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# Summary & analysis of the critical power amplifier design tool - Linearity loadpull characterization

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# Non-50 Ohm Linearity measurement history The challenge of 2 tone test on unmatched device • A novel 2 tone measurement solution $\rightarrow$ MT2000! Beyond active loadpull

- System Offering







# Non-50 Ohm Linearity measurement history





# •••• Introduction

Intermodulation distortion (IMD) is a measure of t passive components.



The third-order intercept point (IP3) or the third-order intercept (TOI), often used interchangeably, are figures of merit for intermodulation distortion.



![](_page_4_Picture_5.jpeg)

### Intermodulation distortion (IMD) is a measure of the nonlinearity of an amplifier and sometime even

![](_page_4_Figure_7.jpeg)

![](_page_4_Picture_8.jpeg)

![](_page_4_Picture_9.jpeg)

10

# •••• Traditional 2 tone/ACPR measurement

![](_page_5_Figure_1.jpeg)

**Signal Source** 

![](_page_5_Picture_3.jpeg)

![](_page_5_Picture_4.jpeg)

![](_page_5_Picture_5.jpeg)

![](_page_6_Picture_0.jpeg)

- 1. Non 50 Ohm characterization -> tuner calibration
- 2. Hardware connection -> manual setting of spectrum analyzer and synchronization, 10MHz synchronization
- 3. Power calibration -> sweep each tone space and each power level, generate a data base table
- 4. Measurement -> recall the table, sweep step by step

![](_page_6_Picture_5.jpeg)

![](_page_6_Picture_7.jpeg)

![](_page_6_Picture_8.jpeg)

![](_page_7_Picture_0.jpeg)

![](_page_7_Figure_1.jpeg)

![](_page_7_Figure_2.jpeg)

*Tuner calibration, critical and inevitable step, but TEDIOUS!* 

mechanical speed

![](_page_7_Picture_5.jpeg)

![](_page_7_Picture_7.jpeg)

# •••• Power calibration with tone balancing

		🐼 Snpw - [Power Calibration (Intermod)]
Options Setup	×	🛞 File Edit Window Help
System Noise Power Intermod ACP Pulse User	Power Calibration (Intermod)	
Tone Spacing (MHz):       5       Optimum SA Power (dBm)         Tone Equality (dB):       0.2       Auto       Meas         Span Ratio (max=1.0):       0.5       -30       Imod Measurement Method         Min SA Atten (dB):       10       Peak Search       Zero Span         Carrier Averaging:       1       1	Frequencies (GHz)       Available: 2.000 GHz to 6.000 GHz, 5 Freqs         2.0000       Add Point       Add Range         Delete Point       Delete All         Set to Available Frequencies       -15.0000         -10.0000       -10.0000         -8.0000       -10.0000         -7.0000       -6.0000         -6.0000       -15.0000         -7.0000       -15.0000         -10.0000       -10.0000	Label: two_tone_power_cal_1MHz Freq Tsource P_programmed P_avail SA_coupln GHz mag phase dBm dBm dB 2.0000 0.056 150.66 -30.000 -34.416 -10.091 -29.000 -33.377 -28.000 -32.399 -27.000 -31.406 -26.000 -30.406 -25.000 -29.404 -24.000 -28.397 -23.000 -27.407 -22.000 -26.404 -21.000 -25.408 -20.000 -24.409 -19.000 -23.409 -18.000 -22.413 -17.000 -21.415
Intermod Averaging:	Thru s-parameters S-parameter file name:	$\begin{array}{rrrr} -16.000 & -20.417 \\ -15.000 & -19.412 \\ -14.000 & -18.414 \\ -13.000 & -17.410 \\ -12.000 & -16.406 \end{array}$
SA IP3 (dBm): 15	thrud.s2p       Browse         Instrument Initialization       Power Measuring Instrument: Power Meter         Tuners:       O Already Initialized Initialize Now         Power Meters:       O Do Nothing Initialized Initialize Now	$\begin{array}{cccccccccccccccccccccccccccccccccccc$
OK Cancel H	Prompt to connect thru after initialization         OK       Cancel	$\begin{array}{cccccccccccccccccccccccccccccccccccc$

![](_page_8_Figure_2.jpeg)

![](_page_8_Picture_3.jpeg)

![](_page_8_Picture_4.jpeg)

### •••• pros and cons

Traditional loadpull based on power meter is the only choice in last century

- Tedious tuner calibration Rely on de-embedding all the way
- Elaborate setting/verification of system For accurate and relatively fast measurement
- Exact power cal.

Table should be created before measurement, if driving amplifier changed, the table should be updated again. Not cheap and complexed to setup

- Spectrum analyzer should be connected
- Operator should be experience enough

![](_page_9_Picture_9.jpeg)

![](_page_9_Picture_12.jpeg)

Cheap at the first glance, but unfortunately NOT in long term view

![](_page_9_Picture_15.jpeg)

![](_page_9_Picture_16.jpeg)

![](_page_9_Picture_17.jpeg)

![](_page_9_Picture_18.jpeg)

# •••• VNA's advanced features for simple 2 tones test

### IMD measurement challenges

– Two signal generators, a spectrum analyzer, and an external combiner are most commonly used, requiring manual setup of all instruments and accessories

 Test times are slow when swept-frequency or swept-power IMD is measured

 Instruments and test setups often cause significant measurement errors due to source-generated harmonics, crossmodulation, and phase noise, plus receiver compression and noise floor

![](_page_10_Picture_5.jpeg)

![](_page_10_Picture_6.jpeg)

![](_page_10_Picture_7.jpeg)

### **Frequency Offset Mode (Option 080)**

- Sets different frequency range for the source and receivers.
- Can be used for harmonics or intermodulation distortion (IMD) measurements with the VNA.

![](_page_10_Picture_13.jpeg)

- Sets different frequency range for the source and receivers.
- Can be used for harmonics or intermodulation distortion (IMD) measurements with the VNA.

