus on describing a specific behavior

RF I-V Waveform Measurement & Engineering
- role in CAD modelling

- State Function I(V) - Q(V) Non-Linear Models
  - Directly Measures Model related parameters I & V
    - I-Q function Extraction
      - *Data Lookup Model Generation*
    - Analytical Model validation and Optimization

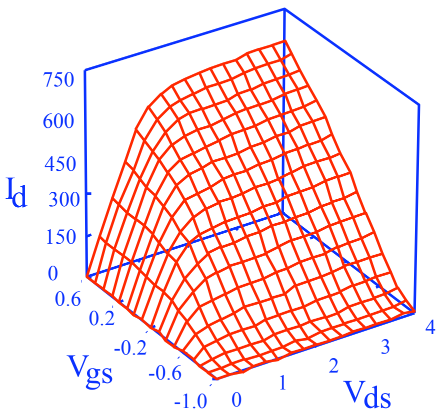
- Behavioural “Black Box” Non-Linear Models
  - Directly Measures Non-Linear Behaviour
    - Directly Import into CAD Tool
      - *Data Lookup behavioural model*
    - Indirectly Import into CAD Tool
      - *Formulated behavioural models (Volterra)*
      - *Emerging non-linear parameter equivalent to linear s-parameters (X-parameters)*

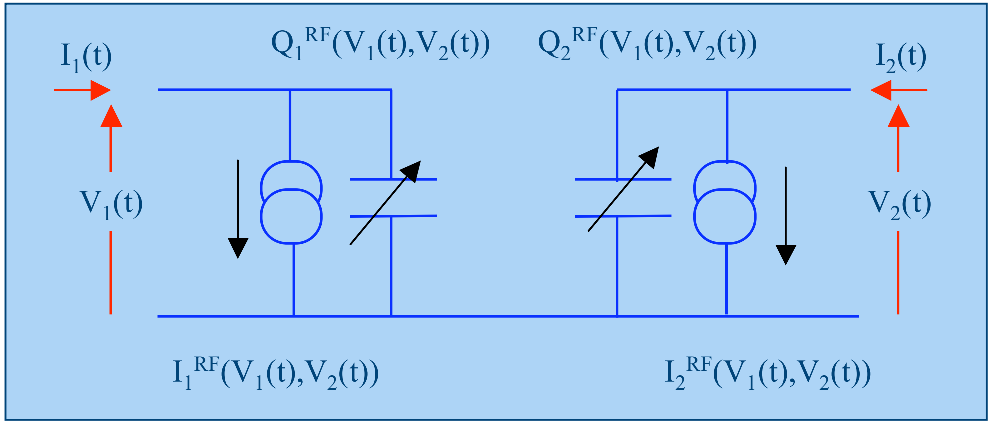
Non-Linear CAD Models:
- state function based formulation

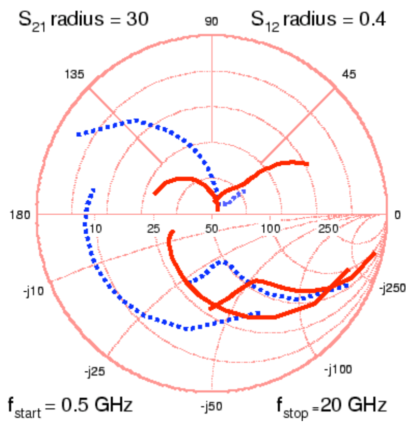
- Requires measurement of the state functions: I & Q
  - DC I-V provides Current State Function
    - Static measurements: trapping and thermal issues
  - S-parameters measure differential of state functions
    - Trapping and thermal issues

$$i_{gs}(t) = I_g\left(v_{gs}(t), v_{ds}(t)\right) + \partial Q_g\left(v_{gs}(t), v_{ds}(t)\right) / \partial t$$

$$i_{ds}(t) = I_d\left(v_{gs}(t), v_{ds}(t)\right) + \partial Q_d\left(v_{gs}(t), v_{ds}(t)\right) / \partial t$$







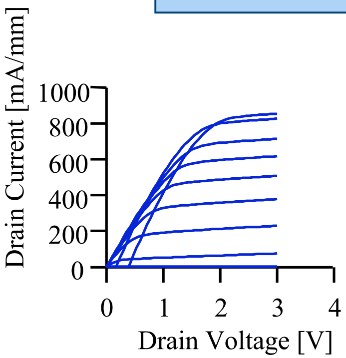
Ideally require direct dynamic measurement of state functions

Non-Linear State Function CAD Models:

- indirect extraction from bias dependent s-parameters

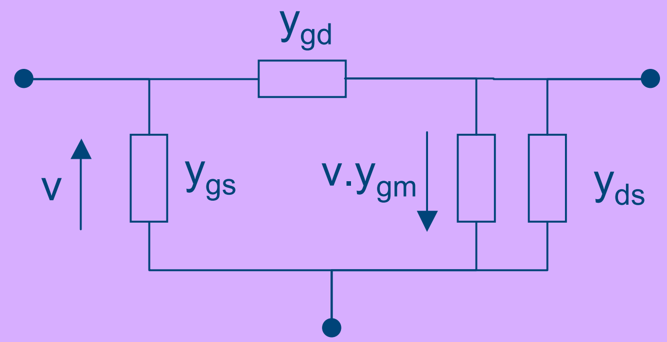
$$i_{gs}(t) = I_g\left(v_{gs}(t), v_{ds}(t)\right) + \partial Q_g\left(v_{gs}(t), v_{ds}(t)\right) / \partial t$$

$$i_{ds}(t) = I_d\left(v_{gs}(t), v_{ds}(t)\right) + \partial Q_d\left(v_{gs}(t), v_{ds}(t)\right) / \partial t$$



Linearize to get s-parameters

Small Signal Equivalent Circuit Model



$$i_{gs} = y_{11}.v_{gs} + y_{12}.v_{ds} \qquad y_{11} = y_{gs} + y_{gd} \qquad y_{12} = -\,y_{gd}$$

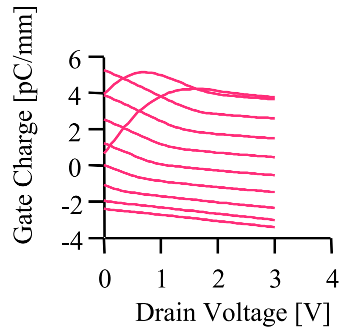
$$i_{ds} = y_{21}.v_{gs} + y_{22}.v_{ds} \qquad y_{21} = y_{gm} - y_{gd} \qquad y_{22} = y_{ds} + y_{gd}$$

Integrate bias dependent linear s-parameters to get non-linear parameters

Non-linear State Functions

$$Q_g = \int \Im(y_{11}).v_{gs} + \int \Im(y_{12}).v_{ds}$$

$$I_d = \int \Re(y_{21}).v_{gs} + \int \Re(y_{22}).v_{ds}$$

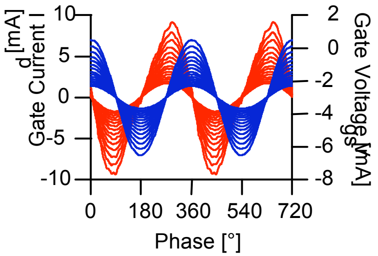


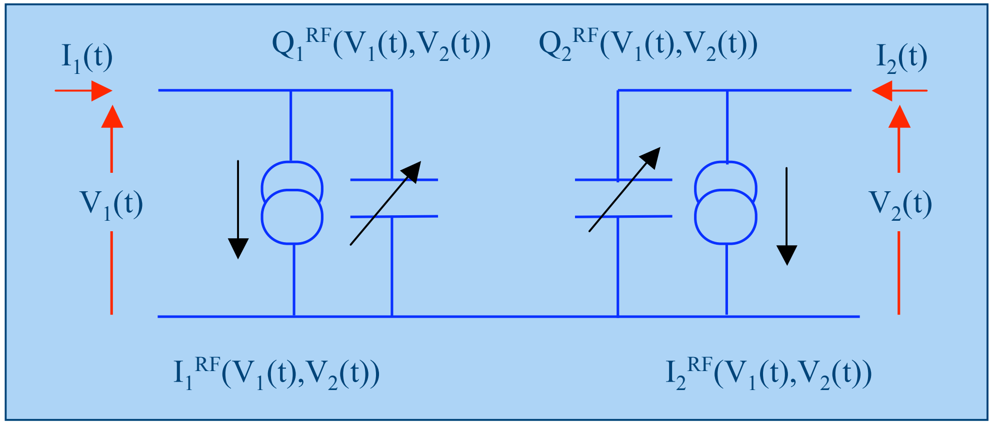
Provides data for Root model or for analytical curve-fitting

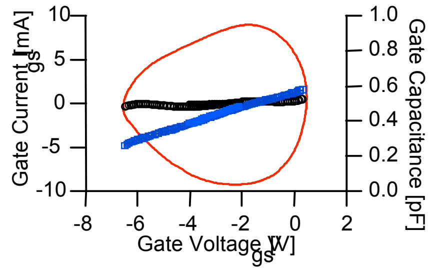
Non-Linear State Function CAD Models:

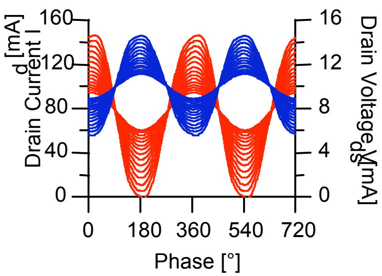
- direct extraction from RF I-V Waveforms

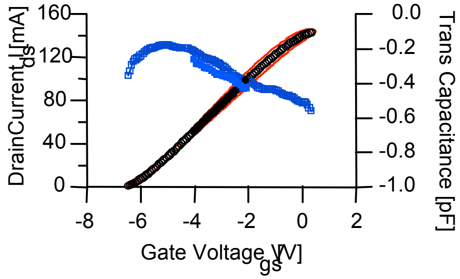
Model uses state functions to describe the arbitrary time dependent terminal current flow resulting from the applied arbitrary time dependent terminal voltages







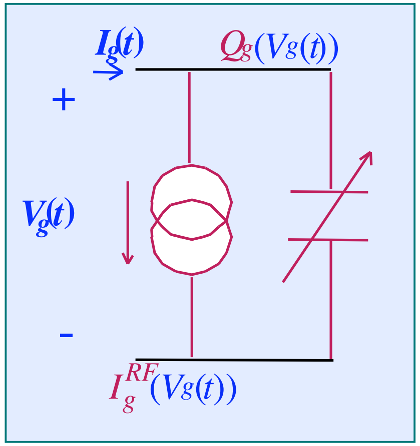




If we have measured the terminal current flow resulting from an applied and measured terminal voltage and we reverse process and determine state functions?

YES: Solutions in both the time and frequency domain.

Non-Linear State Function CAD Models:
- direct extraction from RF I-V Waveforms



- One-Port Problem
  - Two State functions
  - Depend on one variable

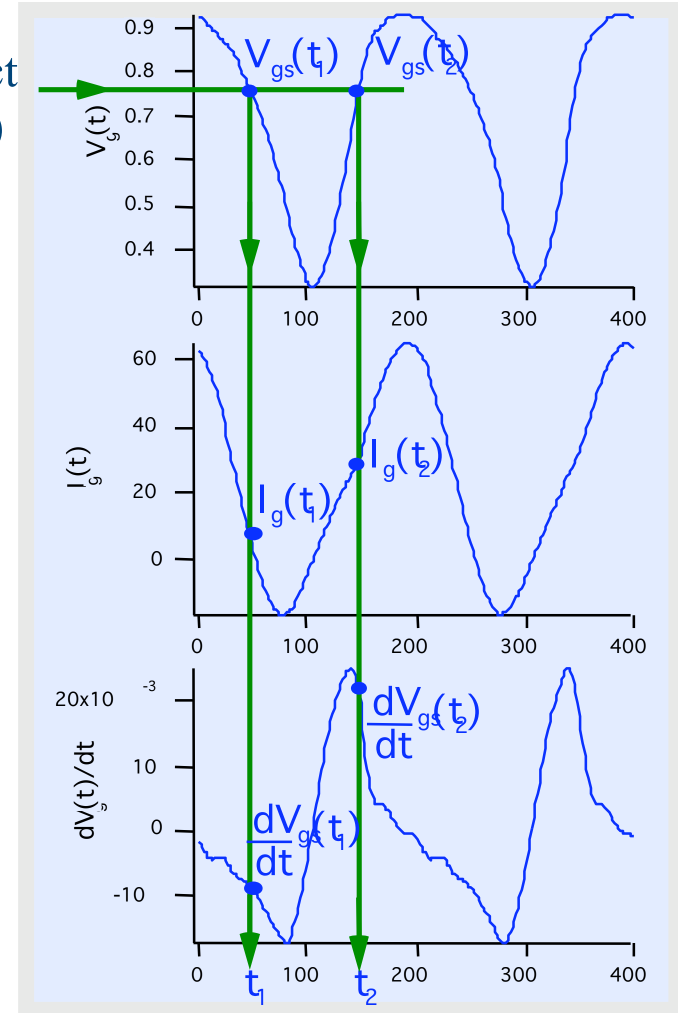
$$i_{gs}(t) = I_g(v_{gs}(t)) + \partial Q_g(v_{gs}(t)) / \partial t$$

$$i_{gs}(t_1) = I_g(v_{gs}(t_1)) + C_g . \partial v_{gs} / \partial t (t_1)$$

$$i_{gs}(t_2) = I_g(v_{gs}(t_2)) + C_g . \partial v_{gs} / \partial t (t_2)$$

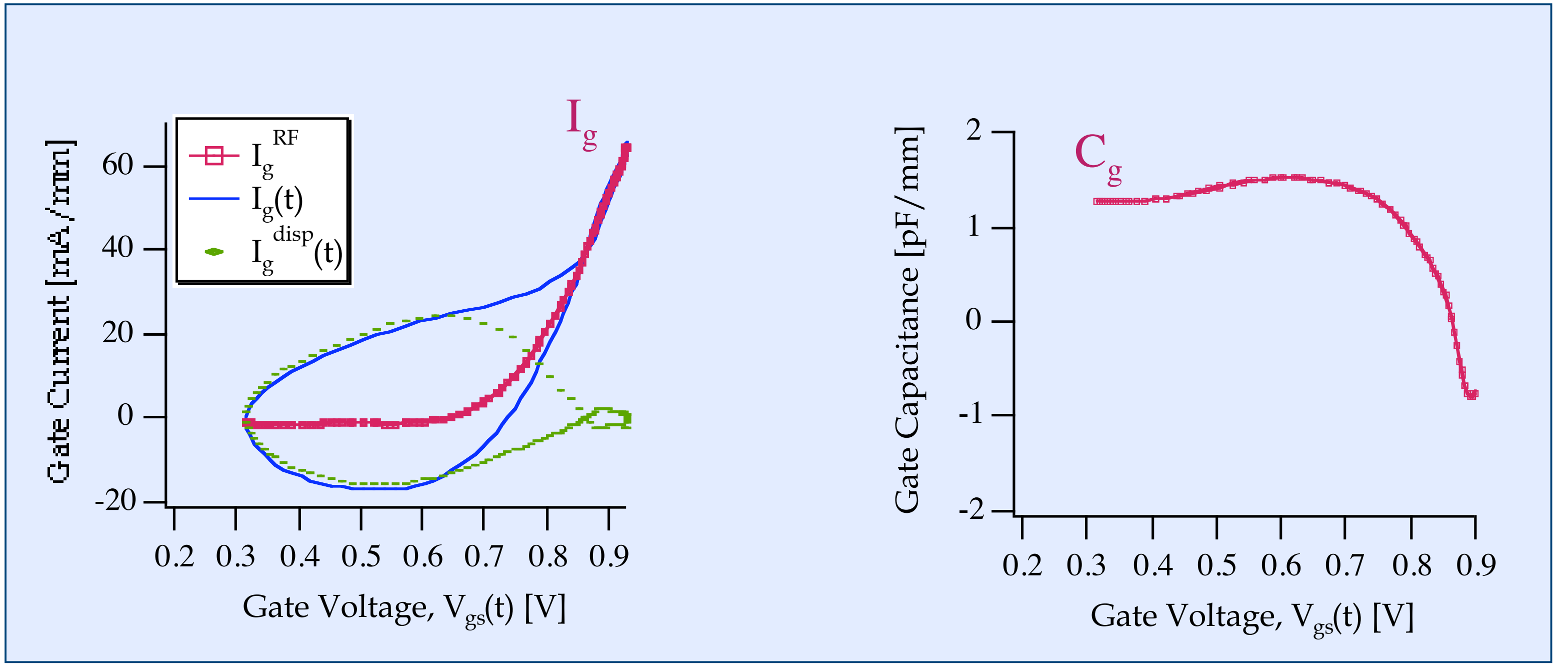
Two equations with two unknowns, so solve for I_g and C_g

Select $V_{gs}(t)$



Schreurs et al, EuMC 1997

Non-Linear State Function CAD Models:
- direct extraction from RF I-V Waveforms

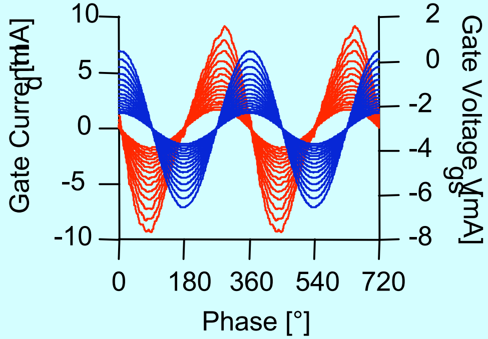


- Extraction of state functions for all measured values of Vgs(t)
- Only one large signal measurement needed
- Model extraction or model validation

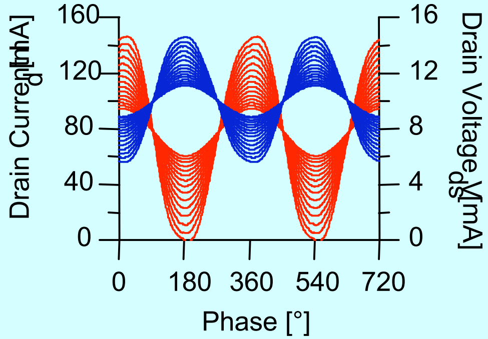
Schreurs et al, EuMC 1997

Non-Linear State Function CAD Models:

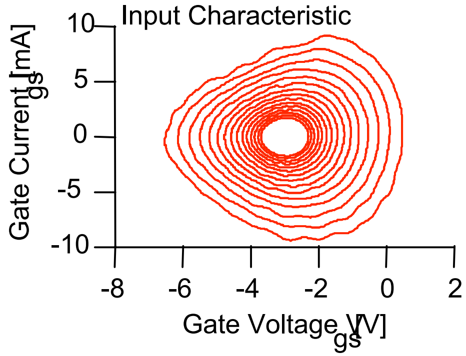
- direct extraction from RF I-V Waveforms



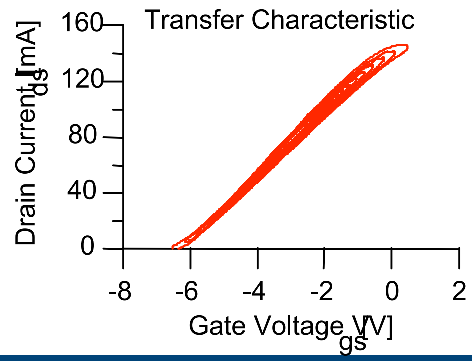
- Waveform Measurement
  Power Sweep @ 1.8 GHz

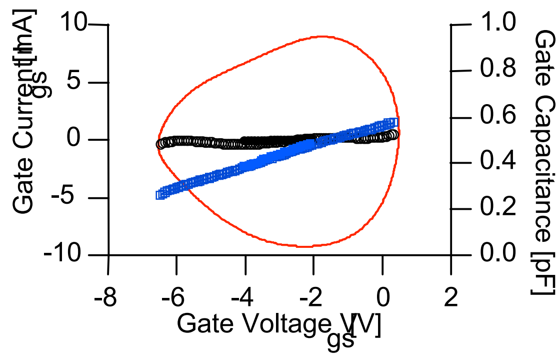


Transistor Behavior

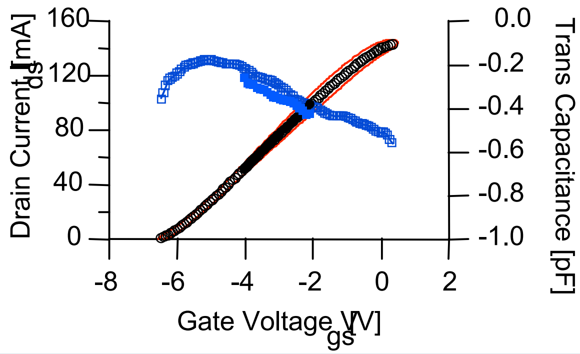


- Performance Understanding
  Reactive Non-Linearity's





- Extraction State Functions I & Q
  Reactive strongly second order



State Functions

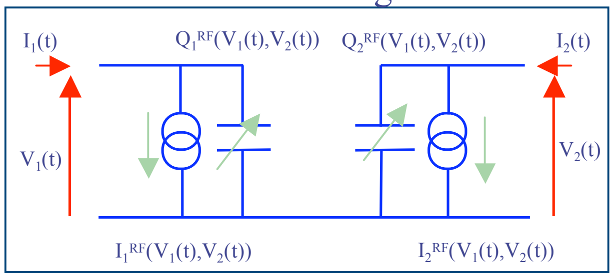
Non-Linear State Function CAD Models:

- direct extraction from RF I-V Waveforms

Stimulate with appropriate engineered waveforms $V_1(t)$ and $V_2(t)$ voltages and perform measurements

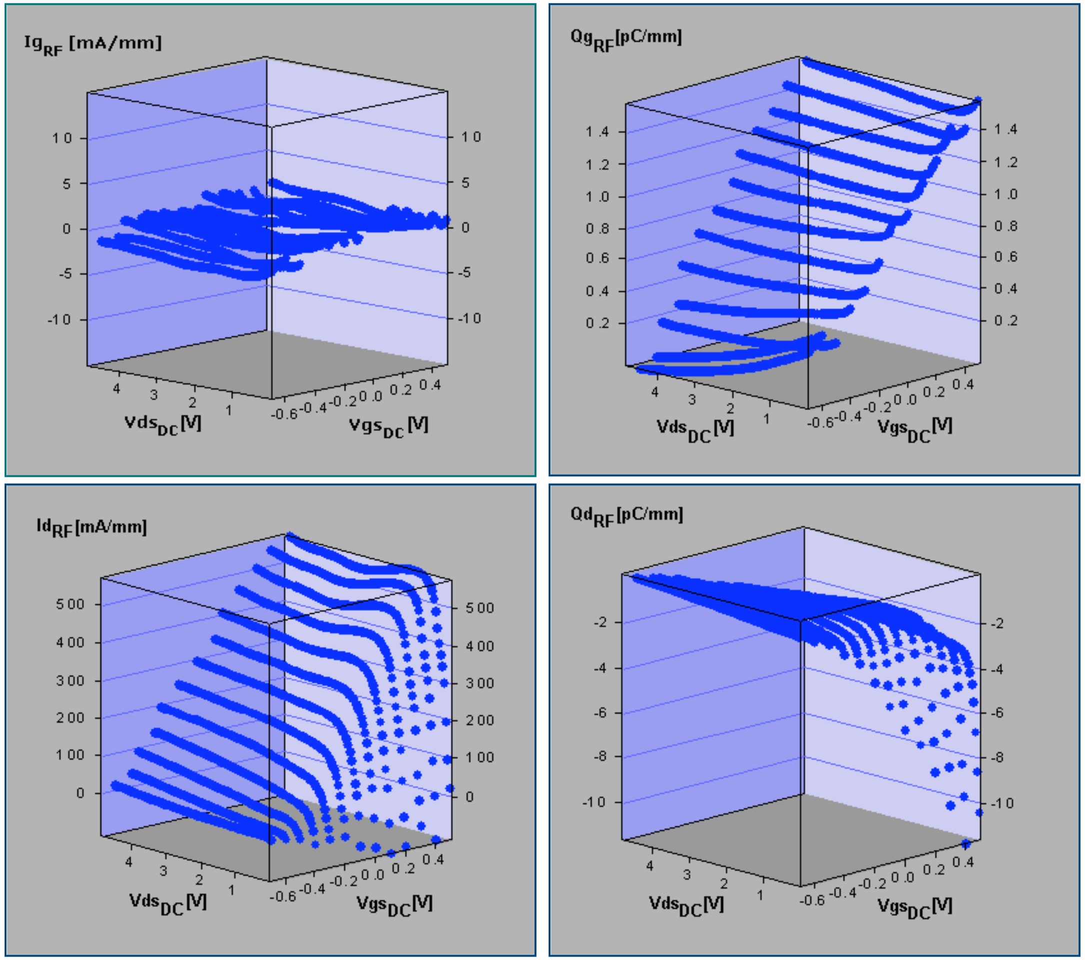
INPUT

Reverse Modelling Process



OUTPUT

Extract I and Q state functions: i.e. their dependence on voltages V_1 and V_2

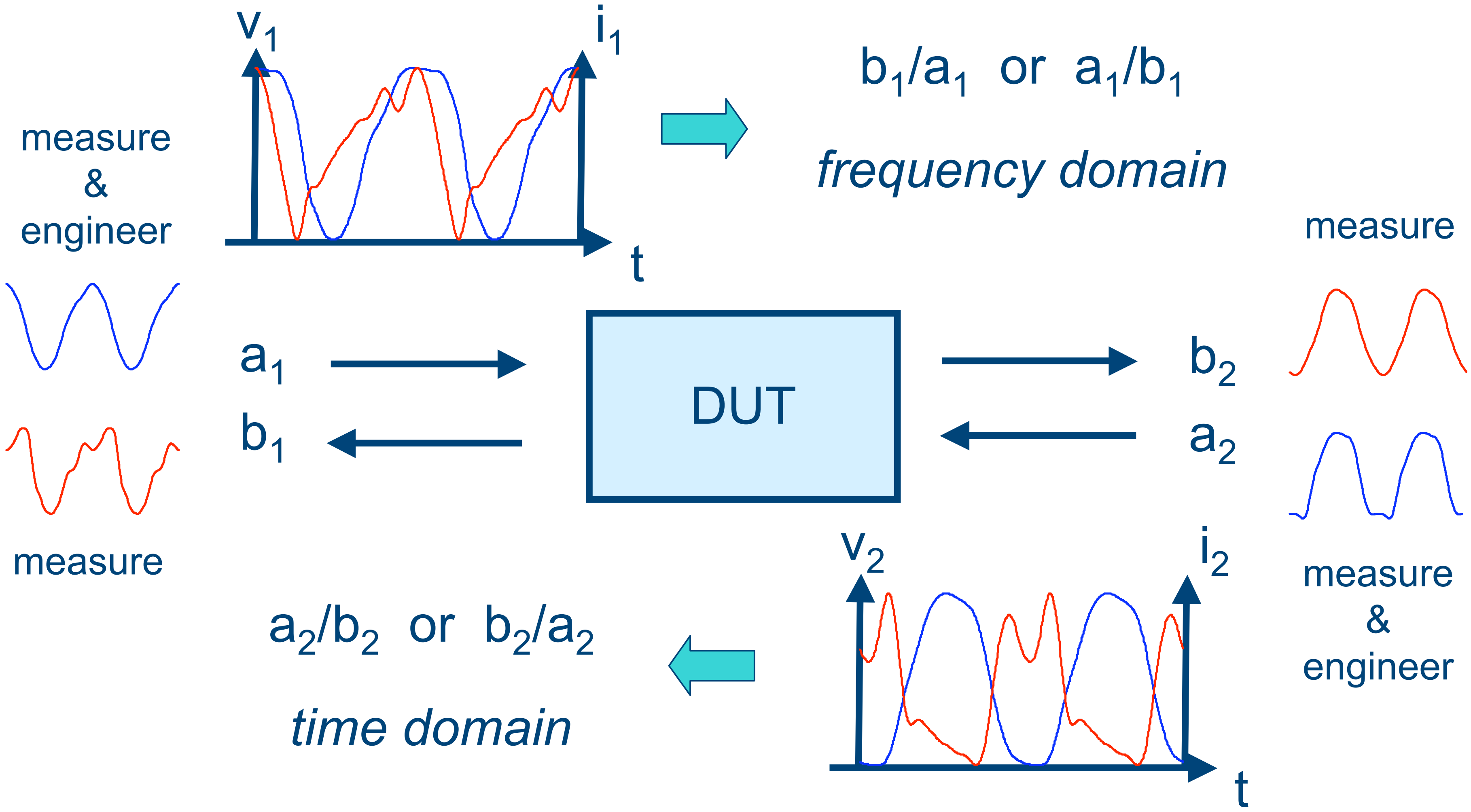


Morgan et al, IMS 2001

- Extracted Fully Dynamic Intrinsic I and Q Surfaces of a pHEMT transistor

Waveform Measurement and Engineering

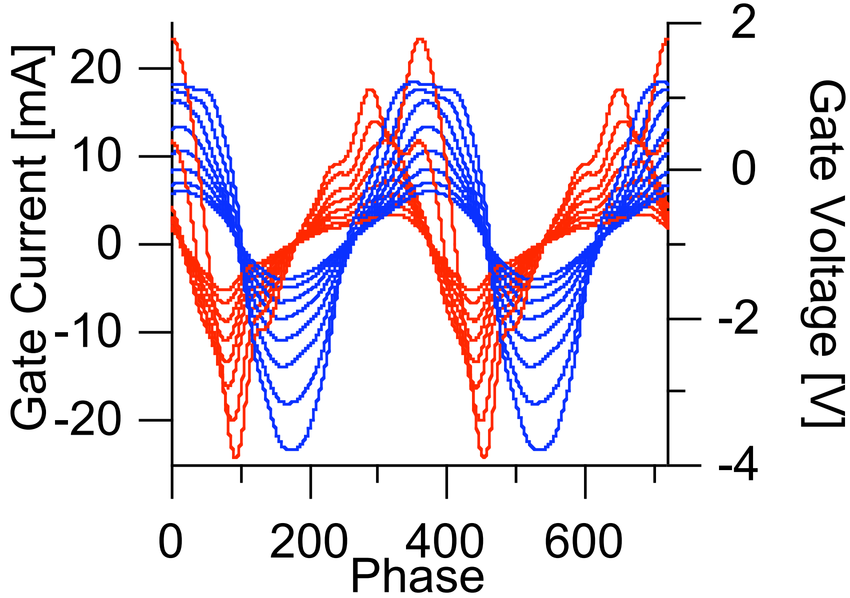
- are we looking at the device or the system?

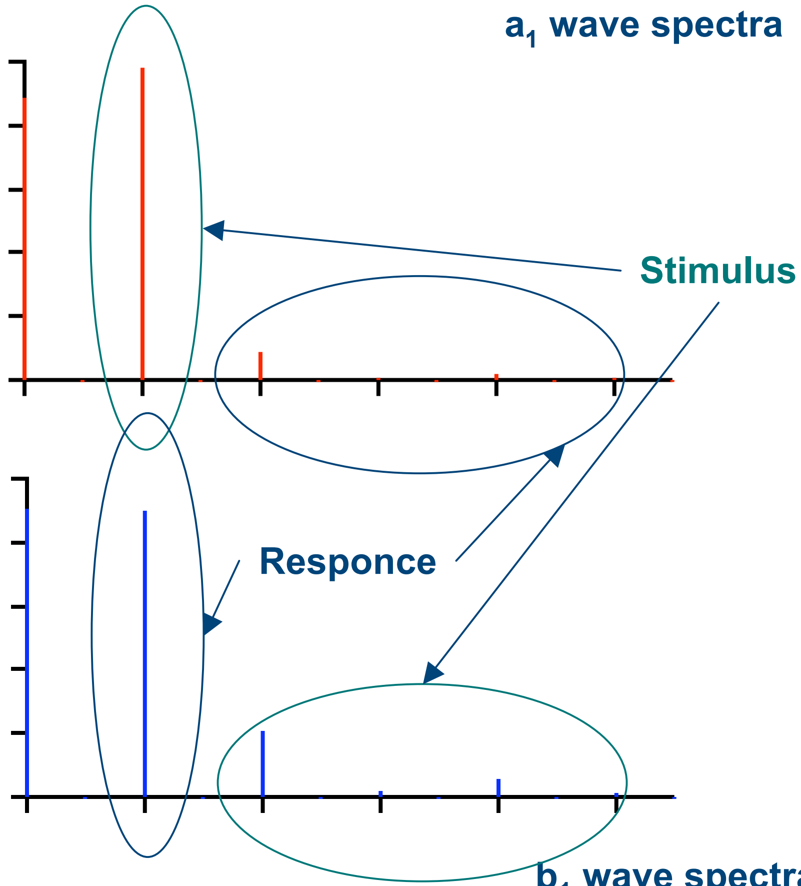


Waveform Measurement and Engineering

- are we looking at the device or the system?

- "Forward and Reverse Looking" Measurements
  - separation in the frequency domain
    - fundamental
      - Input Impedance $S_{11}(b_1/a_1)$
    - harmonics
      - source Impedance (a_1/b_1)

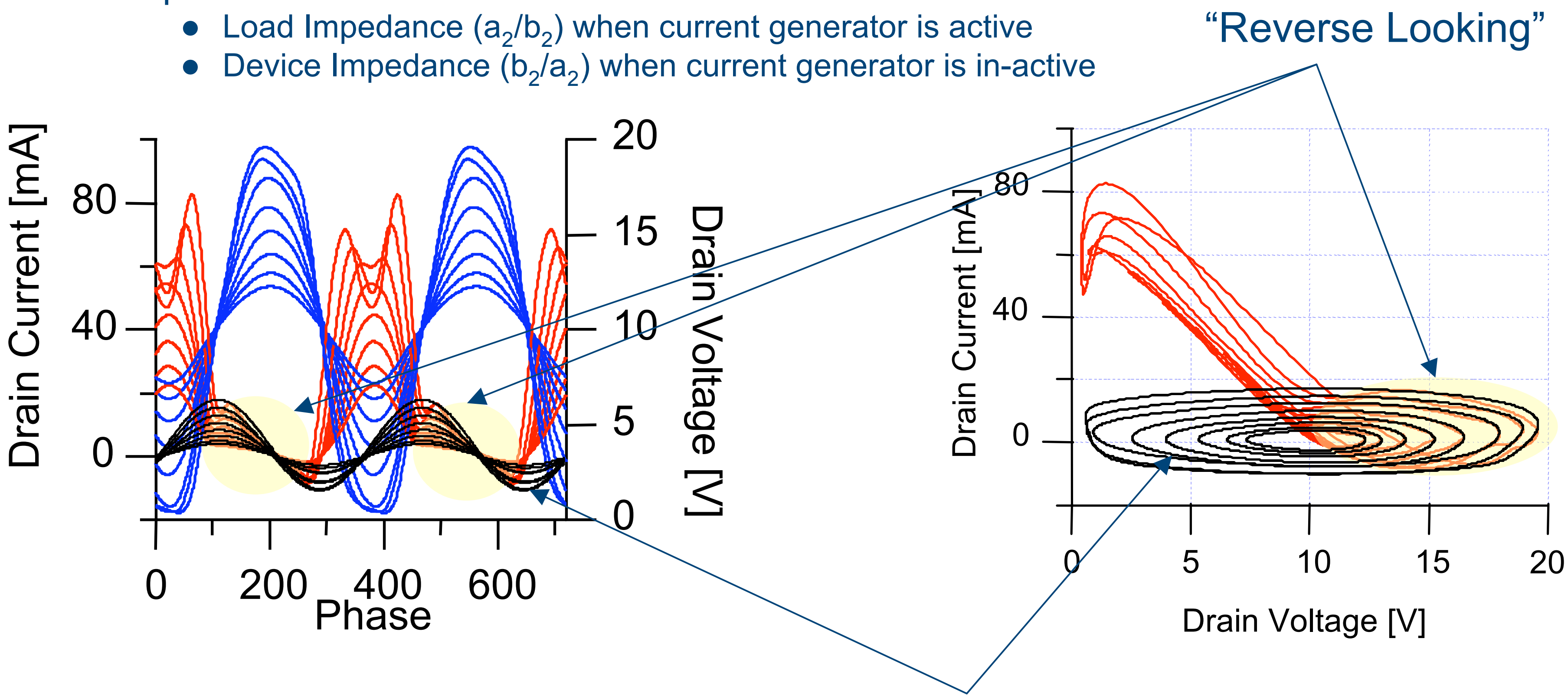




Waveform Measurement and Engineering

- are we looking at the device or the system?

- "Forward and Reverse Looking" Measurements
  - separation in the time domain
    - Load Impedance (a_2/b_2) when current generator is active
    - Device Impedance (b_2/a_2) when current generator is in-active



Extract Output Capacitance C_{ds} = 0.4 pF/mm

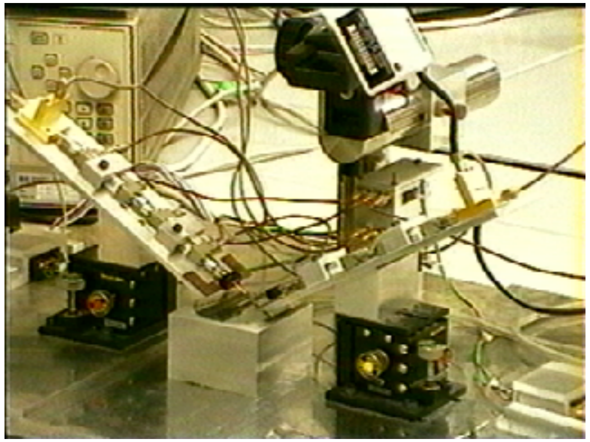
RF I-V Waveform Measurement & Engineering
- role in CAD modelling

- State Function I(V) - Q(V) Non-Linear Models
  - Directly Measures Model related parameters I & V
    - I-Q function Extraction
      - *Data Lookup Model Generation*
    - Analytical Model validation and Optimization

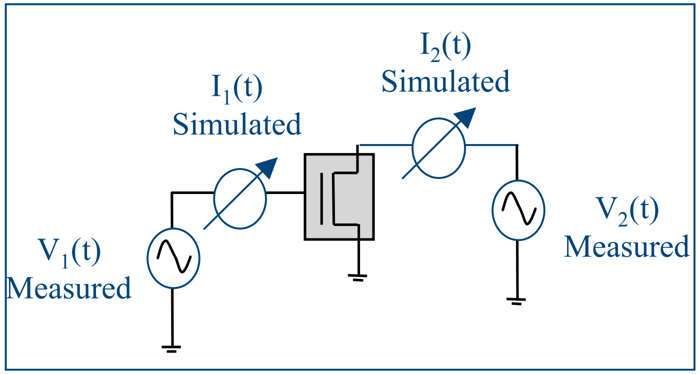
Transistor RF I-V Waveforms

– Verification of non-linear CAD models

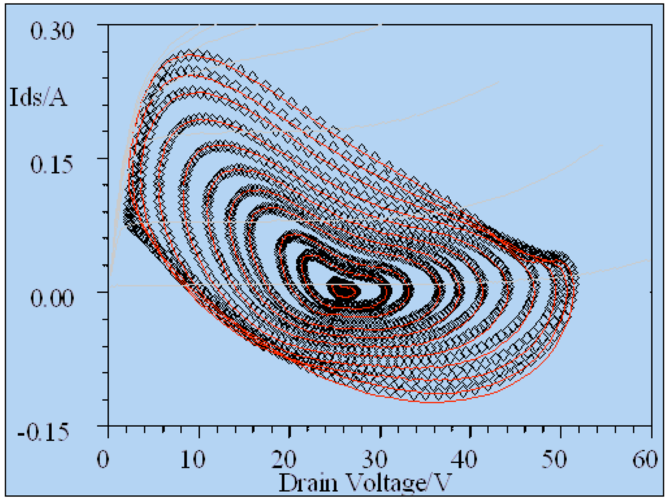
- Control mode of excitation
  - Similar to circuit operation
  - Maximize coverage of output I-V space, state variable space.



Measure: $V_1(t)$, $V_2(t)$ and $I_1(t)$, $I_2(t)$



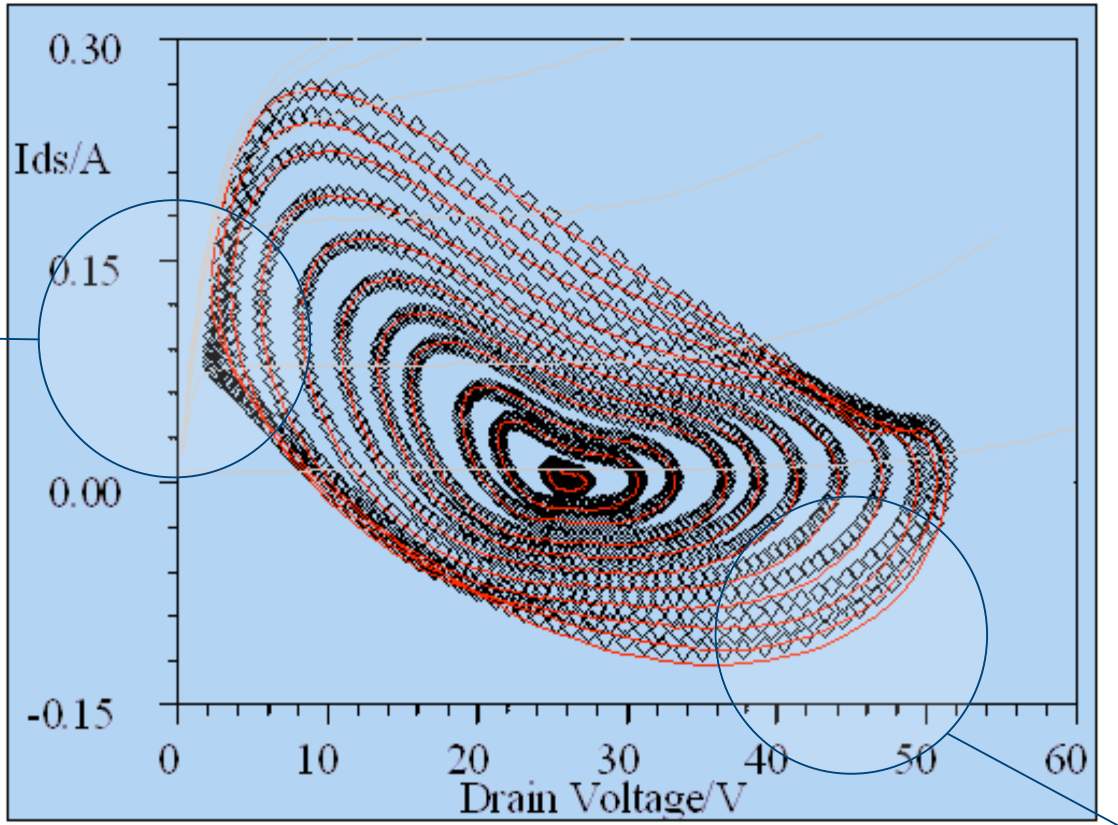
Import Measured $V_1(t)$ and $V_2(t)$ into the simulator



Compare Simulated $I_1(t)$, $I_2(t)$ with Measured $I_1(t)$, $I_2(t)$

Transistor RF I-V Waveforms
– Verification/Optimization of non-linear CAD models

Provides insight to why and where the model is failing to accurately predict non-linear behavior



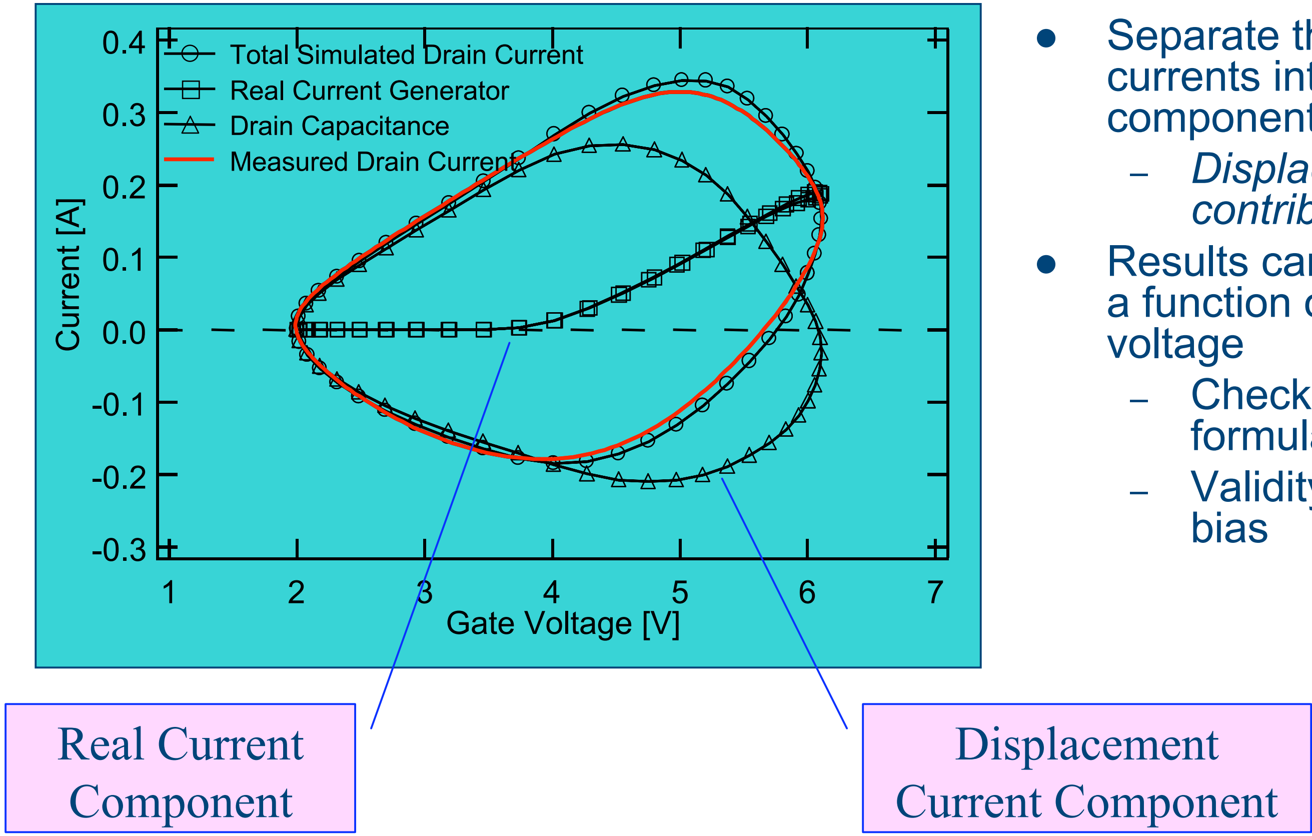
Some divergence near knee

More robust and useful than what is typically done: simply comparing simulated and measured Power performance

Some divergence at pinch-off

Transistor RF I-V Waveforms

– Verification/Optimization of non-linear CAD models



- Separate the measured currents into their individual components
  - *Displacement and real contributions*
- Results can be presented as a function of input or output voltage
  - Check model formulations
  - Validity as a function of bias

- Result, in this case, show that the LDMOS model used is not accurately modelling the variation of output capacitance as a function of gate bias.

