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

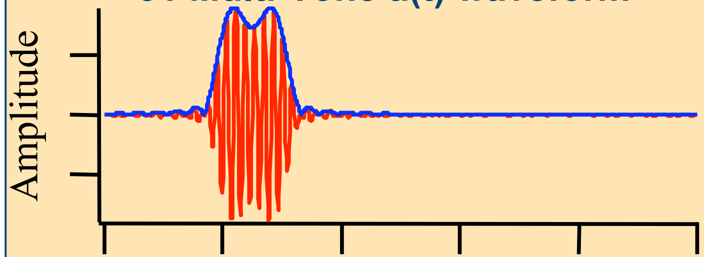
RF I-V Waveform Measurement & Engineering

- Demand for Multi-Tone Excitation

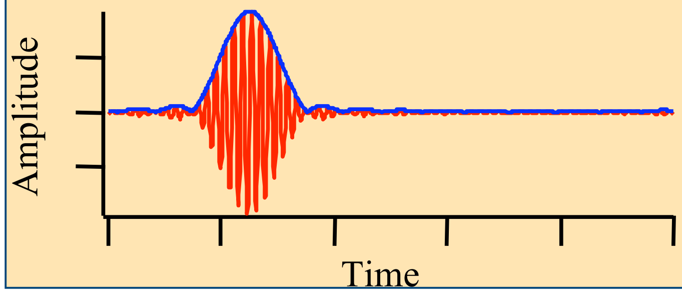
- Synthesize “real” system stimulus

- Pulsed RF ~ *10-100 us*

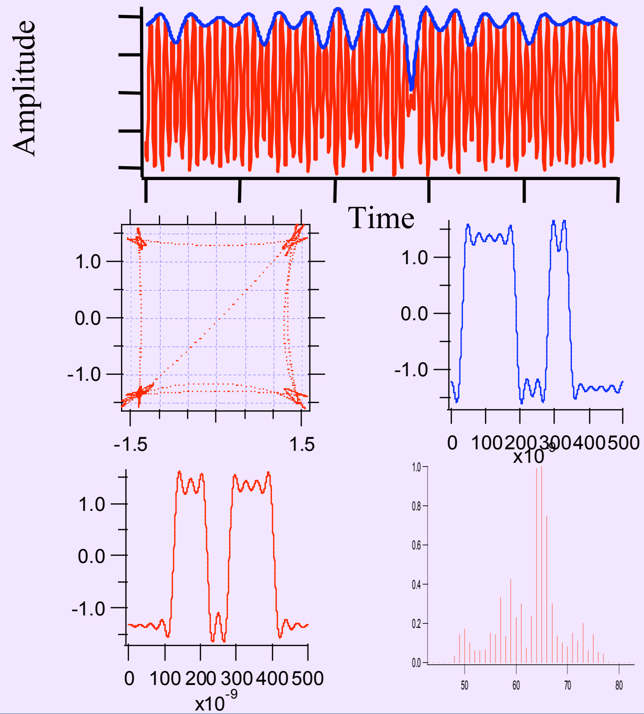
31 Multi-Tone a(t) waveform



15 Multi-Tone a(t) waveform



- 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

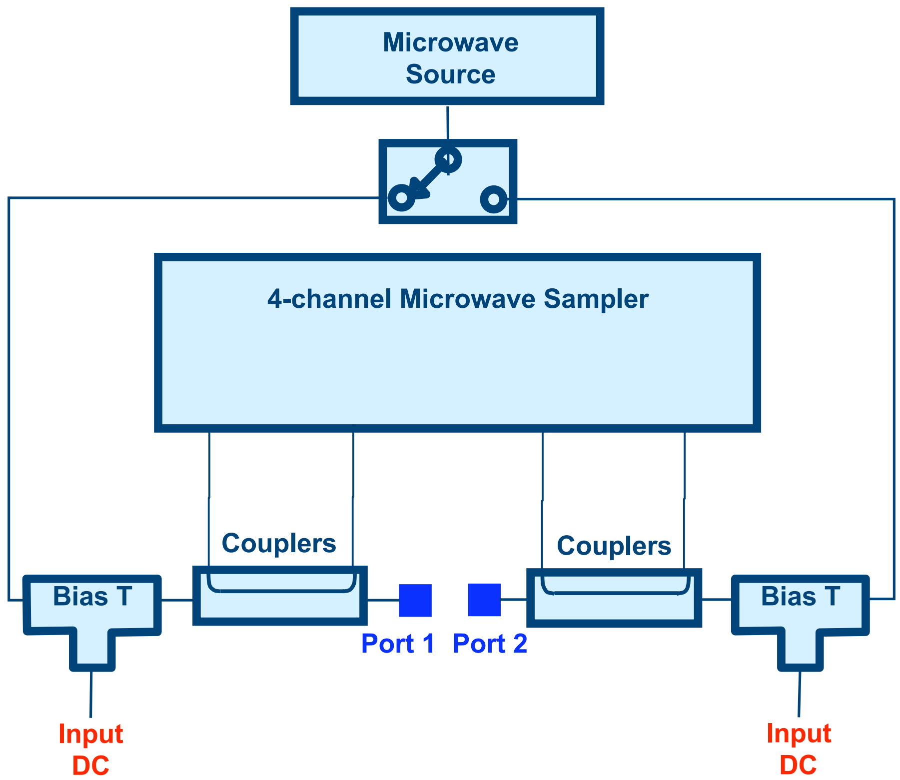
- Application
    - Memory Investigations: Base-band Electrical Memory

- 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

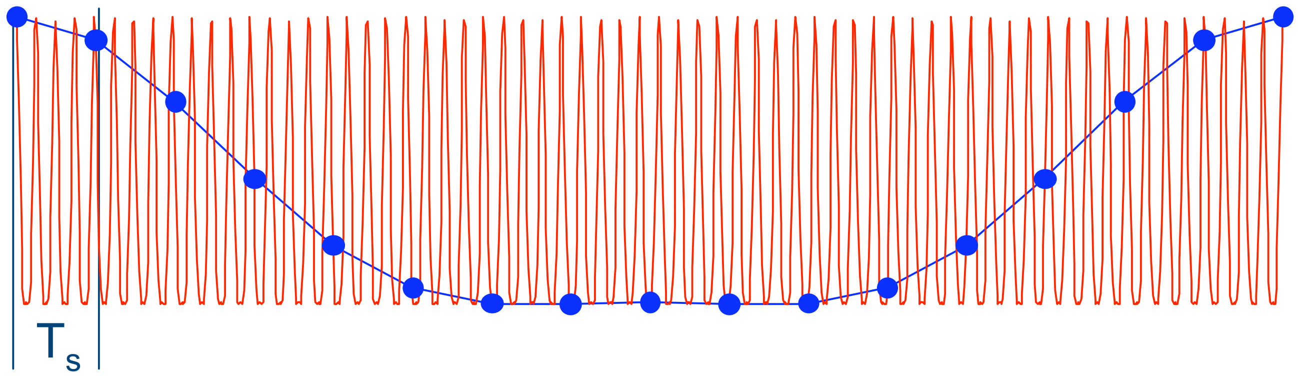
- Need to extend sampling strategy to accommodate multi-tone excitation
  - folded and interleaved sampling
- Need test-set architecture to account for all frequency components
  - RF hardware between DUT and the sampling receivers ignores base-band components

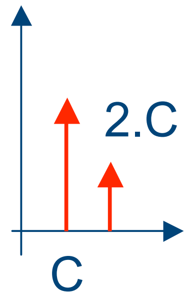


RF I-V Waveform Measurement & Engineering
- Intelligent Sampling: Review CW Case

- 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



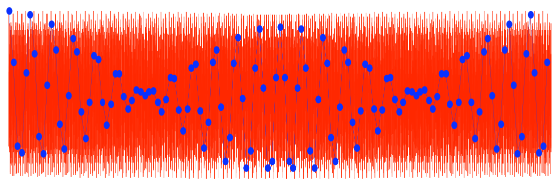


RF I-V Waveform Measurement & Engineering

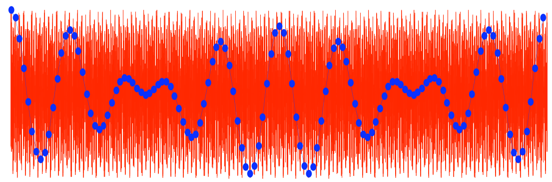
- Intelligent Sampling: Multi-Tone Case

- 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)

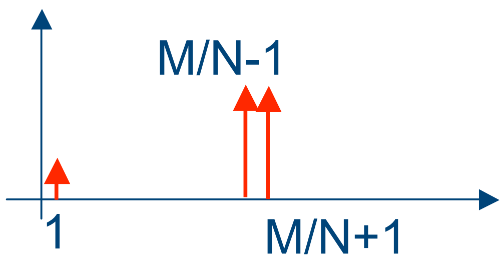
M=50
N=2
P=128
C=25

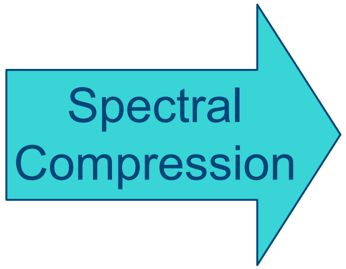


M=50
N=2
P=128
C=9

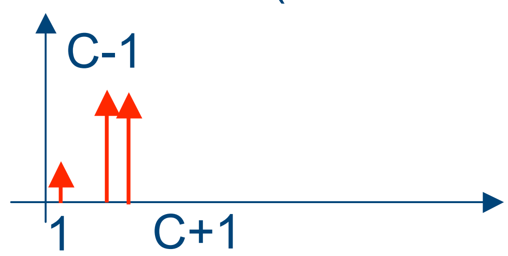


With C=M/N



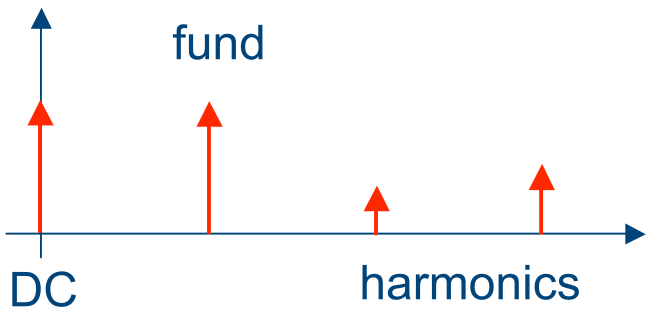


With C≠M/N (=2.Order+1)



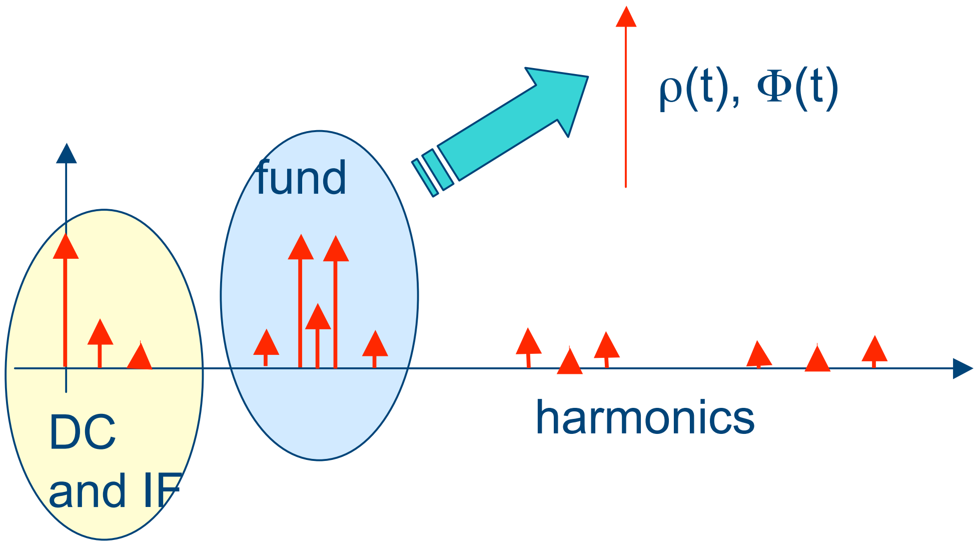
RF I-V Waveform Measurement & Engineering

- Multi-Tone versus CW



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

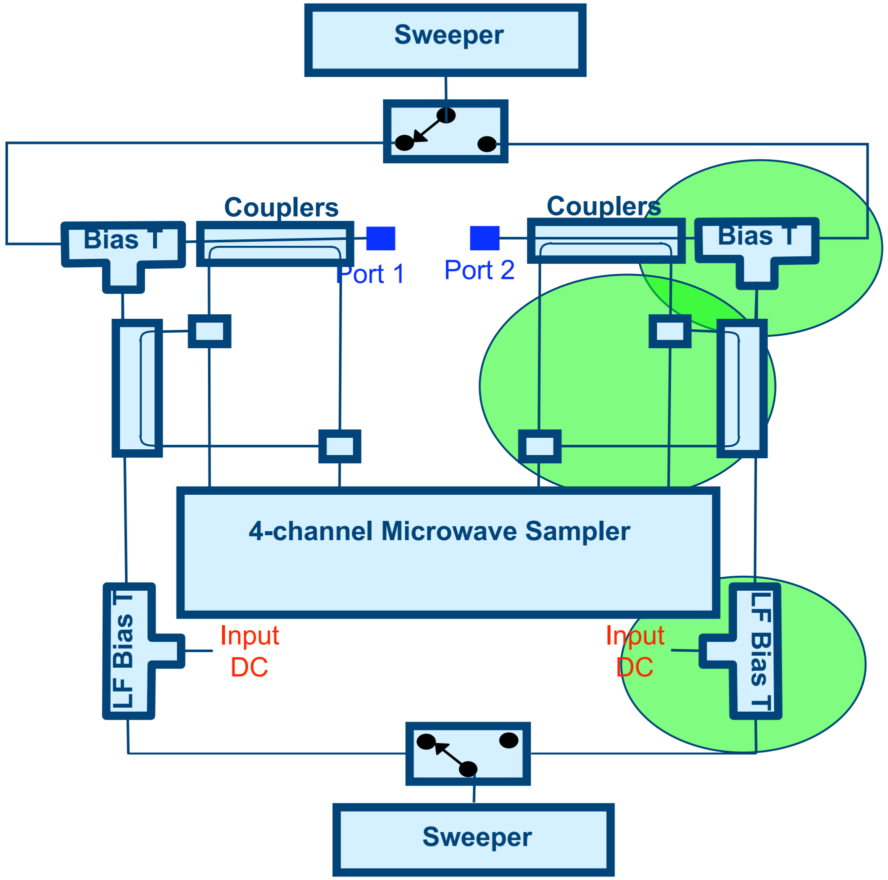
- Spectrally rich but "grouped"
  - Envelope domain
  - intelligent sampling
- RF and IF components
  - measured
  - engineered



Non-Linear Vector Network Analyzer:

- Basic Architecture with RF and IF Test-set

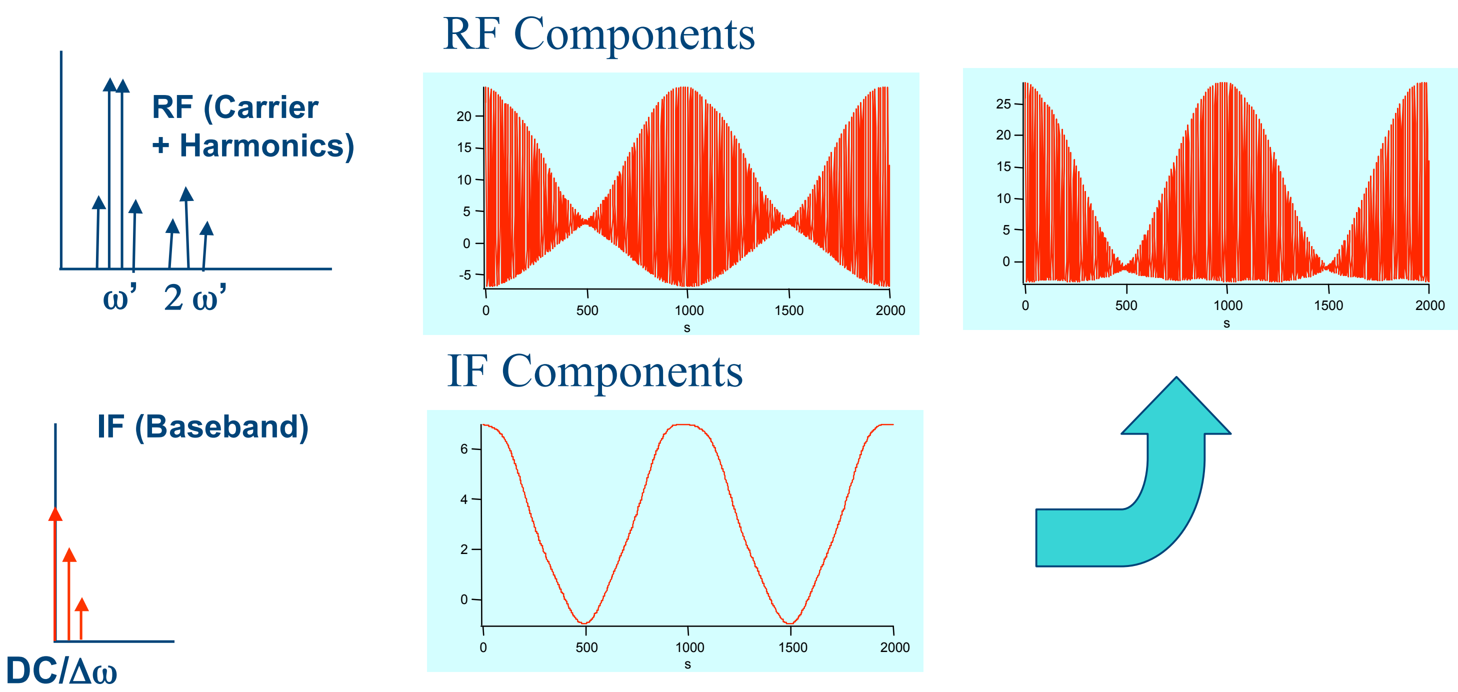
- Requires a very broadband four channel receiver
- Utilizes integrated RF and IF directional couplers for detection/separation of waves
  - Critical components
    - Bias Tee/Diplexer
    - Bias-Tee/Combiner
    - IF Bis-Tee



