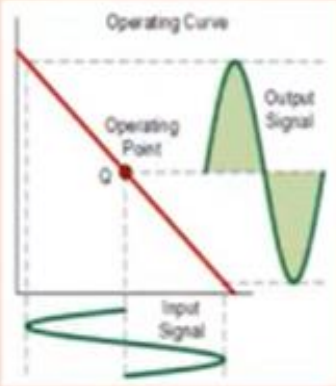
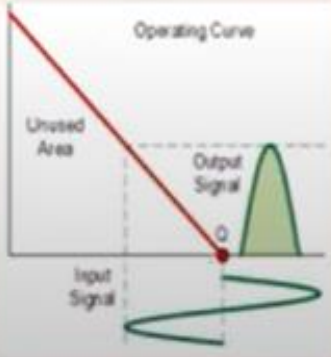

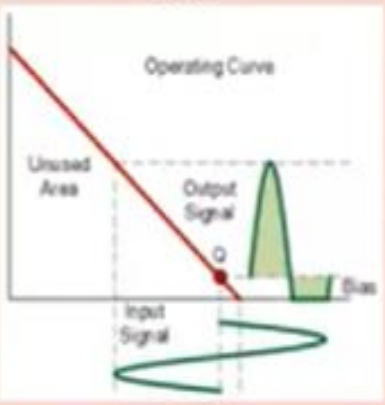
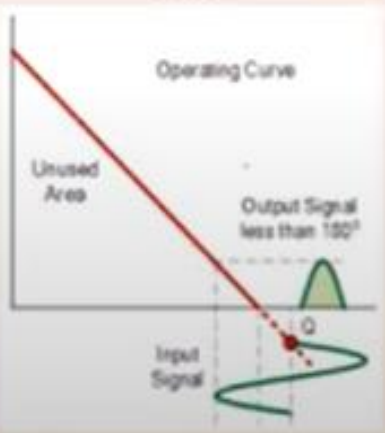


PA Design Requirements

- The PA is typically the primary consumer of power in a transmitter. A major design requirement is how efficiently the PA can convert DC power to RF output power.
- Notice that efficiency translates into either lower operation cost (e.g. cellular base station) or a longer battery life (e.g. wireless handheld).
- PA linearity is another important requirement, the input/ output relationship must be linear to preserve the signal integrity.
- The design of PAs often involves the tradeoff of efficiency and linearity.

PA – Classes of Operation

Class	Theory
A	<p data-bbox="710 329 774 362">Bias</p>  <ul data-bbox="981 329 1754 768" style="list-style-type: none"> -- High linearity and Gain. -- Output stage is biased ON all the time. -- Device conducts full 360 degree of output. -- Due to continuous ON bias, very low efficiency . -- Overheat issues for high power Pass. -- Theoretical efficiency of ~50%.
B	<p data-bbox="722 829 786 862">Bias</p>  <ul data-bbox="981 801 1702 1296" style="list-style-type: none"> -- Less heating problems compared to class A. -- Less linear as compared to class A. -- DC bias current ~ 0 so minimal dc power. -- Push pull design & each device conducts 180 of output waveform. -- Cross over distortion problem. -- Theoretical efficiency of ~78%.

Class	Theory
<div data-bbox="164 435 299 592">  </div>	<div data-bbox="637 292 714 335">Bias</div> <div data-bbox="492 335 879 735">  </div> <div data-bbox="898 307 1748 678"> <ul style="list-style-type: none"> -- Combination of class A & B. -- The device is biased just above its cut off point. -- Device conducts between 180 – 360 depending on bias point. -- Conversion efficiencies reach 50–60%. </div>
<div data-bbox="251 1021 289 1063">C</div>	<div data-bbox="637 821 714 863">Bias</div> <div data-bbox="492 878 879 1306">  </div> <div data-bbox="898 763 1700 1320"> <ul style="list-style-type: none"> -- Highest Efficiency ~80%. -- Poorest linearity & heavy distortion. -- Conduction angle < 180 & generally around 90 region. -- DC bias current ~ 0 so minimal dc power. -- Push pull design & each device conducts 180 of output waveform. -- Cross over distortion problem. </div>

Non-Linear model?

- Good PA design starts with good Non-Linear device model and it is device vendor's responsibility to provide good non-linear model to the PA designers.
- ❑ There are various ways in which designer can obtain a non-linear model:
 - a. SPICE model (can be imported into ADS)
 - b. Non-Linear model card i.e provide parameters for standard model cards such as Curtice Cubic, Statz, BSIM, Angelov, ASM etc. (can be used directly in ADS).
 - c. Design Kit for ADS containing the non-linear models (usually encrypted)
 - d. Develop your own Non-Linear models using tools like Keysight ICCAP
 - e. Use measurement-based models such as X-Parameters



To follow steps shown in this tutorial series, kindly obtain the ADS Design Kit from Wolfspeed/Cree website:
<https://www.wolfspeed.com/rf/tools-and-support/request-access-to-wolfspeed-rf-portal/>

ADS Design Kit version used in this tutorial: **Cree_Wlfspd_ADS_v9p0**

About GaN devices

- One of the most significant features of **GaN** is **the high-power density**. This allows not only the production of smaller device with same output power, but also provides much higher impedance. Higher impedance enables users to match it to the system much easier, eliminating the extra cost and complexity needed for other conventional elements such as GaAs.
- In addition to this, high-voltage properties reduce the need of voltage conversion, leading to higher efficiency operation which in return results in power saving and reduced costs for cooling the system. On the other hand, high frequency operation of GaN device adds an advantage for the bandwidth requirements as well.

Performance analysis of GaN material

Need	Enabling Feature	Performance Advantage
High Power/Unit Width	Wide Bandgap, High Field	Easy to Match
High Linearity	HEMT Topology	Optimum Band Allocation
High Voltage Operation	High Breakdown Field	Reduce Step Down
High Frequency	High Electron Velocity	Bandwidth
High Efficiency	High Operating Voltage	Power Saving, Reduced Cooling

Power Amplifier Case Study for this tutorial

For this tutorial series, we will take a case study of designing a Power Amplifier with following specifications using a Cree GaN 10W device (CGH40010):

Parameters	Specifications
Centre Frequency	2.4 GHz
Bandwidth	+/- 100 MHz
Output Power	10 Watts (40dBm)
Gain	> 10 dB
Return Loss	< -15 dB
PAE	> 50%
TOI / IP3	~45 dBm
Device	CGH40010



Let's start our Power Amplifier design by going through the transistor datasheet....

Note the following while looking at the datasheet:

1. Efficiency & Pout etc
2. Small Signal Gain – Gives us an idea on what to expect during our design
3. Source and Load Impedances – Gives us initial guidance for Load Pull analysis
4. Demo Circuit Schematic and Layout – Gives us an initial idea of possible circuit topology (however it can completely change based on how you design but still a good initial reference)



CGH40010

10 W, DC - 6 GHz, RF Power GaN HEMT

Description

Cree's CGH40010 is an unmatched, gallium nitride (GaN) high electron mobility transistor (HEMT). The CGH40010, operating from a 28 volt rail, offers a general purpose, broadband solution to a variety of RF and microwave applications. GaN HEMTs offer high efficiency, high gain and wide bandwidth capabilities making the CGH40010 ideal for linear and compressed amplifier circuits. The transistor is available in both screw-down, flange and solder-down, pill packages.



Package Types: 440166 & 440196
PINs: CGH40010F & CGH40010P

Features

- Up to 6 GHz Operation
- 16 dB Small Signal Gain at 2.0 GHz
- 14 dB Small Signal Gain at 4.0 GHz
- 13 W typical PSAT
- 65 % Efficiency at PSAT
- 28 V Operation

Applications

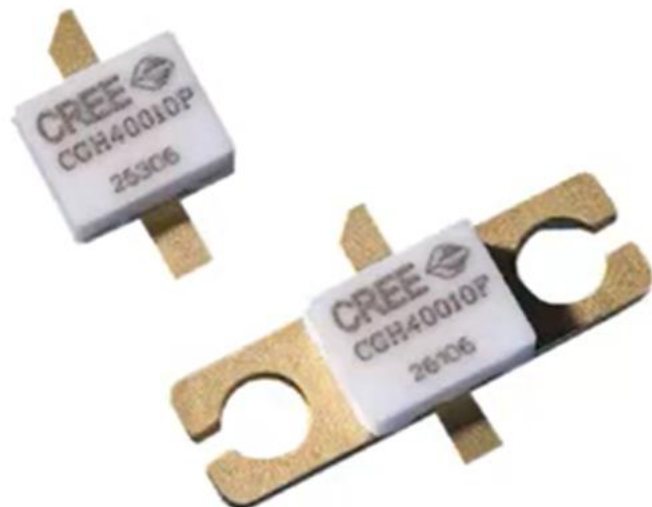
- 2-Way Private Radio
- Broadband Amplifiers
- Cellular Infrastructure
- Test Instrumentation
- Class A, AB, Linear amplifiers suitable for OFDM, W-CDMA, EDGE, CDMA waveforms

CGH40010

10 W, DC - 6 GHz, RF Power GaN HEMT

Description

Cree's CGH40010 is an unmatched, gallium nitride (GaN) high electron mobility transistor (HEMT). The CGH40010, operating from a 28 volt rail, offers a general purpose, broadband solution to a variety of RF and microwave applications. GaN HEMTs offer high efficiency, high gain and wide bandwidth capabilities making the CGH40010 ideal for linear and compressed amplifier circuits. The transistor is available in both screw-down, flange and solder-down, pill packages.



Package Types: 440166 & 440196
PN's: CGH40010F & CGH40010P

Features

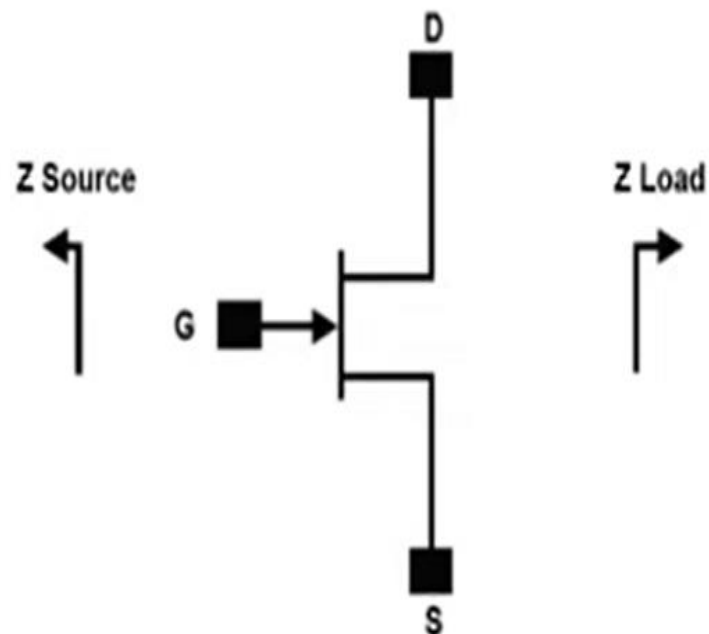
- Up to 6 GHz Operation
- 16 dB Small Signal Gain at 2.0 GHz
- 14 dB Small Signal Gain at 4.0 GHz
- 13 W typical PSAT
- 65 % Efficiency at PSAT
- 28 V Operation

Applications

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



Source and Load Impedances



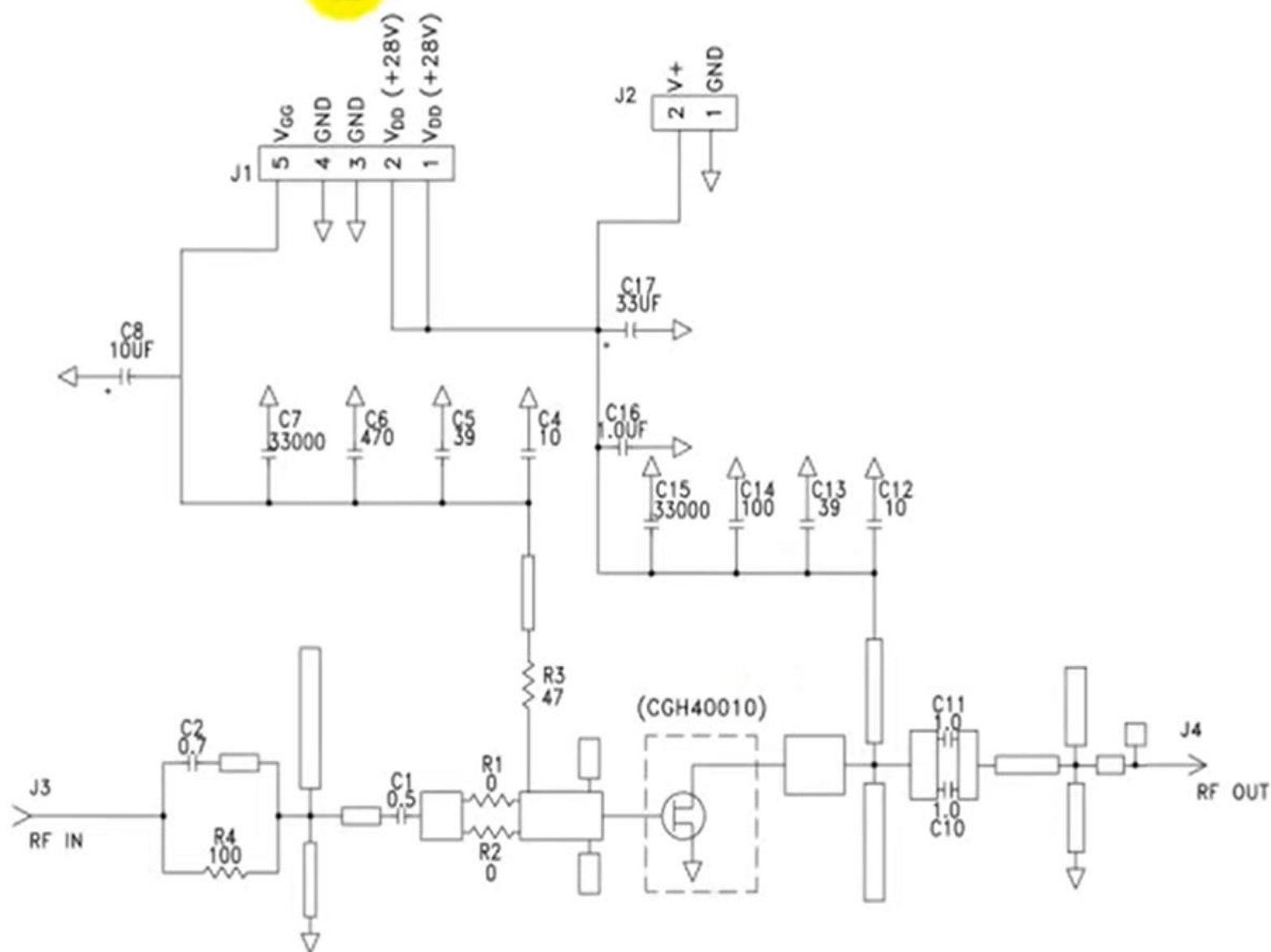
Frequency	Z Source	Z Load
500	$20.2 + j16.18$	$51.7 + j15.2$
1000	$8.38 + j9.46$	$41.4 + j28.5$
1500	$7.37 + j0$	$28.15 + j29$
2500	$3.19 - j4.76$	$19 + j9.2$
3500	$3.18 - j13.3$	$11.6 + j8.45$

Note 1. $V_{cc} = 28V$, $I_{cc} = 200mA$ in the 440166 package.

Note 2. Optimized for power, gain, P_{sat} and PAE.

Note 3. When using this device at low frequency, series resistors should be used to maintain amplifier stability.

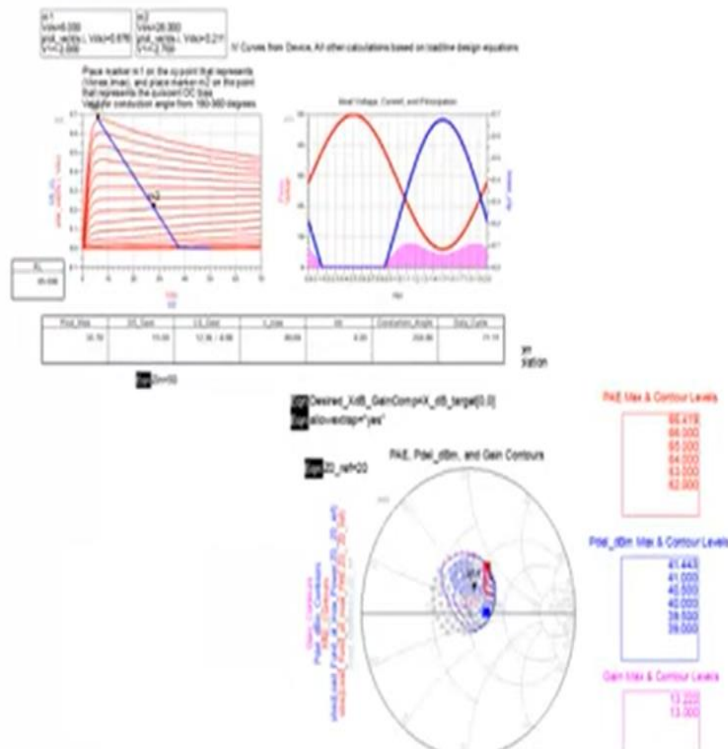
CGH40010-AMP Demonstration Amplifier Circuit Schematic



Power Amplifier Design Tutorial

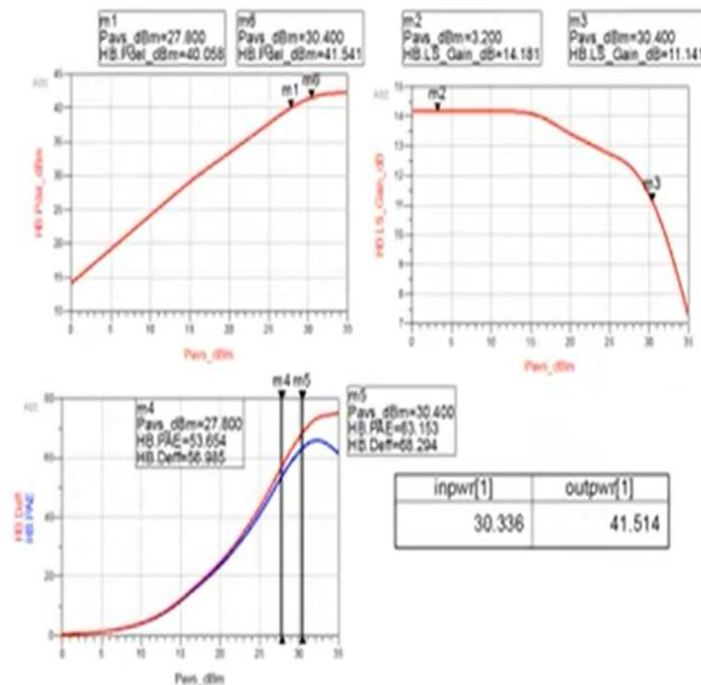
Part 1: Getting Started with PA Design

1. PA Introduction & Classes of Operation
2. DC-IV & Bias Point Analysis
3. Stability Analysis
4. Initial Load Pull
5. 3dB Load Pull – Finalize Source & Load Impedances
6. Validation of Source & Load Impedances with PA Design

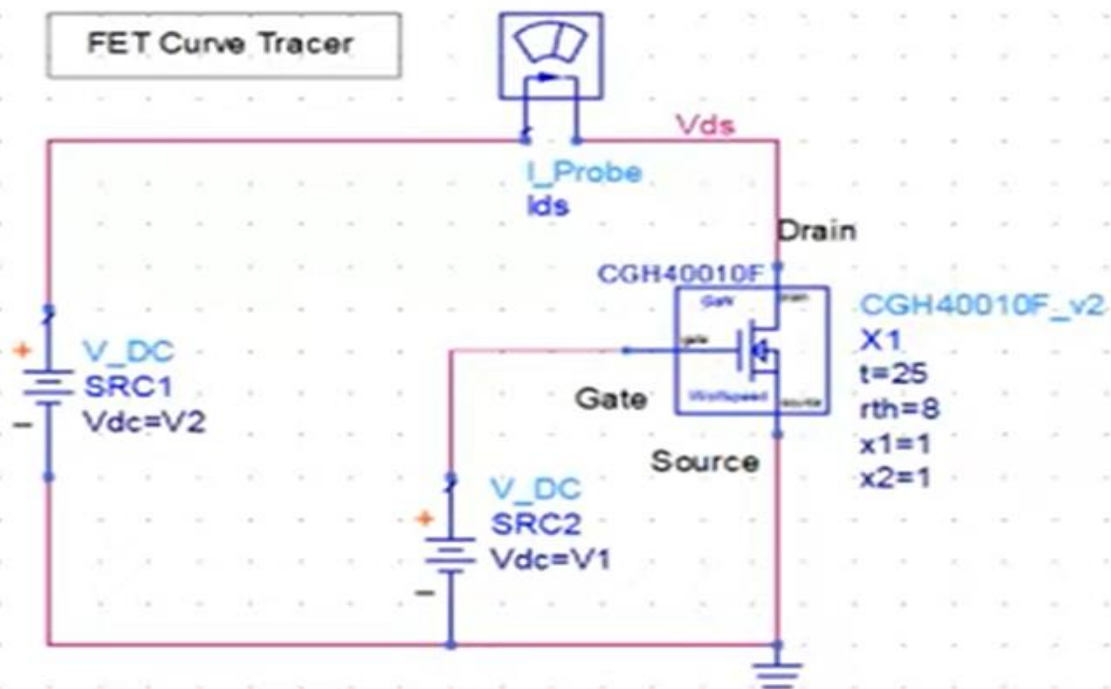


Part 2: Finalize the PA Design

1. Ideal Input & Output Matching Network Design
2. Microstrip Output Matching N/W Design
3. Microstrip Input Matching N/W Design
4. Optimizing PA for Fundamental and Harmonic performance
5. PA Compression & 2-Tone analysis
6. Layout and EM Cosimulation for the final PA Design



FET Curve Tracer



PARAMETER SWEEP

ParamSweep

Sweep1

SweepVar="V1"

SimInstanceName[1]="DC1"

SimInstanceName[2]=

SimInstanceName[3]=

SimInstanceName[4]=

SimInstanceName[5]=

SimInstanceName[6]=

Start=-4

Stop=-2

Step=0.5



DC

DC

DC1

SweepVar="V2"

Start=0

Stop=70

Step=0.5



VAR

VAR1

V2=0 V

V1=0 V

Set drain and gate voltage sweep limits as needed.