RF I-V Waveform Measurement & Engineering
- role in CAD modelling

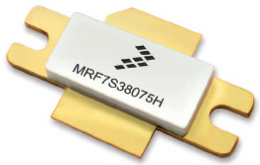
- State Function I(V) - Q(V) Non-Linear Models
  - Directly Measures Model related parameters I & V
    - I-Q function Extraction
      - *Data Lookup Model Generation*
    - Analytical Model validation and Optimization

- Behavioural "Black Box" Non-Linear Models
  - Directly Measures Non-Linear Behaviour
    - Directly Import into CAD Tool
      - *Data Lookup behavioural model*
    - Indirectly Import into CAD Tool
      - *Formulated behavioural models (Volterra)*
      - *Emerging non-linear parameter equivalent to linear s-parameters (X-parameters)*

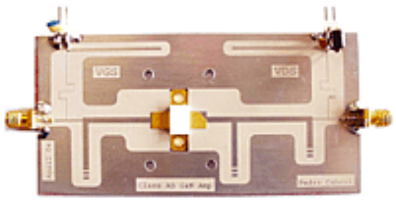
Review Linear Design Situation

- back to basics: s-parameters behavioral models

DUT

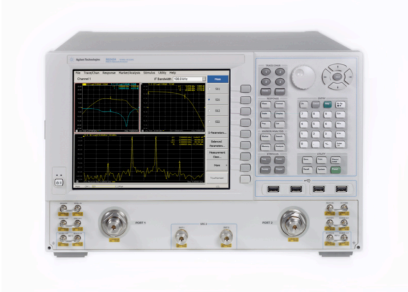


Amplifier



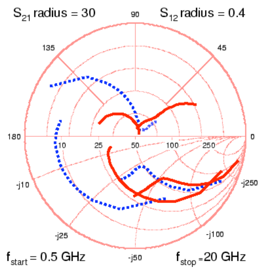
Gain, Bandwidth, Stability, Matching

Vector Network Analyzer



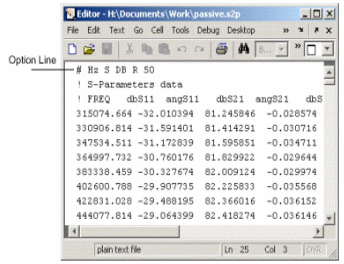
“datasets”

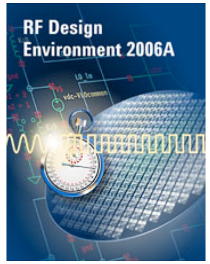
modeling



Characterization and CAD Design Enabling Tool

- *utilize measured s-parameter data tables in RF CAD Tools*





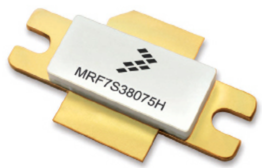
Can simply transform s-parameter to any arbitrary impedance environment

Can also measure say S_{21} and S_{11} as function on input drive to get a very basic non-linear behavioral model

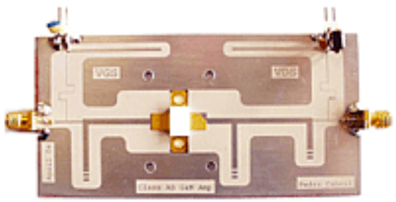
Consider Non-Linear Design Situation

- large signals: waveform based behavioral models

DUT

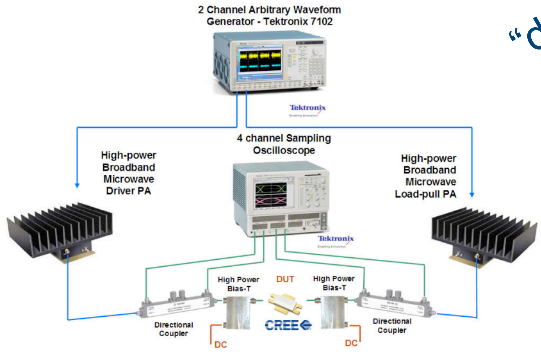


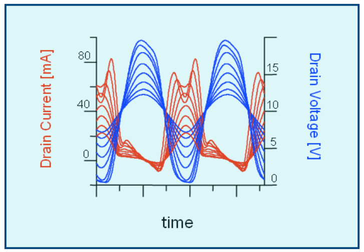
Amplifier



Power, Efficiency, Linearity

Waveform Measurement and Engineering



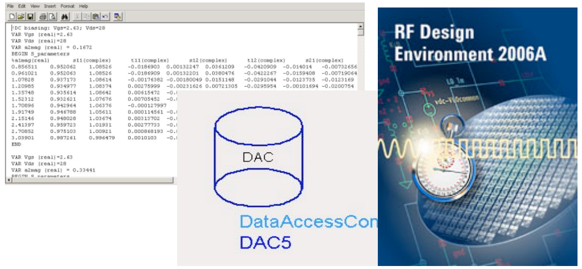


Characterization and CAD Design Enabling Tool

"datasets"

modeling

- *utilize measured waveform data tables in RF CAD Tools*



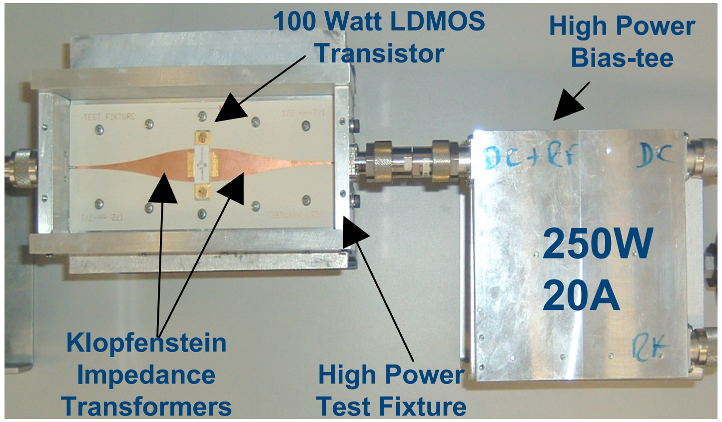
Cannot simply transform waveforms to any arbitrary impedance environment

Can measure as a function of input and/or output fundamental and harmonic load impedances: *CAD interpolation and extrapolation*

CAD Enabled Waveform Engineering

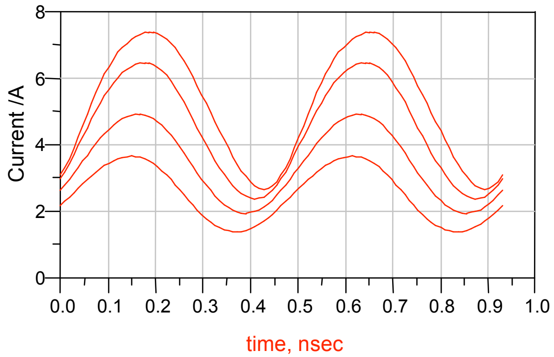
- Direct Waveform Look-up (DWLU) Data Model

Measure Waveforms



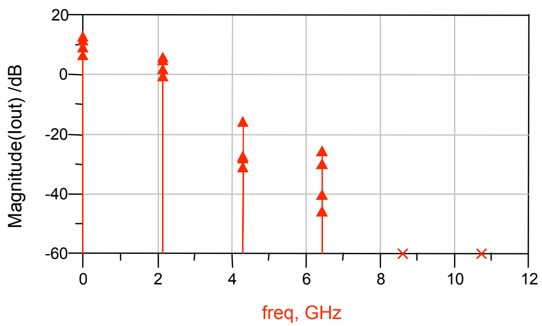
Sweep:

P_{in}, Γ_{LOAD}, Bias

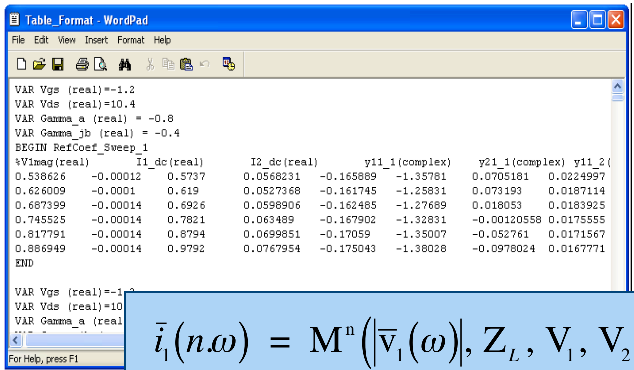


Formulate in frequency domain

FFT



Populate multi-dimensional datasets




```
VAR Vgs (real)=-1.2
VAR Vds (real)=10.4
VAR Gamma_a (real) = -0.8
VAR Gamma_jb (real) = -0.4
BEGIN RefCoef_Sweep_1
%V1mag(real)       I1_dc(real)        I2_dc(real)        y11_1(complex)     y21_1(complex)  y11_2(
0.538626    -0.00012    0.5737    0.0568231    -0.165889    -1.35781    0.0705181    0.0224997
0.626009    -0.0001     0.619     0.0527368    -0.161745    -1.25831    0.073193     0.0187114
0.687399    -0.00014    0.6926    0.0598906    -0.162485    -1.27689    0.018053     0.0183925
0.745525    -0.00014    0.7821    0.063489     -0.167902    -1.32831    -0.00120558  0.0175555
0.817791    -0.00014    0.8794    0.0699851    -0.17059     -1.35007    -0.052761    0.0171567
0.886949    -0.00014    0.9792    0.0767954    -0.175043    -1.38028    -0.0978024   0.0167771
END

VAR Vgs (real)=-1
VAR Vds (real)=10
VAR Gamma_a (real
```

Phase Ref

Scale

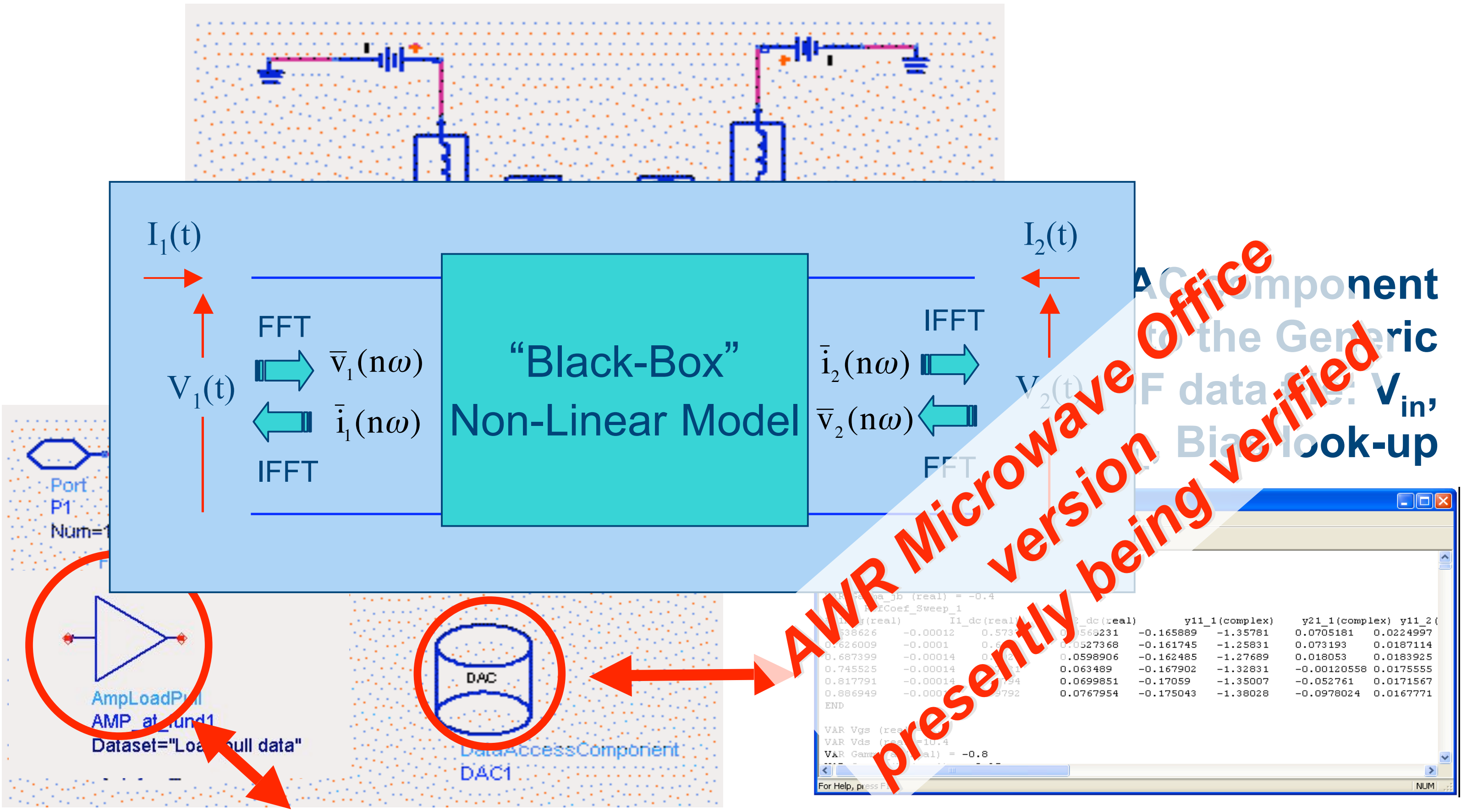
$$\bar{i}_1(n.\omega) = \mathrm{M}^{\mathrm{n}}\left(\left|\bar{\mathrm{v}}_1(\omega)\right|, \mathrm{Z}_L, \mathrm{V}_1, \mathrm{V}_2\right).\bar{\mathrm{v}}_1(\omega)^{\mathrm{n}}$$

$$\bar{i}_2(n.\omega) = \mathrm{N}^{\mathrm{n}}\left(\left|\bar{\mathrm{v}}_1(\omega)\right|, \mathrm{Z}_L, \mathrm{V}_1, \mathrm{V}_2\right).\bar{\mathrm{v}}_1(\omega)^{n}$$

CAD Enabled Waveform Engineering

- DWLU Data Model Implementation

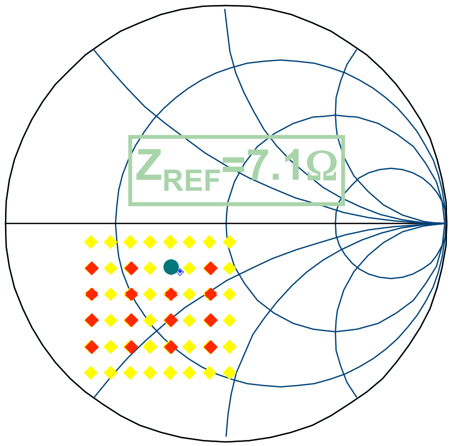
Data Import Unit constructed in *Agilent ADS using FDD & DAC*



Requires Z_L determination

CAD Enabled Waveform Engineering
- DWLU Data Model Utilization

100W LDMOS

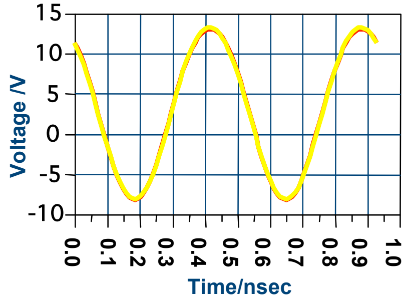


Simulate on Data Look-up Grid

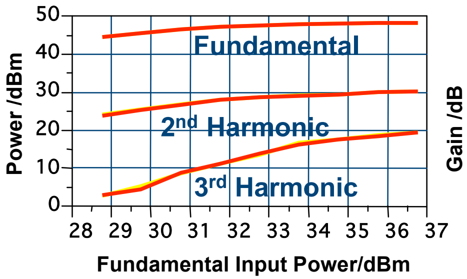
----- *Measured*

----- *Simulated*

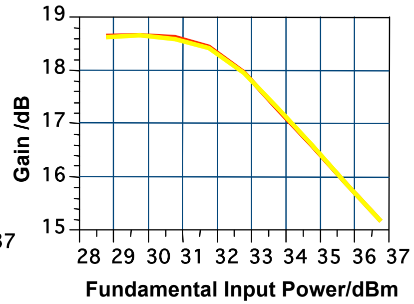
I/P Voltage Waveform



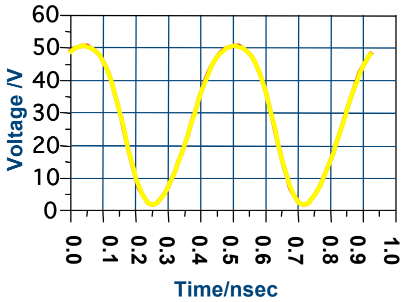
Output Power vs Pin



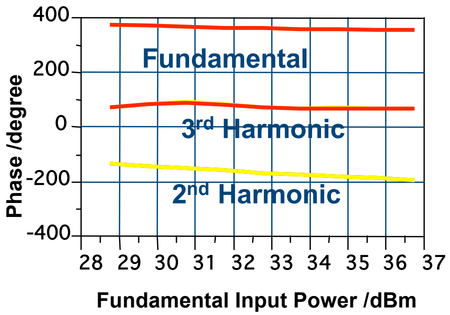
Gain vs Pin



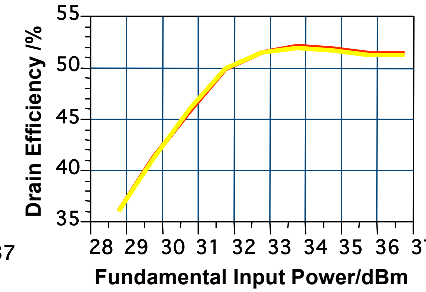
O/P Voltage Waveform



Output Phase vs Pin



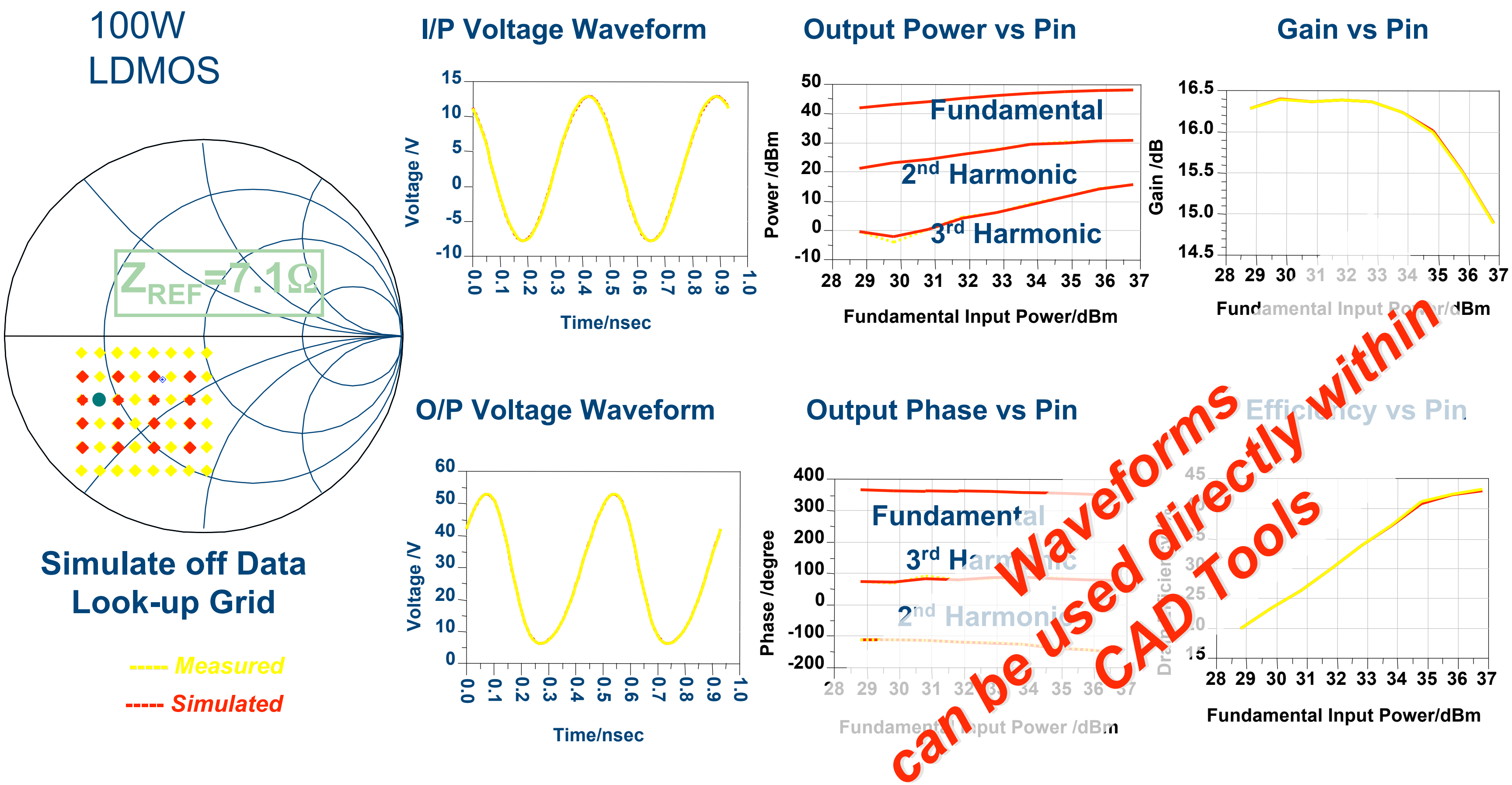
Efficiency vs Pin



DWLU Accurately regenerates RF waveforms

CAD Enabled Waveform Engineering

- DWLU Data Model Utilization



DWLU Accurately interpolates RF waveforms

CAD Based Waveform Engineering
- Parameter Based Data Models: Formulation Concepts

- Non-linear Data look-up
  - Direct looks up measured waveform data
    - Stored in the frequency domain

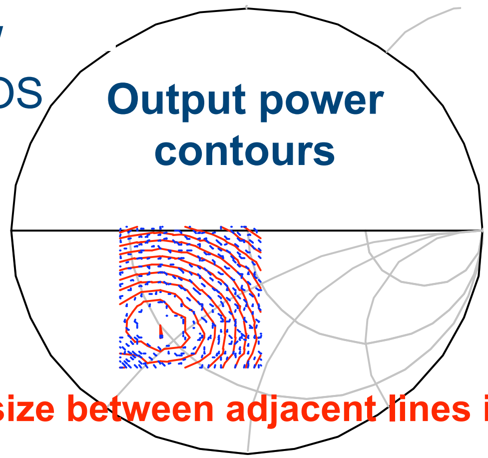
- Non-linear Data Formulation: Parameter look-up
  - Transform waveform data into "circuit parameters"
    - Equivalent functionality to linear data formulation: s-parameters
      - Circuit analysis and design formulation
      - Travelling wave a-b rather than I-V formulations
    - Agilent Solution: X-parameters
      - Natural extension of linear s-parameters data-set to non-linear data-set
    - Cardiff Formulations
      - Natural extension of X-parameters. Cardiff "Mixing" Formulation for load-pull contours: contains higher order mixing terms

CAD Based Waveform Engineering

- Formulated Based Data Lookup Models FDLU

$$b_k = \sum_{m=0}^{\frac{n-1}{2}} C_{k,m}\left(\frac{Q}{P}\right)^m a_1 + \sum_{m=0}^{\frac{n-1}{2}} U_{k,m}\left(\frac{P}{Q}\right)^m a_2 \qquad Q = \text{phase}(a_1),\ P = \text{phase}(a_2)$$

100W LDMOS

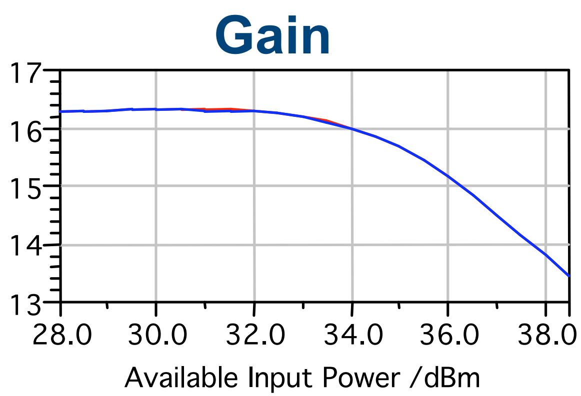


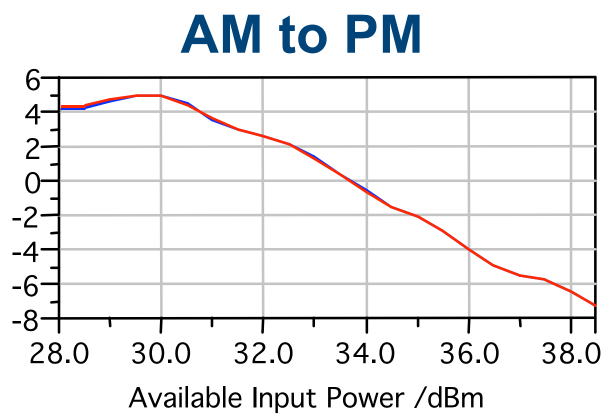
Step size between adjacent lines is 0.2dB

$C_{k,m,} = f(|a_1(f_o)|, |a_2(f_o)|)$ & $U_{k,m,} = f(|a_1(f_o)|, |a_2(f_o)|)$

Good simulation accuracy can be kept for quite a large area on Smith Chart

Fast and robust simulation implementation



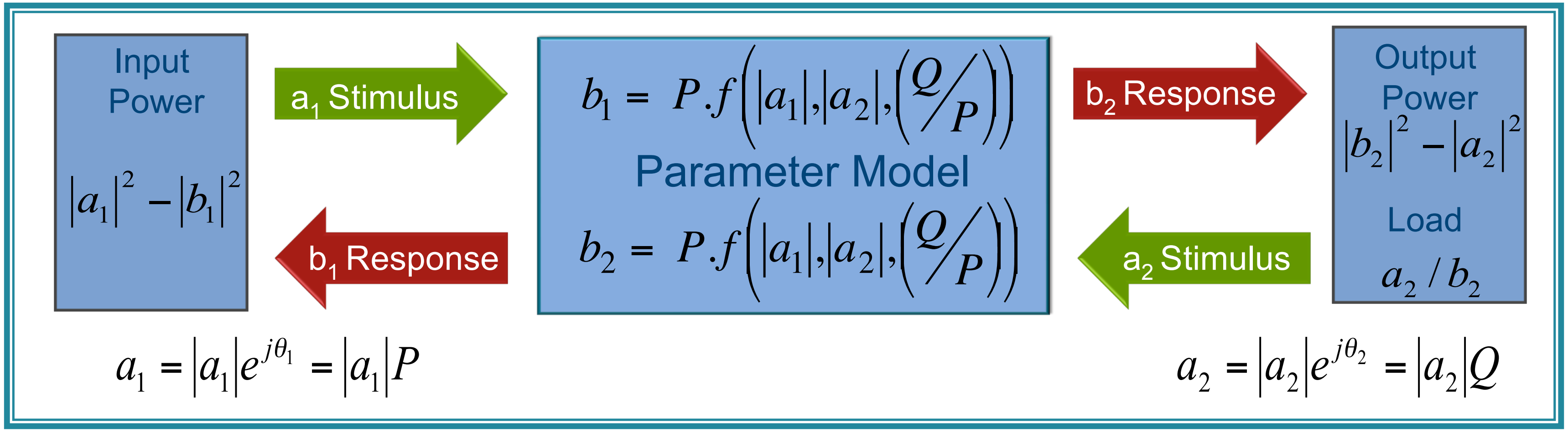


Good accuracy for different drive power levels

CAD based Waveform Engineering

- Parameter Based Data Models: Formulation Concept

- "Circuit" Formulation Requirement: *remove direct reference to load*
  - Component dependency: $f(|a_1|,|a_2|,(Q/P))$



Linear System uses s-parameters: 1st order system

Constant Parameters

$$b_1 = \{S_{11} \cdot |a_1| \cdot P + S_{12} \cdot |a_2| \cdot Q\}$$

$$b_2 = \{S_{21} \cdot |a_1| \cdot P + S_{22} \cdot |a_2| \cdot Q\}$$

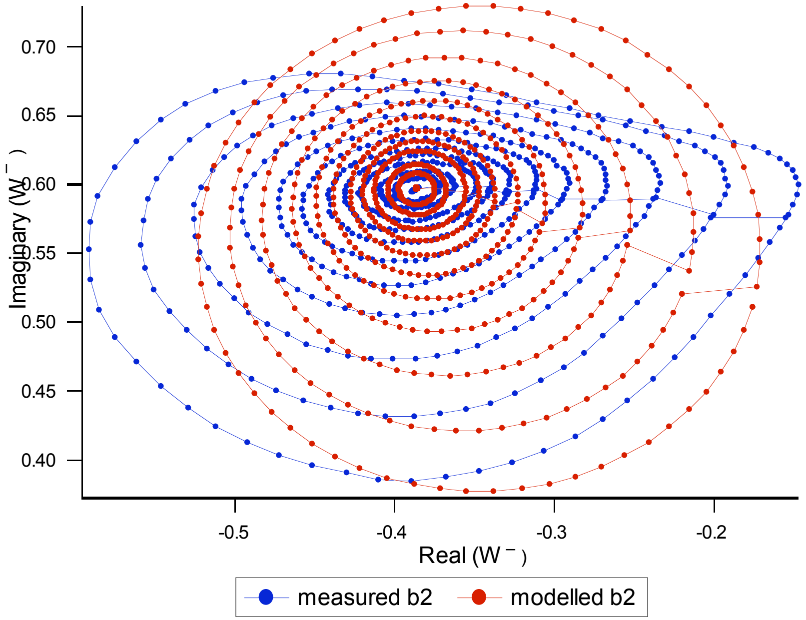
CAD based Waveform Engineering

- Parameter Based Data Models: Formulation Concept

- Use of s-parameters in non-linear design: “Hot” S-parameters
  - Wrong functionality:
    - model circular function
    - measurement elliptical functionality

$$b_1 = P.\left\{ S_{11} \cdot |a_1| \cdot \left(\frac{Q}{P}\right)^0 + S_{12} \cdot |a_2| \cdot \left(\frac{Q}{P}\right)^1 \right\}$$

$$b_2 = P.\left\{ S_{21} \cdot |a_1| \cdot \left(\frac{Q}{P}\right)^0 + S_{22} \cdot |a_2| \cdot \left(\frac{Q}{P}\right)^1 \right\}$$



Parameter dependency: $S_{m,n}(|a_1|,|a_2|)$

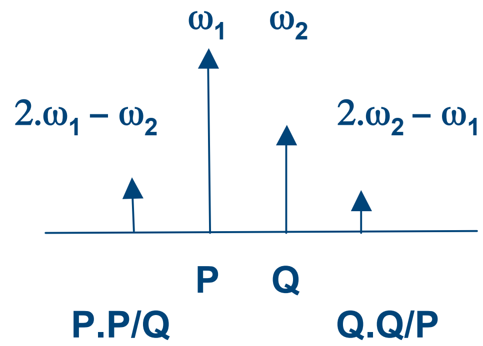
CAD based Waveform Engineering

- Parameter Based Data Models: Formulation Concept

- Non-Linear System: *include mixing components*
  - Weakly Non-Linear System: 3rd order: relates to S&T Parameters (X-parameters)

$$b_1 = \left\{ X^T_{12}\cdot|a_2|\cdot P^2/Q + X^S_{11}\cdot|a_1|\cdot P + X^S_{12}\cdot|a_2|\cdot Q + X^T_{11}\cdot|a_1|\cdot Q^2/P \right\}$$

$$b_2 = \left\{ X^T_{22}\cdot|a_2|\cdot P^2/Q + X^S_{21}\cdot|a_1|\cdot P + X^S_{22}\cdot|a_2|\cdot Q + X^T_{21}\cdot|a_1|\cdot Q^2/P \right\}$$



Allow $\omega_1 = \omega_2$

For small perturbation reduces to three parameters: X-parameters

$$b_1 = P.\left\{ X^T_{12}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + X^S_{11}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{0} + X^S_{12}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{1} + X^T_{11}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{2} \right\}$$

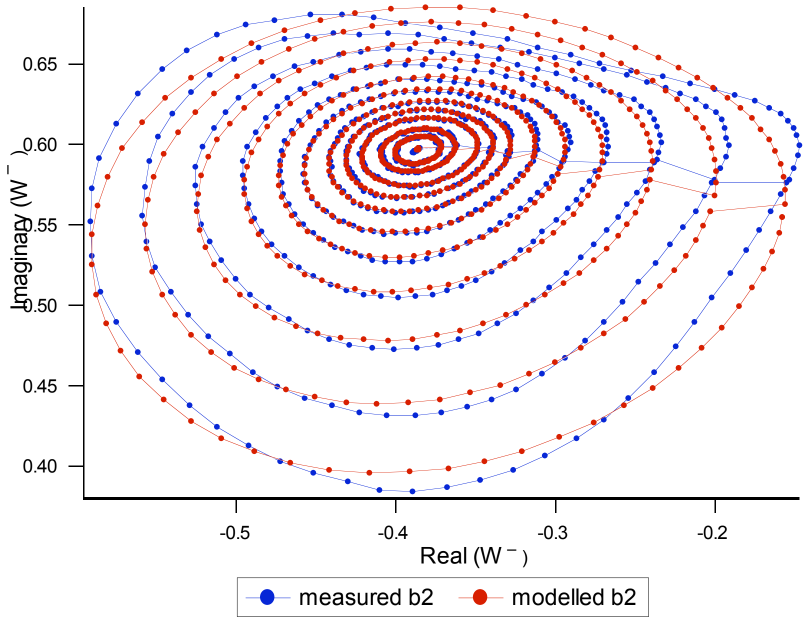
$$b_2 = P.\left\{ X^T_{22}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + X^S_{21}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{0} + X^S_{22}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{1} + X^T_{21}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{2} \right\}$$

Parameter dependency: $X_{m,n}(|a_1|)$

CAD based Waveform Engineering

- Parameter Based Data Models: Formulation Concept

- 3rd Order Mixing Model: S&T-parameters (X-parameters)
  - Significantly improved functionality:
    - model is now an elliptical function
    - measurement elliptical functionality
  - Next Step
    - Compute local X-parameters
      - function of load
    - Allow for full amplitudes dependence
    - Increase order of mixing



$$b_1 = P.\left\{X^T_{12}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + X^S_{11}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{0} + X^S_{12}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{1} + X^T_{11}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{2}\right\}$$

$$b_2 = P.\left\{X^T_{22}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + X^S_{21}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{0} + X^S_{22}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{1} + X^T_{21}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^{2}\right\}$$

Parameter dependency: $X_{m,n}(|a_1|,|a_2|)$

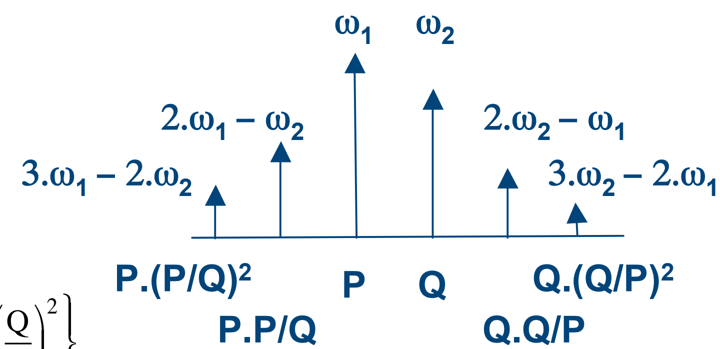
CAD based Waveform Engineering

- Parameter Based Data Models: Formulation Concept

- Non-Linear System: *include mixing components*
  - Strongly Non-Linear System: n^{th} order: relates to C&U Parameters (R-parameters)

$$b_1 = P.\left\{S_{11}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + S_{12}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1\right\}$$

$$b_2 = P.\left\{S_{21}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + S_{22}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1\right\}$$



Allow $\omega_1 = \omega_2$

$$b_1 = P.\left\{X^T_{12}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + X^S_{11}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + X^S_{12}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1 + X^T_{11}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^2\right\}$$

$$b_2 = P.\left\{X^T_{22}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + X^S_{21}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + X^S_{22}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1 + X^T_{21}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^2\right\}$$

$$b_1 = P.\left\{R_{1,-2}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-2} + R_{1,-1}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + R_{1,0}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + R_{1,1}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1 + R_{1,2}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^2 + R_{1,3}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^3\right\}$$

$$b_2 = P.\left\{R_{2,-2}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-2} + R_{2,-1}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^{-1} + R_{2,0}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^0 + R_{2,1}\cdot|a_2|\cdot\left(\frac{Q}{P}\right)^1 + R_{2,2}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^2 + R_{2,3}\cdot|a_1|\cdot\left(\frac{Q}{P}\right)^3\right\}$$

CAD based Waveform Engineering

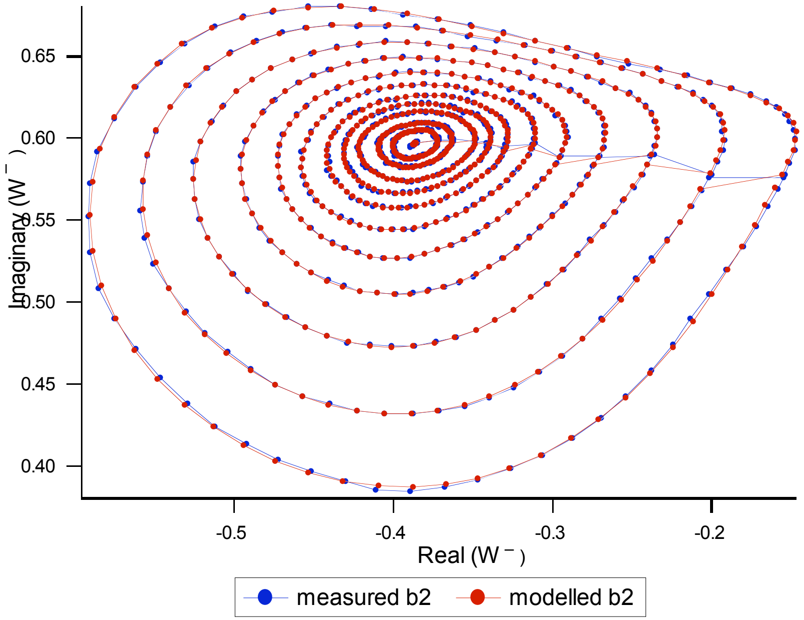
- Parameter Based Data Models: Cardiff Formulation

- Modelling with Extracted Fundamental $R_{m,n}$ components: $g(|a_1|,|a_2|)$
  - Accurate reproduction of measured b_2 contours (load-pull contours) with 7^{th} order (Q/P) phase model
  - Avoids any implicit load based lookup

$$b_m = P.f\left(|a_1|,|a_2|,\left(\frac{Q}{P}\right)\right) = P.\sum_{n=-\left(N-\frac{1}{2}\right)}^{n=\left(N+\frac{1}{2}\right)} \left\{ R_{m,n}\left(\frac{Q}{P}\right)^n \right\}$$

Parameter dependency: $R_{m,n}(|a_1|, |a_2|)$

7^{th} order model: R-parameters



Collapse large data lookup to small (6*12 or 8x12) $R_{m,n}$ parameter lookup

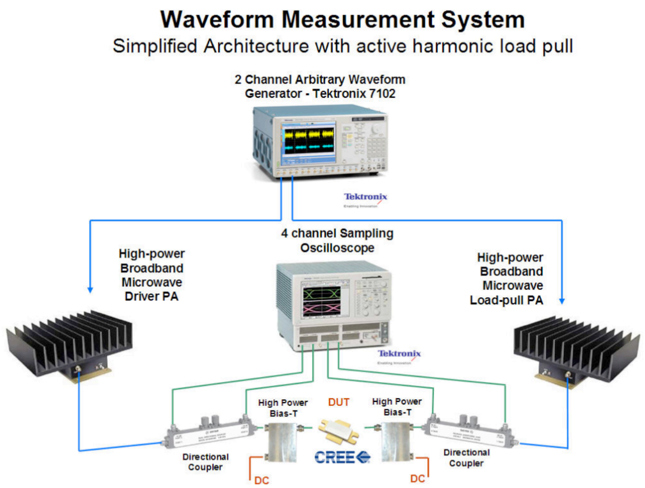
CAD based Waveform Engineering

- *Parameter Based Data Models: Cardiff Formulation*

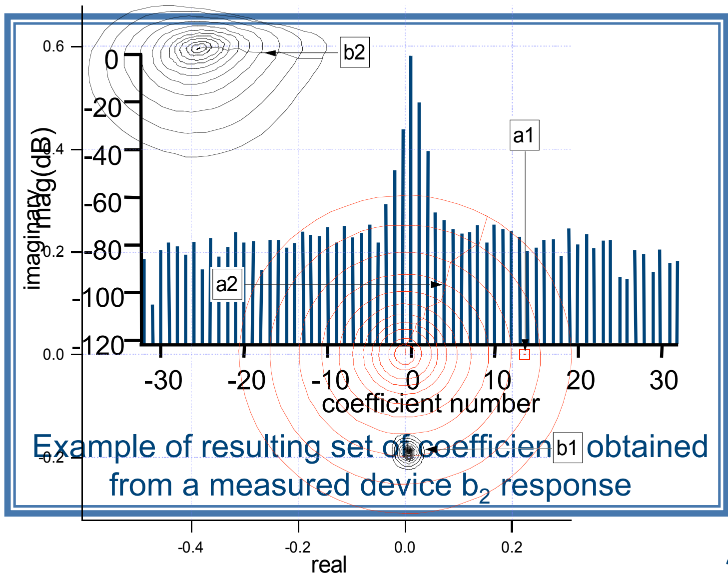
- Cardiff "Circuit" Parameter Formulation
  - Generalized to n^{th} order in terms of the relative phase component (Q/P)

$$b_m = P.f\left(|a_1|,|a_2|,\left(\frac{Q}{P}\right)\right) = P.\sum_{n=-\left(N/2-1\right)}^{n=\left(N/2\right)} \left\{R_{m,n}\left(\frac{Q}{P}\right)^n\right\} \quad \text{where } R_{m,n} = g(|a_1|,|a_2|)$$

  - Determination of parameters $R_{m,n}$ requires measurements at constant $|a_1|$ and $|a_2|$ while sweeping relative phase component (Q/P), normalized to optimum load: easy to achieve with active load-pull



Extract model coefficients

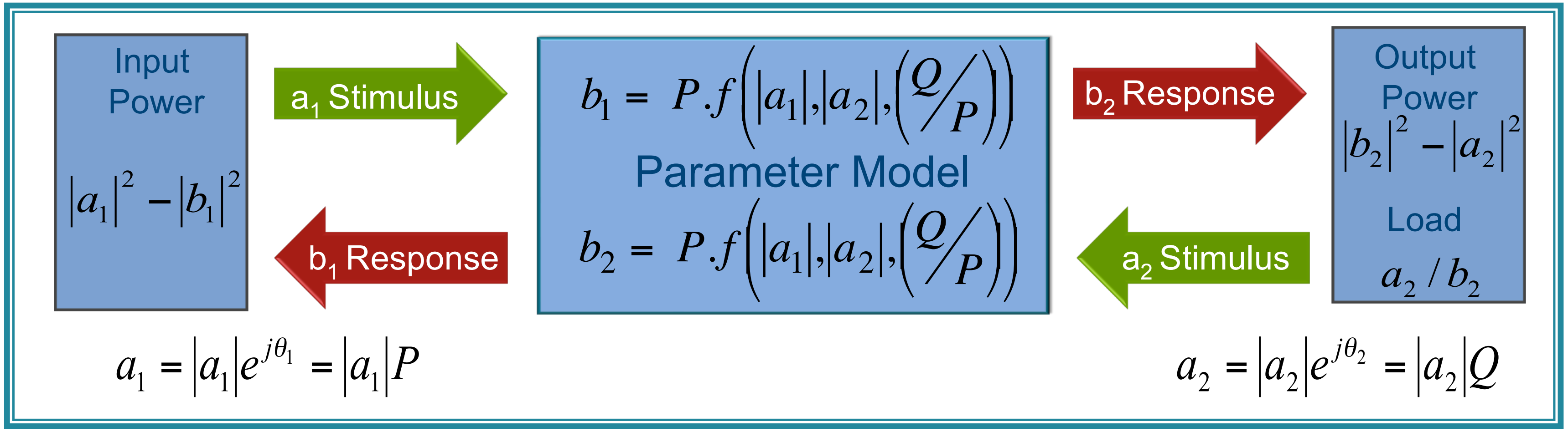


Example of resulting set of coefficients obtained from a measured device b_2 response

CAD based Waveform Engineering

- Parameter Based Data Models: Cardiff Formulation

- "Circuit" Formulation that is an extension of linear s-parameters
  - *remove direct reference to load*
  - Formulation dependency: $f(|a_1|,|a_2|,(Q/P))$
    - Function dependency: $f(|a_1|,|a_2|)$



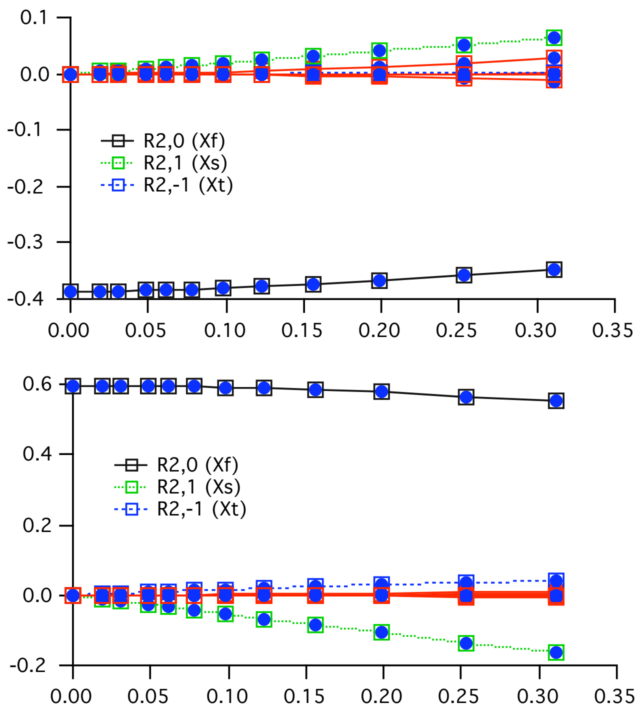
$$b_m = P.f\left(|a_1|,|a_2|,\left(\frac{Q}{P}\right)\right) = P.\sum_{n=-(N/2-1)}^{n=(N/2)} \left\{R_{m,n}\left(\frac{Q}{P}\right)^n\right\}$$

Parameter dependency: $R_{m,n}(|a_1|,|a_2|)$

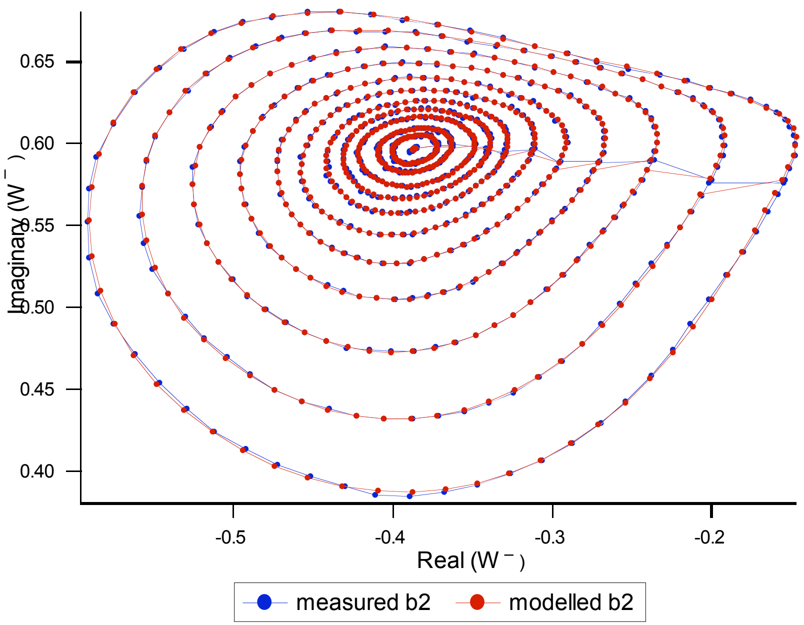
CAD based Waveform Engineering

- Parameter Based Data Models: Cardiff Formulation

- Magnitude Function Fitting to Extracted Fundamental $R_{m,n}$ components: $g(|a_1|,|a_2|)$
  - $R_{m,n} = \alpha_0 + \alpha_1.|a_2| + \alpha_2.|a_2|^2 + \alpha_3.|a_2|^3 + \alpha_4.|a_2|^4 + \alpha_5.|a_2|^5 + \alpha_6.|a_2|^6 + \alpha_7.|a_2|^7$
  - Only 20 relevant coefficients
    - Accurate reproduction of measured b_2 contours (load-pull contours) with 7th order model



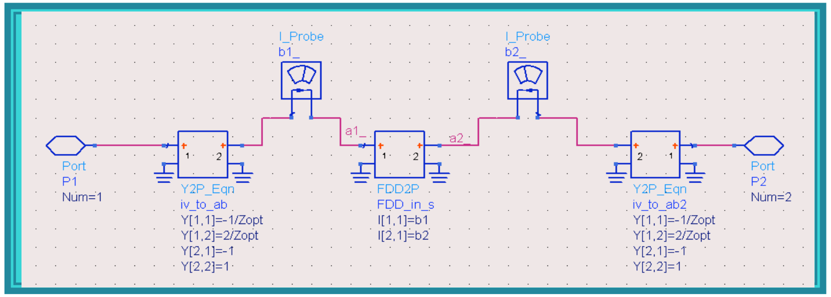
7th order model: R-parameters



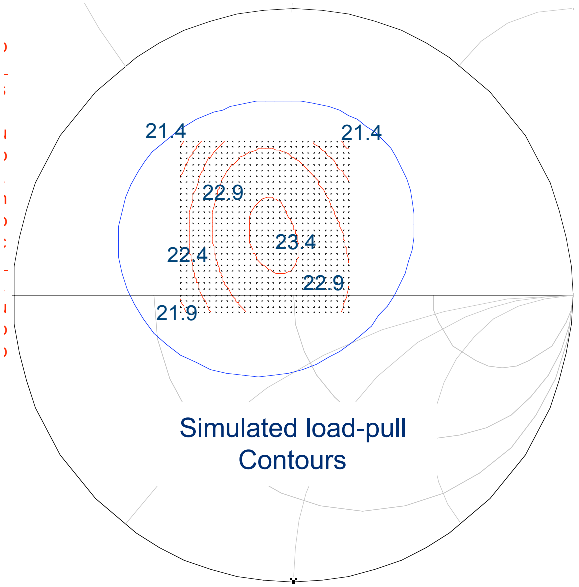
CAD based Waveform Engineering

- Parameter Based Data Models: CAD Implementation

Schematic of ADS Simulation



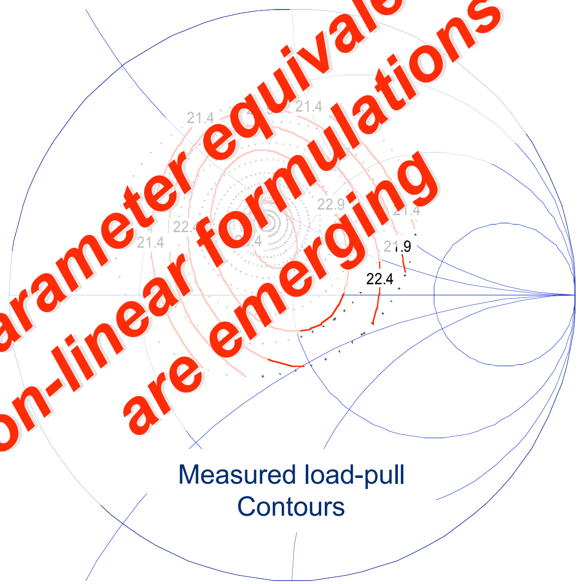
The model can be directly imported into CAD software, after processing the measurement data.