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

RF I-V Waveform Measurement & Engineering

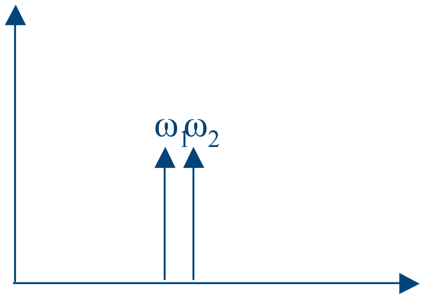
- Need for IF Measurements

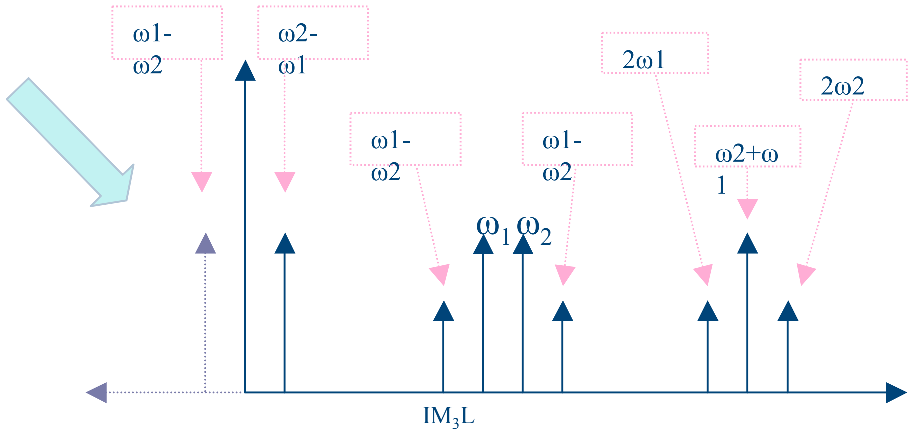


Waveform measurements necessitates all spectral components

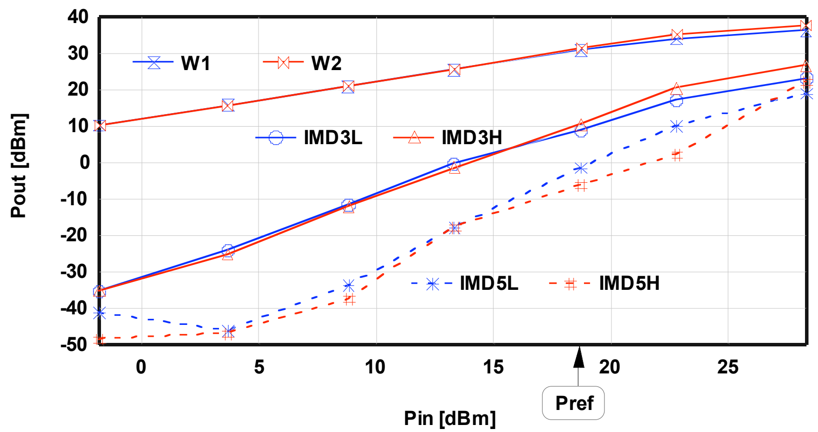
RF I-V Waveform Measurement & Engineering

- Classical IF Measurements and Data Presentation





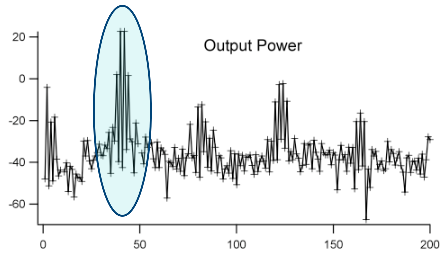
- Classical 2-tone often used
- Observation of IM magnitude and ***symmetry***
- Limitation – Little insight into sources of memory – just the consequences
- Traditional Instrumentation - Spectrum Analysers,
- New Instrumentation - VSA, and recently PNA-X



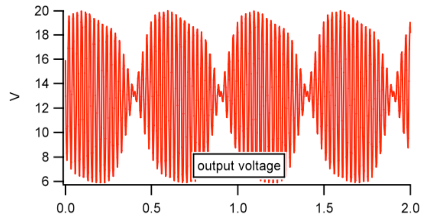
RF I-V Waveform Measurement & Engineering

- Non-Classical IF Measurements and Data Presentation

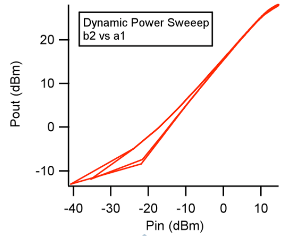
- What is envelope domain analysis
- Powerful approach - intuitive
  - Critical to to capture all significant spectral components
  - DC, Baseband and RF spectra then used to ‘rebuild’ the modulation envelope.
  - Mag and Phase information key in this process.



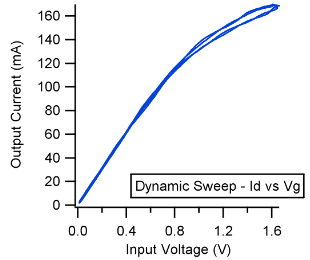
Freq Domain + Phase

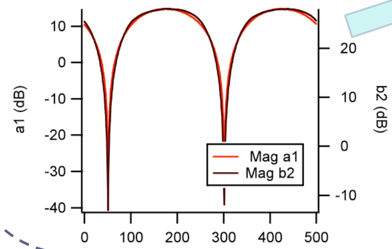


time domain



Dynamic transfer characteristics



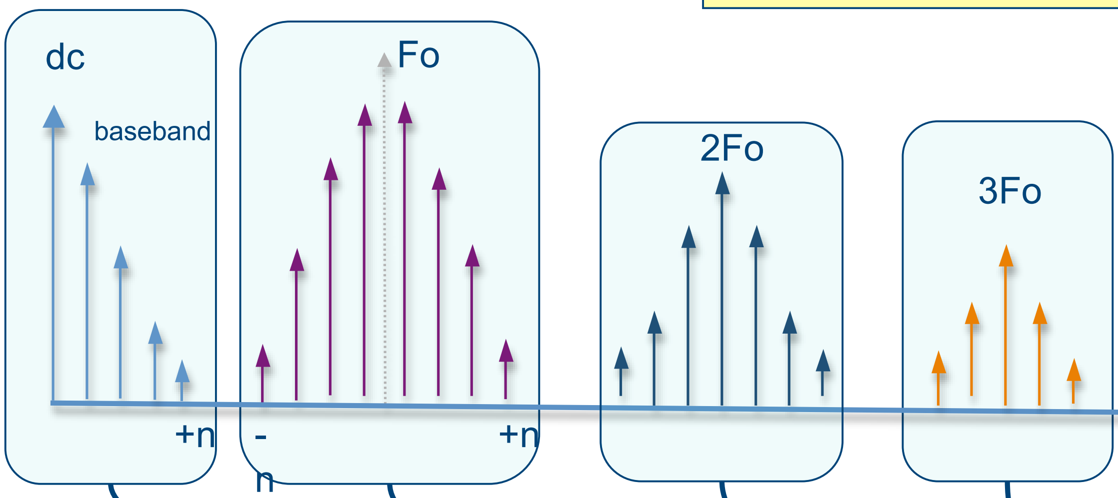


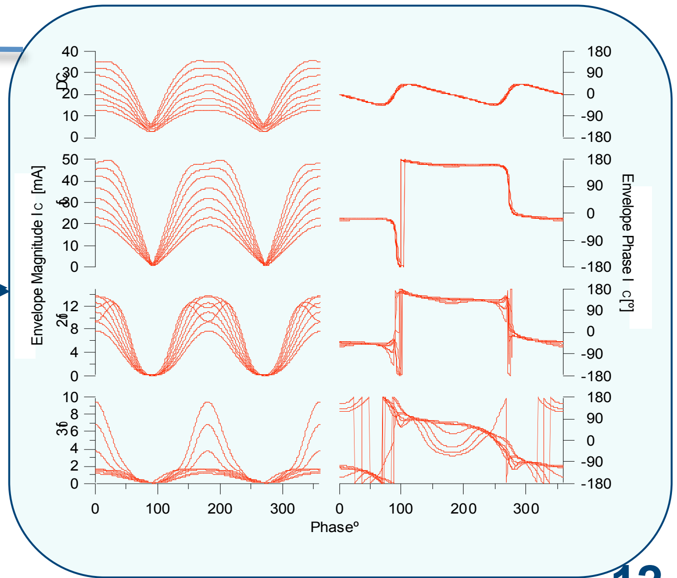
envelope domain (without time)

RF I-V Waveform Measurement & Engineering

- Non-Classical IF Measurements and Data Presentation

Note-need phase information for all of these!



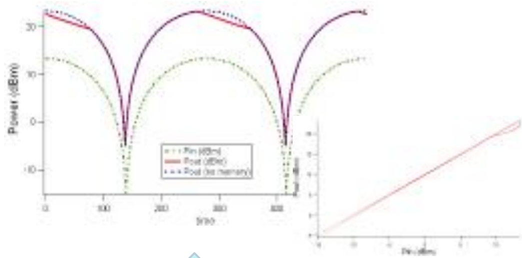


Important

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

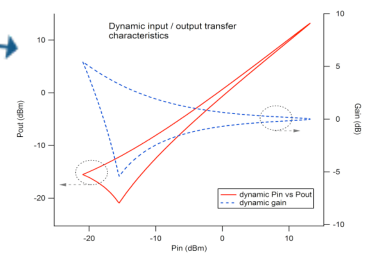
Thermal effects

'evidence' of memory

Asymmetry

Dynamic Looping

Non-realiseable Digital Pre-distortion

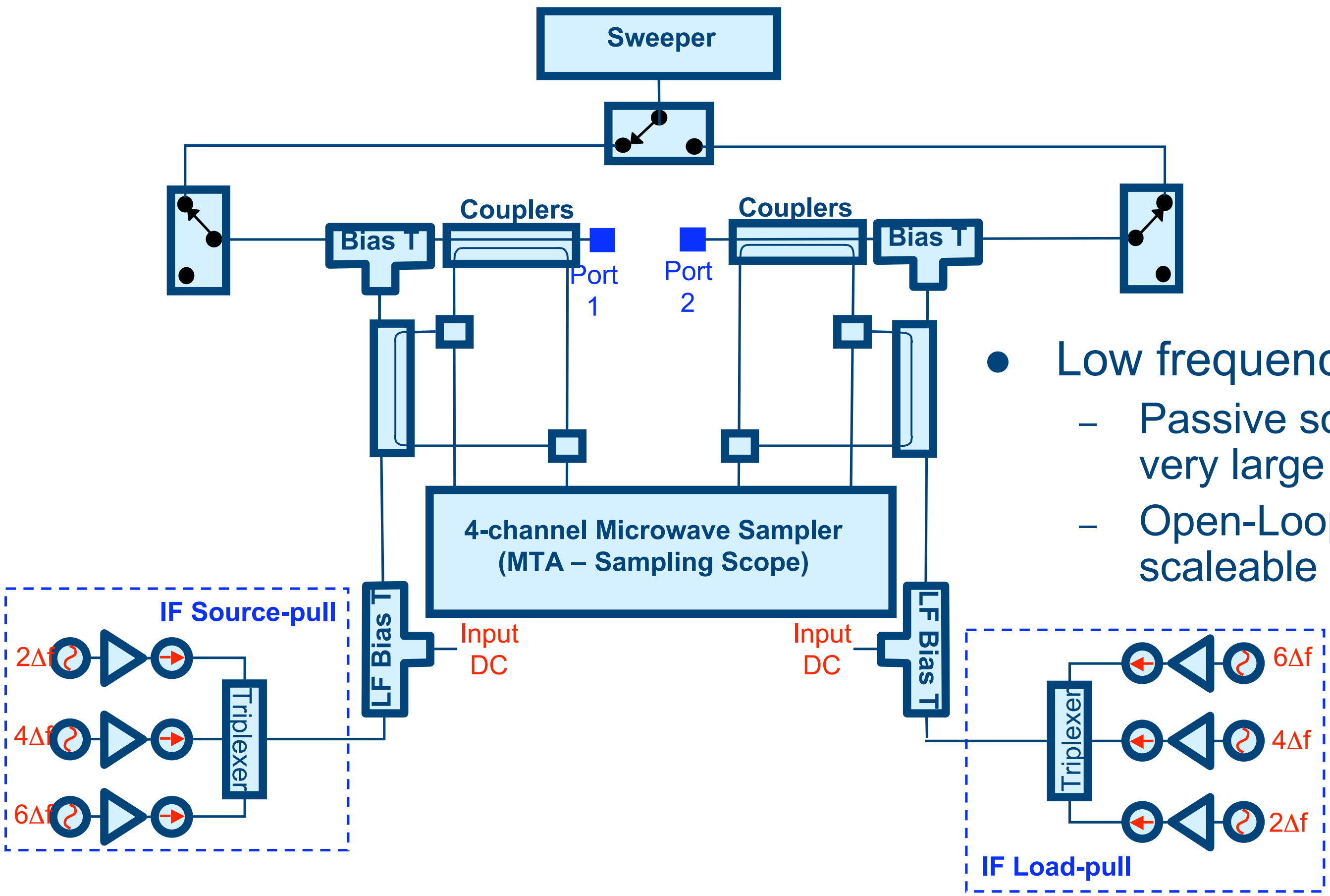


- Baseband
- In-band
- Out-of-band

Combinations

Realization of IF (Base-band) Engineering

- initial focus on bias circuit electrical memory issues

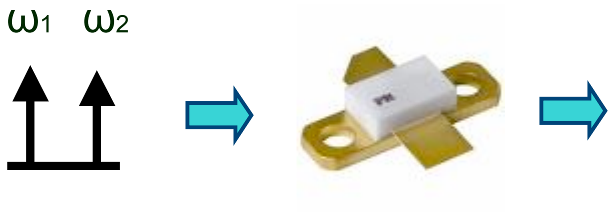


- Low frequencies
  - Passive solution physically very large
  - Open-Loop Active Solution scaleable

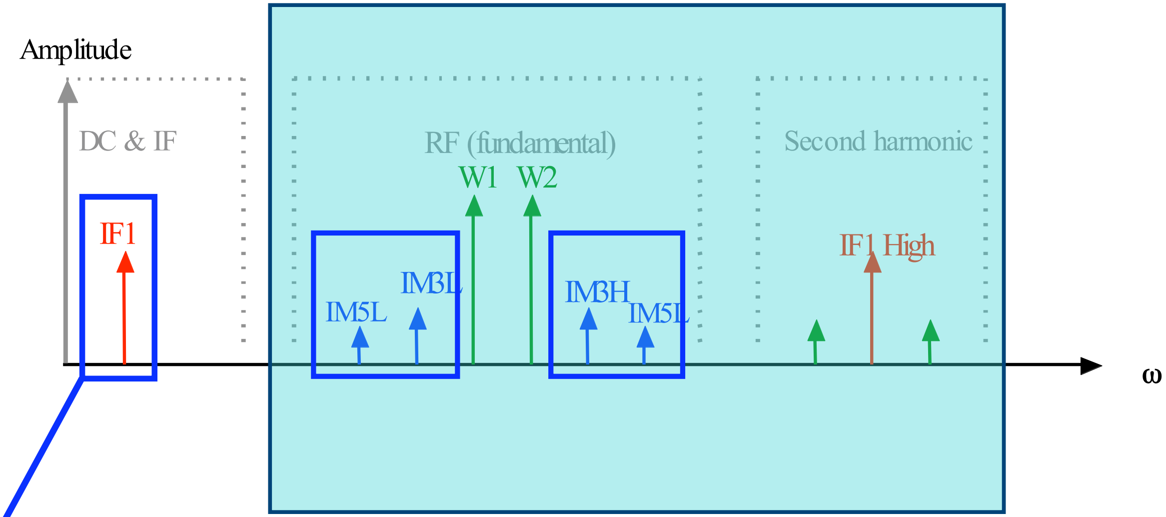
Realization of IF (Base-band) Engineering