DisplayTemplate

disptemp1

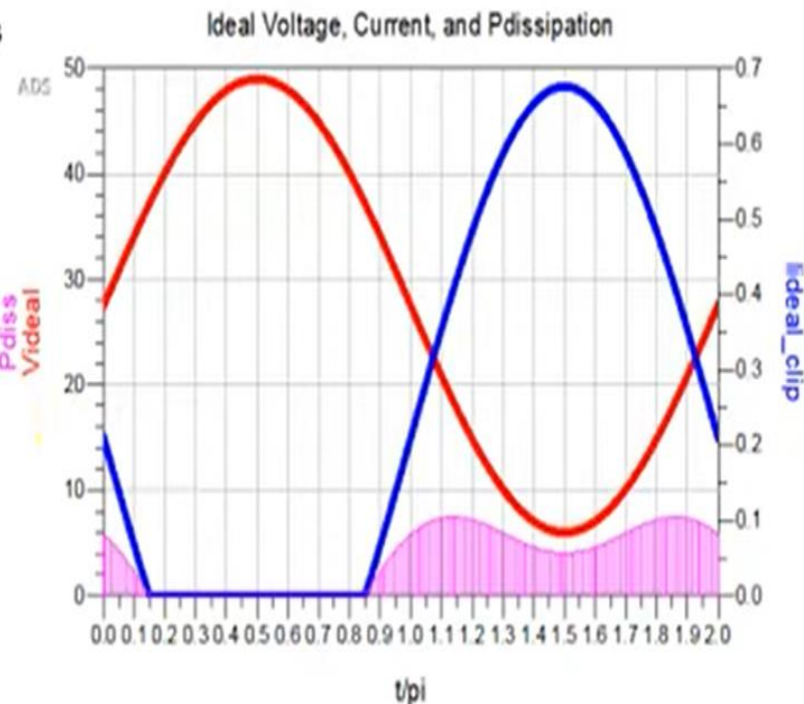
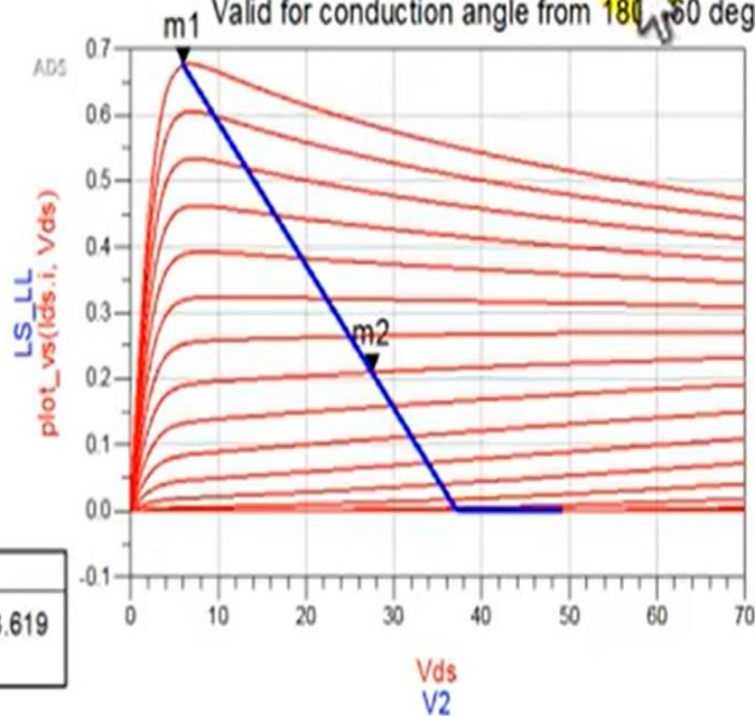
"FET_curve_tracer"

m1
Vds=6.000
plot_vs(lds.i, Vds)=0.676
V1=-2.000

m2
Vds=27.500
plot_vs(lds.i, Vds)=0.210
V1=-2.700

IV Curves from Device, All other calculations based on loadline design equations

Place marker m1 on the xy point that represents (Vknee,Imax), and place marker m2 on the point that represents the quiescent DC bias. Valid for conduction angle from 180 to 60 degrees

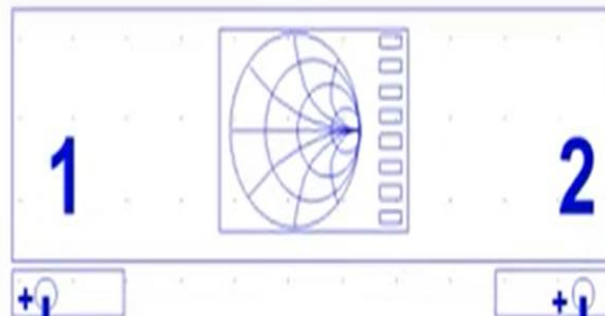


RL

63.619

Pout_Max	SS_Gain	LS_Gain	n_max	Idc	Conduction_Angle	Duty_Cycle
35.60	15.20	12.28 / -0.00	45.63	0.29	257.73	71.59

EqnZin=50



SP_NWA

X1

Start=0.5 GHz

Stop=6 GHz

NumPoints=501

VBias1=-2.7

VBias2=28

Port1Z=50

Port2Z=50

+

Disp
Temp

DisplayTemplate

disptemp1

"SP_NWA_T"

"S_21_11_wZoom"

Activate for available
gain and stability circles:

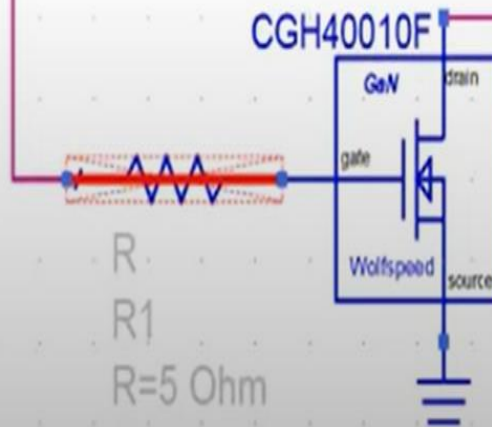
Disp
Temp

DisplayTemplate

disptemp2

"Circles_Ga_Stab"

"Circles_Stability"



CGH40010F_v2

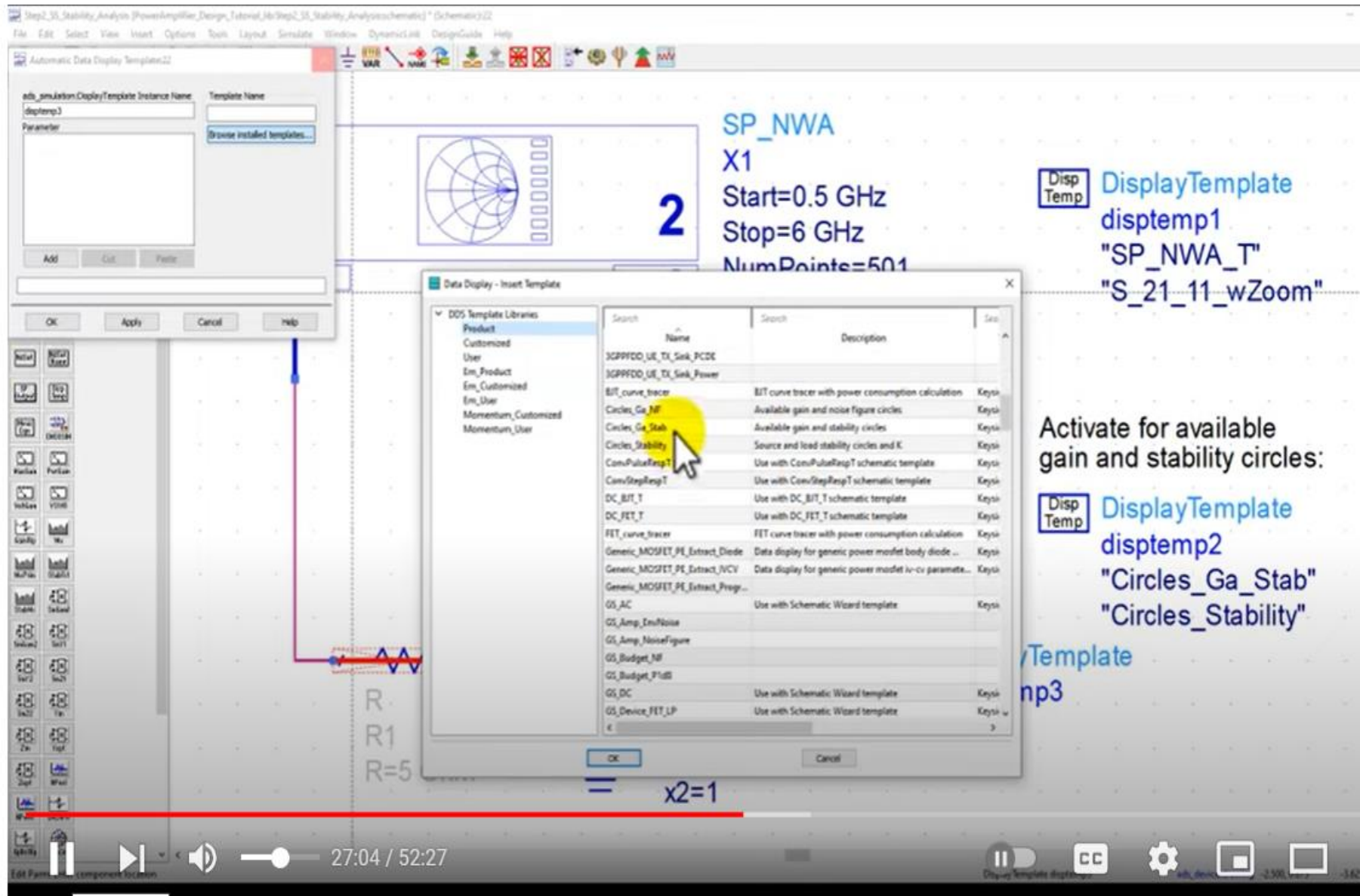
X2

t=25

rth=8

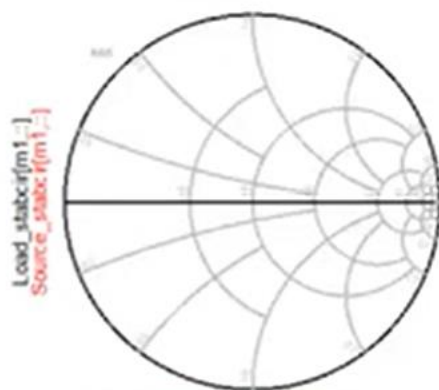
x1=1

x2=1



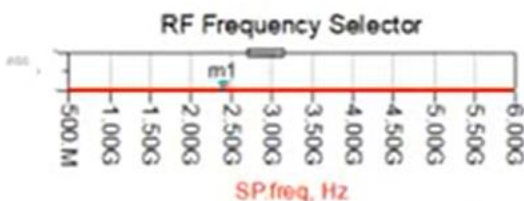
Use with S_params or Sparams_wNoise Schematic Templates

Source and Load Stability Circles



indep:Source_stabcir(m1,...) (0.000 to 51.000)
indep:Load_stabcir(m1,...) (0.000 to 51.000)

Move marker to desired frequency. The stability circles and stability factor, K, will be updated.



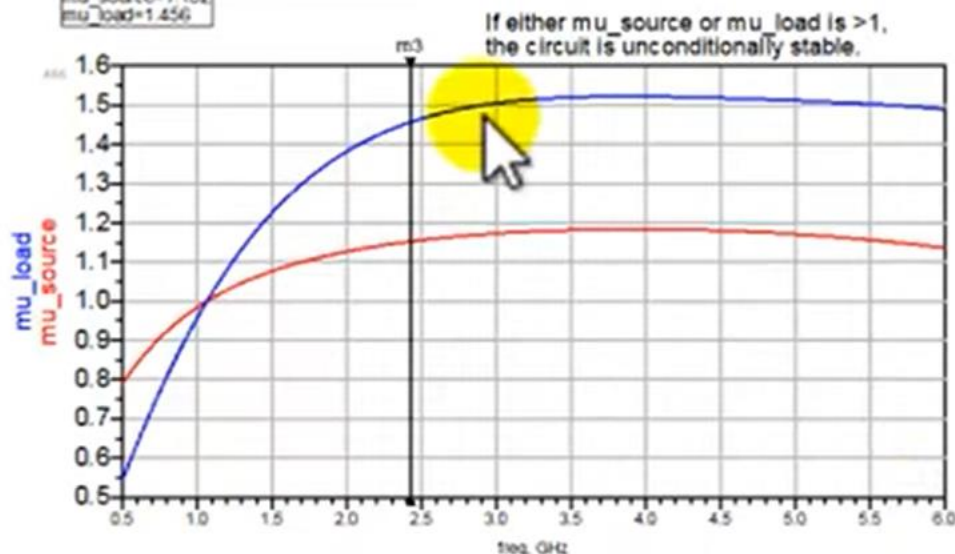
RF Frequency

2.403 GHz

Stability Factor, K

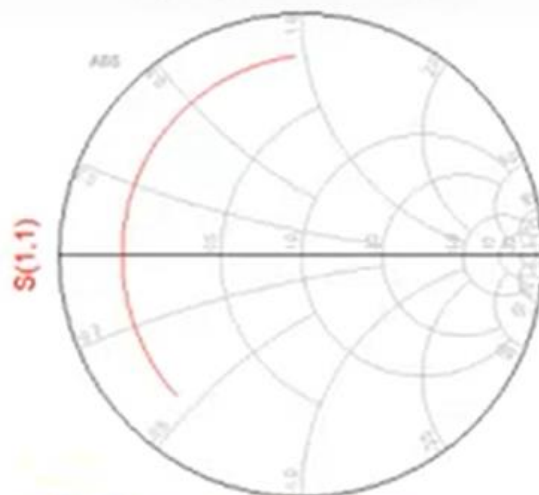
2.243

m3
freq=2.425GHz
mu_source=1.152
mu_load=1.456

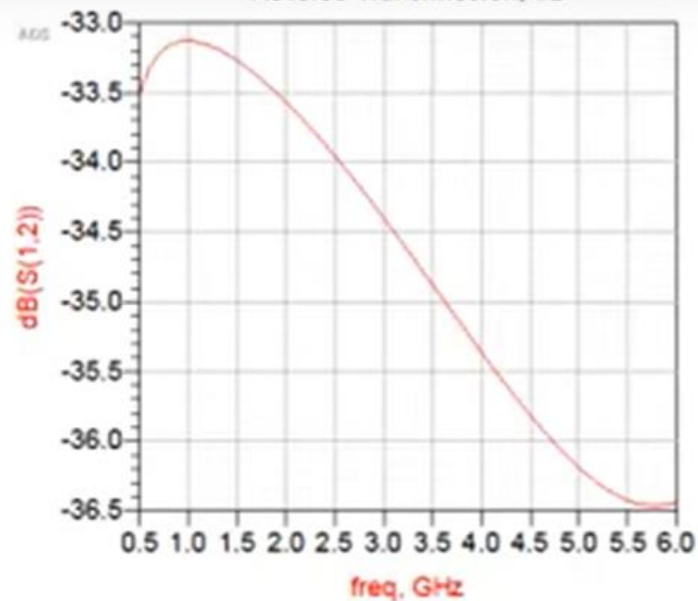


Eqn $\mu_{\text{load}} = \mu(S)$
Eqn $\mu_{\text{source}} = \mu_{\text{prime}}(S)$
Eqn $\text{Source_stabcir} = s_stab_circle(S, 51)$
Eqn $\text{Load_stabcir} = l_stab_circle(S, 51)$
Eqn $K = \text{stab_fact}(S(m1))$

Input Reflection Coefficient



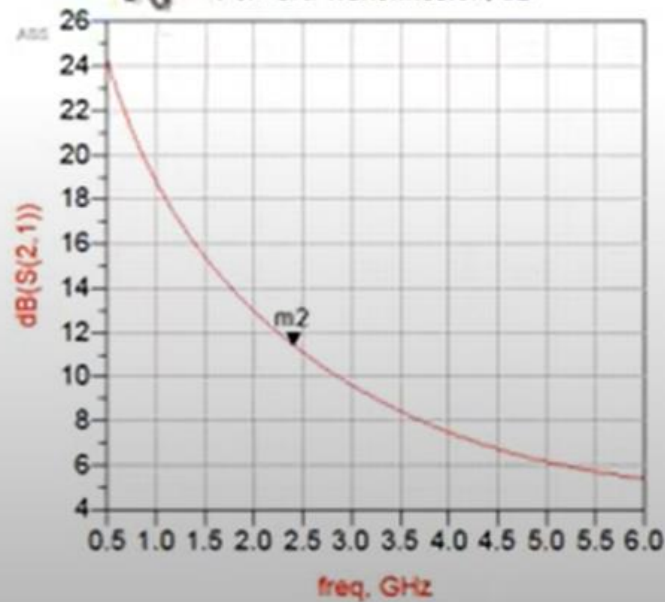
Reverse Transmission, dB



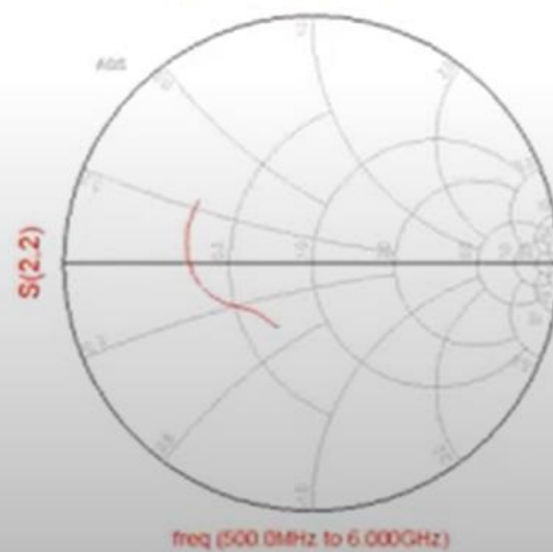
m2
freq=2.403 GHz
dB(S(2,1))=12.431

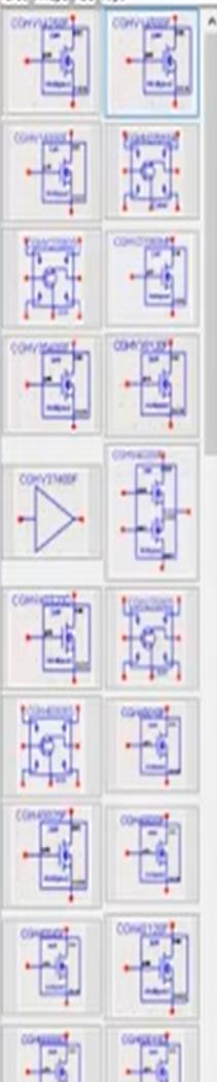
freq (500.0MHz to 6.000GHz)

Forward Transmission, dB



Output Reflection Coefficient





Load_Pull_Instru

X1

V_Bias1=-2.7 V

V_Bias2=28 V

RF_Freq=2400 M

Pavs_dBm=29

Z_Load_Center_

Z_Load_Center_

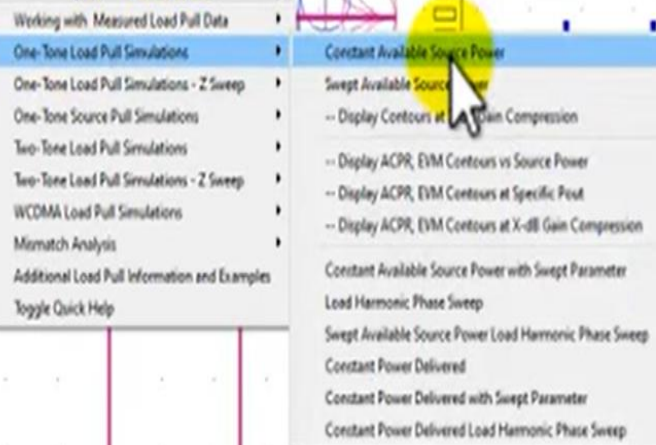
Z_Load_Center_

Z_Source_Fund=

- Amplifier
- Bluetooth
- Filter
- Freq Multipliers and Dividers
- Mixers
- Oscillator
- Passive Circuit
- UWB
- Analog/Digital Conversion
- Budget Analysis
- HDMI
- Load Pull
- Radar Applications
- SASII
- UHSII
- USB3
- VPI Link Utility
- Signal Integrity Applications
- Wireline Applications
- cdma2000
- IBIS AMI
- TDSCDMA
- WLAN
- MMIC 3 Stage PA
- MMIC_Workshop
- MMIC SPOT Design
- Preferences...

Load Pull Instrument 1

1-Tone



Push into instrument subcircuit to see or modify bias network, if necessary.

CGH40010F

R
R1
R=5 Ohm

CGH40010F_v2

X2

t=25

rth=8

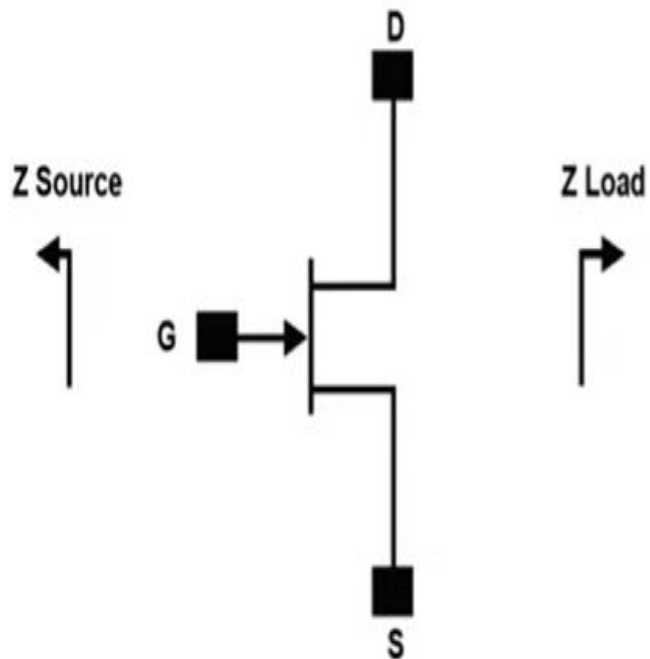
x1=1

x2=1

CGH40010



Source and Load Impedances



Frequency	Z Source	Z Load
500	$20.2 + j16.18$	$51.7 + j15.2$
1000	$8.38 + j9.46$	$41.4 + j28.5$
1500	$7.37 + j0$	$28.15 + j29$
2500	$3.19 - j4.76$	$19 + j9.2$
3500	$3.18 - j13.3$	$14.6 + j7.45$

At load that gives maximum power (and gain):

BiasCurrent_at_MaxPower	Zload_at_MaxPower	MaxPowerRho
0.060	13.189 + j1.883	0.583 / 175.365

PAE_at_MaxPower
57.023

Z_in_at_MaxPower
5.696 + j4.211

Gain_at_MaxPower
12.589

Pdel_dBm_Max
41.589

At load that gives maximum PAE:

BiasCurrent_at_MaxPAE	Zload_at_MaxPAE	MaxPAERho
0.303	11.632 + j13.002	0.643 / 149.1...