Simulated load-pull Contours (Left)

Load-pull Power Contours

Measured load-pull Contours (Right)



S-parameter equivalent non-linear formulations are emerging

RF I-V Waveform Measurement & Engineering

- role in CAD modelling

- State Function I(V) - Q(V) Non-Linear Models
  - Directly Measures Model related parameters I & V
    - Analytical Model validation and optimization
    - I-Q function Extraction
      - *Data Lookup Model Generation*

- Behavioral “Black Box” Non-Linear Models
  - Directly Measures Non-Linear Behaviour
    - Directly Import into CAD Tool
      - *Data Lookup behavioural model*
    - Indirectly Import into CAD Tool
      - *Formulated behavioural models (Volterra)*
      - *Emerging non-linear parameter equivalent to linear s-parameters (X-parameters)*

RF IV Waveform Measurement and Engineering
- Role in Transistor Characterization and Amplifier Design -

Centre for High Frequency Engineering

School of Engineering

Cardiff University

Contact information

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IEEE MTT-S Distinguished Microwave Lecturer 2008-2010

RF Waveform Measurement and Engineering

- powerful dynamic transistor characterization tool

- Basic Concept
  - Use RF Waveform Measurement and Engineering Systems to investigated both the transistors dynamic I-V (Current-Voltage) plane and its Q-V (Charge-Voltage) plane
    - Both qualitative and quantitative
    - Alternatives: DC I-V, Pulsed I-V, bias dependent s-parameters

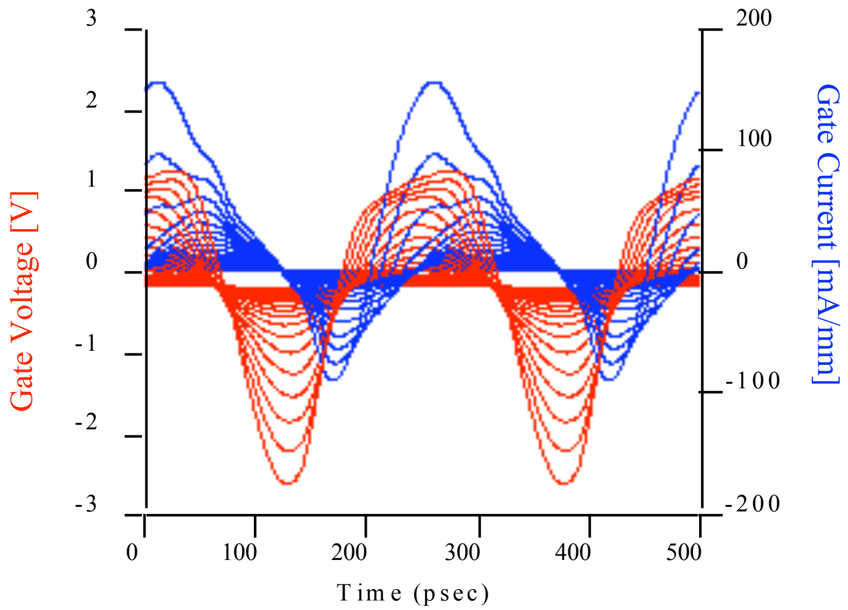
- Applications
    - Technology Evaluation
      - *Observe and quantify its dynamic large signal response*
    - Technology Optimization
      - *Link technology design to system performance*
    - Technology Modelling
      - *support the development of CAD tools*
    - Circuit Design Tool
      - *Support the development of Power Amplifiers*

RF Waveform Measurement and Engineering
- powerful dynamic transistor characterization tool

- Transistor Characterization: Case Study
  - Use RF Waveform Measurement and Engineering Systems to investigated general performance of Transistor Technology
    - Current Limits, Modes of Operation, RF Cooling

Transistor RF I-V Waveforms
– Detailed Insight into Dynamic Behaviour Limitations

- Measure Input voltage and current waveforms
  - function of input drive level

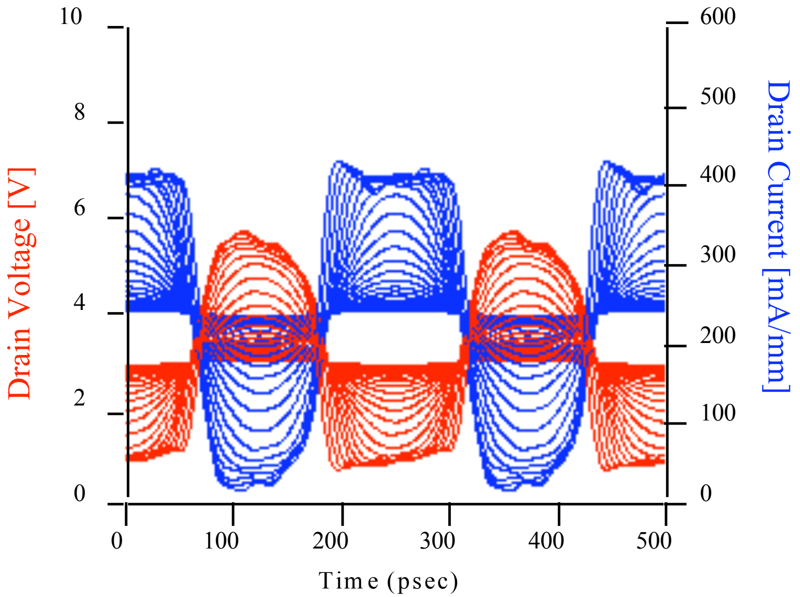


AlGaAs/InGaAs HFET @ 4 GHz

- Detailed Insight into Dynamic Behaviour
  - Gate Diode: Forward Diode Conduction and Reverse Breakdown
  - Gate Capacitance
- Relevant information for both
  - Device Engineer
  - PA Circuit Designer

Transistor RF I-V Waveforms
– Detailed Insight into Dynamic Behaviour Limitations

- Measure Output voltage and current waveforms
  - function of input drive level

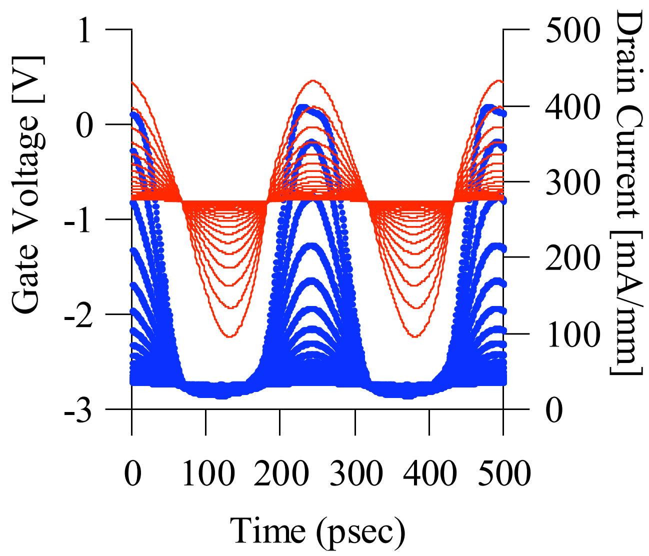


AlGaAs/InGaAs HFET @ 4 GHz

- Detailed Insight into Dynamic Behaviour
  - Drain Current Saturation: Knee Region and Breakdown
  - Gate-Drain Trans-capacitance
- Relevant information for both
  - Device Engineer
  - PA Circuit Designer

Transistor RF I-V Waveforms

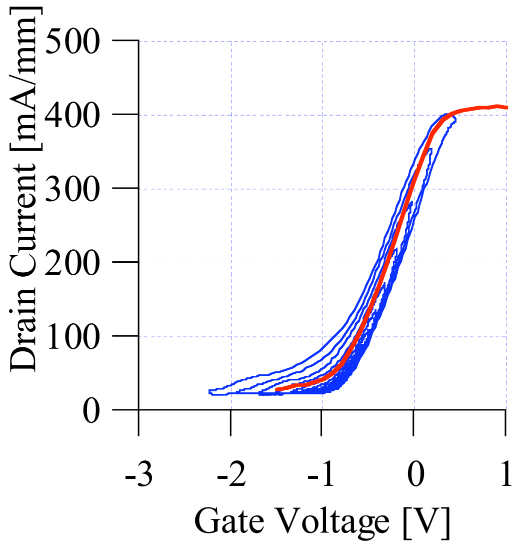
– Detailed Insight into Dynamic Behaviour Limitations



@ 4.0 GHz

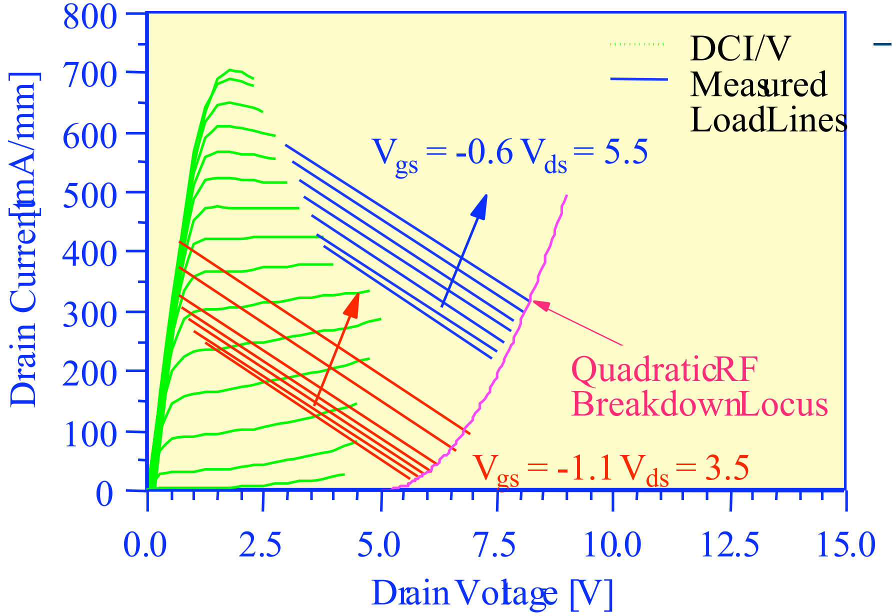
Dynamic Transfer Characteristic Measurements

- Device Response
  - Waveform Shapes
  - Insight provided by eliminating time axes
    - Effects of dynamic transfer characterisation clearly observed
      - DC/RF Dispersion
    - Effects of Delay/Trans-capacitance clearly observed
      - I-Q Extraction



Transistor RF I-V Waveforms

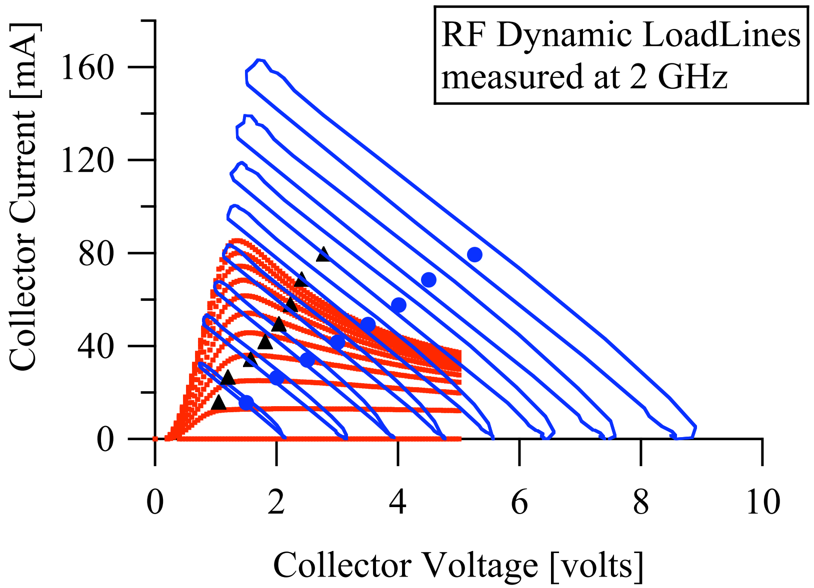
– Detailed Insight into Dynamic Behaviour Limitations



Dynamic Breakdown
in Low Noise
AlGaAs/InGaAs HFET's

- Device Response
  - Waveform Shapes
- – Insight provided by eliminating time axes
  - Effects of dynamic gate-drain breakdown clearly observed

Transistor RF I-V Waveforms
– Detailed Insight into Dynamic Behaviour Limitations

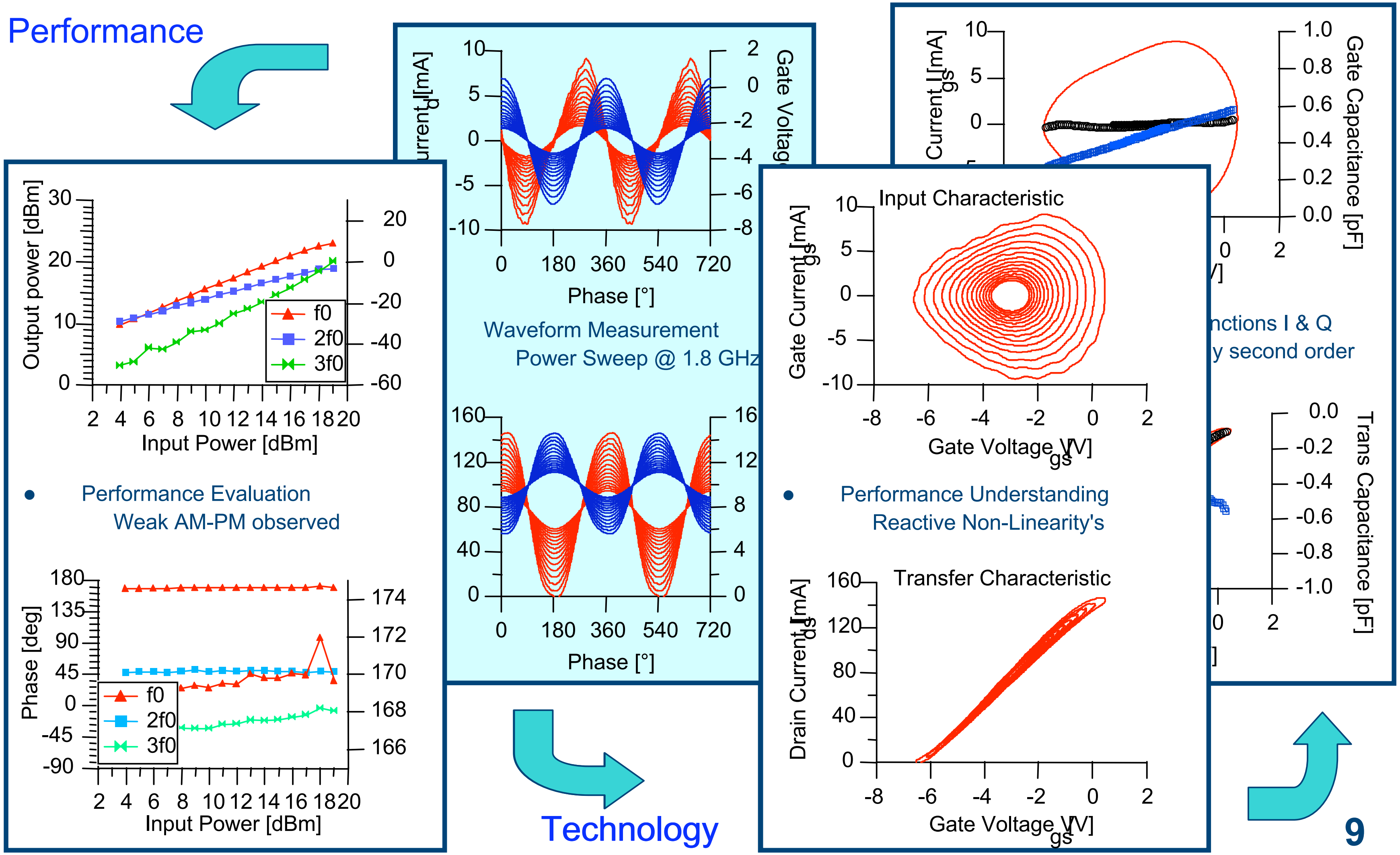


- Device Response
  - Waveform Shapes
- – Insight provided by eliminating time axes
  - Effects of dynamic RF cooling clearly observed
- – Linked with pulsed RF I-V technique

RF Cooling in
Handset PA
AlGaAs/InGaAs HBT's

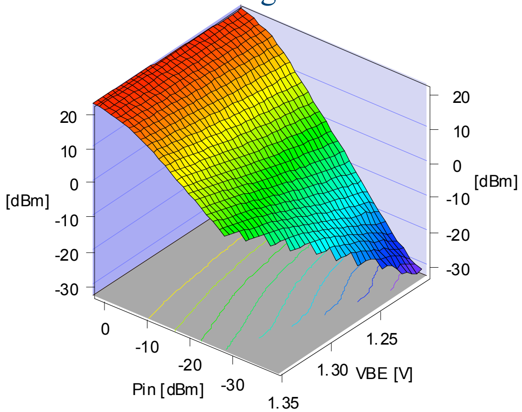
Measured RF I-V Waveforms

– Unifying Analysis Tool

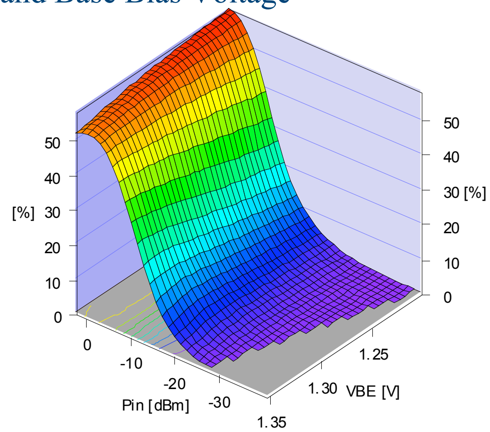


Measured RF I-V Waveforms
– General purpose Analysis Tool

Output Power versus Input Power and Base Bias Voltage



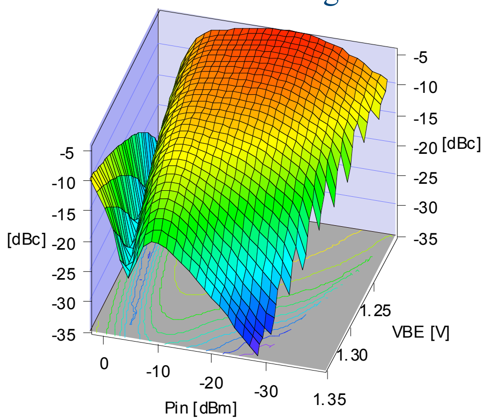
Efficiency versus Input Power and Base Bias Voltage



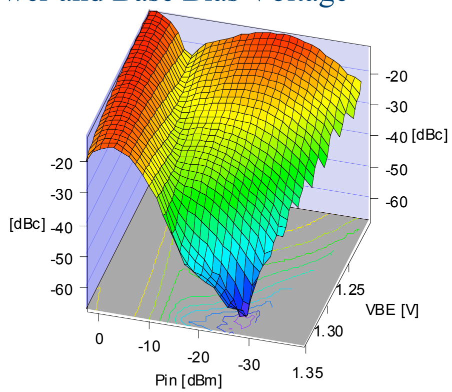
Experimental Emulate the affect of varying external parameters: In this case input drive level and input DC bias voltage

Note, have all information on magnitude and phase of all voltage and current Fourier components

2nd Harmonic Output Power versus Input Power and Base Bias Voltage



3rd Harmonic Output Power versus Input Power and Base Bias Voltage



GaAs HBT Performance as a function of Load Impedance

RF Waveform Measurement and Engineering

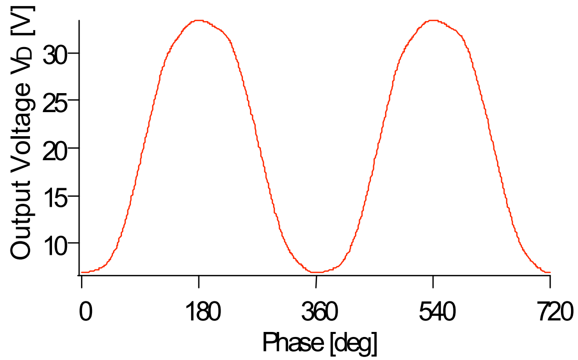
- powerful dynamic transistor characterization tool

- Transistor Characterization: Case Study
  - Use RF Waveform Measurement and Engineering Systems to investigated factor limiting the observed power performance of the emerging GaN Transistor Technology
    - Current Collapse, Knee Walkout, Poor Pinch-off

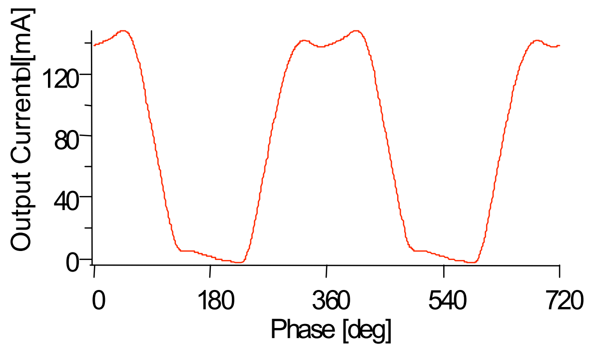
Transistor Characterization: GaN Case Study

- visualizing the DC-RF Dispersion Problem

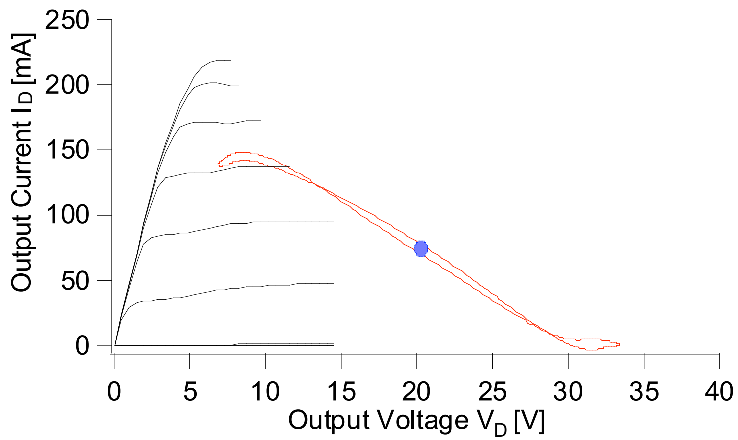
Commonly observed that the RF Power Performance of the GaN transistor was less than predicted (DC I-V & s-parameters)



Approach: Drive the GaN transitor in to compression while measuring RF Output V & I Waveforms (840MHz)



Plot against one another to give the RF Load-line

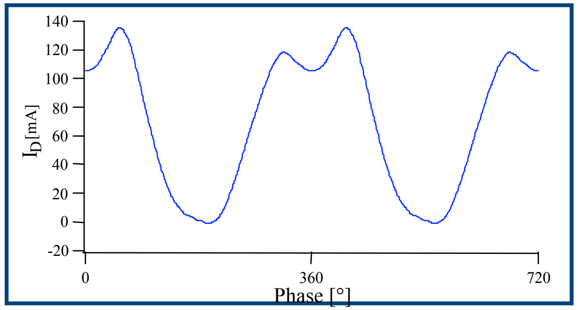


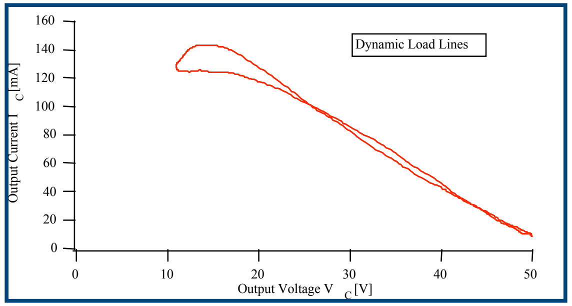
Waveforms show compression at RF Boundaries differs from the DC Boundaries, hence clearly identifying source of the problem: knee walkout or current collapse

Transistor Characterization: GaN Case Study

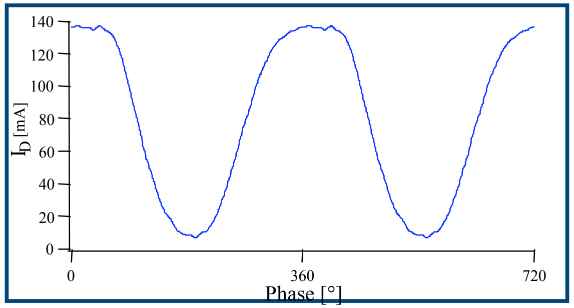
- visualizing the DC-RF Dispersion Problem

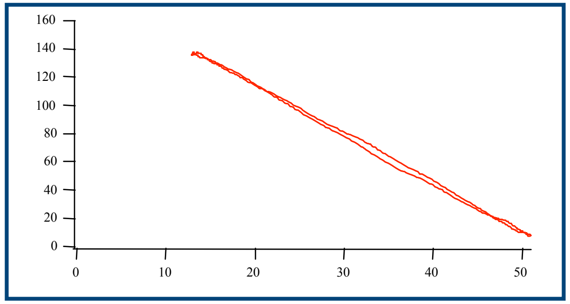
- Measured drain current with fundamental load-pull only
  - Complex load-lines are more difficult to interpret: cause concern in extracting boundaries





- Measured drain current with 3-harmonic load-pull
  - Simple load-lines are easy to interpret: no ambiguity in extracting boundaries



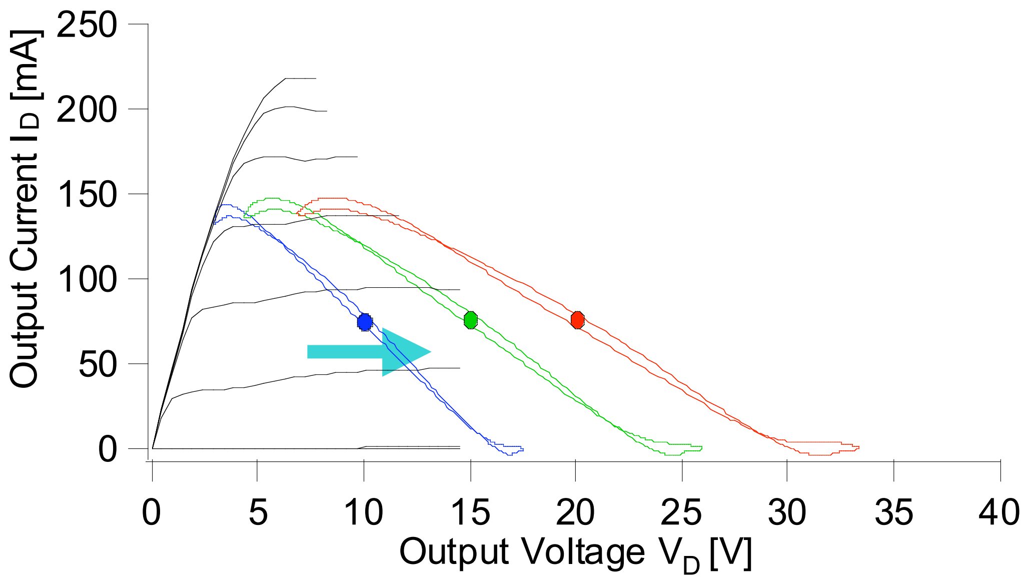


- For quantitative results make full use of waveform engineering, however, fundamental alone does provide for qualitative insight.

Transistor Characterization: GaN Case Study

- visualizing the DC-RF Dispersion Problem

- Investigate factors that influence the knee walkout or current collapse problem: Quiescent Drain Bias Voltage



The Dynamic RF knee boundary shifts as DC drain bias increases

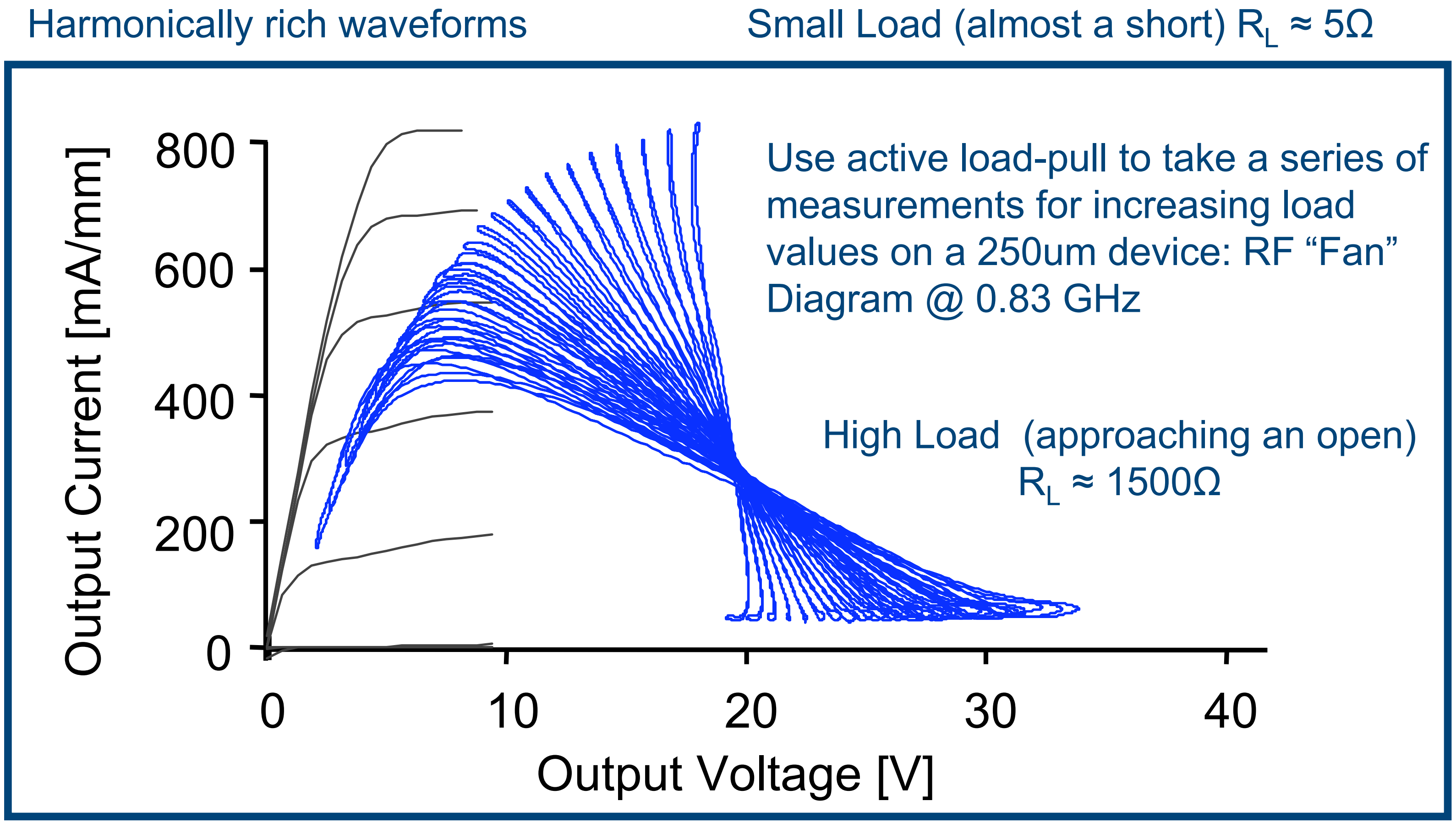
(10, 15 and 20V)

This limits achievable power densities

Still unclear whether should relate problem to knee walkout or current collapse

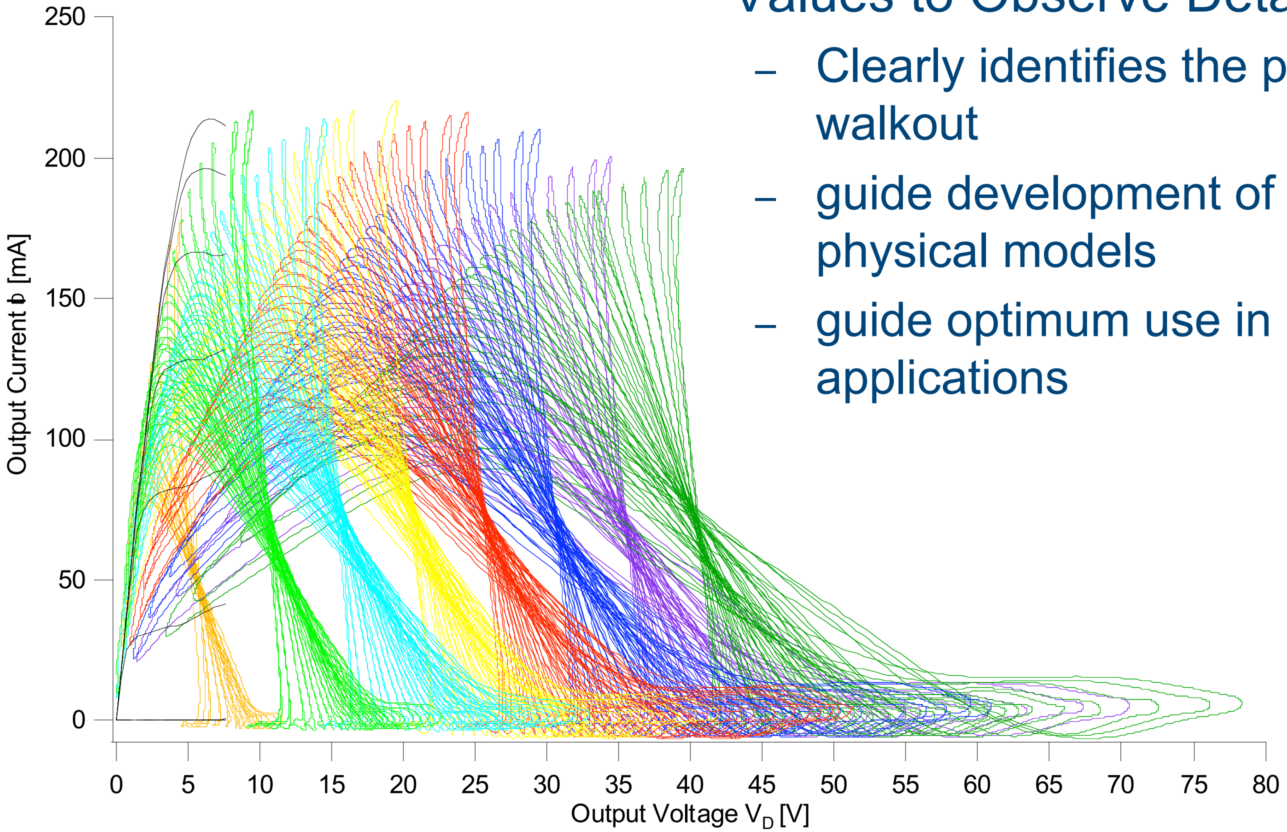
RF "Fan Diagram": GaN HFET Application

- evaluation of trapping ("knee walkout") problem



RF “Fan Diagram”: GaN HFET Application

- evaluation of trapping (“knee walkout”) problem



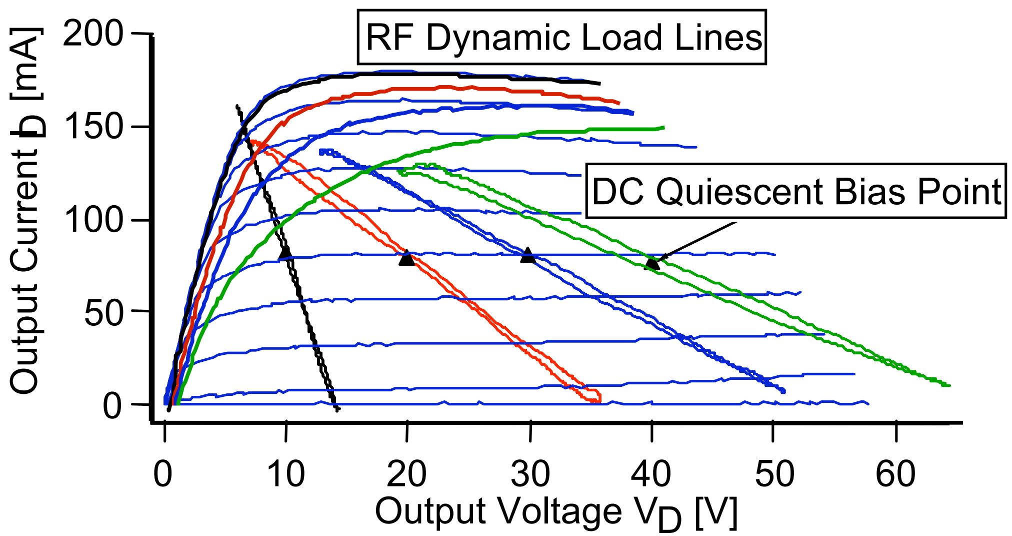
- Repeat for a Range of Drain Bias Values to Observe Detailed Features
  - Clearly identifies the problem: knee walkout
  - guide development of appropriate physical models
  - guide optimum use in circuit applications

Transistor Characterization: GaN Case Study

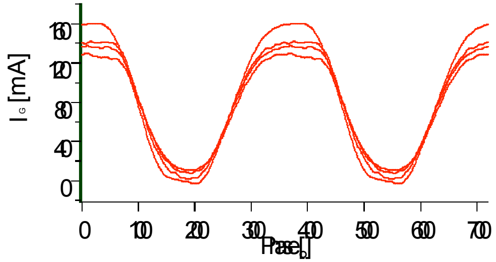
- Class A RF I-V Waveforms versus Pulsed I-V

- Comparison with pulsed I-V Measurements
  - Determine boundaries by simultaneously pulsing both gate and drain voltage (DIVA System) from quiescent Class A bias point

- Clearly observe both predict very similar “RF knee-walkout” as V_D increases



- Compressed current waveforms confirm that the device is in compression

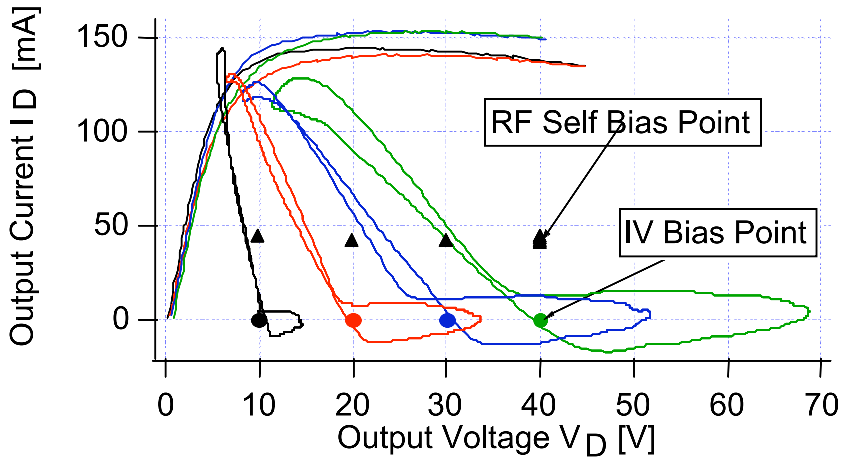


Transistor Characterization: GaN Case Study

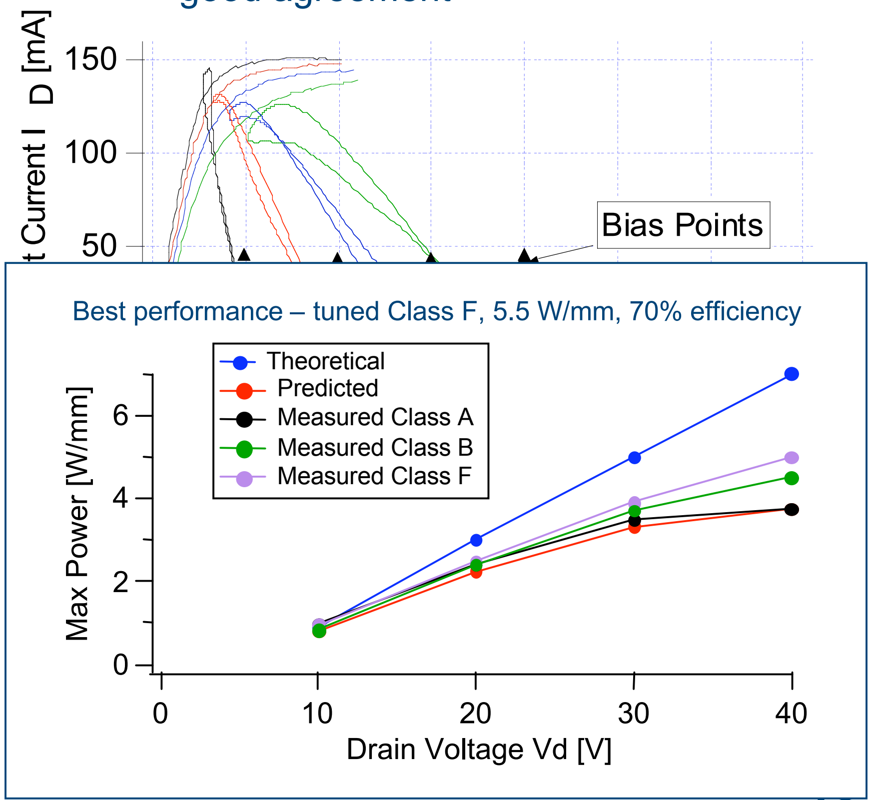
- Class B RF I-V Waveforms versus Pulsed I-V

- Comparison with pulsed I-V Measurements
  - Problem in this case is that the quiescent bias point is not on the DC I-V plane: Where do we pulse from?