- initial focus on bias circuit electrical memory issues

Here limited to 2 Harmonics and 5th Order



Constant Impedance Environment



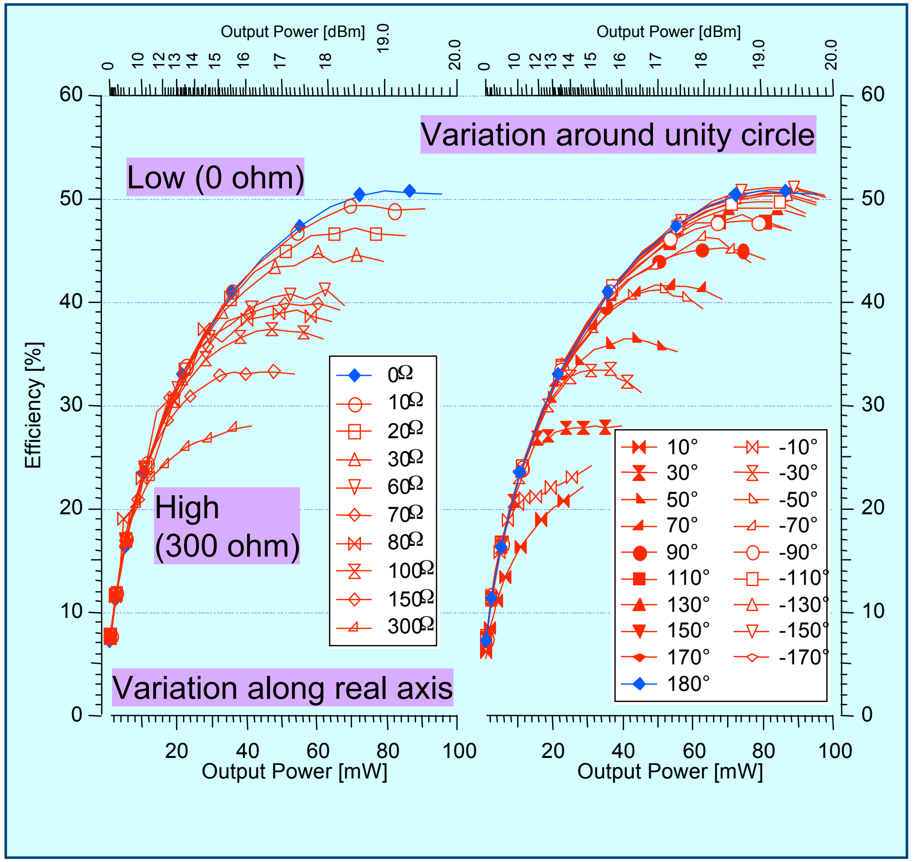
simplified two-tone spectrum up to fifth-order component polynomial transfer characteristic

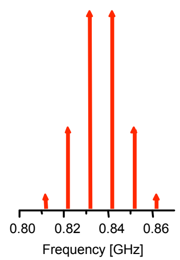
Investigate role of these signals on RF components - engineering the base-band impedance

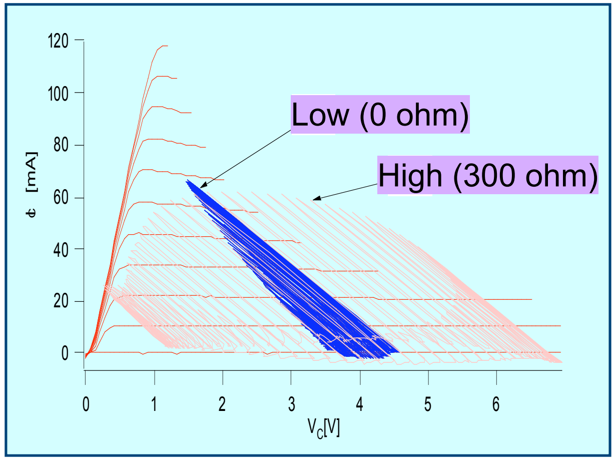
IF Output Voltage Engineering (Envelope Tracking)

- Effect on RF Carrier Output Power (HBT)

IF Load-Pull Effect on Output Power and Efficiency







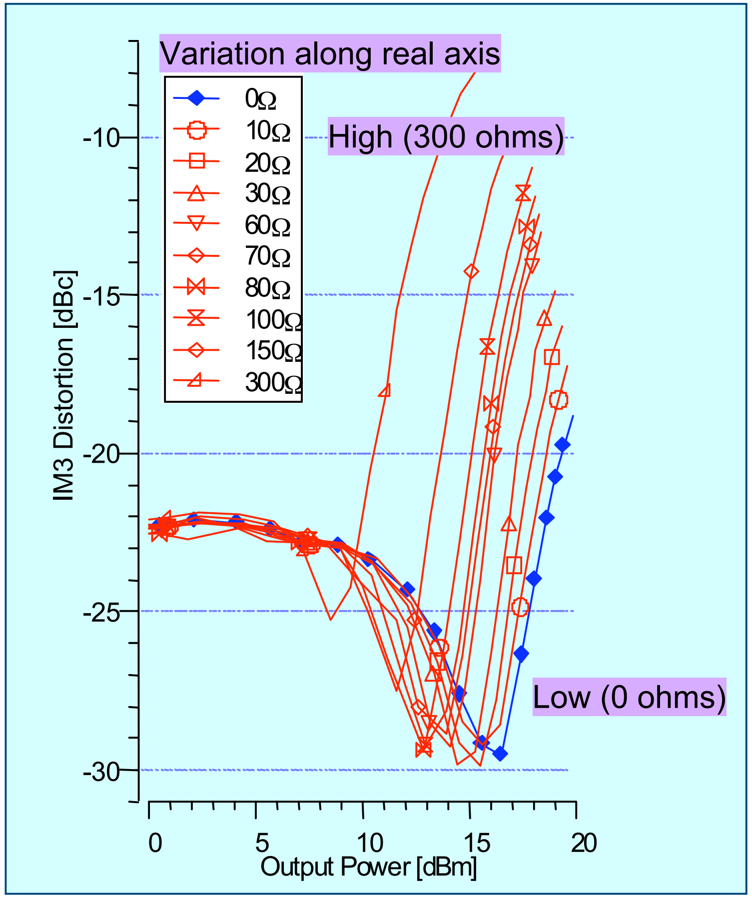
Control of interaction of output dynamic waveforms with knee region explains carrier

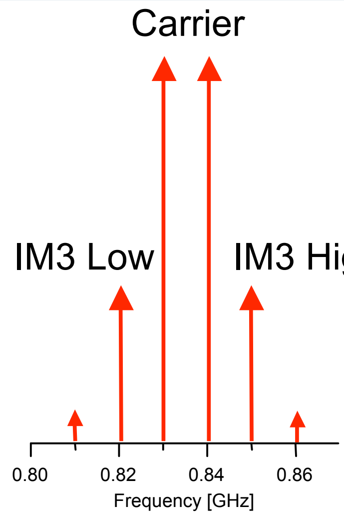
Power and efficiency sensitive to IF load impedance.

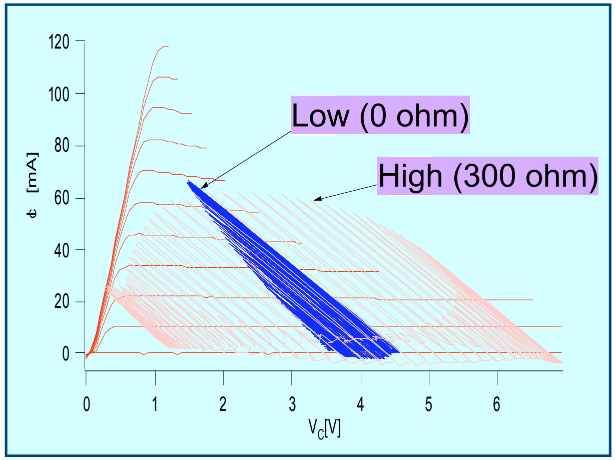
IF Output Voltage Engineering (Envelope Tracking)

- Effect of Amplitude on Intermodulation Distortion (HBT)

IF Load-Pull Effect on IM3 Distortion



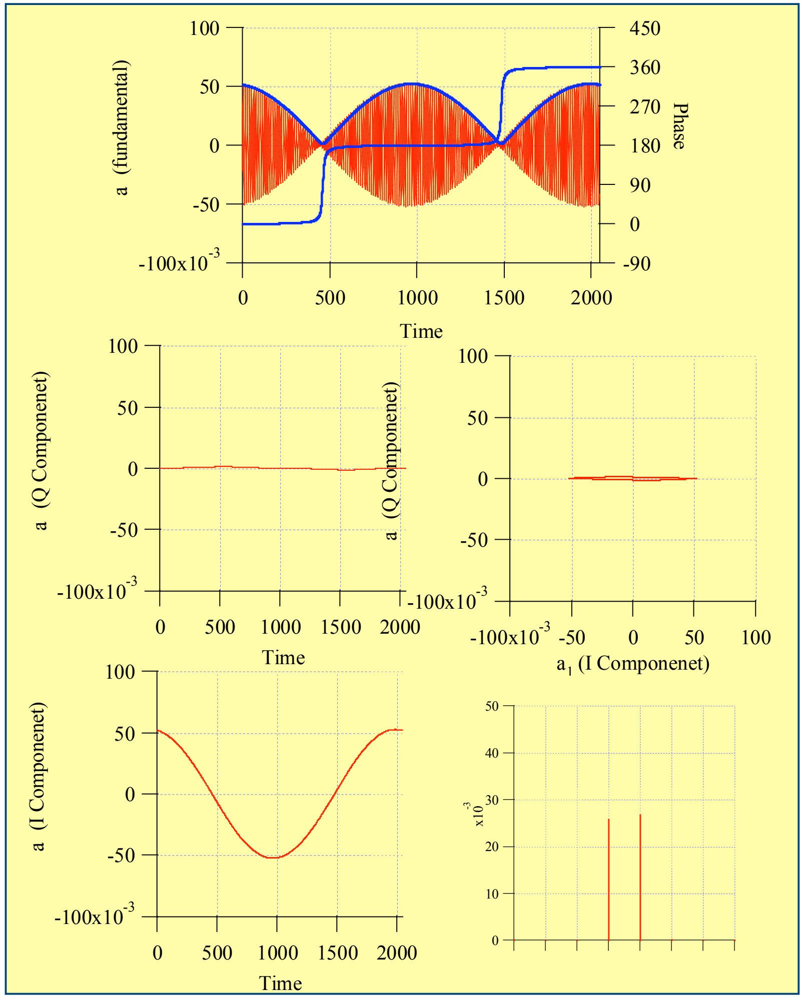


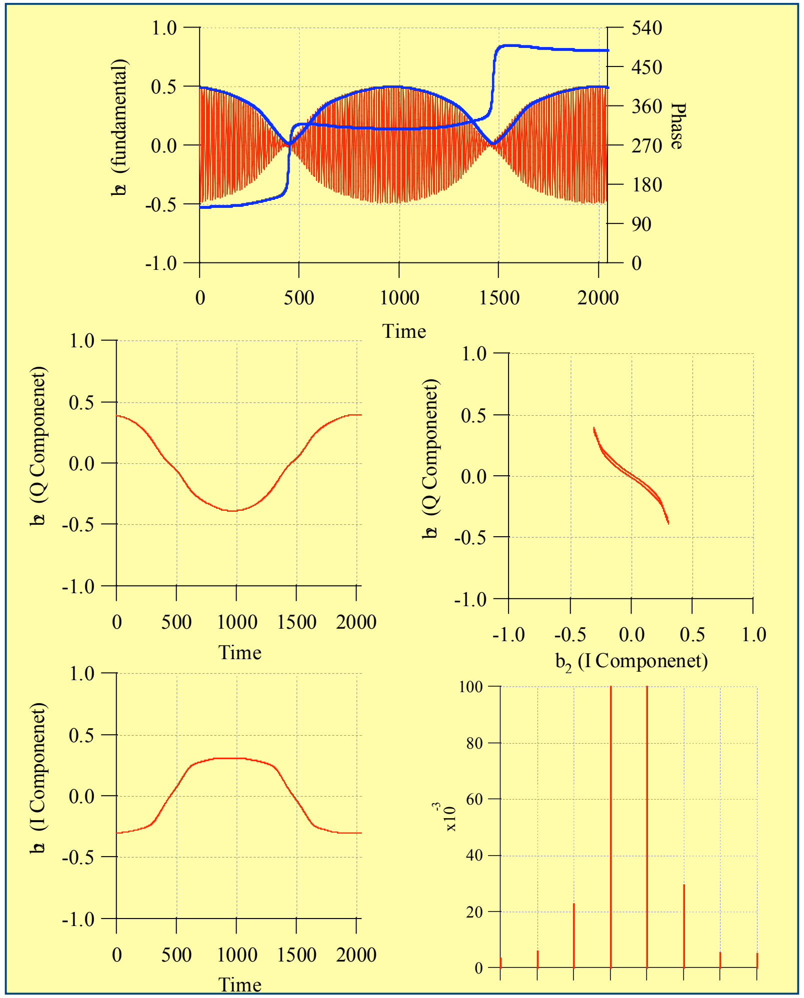


Control of interaction of output dynamic waveforms with knee region explains intermodulation sensitive to IF load impedance.

IF Output Voltage Engineering (Envelope Tracking)

- Effect of Amplitude on Intermodulation Distortion (HBT)