PAEmax
65.825

Z_in_at_MaxPAE
5.745 + j4.924

Gain_at_MaxPAE
10.965

Pdel_dBm_at_MaxPAE
39.965

At load selected by marker m1:

BiasCurrent_at_m1	Zload_at_m1	Rho_at_m1
0.002	20.384 + j11.981	0.449 / 168.356

PAE_at_m1
63.783

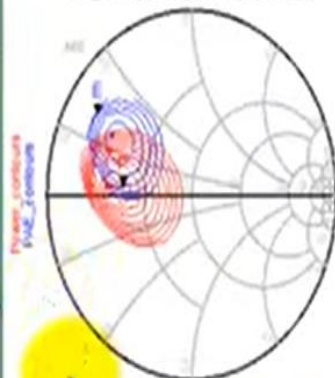
Z_in_at_m1
6.134 + j4.873

Gain_at_m1
11.671

Pdel_dBm_at_m1
40.671

System Reference Impedance Z0: 50.000
A Rho of 0 corresponds to a load impedance of conj(Z0).

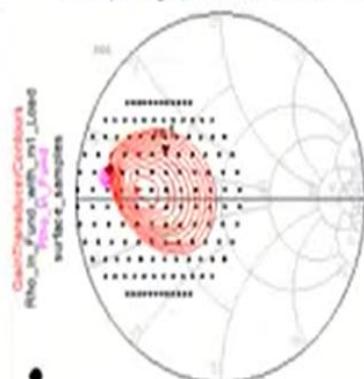
PAE and Delivered Power Contours



Power contours
PAE contours
F level=5.0, number=1
6.573 + j15.885

P (Power Delivered, dBm)
level=41.548, number=94
17.734 + j2.133

Transducer Power Gain Contours, Simulated Load Reflection Coefficients and Corresponding Input Reflection Coefficients



Black dot is input reflection coefficient with load selected by marker m1.

Power contour levels, dBm

41.55
41.40
41.20
41.00
40.80
40.60
40.40

PAE contour levels, %
65.759
64.800
62.000
60.000
58.000
56.000

Available Source Power, dBm
25.000

Source Impedance at Fundamental
5.000

Transducer Power Gain contour levels, dB

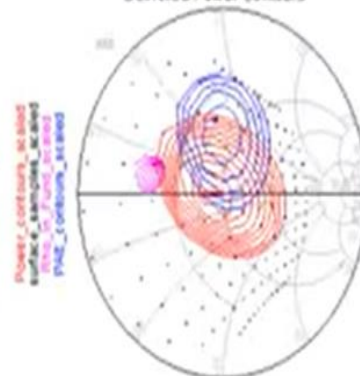
12.577
12.400
12.200
12.000
11.800
11.600
11.400

Data Display: Step3 LoadPull Analysis
Dataset Date/Time: Jan 05, 2021 08:15:50 PM
Dataset: Step3_LoadPull_Analysis

Set new reference impedance

Z0new=17.5-j2.1

Re-Normalized PAE and Delivered Power Contours

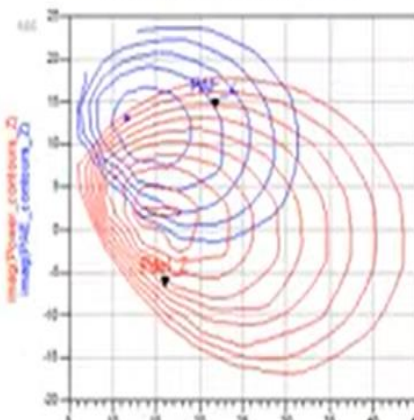


Power contours, scaled
PAE contours, scaled
F level=5.0, number=1
6.573 + j15.885

PAE_2
level=62.000, number=13
21.794 + j14.220

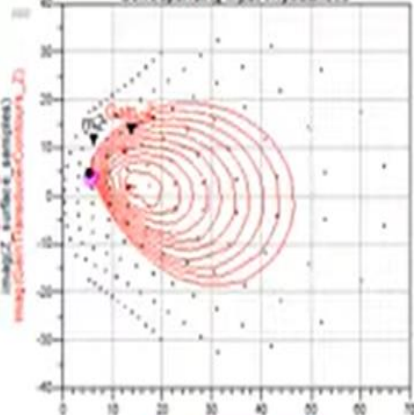
Pdel_2
level=40.600, number=24
15.994 - j6.690

PAE and Delivered Power Contours



real(PAE_contours_Z)
real(Pdel_contours_Z)

Transducer Power Gain Contours, Simulated Load Impedances and Corresponding Input Impedances



m2 Z
6.147 + j10.780
real(GainTransducerContours_Z)
real(Z_surface_samplings)
real(Z_in_Fund)
real(Z_in_with_m2_load)

Gain_2
level=11.200, number=4

13.683 + j12.954

er (and gain):

MaxPowerRho

0.583 / 175.365

it_MaxPower

12.589

E:

MaxPAE_Rho

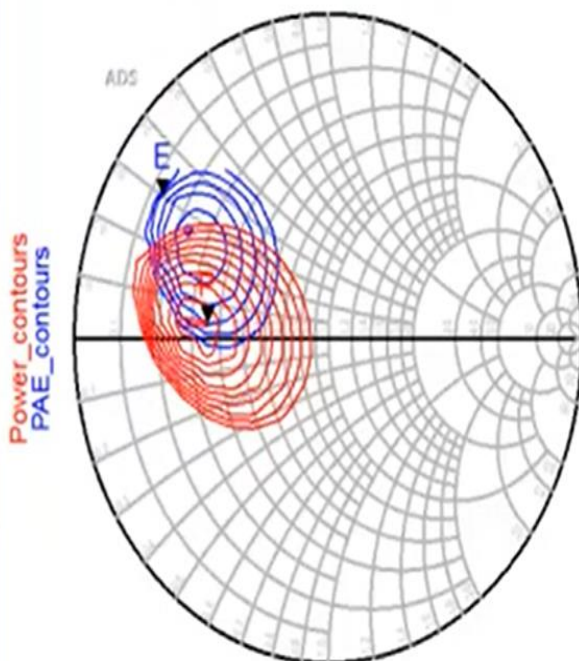
0.643 / 149.1...

System Reference Impedance Z0:

50.000

A Rho of 0 corresponds to a load impedance of $\text{conj}(Z_0)$.

PAE and Delivered Power Contours



Power
contour
levels, dBm:

41.55
41.40
41.20
41.00
40.80
40.60
40.40

PAE contour
levels, %:

65.759
64.000
62.000
60.000
58.000
56.000

(PAE, %)
E
level=58.000, number=1
 $6.513 + j15.085$

(Power Delivered, dBm)
P
level=41.548, number=94
 $17.734 + j2.133$

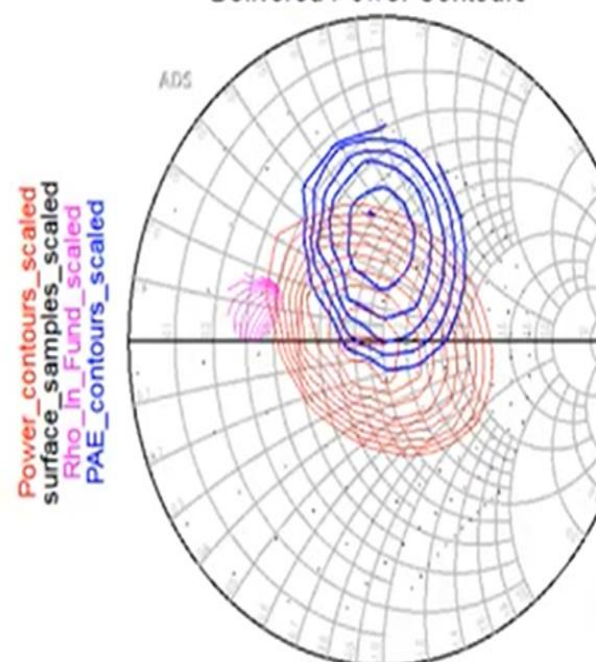
Transducer Power Gain Contours,

Available Source
Power, dBm

Set new reference impedance:

Eqn Z0new=17.5-j*2.1

Re-Normalized PAE and
Delivered Power Contours



At load that gives maximum power (and gain):

BiasCurrent_at_MaxPower	Zload_at_MaxPower	MaxPowerRho
0.860	$13.189 + j1.883$	0.583 / 175.365

PAE_at_MaxPower
57.023

Z_In_at_MaxPower
$5.696 + j4.211$

Gain_at_MaxPower
12.589

Pdel_dBm_Max
41.589

At load that gives maximum PAE:

BiasCurrent_at_MaxPAE	Zload_at_MaxPAE	MaxPAE_Rho
0.503	$11.632 + j13.092$	0.643 / 149.1...

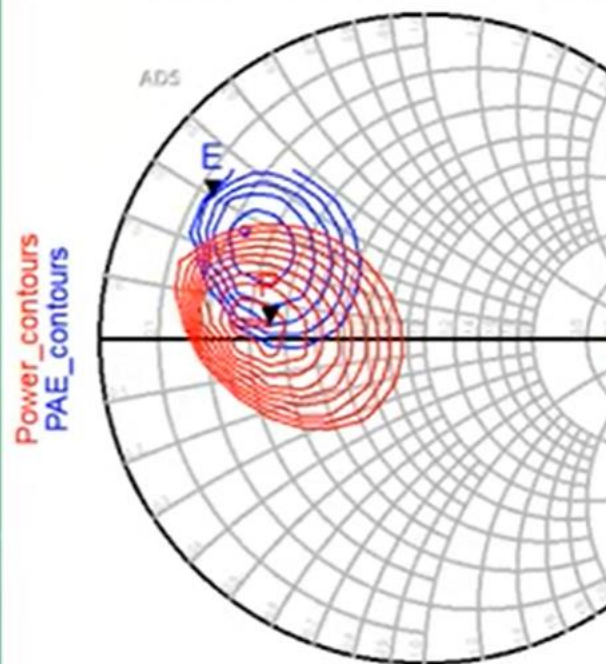
PAEmax
65.825

Z_In_at_MaxPAE
$5.745 + j4.924$

Gain_at_MaxPAE
10.965

System Reference Impedance Z0:
 A Rho of 0 corresponds to a load impedance of conj(Z0).

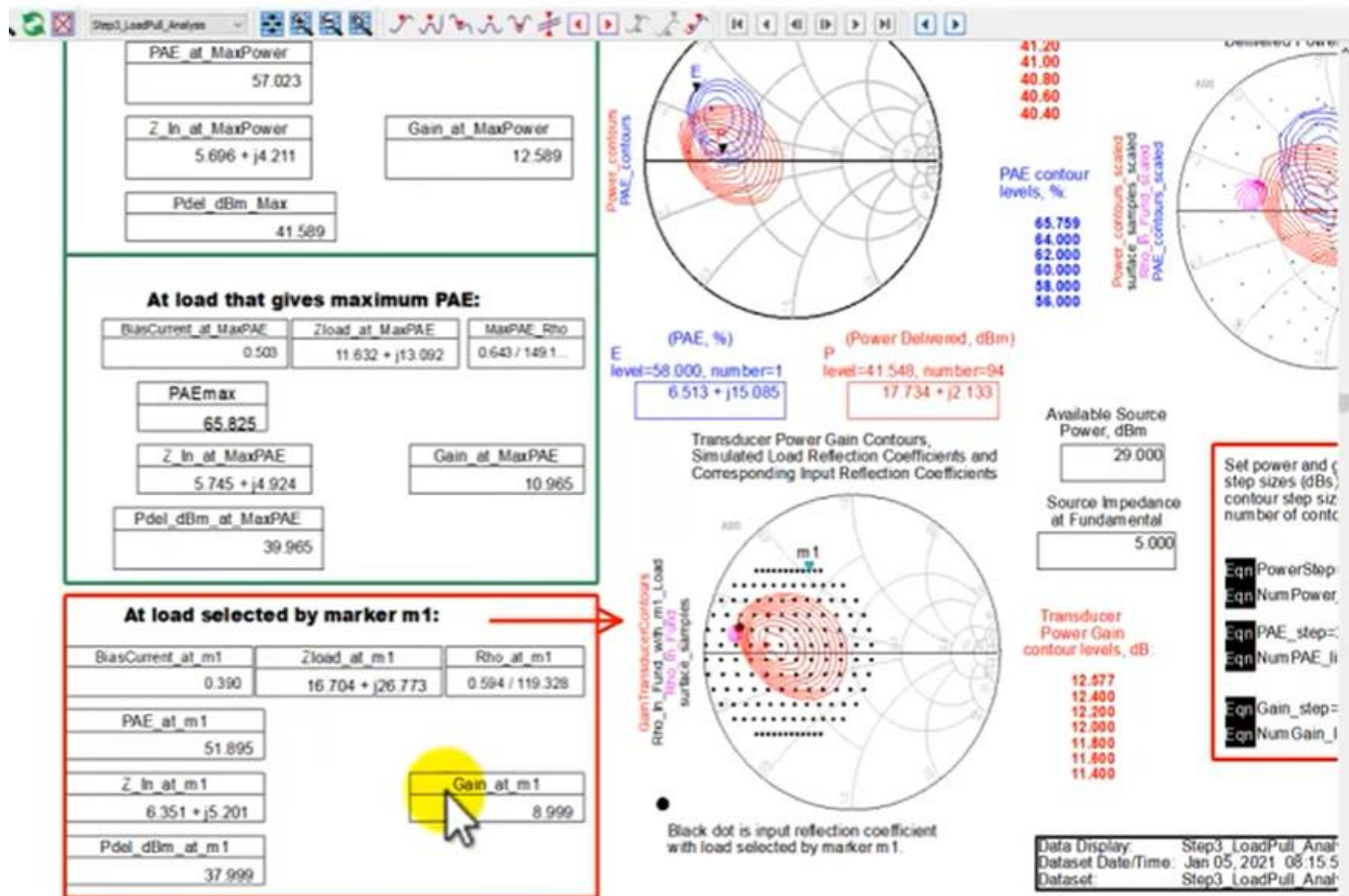
PAE and Delivered Power Co



(PAE, %)
 E level=58.000, number=1
 $6.513 + j15.085$

(Pow
 level=4

Transducer Power Gain Co
 Simulated Load Reflection
 Corresponding Input Refle



Load Pull Instru

X1

V_Bias1=-2.7 V

V_Bias2=28 V

RF_Freq=2400 M

Pavs_dBm=29

Z_Load_Center_

Z_Load_Center_

Z_Load_Center_

Z_Source_Fund=

- Filter
- Freq Multipliers and Dividers
- Mixers
- Oscillator
- Passive Circuit
- UWB
- Analog/Digital Conversion
- Budget Analysis
- HDMI
- Load Pull
- Radar Applications
- SASII
- UHSII
- USB3
- VPI Link Utility
- Signal Integrity Applications
- Weeline Applications
- cdma2000
- IBIS AMI
- TDSCDMA
- WLAN
- MMIC 3 Stage PA
- MMIC_Workshop
- MMIC SPOT Design
- Preferences...

Load Pull Instrument 1

1-Tone

Working with Measured Load Pull Data

One-Tone Load Pull Simulations

One-Tone Load Pull Simulations - Z Sweep

One-Tone Source Pull Simulations

Two-Tone Load Pull Simulations

Two-Tone Load Pull Simulations - Z Sweep

WCDMA Load Pull Simulations

Mismatch Analysis

Additional Load Pull Information and Examples

Toggle Quick Help

Constant Available Source Power

Swept Available Source Power

-- Display Contours at X-dB Compression

-- Display ACPR, EVM Contours vs Source Power

-- Display ACPR, EVM Contours at Specific Point

-- Display ACPR, EVM Contours at X-dB Gain Compression

Constant Available Source Power with Swept Parameter

Load Harmonic Phase Sweep

Swept Available Source Power Load Harmonic Phase Sweep

Constant Power Delivered

Constant Power Delivered with Swept Parameter

Constant Power Delivered Load Harmonic Phase Sweep

Push into instrument subcircuit to see or modify bias network, if necessary.

CGH40010F

GaN

drain

source

CGH40010F_v2

X2

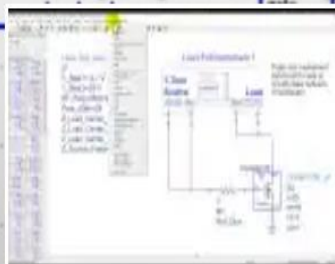
t=25

rth=8

x1=1

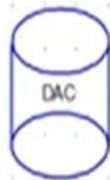
x2=1

^ Pull up for precise seeking



You must click the Optimize (not Simulate) icon for

Using o
compre
and cor
a load p
X-dB ga



.DataAccessComponent
DAC1

File="C:\Users\anbharga\ADS2021_Work\Video_Tutorials\Power_Amp\LoadPull_Tutorials_wrk\Load_Fund_Cree.mdf"

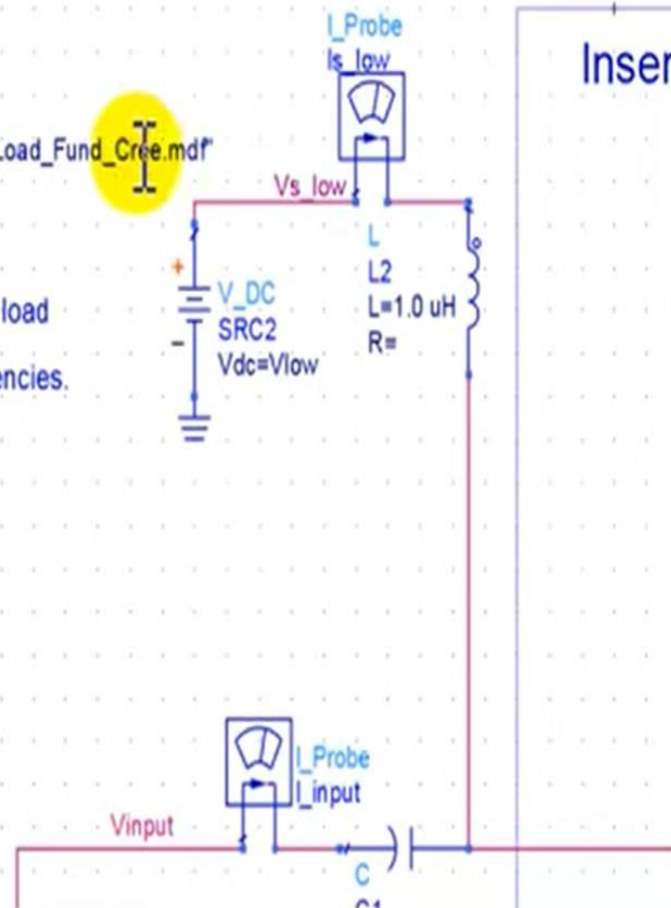
The load pull tuner sweeps the fundamental loads in a region of the Smith Chart determined by the .mdf file you specify (you create this file before this optimization by using one of the Select_Loads_to_Use_* data displays):

Specify the load harmonic reflection magnitudes and phases, or specify load harmonic impedances on the load pull tuner.
Specify the source impedances at the fundamental and harmonic frequencies.

VAR
VAR6

S_Load_Mag=0.95
S_Load_2nd_Phi=-180
S_Load_3rd_Phi=-180
Z_s_fund=5.7-j*4.2
Z_s_2=fz(Src_2nd)
Z_s_3=fz(Src_3rd)
Z_s_4=Z0+j*0
Z_s_5=Z0+j*0
S_Src_Mag=0.95
S_Src_2nd_Phi=-180
S_Src_3rd_Phi=-180
Src_2nd=S_Src_Mag*exp(j*S_Src_2nd_Phi*pi/180)
Src_3rd=S_Src_Mag*exp(j*S_Src_3rd_Phi*pi/180)

ng nominal Load Pull



Insert

Specify the load harmonic reflection magnitudes and phases, or specify load harmonic impedances on the load pull tuner.
Specify the source impedances at the fundamental and harmonic frequencies.

```

VAR
VAR6
S_Load_Mag=0.95
S_Load_2nd_Phi=-180
S_Load_3rd_Phi=-180
Z_s_fund=5.7-j*4.2
Z_s_2=fz(Src_2nd)
Z_s_3=fz(Src_3rd)
Z_s_4=Z0+j*0
Z_s_5=Z0+j*0
S_Src_Mag=0.95
S_Src_2nd_Phi=-180
S_Src_3rd_Phi=-180
Src_2nd=S_Src_Mag*exp(j*S_Src_2nd_Phi*pi/180)
Src_3rd=S_Src_Mag*exp(j*S_Src_3rd_Phi*pi/180)

```

Minimal Load Pull

Specify the available source power, Pavs_dBm, used to calculate the reference gain. Ideally, this Pavs_dBm should be near (or slightly less than) the value that causes the maximum gain.
Specify the desired amount of gain compression, X_dB_target.

```

VAR
VAR2
Pavs_dBm=28
X_dB_target=3

```

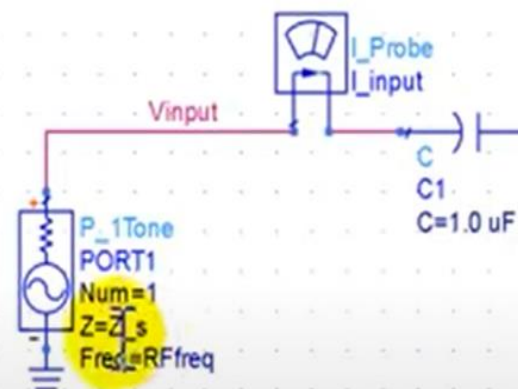
Outputs here

Specify the source frequency, bias voltages, and characteristic impedance as needed:

```

VAR
VAR1
RFfreq=2400 MHz
Vhigh=28 V
Vlow=-2.7 V

```



If you change the node or current probe names or add or delete DC bias sources, you will need to modify the Pdc equation in Meas1.

```

MeasEqn
Meas1

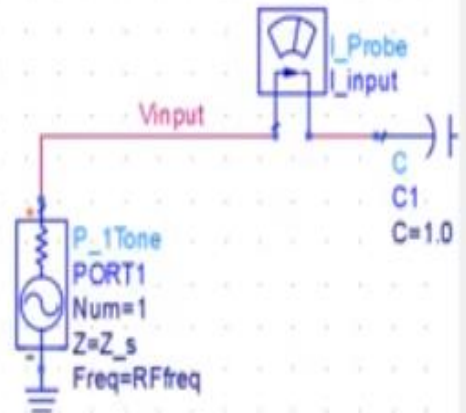
```



```

Z_s_2=fz(Src_2nd)
Z_s_3=fz(Src_3rd)
Z_s_4=Z0+j*0
Z_s_5=Z0+j*0
S_Src_Mag=0.95
S_Src_2nd_Phi=-180
S_Src_3rd_Phi=-180
Src_2nd=S_Src_Mag*exp(j*S_Src_2nd_Phi*pi/180)
Src_3rd=S_Src_Mag*exp(j*S_Src_3rd_Phi*pi/180)
    
```

Specify the available source power, Pavs_dBm, used to calculate the reference gain. Ideally, this Pavs_dBm should be near (or slightly less than) the value that causes the maximum gain. Specify the desired amount of gain compression, X_dB_target.