- Same voltage V_G bias point
  - poor agreement



- Same current I_D bias point
  - good agreement



- "RF knee-walkout" is sensitive to mode of operation

RF Waveform Measurement and Engineering

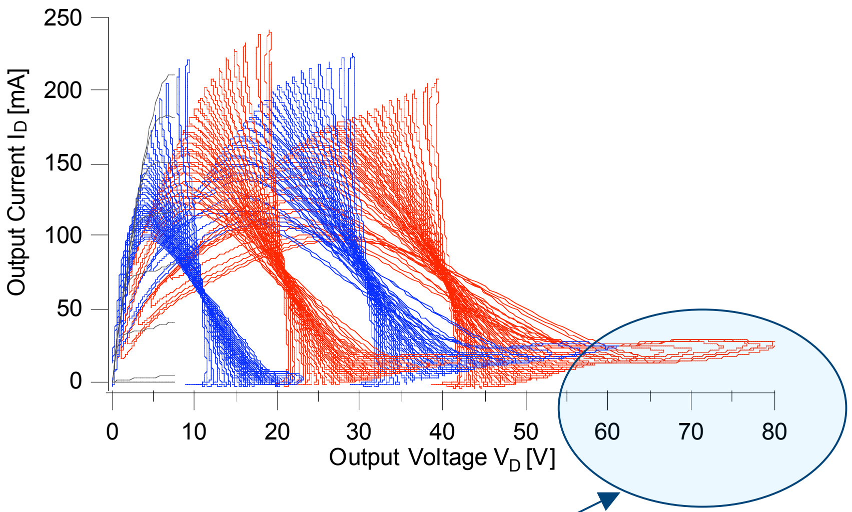
- powerful dynamic transistor characterization tool

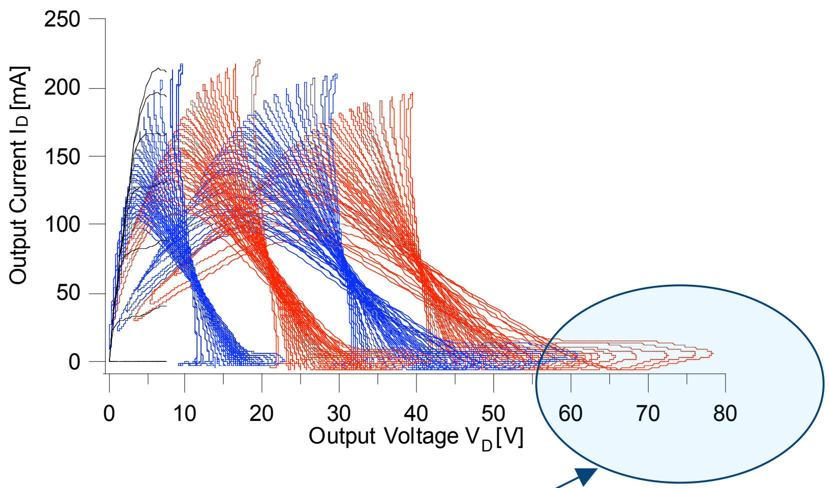
- Transistor Characterization: Technology Evaluation and Optimization
  - Poor Pinch-off very similar to knee walkout investigations
  - Reliability and device stress: emerging area.

RF "Fan Diagram": GaN HFET Application

- evaluation of buffer layer design ("soft pinch-off")

- Evaluate Different Buffer Layer Design (Level of Fe Doping)
  - Elimination of soft pinch-off
  - No significant effect at the Knee Region





Undesirable "Soft" Pinch-off Behaviour

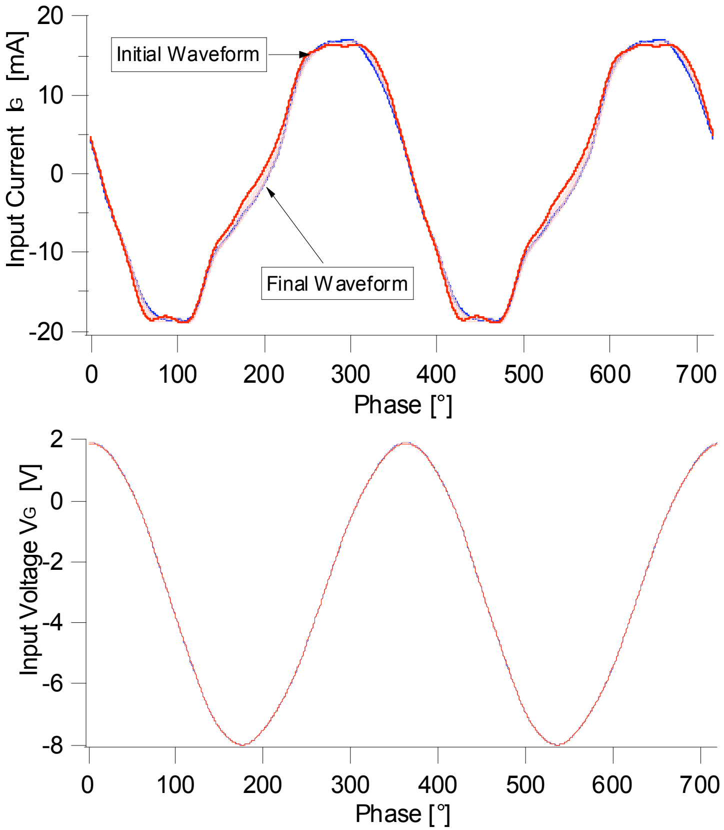
Improved Pinch-off Behaviour

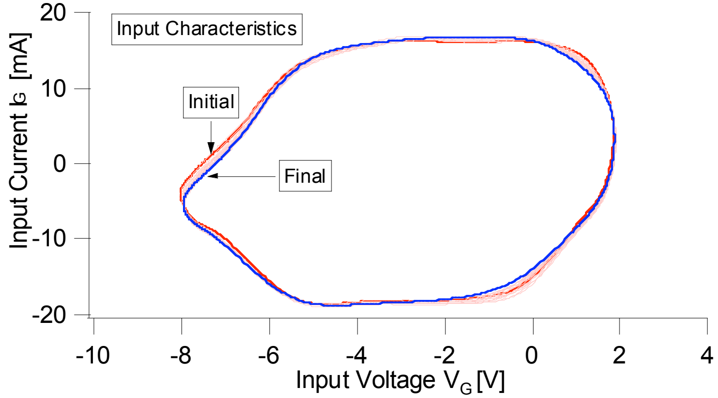
Increased Fe

Transistor RF I-V Waveforms: GaN HFET Application

– Detailed Insight into Dynamic stress/reliability Limitations

- RF waveforms were periodically sampled 100 times during the 1.5hour RF stress period
- 1.8GHz Large-signal CW (≈ 3dB of gain compression), V_D = 20V, Class A, $Zf_0 \approx P_{OUT}$

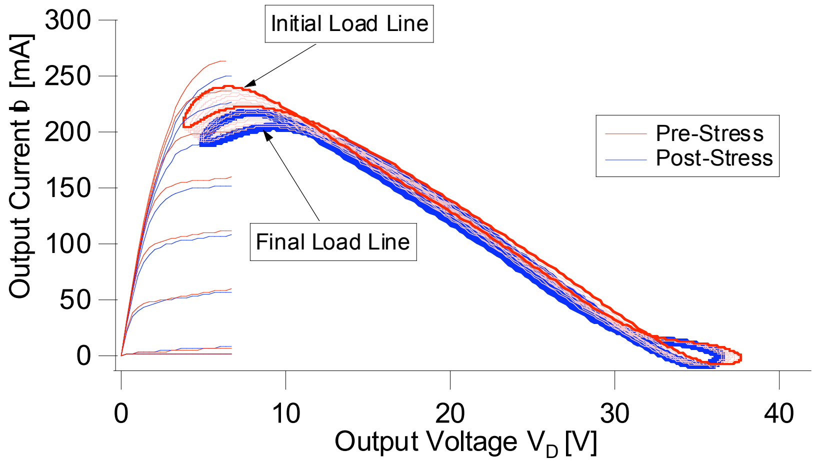




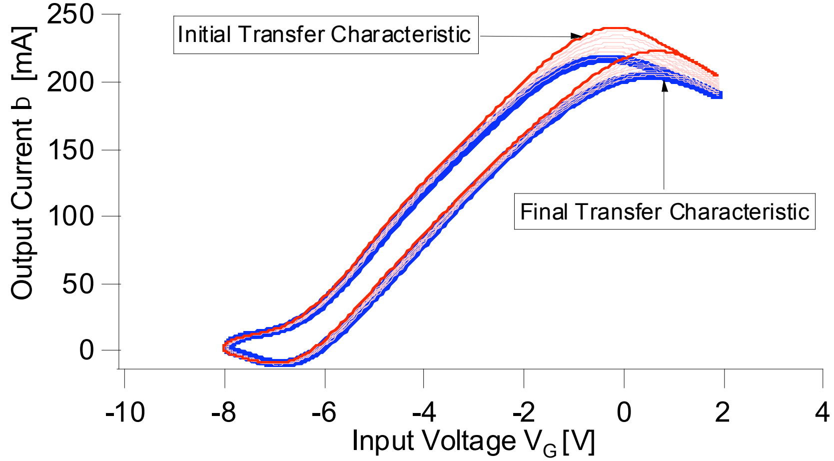
- Dynamic Input Characteristics
  - Highlights the displacement current through C_{GS}
  - A small increase in leakage can be seen at the breakdown end

Transistor RF I-V Waveforms: GaN HFET Application

– Detailed Insight into Dynamic stress/reliability Limitations



- Dynamic Load lines (overlaid on DC-IVs)
  - Useful for visualising DC-RF dispersion – a non-permanent problem
  - Here the degradation is permanent suggesting a different mechanism



- Dynamic Transfer Characteristics
  - Very little degradation until V_G swings above -3V
  - No change around $V_T \approx$ -6V

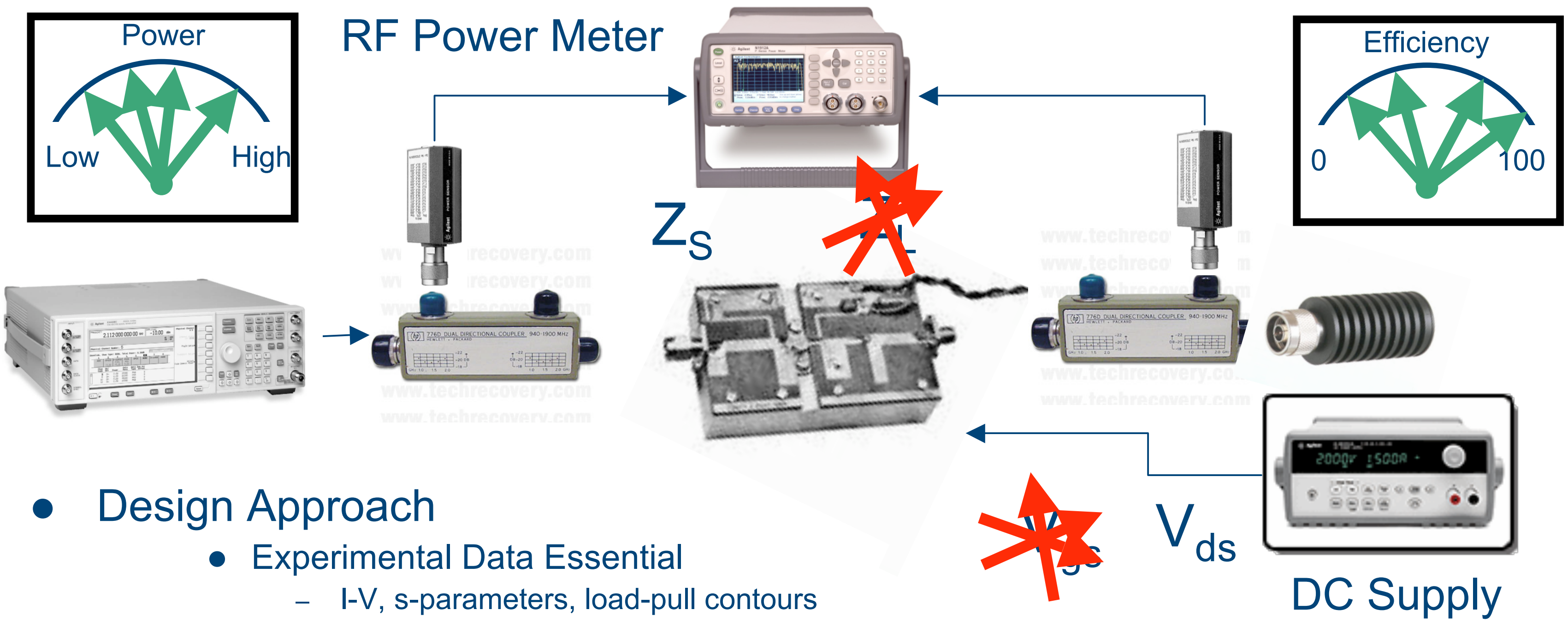
RF Waveform Measurement and Engineering

- powerful "real time" design tool

- Basic Concept
  - Use RF Waveform Measurement and Engineering Systems to investigated and achieve the required circuit/system performance.
    - Key: Performance is theoretically defined in terms of the voltage and/or current waveforms
    - Alternatives: build and test, CAD tools (*requires non-linear model*)

- Relevant Circuit Design Problem
  - Those that involve strongly non-linear ('large signal") device operation, not weakly non-linear or linear operation
    - **Power Amplifier Design beyond Class A/AB**
    - Switching Amplifiers
    - Frequency Multipliers/Dividers

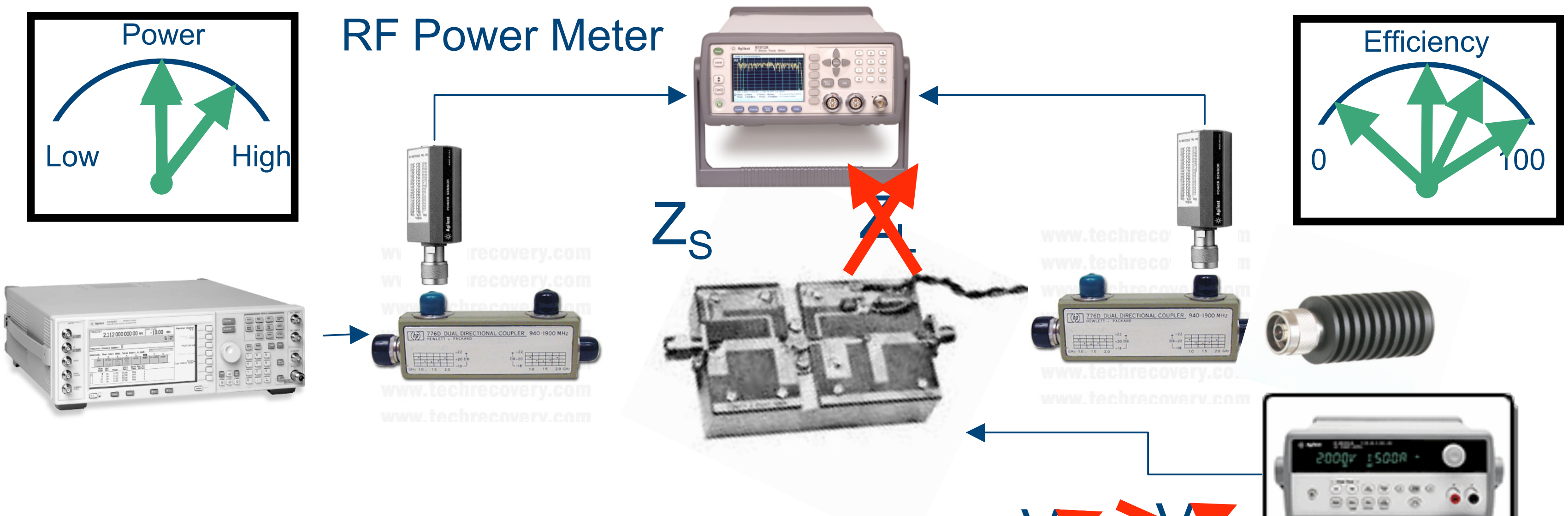
Review PA Design Situation
- too reliant on Build & Test



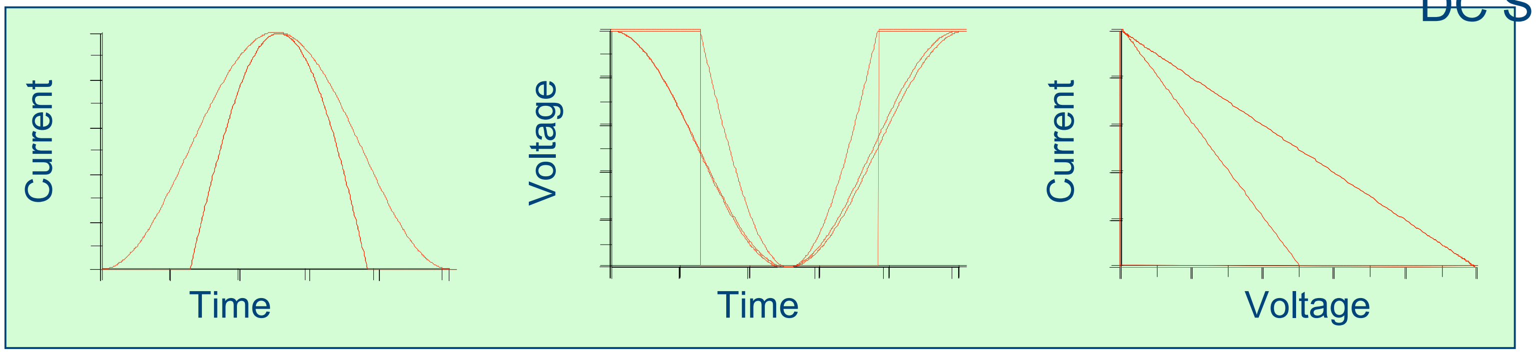
- Design Approach
  - Experimental Data Essential
    - I-V, s-parameters, load-pull contours
  - Design Knowledge: mode of operation, class A, AB,
    - Efficiency Demands: *Move to more complex modes B, F, E or switching modes*
  - Build, Evaluate and Adjust
    - Bias point
    - Load and Source impedance @ fundamental (*and harmonics*)

Review PA Design Situation

- incorporate Basic Principles: "Waveform Engineering"



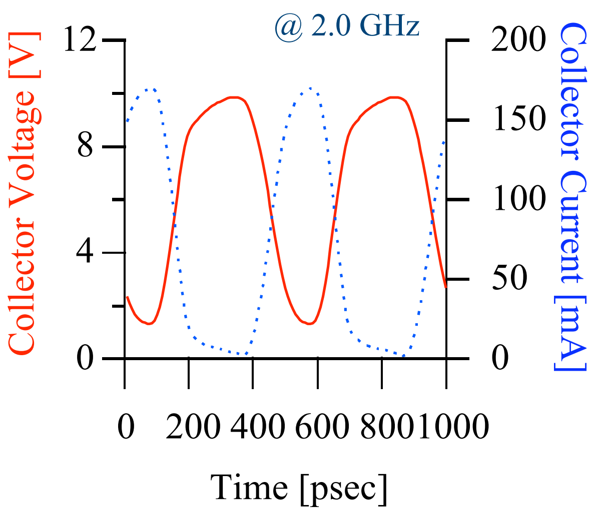
- Waveform Engineering

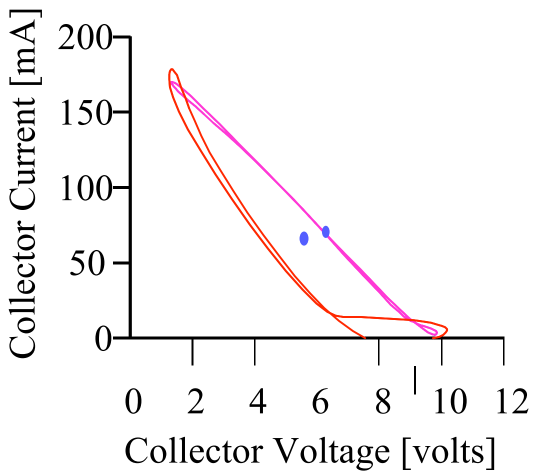


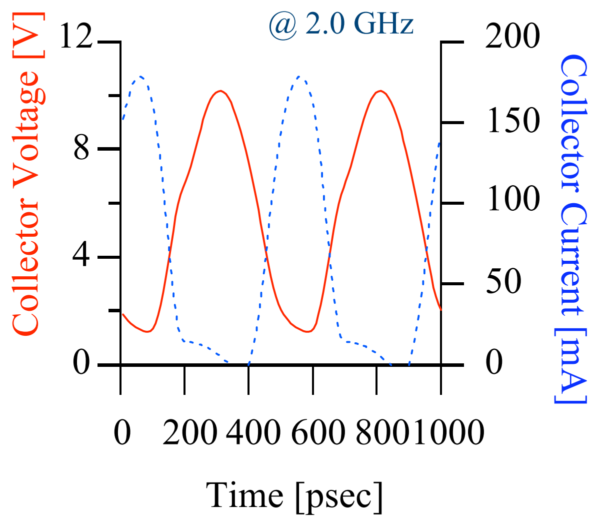
RF I-V Waveform Engineering
- insight provided by having measured waveforms

HBT biased to operate in class B, low quiescent current
- Current waveform is half rectified
- Voltage waveform is not sinusoidal

Engineer harmonic impedances: Short second/third harmonic
- Current waveform is half rectified
- Voltage waveform is now sinusoidal







"Class B Operation"

Efficiency increased from 44% to 55%

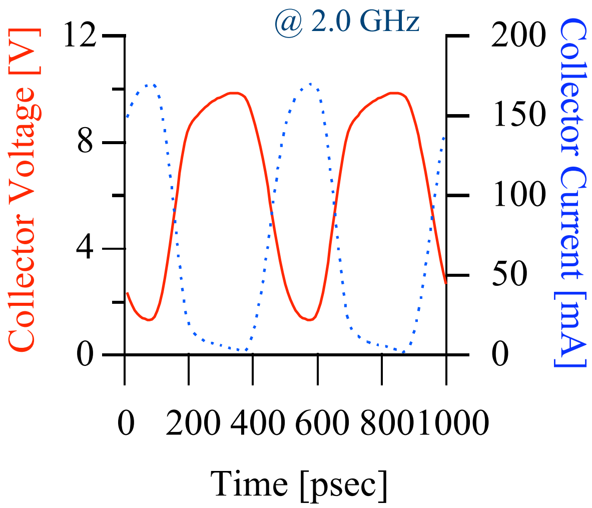
Design Example: Class B Amplifier Emulation/Measurement

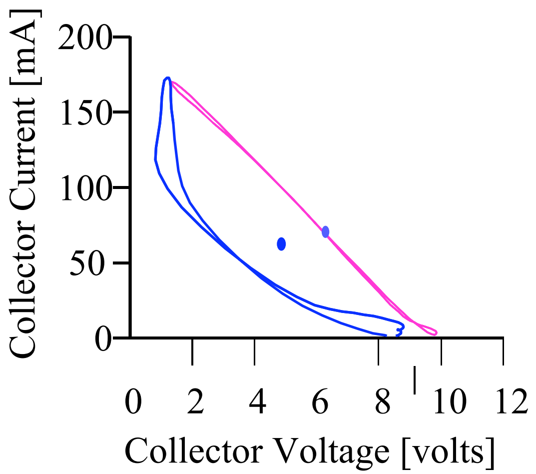
RF I-V Waveform Engineering

- insight provided by having measured waveforms

HBT biased to operate in class B, low quiescent current

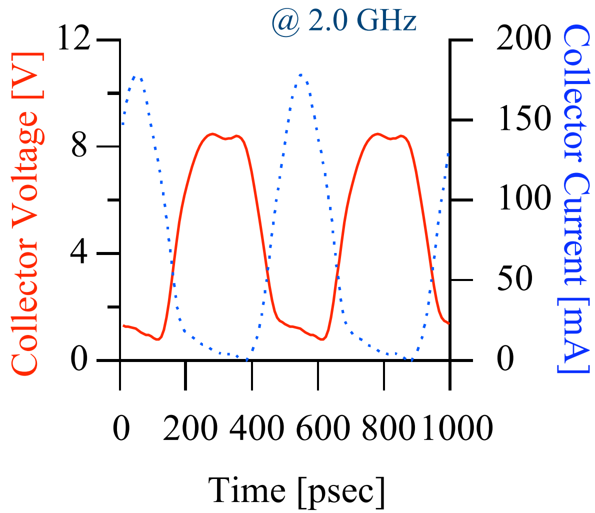
- Current waveform is half rectified
- Voltage waveform is not sinusoidal





Engineer harmonic impedances: Short/open second/third harmonic

- Current waveform is half rectified
- Voltage waveform is now a square wave



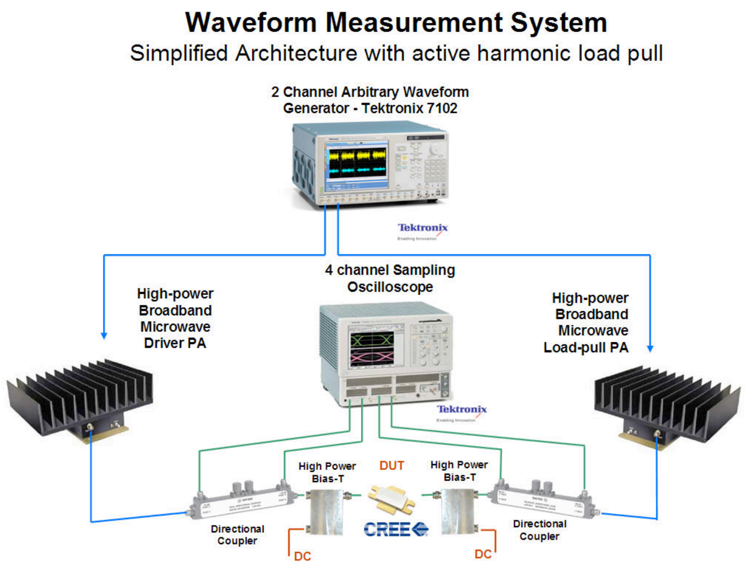
"Class F Operation"

Efficiency increased from 44% to 65%

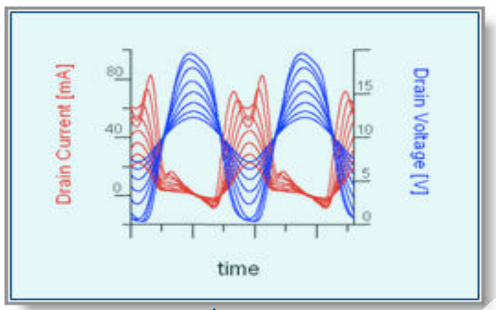
Design Example: Class F Amplifier Emulation/Measurement

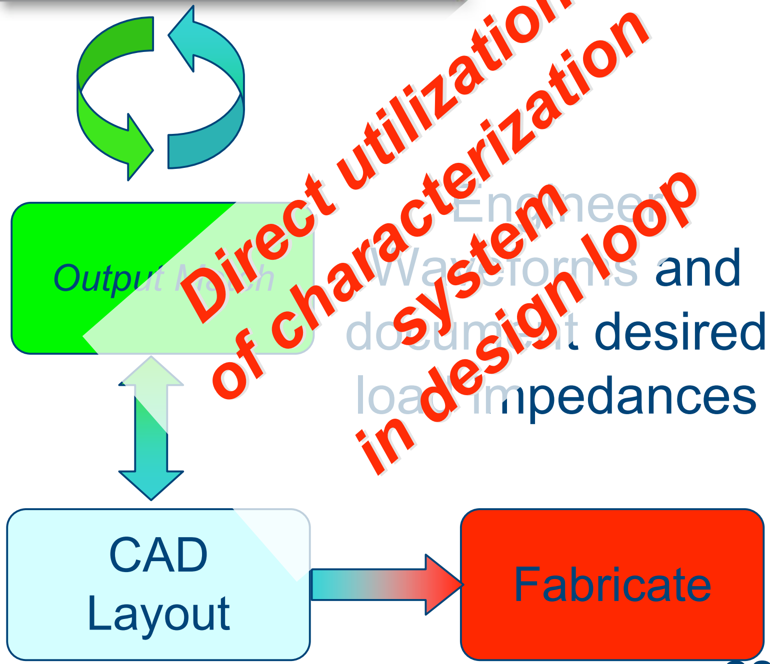
RF Waveform Measurement and Engineering

- "on-line" direct utilization in amplifier design cycle



Waveform Data





- Relevant Circuit Design Problems
  - Those that involve strongly non-linear ('large signal") device operation.
    - **Power Amplifier Design beyond Class A/AB**
    - Switching Amplifiers
    - Frequency Multipliers/Dividers
    - Etc.

RF Waveform Measurement and Engineering

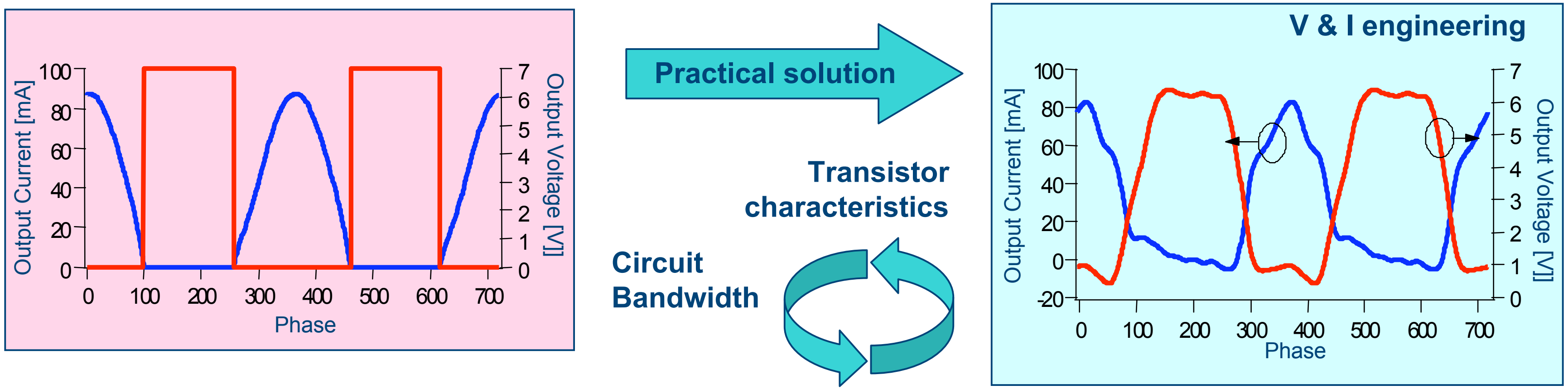
- powerful dynamic transistor amplifier design tool

- Transistor Amplifier Design: Case Study
  - Use RF Waveform Measurement and Engineering Systems to investigated how to realize in practice the theoretically predicted high efficiency modes of operation
    - Class B, Class F or their variants

Design of Highly Efficient RF Power Amplifier

- requires engineer of voltage and current waveforms

Simple Theoretical Understanding



Advanced Theoretical Understanding

- Designed in an intelligent manner a class F efficient RF Power Amplifier
  - Maximized Output Power
  - Realized 75% PAE

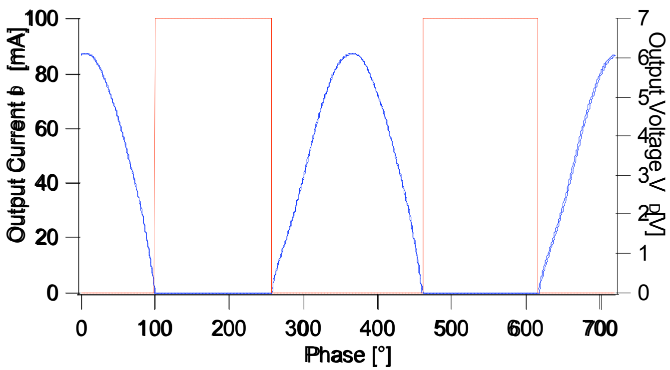
- Ready for realization

Design of Highly Efficient RF Power Amplifier

- review of theoretical understanding: Class F

Ideal Class F occurs if the current and voltage waveforms are simultaneously engineered such that:

The current waveform contains f_0 and correct proportions of the even harmonics



The voltage waveform contains f_0 and correct proportions of the odd harmonics

If this is achieved there is no overlap between the waveforms, resulting in no dissipated power and 100% efficiency.

Design of Highly Efficient RF Power Amplifier

- review of practical constraints: System and Circuit Bandwidth

- The achievable efficiency in a real design is constrained by our ability to correctly engineer the ideal waveforms.
  - Circuit Bandwidth
    - In real PA designs harmonic control is commonly limited to $2f_0$ and $3f_0$ due to the complexity of matching circuits.
    - Following the analysis of Rhodes,* for a Class F design with harmonics only up to $3f_0$ ideally terminated, the maximum achievable efficiency is limited to an upper limit of 90.6% - assuming your matching network is lossless!

We can quantify the ability to engineer ideal waveforms by two factors $\eta_{current}$ and $\eta_{voltage}$ using the DC and fundamental RF components:

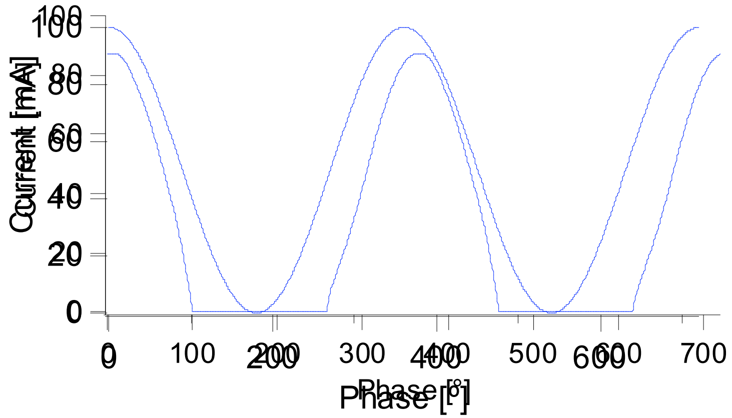
$$\eta_{current} = i_{RF} \Big/ \left(\sqrt{2} \times I_{DC}\right) \qquad \eta_{voltage} = v_{RF} \Big/ \left(\sqrt{2} \times V_{DC}\right)$$

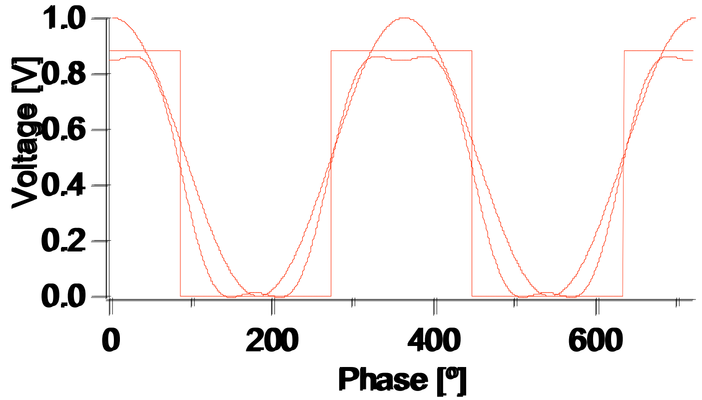
* J.D. Rhodes "Output universality in maximum efficiency linear power amplifiers" International Journal of Circuit Theory and Applications, volume 31, 2003, pp.385-405

Design of Highly Efficient RF Power Amplifier

- review of practical constraints: System and Circuit Bandwidth

Class	$\eta_{current}$	$\eta_{voltage}$	$\eta = \eta_{current} \times \eta_{voltage} \times 100$ [%]
A	0.707	0.707	**50**
B	1.111	0.707	**78.5**
F (Ideal)	1.111	0.900	**100**
F ($3f_0$)	1.111	0.816	**90.6**

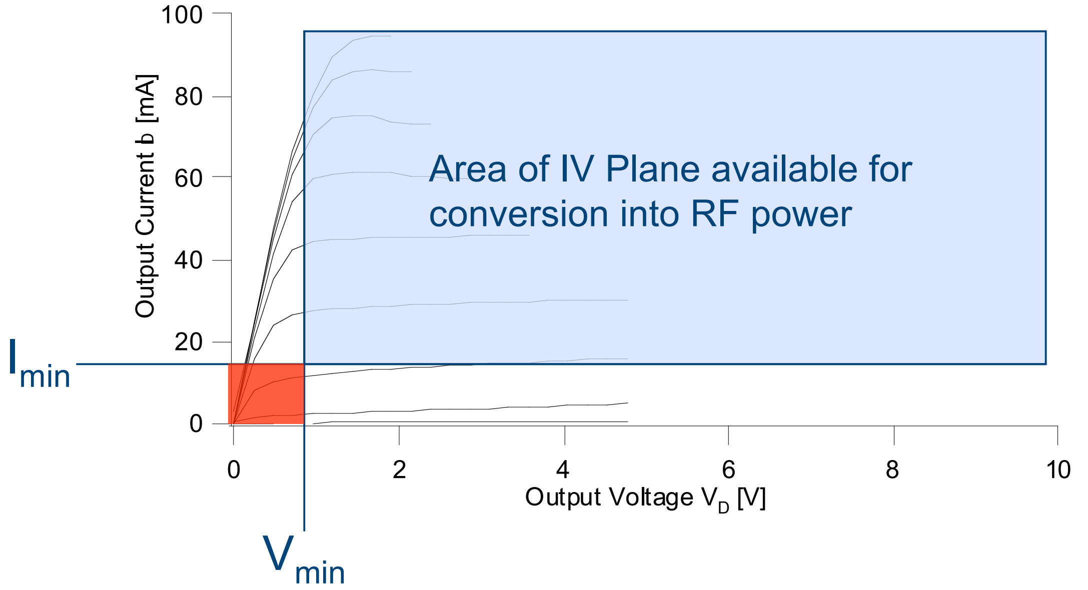




Design of Highly Efficient RF Power Amplifier

- review of practical constraints: Transistor Limitations

- A further limitation on achievable efficiency in practical designs arises from features of real transistor characteristics which make a fraction of the dc dissipated power unavailable for conversion to RF power:



Achievable efficiency is scaled by the ratio of Available to Unavailable IV plane Area

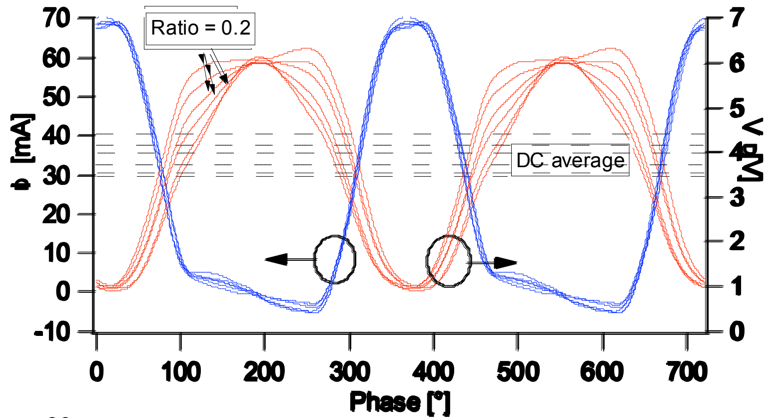
We can quantify the ability to engineer ideal waveforms by two factors $\eta_{current}$ and $\eta_{voltage}$ using the DC and fundamental RF components:

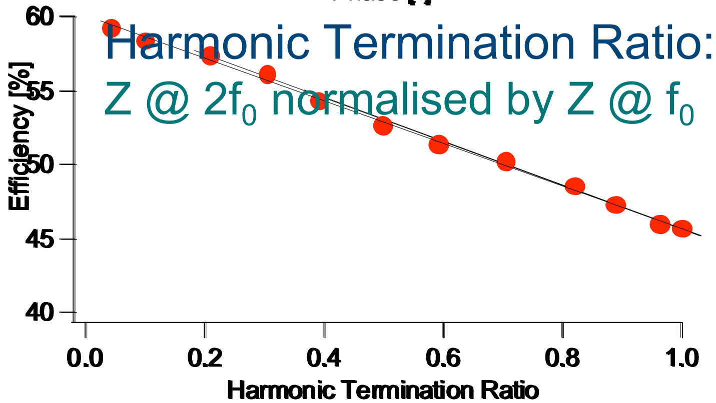
$$\eta_{current} = i_{RF} \Big/ \left(\sqrt{2} \times I_{DC}\right) \qquad \eta_{voltage} = v_{RF} \Big/ \left(\sqrt{2} \times V_{DC}\right)$$

Design of Highly Efficient RF Power Amplifier

- review of practical constraints: Impedance Scaling

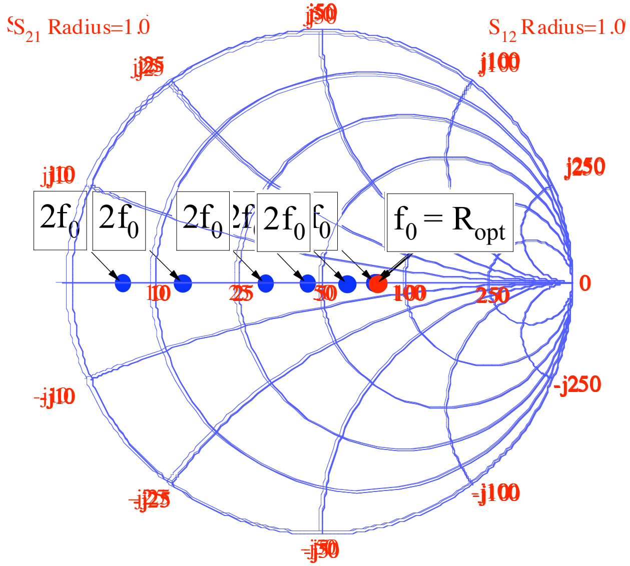
- Starting with Class B bias for a half rectified current waveform, what is the effect of tuning the second harmonic to a short?





Harmonic Termination Ratio:

Z @ $2f_0$ normalised by Z @ f_0

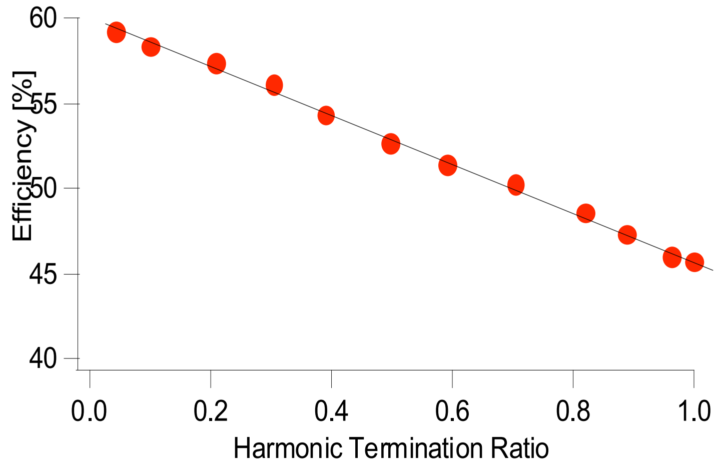


Eliminated 2nd harmonic from voltage waveform

Design of Highly Efficient RF Power Amplifier

- review of practical constraints: Impedance Scaling

- Good short circuits harder to achieve relative to a Small R_{opt}
- Makes high efficiency harder to achieve in large devices
- Possible solution - include numerous short circuits integrated onto the die to allow subsets of transistor cells to be given a better short…
- Packaging parasitics can form a filter blocking higher harmonics…



Harmonic Termination Ratio:
Z @ $2f_0$ normalised by Z @ f_0

Design of Highly Efficient RF Power Amplifier

- review of practical constraints: Transistor Transfer Characteristic

- Need to select a suitable drive level for harmonic generation (approaching P1dB)

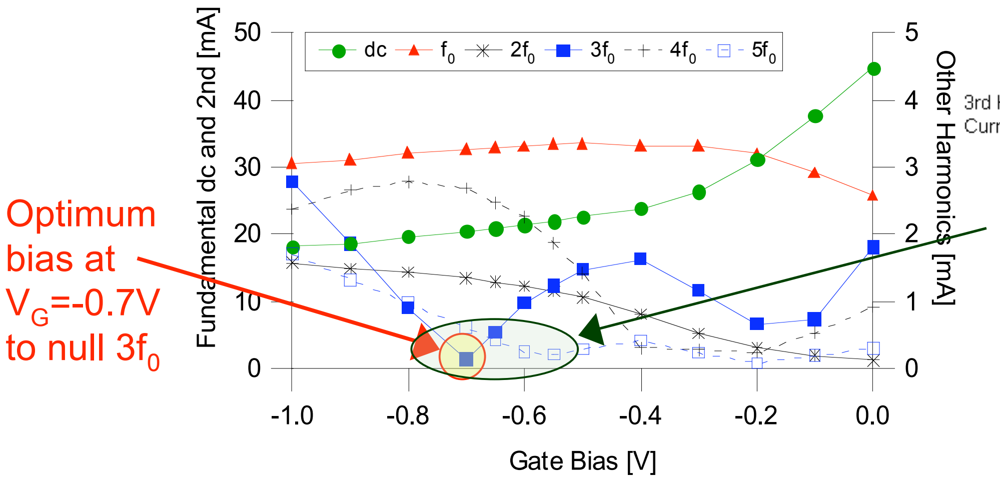
- Ideally we need to ensure we have separated the harmonics:
  - only odds in the voltage waveform
  - only evens in the current waveform

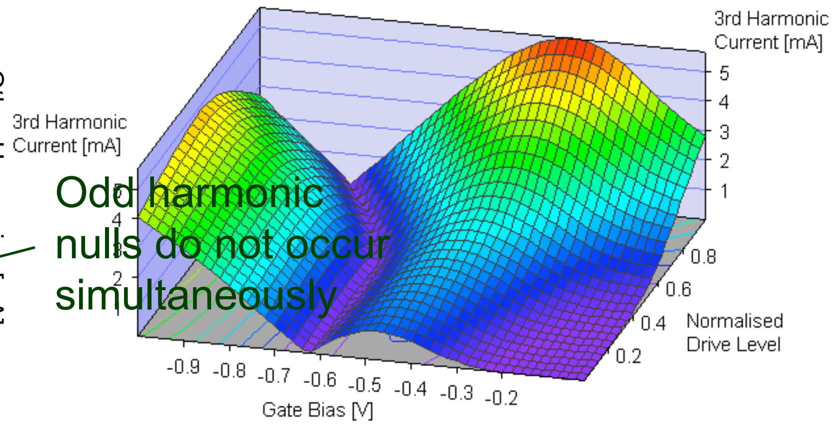
…but will the practical device allow this!