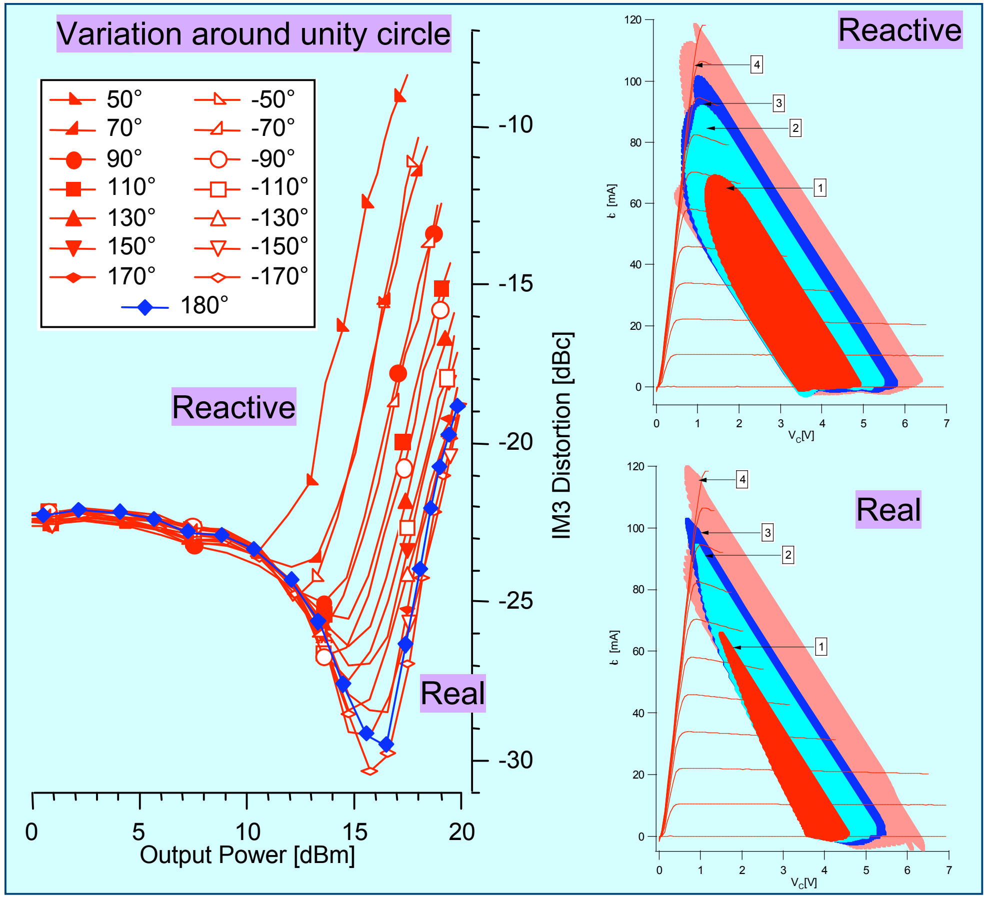


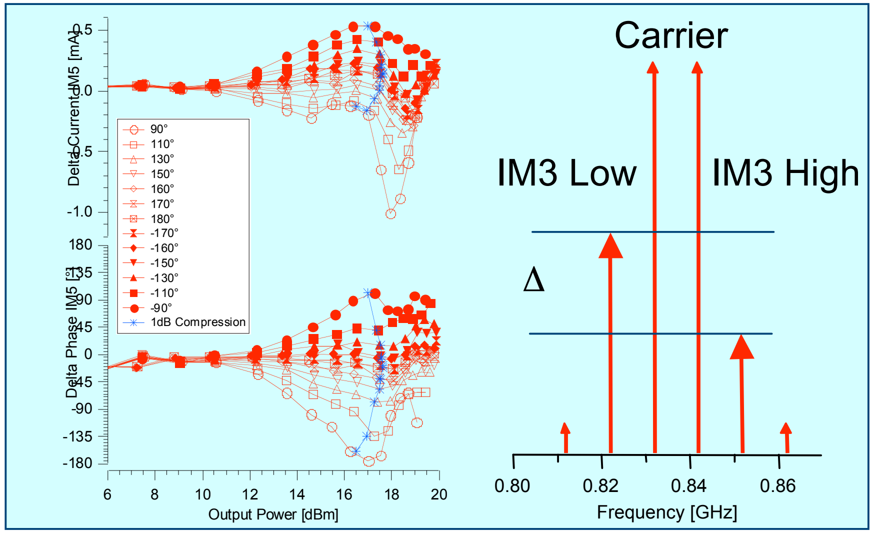


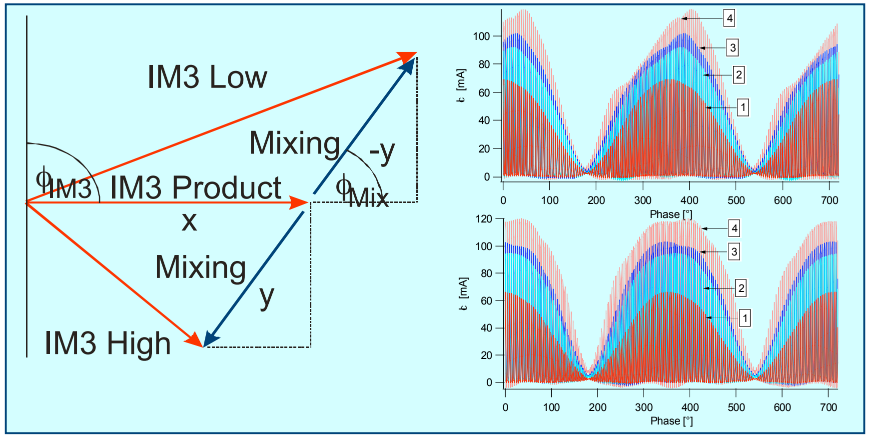
IF Output Voltage Engineering (Envelope Tracking)

- Effect of Phase on Intermodulation Distortion (HBT)

IF Load-Pull Effect on IM3 Distortion



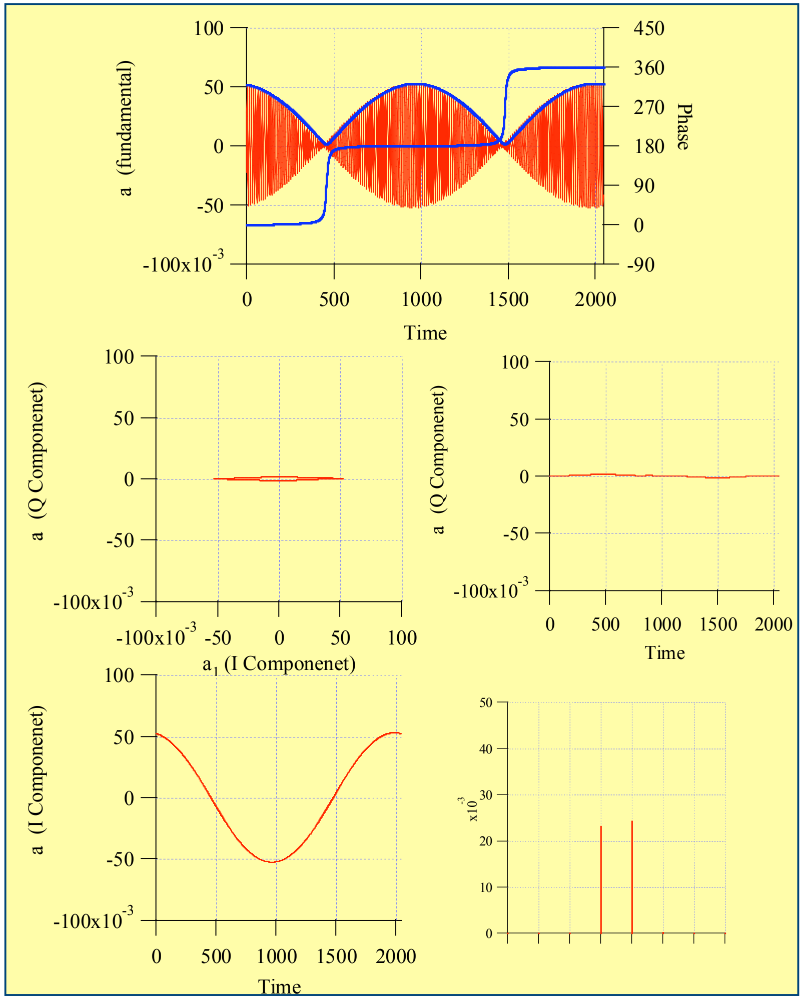


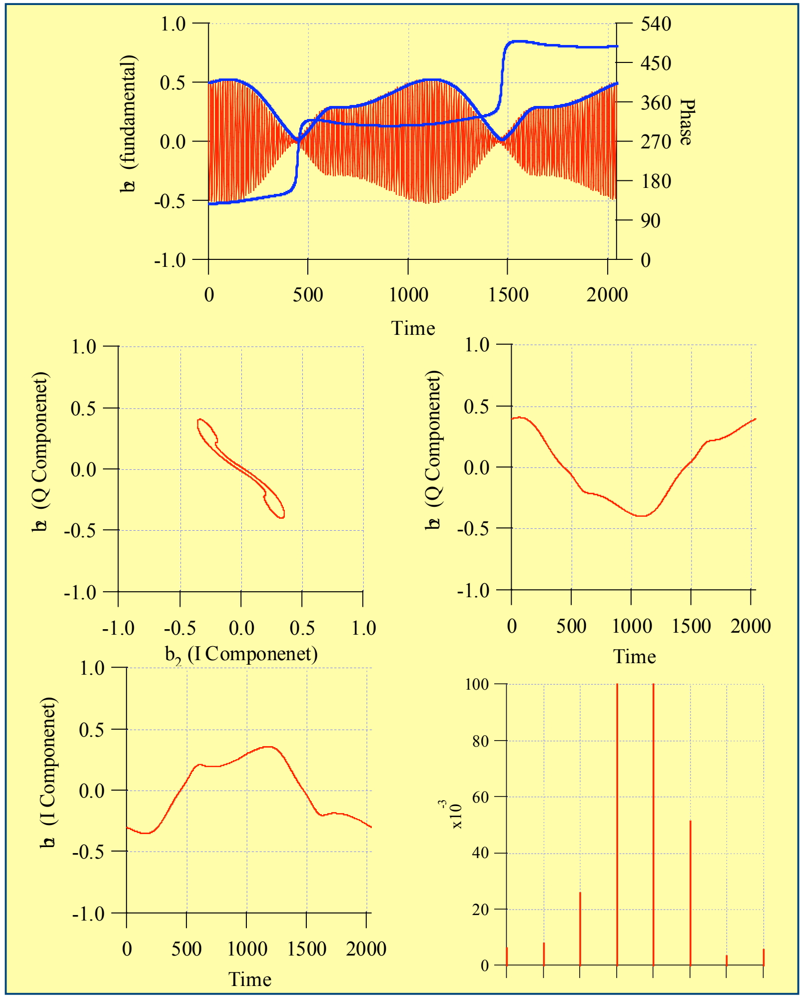


Mixing of transfer and output non-linearities caused by interaction of dynamic output waveforms with knee region explains sensitivity to IF load impedance.

IF Output Voltage Engineering (Envelope Tracking)

- Effect of Phase on Intermodulation Distortion (HBT)

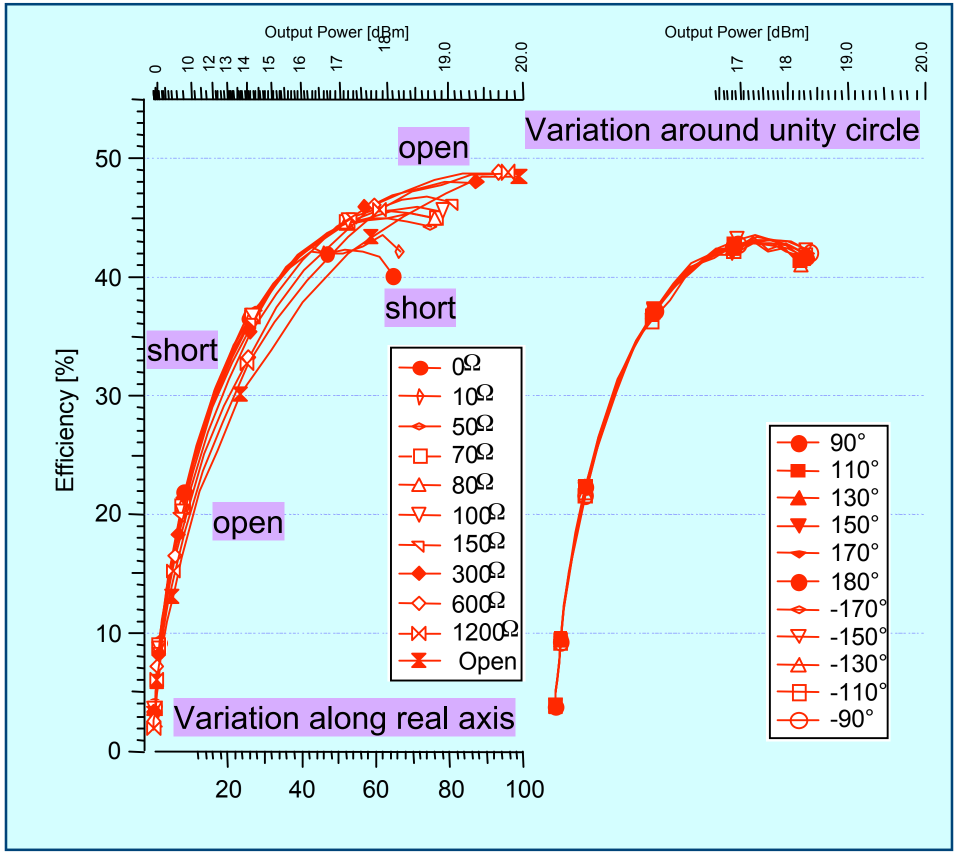


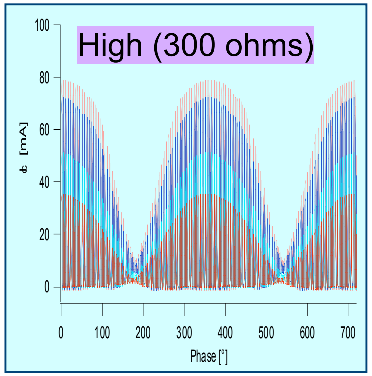


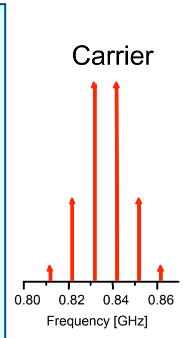
IF Input Voltage Engineering (Pre-distortion)

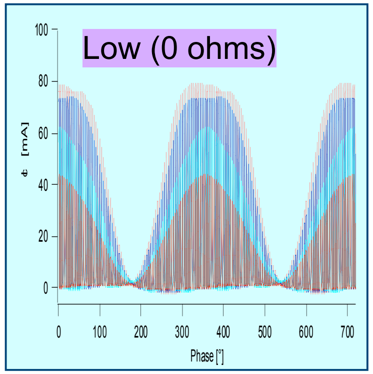
- Effect on RF Carrier Output Power (HBT)

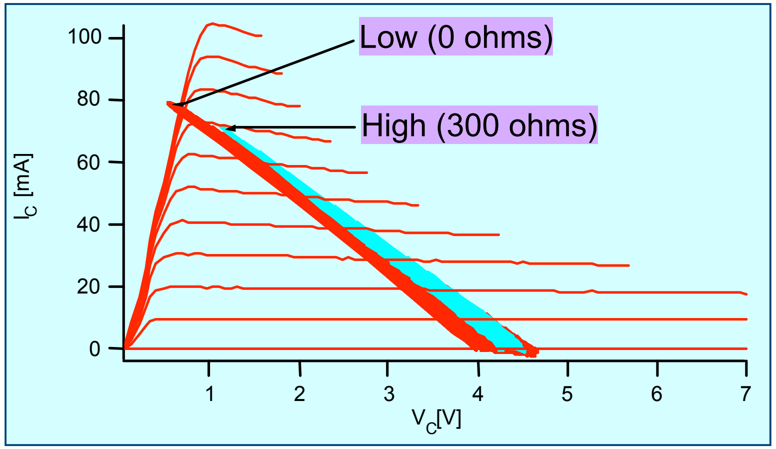
IF Source-Pull Effect on Output Power and Efficiency









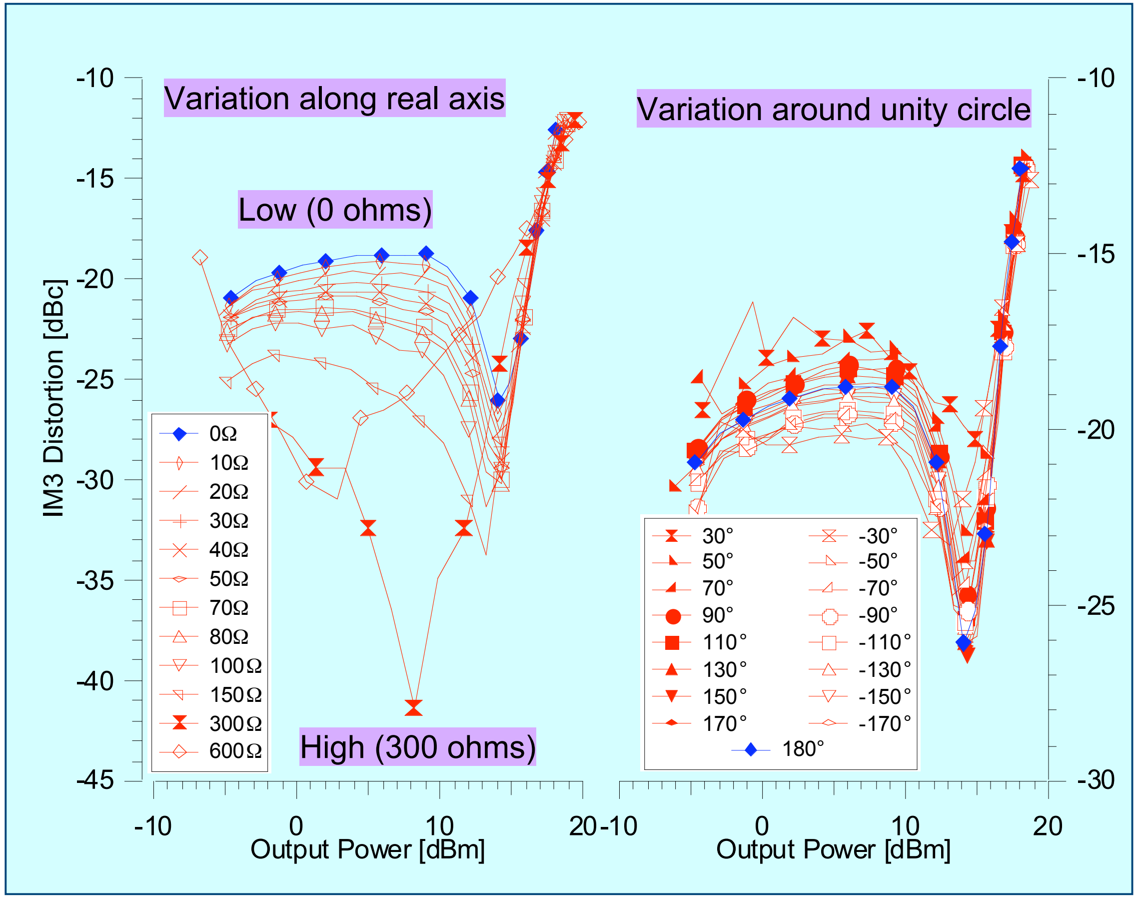


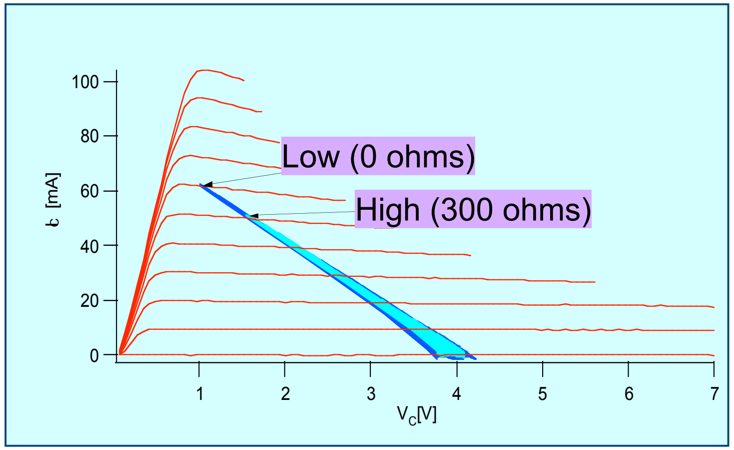
Waveform shape explains carrier power and efficiency sensitive to IF source impedance.