Enter proper inputs here

```

VAR
VAR2
Pavs_dBm=28
X_dB_target=1
    
```

Specify the source frequency, bias voltages, and characteristic impedance as needed:

```

VAR
VAR1
RFfreq=2400 MHz
Vhigh=28 V
Vlow=-2.7 V
    
```

If you change the node or current probe names or add or delete DC bias sources, you will need to modify the Pdc equation in Meas1.

```

MeasEqn
Meas1
    
```

No need to change anything inside

PARAMETER SWEEP
ParamSweep
Set_Opt_Sequence

```

VAR
Swept_Var_initialization
    
```

```

VAR
Fund_Load_rho_from_file
    
```

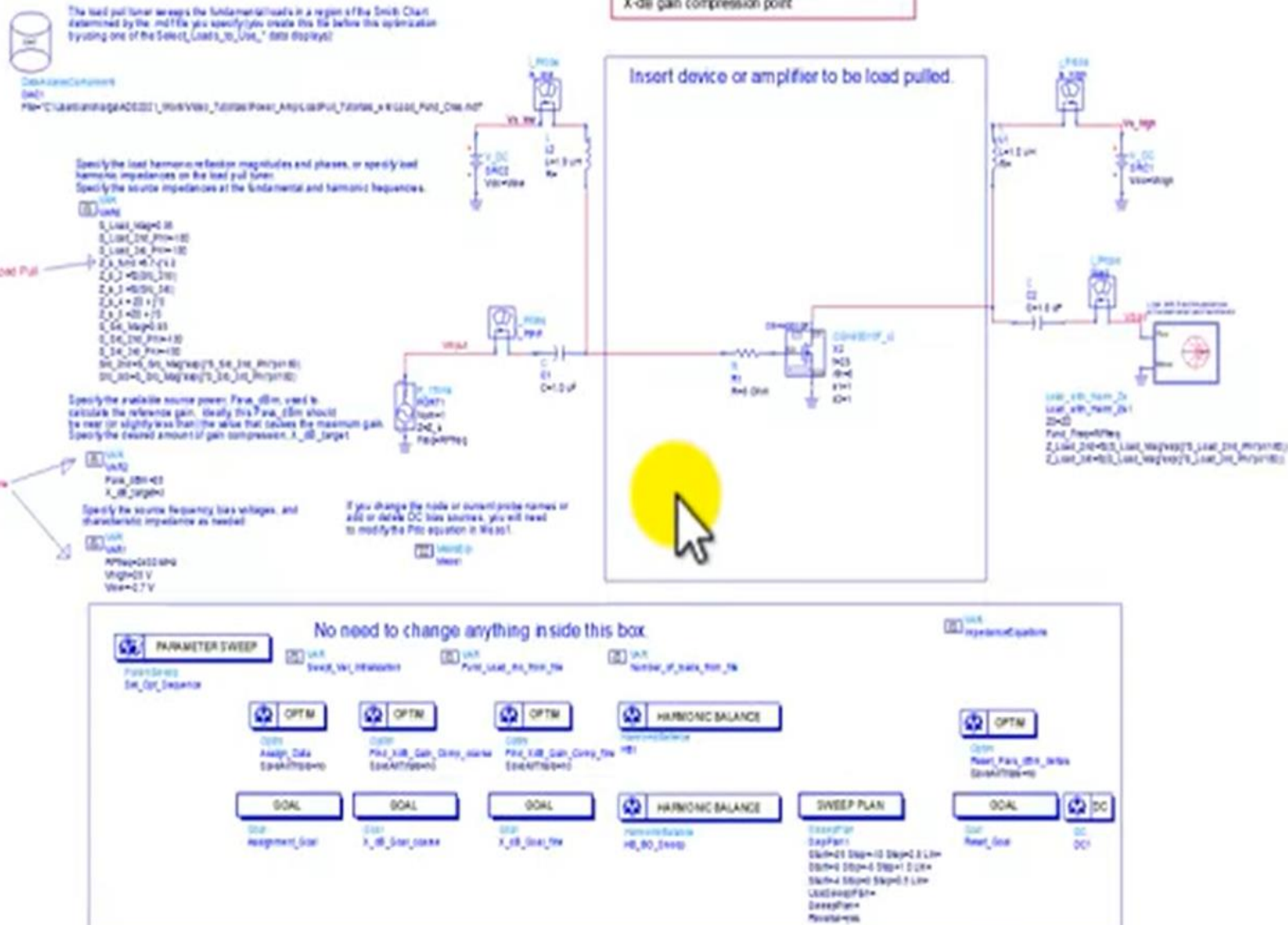
OPTIM

OPTIM

OPTIM

You must click the Optimize (not Simulate) icon for this to run properly!

Using optimization to find the X-dB gain compression point (relative to the maximum gain) and corresponding output power and PAE, within a load pull sweep, with a power sweep up to the X-dB gain compression point



Specify the load harmonic reflection magnitudes and phases, or specify load harmonic impedances on the load pull tuner.
Specify the source impedances at the fundamental and harmonic frequencies.

VAR
VAR6

S_Load_Mag=0.95
S_Load_2nd_Phi=-180
S_Load_3rd_Phi=-180
Z_s_fund=5.7-j*4.2
Z_s_2=fz(Src_2nd)
Z_s_3=fz(Src_3rd)
Z_s_4=Z0+j*0
Z_s_5=Z0+j*0
S_Src_Mag=0.95
S_Src_2nd_Phi=-180
S_Src_3rd_Phi=-180
Src_2nd=S_Src_Mag*exp(j*S_Src_2nd_Phi*pi/180)
Src_3rd=S_Src_Mag*exp(j*S_Src_3rd_Phi*pi/180)

Specify the available source power, Pavs_dBm, used to calculate the reference gain. Ideally, this Pavs_dBm should be near (or slightly less than) the value that causes the maximum gain.
Specify the desired amount of gain compression, X_dB_target.

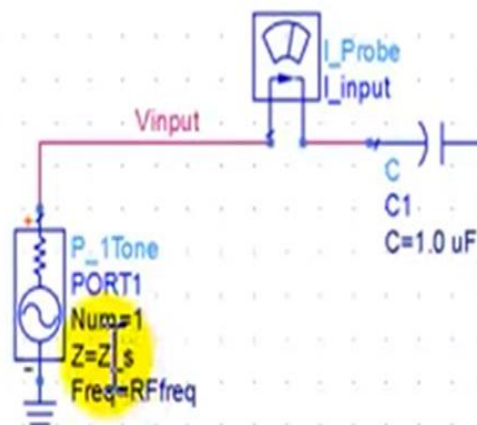
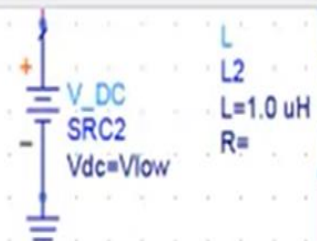
VAR
VAR2

Pavs_dBm=28
X_dB_target=3

Specify the source frequency, bias voltages, and characteristic impedance as needed:

VAR
VAR1

RFfreq=2400 MHz
Vhigh=28 V
Vlow=-2.7 V



If you change the node or current probe names or add or delete DC bias sources, you will need to modify the Pdc equation in Meas1.

MeasEqn
Meas1

Minimal Load Pull

Outputs here

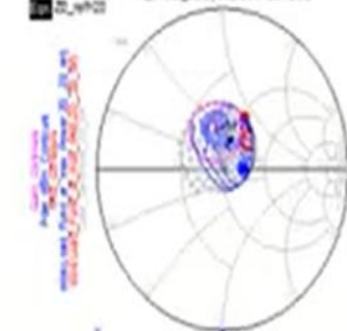
These are the maximum PAE and Power data:

Power_dBm_at_max_PAE	Power_dBm_at_max_Power	Power_dBm_at_m1
41.513	41.457	41.724
PAE_at_max_PAE	PAE_at_max_Power	PAE_at_m1
50.524	51.254	50.796
Desired_Gain_at_max_PAE	Desired_Gain_at_max_Power	Desired_Gain_at_m1
22.113 + j0.497	21.113 + j0.497	21.185 + j0.580
Desired_Load_at_max_PAE	Desired_Load_at_max_Power	Desired_Load_at_m1
0.004 + j0.149	0.003 + j0.153	0.230 + j0.709
Gain_at_max_PAE	Gain_at_max_Power	Gain_at_m1
12.835	12.895	13.115
Power_dBm_at_max_PAE	Power_dBm_at_max_Power	Power_dBm_at_m1
27.595	28.779	28.123
Desired_Load_at_max_PAE	Desired_Load_at_max_Power	Desired_Load_at_m1
0.002 - j0.000	0.002 - j0.000	0.002 - j0.000
Desired_Load_at_max_PAE	Desired_Load_at_max_Power	Desired_Load_at_m1
0.002 - j0.000	0.002 - j0.000	0.002 - j0.000
Desired_Load_at_max_PAE	Desired_Load_at_max_Power	Desired_Load_at_m1
0.002 - j0.000	0.002 - j0.000	0.002 - j0.000
Desired_Load_at_max_PAE	Desired_Load_at_max_Power	Desired_Load_at_m1
0.002 - j0.000	0.002 - j0.000	0.002 - j0.000

The Desired_XdB_GainComp value can be different from the X_dB_target value used on the schematic. If interpolation may occur? If you specify a larger value here.

Desired_XdB_GainComp_dB_large[0.0]
Interpolation="yes"

PAE, Power_dBm, and Gain Contours



m1
Load: index_105.000
Load: Dominant_22.113 + j0.497
Impedance = 22.113 + j0.497

PAE Max & Contour Levels



Power_dBm Max & Contour Levels



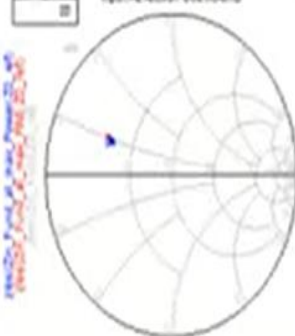
Gain Max & Contour Levels



Set bias current
contour step size
and PAE contour step
size (%), and number of
contour lines

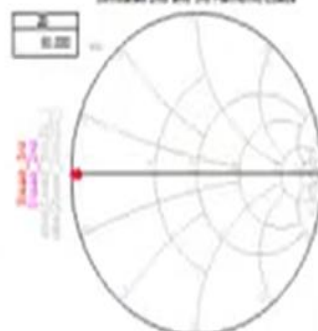
PAE_step=1
NumPAE_lines=5
Gain_step=1
NumGain_lines=5
PowerStep=0.5
NumPower_lines=5

Input Reflection Coefficients



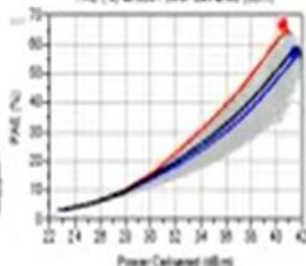
Desired_Load_at_max_PAE
Desired_Load_at_max_Power
Desired_Load_at_m1

Simulated 2nd and 3rd Harmonic Loads

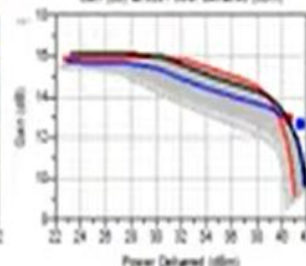


Gray traces are results from all power and fundamental load sweeps.
Red traces and X's are minimum PAE data. Blue traces and X's are maximum Power data.
Black traces and X's are with fundamental load selected (symbaker m1).

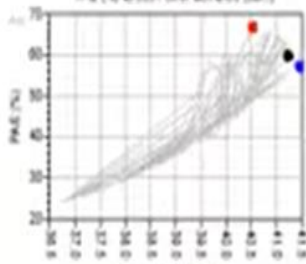
PAE (%) versus Power Delivered (dBm)



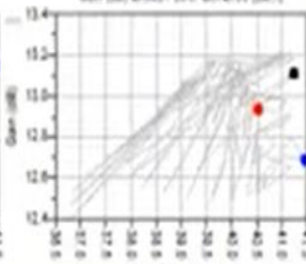
Gain (dB) versus Power Delivered (dBm)



PAE (%) versus Power Delivered (dBm)



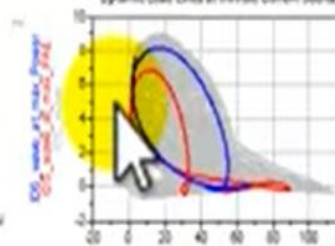
Gain (dB) versus Power Delivered (dBm)



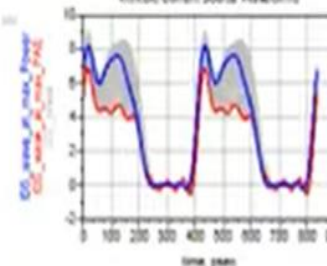
If the device model outputs intrinsic current source data, use those equations to see the waveforms plotted. If devices are in parallel, currents are added together, but only one voltage is used.

C01=Find_XdB_Gain_Comp_line HB1 HB XZ Q1 id
C02=Find_XdB_Gain_Comp_line HB1 HB XZ Q1 id
C03=Find_XdB_Gain_Comp_line HB1 HB XZ Q1 id
C04=Find_XdB_Gain_Comp_line HB1 HB XZ Q1 id
V05=Find_XdB_Gain_Comp_line HB1 HB XZ Q1 vol

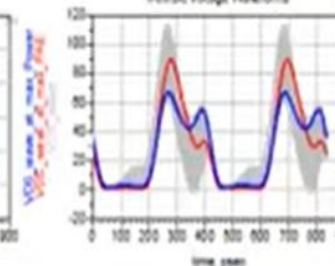
Dynamic Load Lines of Intrinsic Current Source



Intrinsic Current Source Waveforms



Intrinsic Voltage Waveforms



Specify file name, then activate X equation to write out max efficiency, max power, and m1 marker load data to file for subsequent simulations:

File Name: Load_and_Sources_Gainmax.mif

File Name: Load_and_Sources_Gainmax.mif



Palette



may occur if you specify a target value here.

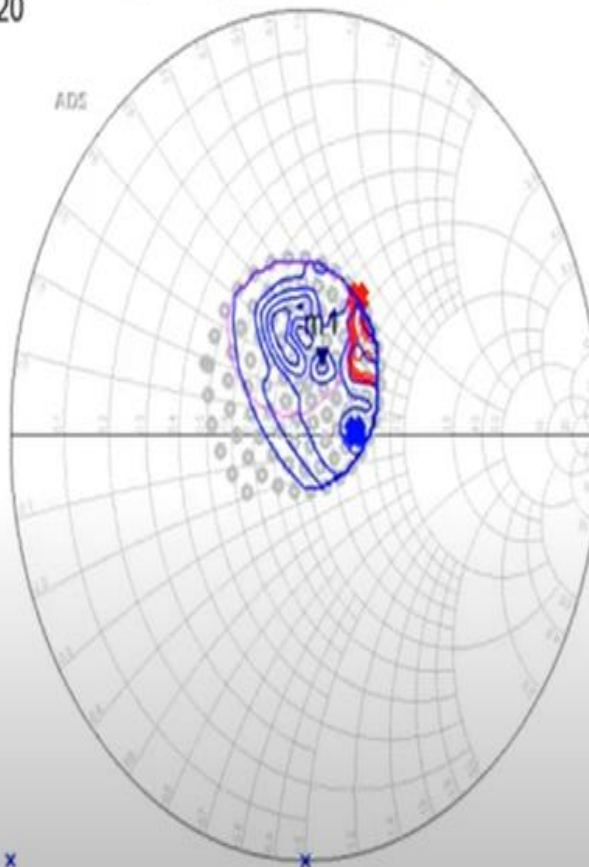
EqnDesired_XdB_GainComp=X_dB_target[0,0]

Eqnallowextrap="yes"

EqnZ0_ref=20

PAE, Pdel_dBm, and Gain Contours

Gain_Contours
Pdel_dBm_Contours
PAE_Contours
stos(Load_Fund_at_max_Power,Z0_ref)
stos(Load_Fund_at_max_PAE,Z0_ref)
Load_Gamma5_Z0_ref



PAE Max & Contour Levels

66.419
66.000
65.000
64.000
63.000
62.000

Pdel_dBm Max & Contour Levels

41.443
41.000
40.500
40.000
39.500
39.000

Gain Max & Contour Levels

13.222
13.000

Set bias current
contour step size
and PAE contour step
size (%), and number
contour lines

EqnPAE_step=1

EqnNumPAE_lines=

EqnGain_step=1

EqnNumGain_lines=

EqnPowerStep=0.5

EqnNumPower_line

m1

Load_index = 35.000

Load_Gamma5_Z0_ref = 0.470 + j0.744

Pdel_dBm_at_max_PAE
40.525

PAE_at_XdB_max
66.824

Zload_Fund_at_max_PAE
 $22.133 + j16.627$

Zin_Fund_at_max_PAE
 $6.084 + j4.049$

Gain_at_max_PAE
12.935

Pavs_dBm_at_max_PAE
27.590

Sload_2nd_at_max_PAE
 $0.950 / -180.000$

Sload_3rd_at_max_PAE
 $0.950 / -180.000$

Src_2nd_at_max_PAE
 $0.950 / -180.000$

Src_3rd_at_max_PAE
 $0.950 / -180.000$

Pdel_dBm_at_XdB_max
41.457

PAE_at_max_Power
57.254

Zload_Fund_at_max_Power
 $28.115 + j0.497$

Zin_Fund_at_max_Power
 $6.575 + j3.783$

Gain_at_max_Power
12.686

Pavs_dBm_at_max_Power
28.770

Sload_2nd_at_max_Power
 $0.950 / -180.000$

Sload_3rd_at_max_Power
 $0.950 / -180.000$

Src_2nd_at_max_Power
 $0.950 / -180.000$

Src_3rd_at_max_Power
 $0.950 / -180.000$

Pdel_dBm_at_m1
41

PAE_at_m1
59

Zload_Fund_at_m1
 $21.185 + j7.$

Zin_Fund_at_m1
 $6.238 + j3.$

Gain_at_m1
13

Pavs_dBm_at_m1
28

Sload_2nd_at_m1
 $0.950 / -180.$

Sload_3rd_at_m1
 $0.950 / -180.$

Src_2nd_at_m1
 $0.950 / -180.$

Src_3rd_at_m1
 $0.950 / -180.$

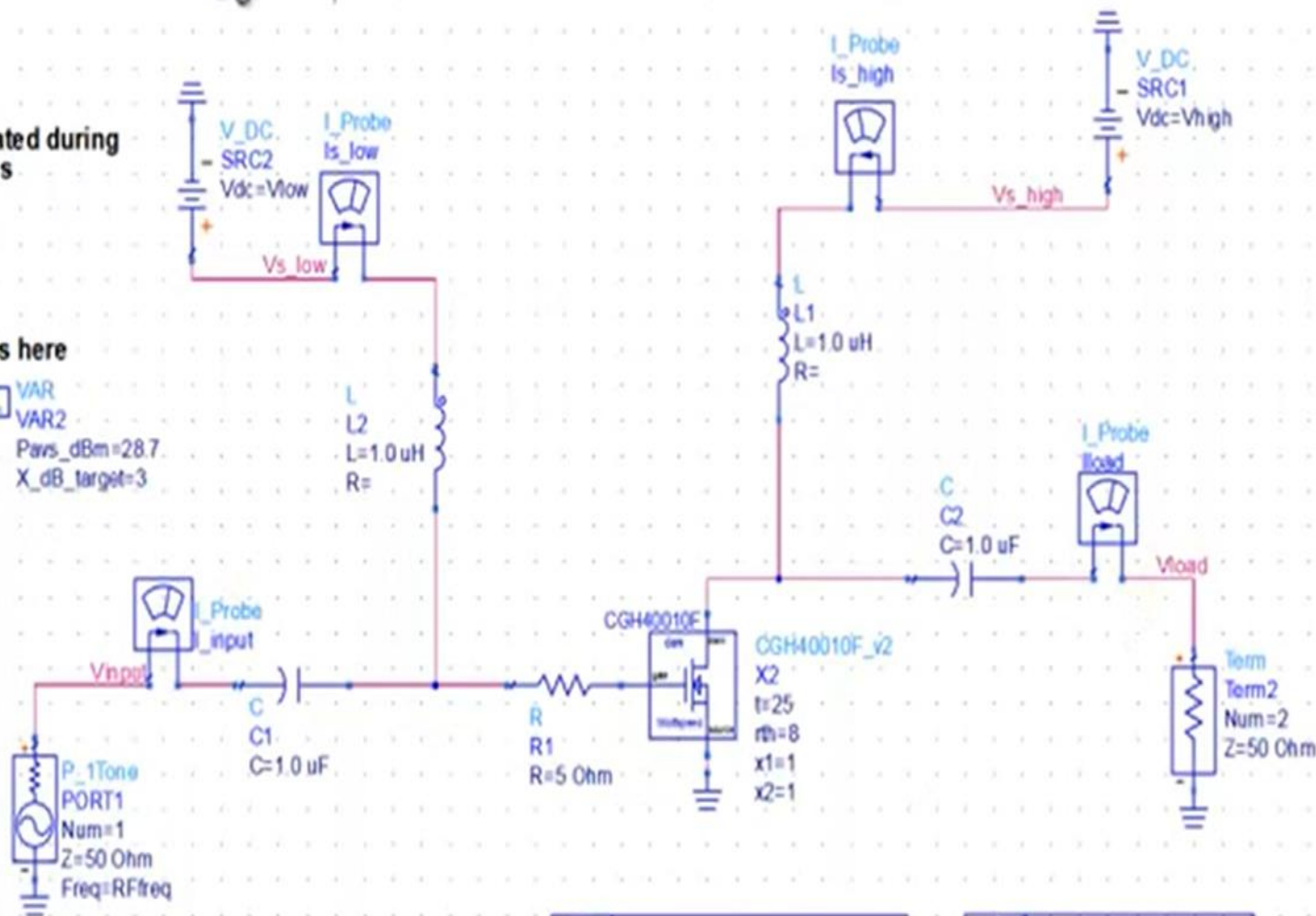
Enter Z_s & Z_L calculated during the Load Pull analysis