Engineering The Current Waveform

– Gate bias control to null the odd harmonics

- In class F optimum performance will only occur if the most significant odd harmonics (usually only consider $3f_0$) are not present in the current waveform.
- Using Fourier analysis of the measured current waveforms we can locate this optimal case…



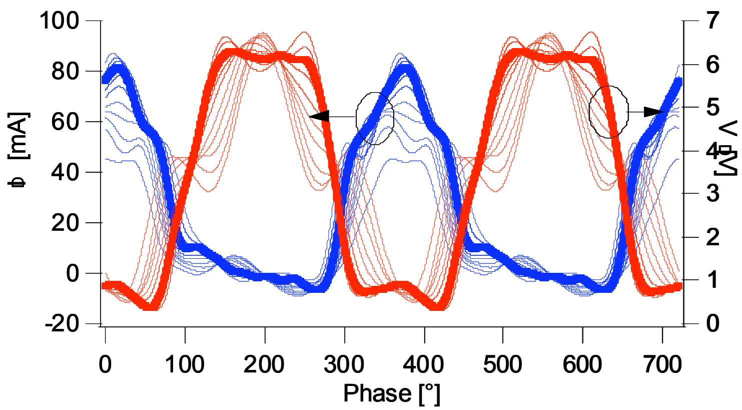


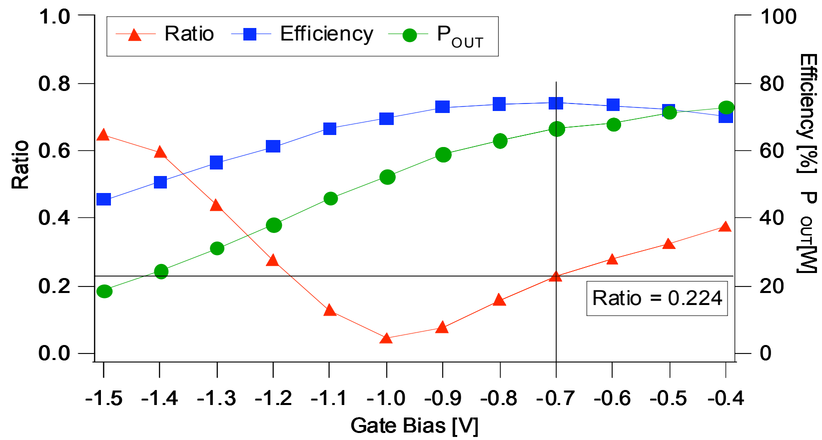
- Practical constraints:
  - Other harmonics are not zero
  - Optimum bias is a function of voltage waveform “shape” and RF drive level

Engineering The Voltage Waveform

- Open tuned 3rd harmonic gate bias sweep

- Engineering the voltage waveform to a square wave involves tuning the 3rd harmonic to an open and increasing the fundamental load to maintain the same current swing.
  - Note, the optimum Class F behaviour will only occur if the current at $3f_0$ remains null.



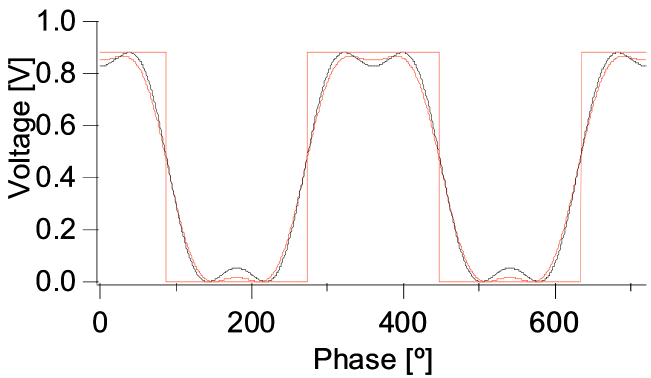


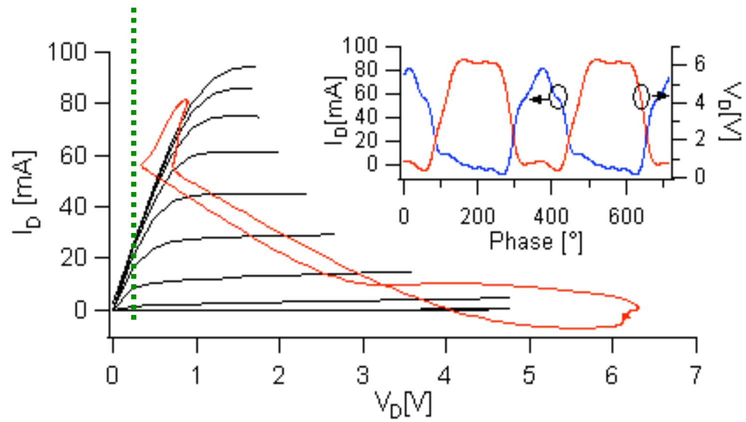
- Since Class F requires an open termination at $3f_0$, it is impossible to verify this condition has been met by direct measurement of the $3f_0$ harmonic current.
  - Consider v_{3rd}/v_{fund} ratio. Theory predicts 1/6 (=0.167)

Engineering The Voltage Waveform

- Why was extra third harmonic developed?

- Plotting the dynamic load-line for the final design shows the interaction of the waveforms with the knee region.
  - Ideal square wave requires all harmonics – we only control the first 3
  - Optimal 3 harmonic only voltage waveform has a v_{3rd}/v_{fund} ratio of 1/6 if the boundary conditions are ideal (vertical)
  - However due to the finite on-resistance of the real knee boundary the optimal ratio is higher, at almost 1/4



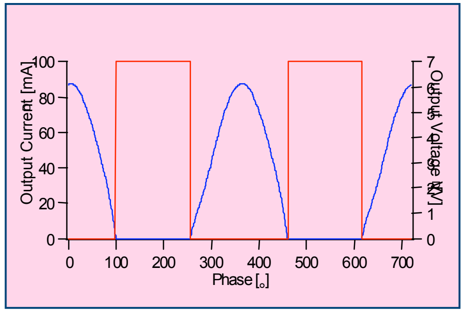


- The final experimentally engineered "class F" waveforms achieved a drain efficiency value of 75%,
- This is extremely high given the boundary conditions and drain bias of the real device used.

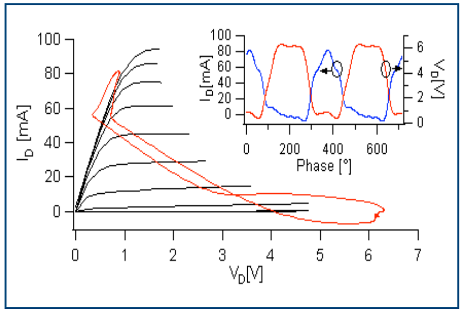
RF Waveform Measurement and Engineering

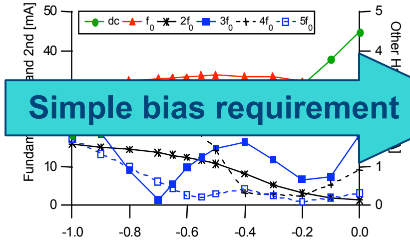
- "on-line" direct utilization in amplifier design cycle

Simple Theoretical Understanding: *Provides If not How and Why*

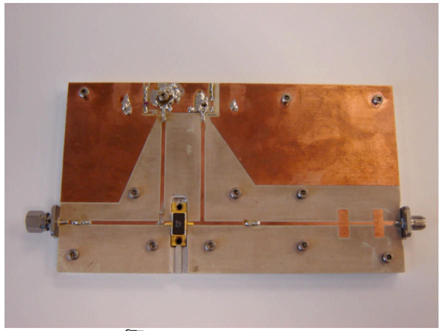


Transistor characteristics **Circuit Bandwidth**

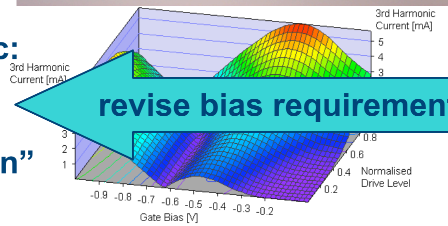




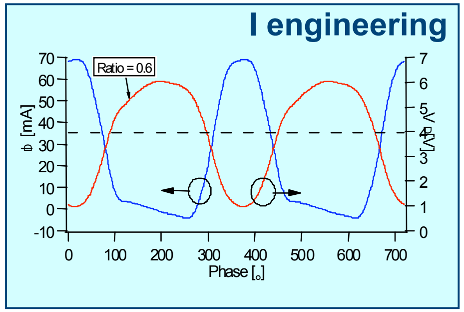
Simple bias requirement



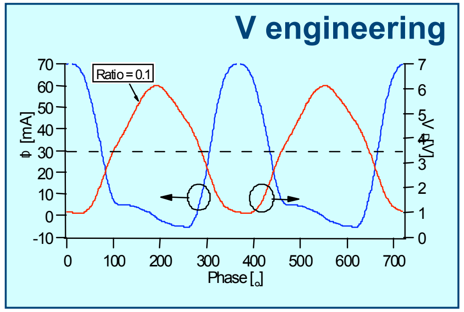
3rd harmonic: open circuit "relaxation"



revise bias requirement



2nd Harmonic short circuit



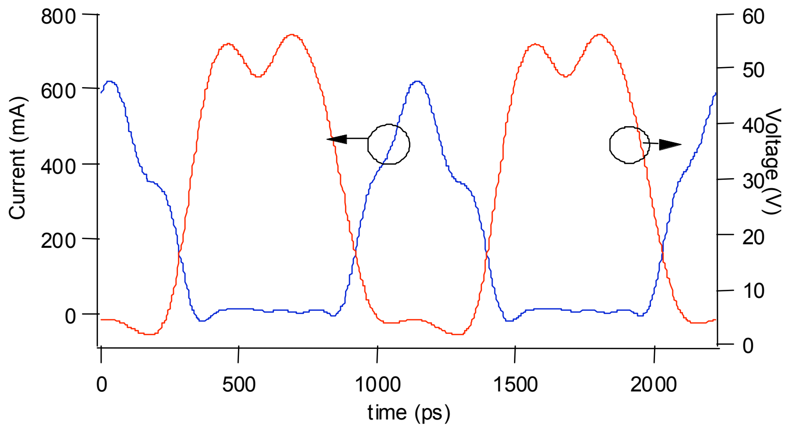
Advanced Theoretical Understanding: *Must provide How and Why*

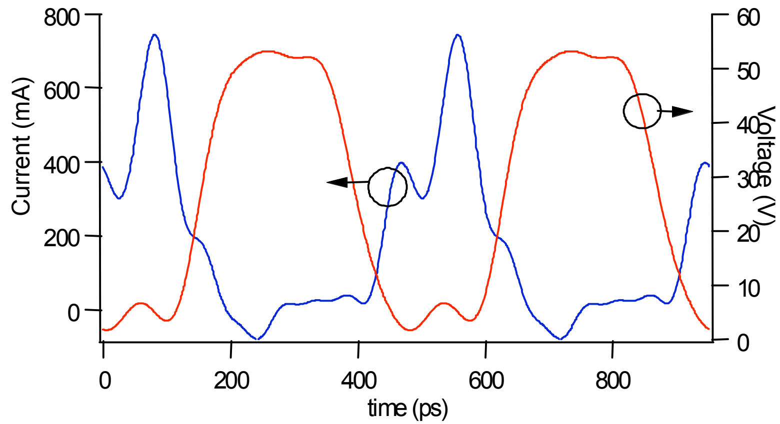
developing theoretically based but practically relevant waveform engineering design methodologies

Apply Waveform Design Methodology

- 5W Si LDMOS into Class F Emulation/Design

Engineered and Measured Intrinsic Waveforms: Design Aid





High Power Class F Design

5W Si LDMOS @ 900 MHz

- Class F clearly achieved
- High Power 36.0 dBm (4W)
- High Efficiency 77.2%

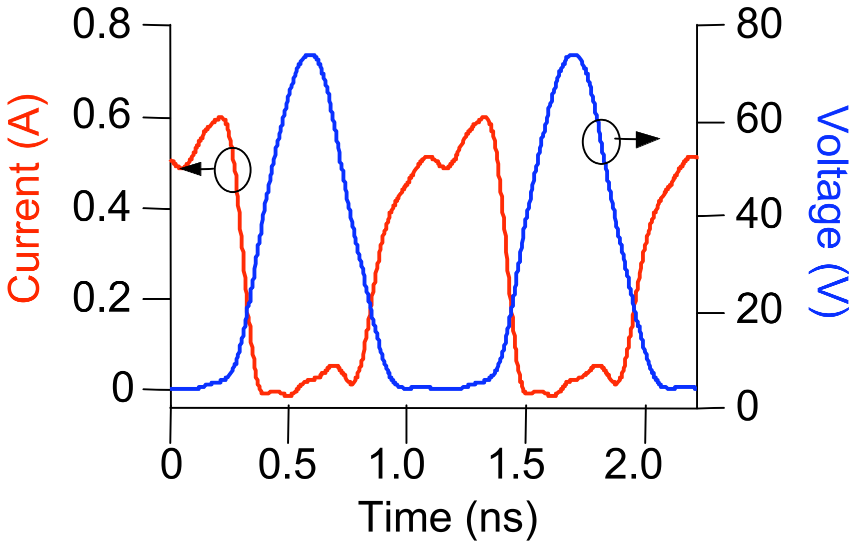
5W Si LDMOS @ 2100 MHz

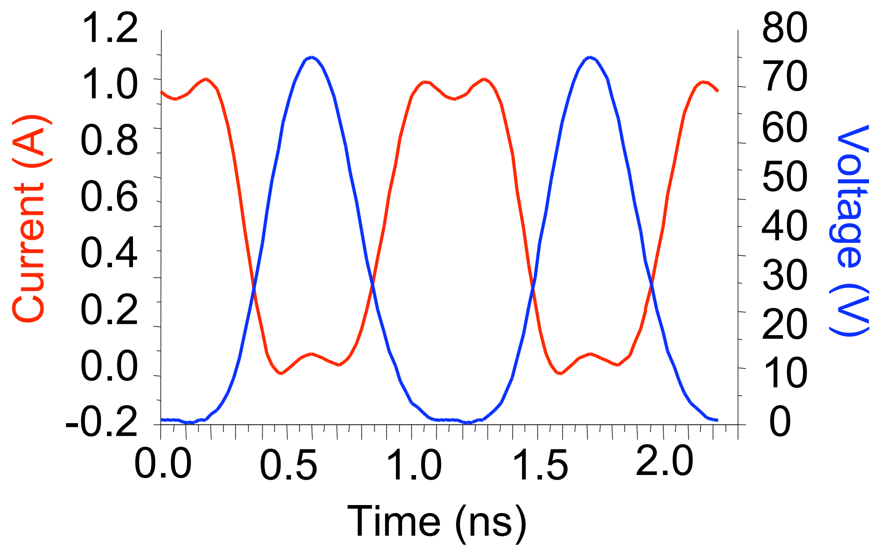
- Class F clearly achieved
- High Power 35.9 dBm (4W)
- High Efficiency 77.1%

Apply Waveform Design Methodology

- 10W GaN HFET & 5W Si LDMOS into Inverse Class F

Engineered and Measured Intrinsic Waveforms: Design Aid





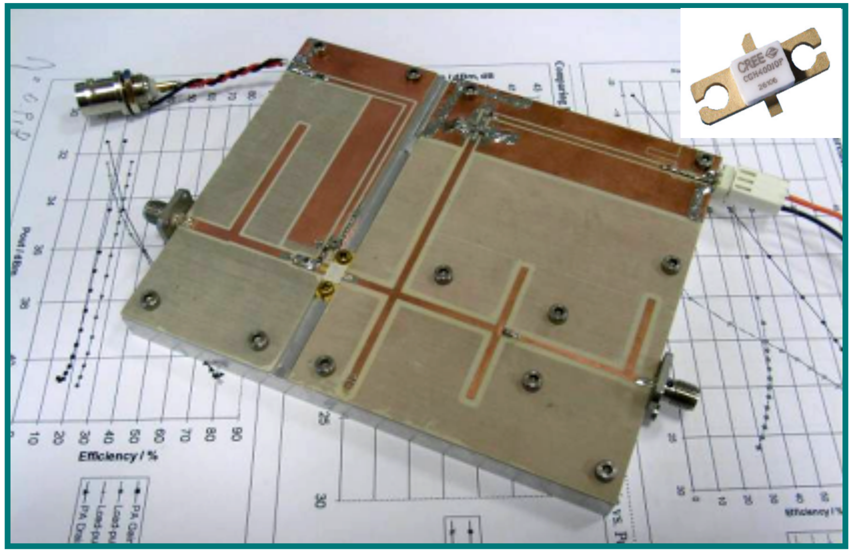
5W Si LDMOS @ 900 MHz

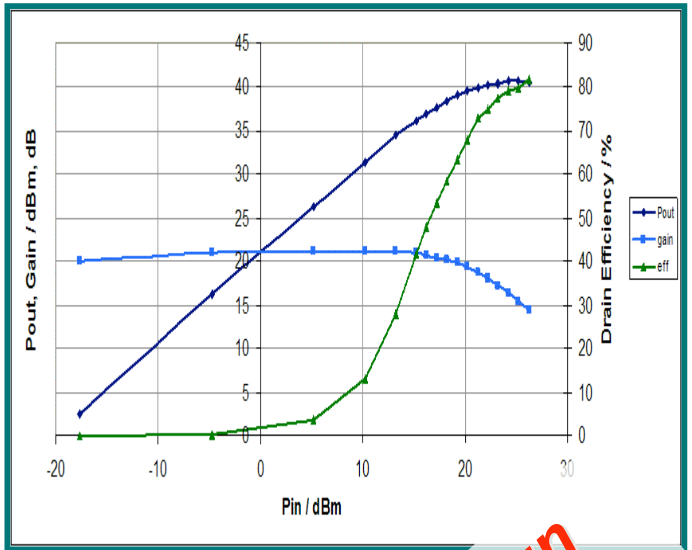
- Inverse Class F clearly achieved
- High Power 37.3 dBm (5.4W)
- High Efficiency 73%

10W GaN HFET @ 900 MHz

- Inverse Class F clearly achieved
- High Power 40.8 dBm (12W)
- High Efficiency 81.5%

12W Inverse class-F Amplifier Realisation
– right first time design using CREE 10W device





- *'Right first time'* waveform based design through the realisation of a high-performance inverse class-F PA
- Impressive efficiency of 81% at high output powers
- High Power achieving 12W form a 10W device

Inverse Class-F PA Performance Summary	
Max. Pout:	[illegible].6dBm
Max. Gain:	21.2dB
Compression @ max. Pout:	Approx. 5dB
Max. Drain Efficiency:	81.8%

First Pass Design Success

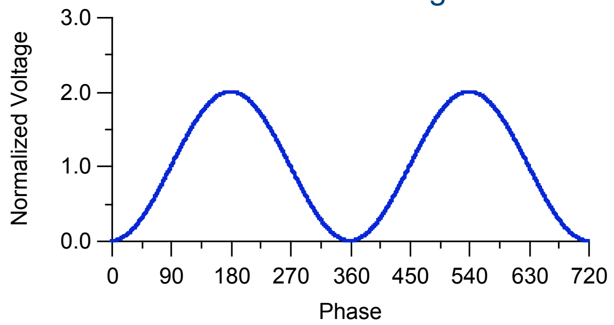
RF Waveform Measurement and Engineering
- powerful dynamic transistor amplifier design tool

- Investigation of "New Design Space"
  - Use RF Waveform Measurement and Engineering Systems to stimulate new theoretically investigations in alternative high efficiency modes of operation
  - Move beyond the discrete design point thinking to design continuum thinking
  - The Class B to Class J Continuum
    - New Theory
    - Improved Bandwidth

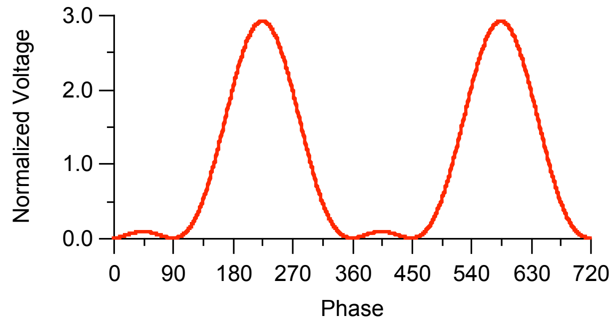
RF Waveform Measurement and Engineering
- provides for new theoretical insight

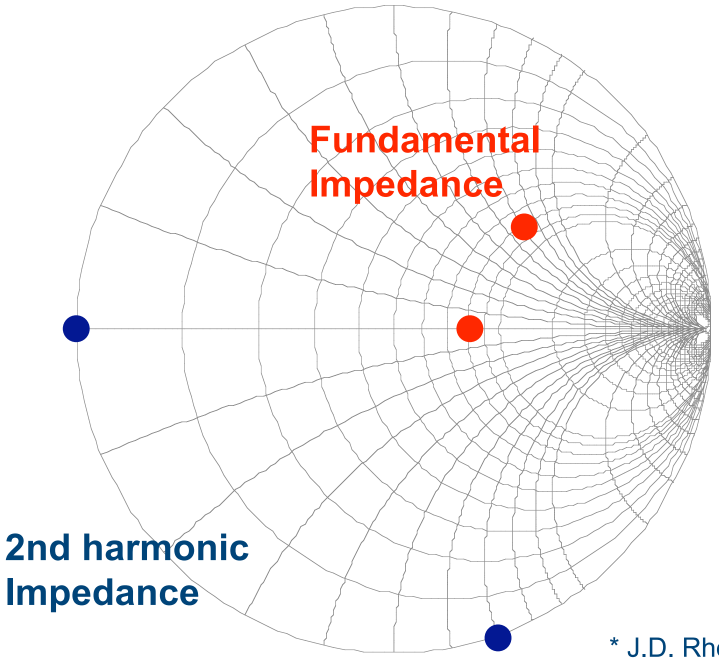
- Consider the Class B and Class J Mode of operation
  - Both have a half rectified current waveform
  - Both have the same theoretical power and efficiency values
  - But have very different voltages waveforms
    - Different fundamental and 2nd harmonic reactance's

Normalised Class B voltage waveform



Normalised Class J voltage waveform





- Are these not just different solutions of the same mode?
  - Rhodes* provide some mathematical insight
    - Optimum fundamental reactance is mathematical defined by harmonic reactive terminations

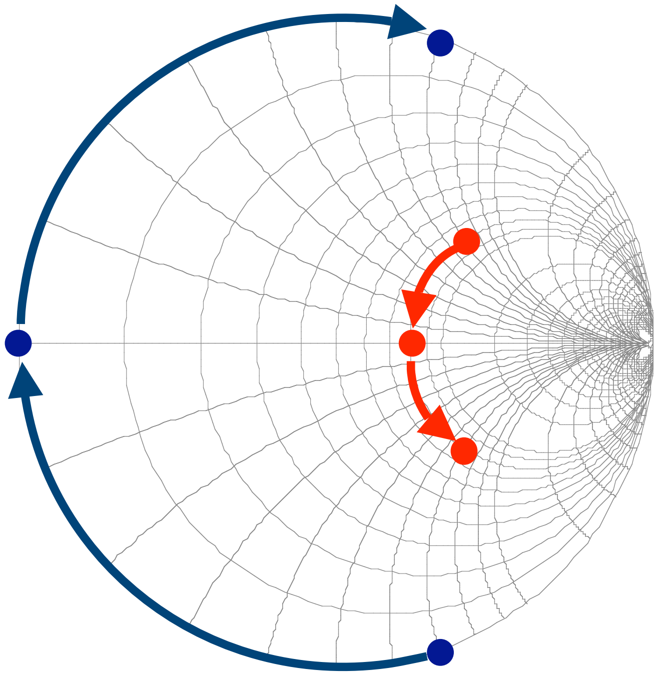
* J.D. Rhodes "Output universality in maximum efficiency linear power amplifiers" International Journal of Circuit Theory and Applications, volume 31, 2003, pp.385-405

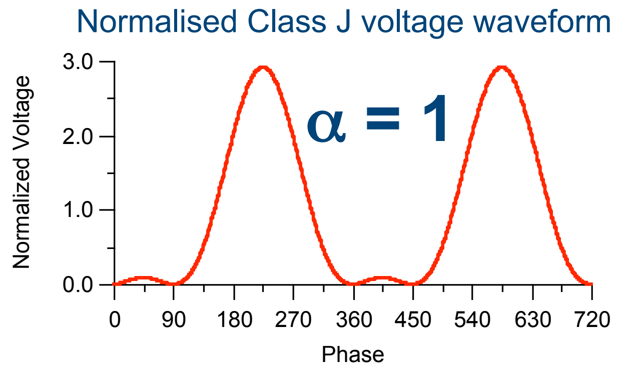
RF Waveform Measurement and Engineering
- provides for new theoretical insight

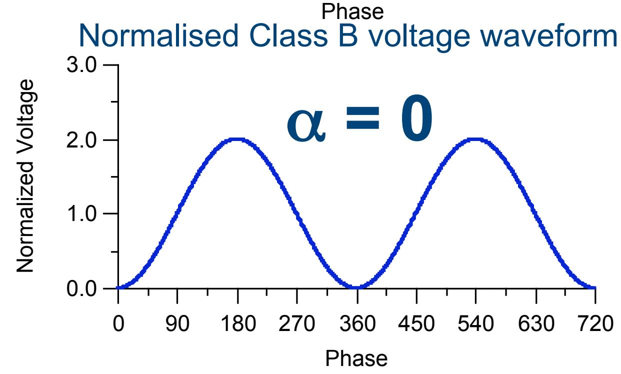
- They are just different solutions of the same mode?
  - The Class J - Class B - Class J* Continuum

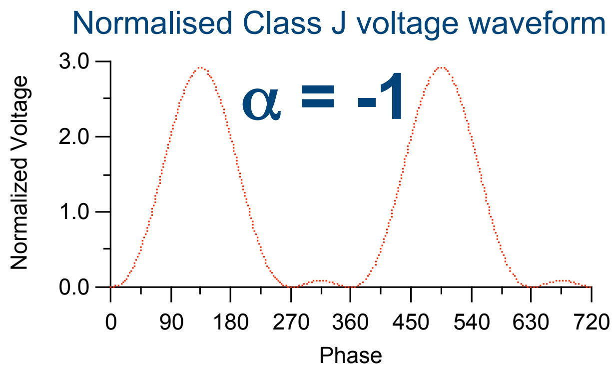
$$v(\theta) = (1-\beta\cos\theta)(1-\alpha\sin\theta), \quad (-1<\alpha<1)$$

  - Many more possible solutions









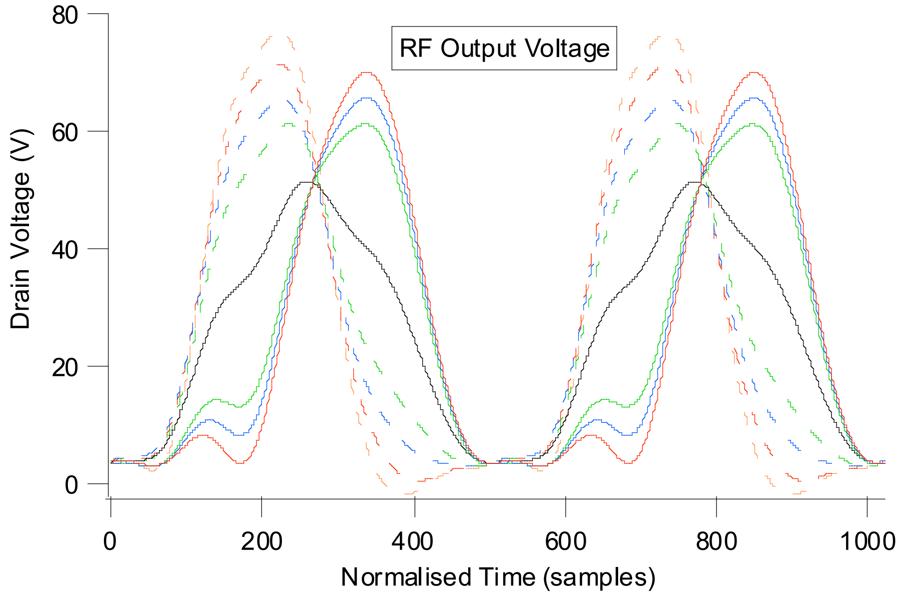
RF Waveform Measurement and Engineering

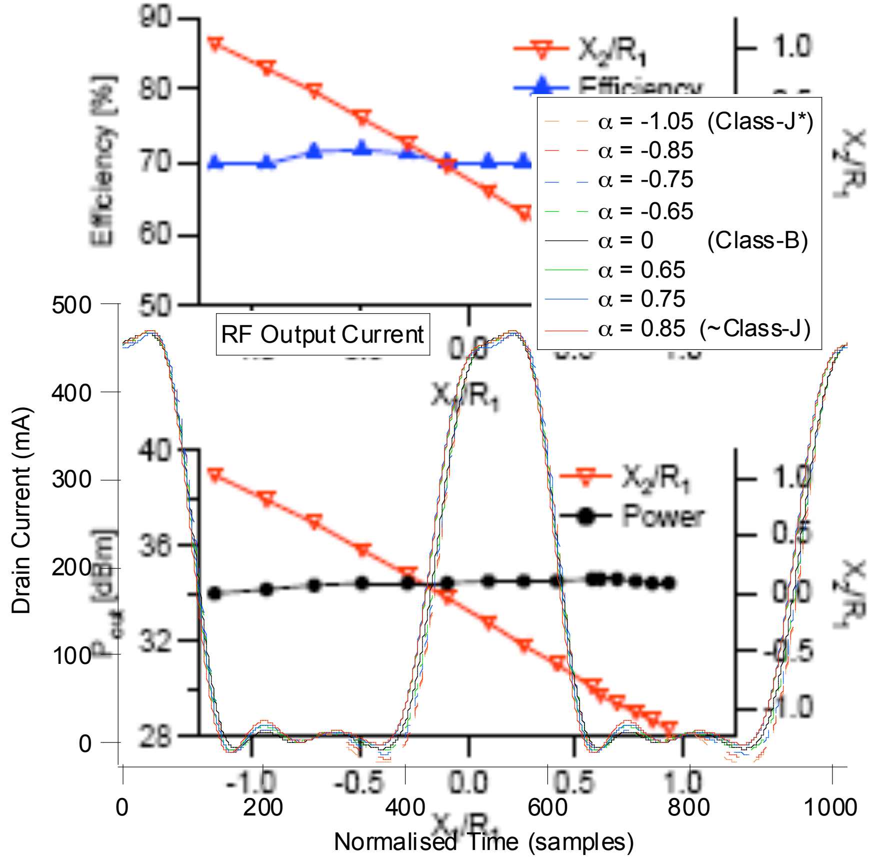
- experimental validation of new theoretical insight

$\alpha = X_1/R_1 = -X_2/R_1$

On Cree 2W on-wafer device:

- Maintain constant P_{in} to device
- Vary $Z(f_0) = R_{opt} + j\,k\,R_{opt}$
- Vary $Z(f_2) = -\,j\,k\,R_{opt}$ $-1 \le k \le 1$



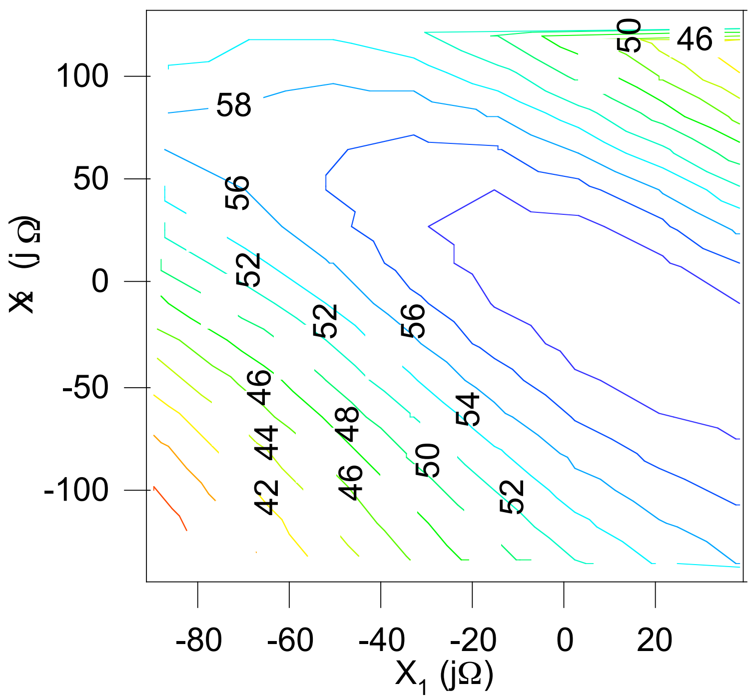


RF Waveform Measurement and Engineering

- Class J-B-J Continuum Sensitivity Analysis*

On Cree 2W on-wafer device:

- R_1 held to R_{opt}, R_2 held to 1.5Ω
- X_1 and X_2 were swept to examine the impact of the deviation off the Class-JB continuum contour



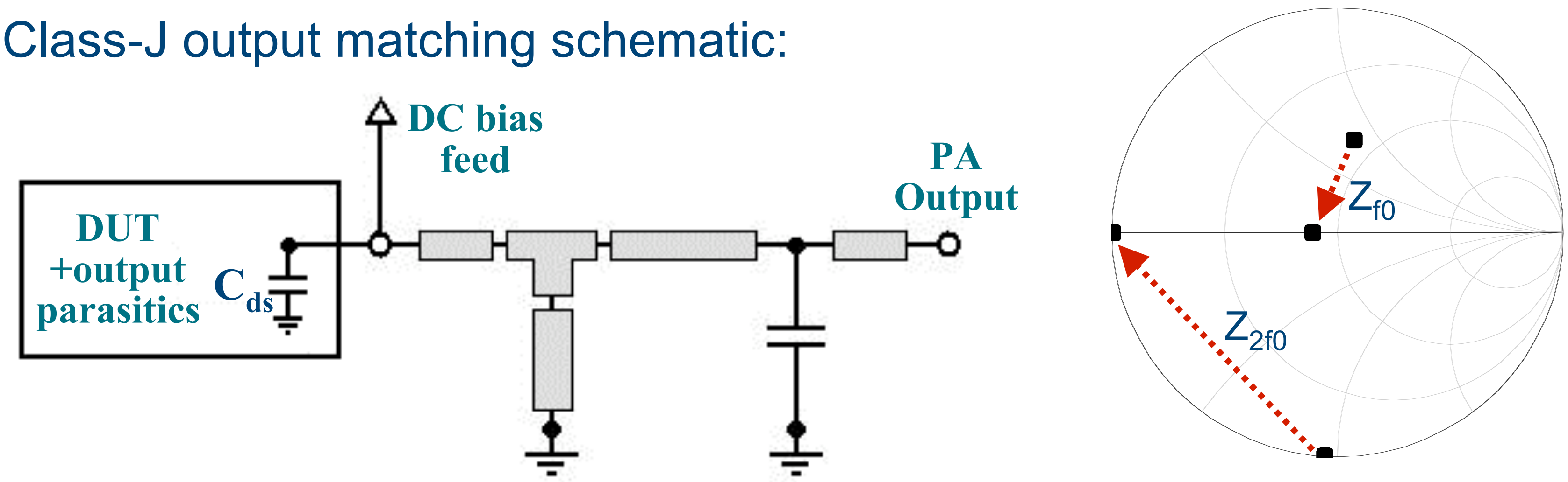
Results

- Class-JB continuum visually identifiable with a high efficiency contour
- Roll-off of efficiency is greater for a deviation in fundamental load compared to second harmonic

Increased design flexibility

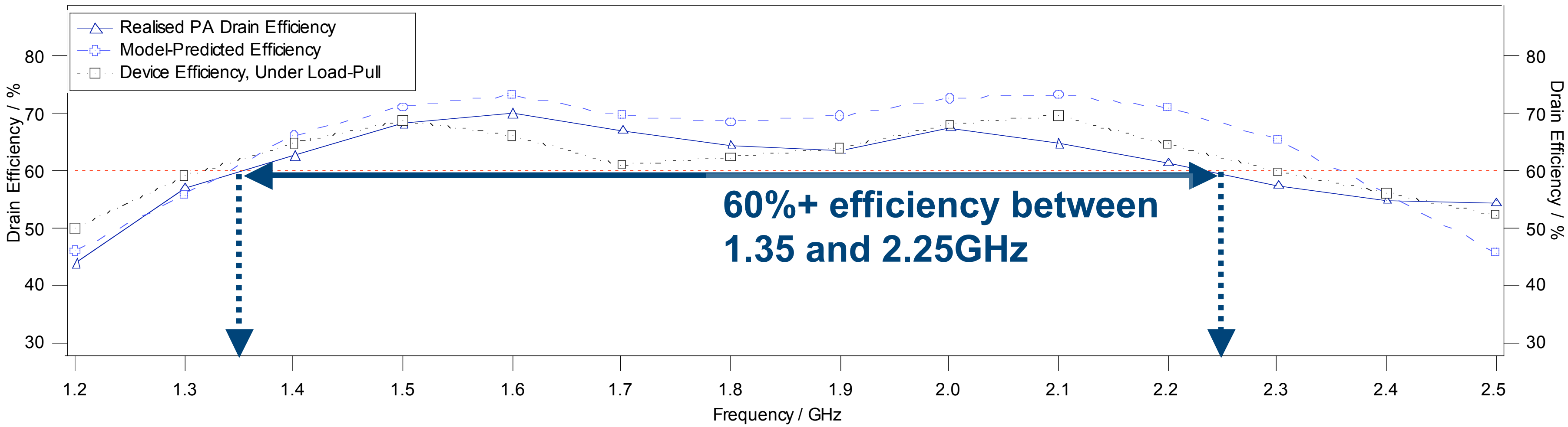
Realising Class-J Matching

Class-J output matching schematic:



- Compromises need to be made/considered across this size of bandwidth.
- **Fundamental load impedance matching given priority.**
- Second harmonic already close to optimum class-J reactance at centre frequency of desired bandwidth as a result of output capacitance C_{ds}
  → Z_{2f0} allowed more latitude during the design.
- Shunt shorted-stub increases the effective capacitive reactance of second harmonic load at lower frequencies.

Performance of PA Prototype (1st it.)

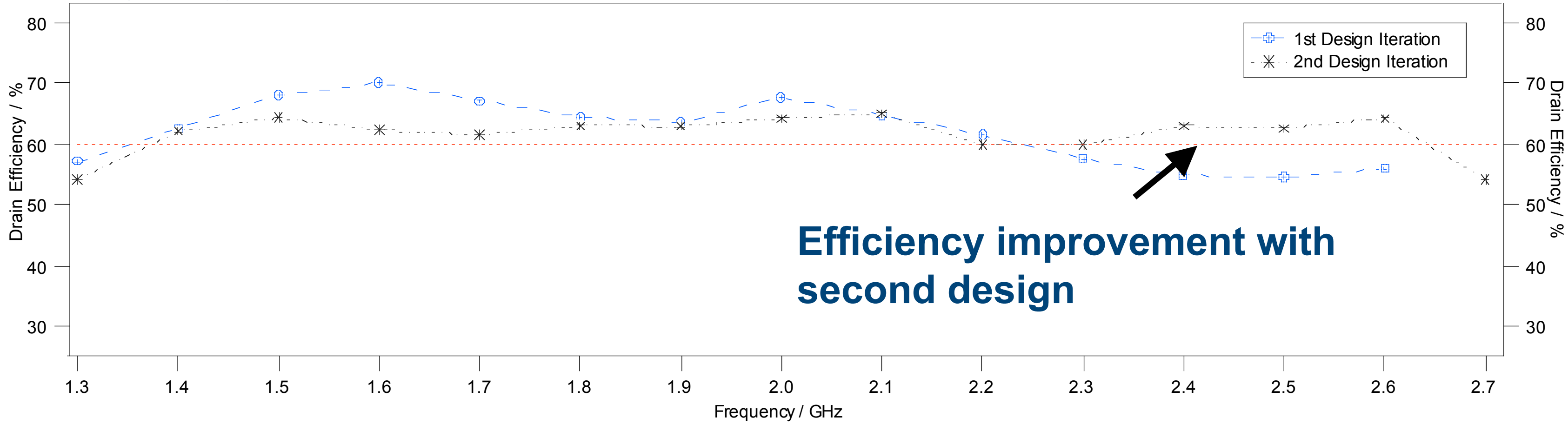


- The PA shows a measured 60%-and-above drain efficiency across the frequency range 1.35-2.25GHz.
- **Drain efficiency measured for PA, model simulation and load-pull emulation.**
- Closely agreeing results with the load-pull emulation.
- **Output power across this same bandwidth is 9-11Watts (device-rated power).**

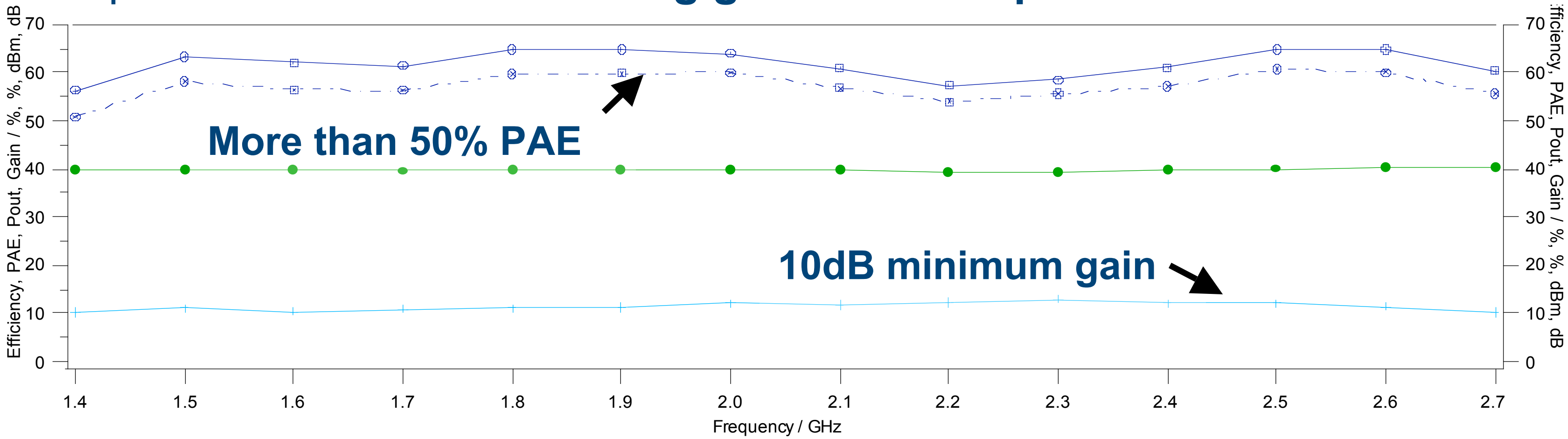
Proposed bandwidth not met entirely, but still a 50% bandwidth PA achieved.

Performance of PA Prototype (2nd it.)