IF Input Voltage Engineering (Pre-distortion)

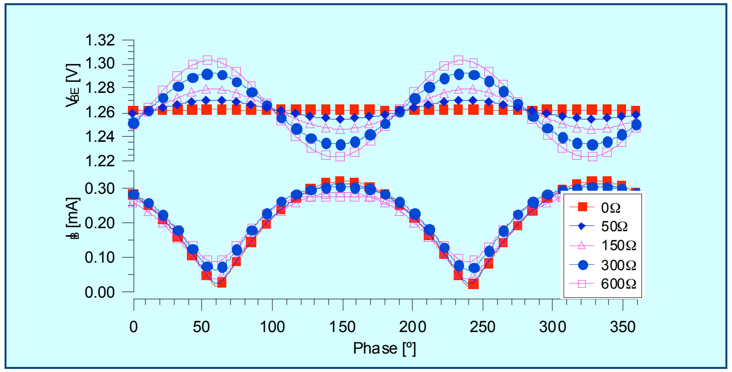
- Effect on Intermodulation Distortion (HBT)

IF Source-Pull Effect on IM3 Distortion





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



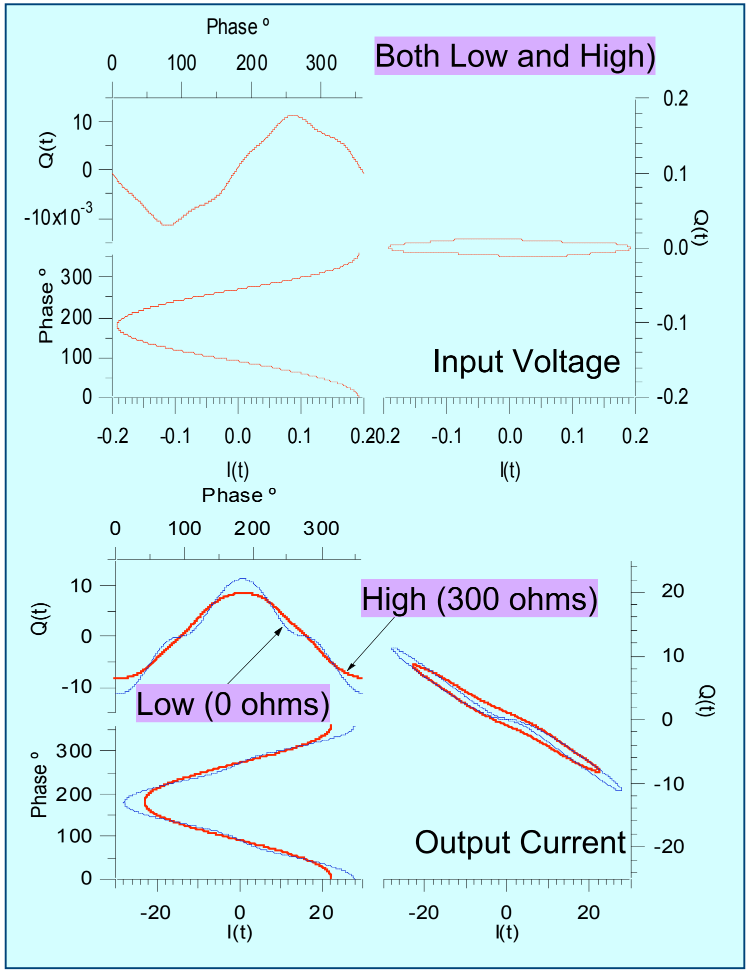
$i_o(t) = a_0 + a_1.v_i(t) + a_2.v_i(t)^2 + a_3.v_i(t)^3$

Transfer function explains intermodulation sensitivity to IF source impedance

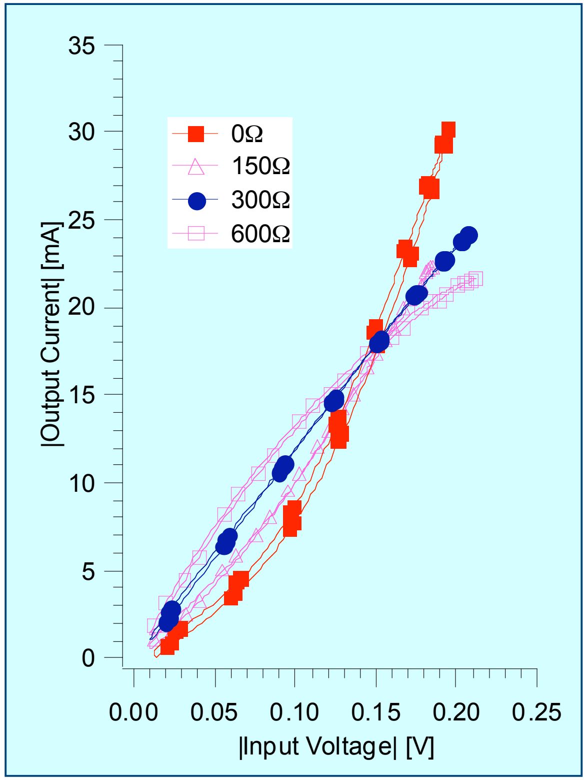
IF Input Voltage Engineering (Pre-distortion)

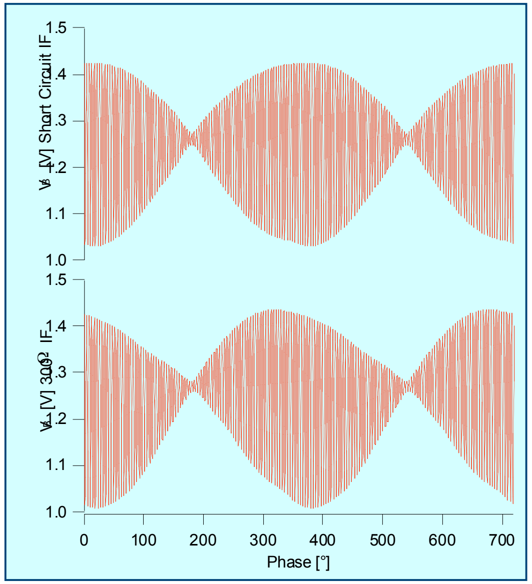
- Optimization of Linearization Process (HBT)

Input Voltage and Output Current Carrier Envelopes



Engineered Carrier Envelope Transfer Function



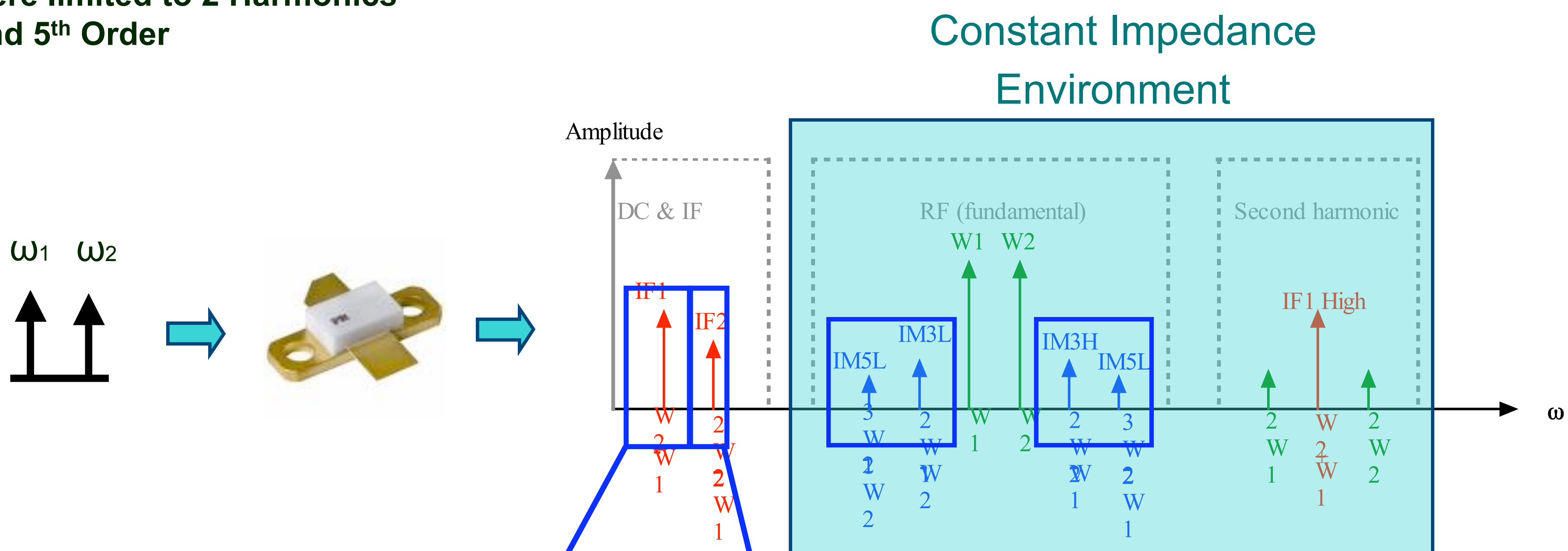


Utilize IF source (input) impedance to engineering predistorted input signal

Realization of IF (Base-band) Engineering

- continue focus on bias circuit electrical memory issues

Here limited to 2 Harmonics and 5th Order



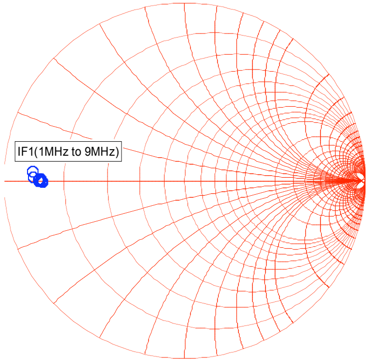
simplified two-tone spectrum up to fifth-order component polynomial transfer characteristic

Previous work investigated IM sensitivity to IF1.

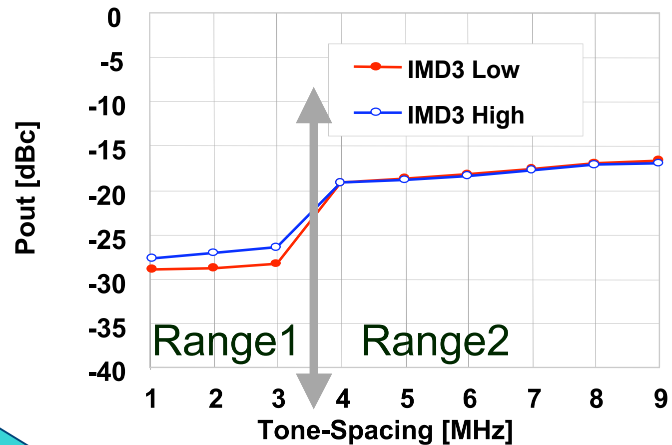
But is some device, high power LDMOS base-band spectra is more complex

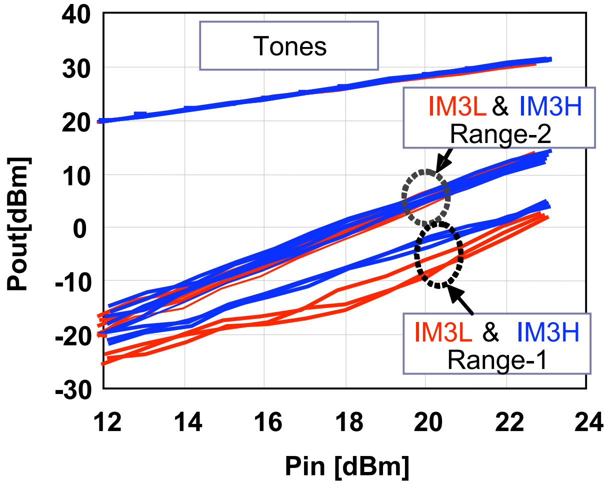
Linearity and Memory Investigations:
- 20W Si LDMOS

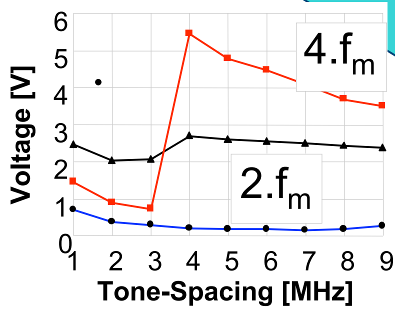
Waveform Engineering:
- Minimize Source of Electrical Memory
- 0.5 to 4.5 MHz AM Modulation (Two Tone: 2.f_m)

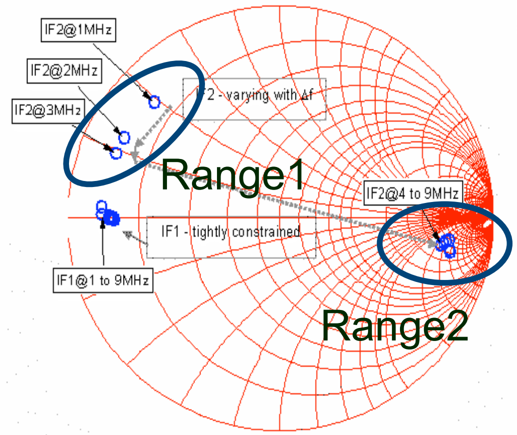


Limitations of Passive Load-Pull)









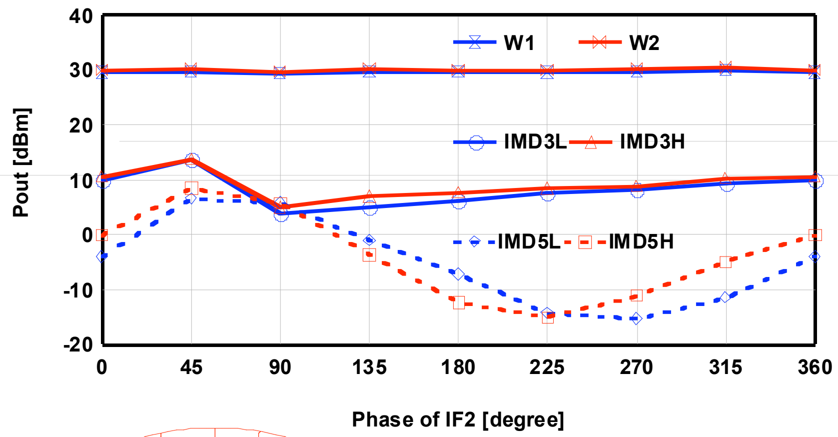
Observations
- Weak Memory Resulted
- Memory/Linearity sensitive to 4 times modulation BW

Alghanim, *EuMC 2007*

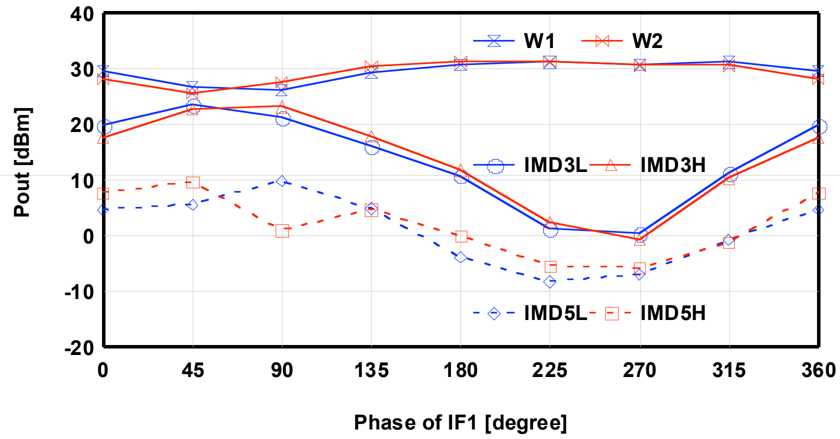
IF Waveform Engineering

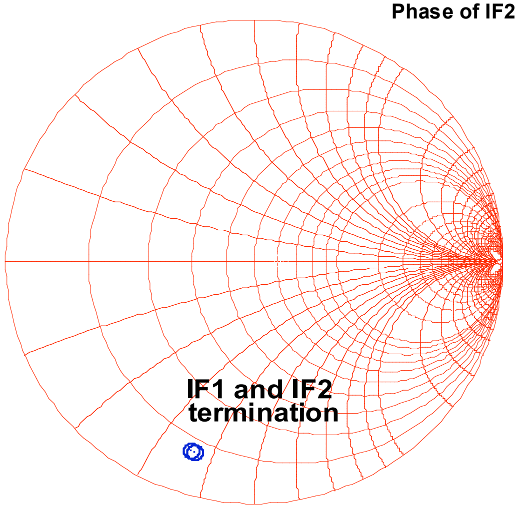
- Optimum IF termination to simultaneously minimize IMD3 and IMD5