![](_page_10_Picture_16.jpeg)

![](_page_10_Picture_23.jpeg)

### Block diagram of 4 port PNAX with combiner for 2 tones

![](_page_11_Figure_1.jpeg)

![](_page_11_Picture_2.jpeg)

![](_page_11_Picture_3.jpeg)

### Block diagram of 2 port PNA with coupler for 2 tones

![](_page_12_Figure_1.jpeg)

![](_page_12_Picture_2.jpeg)

![](_page_12_Picture_3.jpeg)

![](_page_12_Picture_4.jpeg)

![](_page_13_Picture_0.jpeg)

![](_page_13_Figure_1.jpeg)

**Agilent Power Supply** 

### **Better loadpull structure based on VNA advanced architecture**

### VNA based loadpull / > Vector Veceiver loadpull / > Real Time loadpull

![](_page_13_Picture_6.jpeg)

![](_page_13_Picture_7.jpeg)

### Better loadpull structure based on VNA advanced architecture

![](_page_14_Figure_1.jpeg)

![](_page_14_Figure_2.jpeg)

![](_page_14_Figure_3.jpeg)

![](_page_14_Figure_4.jpeg)

![](_page_14_Picture_5.jpeg)

![](_page_14_Picture_6.jpeg)

### Calibration routine of VNA based LP

Tuner calibration -> much lower density needed compared with traditional one. Receiver vector calibration -> fast, no sensitive to source and load match. Receiver power calibration -> absolute power cal. of receiver by power meter

![](_page_15_Picture_2.jpeg)

![](_page_15_Picture_3.jpeg)

![](_page_15_Picture_5.jpeg)

![](_page_15_Picture_6.jpeg)

### **Pros and cons**

Integrated and fast solution necessary

Reduced tuner calibration time real time measure mode of receiver Fast tone balance leveling real-time power calibration is not necessary Change driving PA without calibration

power calibration again even change driving PA

PNAX should be occupied always by system PA linearity is prerequisite for accurate device linearity measurement

### frequency offset measurement mode for IMD3, Spectrum analyzer is not

# 8 terms model doesn't rely on source/load match, not necessarily do raw

![](_page_16_Picture_8.jpeg)

![](_page_16_Picture_9.jpeg)

# The challenge of 2 tone test on unmatched device

![](_page_17_Picture_1.jpeg)

![](_page_17_Picture_2.jpeg)

![](_page_17_Picture_3.jpeg)

![](_page_17_Picture_4.jpeg)

### Challenge in the non 500hm linearity measurement

Modulation	Freq. range	Bandwidth (single channel)	Total Bandwidth (1 Channel + ACLR)
W-CDMA	800 MHz –3.5 GHz	5 MHz	15 MHz
Multi-carrierW-CDMA	800 MHz –3.5 GHz	15 MHz	25 MHz
LTE	600 MHz –6 GHz	20 MHz	60 MHz
802.11a/b/g	2.4 GHz	20 MHz	60 MHz
802.11n	2.4 GHz, 5 GHz	40 MHz	160 MHz
LTE-A	800 MHz –3.5 GHz	100 MHz	300 MHz
802.11ac	5 GHz	160 MHz	480 MHz
5G	600 MHz –6 GHz	100 MHz	300 MHz
5G	28 GHz	~1 GHz	
5G	38 GHz	~1 GHz	

Bandwidth is more than 40 MHz in 4G times, it will be much wider in the coming 5G times, what are the challenges for linearity non-50 load pull test for PA?

![](_page_18_Picture_4.jpeg)

![](_page_18_Picture_5.jpeg)

![](_page_19_Picture_0.jpeg)

Phase shift issue

![](_page_19_Figure_2.jpeg)

![](_page_19_Figure_3.jpeg)

VSWR versus Frequency of a two-probe slide-screw tuner.

The great phase shift is not permitted in the real matching network

![](_page_19_Picture_8.jpeg)

![](_page_19_Figure_10.jpeg)

For passive tuner, where there is distance of probe to DUT, there will be phase shift, longer the distance, greater the phase shift

![](_page_19_Picture_12.jpeg)

![](_page_19_Picture_13.jpeg)

![](_page_19_Picture_22.jpeg)

### **Tuner matching frequency response of a typical position** 2GL01 5979 PL LFP, C=100 11 29 2017

Marker 1: Freq = 4.600 GHz, S11 VSWR = 24.2167

![](_page_20_Figure_2.jpeg)

782942 MT982GL01 5979 PL LFP, C=100 11 29 2017 Marker 1: Freq = 3.500 GHz, S11 Phase = 132.7817 Deg

Tuner is a very narrow freq. response device which is not optimum for wideband measurement

![](_page_20_Figure_5.jpeg)

### Narrow response issue

![](_page_20_Picture_7.jpeg)

Model: MT982GL01,0.65-18GHz, crossover freq.: 4.6GHz Position: carriage, probe1, probe2: (100, 0, 5000)

![](_page_20_Picture_10.jpeg)

![](_page_20_Picture_11.jpeg)

### Setup for passive 2 tones benchmark

![](_page_21_Picture_1.jpeg)

Load pull bench for 2 tones measurement Measure the load impedance in *real time* on a thru

![](_page_21_Picture_3.jpeg)

![](_page_21_Picture_5.jpeg)

![](_page_21_Picture_6.jpeg)

![](_page_21_Picture_7.jpeg)

### Summary of the challenges, NO. 1, phase shift

*Carrier freq.: 3.5GHz* Load gamma: 0.8<120° (carrier)

![](_page_22_Figure_2.jpeg)

![](_page_22_Picture_3.jpeg)

## Summary of the challenge , No. 2, system non-linearity

*Carrier freq: 3.5GHz* Load gamma: 0.8<120 ° (carrier) *Tone space: 1, 5, (10, 30)MHz* 

![](_page_23_Figure_2.jpeg)

### IMD3 (dBm) vs. Total Pin(dBm)

![](_page_23_Picture_5.jpeg)

![](_page_23_Picture_6.jpeg)

![](_page_23_Picture_7.jpeg)

![](_page_23_Picture_8.jpeg)

![](_page_24_Picture_0.jpeg)

### Shrined tuning range, inevitable, insoluble by passive tuner itself

![](_page_24_Picture_4.jpeg)

![](_page_24_Picture_5.jpeg)

![](_page_24_Picture_6.jpeg)

Greatly subject to loss between Tuner and DUT, especially on wafer!