VAR
VAR6
 $Z_s = 6.5 - j3.7$
 $Z_L = 28 + j0.5$

Enter proper inputs here

VAR
VAR1
RFreq=2400 MHz
Vhigh=28 V
Vlow=2.7 V

VAR
VAR2
Pavs_dBm=28.7
X_dB_target=3



MeasEqn

```
Meas1
Pdel_W=0.5*real(Vload[1]*conj(Iload[1]))
Pdel_dBm=10*log(Pdel_W)+30
Pin_W=0.5*real(Vinput[1]*conj(Iinput[1]))
Pdc=real(Vs_low[0]*Is_low[0]+Vs_high[0]*Is_high[0])
PAE=100*(Pdel_W-Pin_W)/Pdc
Deff=100*Pdel_W/Pdc
LS_Gain_dB=Pdel_dBm-Pavs_dBm
```

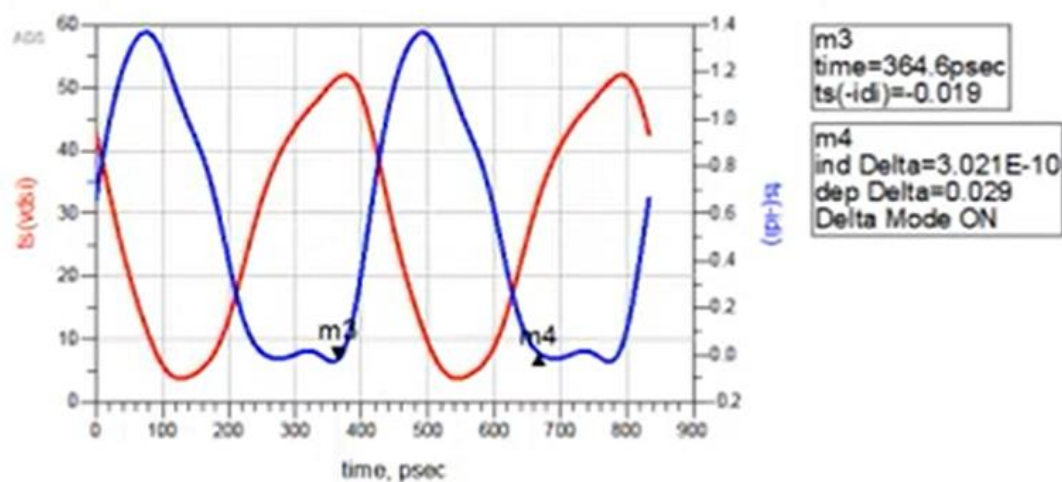
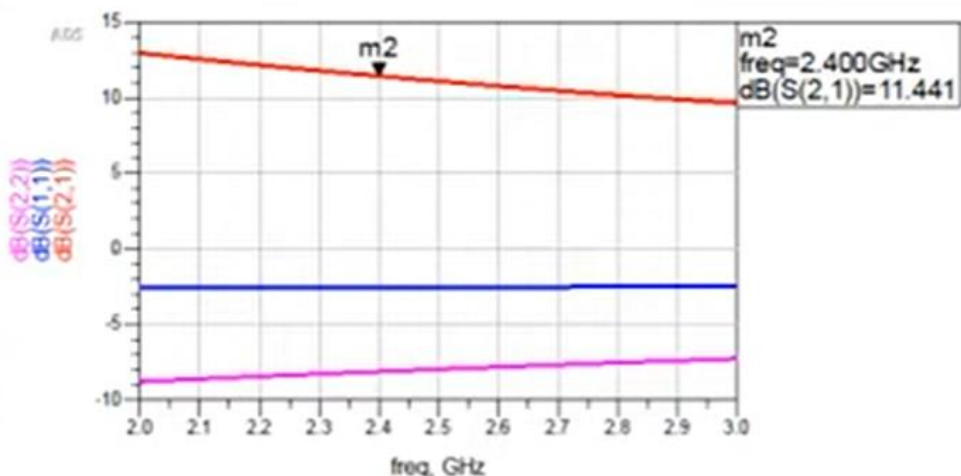
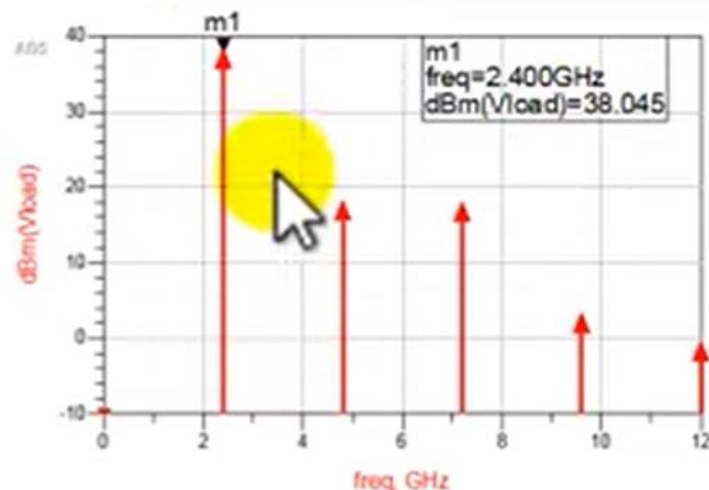
HARMONIC BALANCE

HarmonicBalance
HB1
Freq[1]=RFfreq
Order[1]=5

S-PARAMETERS

S_Param
SP1
Start=2 GHz
Stop=3 GHz
Step=0.01 GHz

Pdel_dBm	PAE	Deff	LS_Gain_dB	Pdel_W
38.045	39.601	41.748	9.345	6.376



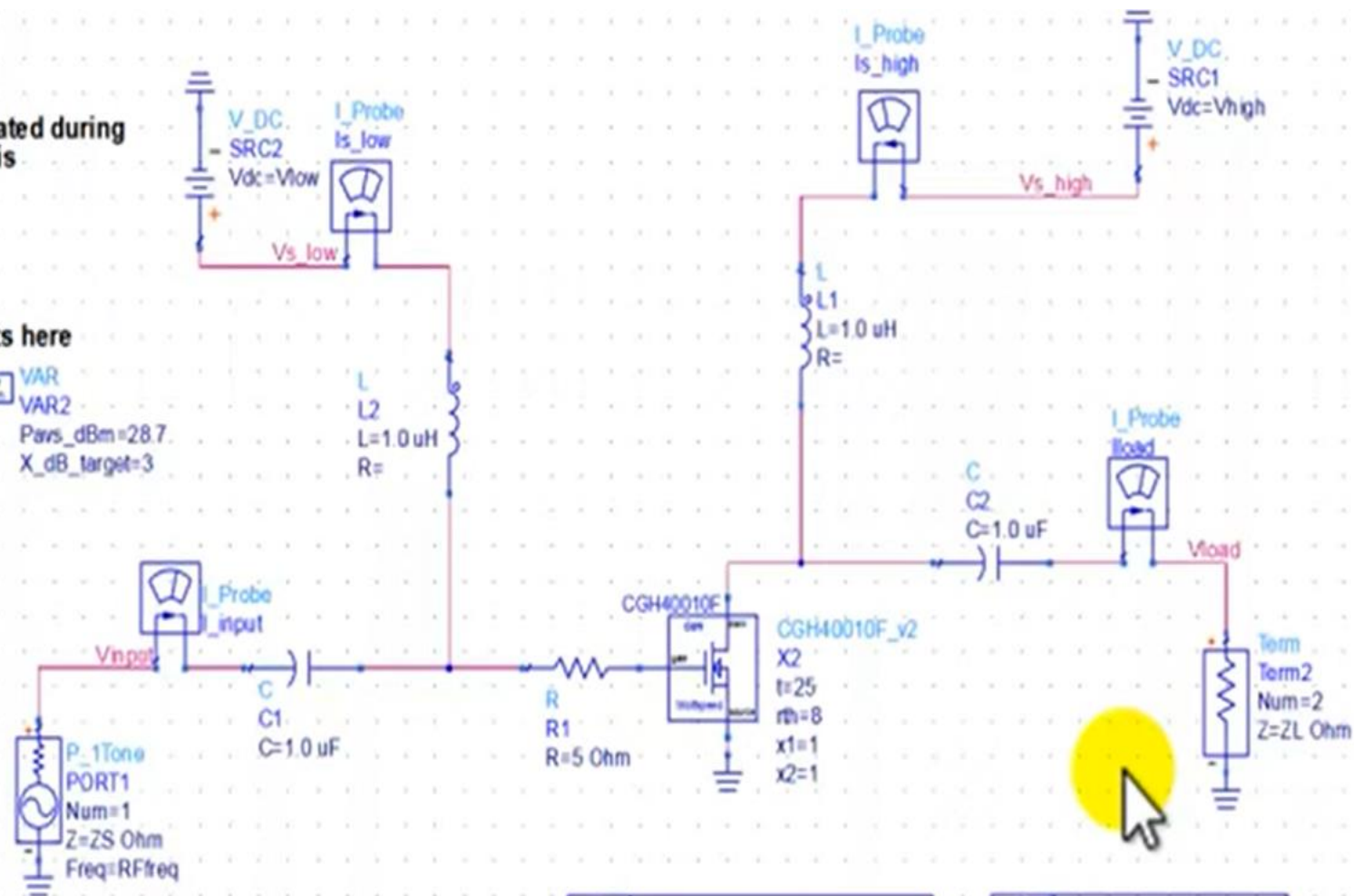
Enter Zs & ZL calculated during the Load Pull analysis

VAR
VAR6
 $ZS=6.5-j*3.7$
 $ZL=28+j*0.5$

Enter proper inputs here

VAR
VAR1
RFfreq=2400 MHz
Vhigh=28 V
Vlow=-2.7 V

VAR
VAR2
Pavs_dBm=28.7
XdB_target=3



MeasEqn
Meas1
 $Pdel_W=0.5*real(Vload[1]*conj(Iload[1]))$
 $Pdel_dBm=10*log(Pdel_W)+30$
 $Pin_W=0.5*real(Vinput[1]*conj(Iinput[1]))$
 $Pdc=real(Vs_low[0]*Is_low[0]+Vs_high[0]*Is_high[0])$
 $PAE=100*(Pdel_W-Pin_W)/Pdc$
 $Deff=100*Pdel_W/Pdc$
 $LS_Gain_dB=Pdel_dBm-Pavs_dBm$

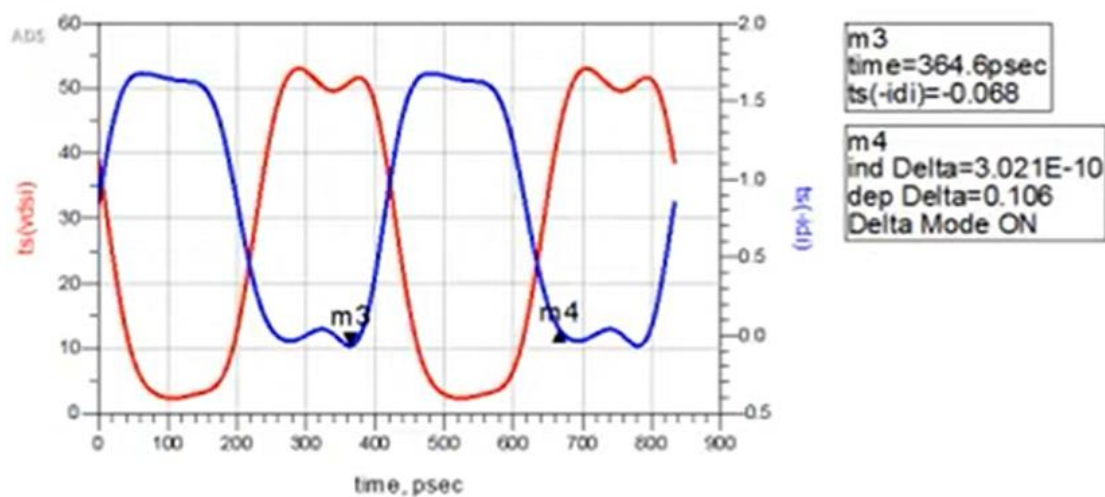
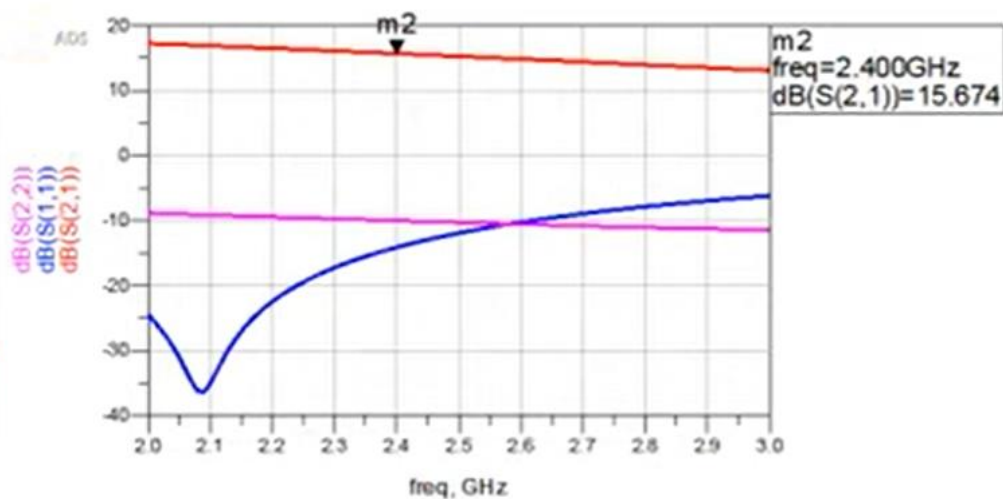
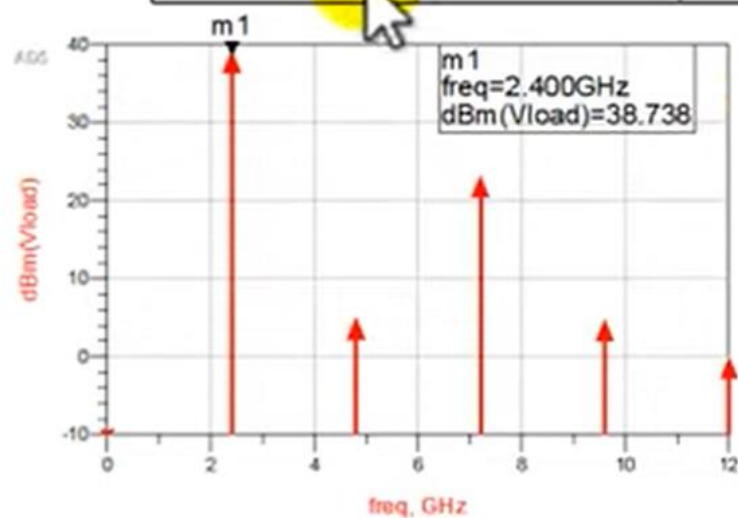
HARMONIC BALANCE

HarmonicBalance
HB1
Freq[1]=RFfreq
Order[1]=5

S-PARAMETERS

S_Param
SP1
Start=2 GHz
Stop=3 GHz
Step=0.01 GHz

Pdel_dBm	PAE	Deff	LS_Gain_dB	Pdel_W
41.255	56.840	60.169	12.555	13.350



Features

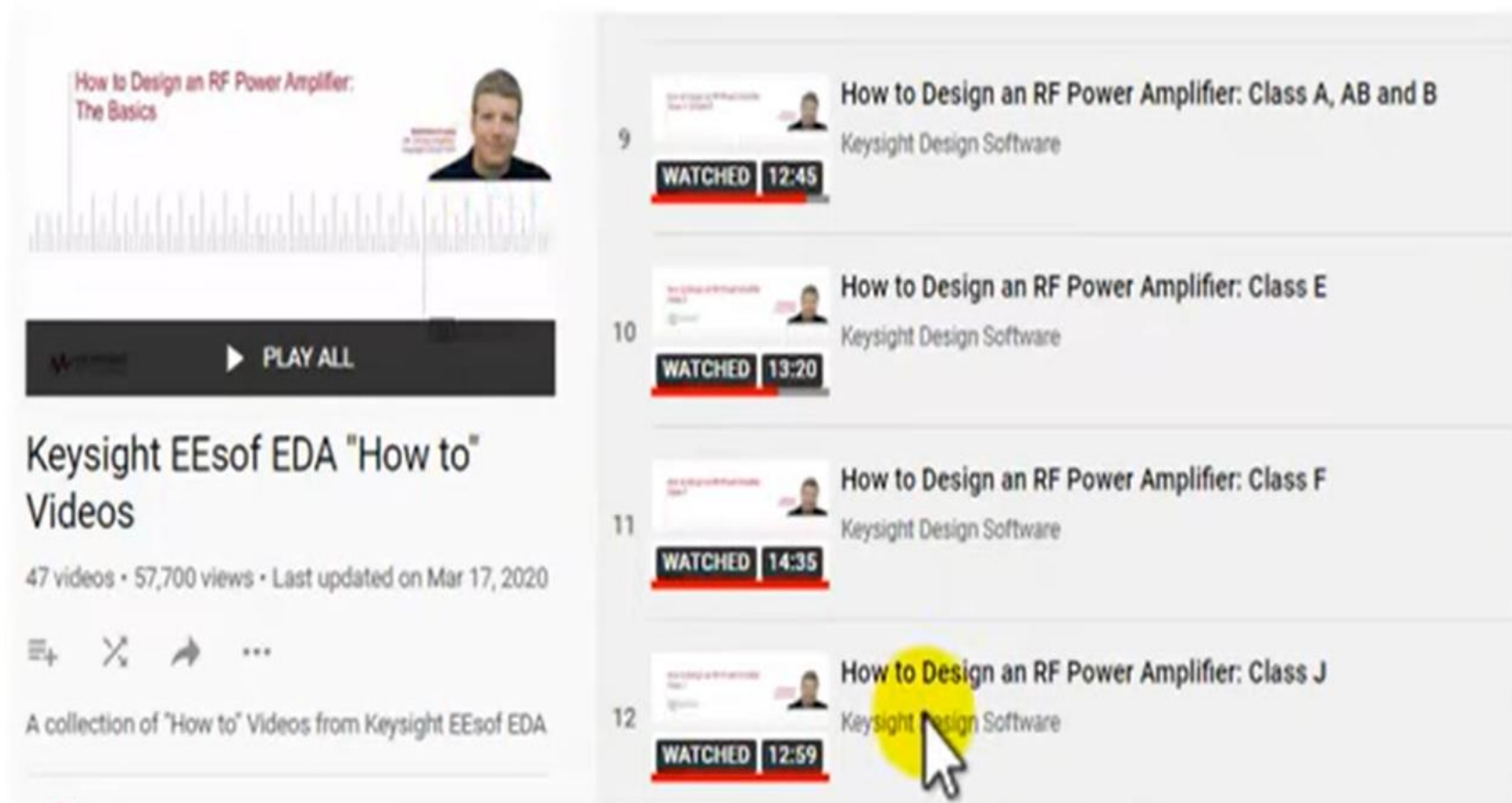
- Up to 6 GHz Operation
- 16 dB Small Signal Gain at 2.0 GHz
- 14 dB Small Signal Gain at 4.0 GHz
- 13 W typical PSAT
- 65 % Efficiency at PSAT
- 28 V Operation

Applications

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

Click on this link in the description:

<https://youtube.com/playlist?list=PLtq84kH8xZ9HIYgBYDsP7TbqBpftidzI8>



The image shows a screenshot of a YouTube playlist page. On the left, the playlist's main image features a waveform and the text 'How to Design an RF Power Amplifier: The Basics'. Below the image is a 'PLAY ALL' button. The playlist title is 'Keysight EEsof EDA "How to" Videos', with 47 videos, 57,700 views, and a last update on Mar 17, 2020. On the right, a list of video thumbnails is shown, each with a 'WATCHED' status and a duration. A yellow circle highlights the 12th video, 'How to Design an RF Power Amplifier: Class J', with a mouse cursor pointing at it.