Measured IMD magnitude vs. phase of IF2



Measured IMD magnitude vs. phase of IF1



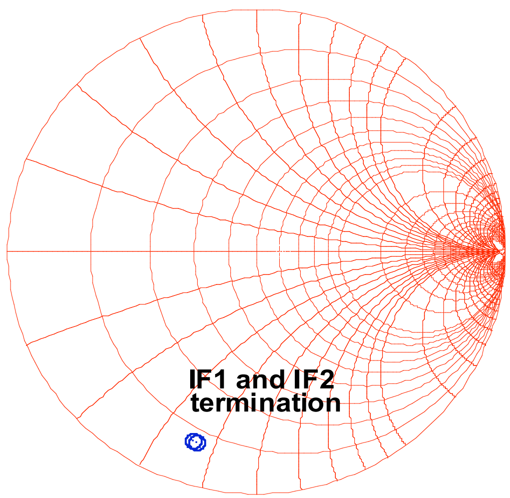


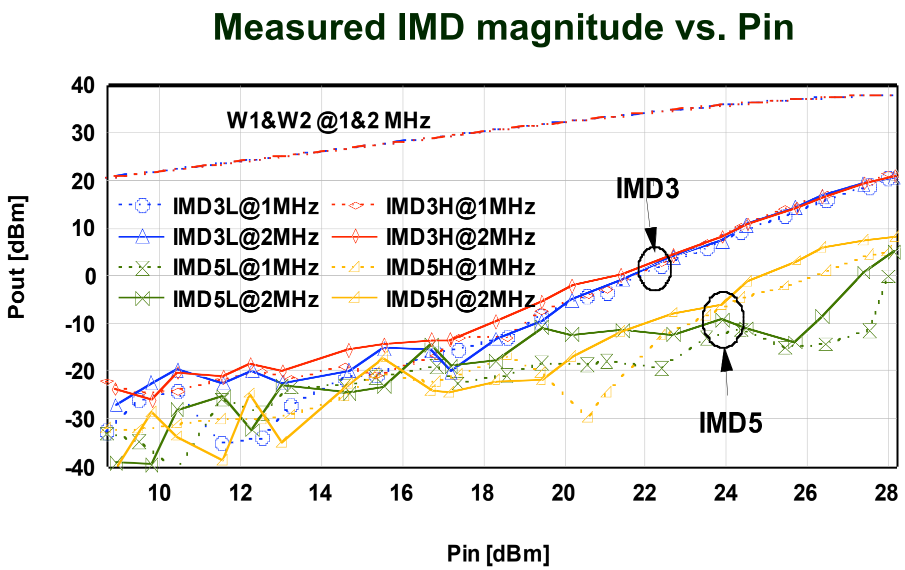
Improvement of IMD3 by -16 dB and IMD5 by -11 dB

IF Waveform Engineering

- Optimum IF termination to simultaneously minimize IMD3 and IMD5

Do these identified optimums change with tone-spacing?



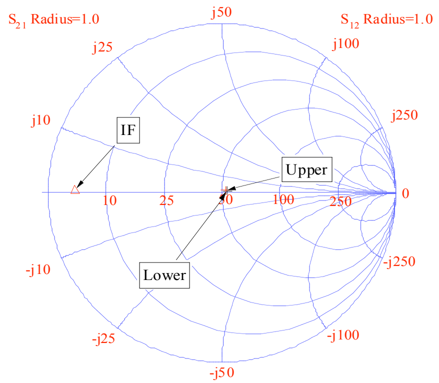


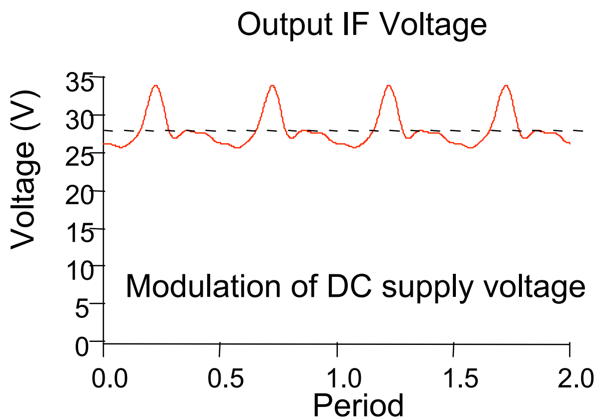
- Indications are that the optimum IF impedances is independent of modulation frequency
- These impedances can be easily synthesised using an ET process

IF Waveform Engineering

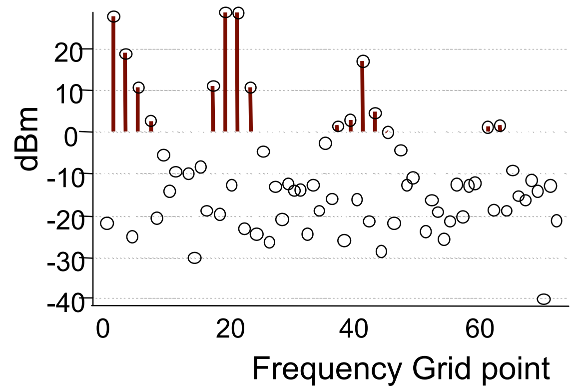
- Envelop Domain: Linearity Investigations

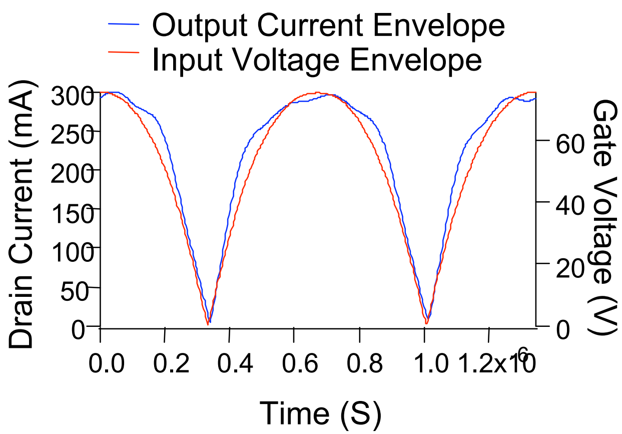
Device: 20W LDMOS
Carrier: 2.1 GHz
Tone spacing: 800 kHz,
Bias A-B (10%Idmax)
Passive IF short

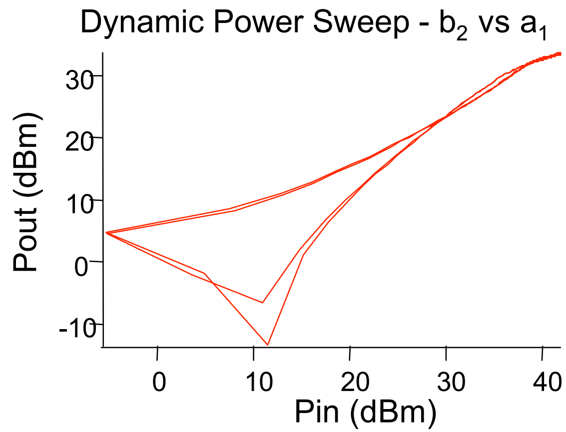




P_{in}_avail = 40 dBm







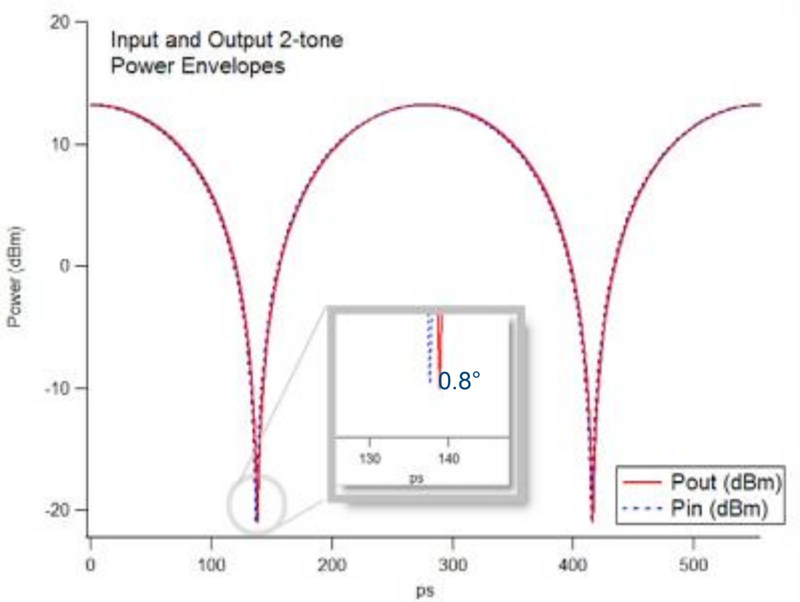
IF Waveform Engineering

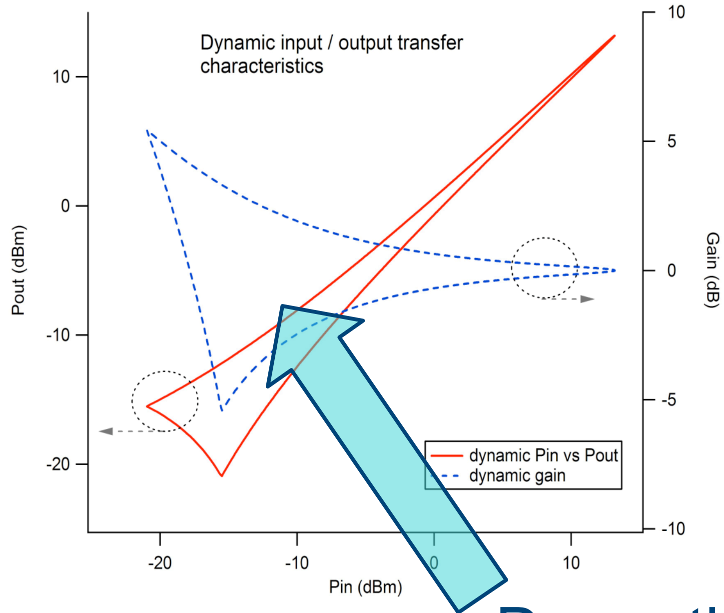
- Demystifying Memory: Envelop Domain Simulations

- 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

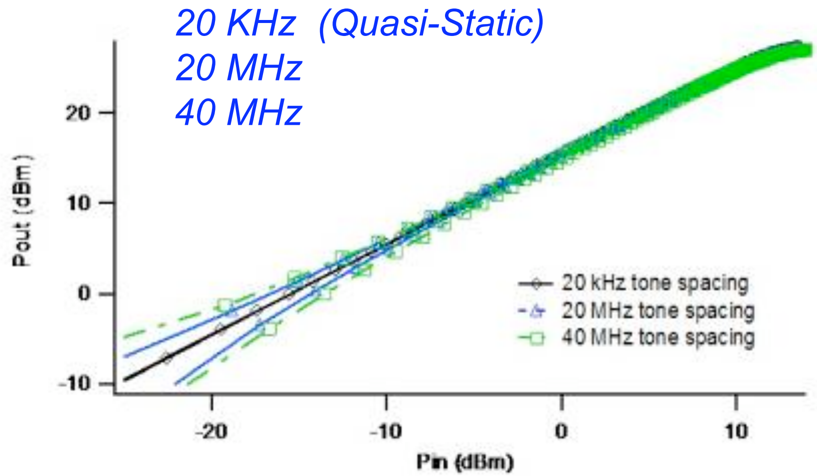
- Demystifying Memory: Active Device Measurements

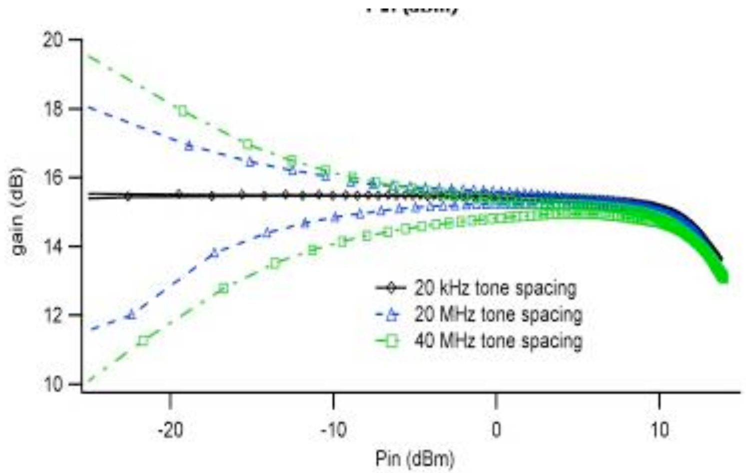
Device specifics

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



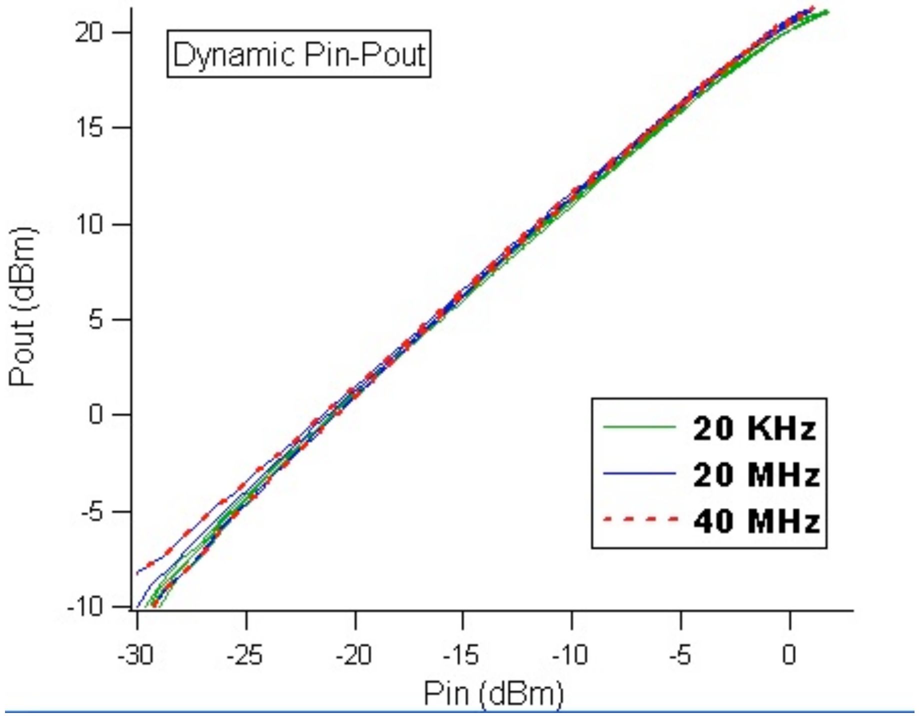


IF Waveform Engineering

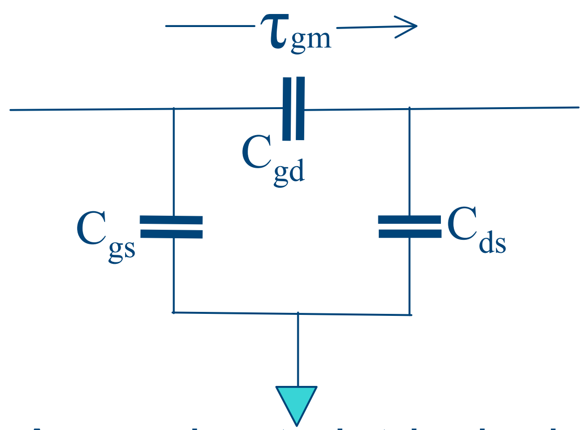
- Demystifying Memory: Active Device Measurements

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.