Tuner planeCoaxial/Waveguide planeProbe tip plane

![](_page_24_Picture_11.jpeg)

![](_page_24_Picture_12.jpeg)

![](_page_24_Picture_13.jpeg)

![](_page_24_Picture_14.jpeg)

### Common issues of the passive 2 tones loadpull system

- Tedious tuner calibration
- Limited matching range due to passive tuner
- Tone balancing is necessary which limit the speed
- source and amplifier

![](_page_25_Picture_6.jpeg)

![](_page_25_Picture_7.jpeg)

![](_page_25_Picture_8.jpeg)

![](_page_25_Picture_9.jpeg)

# A novel 2 tone measurement solution $\rightarrow$ MT2000!

![](_page_26_Picture_1.jpeg)

![](_page_26_Picture_2.jpeg)

![](_page_26_Picture_3.jpeg)

# Our solution on the challenging request

### A brand new architecture for wideband loadpull

- Baseband signal generation including 2 tone
- driving amplifier

Specific receiver covers both small and large signal measurement DPD similar algorithm for non linearity minimization of source or even

Ultra-broadband tone spacing supported up to 166MHz or wider Ultrafast system calibration and measurement, order of few minutes

![](_page_27_Picture_10.jpeg)

![](_page_27_Picture_11.jpeg)

# •••• System architecture

MT1000/MT2000 architecture combines traditional analog and microwave techniques with lowfrequency signal acquisition (A/D converters) and generation (Wideband AWG).

![](_page_28_Figure_2.jpeg)

- A vector network analyzer VNA is integrated
- Two-port and power calibration to measure S-parameters and power
- Wideband ADCs allow measurement of wideband signals (power, ACPR, EVM)
- System includes 6 VSGs to generate custom modulations up to 240 MHz bandwidth
- Each VSG can be used as an active tuner

![](_page_28_Picture_9.jpeg)

![](_page_28_Picture_10.jpeg)

![](_page_28_Picture_11.jpeg)

![](_page_29_Picture_0.jpeg)

![](_page_29_Figure_1.jpeg)

![](_page_29_Picture_2.jpeg)

- Test signals are generated in the timedomain at low frequency with AWGs
- Single local oscillator (LO) up-converts the waveforms at fundamental and harmonic frequencies by means of multipliers to guarantee phase coherency

![](_page_29_Picture_5.jpeg)

![](_page_29_Picture_6.jpeg)

# Active load for wideband impedance tuning

![](_page_30_Figure_1.jpeg)

Two-port device represented in terms of S-

parameters and a-waves and b-waves

Formula governing Gamma in relation to a-waves and b-waves

![](_page_30_Figure_3.jpeg)

$$\Gamma_{x,n}(f_n) = \frac{a_{x,n}(f_n)}{b_{x,n}(f_n)}$$

![](_page_30_Figure_5.jpeg)

Changing magnitude and phase of b<sub>2</sub> will result in nearly any impedance on Smith Chart

A passive mechanical tuner is used to reflect a portion of the DUT's energy b2 back towards DUT as a<sub>2</sub>. The position of the probe will determine the magnitude and phase of the reflection.  $\Gamma$  will be lower than 1 since  $a_2 < b_2$  due to losses.

A signal generator with magnitude and phase control is used to inject a new signal  $a_2$  into the output of the DUT.  $\Gamma$  can be equal or greater than 1 since  $a_2$  is independent of  $b_2$ .

![](_page_30_Picture_10.jpeg)

![](_page_30_Picture_11.jpeg)

![](_page_30_Figure_12.jpeg)

# •••• Active tuning methodology

### **Open loop active**

![](_page_31_Figure_2.jpeg)

Open loop active requires custom algorithms for iterative convergence to synthesize desired reflection coefficients because the output of DUT (transmitted traveling wave, b2) is dependent on device operating conditions The load impedance is controlled by an RF signal provided by a load RF source. The load signal is not looped, so oscillation will never be observed (because the loop is only in the software, with an algorithm which controls the gamma)

Maury provides open loop solution!

![](_page_31_Picture_5.jpeg)

![](_page_31_Picture_6.jpeg)

### Close loop active

![](_page_31_Figure_8.jpeg)

the bout signal is looped into a circuit that change the magnitude and phase of the coupled RF signal, and this signal is then reinjected toward the DUT ( aout ). The oscillation risk is high because some unwanted coupling can take place, and this parasitic coupled signal is then amplified and

phase shifted as well. Looking at this parasitic coupling path, if the magnitude reach [1], and the phase reach (180°), then an oscillation will occur.