How to Design an RF Power Amplifier: The Basics

PLAY ALL

Keysight EEsof EDA "How to" Videos

47 videos • 57,700 views • Last updated on Mar 17, 2020

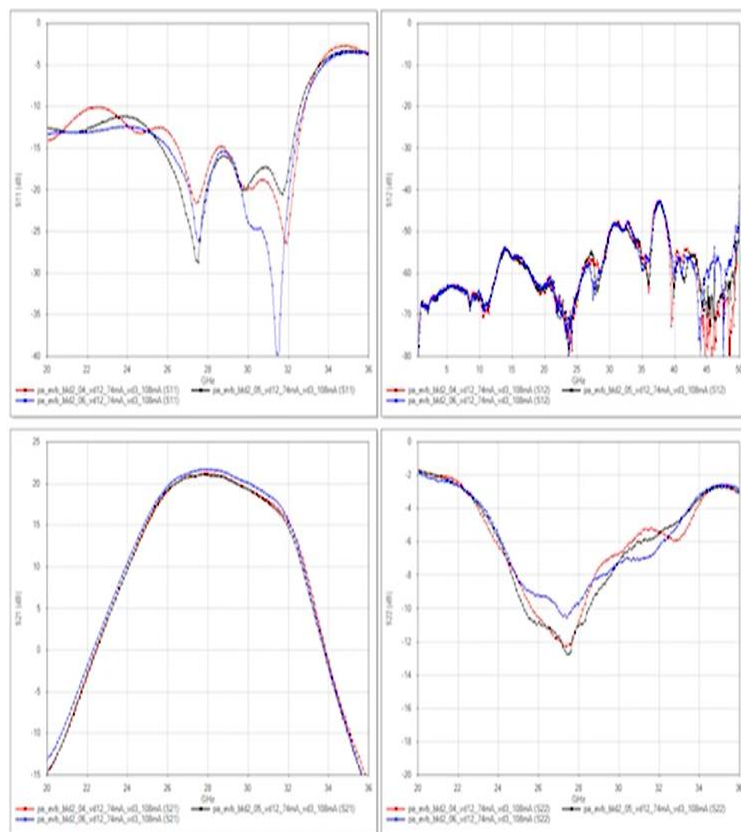
9 How to Design an RF Power Amplifier: Class A, AB and B
Keysight Design Software
WATCHED 12:45

10 How to Design an RF Power Amplifier: Class E
Keysight Design Software
WATCHED 13:20

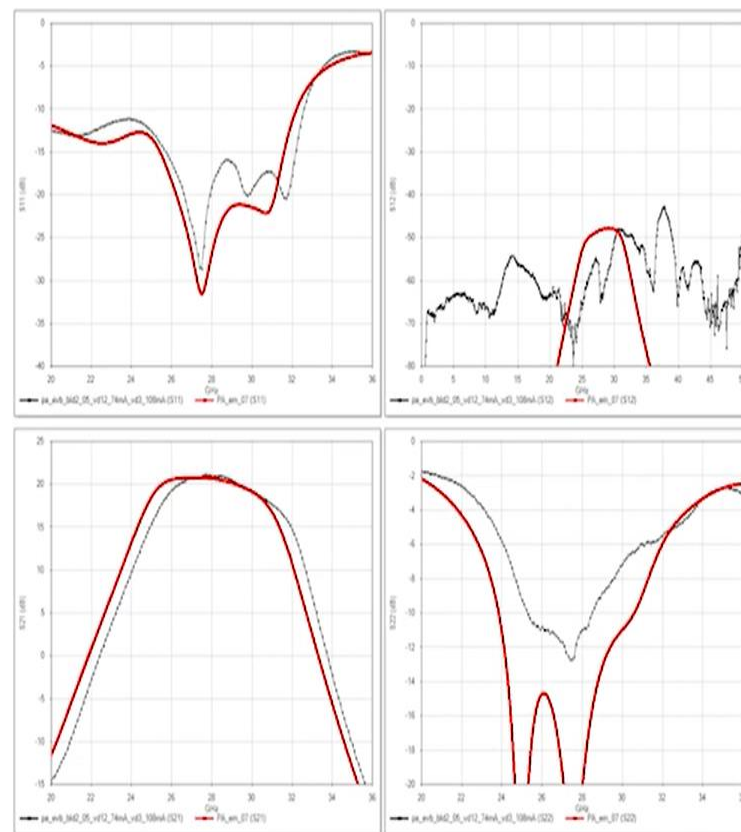
11 How to Design an RF Power Amplifier: Class F
Keysight Design Software
WATCHED 14:35

12 How to Design an RF Power Amplifier: Class J
Keysight Design Software
WATCHED 12:59

28GHz PA - Measured to Modelled S-parameters

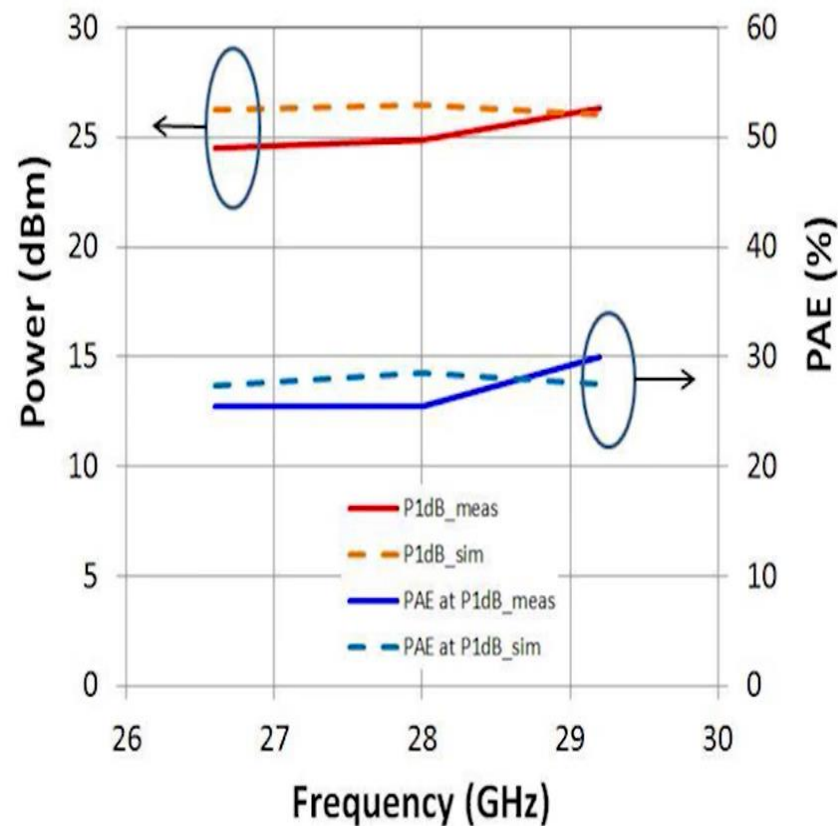


Measured results for 3 samples



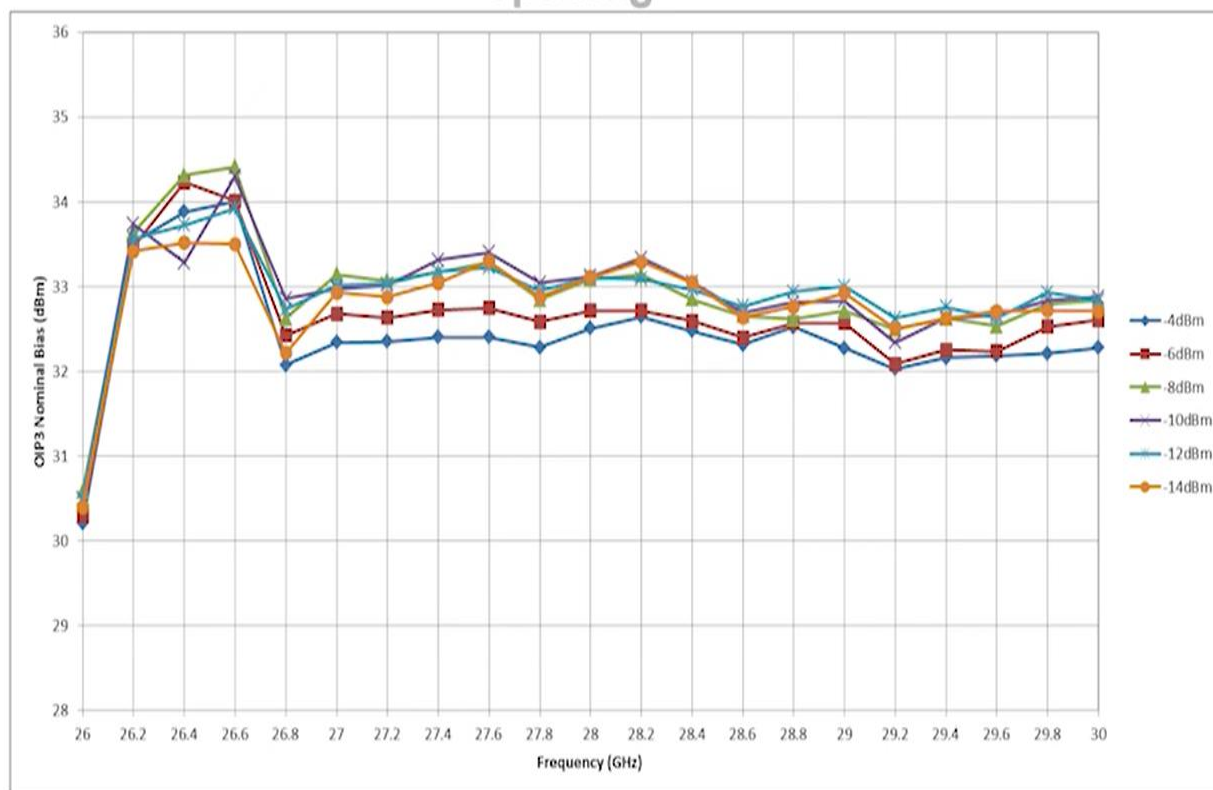
Measured to modelled

28GHz PA - Measured to Simulated

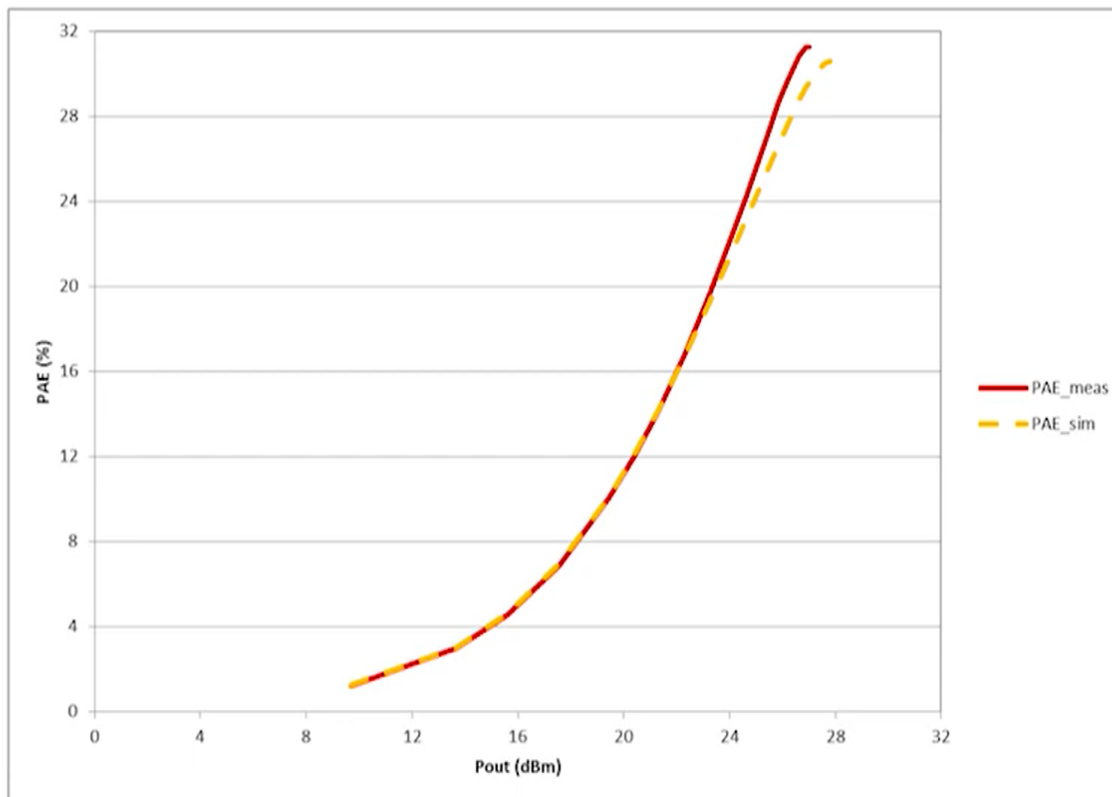


Measured Output IP3

Input tone powers of -14dBm to -4dBm per tone, 100MHz tone spacing

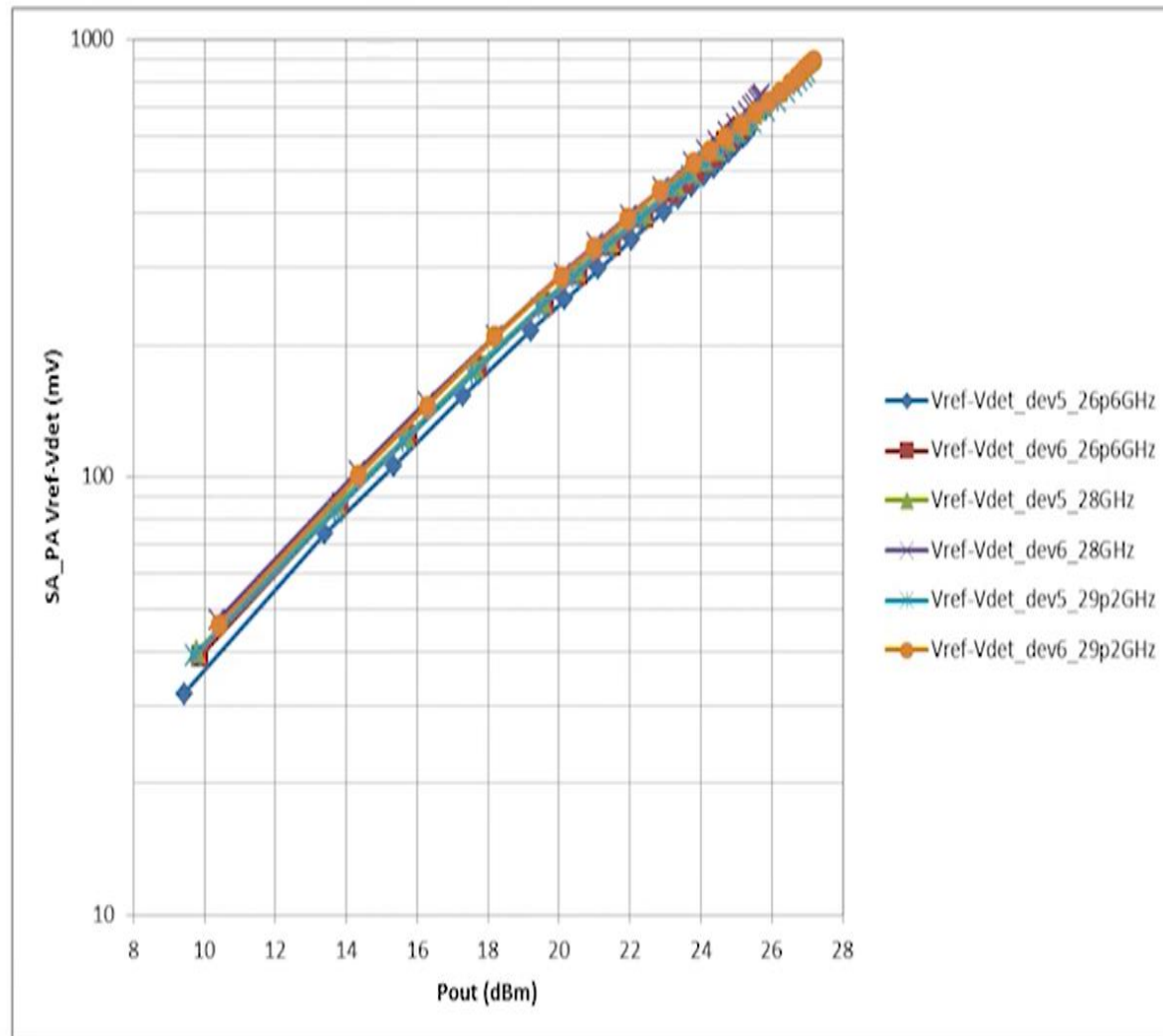


Comparison of Measured to Modelled PAE vs Pout at 29.2GHz



Measured RF Power Detector

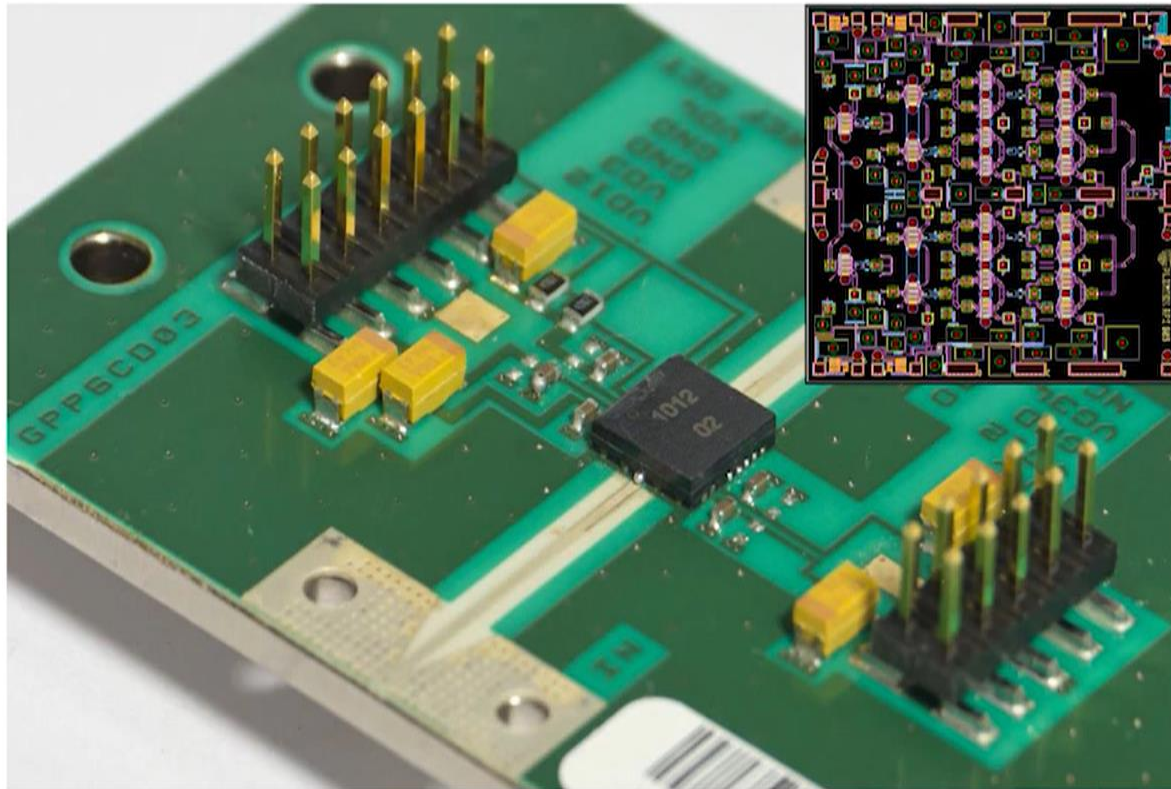
Two samples, 3 frequencies versus RF output power



39GHz PA Overview

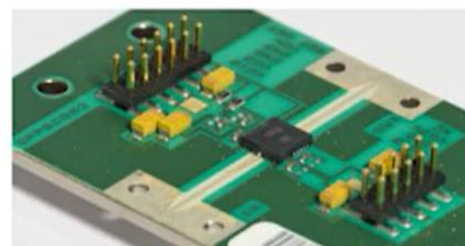
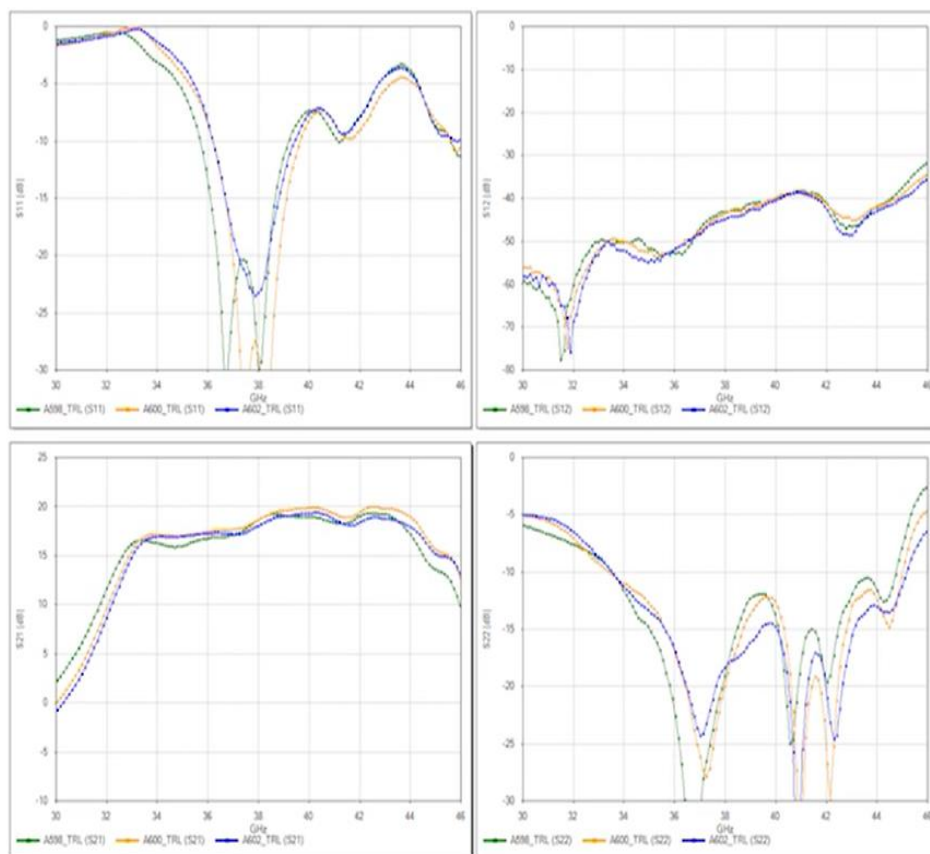
- Process: 0.15 μ m PHEMT
- Package: Air cavity QFN
- Covers 39GHz 5G band (good performance 37 – 42GHz)
- Measurement conditions:
 - Packaged part assembled onto laminate evaluation PCB
 - Measurements referenced to package
 - Ambient = 25°C
 - Vdd = 6V
 - Idq = 1260mA (131mA/mm)
 - Micro-strip style PCB
 - All measurement results are CW