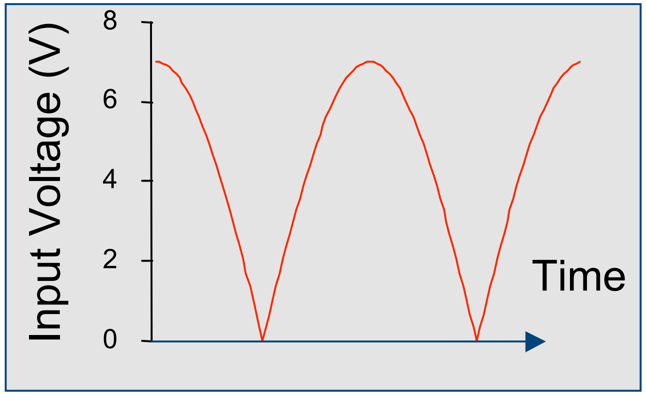
Approximate intrinsic delay

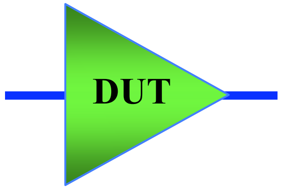
Cgs ~ 0.72 pF ~ 35 ps
Cgd ~ 0.06 pF ~ 3 ps
Cds ~ 0.13 pF ~ 6 ps
τgm ~ 2 ps

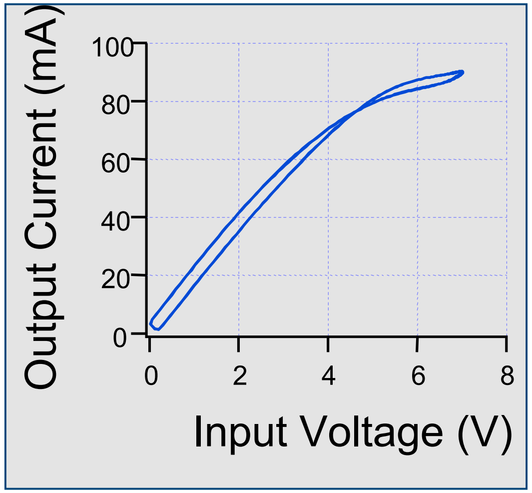
Total delay ~ 46 ps

IF Waveform Engineering
- Envelop Domain: Linearity Investigations

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

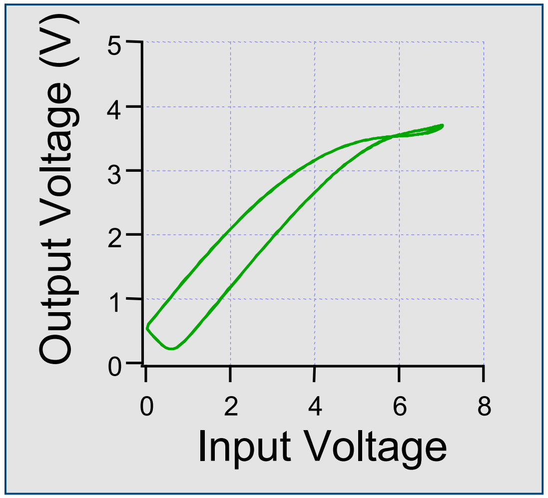






- Investigate Dynamic Envelop Response
  - Transistor “Memory”
  - RF Impedance variation “Memory”

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

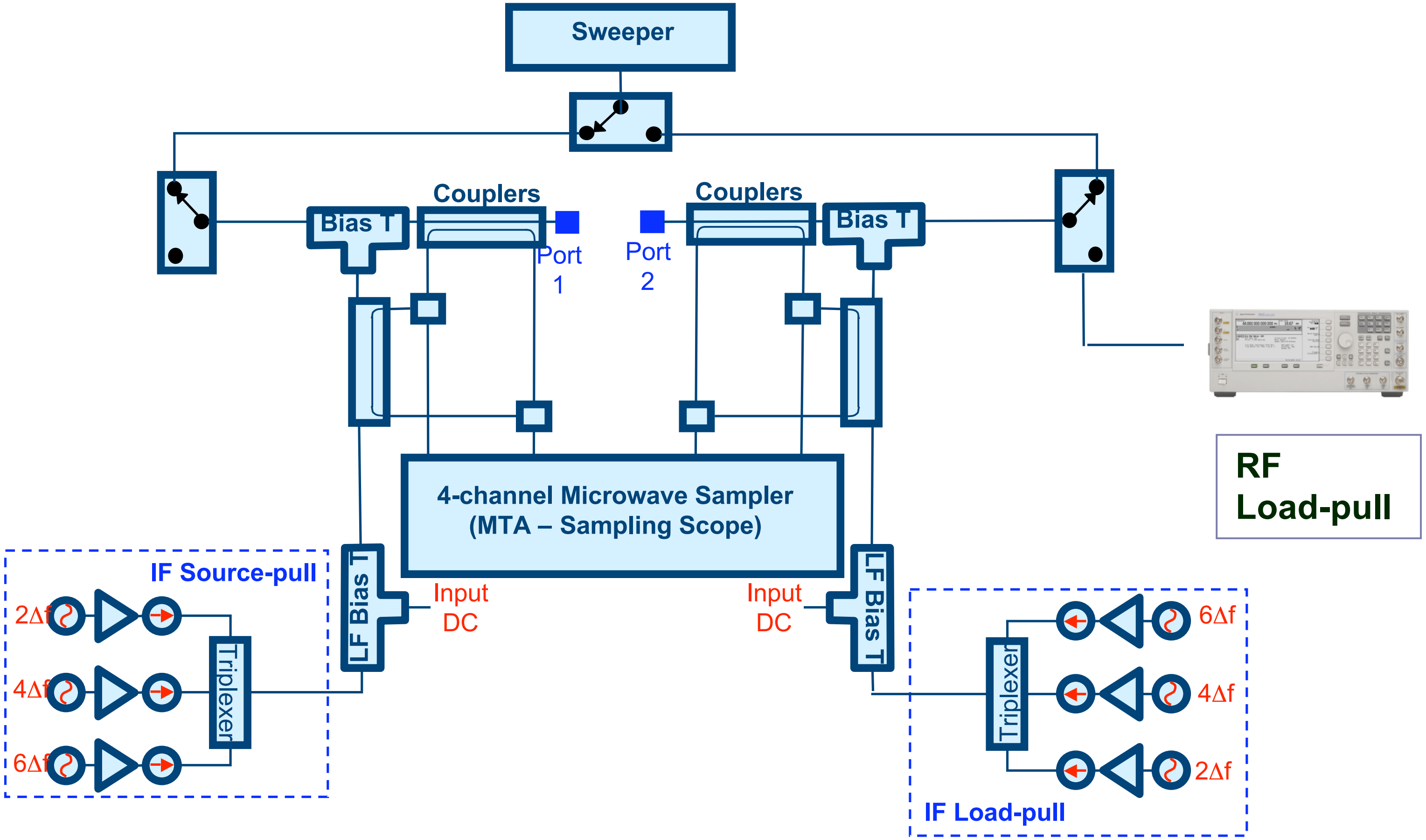
- CW (Single Tone) to Modulated (Multi-Tone) Measurement System Development
  - RF Multi-Tone I-V Waveform Measurement
    - Intelligent Sampling
    - Inclusion of IF (Base-band signals)
  - RF Multi-Tone IV Waveform Engineering
    - IF (Base-band) active load-pull

- 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)

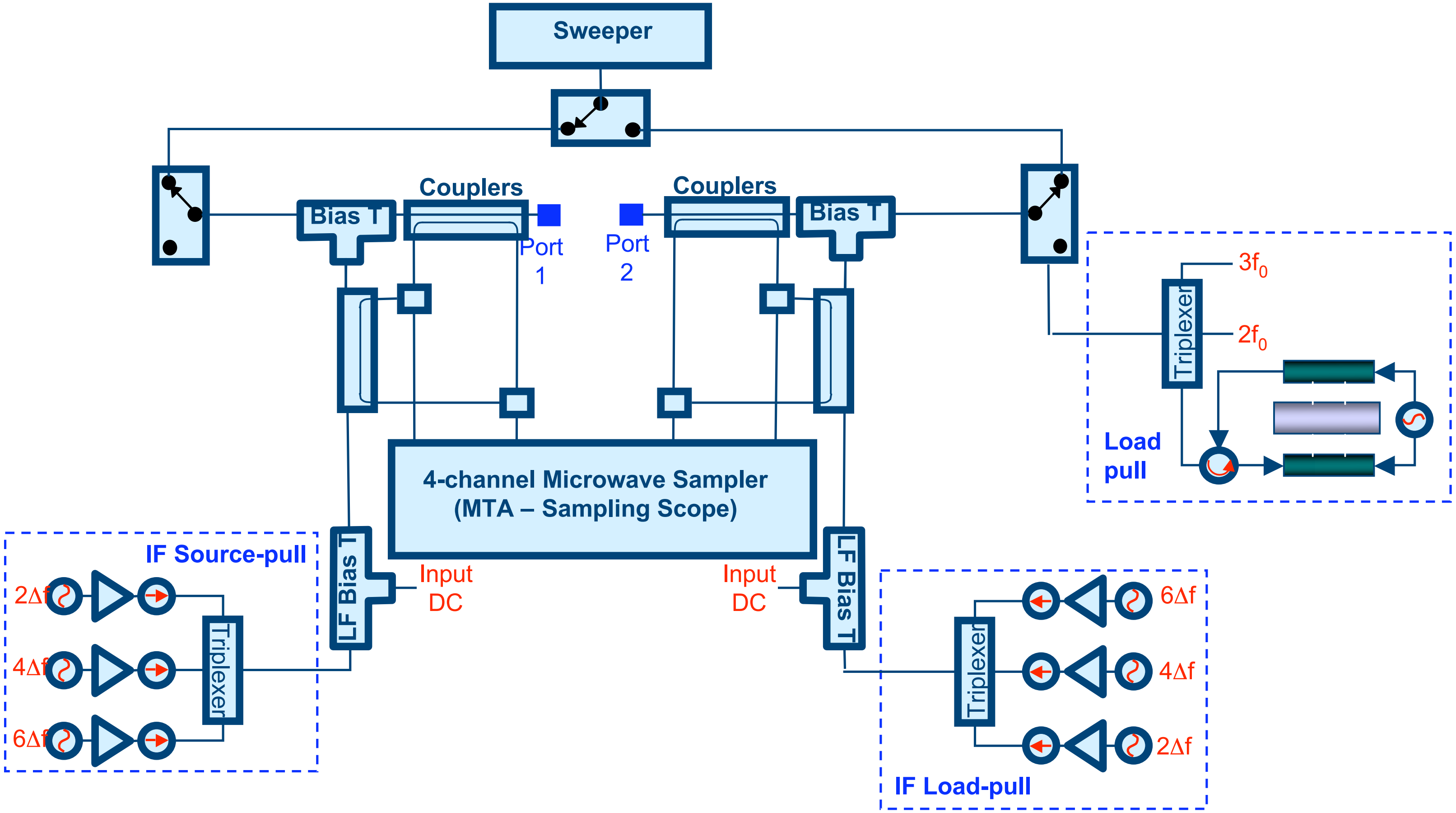
Realization of RF (Multi-Tone) Waveform Engineering

- consider in-band and harmonic circuit electrical memory issues



Realization of RF (Multi-Tone) Waveform Engineering

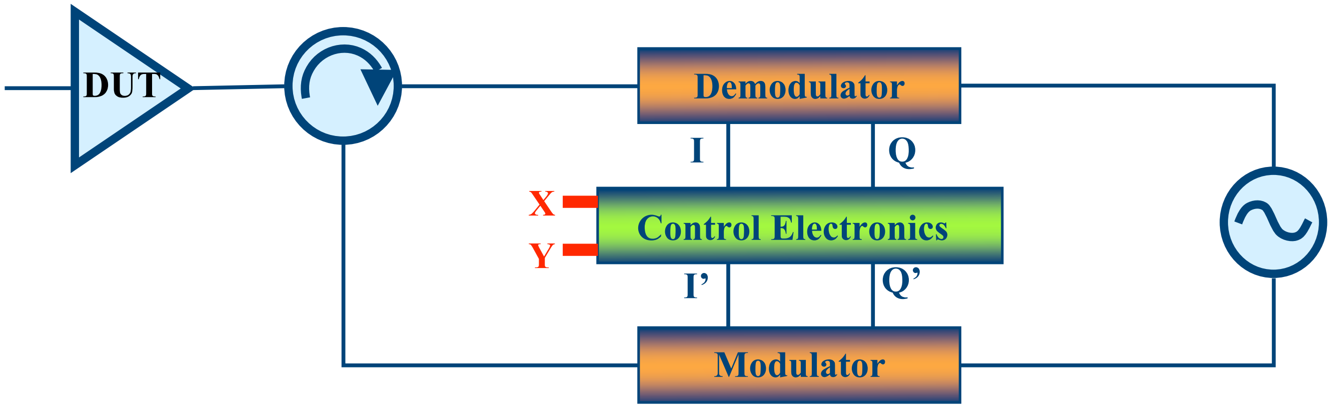
- consider in-band and harmonic circuit electrical memory issues



Realization of RF (Multi-Tone) Waveform Engineering

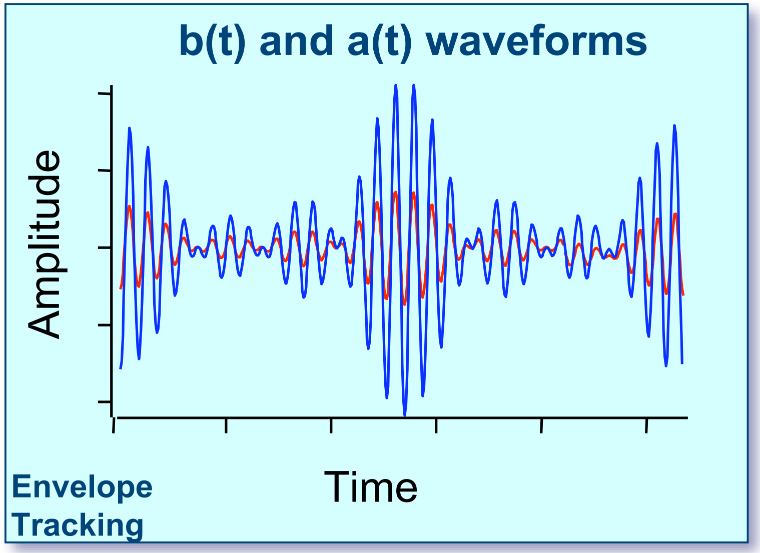
- Envelope load-pull solution: Envelop Tracking

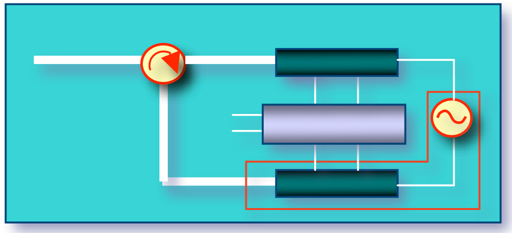
- Open loop at RF but a closed loop at envelope frequencies
  - No loop oscillations as no direct RF feedback
  - Reflection coefficient constant irrespective of the signal coming from DUT
- Impedances set by simple electronics controlled by the X & Y inputs
  - Suitable for modulated signals

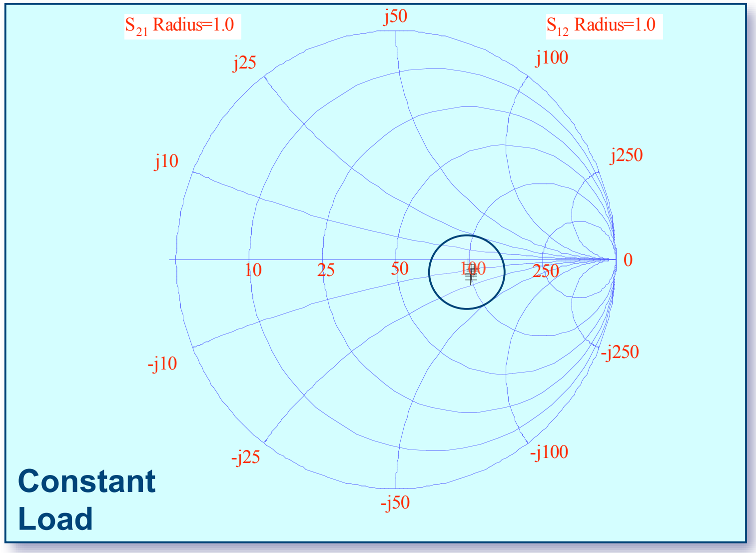


Realization of RF (Multi-Tone) Waveform Engineering

- Envelope load-pull solution: Envelop Tracking



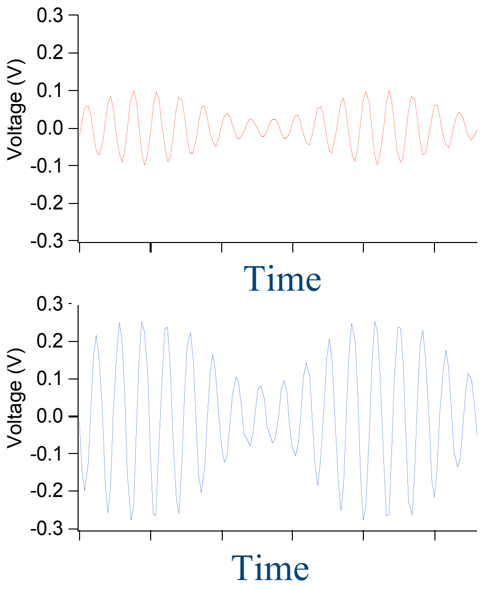




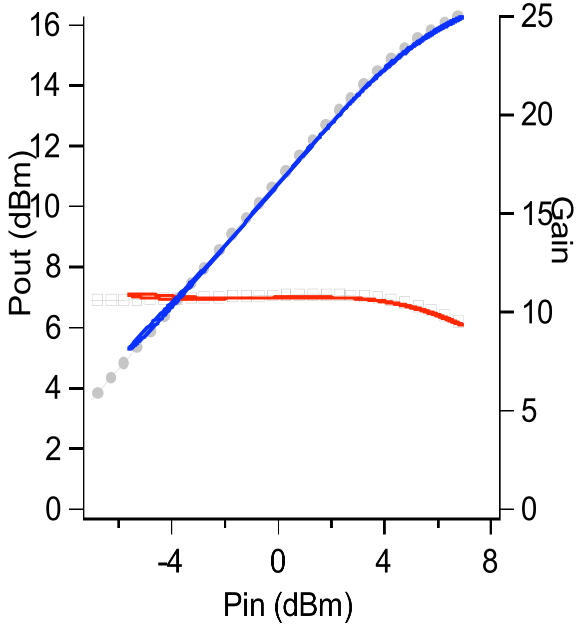
9 Tone Modulated Signal
=> Confined to a few 100 kHz at present