![](_page_31_Picture_11.jpeg)

![](_page_31_Picture_12.jpeg)

![](_page_31_Picture_17.jpeg)

# Wideband multi-tones arbitrary impedance tuning

Carrier freq: 2.6GHz Carrier impedance: 0.8<110 ° Tone space: 20 MHz

× termination
× passive tuning
× active tuning

![](_page_32_Picture_3.jpeg)

Selected termination

Measured gamma load real time

The impedance of f1 and f2 by active tuning can be converged to desired target, avoid the phase shift by passive tuning naturally

![](_page_32_Figure_8.jpeg)

Zoom in plot

![](_page_32_Picture_10.jpeg)

![](_page_32_Picture_11.jpeg)

### Pre-distortion calibration to remove the system non-linearity 34

<u>≪</u> /¥2			
tup Test	Start [dBm]	Stop [dBm]	Step [dB]
<sup>p</sup> ower Sweep:	10	40	0.5
	Frequency List	t [GHz] (separate v	vith "," or ";")
Carrier List 🔹	2.1, 2.2, 2.3, 2	.4, 2.5, 2.6, 2.7, 2.8	3, 2.9, 3, 3.1, 3.2, 3.
	Delta List [MHz	] (separate with ","	' or ";")
Delta List 🔹	1, 5, 10, 20		
	]	-	
arget Threshold [d	B] -70		
terations Limit:	40		
Average Factor:	1		

- Connect the driving amplifier in the loop
- Input the target of minimization
- tone space

![](_page_33_Figure_6.jpeg)

Run the pre-distortion algorithm for each carrier,

It will cost few minutes before test, but worthy!

![](_page_33_Picture_9.jpeg)

![](_page_33_Picture_10.jpeg)

## Wideband multi-tones pre-distortion calibration

*Carrier freq.: 2.6 GHz Carrier impedance: 0.8<110* ° *Tone space: 20 MHz Power sweep: P*<sub>avs</sub> *from 3 to 37 dBm (DUT plane)* 

![](_page_34_Figure_2.jpeg)

With the pre-distortion calibration, the non-linearity of system has been removed completely with the same hardware configuration, user get greatly improved system capacity **without any cost** except the calibration time of few minutes!

-60

2.57E+09

2.58E+09

2.59E+09

2.6E+09

Frequency

2.61E+09

![](_page_34_Figure_4.jpeg)

![](_page_34_Picture_5.jpeg)

2.63E+

2.62E+09

![](_page_34_Picture_6.jpeg)

![](_page_34_Picture_7.jpeg)

![](_page_35_Picture_0.jpeg)

### <u>Tuner calibration</u>

- Receiver vector calibration
- -> fast, no sensitive to source and load match.
- Receiver power calibration
- -> absolute power cal. of receiver by power meter • Pre-distortion calibration with the driving PA -> Improves the linearity of the system

![](_page_35_Picture_8.jpeg)

# -> much lower density needed compared with traditional one.

![](_page_35_Picture_12.jpeg)

![](_page_35_Picture_13.jpeg)

# Measurement Example: Two-Tone Load Pull

![](_page_36_Figure_1.jpeg)

![](_page_36_Picture_2.jpeg)

![](_page_36_Picture_3.jpeg)

# •••• **30GHz 2-tone measurement, tone space 10MHz**

![](_page_37_Figure_1.jpeg)

![](_page_37_Figure_2.jpeg)

![](_page_37_Figure_4.jpeg)

![](_page_37_Figure_5.jpeg)

![](_page_37_Picture_6.jpeg)

![](_page_37_Picture_7.jpeg)

![](_page_37_Picture_8.jpeg)

# •••• Summary of MT2000's advantages for 2 tones test

- **Baseband signal generation including 2 tone**
- external driving amplifier and even system
- Ultra-broadband tone spacing supported up to 166MHz
- Ultra-fast calibration and measurement speed

A brandy-new active architecture for 2 tones in semiconductor industry

Pre-distortion calibration algorithm for non-linearity minimization of

![](_page_38_Picture_8.jpeg)

![](_page_38_Picture_9.jpeg)

# •••• Benchmark of MT2000 on same device

![](_page_39_Figure_1.jpeg)

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					12	12
					4Z	12

TABLE 1         COMPARISON OF LOAD-PULL MEASUREMENT TIME (MINUTES UNLESS STATED)						
	Tuner Cal	System Cal	Step 1	Step 2	Step 3	
Setup			f <sub>0</sub> Load-Pull, Fixed 2f <sub>0</sub> at 50 ohms (35 Loads, 16 Powers)	2f <sub>0</sub> Load-Pull, fixed f <sub>0</sub> at Optimized Value (20 Loads, 16 Powers)	f <sub>0</sub> Load-Pull, fixed 2f <sub>0</sub> at Optimized Value (35 Loads, 16 Powers)	
Scalar Harmonic (2 tuning elements)	22	3	11.1	6.4	11.1	
Vector-Receiver Harmonic (2 tuning elements)	22	5	5.3	3.1	5.3	
Hybrid-Active Harmonic (1 tuning element)	11	5	4.2	7.3	7.5	
Mixed-Signal Active (0 tuning elements)	No Tuner	5	15 seconds	35 seconds	50 seconds	

![](_page_39_Picture_4.jpeg)

![](_page_39_Picture_5.jpeg)

е

![](_page_40_Picture_0.jpeg)

![](_page_40_Picture_1.jpeg)

# Beyond active loadpull

![](_page_40_Picture_3.jpeg)

![](_page_40_Picture_4.jpeg)

### Measurement Example: High-Speed Fo Load Pull

### CW signal at 2 GHz 55 F0 impedances

\* Every impedance is accurate within -40 dB because of software convergence iterations **16** power levels 880 measurement states Total time: **3 minutes** 

a-waves and b-waves measured from which we calculate Pout, Pin, Pavs, Eff, PAE, Vin, Vout, lin, lout

![](_page_41_Figure_4.jpeg)

![](_page_41_Picture_6.jpeg)

![](_page_41_Picture_7.jpeg)

![](_page_41_Picture_8.jpeg)

![](_page_41_Picture_9.jpeg)

# Measurement Example: 2F0+3F0 Load Pull

### CW signal at 2 GHz *16 2F0 impedances* 16 3F0 impedances

\* Every impedance is accurate within -40 dB because of software convergence iterations **17** power levels 4352 measurement states Total time: **15 minutes** 

a-waves and b-waves measured from which we calculate Pout, Pin, Pavs, Eff, PAE, Vin, Vout, lin, lout

![](_page_42_Figure_4.jpeg)

![](_page_42_Picture_6.jpeg)

![](_page_42_Picture_7.jpeg)

![](_page_42_Picture_8.jpeg)

# Application Example: On-Wafer Production Test

High-speed load pull measurements optimized for on-wafer production test (check every device at the wafer level before dicing)

0.4 seconds per load pull for 50 points on Smith Chart at one power level, 1.4 seconds per load pull at 20 power levels

![](_page_43_Figure_3.jpeg)

![](_page_43_Picture_5.jpeg)

### http://www.youtube.com/watch?v=NFFGW34tjYM&feature=youtu.be

![](_page_43_Picture_7.jpeg)

![](_page_43_Picture_8.jpeg)

![](_page_43_Picture_9.jpeg)

### Multi-Tone and Modulated Load Pull

For multi-tone and modulated load pull, each tone of the wideband baseband signal constitutes a portion of an RF wideband signal. Therefore the entire wideband baseband signal is required to set a single impedance at a single power.