39GHz PA in 5mm x 5mm Air-Cavity Plastic

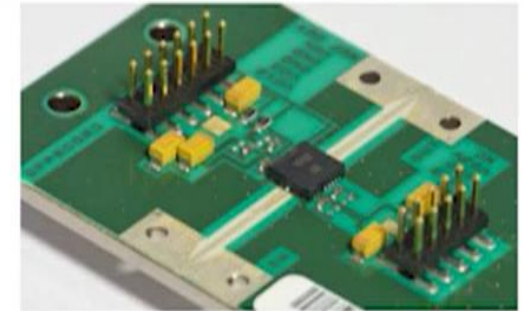
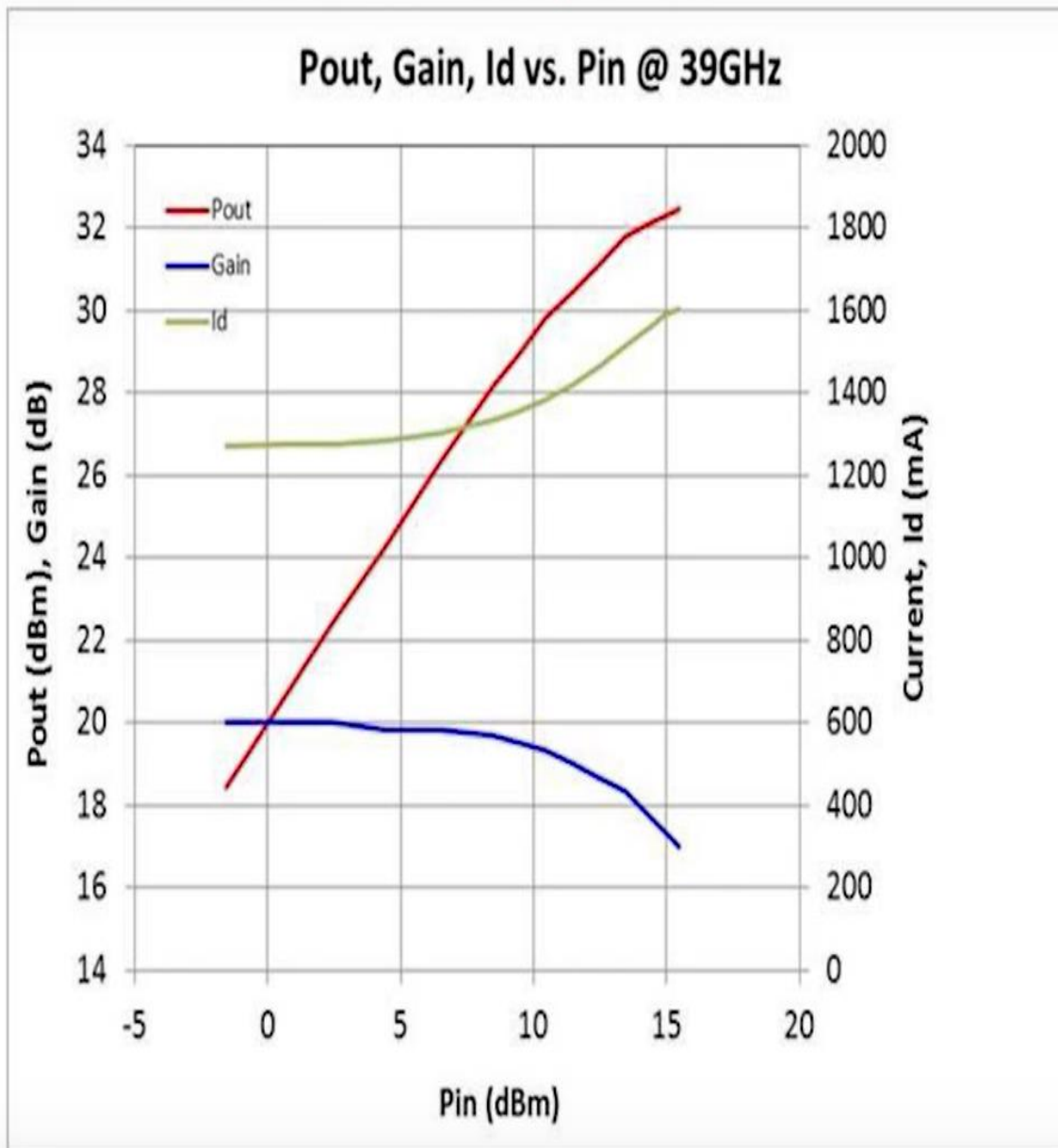


39GHz PA in 5mm x 5mm Air-Cavity QFN

Measurements on eval PCB referenced to package ports

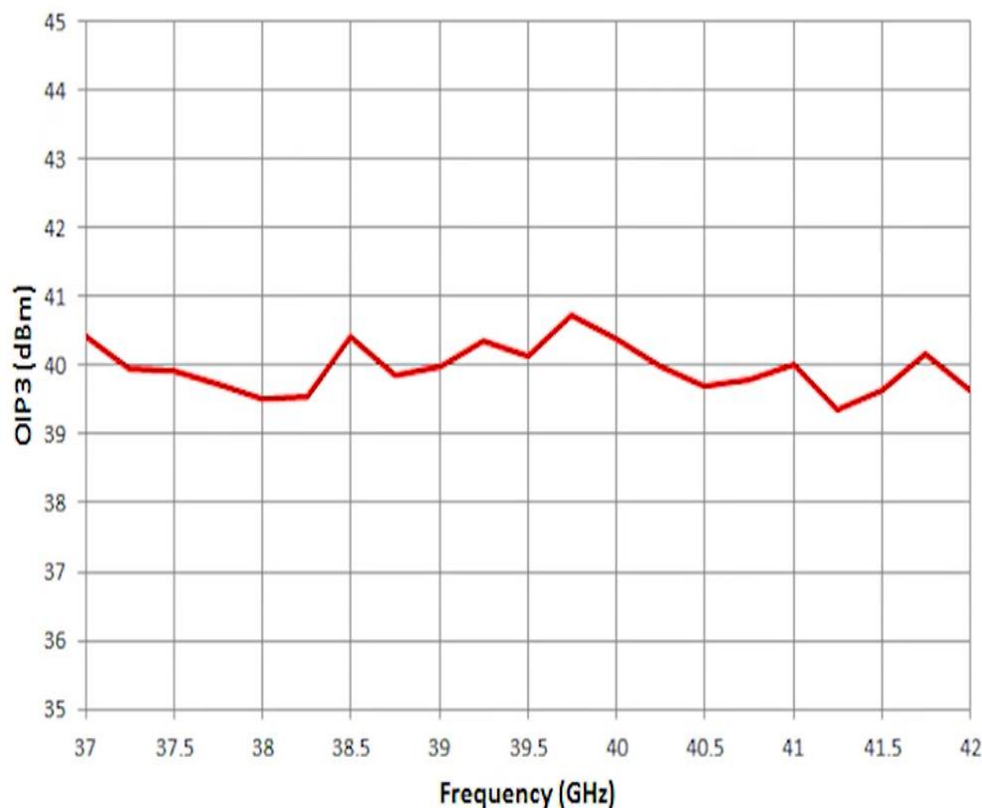


39GHz PA – Pout, Gain and Id vs. Pin at 39GHz



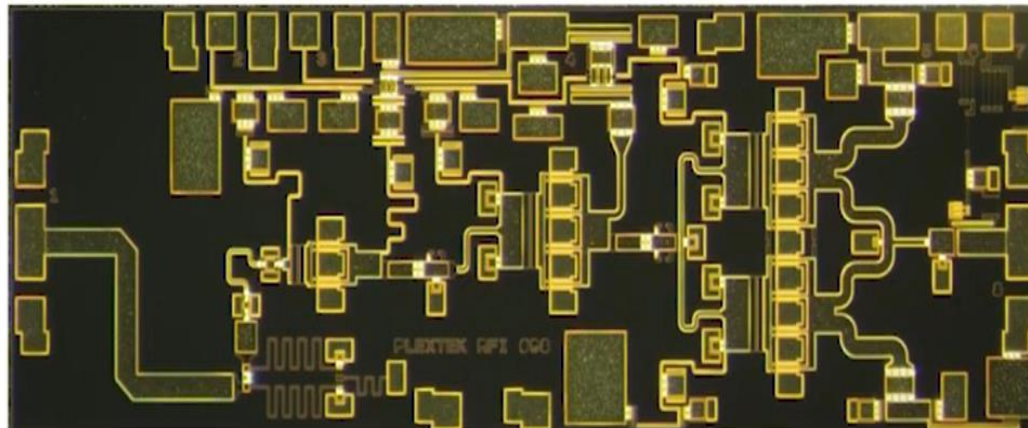
39GHz PA in 5mm x 5mm Air-Cavity QFN

Measurements on eval PCB referenced to package ports



PA for 26GHz 5G Pioneer Band - Overview

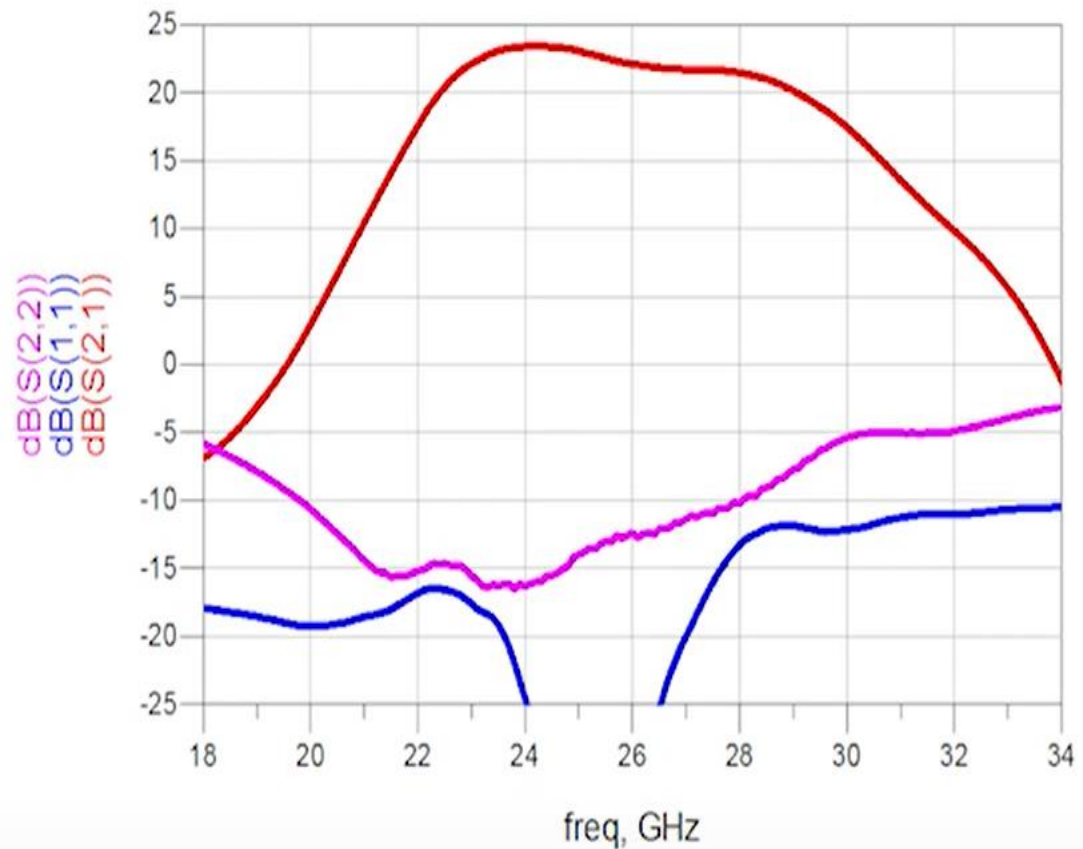
- Covers 24 – 28GHz (pioneer band is 24.25 – 27.5GHz)
- Includes on-chip temperature compensated power detector
- Die size: 3.5mm x 1.2mm (x-dimension can be reduced to 3mm)
- Fabricated on a 0.15 μ m PHEMT process from WIN
- Gain ~ 22dB; P-1dB ~ 26dBm; PAE ~ 30%



RFOW Measured Performance

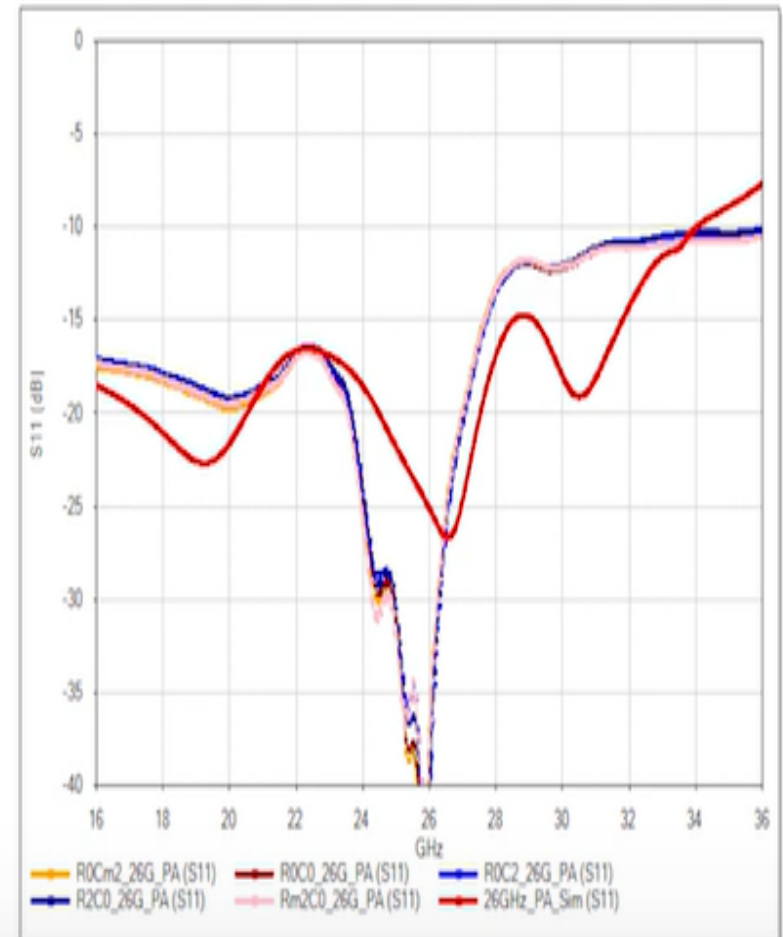
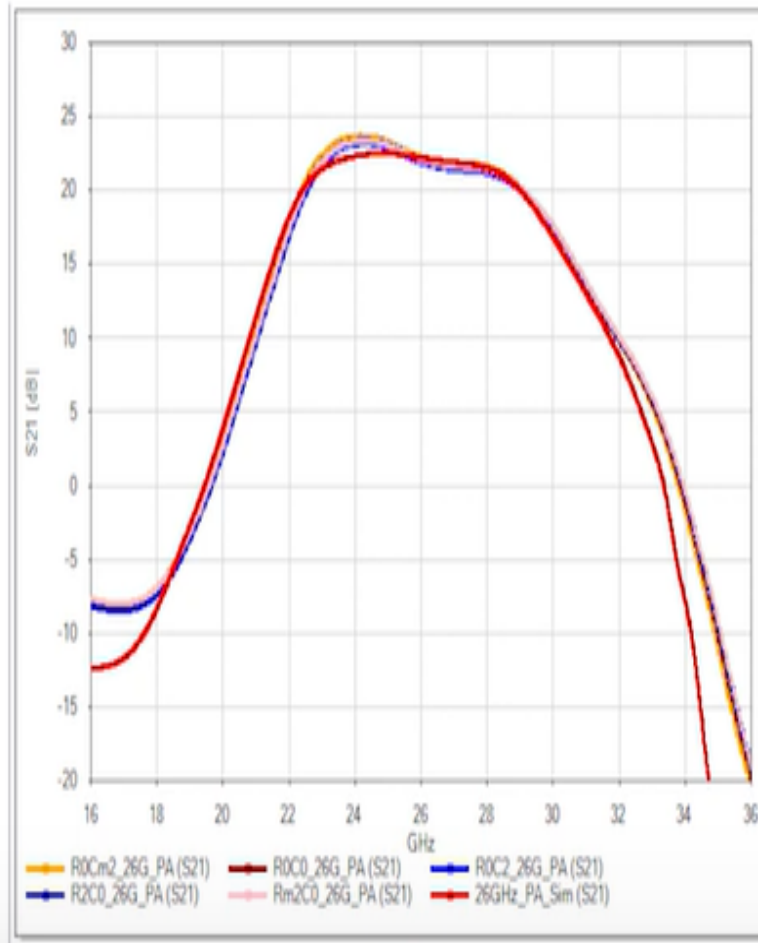
S-parameters

- Biased at 6V V_{ds} and 210mA I_{ds}

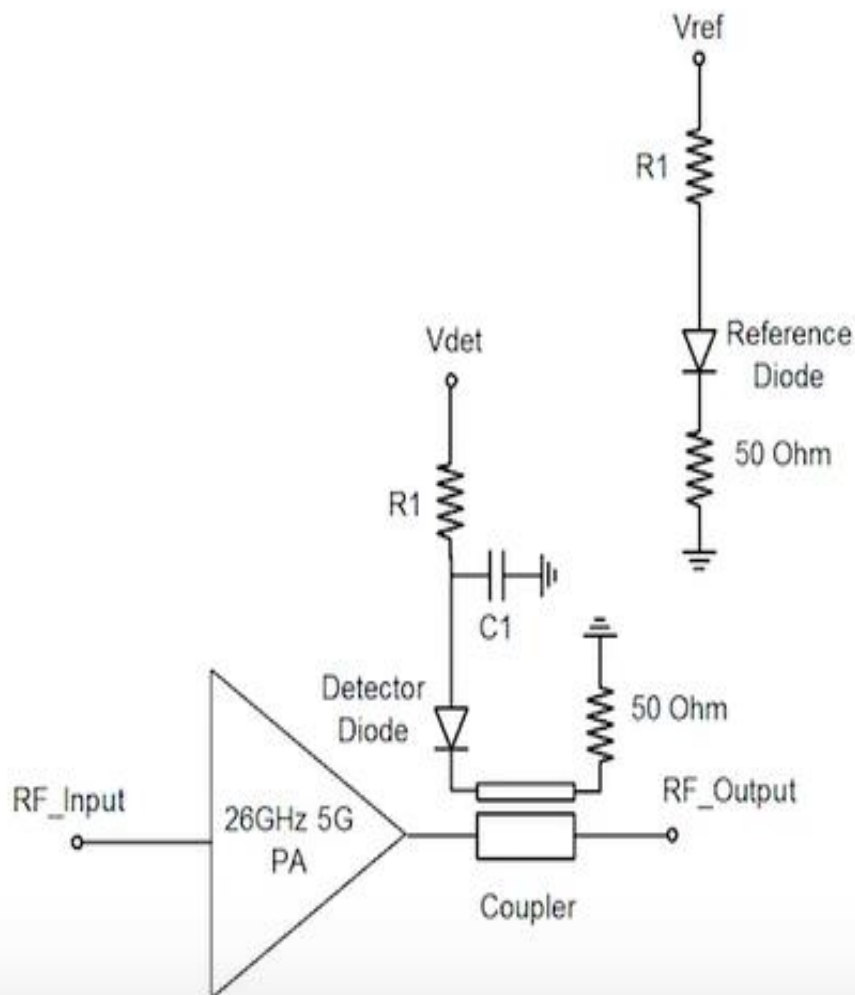


RFOW Measured Performance Compared to Simulated

- 5 RFOW measured parts compared to **simulated**



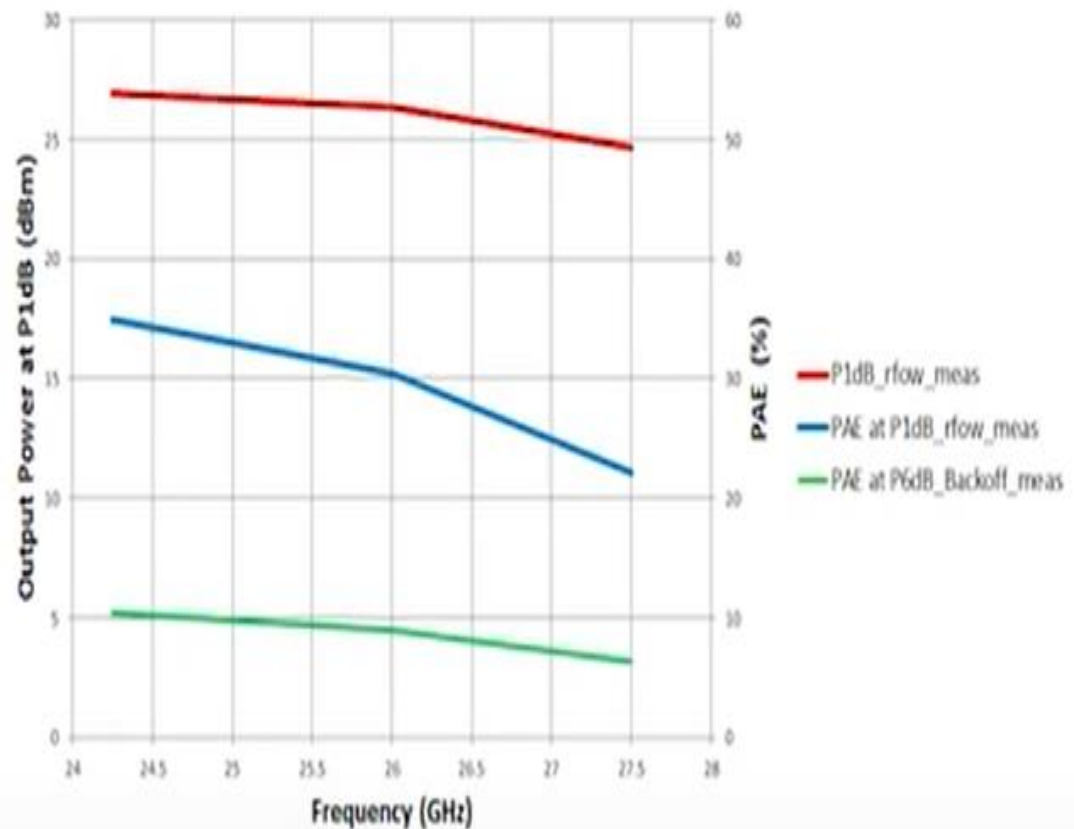
Temperature-Compensated Power Detector



RFOW Measured Performance

Power Compression

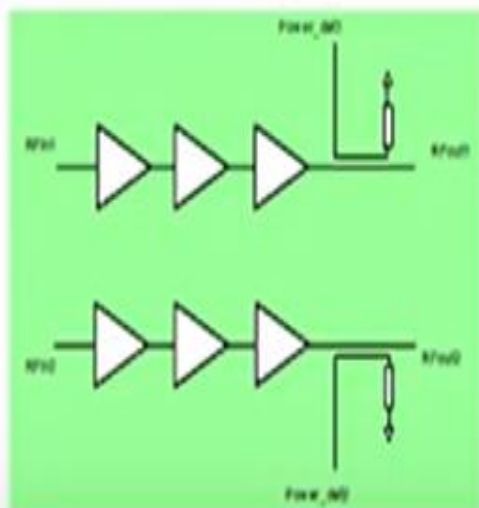
- P-1dB ~ 26dBm
- PAE @ P-1dB ~ 30%
- PAE @ 6dB BO ~ 9%