- Second design iteration extending high-efficiency operation across the originally intended PA bandwidth of 1.5-2.5GHz

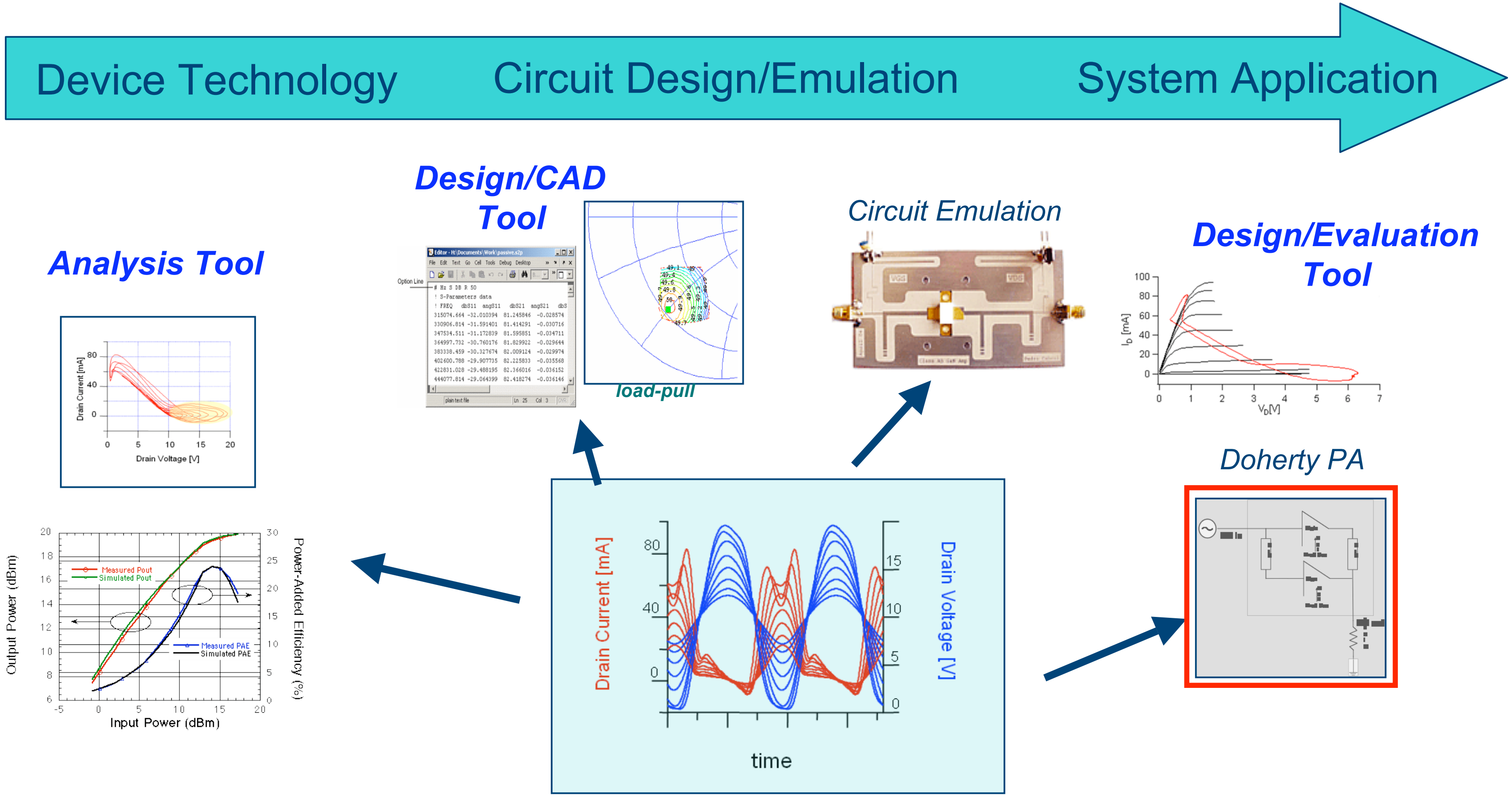


- Input matched PA → **Resulting gain and PAE profiles**



RF Waveform Measurements and Engineering

– a powerful tool and concept



Waveform are the unifying link between device technology, circuit design and system performance

RF IV Waveform Measurement and Engineering

- Emerging Multi-Tone Systems -

Centre for High Frequency Engineering

School of Engineering

Cardiff University

Contact information

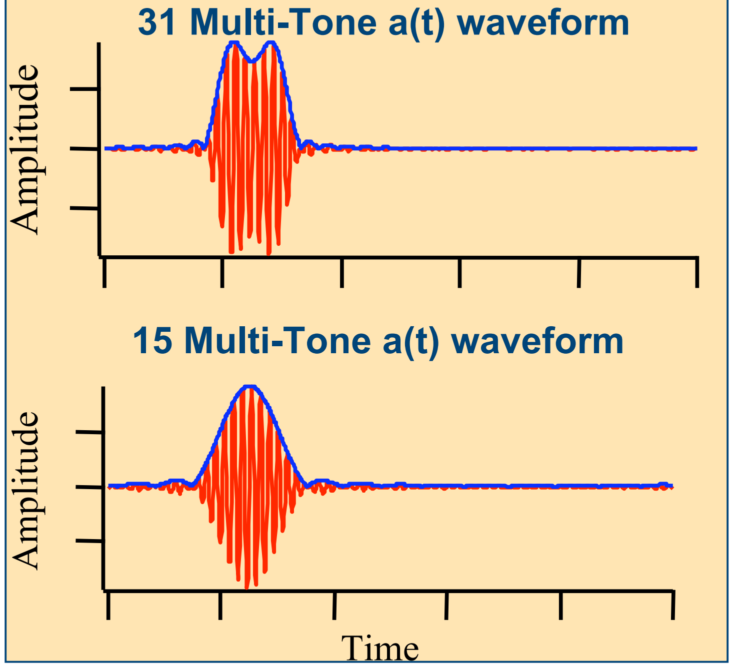
Prof. Paul J Tasker – ***tasker@cf.ac.uk***

website: www.engin.cf.ac.uk/chfe

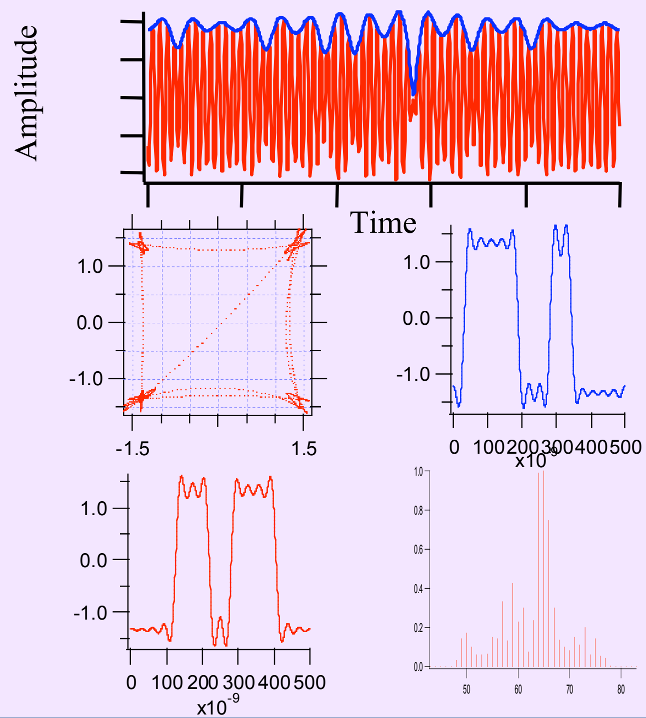
RF I-V Waveform Measurement & Engineering
- Demand for Multi-Tone Excitation

- Synthesize “real” system stimulus

- Pulsed RF ~ *10-100 us*



- Complex Modulation/Multi-Carrier



RF I-V Waveform Measurement & Engineering

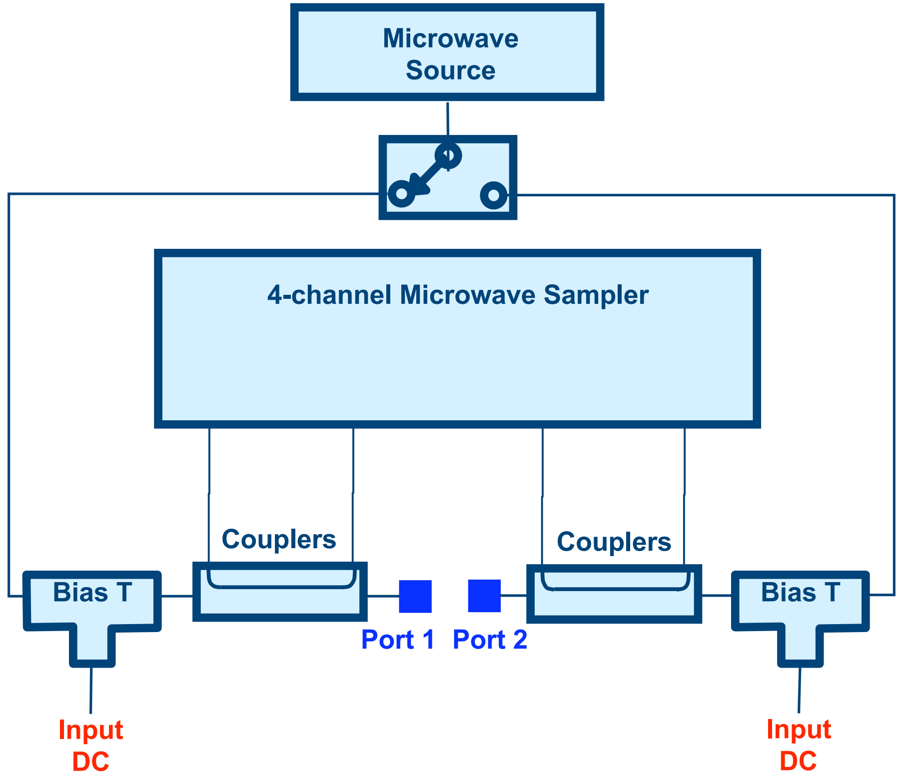
- Demand for Multi-Tone Excitation

- CW (Single Tone) to Modulated (Multi-Tone) Measurement System Development
  - RF Multi-Tone I-V Waveform Measurement
    - Intelligent Sampling
    - Inclusion of IF (Base-band signals)
  - RF Multi-Tone IV Waveform Engineering
    - IF (Base-band) active load-pull
- Application
    - Memory Investigations: Base-band Electrical Memory
- CW (Single Tone) to Modulated (Multi-Tone) Measurement System Development
  - RF Multi-Tone IV Waveform Engineering
    - RF active load-pull (Digital ELP)

RF I-V Waveform Measurement & Engineering

- Multi-Tone Measurement Requirements

- Need to extend sampling strategy to accommodate multi-tone excitation
  - folded and interleaved sampling
- Need test-set architecture to account for all frequency components
  - RF hardware between DUT and the sampling receivers ignores base-band components

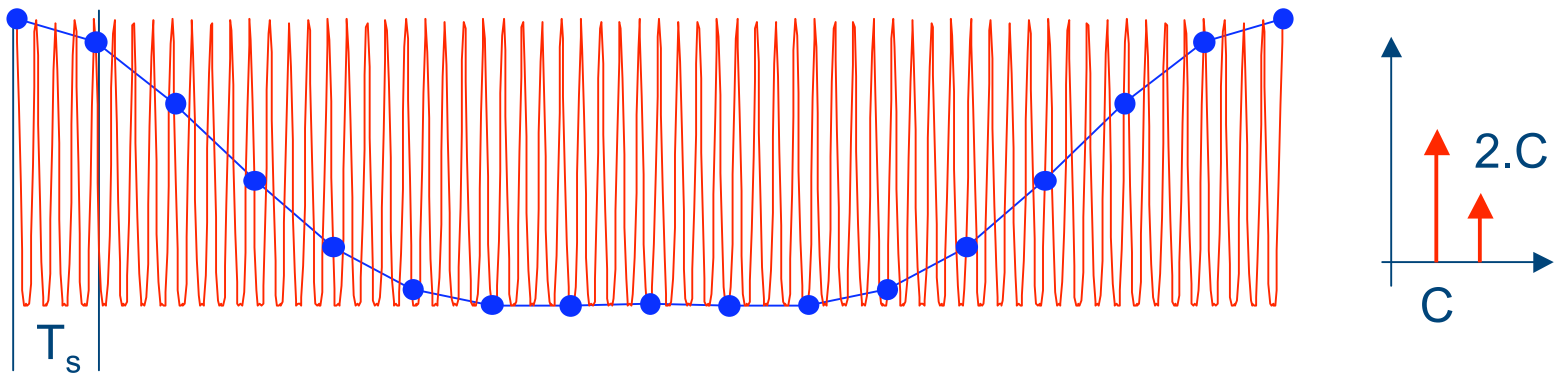


RF I-V Waveform Measurement & Engineering

- Intelligent Sampling: Review CW Case

- CW Period Stimulus on a Specific Frequency Grid
  - Sample over many RF cycles (M.P + C.Prime)
    - M is the number of RF cycles contained within the sample period
  - Engineer Sampling T_s=M.T_{rf} + C.Prime.T_{rf}/P (P=sampled points, C=cycles),
    - Multiple solutions f_{rf} = f_s.(M.P+C.Prime)/P are sampled into Fourier location C
    - If Prime (prime number) is greater than 1, time interleaving also occurs
  - Independently Engineer the Fourier location of frequency components

M=4
P=16
C=1

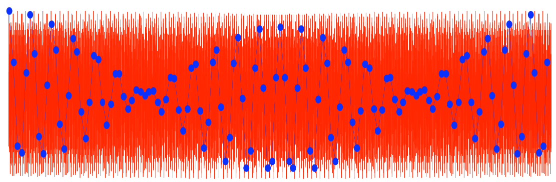


RF I-V Waveform Measurement & Engineering

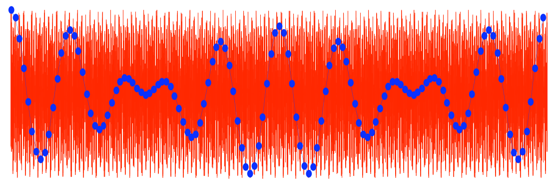
- Intelligent Sampling: Multi-Tone Case

- Multi-Tone Period Stimulus
  - Sample over many modulated RF Cycles
  - Independently engineer Fourier location of carrier (and harmonics) and modulation (and distortion)
    - $T_s = N.T_{mod} + T_{mod}/P$ thus $f_{mod} = f_s.(N.P+1)/P$ (Fourier Location 1)
    - $T_s = M.T_{rf} + C.T_{rf}/P$ thus $f_{rf} = f_s.(M.P+C)/P$ (Fourier Location C)

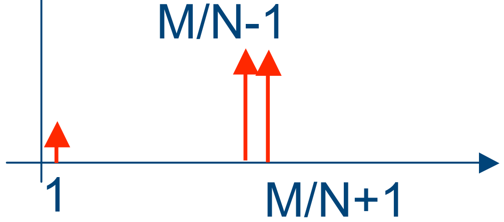
M=50
N=2
P=128
C=25

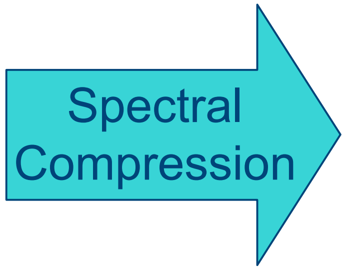


M=50
N=2
P=128
C=9

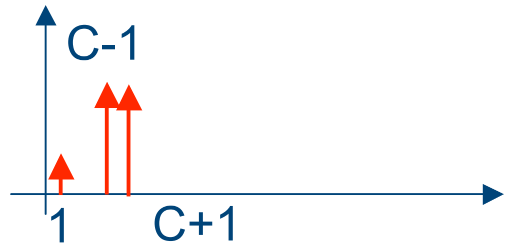


With C=M/N

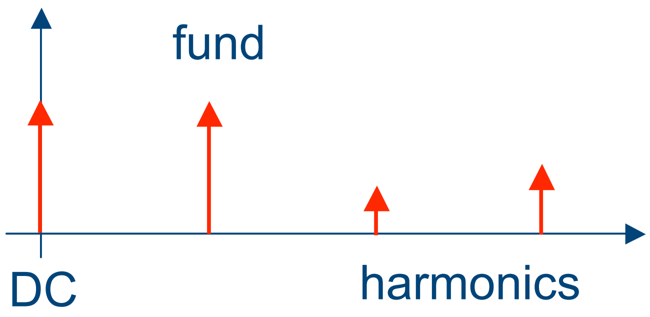




With C≠M/N (=2.Order+1)

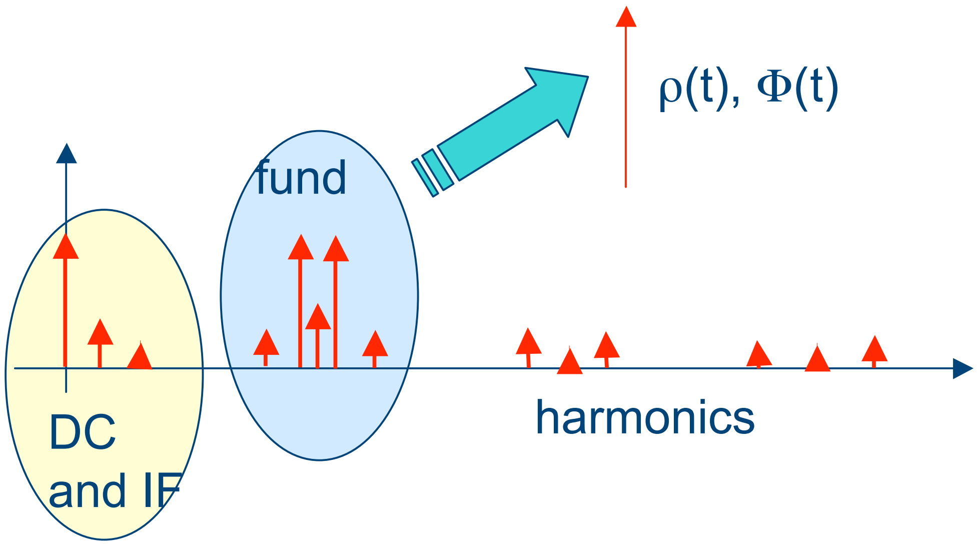


RF I-V Waveform Measurement & Engineering
- Multi-Tone versus CW



- Spectrally sparse
  - Simple sampling (measurement)
- Only RF components
  - Simple engineering

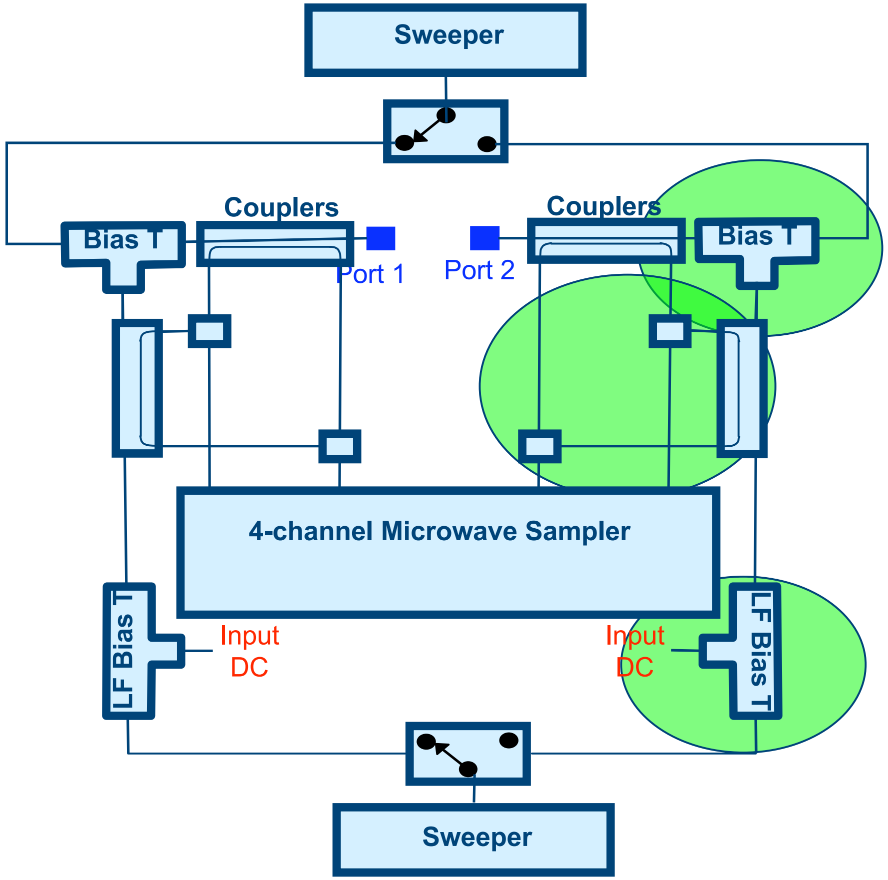
- Spectrally rich but “grouped”
  - Envelope domain
  - intelligent sampling
- RF and IF components
  - measured
  - engineered



Non-Linear Vector Network Analyzer:

- Basic Architecture with RF and IF Test-set

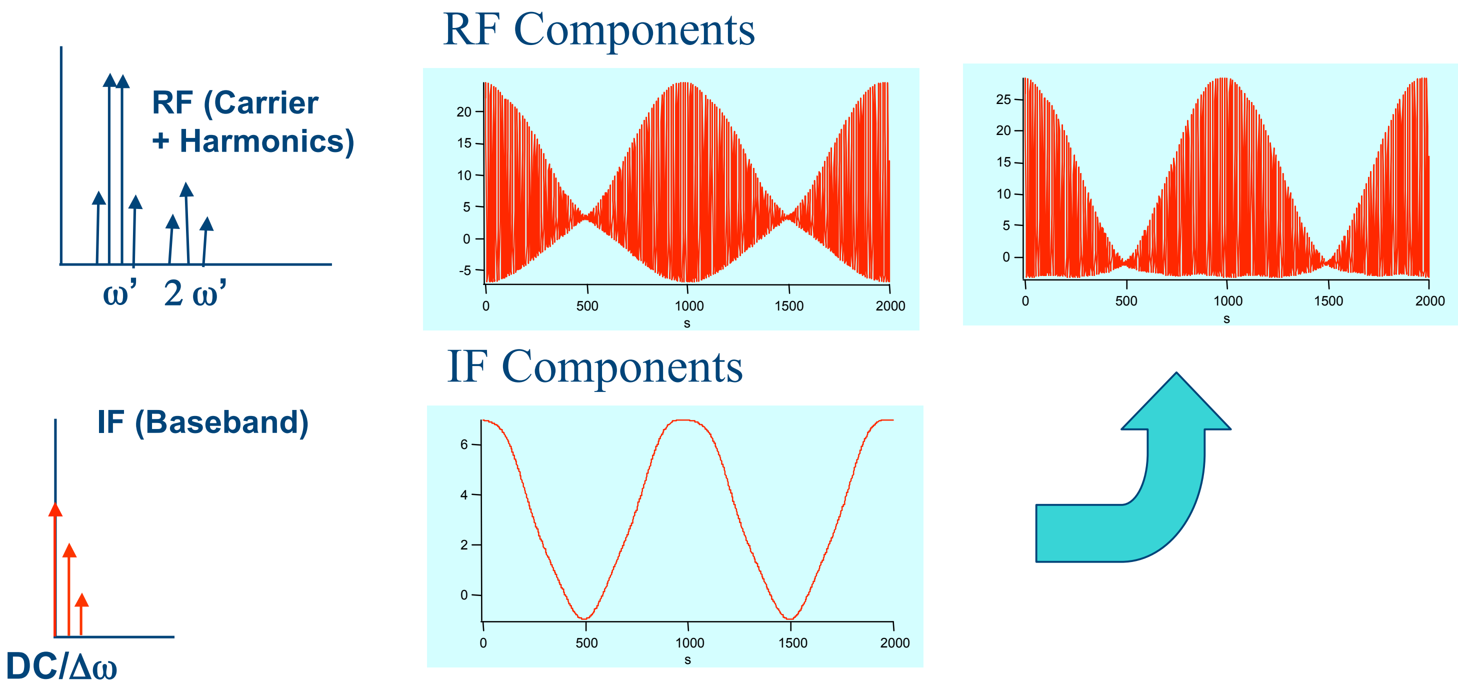
- Requires a very broadband four channel receiver
- Utilizes integrated RF and IF directional couplers for detection/separation of waves
  - Critical components
    - Bias Tee/Diplexer
    - Bias-Tee/Combiner
    - IF Bis-Tee



Measures RF & IF $a_n(t)$ and $b_n(t)$ time varying Voltage Travelling Waves

RF I-V Waveform Measurement & Engineering

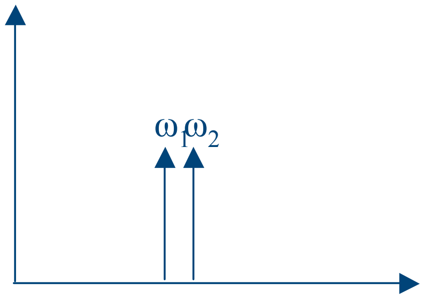
- Need for IF Measurements

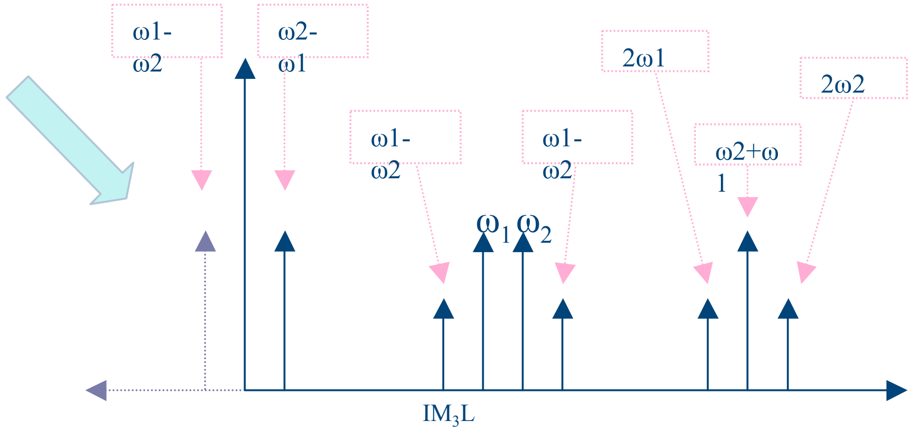


Waveform measurements necessitates all spectral components

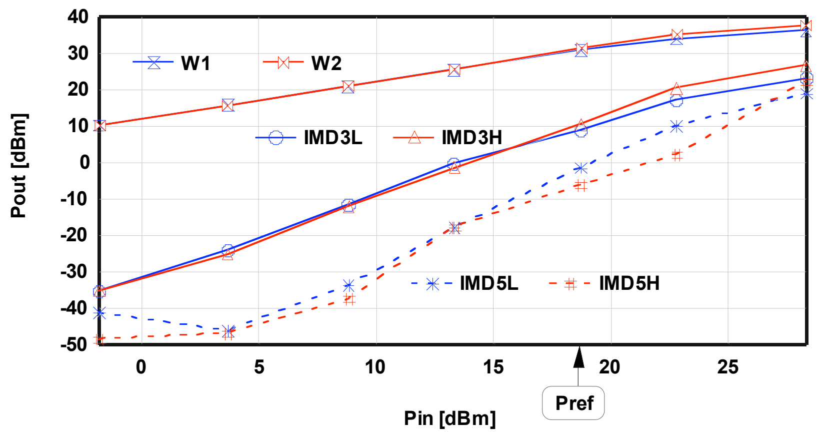
RF I-V Waveform Measurement & Engineering

- Classical IF Measurements and Data Presentation





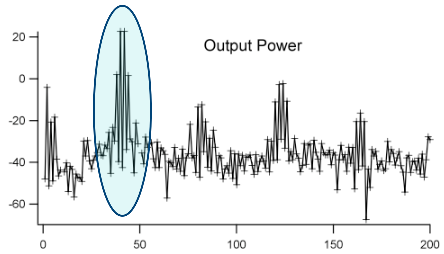
- Classical 2-tone often used
- Observation of IM magnitude and ***symmetry***
- Limitation – Little insight into sources of memory – just the consequences
- Traditional Instrumentation - Spectrum Analysers,
- New Instrumentation - VSA, and recently PNA-X



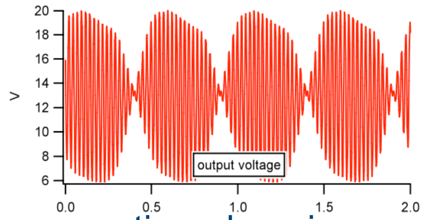
RF I-V Waveform Measurement & Engineering

- Non-Classical IF Measurements and Data Presentation

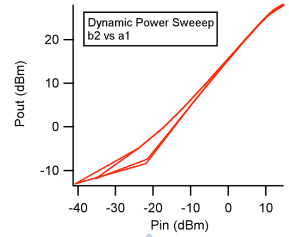
- What is envelope domain analysis
- Powerful approach - intuitive
  - Critical to to capture all significant spectral components
  - DC, Baseband and RF spectra then used to ‘rebuild’ the modulation envelope.
  - Mag and Phase information key in this process.

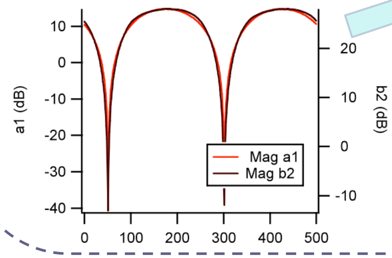


Freq Domain + Phase

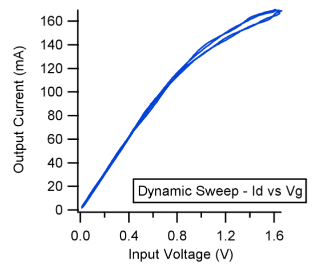


time domain





Dynamic transfer characteristics

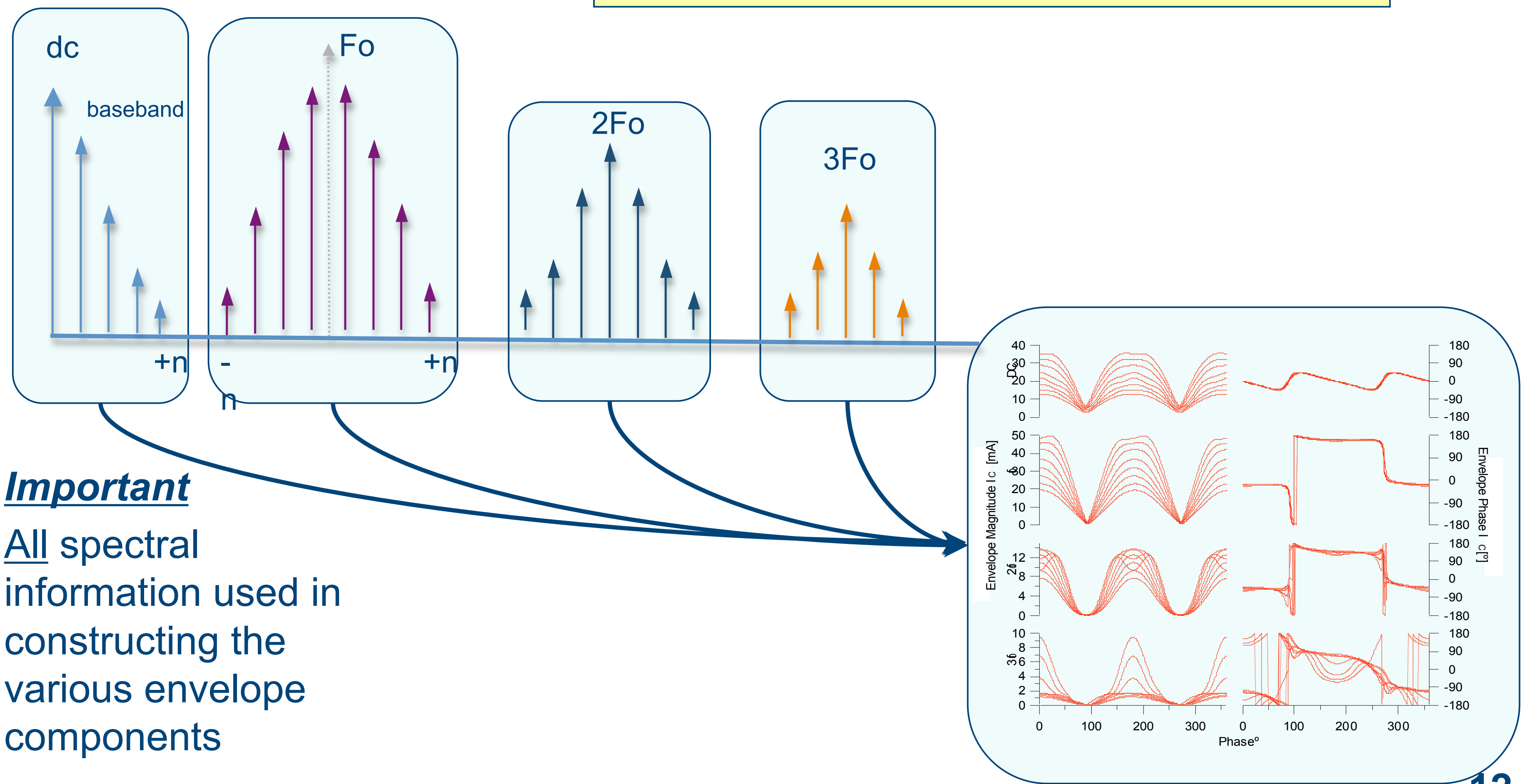


envelope domain (without time)

RF I-V Waveform Measurement & Engineering

- Non-Classical IF Measurements and Data Presentation

Note-need phase information for all of these!

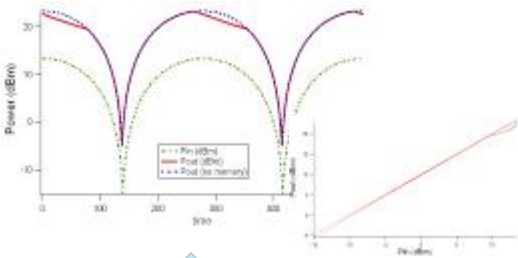


Important

All spectral information used in constructing the various envelope components

RF I-V Waveform Measurement & Engineering

- Investigation Linearity Issues (i.e. Memory)



Surface effects

Electrical effects

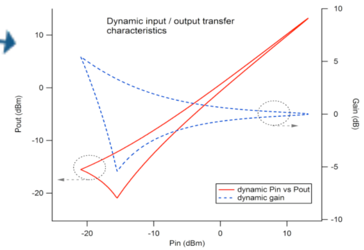
Thermal effects

‘evidence’ of memory

Asymmetry

Dynamic Looping

Non-realiseable Digital Pre-distortion

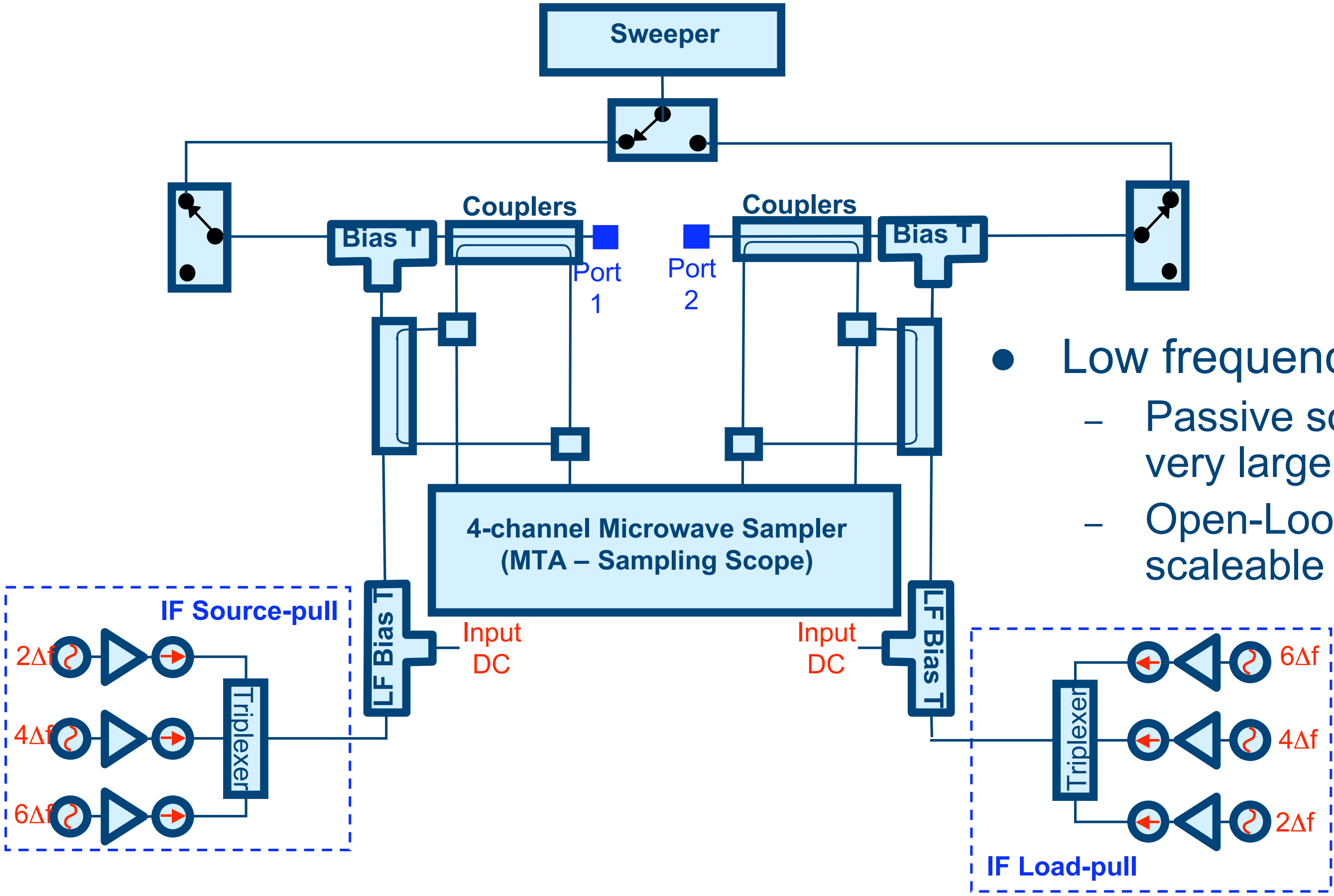


- Baseband
- In-band
- Out-of-band

Combinations

Realization of IF (Base-band) Engineering

- initial focus on bias circuit electrical memory issues



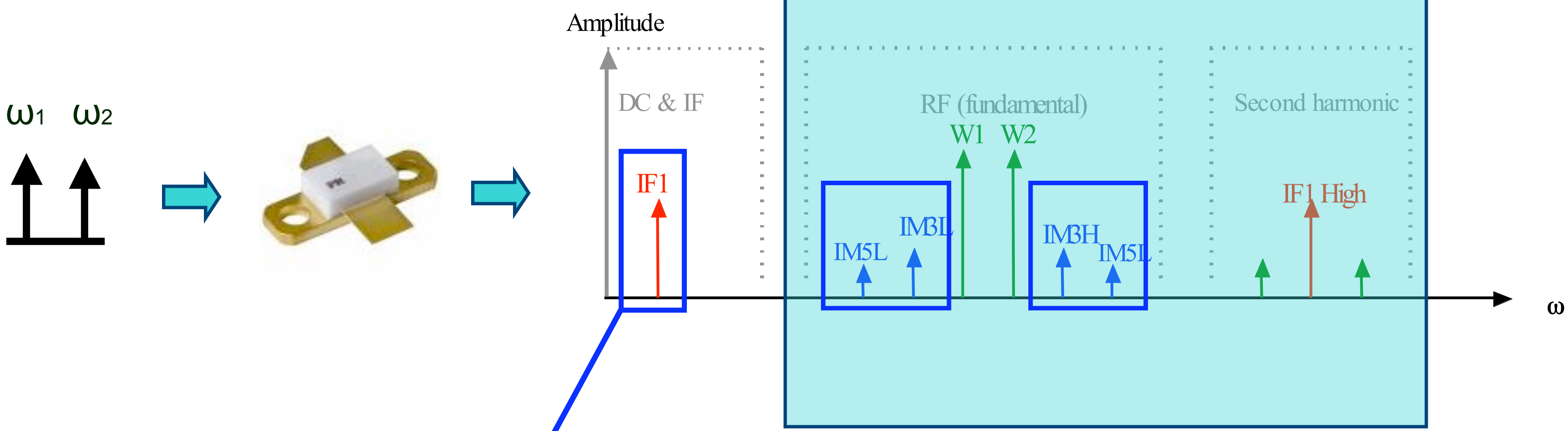
- Low frequencies
  - Passive solution physically very large
  - Open-Loop Active Solution scaleable

Realization of IF (Base-band) Engineering

- initial focus on bias circuit electrical memory issues

Here limited to 2 Harmonics and 5th Order

Constant Impedance Environment



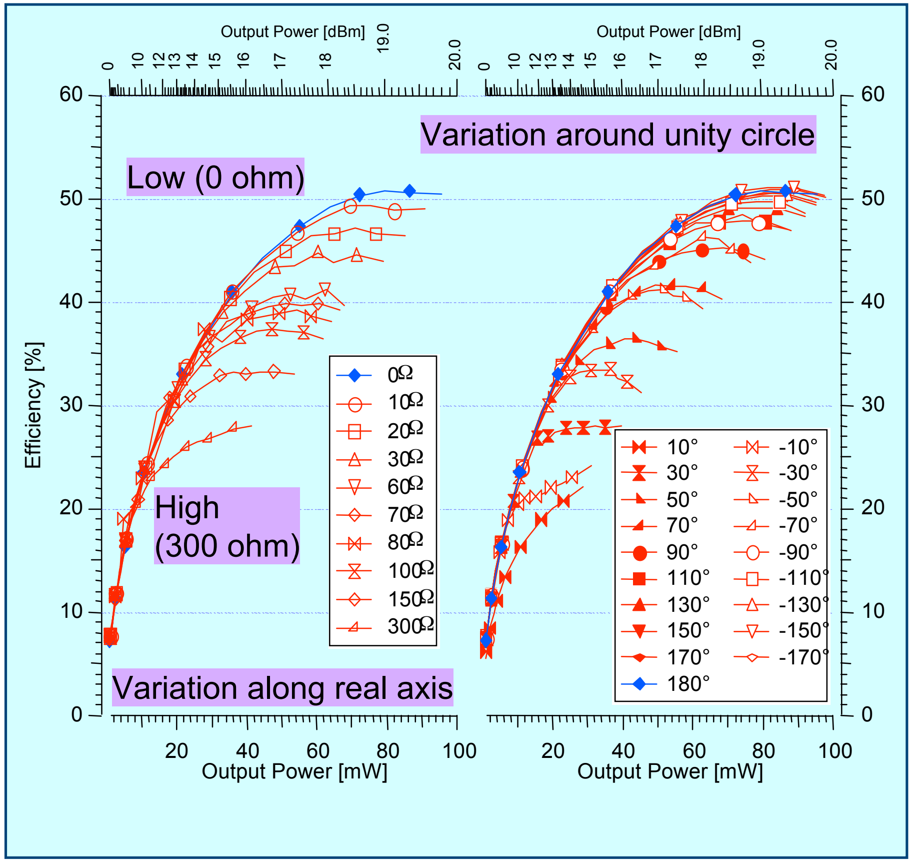
simplified two-tone spectrum up to fifth-order component polynomial transfer characteristic

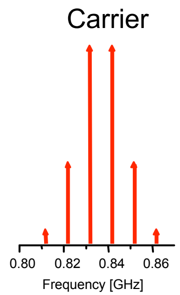
Investigate role of these signals on RF components - engineering the base-band impedance

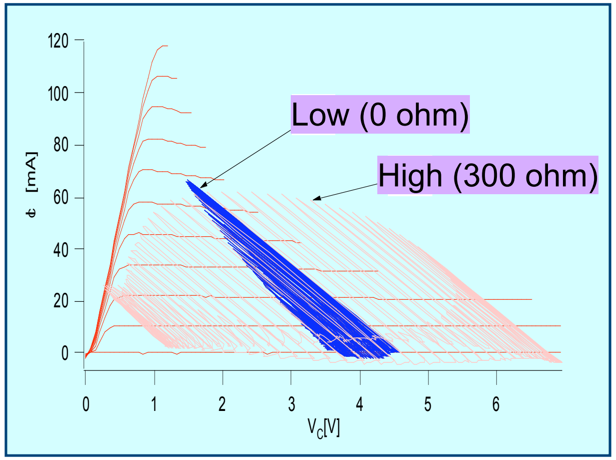
IF Output Voltage Engineering (Envelope Tracking)

- Effect on RF Carrier Output Power (HBT)

IF Load-Pull Effect on Output Power and Efficiency







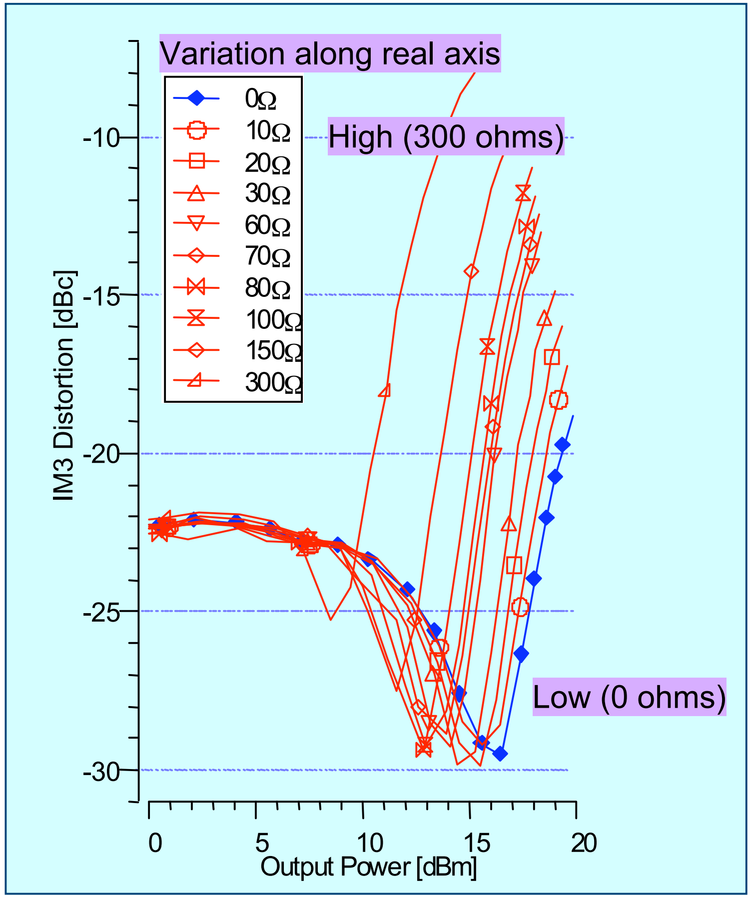
Control of interaction of output dynamic waveforms with knee region explains carrier

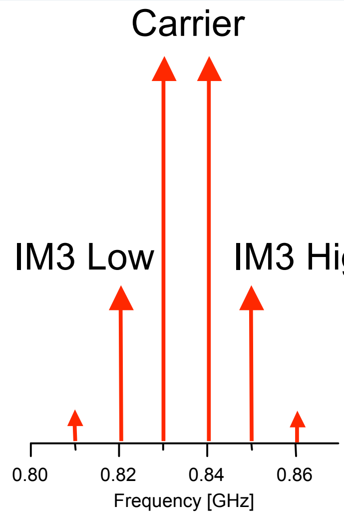
Power and efficiency sensitive to IF load impedance.