- Step 1: specify the list of impedances and powers at the DUT reference plane
- Step 2: calculate the baseband waveform required to present each impedance and power
- Step 3: set the wideband baseband signal and measure RF signal at DUT reference plane
- Step 4: correct baseband signal as required

Note: impedance can be fundamental and/or harmonic, two-tone or modulated

![](_page_44_Figure_8.jpeg)

Modulated waveform for realistic wideband signal

![](_page_44_Picture_10.jpeg)

![](_page_44_Picture_11.jpeg)

![](_page_44_Picture_12.jpeg)

![](_page_45_Picture_0.jpeg)

![](_page_45_Figure_1.jpeg)

**Step 1:** A non-linear device excited with a modulated signal will emanate waves (b-waves) at the harmonic and baseband frequencies

![](_page_45_Figure_3.jpeg)

**Step 3:** Software iteration based on the reflection coefficient measurements at the DUT reference planes

![](_page_45_Figure_6.jpeg)

**Step 2:** By measuring the b-waves scattered by the DUT, the a-waves to be injected to obtain a user-specified reflection coefficient can be estimated.

$$a_{x,n}(f_n) = b_{x,n}(f_n) \cdot \Gamma_{x,n}(f_n)$$

x =source (*s*) or load (*l*) n = frequency band, e.g. baseband (0), fundamental (1) and harmonic (2 and up)  $\Gamma_{x,n}(f_n)$  = user defined reflection coefficient vs. frequency

![](_page_45_Picture_10.jpeg)

![](_page_45_Picture_11.jpeg)

![](_page_45_Picture_12.jpeg)

### Measurement Example: Modulated Load Pull

- Impedance vs frequency across bandwidth are balanced so that 99% of the total signal power converges to within -40 dB at the DUT reference plane
- Pout, Pin Pavs are measured at every tone at fundamental and harmonics (up to the frequency band of the MT2000)
- *Eff, PAE, ACPR and EVM are* calculated automatically

![](_page_46_Figure_4.jpeg)

![](_page_46_Picture_6.jpeg)

![](_page_46_Picture_7.jpeg)

## Vector Signal Generator / Analyzer Combination Capable of Measuring ACPR and EVM

![](_page_47_Figure_1.jpeg)

Minimum requirements: 2-loop MT2000 with MT2001A, B software

Min measurable ACPR (LTE): -55dBc Min measurable EVM: -40dBc Typical values, influenced by signal, bandwidth, power level...

![](_page_47_Picture_5.jpeg)

### Measurement Example: NVNA Load Pull, loadline

- *Time-domain waveforms* and load lines can be measured by adding a phase calibration step
- MT1000/MT2000 has *integrated tone generator* which acts as a harmonic phase reference
- NVNA measurements do not add any additional time to load pull measurements

![](_page_48_Figure_4.jpeg)

![](_page_48_Picture_6.jpeg)

![](_page_48_Picture_7.jpeg)

![](_page_48_Picture_8.jpeg)

### Behavioral Model Extraction Tool Capable of Black-Box and Database Modeling

![](_page_49_Figure_1.jpeg)

Minimum requirements: 2-loop MT1000 or MT2000 with MT2001A, D software

**Red = measured** Blue = model simulation

![](_page_49_Picture_4.jpeg)

![](_page_49_Picture_5.jpeg)

![](_page_49_Figure_6.jpeg)

![](_page_49_Picture_7.jpeg)

![](_page_49_Picture_8.jpeg)

### MT1000/MT2000 Architecture

![](_page_50_Figure_1.jpeg)

- Similar basic receiver architecture
- modulation acquisition
- VNA uses single CW source; MT2000 uses multiple vector signal generators (AWGs)

VNA uses narrowband filtering; MT2000 does not use narrowband filtering in order to allow wideband

![](_page_50_Picture_9.jpeg)

![](_page_50_Picture_10.jpeg)

![](_page_50_Picture_11.jpeg)

### •••• VNA Capable of Measuring CW and Pulsed-CW S-Parameters

![](_page_51_Figure_1.jpeg)

Minimum requirements: 2-loop MT1000 or MT2000 with MT2001A software

![](_page_51_Picture_4.jpeg)

![](_page_51_Picture_5.jpeg)

**b** 0 🌶

![](_page_51_Picture_7.jpeg)

### Introduction (recap)

In 2010, the MT1000/MT2000 technology was launched as the fastest active load pull system in the world, and the only load pull system capable of controlling impedances over wide bandwidths for modulated measurements

following capabilities:

- **NVNA capable of measuring time-domain waveforms and load lines**
- > VNA capable of measuring CW and pulsed-CW S-parameters > Multi-tone signal generator/spectrum analyzer combination capable of measuring
- intermodulation products
- > Vector signal generator/analyzer combination capable of measuring ACPR and EVM Oscilloscope capable of measuring voltages and currents
- Behavioral model extraction tool capable of black-box and database modeling

used equally as well in 50 $\Omega$  as in non-50 $\Omega$ 

![](_page_52_Picture_10.jpeg)

The system architecture required to achieve these breakthrough measurements included the