Realization of RF (Multi-Tone) Waveform Engineering

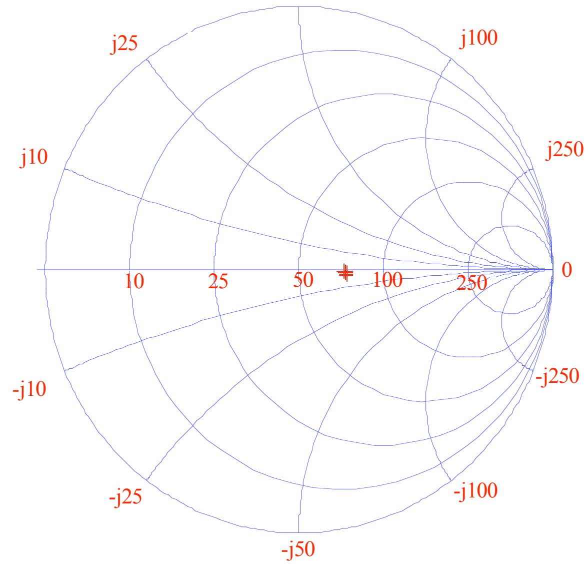
- Envelope load-pull solution: 'Instantaneous' power sweeps



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



Comparison between 'instantaneous' and CW power sweep

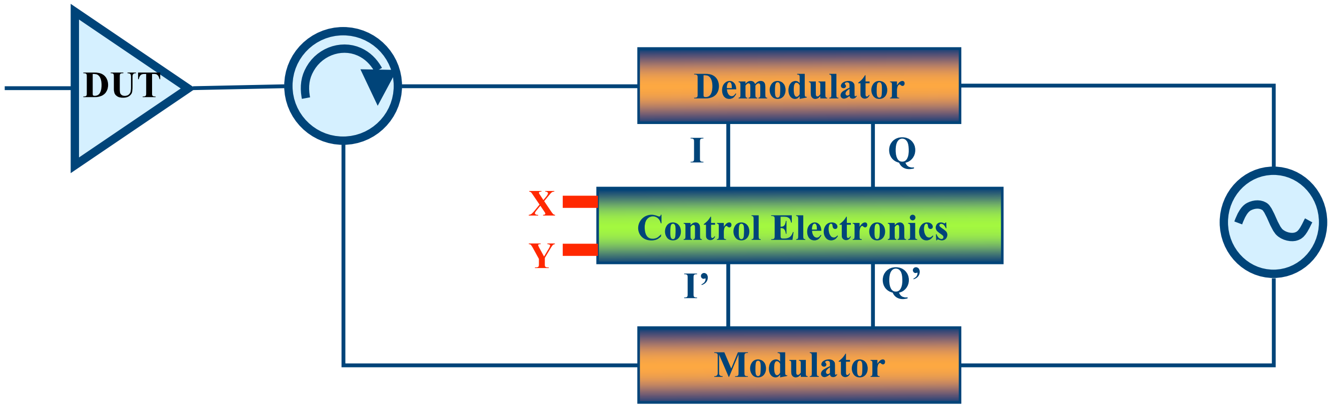


Impedance measured during 'instantaneous' power sweep

Realization of RF (Multi-Tone) Waveform Engineering

- Envelope load-pull solution: Envelop Tracking

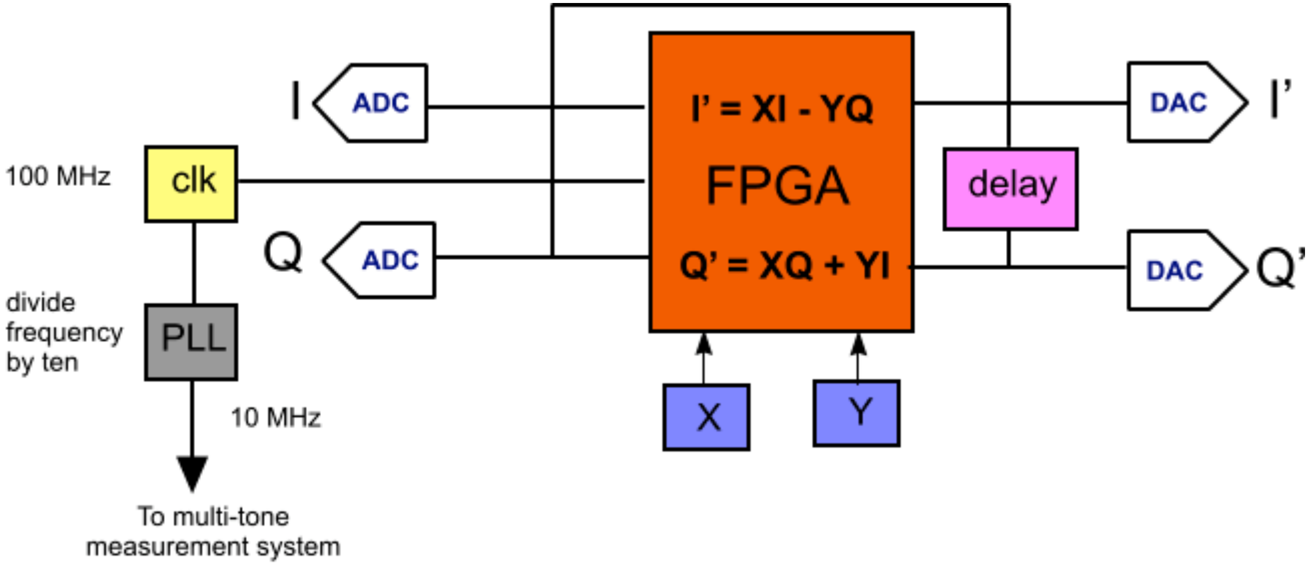
- Open loop at RF but a closed loop at envelope frequencies
  - No loop oscillations as no direct RF feedback
  - Reflection coefficient constant irrespective of the signal coming from DUT
- Impedances set by simple electronics controlled by the X & Y inputs
  - Need high speed control electronics for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

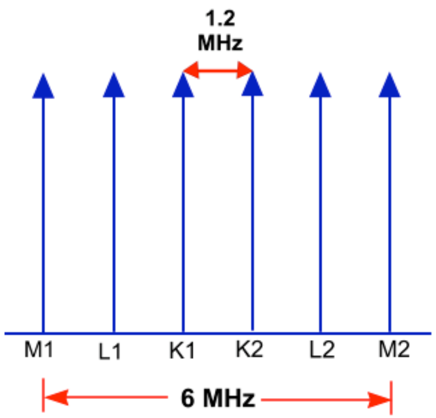


RF I-V Waveform Engineering

- 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*

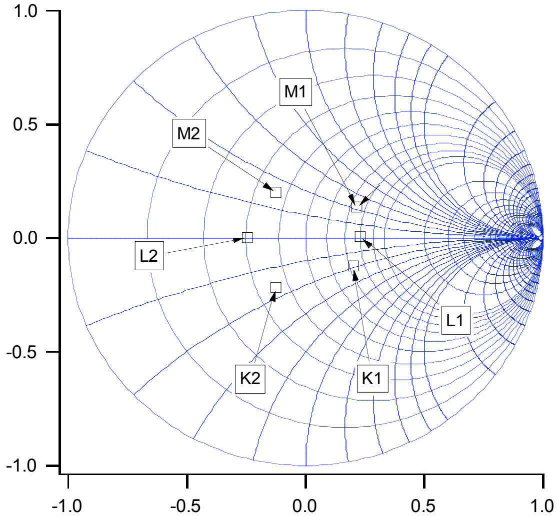


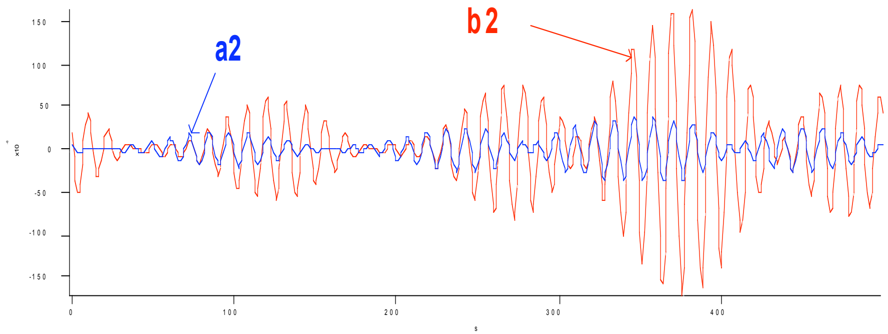


40

RF I-V Waveform Engineering

- Next generation ELP Systems: Time Delay problem



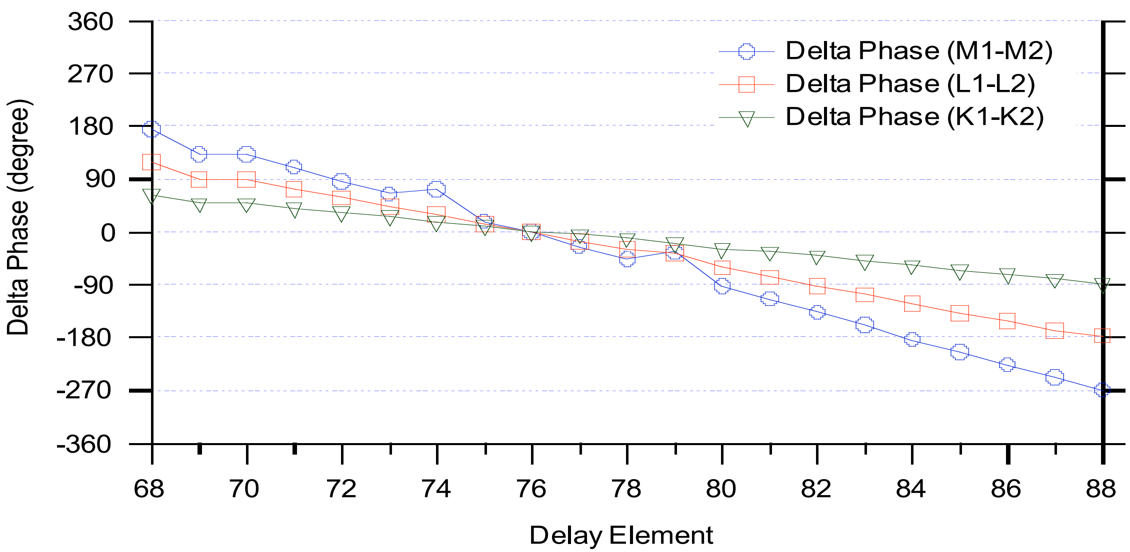


- The control unit can support wideband stimulus albeit delay
- Phase variation over length of cable and components (group delay or envelope delay)
  - Must be compensated for accurate load impedance matching
- The repetitive nature of the measurement stimulus made delay compensation possible in the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

RF I-V Waveform Engineering

- Next generation ELP Systems: Delay compensation determination

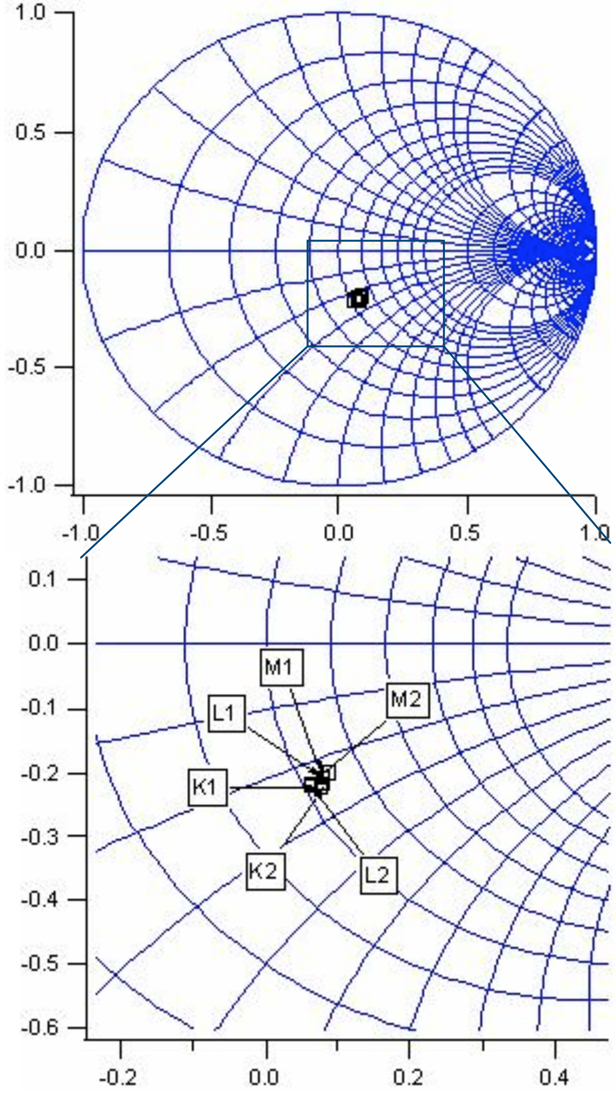
- Configurable FIFO RAM based unit delay
  - Unit delay is 10 ns (100 MHz clock)
  - Delay is compensated after 76 delay elements
  - *Latest development of delay compensation is not limited to unit delay*
- Linear group delay can be observed from the graph

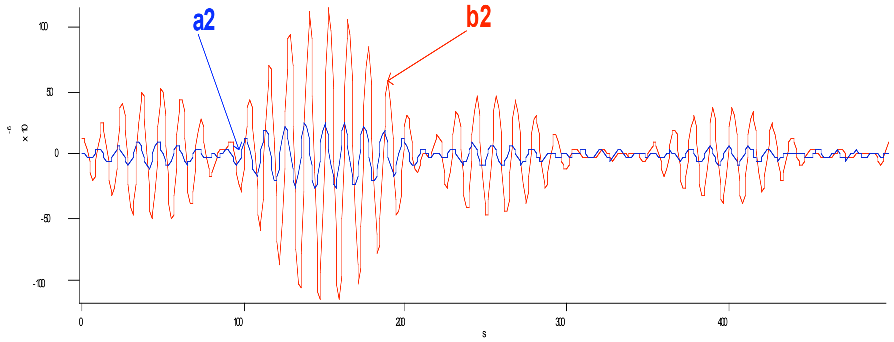


42

RF I-V Waveform Engineering

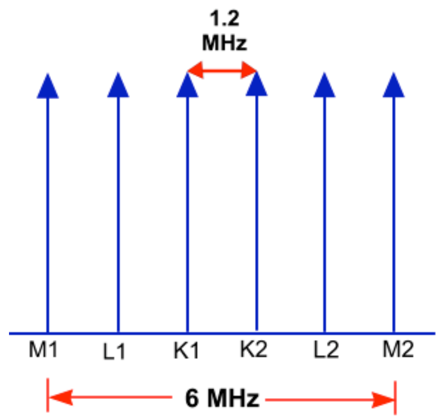
- Next generation ELP Systems: Digital control using FPGA using delay





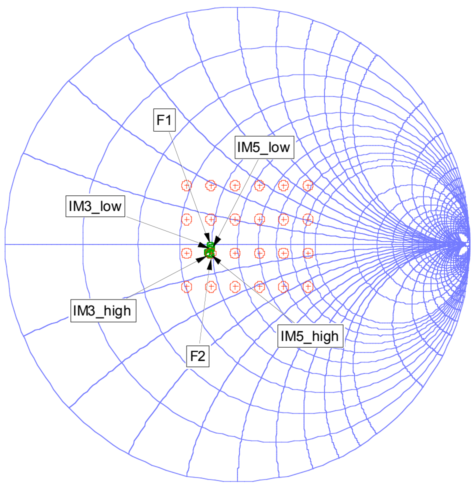
results

- 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