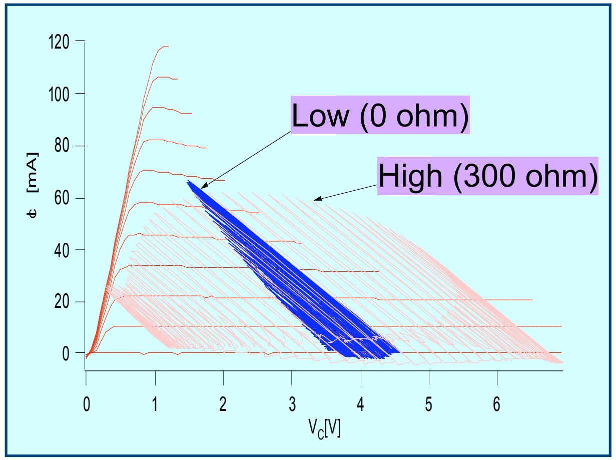
IF Output Voltage Engineering (Envelope Tracking)

- Effect of Amplitude on Intermodulation Distortion (HBT)

IF Load-Pull Effect on IM3 Distortion



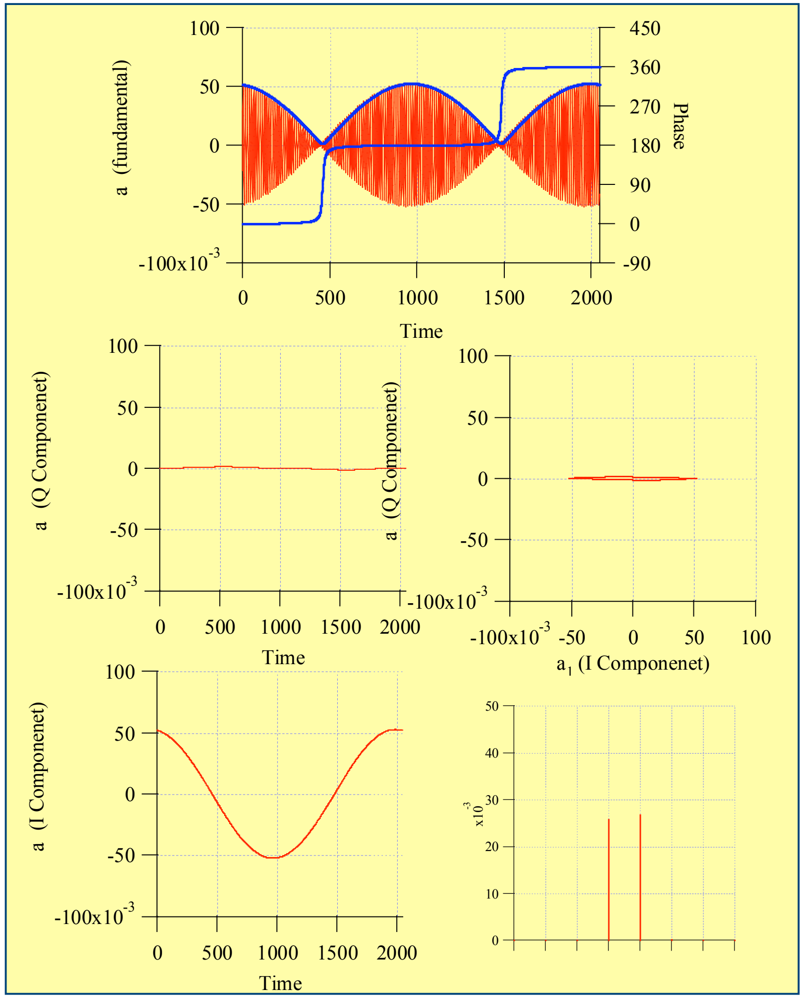


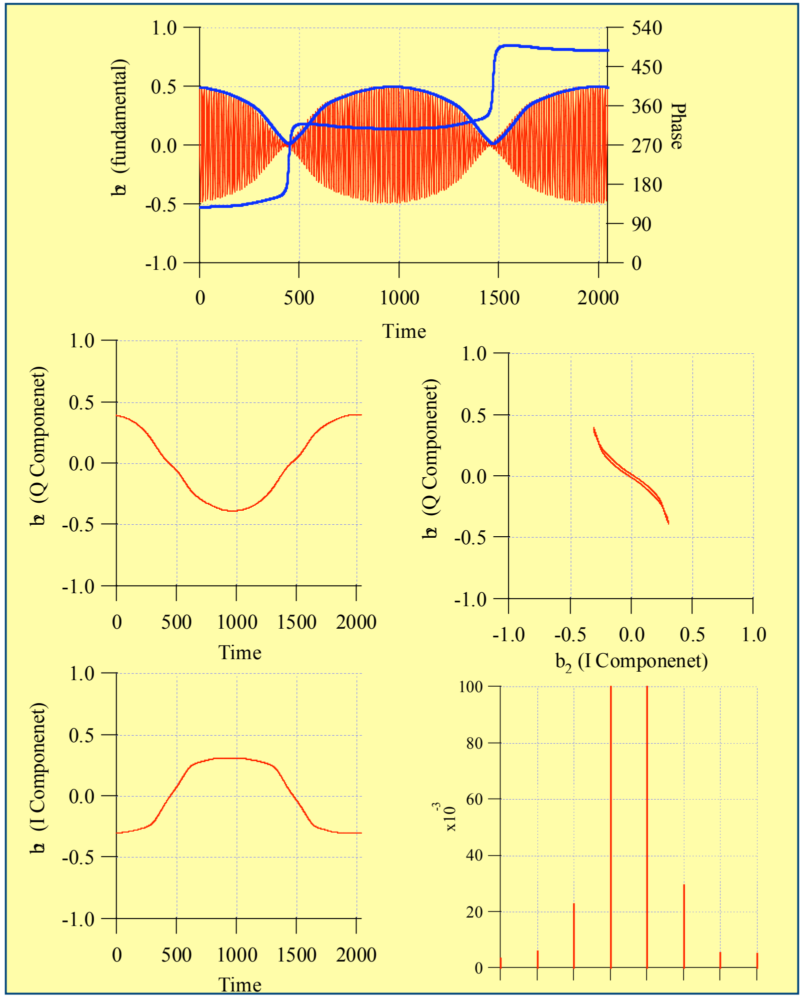


Control of interaction of output dynamic waveforms with knee region explains intermodulation sensitive to IF load impedance.

IF Output Voltage Engineering (Envelope Tracking)

- Effect of Amplitude on Intermodulation Distortion (HBT)

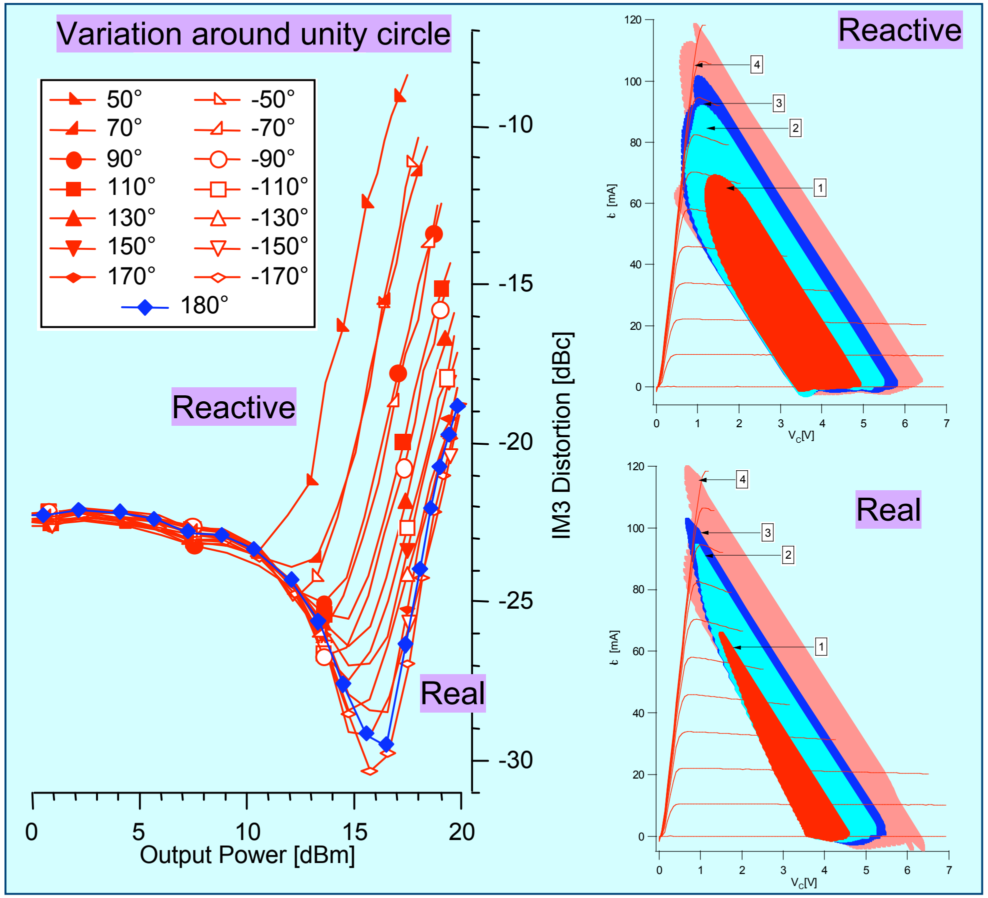


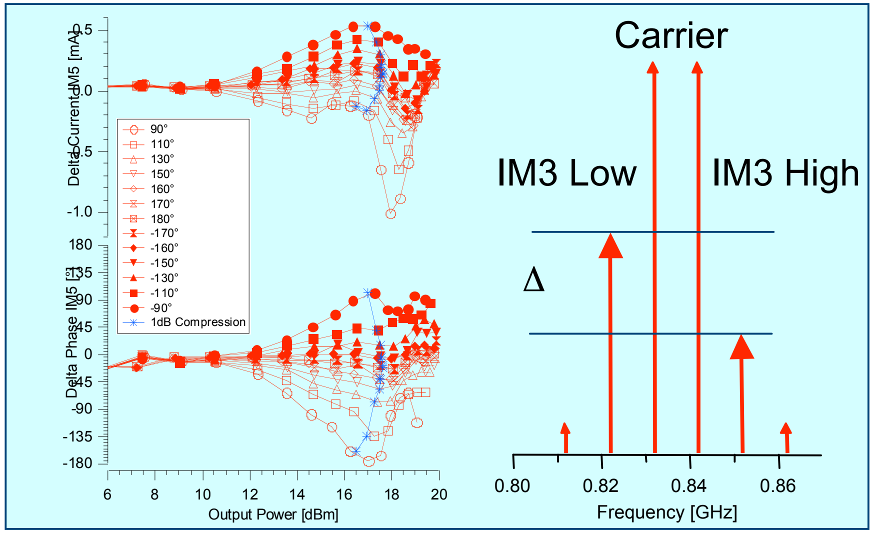


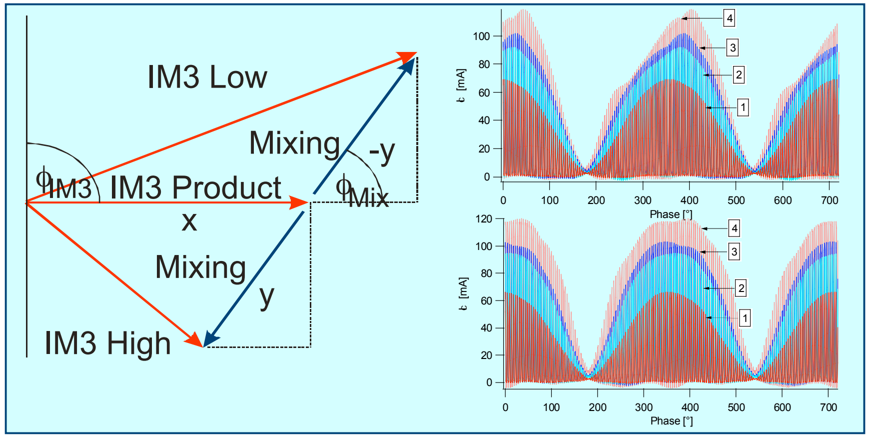
IF Output Voltage Engineering (Envelope Tracking)

- Effect of Phase on Intermodulation Distortion (HBT)

IF Load-Pull Effect on IM3 Distortion



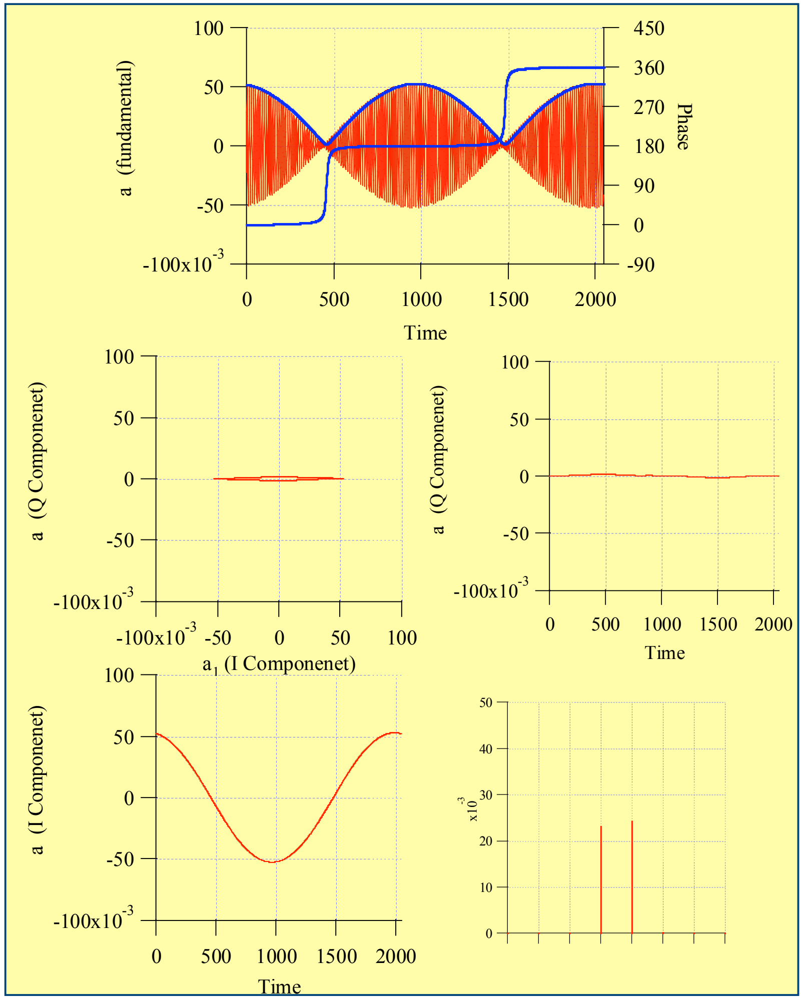


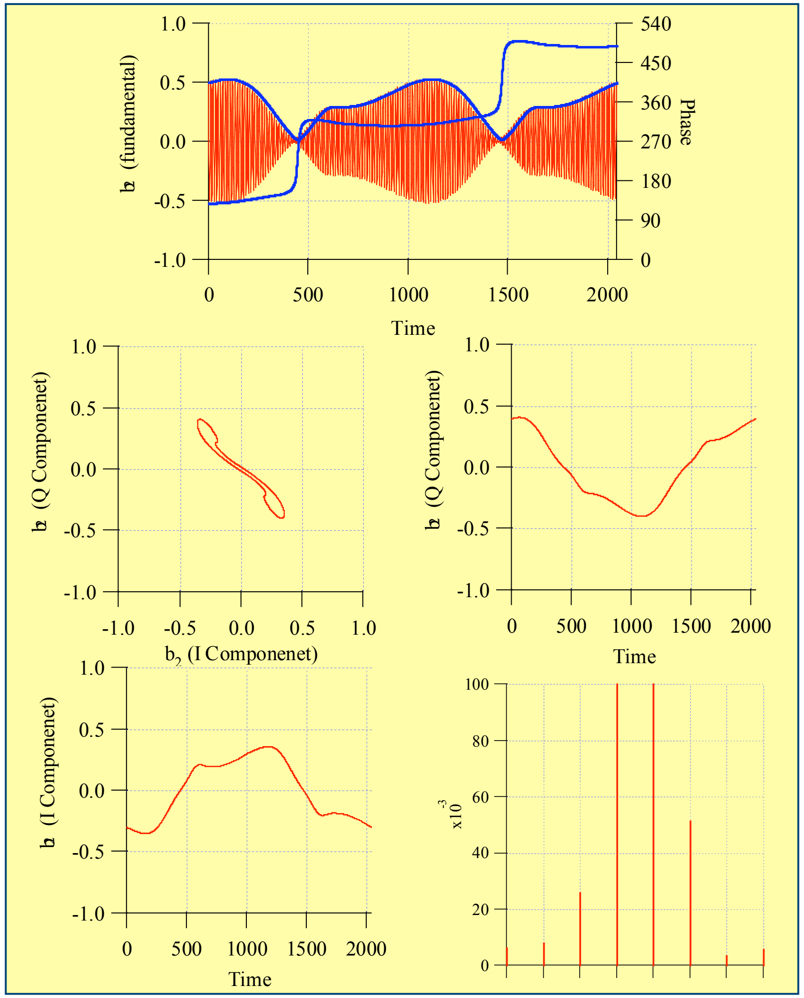


Mixing of transfer and output non-linearities caused by interaction of dynamic output waveforms with knee region explains sensitivity to IF load impedance.

IF Output Voltage Engineering (Envelope Tracking)

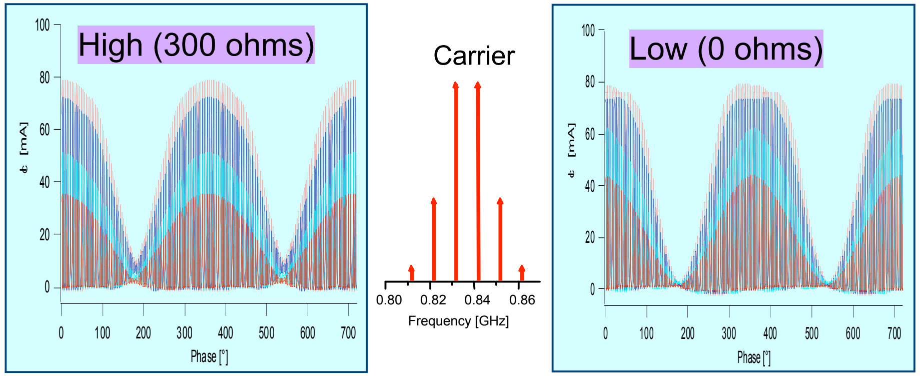
- Effect of Phase on Intermodulation Distortion (HBT)



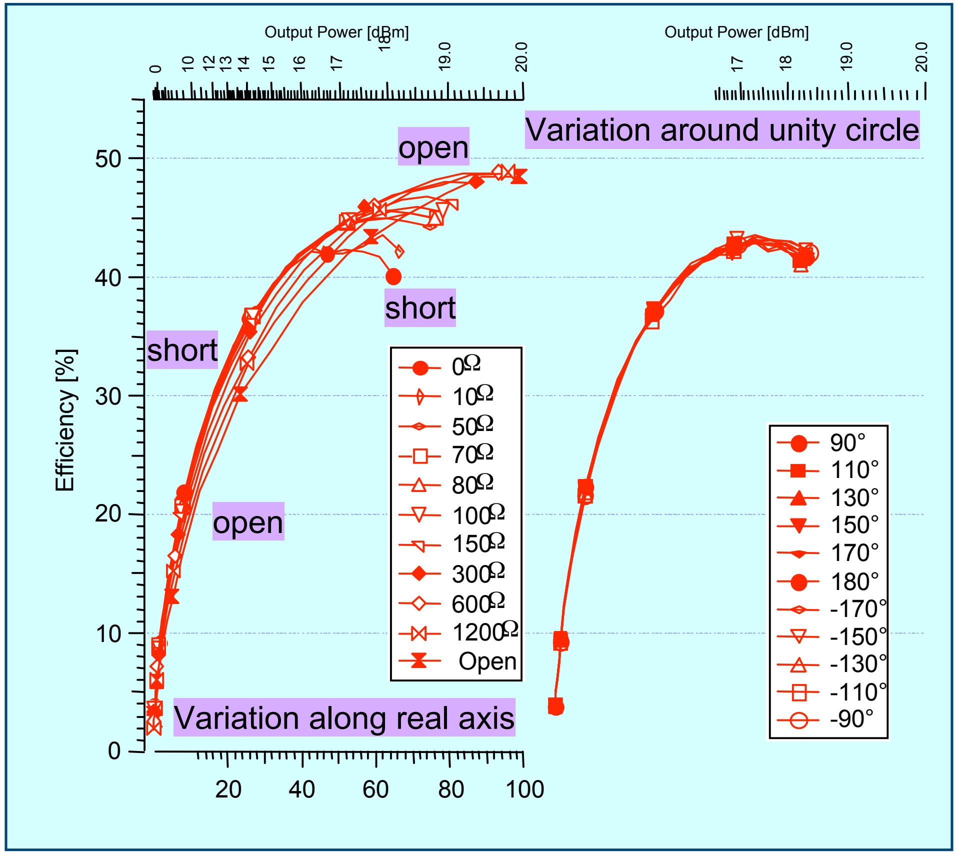


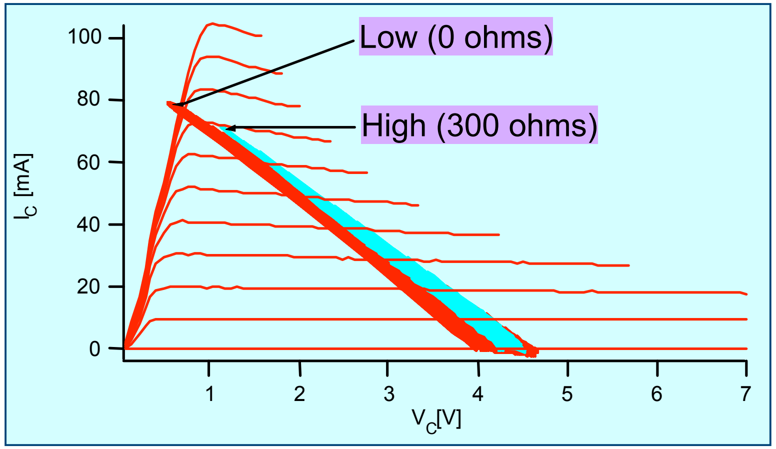
IF Input Voltage Engineering (Pre-distortion)

- Effect on RF Carrier Output Power (HBT)



IF Source-Pull Effect on Output Power and Efficiency



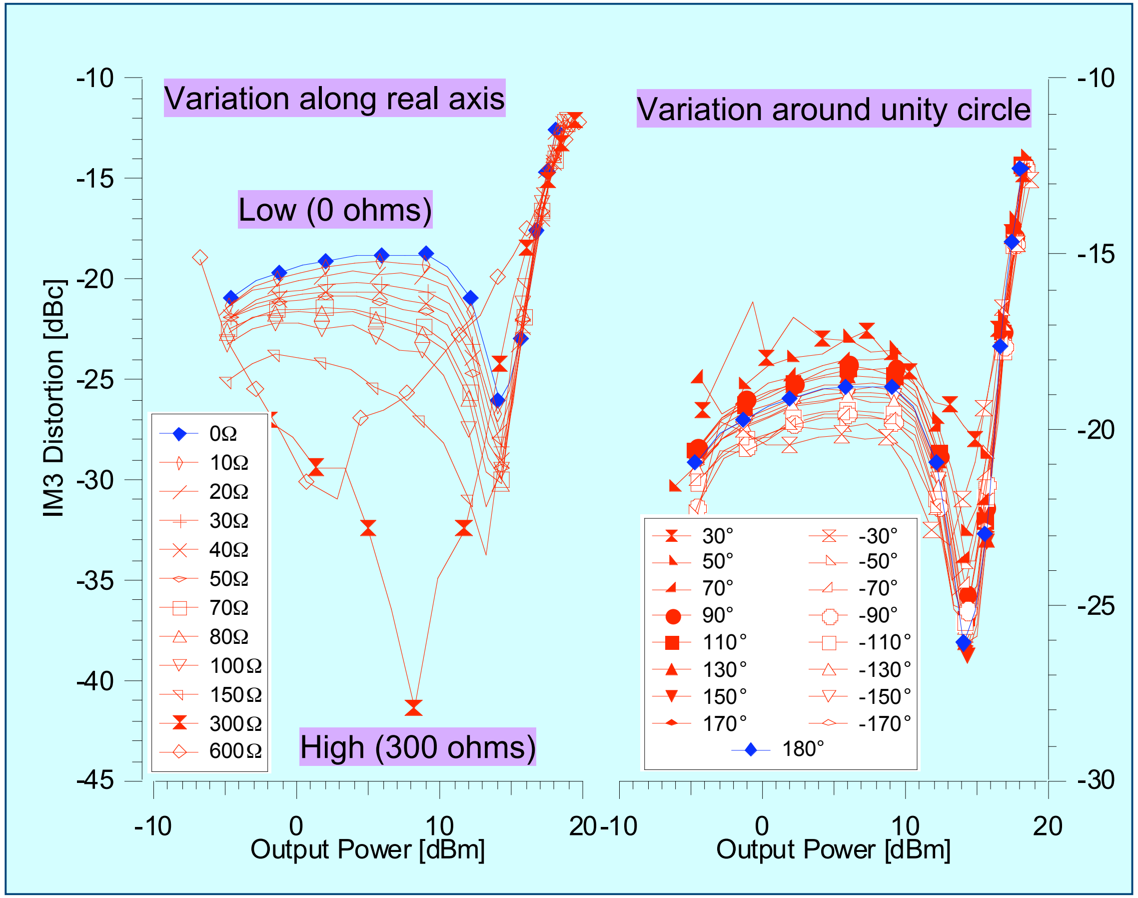


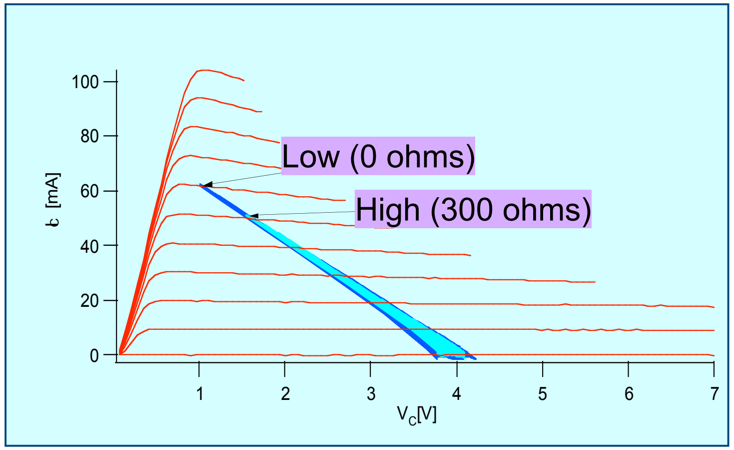
Waveform shape explains carrier power and efficiency sensitive to IF source impedance.

IF Input Voltage Engineering (Pre-distortion)

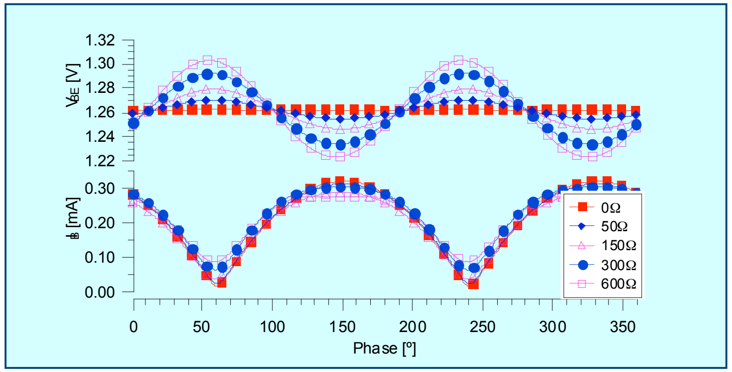
- Effect on Intermodulation Distortion (HBT)

IF Source-Pull Effect on IM3 Distortion





$v_i(t) = A.v_i(\omega_1 t) + B.v_i(\omega_2 t) + C.v_i(2.\Delta\omega t)$



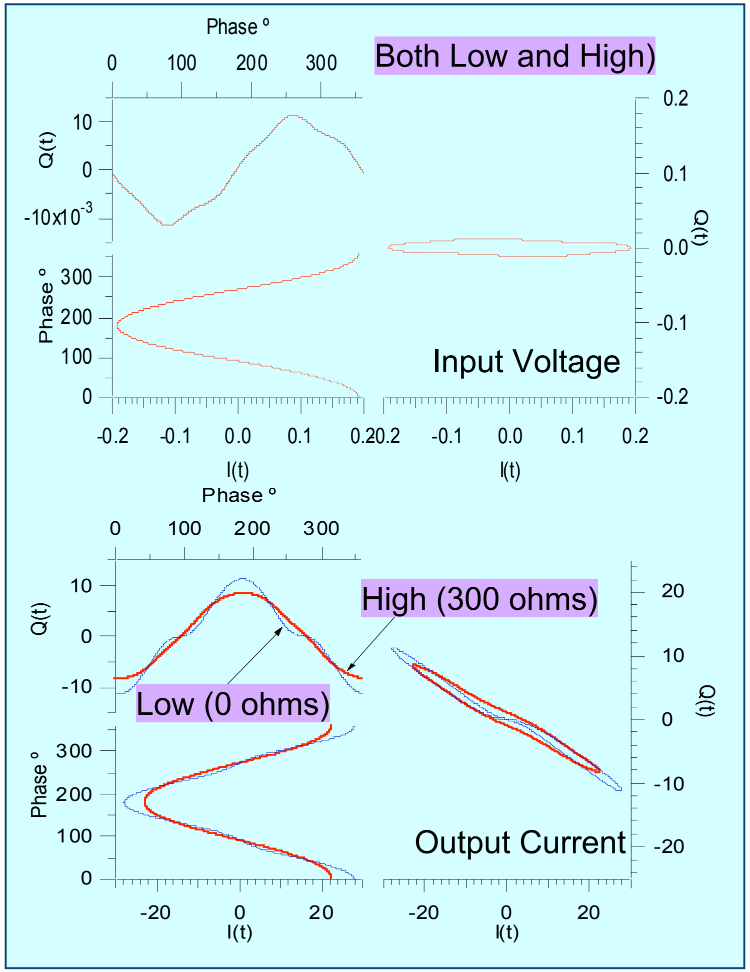
$i_o(t) = a_0 + a_1.v_i(t) + a_2.v_i(t)^2 + a_3.v_i(t)^3$

Transfer function explains intermodulation sensitivity to IF source impedance

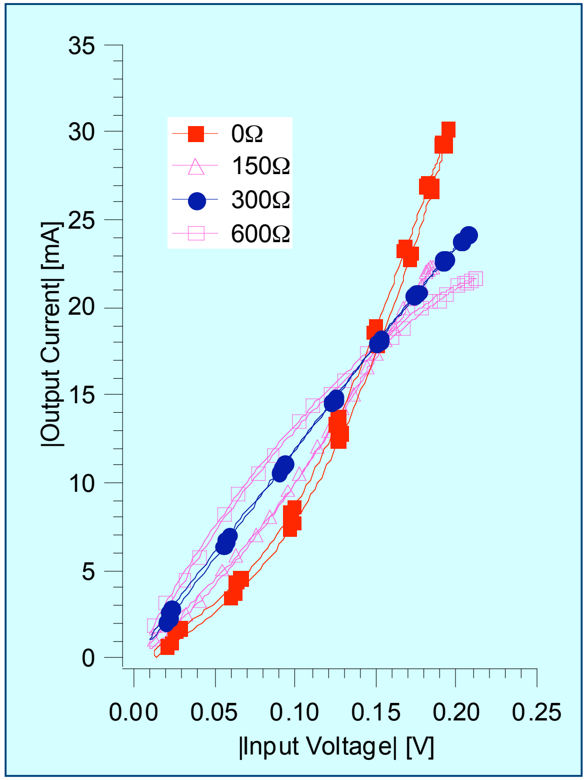
IF Input Voltage Engineering (Pre-distortion)

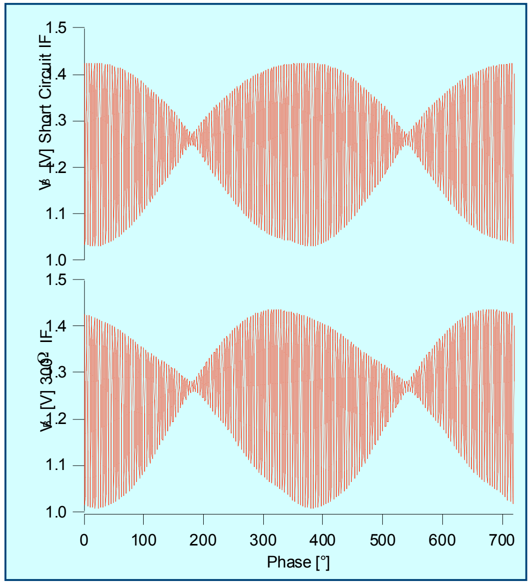
- Optimization of Linearization Process (HBT)

Input Voltage and Output Current Carrier Envelopes



Engineered Carrier Envelope Transfer Function





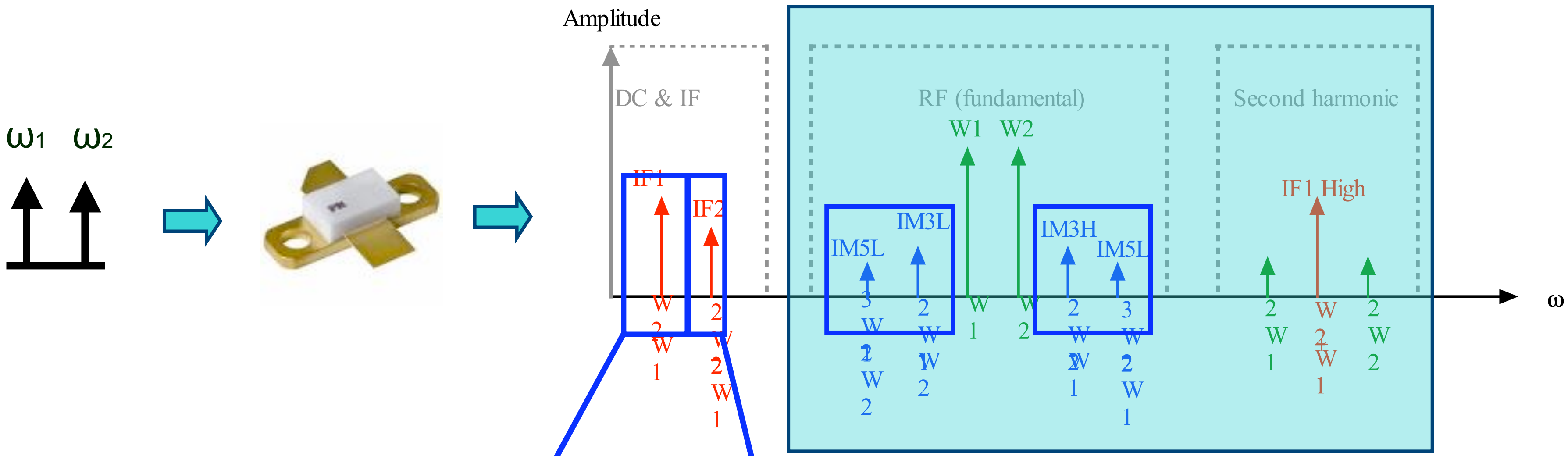
Utilize IF source (input) impedance to engineering predistorted input signal

Realization of IF (Base-band) Engineering

- continue focus on bias circuit electrical memory issues

Here limited to 2 Harmonics and 5th Order

Constant Impedance Environment



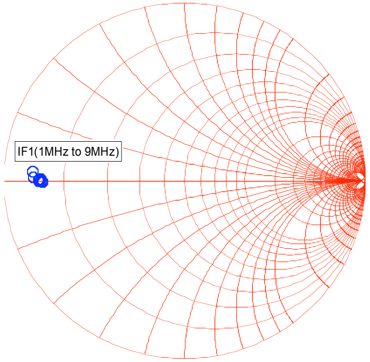
simplified two-tone spectrum up to fifth-order component polynomial transfer characteristic

Previous work investigated IM sensitivity to IF1.

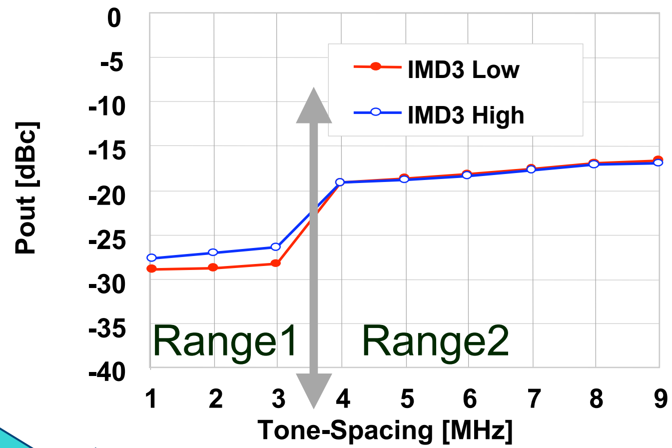
But is some device, high power LDMOS base-band spectra is more complex

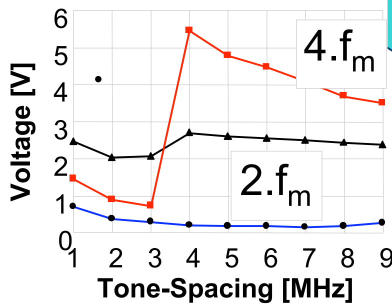
Linearity and Memory Investigations:
- 20W Si LDMOS

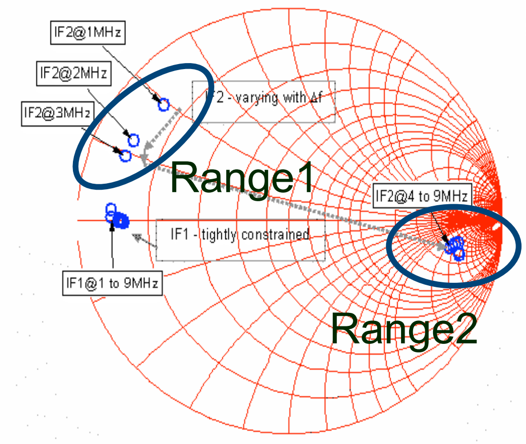
Waveform Engineering:
- Minimize Source of Electrical Memory
- 0.5 to 4.5 MHz AM Modulation (Two Tone: $2.f_m$)

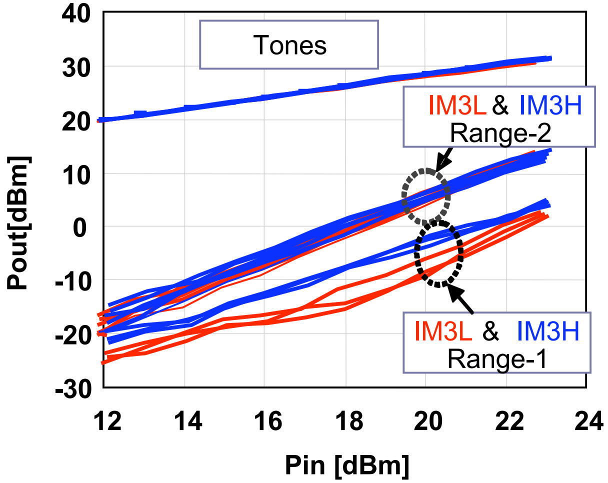


Limitations of Passive Load-Pull)







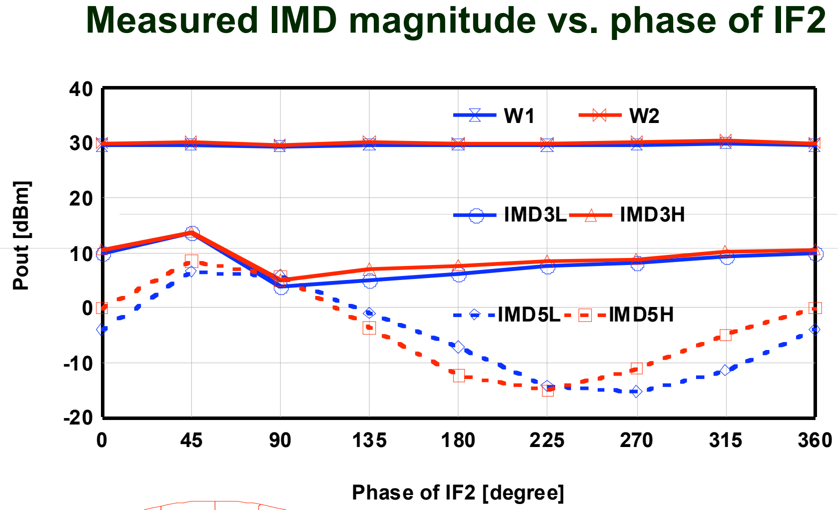


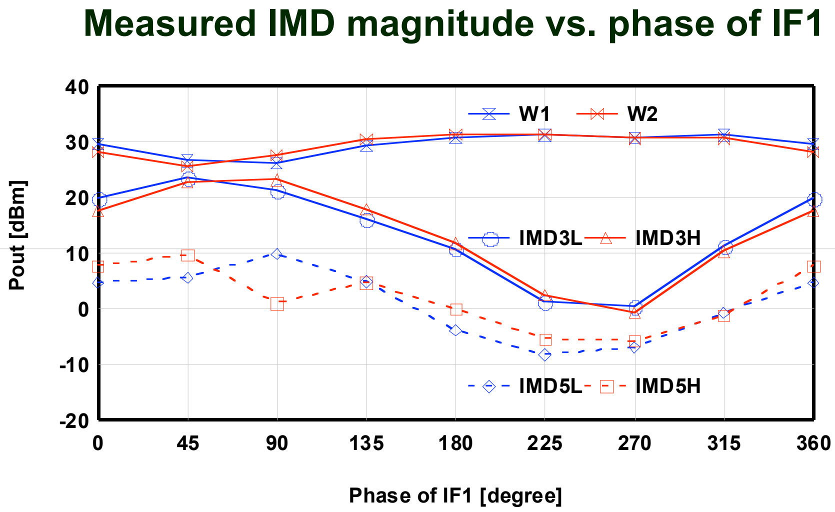
Observations
- Weak Memory Resulted
- Memory/Linearity sensitive to 4 times modulation BW

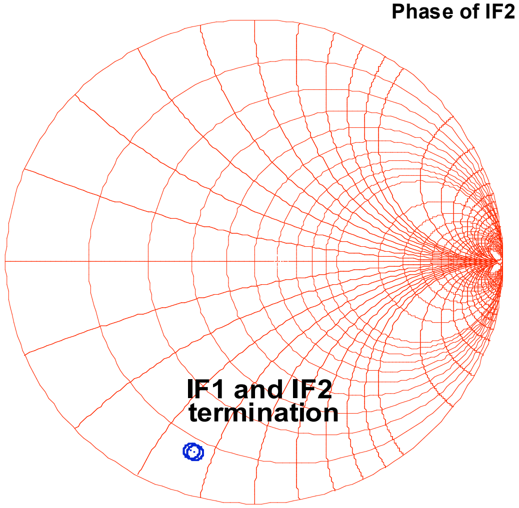
Alghanim, *EuMC 2007*

IF Waveform Engineering

- Optimum IF termination to simultaneously minimize IMD3 and IMD5





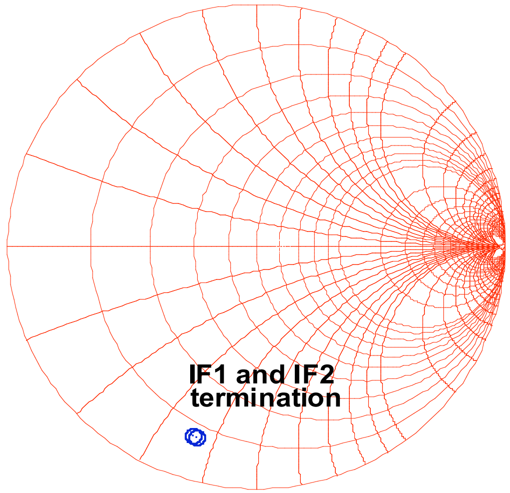


Improvement of IMD3 by -16 dB and IMD5 by -11 dB

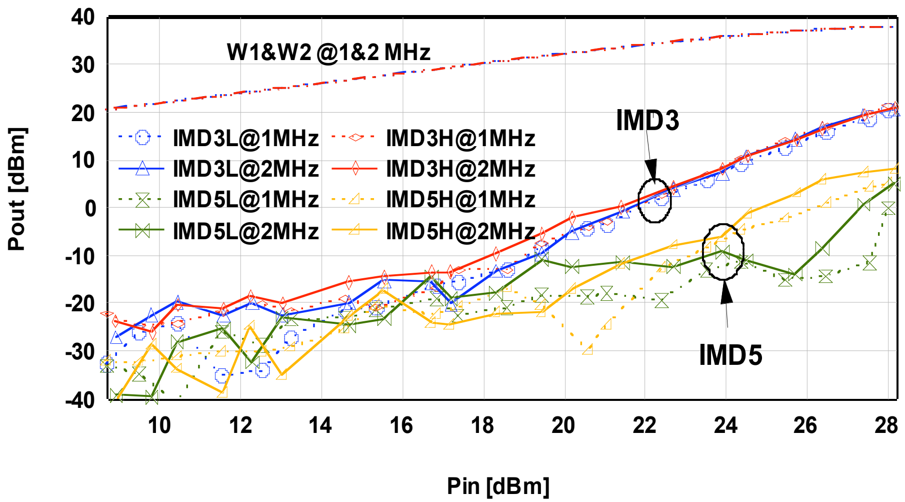
IF Waveform Engineering

- Optimum IF termination to simultaneously minimize IMD3 and IMD5

Do these identified optimums change with tone-spacing?