While marketed as the world's most advanced load pull system, the MT1000/MT2000 can be

![](_page_52_Picture_13.jpeg)

![](_page_52_Picture_14.jpeg)

![](_page_52_Picture_15.jpeg)

### **References**

Most MT1000/MT2000 customers have signed NDAs, however several have published IEEE papers and others have agreed to be contacted as references

GeMiC 2014 · March 10-12, 2014, Aachen, Germany

### Source/Load Pull Investigation of AlGaN/GaN Power Transistors with Ultra-High Efficiency

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Abstract — This paper presents the investigation of highly performing AlGaN/GaN HEMT power transistors through source-pull and load-pull analysis using an active harmonic load-pull system. The advantages of the GaN technology together with the right terminations lead to power transistors with promising output power and efficiency. When setting properly the first three output terminations, a drain efficiency as high as \$4.3% has been achieved at 2 GHz while delivering 4.3 W of output power for a 1.2 mm device gate width. However, it has been seen that the achievement and the set of the optimum output terminations the achievement and the set of the optimum output terminations do not lead to the best device performance. When presenting such three optimum output impedances together with the proper second harmonic source termination, it has been demonstrated second humonom source termination, it and been unsured to that higher drain efficiency up to 83% can be obtained delivering output power as high as 4.4 W and a power gain of 14.9 dB. Indeed the GaN HELMT used in this work has reached record peak drain efficiency of 90% delivering output power of 3.5 W.

156986469

Index Terms- Aluminum gallium nitride, high efficiency microwave measurements, power amplifiers, power transistor

### I. INTRODUCTION

DOWER AMPLIFIER designs used in wireless communication P networks are becoming more and more sophisticated in order to meet the modern requirements. Among the various PA output specifications, one of the most important parameter is still the efficiency. High efficiency means low power consumption and therefore less power dissipated in the environment. In the last decades various PA high efficiency classes have been studied, starting from the more standard – Fig. 1. Microscope photograph of the IAF 1.2 mm AlGaN/GaN HEMT powe lass-AB [1-3] going through the switch modes Class-D and Class-E [1-7] to the harmonically tuned modes Class-F and Inverse Class-F [1-3, 8-9]. In these cases the high harmoni can be properly set in order to increase the PA efficiency and nize the overall power in order to reach certain performances at the PA stage, the The experimental measurements have been conducted or role in the overall output performance. This paper will show at 2 GHz of operating fundamental frequency, drain bia an harmonic load/source pull analysis based on the in house (IAF) highly performed 250 nm AlGaN/GaN power transistors V (IAF) highly performed 250 nm AlGaN/GaN power transistors [10-12] for which very high drain efficiency is achieved. device and validate the experiment is an active harmonic

### II. ALGAN/GAN TECHNOLOGY

The device used in this work is a HEMT (High Electron Mobility Transistor) power transistor in AlGaN/GaN technology grown on a 3-inch semi-insulating SiC (Silicon Carbide) substrate [10-12] with the photo shown in Fig. 1. The epitaxy of the AlGaN/GaN heterostructure is carried out using multi-wafer metal organic chemical vapor deposition (MOCVD). In particular the frontside processing involve alloyed Ti/Al/Ni/Au ohmic contacts, implantation isolation and SiN passivation assisted T-gates processed by usin beam lithography as well as a source termin Here the device is fabricated with a gate length of L<sub>g</sub>=250 nm and a gate width of Wo=1.2 mm (6x200 um) optimized for high gain, high power density as well as very high efficiency.

![](_page_53_Picture_11.jpeg)

### III. LOAD PULL EXPERIMENTAL INVESTIGATION Z<sub>L,F0</sub>, Z<sub>L,2F0</sub>, Z<sub>L,3F0</sub>

device itself and therefore the adopted technology plays a key the 1.2 mm AlGaN/GaN power device described in Section II

Improvements in High Power LDMOS Amplifier Efficiency Realized Through the Application of Mixed-Signal Active Loadpull

Travis A. Barbieri and Basim Noori

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*Abstract* — This paper presents the results of experimental large-signal characterization of a high power LDMOS amplifier using a mixed-signal active load pull system. The architecture of the system provides the freedom to present unique and independent reflection coefficients at multiple different frequencies. In this case the fundamental frequency, and the 2<sup>ad</sup> harmonic frequency were chosen, and the reflection coefficients presented to the output terminal of the transistor were captured at these two frequencies. A high voltage LDMOS power amplifier from Freescale Semiconductor was studied and the results will demonstrate that a distinct improvement in drain efficiency is realized through careful magnitude and phase selection of the reflection coefficient at the 2<sup>nd</sup> harmonic frequency while keeping the refection coefficient presented at the fundamental frequency at a constant optimized value.

Index Terms — Loadpull, High Power Measurement, Harmonic Tuning, power amplifiers

### I. INTRODUCTION

Loadpull systems that are used to characterize high-power ransistors for wireless infrastructure applications continue to be based primarily on mechanical (passive) tuners [1]. This technique has been adopted as the standard for high power applications due to its simple nature compared to alternative approaches and the tuner's ability to handle high pulsed peakpower levels.

While passive tuners have many advantages one disadvantage is the lack of control over refection coefficients presented by the tuner at uncalibrated frequencies [2]. Passive tuners are designed to have very high quality factors which allow them to present a high refection coefficient to the device under test. This very desirable trait, however, reduces the tuning range to a very small frequency bandwidth [2]. Energy that is generated or reflected by the device under test (DUT) at the uncalibrated frequencies will be partially absorbed and pre-determined. As a result, any changes to the devices to the device under test being completely synthesized [2]. behavior due to this stray energy could potentially lead to inaccurate device characterization or misunderstanding of device behavior [2].

Several innovative passive techniques that allow for calibration and impedance control at multiple frequencies (mostly the harmonic frequencies) have become commercially available over the past several years. These systems accomplish harmonic manipulation by adding additional

tuners for each harmonic frequency either in cascade or through a network of filters in the form of a diplexer or triplexer [3,4].

In the case of cascaded tuners there are simply additional tuners (or resonators within the same tuner) that are placed between the DUT and the fundamental tuner. The cascaded resonators work in conjunction with each other to provide the desired refection coefficient magnitude and phase for each frequency of interest. The benefit of this approach is the relatively similar set up and operation compared to a standard passive loadpull configuration. The disadvantages are the increased insertion loss between the DUT and the fundamental tuner and poor isolation between the multiple resonators. High isolation between resonators within the same tuner can be achieved within very narrow bandwidths.

In the case of the diplexer/triplexer configuration multiple tuners are given a direct connection to the DUT via filters that direct the signals to the appropriate tuners based on frequency The configuration of this system is relatively complicated and is limited to the availability of diplexers and triplexers that can be purchased for the frequency bands of interest. The benefit is highly isolated control of the harmonic frequencies with only small insertion losses.

While effective, these approaches require additional peripheral hardware and characterization time. Automated mechanical tuners with high gamma capabilities can also be expensive to purchase and maintain. Active load pull has become a popular choice for wide band and multi-harmonic tuning. Standard system architectures can support multiple frequency agnostic loops for tuning while stray energy generated within the system is terminated with the characteristic impedance of the system. Open loop active load pull systems are also capable of accommodating relatively partially re-reflected by the tuners in a manner that cannot be large signal bandwidths due to the impedance being presente

### II. MIXED-SIGNAL HARMONIC LOADPULL

The high data traffic on today's cellular networks has created demand for a power amplifier that is both linear and efficient. LDMOS power amplifiers biased in class AB and class B offer acceptable theoretical efficiencies along with distortion products that can be sufficiently corrected using appropriate impedance matching or digital pre-distortion

ISBN 978-3-8007-3585-3

![](_page_53_Picture_32.jpeg)

![](_page_53_Picture_33.jpeg)

![](_page_53_Picture_34.jpeg)

### **MICHIGAN STATE** UNIVERSITY

### DESIGN OF AN ULTRA-EFFICIENT GAN HIGH POWER AMPLIFIER FOR RADAR FRONT-ENDS USING ACTIVE HARMONIC LOAD-PULL

Tushar Thrivikraman, James Hoffman

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### Keywords: GaN Power Amplifier, Active Load-pull, timize the high power amplifier design using GaN HEMT Harmonic tuning Abstract

This work presents a new measurement technique, mixedory behind active load-pull is presented and why load-pull lated telecon dition, an example procedure is presented that outlines a typical radar signals. methodology for amplifier design using this measurement This work will present an overview of a wide-band mixed amplifier design for real radar waveforms that in turn will efficiencies to > 70 %. This system was developed by simplify implementation of space-based radar systems.

### 1 Introduction

GaN devices are increasingly becoming an enabling technology for advanced space-based radar systems. The use of GaN allows for improved system performance due to its high efficiency and output power. In addition, the adoption of GaN into commercial applications, such as cell phone proposed DSI TRM with the measured results of this design base stations has allowed the technology to mature and improve reliability and device performance. Such high priority missions as the proposed Earth Radar Mission's (ERM) DESDynI (Deformation, Ecosystem The basic concept of "load-pull" is to present known Structure, and Dynamics of Ice) SAR Instrument (DSI) uti-impedances to devices under test (DUT) in order to de-

it/receive modules) (> 100 W output r TRM (tra not suitable for this space borne system.

pact TRM, reducing mission costs. In order to fully op-

technology, the new characterization technique, active harmonic load-pull, is being developed to increase efficiencies and reduce harmonic levels over a wide-band [3]. Though tuning load and harmonic impedances Class-J current and signal active harmonic load-pull (MSALP) developed by voltage waveforms can be engineered that provide optimal Anterverta-mw in partnership with Maury Microwave, that balance between performance, bandwidth, and linear reallows for wide-band ultra-high efficiency amplifiers to be sponse. There is increasingly more literature on the use of designed using GaN technology. An overview of the the these systems for designing amplifiers for use with modu nications signals, but to the authors know is important for high-power device characterization. In ad-edge, no work has been demonstrated this technique for

system. Lastly, measured results of a 10W GaN amplifier signal active harmonic load-pull system (MSALPS) [4] that are presented. This work aims to highlight the benefit of us-is capable of harmonic tuning over a real radar waveform ing this sophisticated measurement systems for to optimize (such as a chirp) to optimize amplifier performance and Anteverta-mw in partnership with Maury Microwave and a detailed discussion of the load-pull system is presented in [5]. Section 1 will provide an overview the theory behind used for amplifier characterization. Section 2 will present a design overview of an L-band GaN amplifier for use in the

### 2 Mixed-Signal Active Load-pull Measurement Overview

lizing the SweepSAR concept are made feasible by the use termine their characteristic response, enabling performance of high power, high efficiency solid state power amplifiers optimization for non-linear devices. Fig. 1 shows the signal [1, 2]. In the design concepts for this mission, multiple high flow graph for a non-linear two-port device where  $a_{1,2}$  rep resent the incident waves and  $b_{1,2}$  are the reflected w power) that are thermally managed by the surface area of  $Sxx^*$  represents the large signal s-parameters of the DUT. the TRM acting as the thermal radiator. For typical duty cy-For a small-signal network analyzer, the DUT is insensitive cles and efficiencies, over 20 W of power must be dissipated to load impedance and therefore standard VNA error corby this surface, requiring extremely large TRM, which are rection terms can be used to calibrate to the reference plane of the device to extract s-parameters. However, for large GaN technology presents two benefits for the proposed signal conditions, load-pull is necessary since the DUT DSI: (1) a potential reduction of thermal stresses due to in-is no longer linear and therefore linear superposition and creased efficiency and (2) ability to operate at higher junc-tion temperatures. By easing the thermal requirement, the radiator size may be decreased allowing for a more com-