Measured IMD magnitude vs. Pin



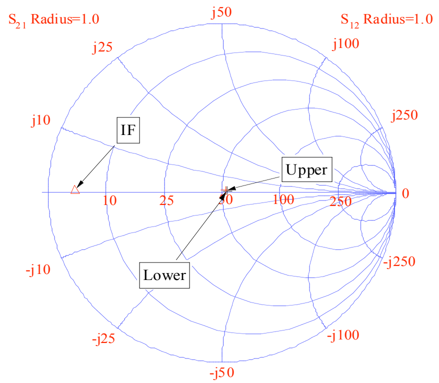
- Indications are that the optimum IF impedances is independent of modulation frequency
- These impedances can be easily synthesised using an ET process

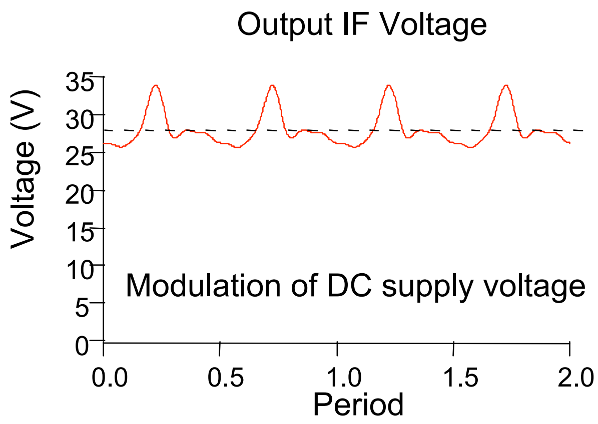
IF Waveform Engineering

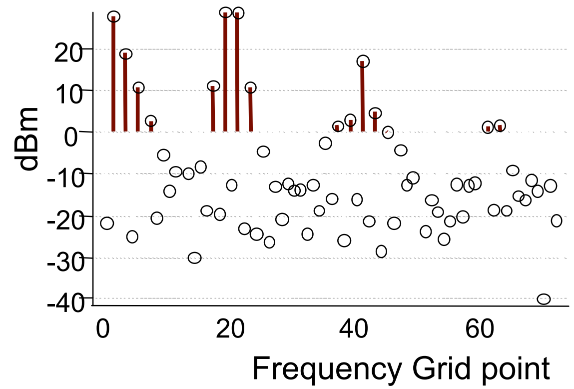
- Envelop Domain: Linearity Investigations

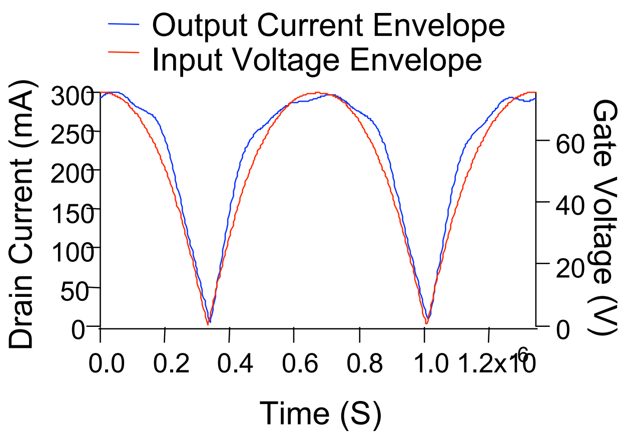
Device: 20W LDMOS
Carrier: 2.1 GHz
Tone spacing: 800 kHz,
Bias A-B (10%Idmax)
Passive IF short

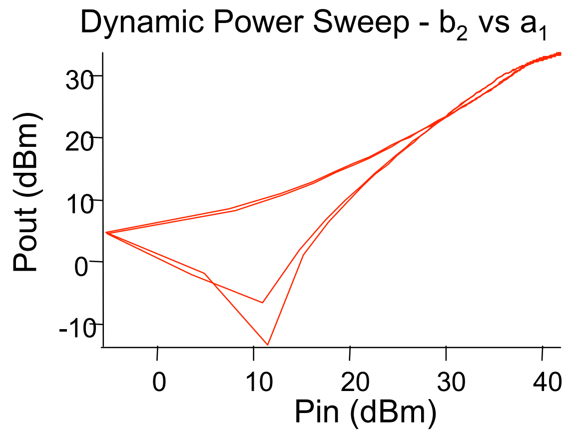
P_{in}_avail = 40 dBm











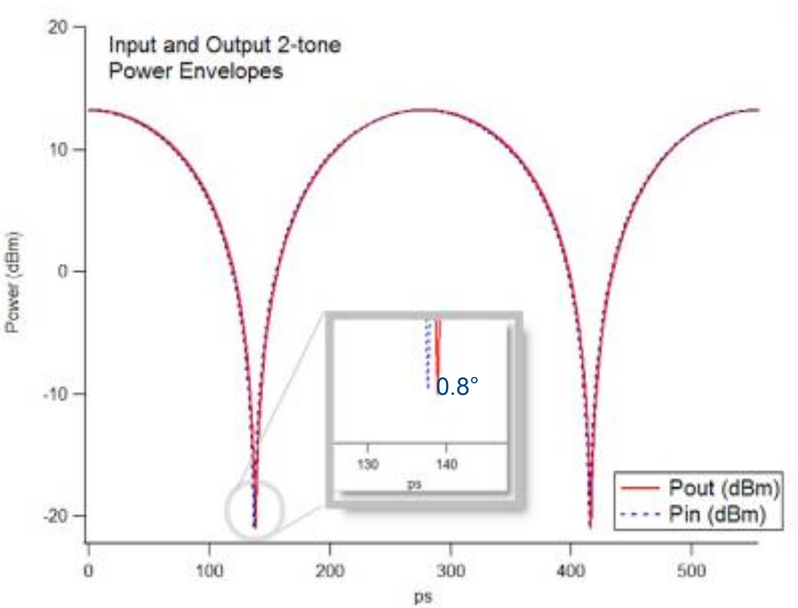
IF Waveform Engineering

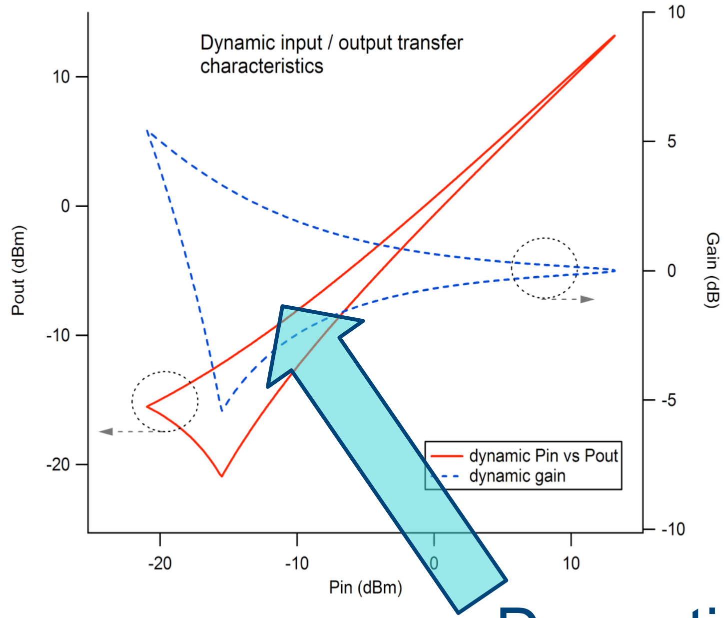
- Demystifying Memory: Envelop Domain Simulations

- 27ps delay line used as DUT
- 2-tone excitation
- 80 MHz tone separation used
- imparts 0.8 degree phase shift onto the envelope

Cause …

Dynamic range
Envelope Dynamics





Dramatic effect

IF Waveform Engineering

- Demystifying Memory: Active Device Measurements

Device specifics

2W GAN Cree die.

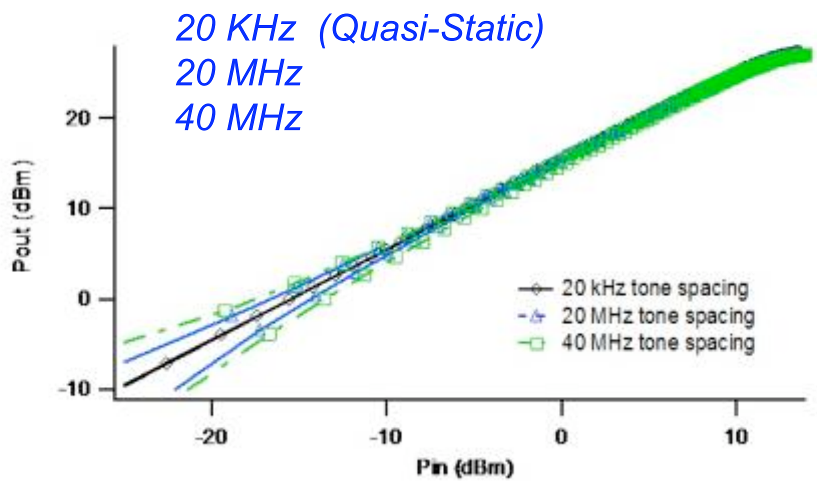
Fmax 40 GHz, gate width: 2x360um

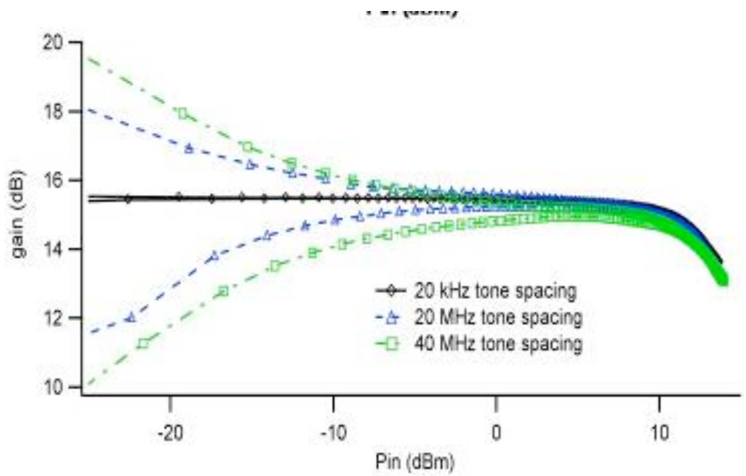
gate length 0.45um, Transit time 2.2ps

Gm=180uS.

Observations

- Dynamic trajectories are well aligned with quasi-static case.
- Again, under controlled conditions, becomes possible to expose delay.
- The delay here is bigger however (~45ps) than that observed for the 27ps delay line.
- This can be explained here by transit time and charge time for intrinsic parasitics



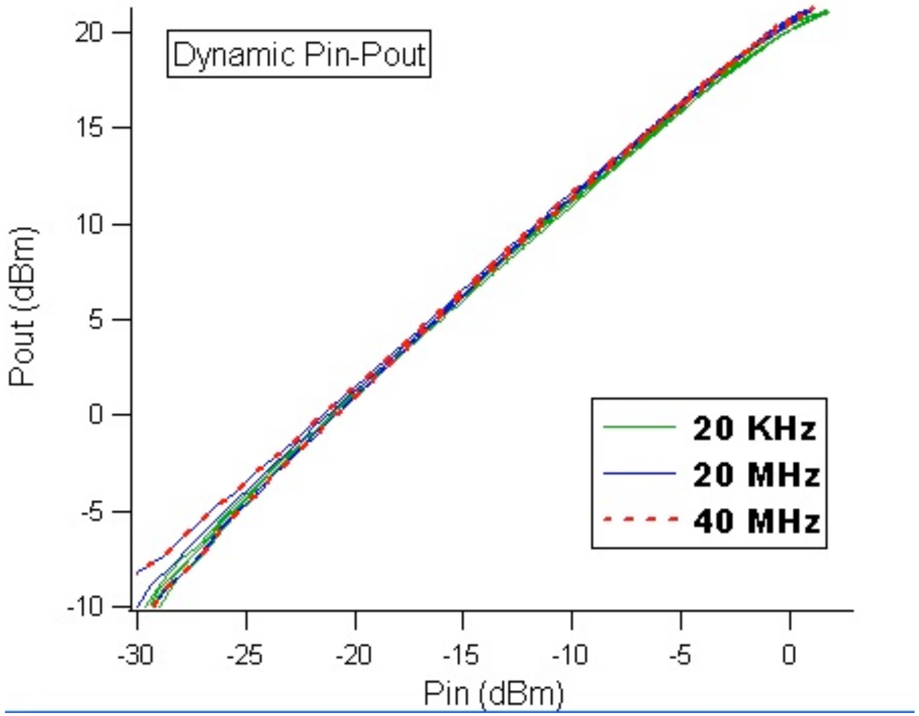


IF Waveform Engineering

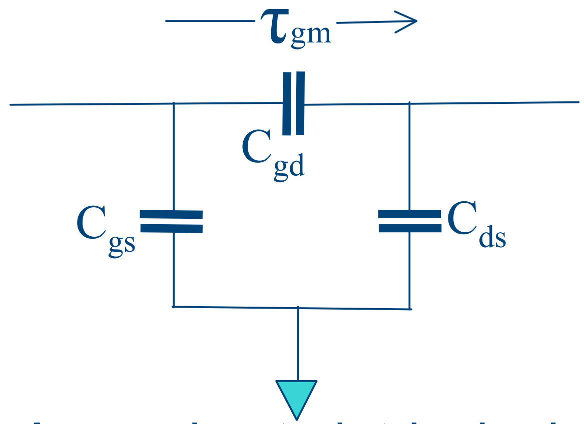
- Demystifying Memory: Active Device Measurements

Observation

Majority of Looping can be removed by applying an approximate -45 ps linear delay to the output envelope



Observed delay can be explained (in this case) by intrinsic parasitic delay and transit time.



Approximate intrinsic delay

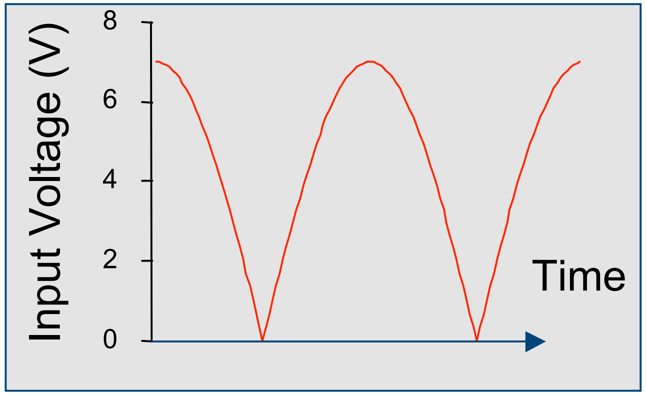
Cgs ~ 0.72 pF ~ 35 ps
Cgd ~ 0.06 pF ~ 3 ps
Cds ~ 0.13 pF ~ 6 ps
τgm ~ 2 ps

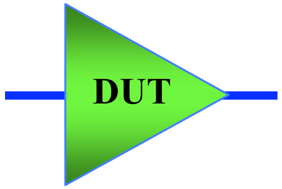
Total delay ~ 46 ps

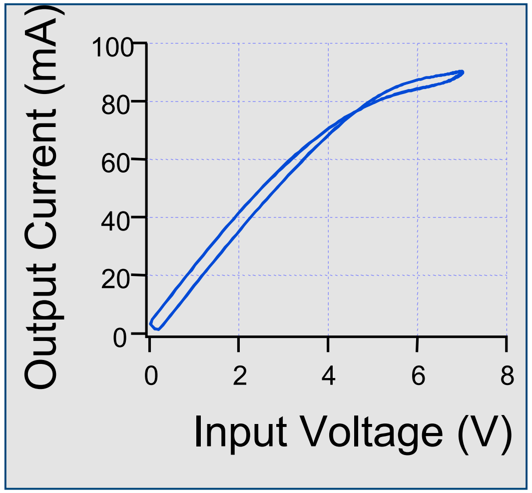
IF Waveform Engineering

- Envelop Domain: Linearity Investigations

- Stimulate with Two-Tone Signal
  - Analyze in Envelope Domain

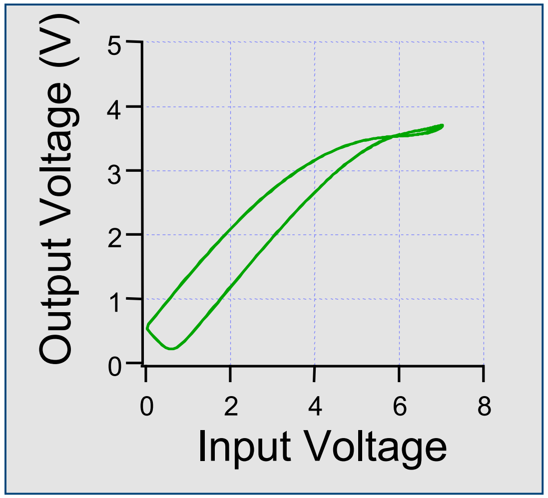






- Investigate Dynamic Envelop Response
  - Transistor "Memory"
  - RF Impedance variation "Memory"

Device: 0.5 W GaN HFET
Carrier: 1.8 GHz
Tone spacing: 4 MHz,
Passive IF short



RF I-V Waveform Measurement & Engineering

- Demand for Multi-Tone Excitation

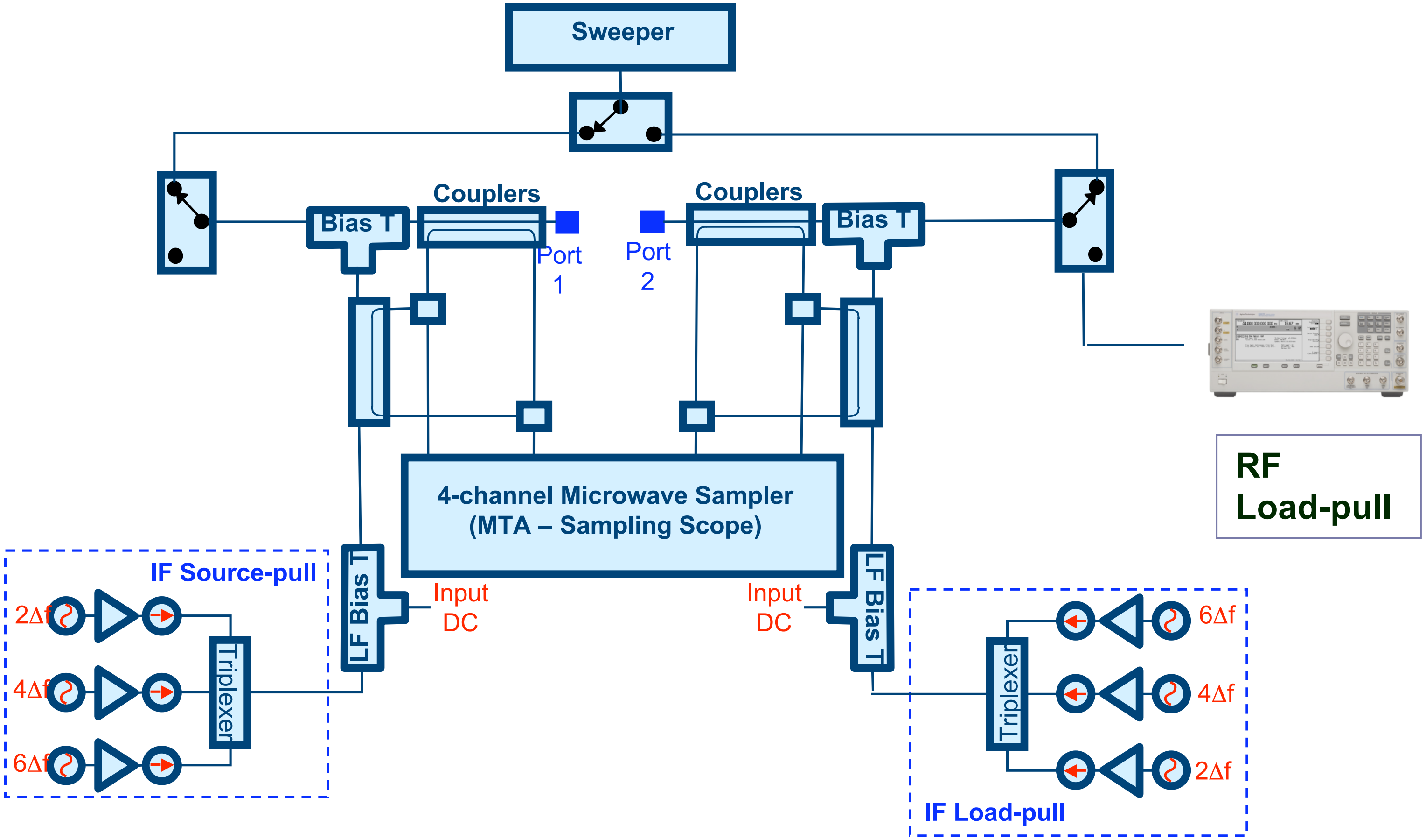
- CW (Single Tone) to Modulated (Multi-Tone) Measurement System Development
  - RF Multi-Tone I-V Waveform Measurement
    - Intelligent Sampling
    - Inclusion of IF (Base-band signals)
  - RF Multi-Tone IV Waveform Engineering
    - IF (Base-band) active load-pull

- Application
    - Memory Investigations: Base-band Electrical Memory

- CW (Single Tone) to Modulated (Multi-Tone) Measurement System Development
  - RF Multi-Tone IV Waveform Engineering
    - RF active load-pull (Digital ELP)

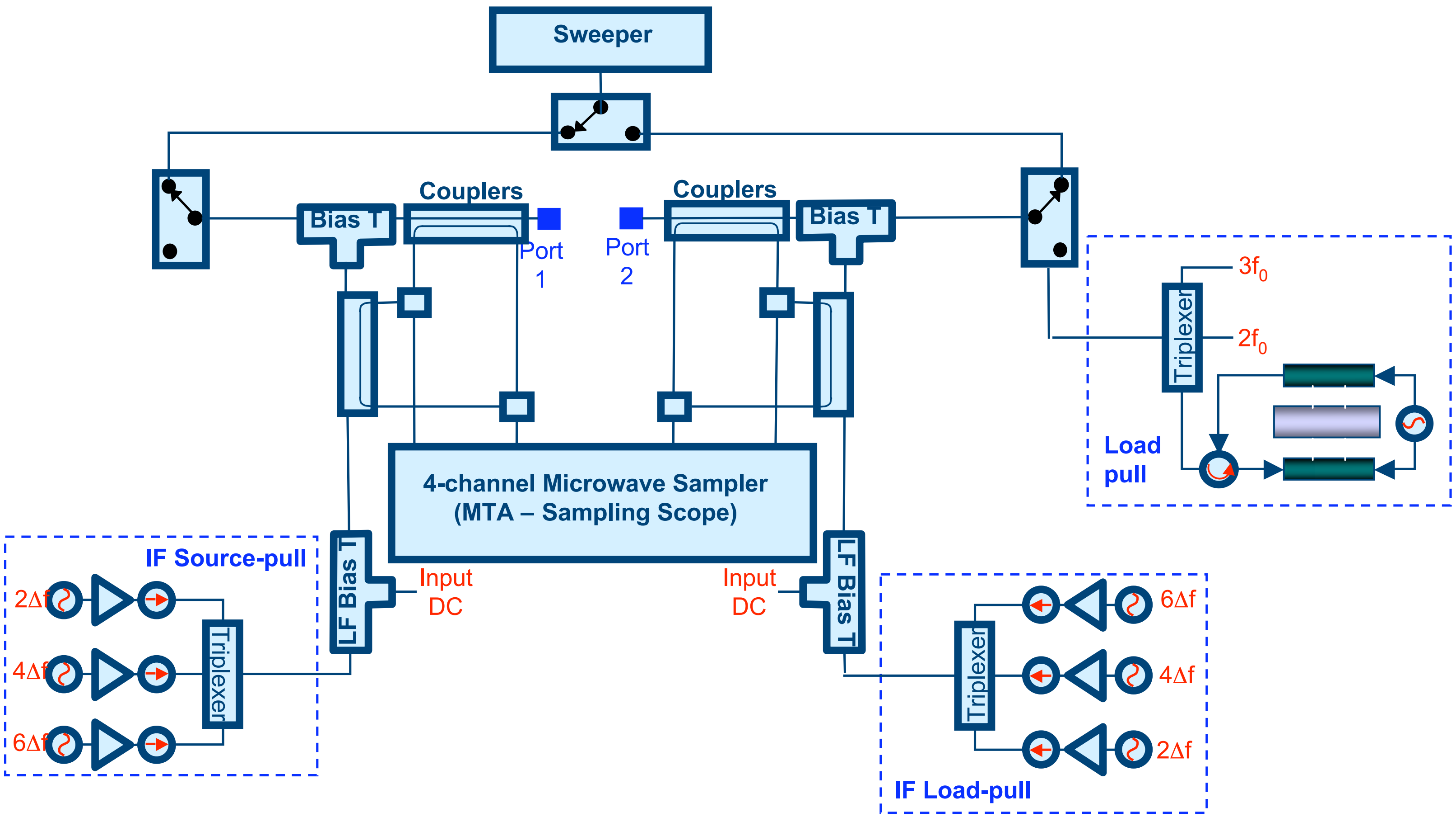
Realization of RF (Multi-Tone) Waveform Engineering

- consider in-band and harmonic circuit electrical memory issues



Realization of RF (Multi-Tone) Waveform Engineering

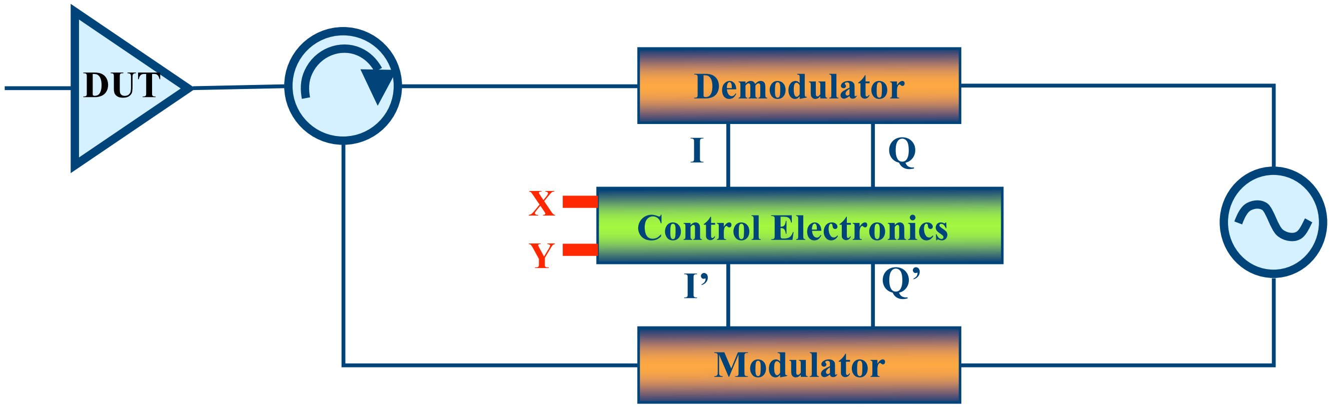
- consider in-band and harmonic circuit electrical memory issues



Realization of RF (Multi-Tone) Waveform Engineering

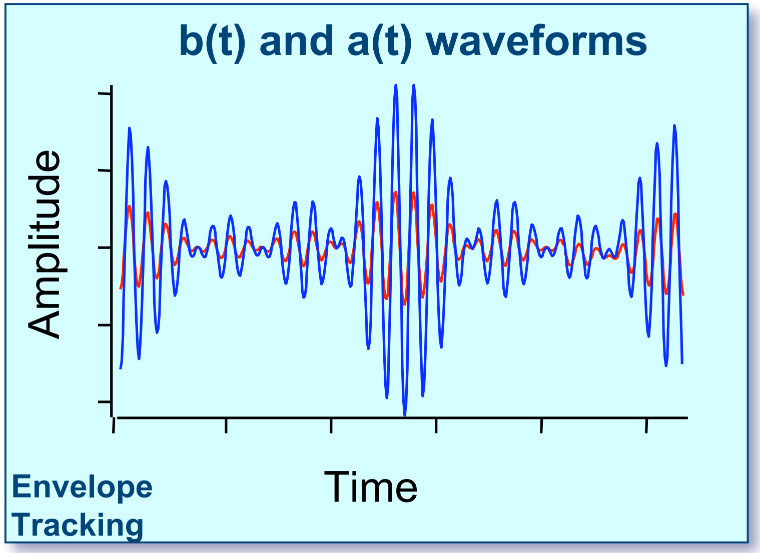
- Envelope load-pull solution: Envelop Tracking

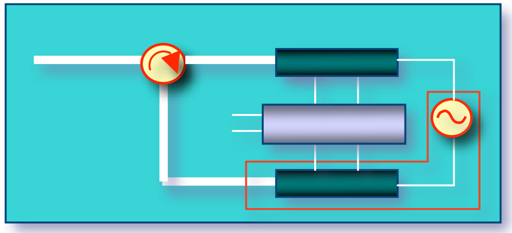
- Open loop at RF but a closed loop at envelope frequencies
  - No loop oscillations as no direct RF feedback
  - Reflection coefficient constant irrespective of the signal coming from DUT
- Impedances set by simple electronics controlled by the X & Y inputs
  - Suitable for modulated signals

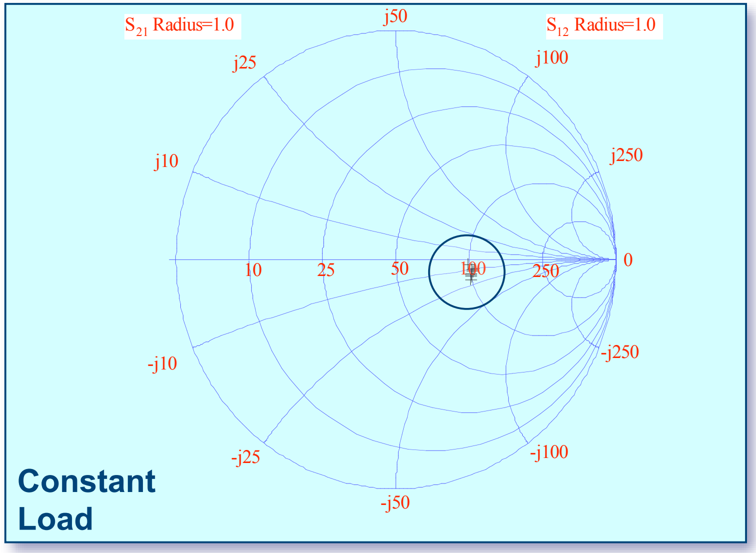


Realization of RF (Multi-Tone) Waveform Engineering

- Envelope load-pull solution: Envelop Tracking



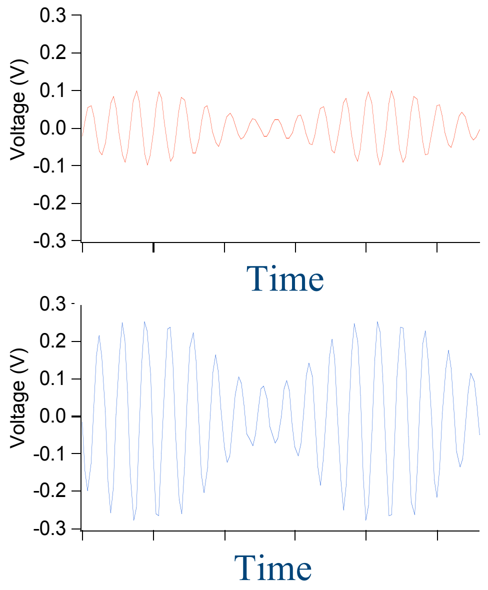




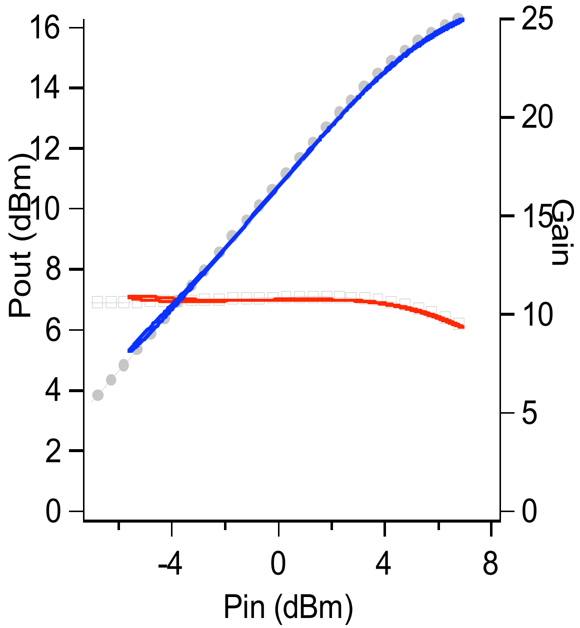
9 Tone Modulated Signal
=> Confined to a few 100 kHz at present

Realization of RF (Multi-Tone) Waveform Engineering

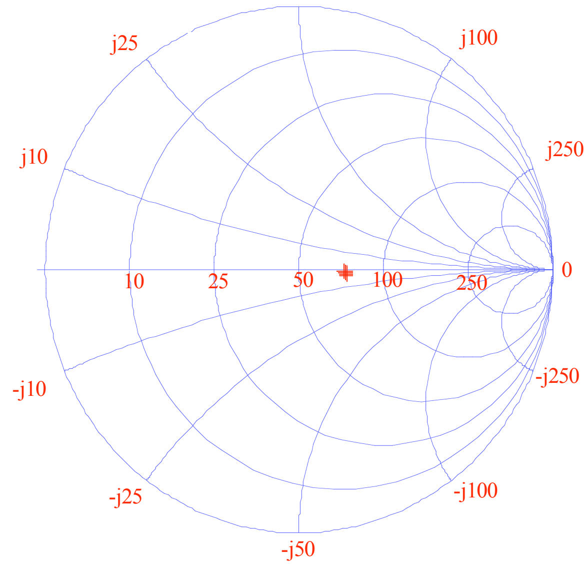
- Envelope load-pull solution: 'Instantaneous' power sweeps



Capture input (red) and output (blue) waveforms modulated with 200Hz



Comparison between 'instantaneous' and CW power sweep

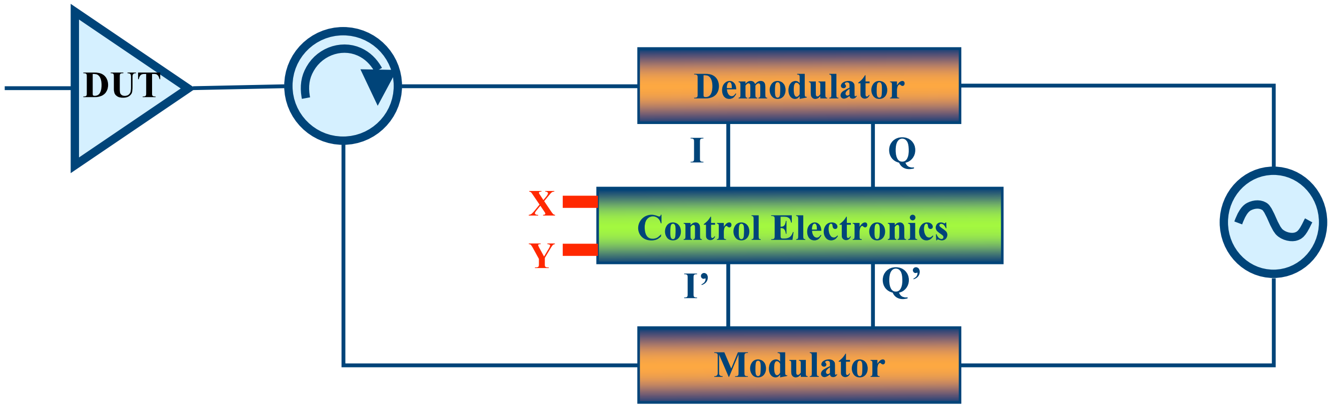


Impedance measured during 'instantaneous' power sweep

Realization of RF (Multi-Tone) Waveform Engineering

- Envelope load-pull solution: Envelop Tracking

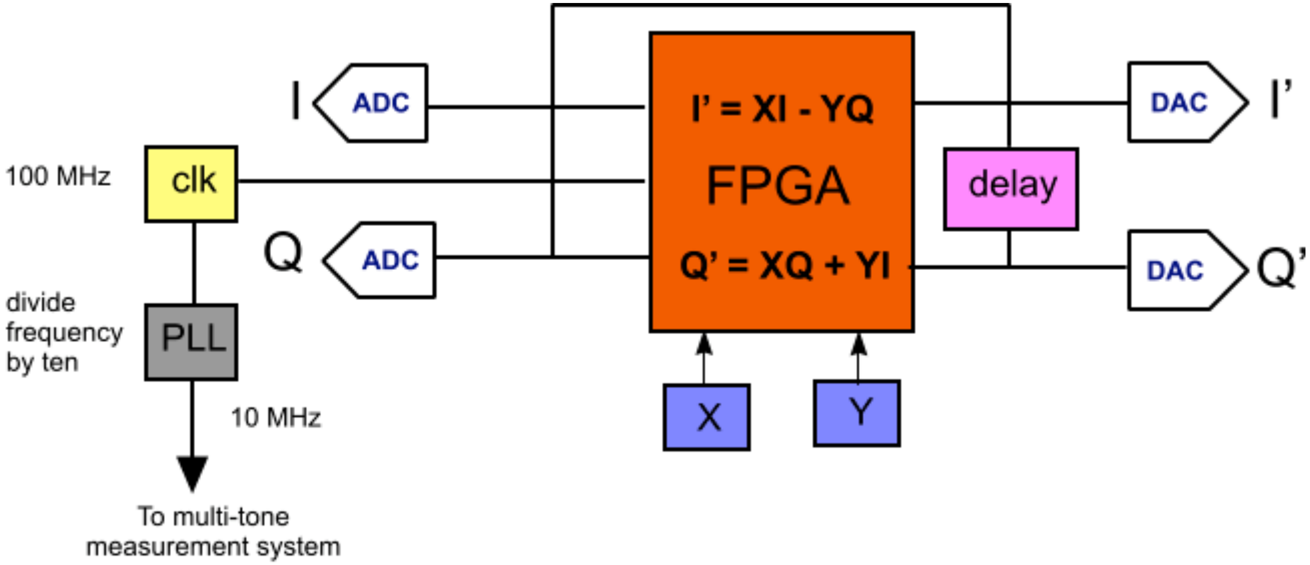
- Open loop at RF but a closed loop at envelope frequencies
  - No loop oscillations as no direct RF feedback
  - Reflection coefficient constant irrespective of the signal coming from DUT
- Impedances set by simple electronics controlled by the X & Y inputs
  - Need high speed control electronics for relevant bandwidth modulated signals: **Digital Solution Required**

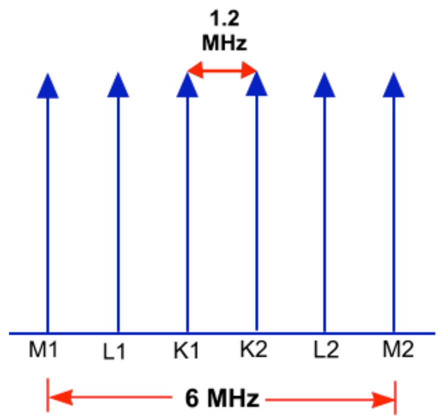


RF I-V Waveform Engineering

- Next generation ELP Systems: Digital control using FPGA

- DSP development board Stratix II edition
  - FPGA is Altera Stratix II clocked at 100 MHz
  - Two-channel, 12 bit, 125-MSPS A/D converter
  - Two-channel, 14 bit, 165-MSPS D/A converter
- The multi-tone measurement system is clocked by 10 MHz derived clocked from the FPGA master clock
- The control algorithm is implemented in time domain
- Frequency domain control will offer more functionality such as individual tone control
  - *enable emulation of real world impedance matching network*





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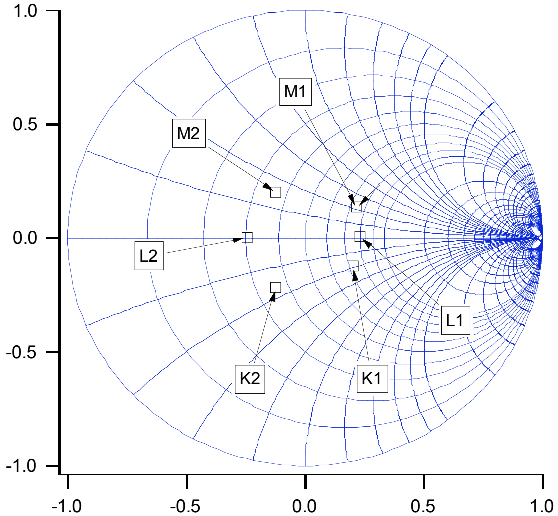
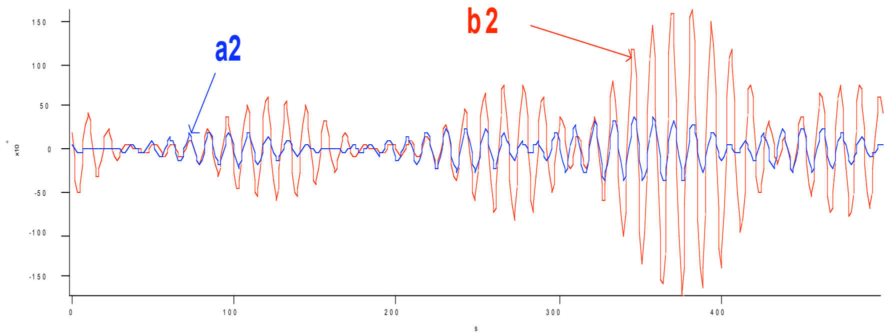
RF I-V Waveform Engineering

- Next generation ELP Systems: Time Delay problem



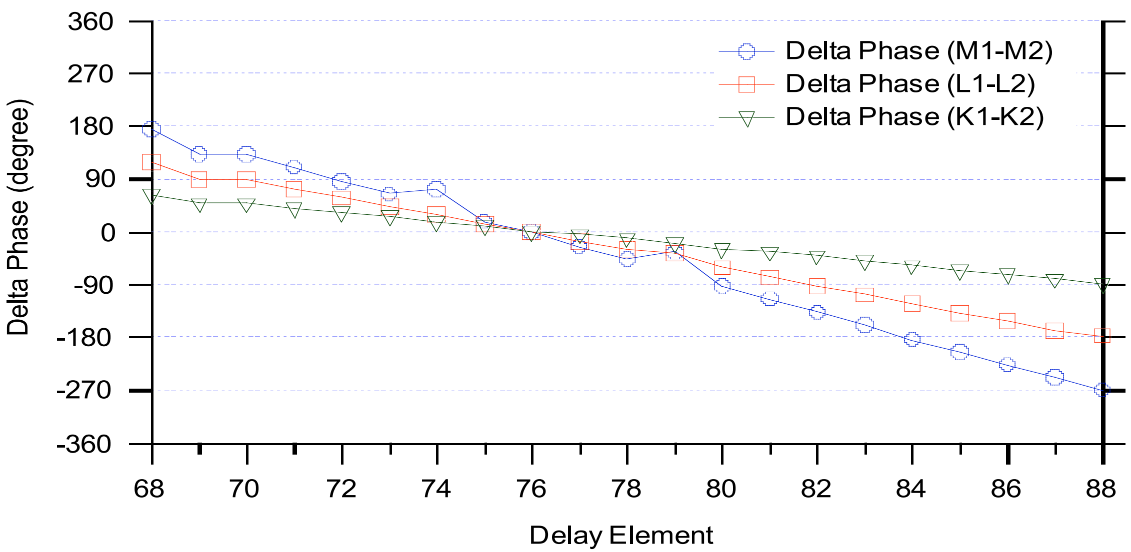


- The control unit can support wideband stimulus albeit delay
- Phase variation over length of cable and components (group delay or envelope delay)
  - Must be compensated for accurate load impedance matching
- The repetitive nature of the measurement stimulus made delay compensation possible in the next repetition or N repetition later

RF I-V Waveform Engineering

- Next generation ELP Systems: Delay compensation determination

- Configurable FIFO RAM based unit delay
  - Unit delay is 10 ns (100 MHz clock)
  - Delay is compensated after 76 delay elements
  - *Latest development of delay compensation is not limited to unit delay*
- Linear group delay can be observed from the graph



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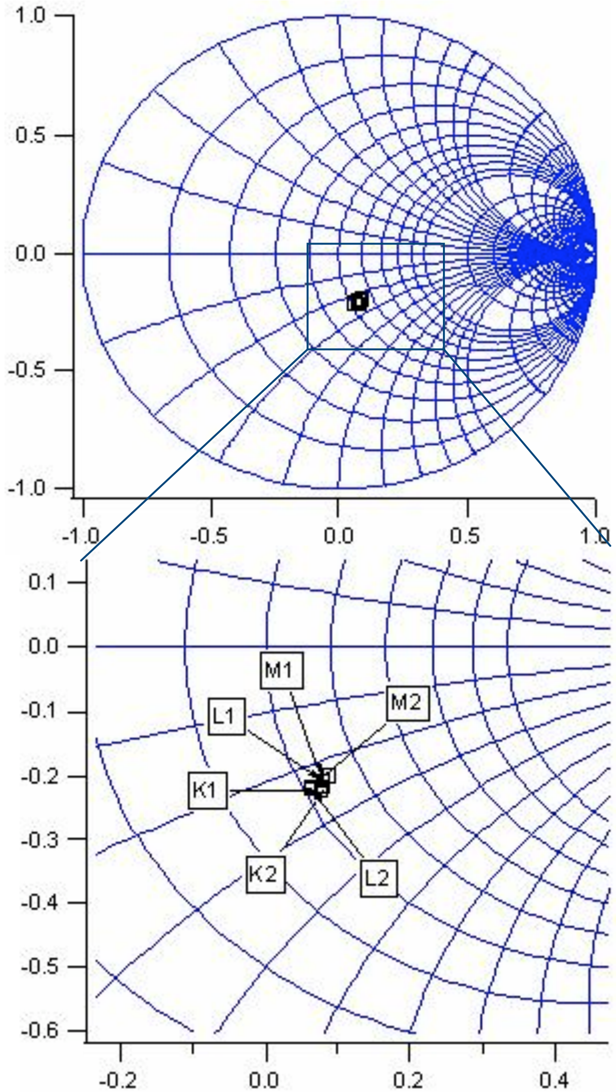
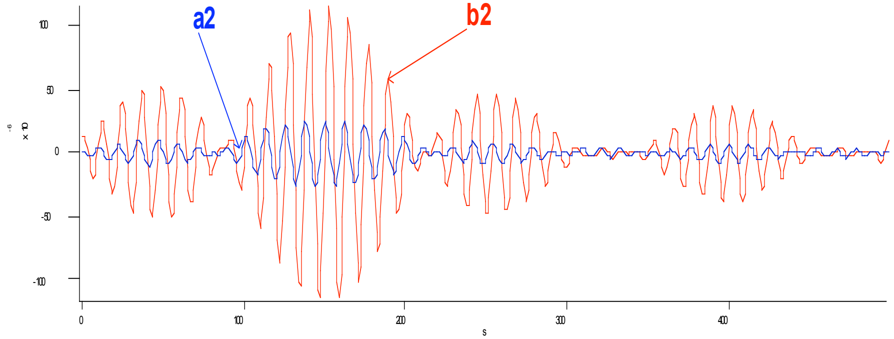
RF I-V Waveform Engineering

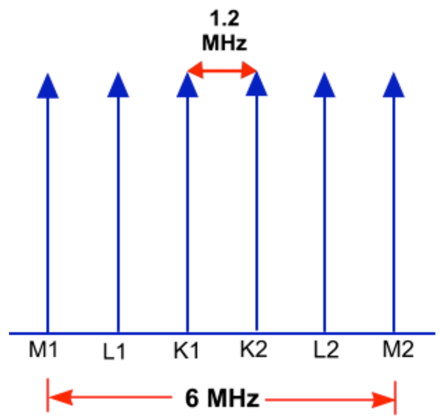
- Next generation ELP Systems: Digital control using FPGA using delay





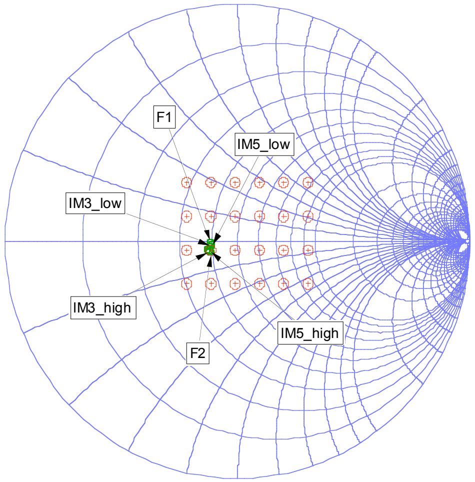
results

- Smith chart showing compensated delay (zoom)



RF I-V Waveform Engineering

- Next generation ELP Systems: Two-Tone Signal with 2MHz separation



Constant Impedance over 10 MHz bandwidth