### **Design of an Ultra-High Efficiency GaN High-Power Amplifier for SAR Remote Sensing**

Tushar Thrivikraman Radar Science and Engineering Jet Propulsion Laboratory California Institute of Technolog 4800 Oak Grove Drive, Pasadena, CA 91109 818-393-8628 Tushar.Thrivikraman@jpl.nasa.gov

Abstract-This work describes the development of a high-power Abstract—This work describes the development of a high-power amplifier for use with a remote sensing SAR system. The am-plifier is intended to meet the requirements for the SweepSA R technique for use in the proposed DESDyn1 SAR instrument. In order to optimize the amplifier design, active load-pull technique is employed to provide harmonic tuning to provide efficiency improvements. In addition, some of the techniques to overcome the challenges of load-pulling high power devices are presented. The design amplifier was measured to have 49 dBm of output power with 75% PAE, which is suitable to meet the proposed system requirements.

### TABLE OF CONTENTS

- **1** INTRODUCTION.
- 2 MIXED-SIGNAL ACTIVE LOAD-PULL MEA-SUREMENT
- 3 LOAD-PULLING HIGH POWER TRANSISTORS .
- 4 HIGH POWER AMPLIFIER DESIGN. 5 SUMMARY
- REFERENCES BIOGRAPHY

### 1. INTRODUCTION

Requirements for next generation SAR remote sensing systems demand new technology to allow these systems t be feasible. Increased swath size, high resolution, rapi global coverage, as well as sub-cm interferometry and p larimetry require advanced techniques such as SweepSAR, which would be employed by the proposed Earth Radar Mis-sion's (ERM) DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) SAR Instrument (DSI). SweepSAR would use multiple transmit/receive (T/R) channels and digi tal beamforming to achieving simultaneously high resolution and large swath [1].

The SweepSAR technique (Fig. 1) would use a large aper-ture reflector with a linear patch feed array, with each set of patches fed by a single T/R module. On transmit, all T/R modules would be used in unison, sub-illumin the reflector creating a large swath on the ground. While on receive, individual beams would be formed by stitching multiple receivers together using digital beamforming [2] This technique would produce, for transmit, an electrically small antenna, illuminating a large area on the ground, while on receive, smaller beams would be formed, yielding higher resolution. Due to the large swath, a receiver would have

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Radar Science and Engineering

Jet Propulsion Laboratory California Institute of Technolog

Figure 1. SweepSAR technique highlighting transmit and

receive operation. Beamforming on transmit would produce a single large beam covering a wide-swath. Digital beamforming on receive would allow for multiple high resolution

valid data across many transmit events, therefore, any trans-mit event would cause a loss of science data (gaps in the swath). Therefore, the transmit pulse width should be narrow as possible, limiting the total amount of power available to illuminated the ground. However, due to the size of the swath, the transmit energy would be spread over a large area, which would demand a longer pulse width and higher peak transmit power. A longer pulse width is not an option, therefore, multiple high-power T/R modules would be required.

Previous generations of high-power amplifiers for use in remote sensing applications utilized GaAs and Si Bipolar transistors and are not suitable for large arrays containing multiple high-power amplifiers. However, Gallium Nitride (GaN) High Electron mobility transistors (HEMTs) are an merging technology that offers high-power density as well as high efficiency, making them an effective solution for SweepSAR applications. The high breakdown voltage of GaN as well as its excellent thermal properties make it a perfect candidate for high-power amplifiers [3]. For commercial applications, GaN has begun to become the technology of choice for RF transmitters in a variety of market segments.

![](_page_53_Picture_71.jpeg)

![](_page_53_Picture_72.jpeg)

![](_page_53_Picture_75.jpeg)

### U.S. Patent No. 8,456,175 B2 Several international patents also available

![](_page_54_Picture_1.jpeg)

![](_page_54_Picture_2.jpeg)

![](_page_54_Picture_3.jpeg)

![](_page_54_Picture_4.jpeg)

# System Offering

![](_page_54_Picture_6.jpeg)

![](_page_54_Picture_7.jpeg)

### MT1000/MT2000 Hardware

### *Five Frequency Range are available: Five options of Active Tuning loops are available:* ✤ 0.001 – 2 GHz (50W CW, 500W Pulsed) 2 loops s(f0 source/load pull) ✤ 0.03 – 2 GHz (50 CW, 500W Pulsed) ✤ 3 loops (f0, 2fo source/load pull) ◆ 0.3 – 6 GHz (100W CW, 1000W Pulsed) ✤ 0.2 – 18 GHz (100W CW, 1000W Pulsed) ✤ 0.7 – 40 GHz (20W CW, 200W Pulsed) ✤ 6 loops (f0, 2f0 and 3f0 source/load pull)

### Three Modulation Bandwidth options are currently available (MT2000 only):

- ✤ 100 MHz
- \* 200 MHz
- ✤ 500 MHz
- ❖ 2019 1 GHz

Note: **MT1000** series doesn't support two tones and modulated measurements

![](_page_55_Picture_8.jpeg)

![](_page_55_Picture_9.jpeg)

- ✤ 4 loops (f0, 2f0 and 3f0 source/load pull with 4 of 6 possible combinations)
- ✤ 5 loops (f0, 2f0 and 3f0 source/load pull with 5 of 6 possible combinations)

![](_page_55_Picture_15.jpeg)

![](_page_55_Picture_16.jpeg)

![](_page_55_Picture_18.jpeg)

![](_page_56_Picture_0.jpeg)

### Maury's MT1000/2000 works closely with commercial VNA, help complete device measurement perfectly with distinguished power together!

![](_page_56_Picture_2.jpeg)

For more info. Pls. visit: https://www.maurymw.com/MW\_RF/Mixed\_Signal\_Active\_Load\_Pull\_System.php

# Thank You!

![](_page_56_Picture_5.jpeg)