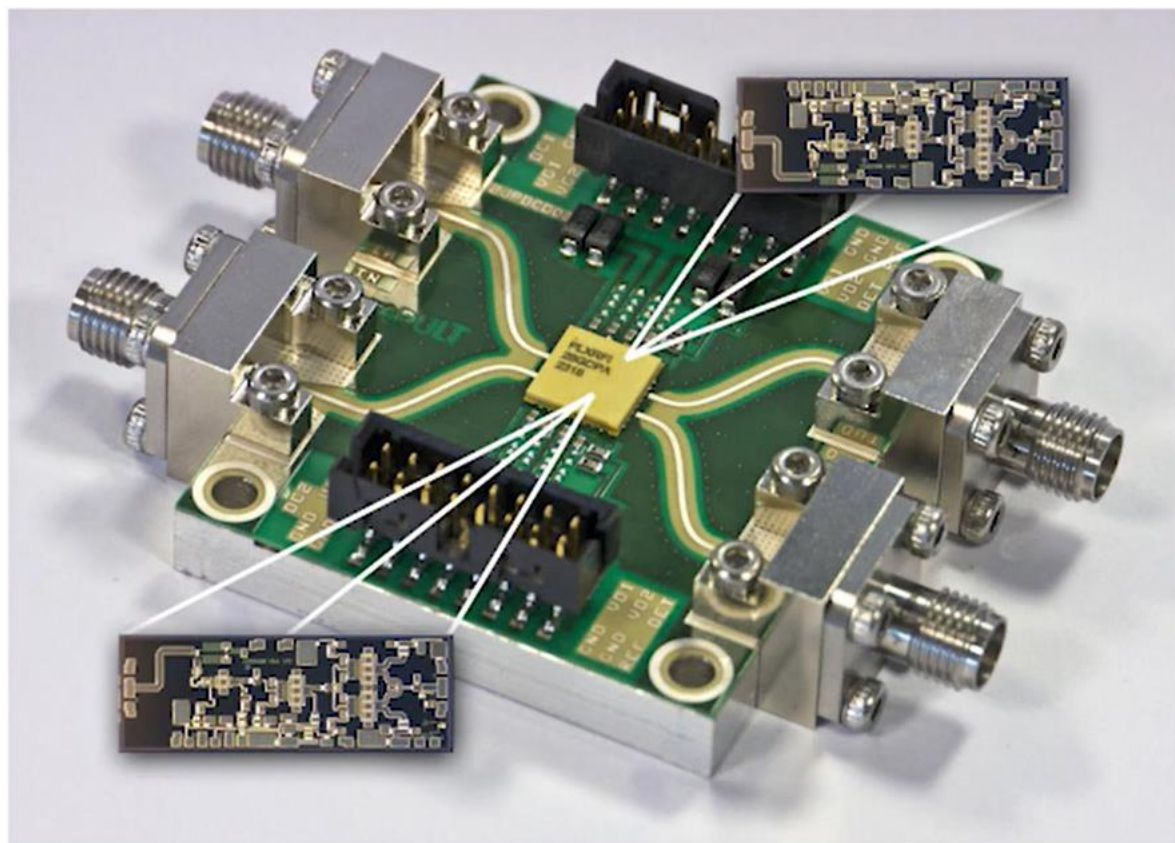
Packaging of Dual Channel Component

Overview

- Laminate substrate for base and lid
- QFN package with solid Cu base
- Custom design for optimum RF performance
- Two die co-packaged to yield dual-channel part
- Package manufacture and assembly by Filtronic

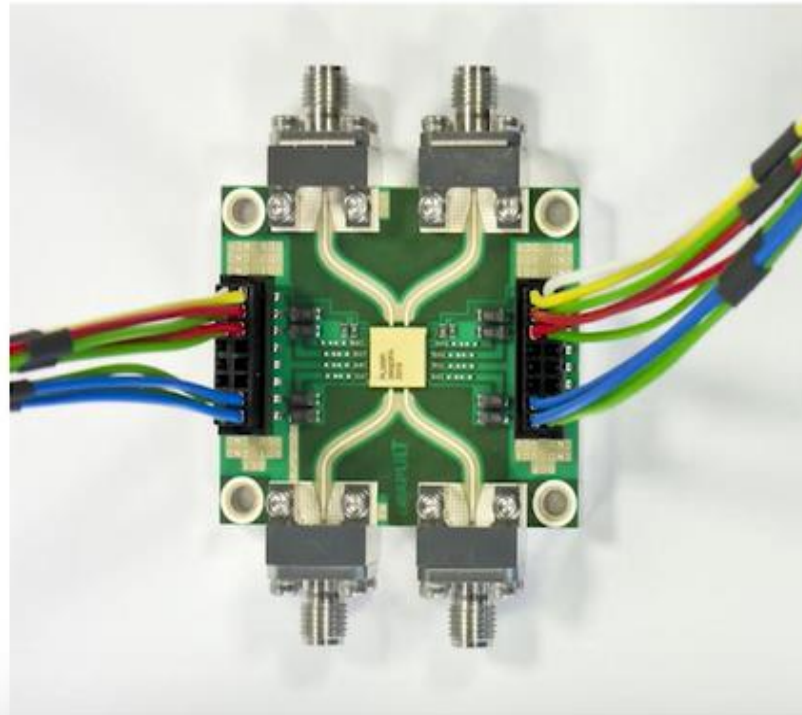


Evaluation Board for Dual Channel Component



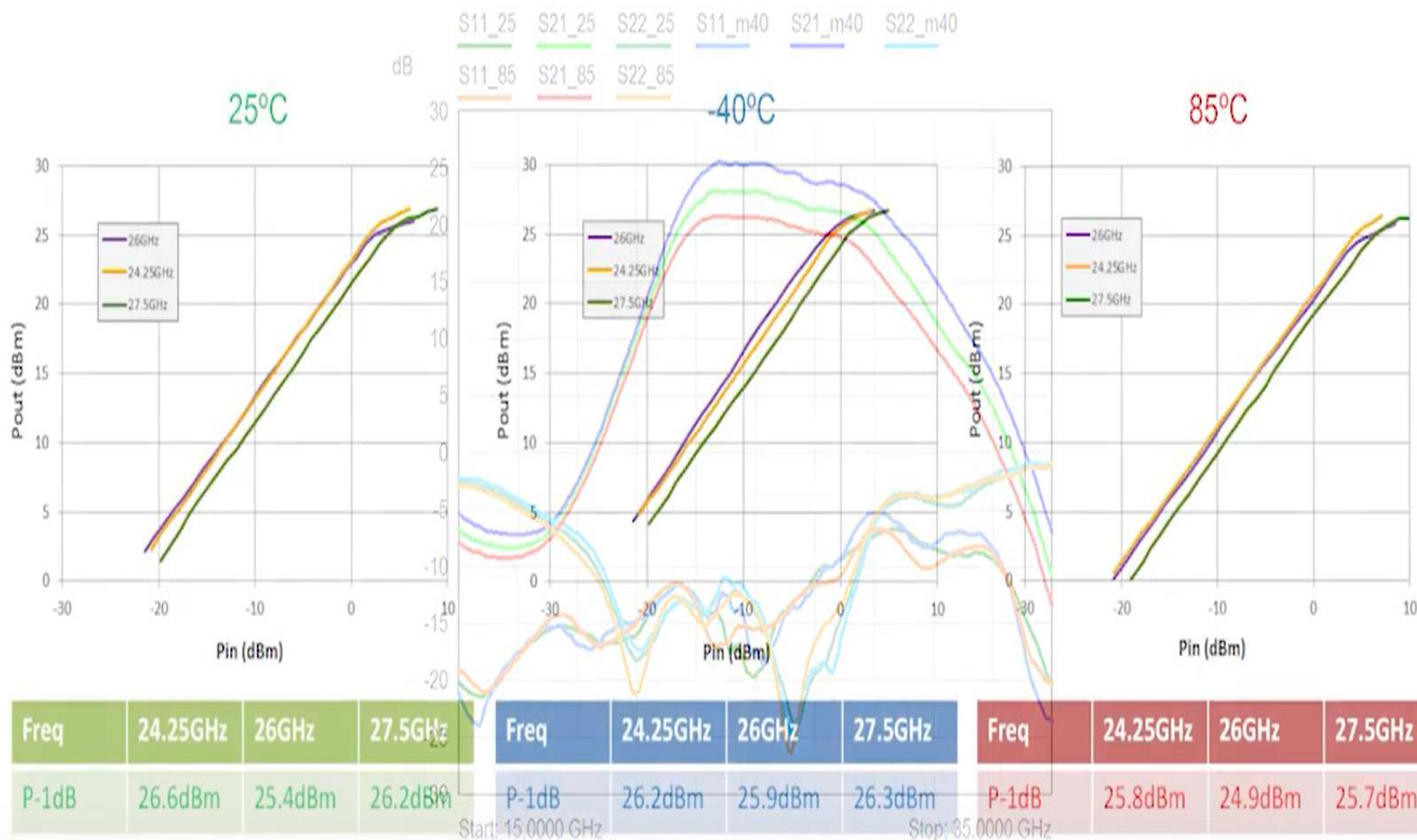
Evaluation Board for Dual Channel Component

Connection of DC Bias Cables



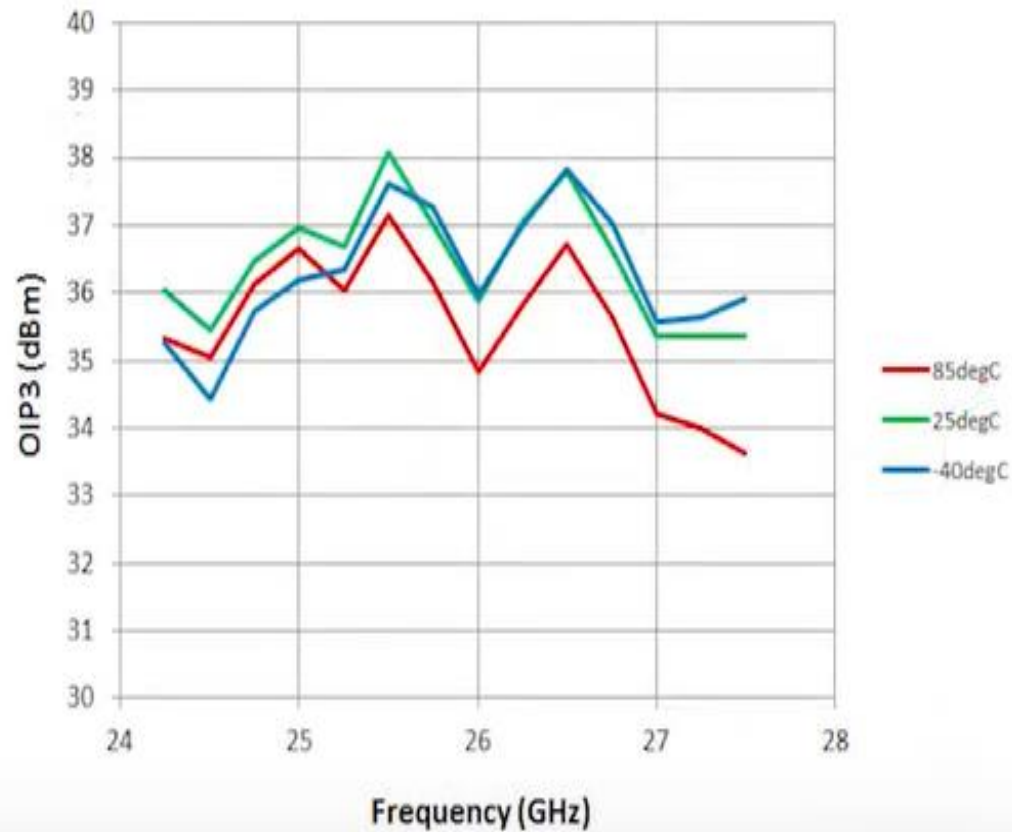
Measured Performance of Packaged Components

Power Compression of Typical PA Over Temperature



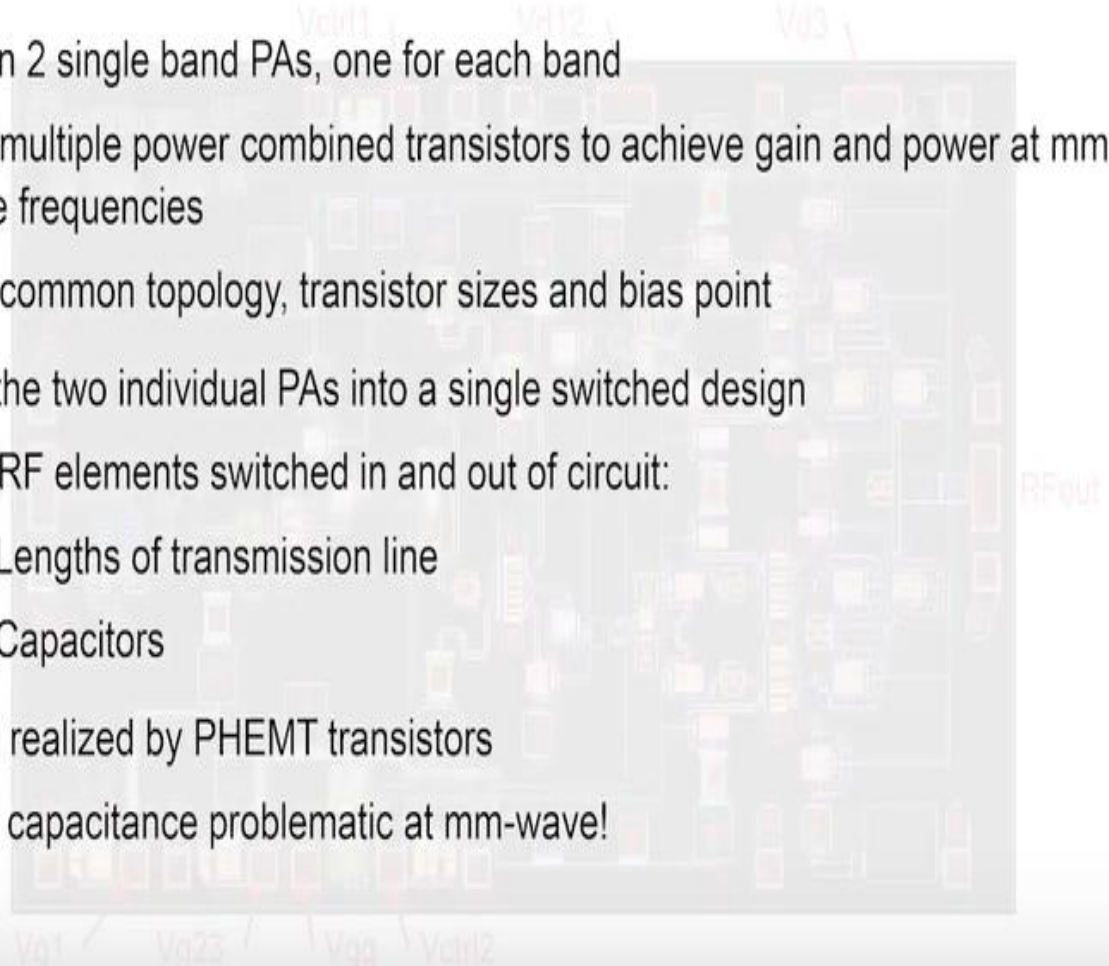
Measured Performance of Packaged Components

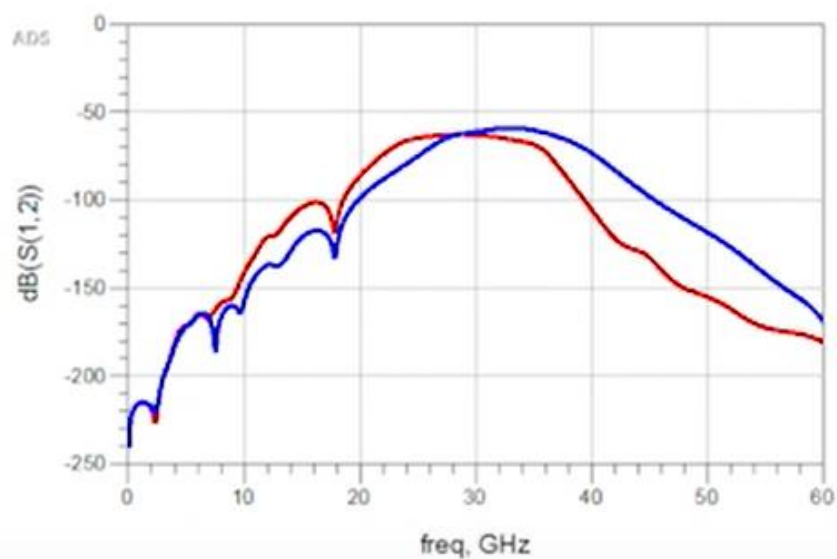
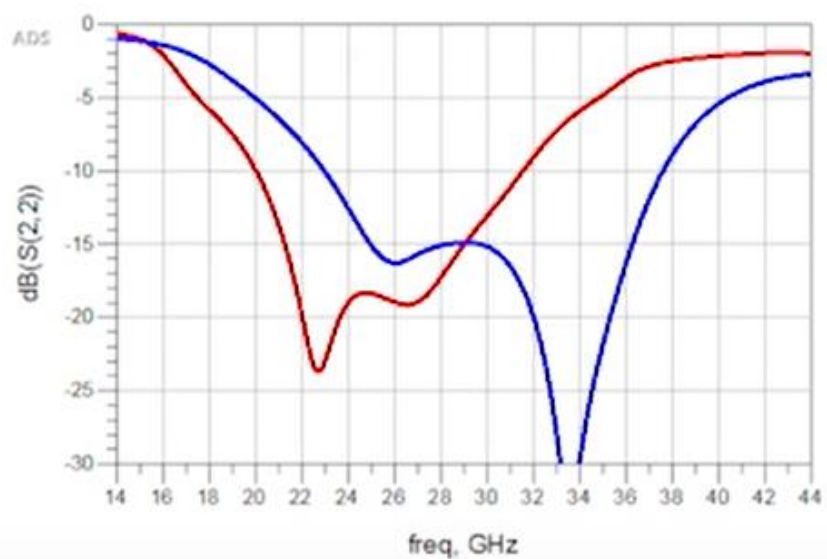
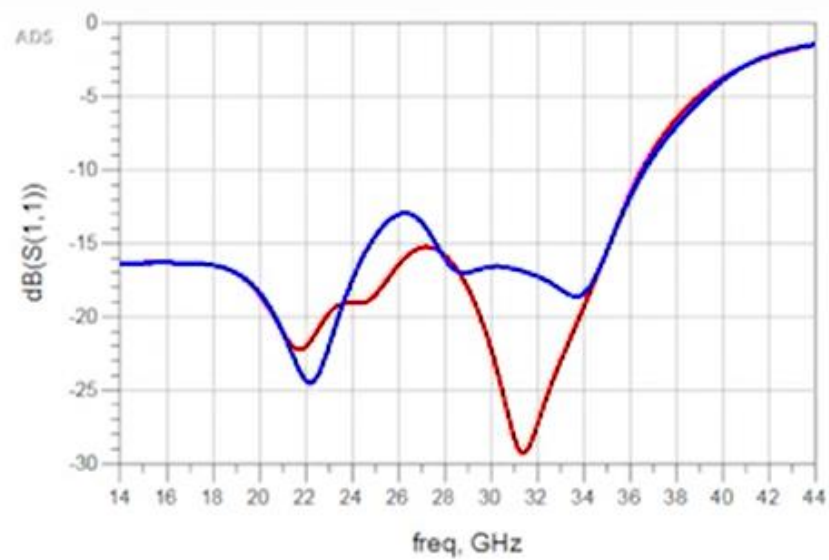
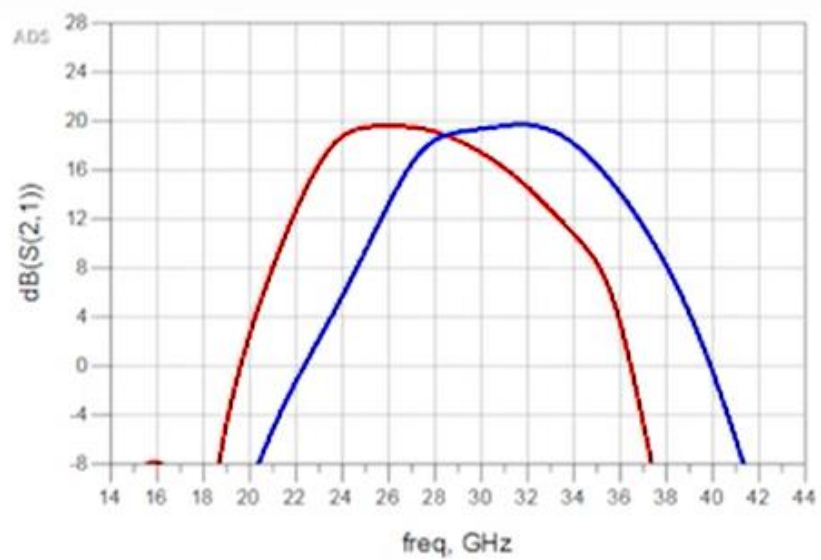
IP3 of Typical PA Over Temperature



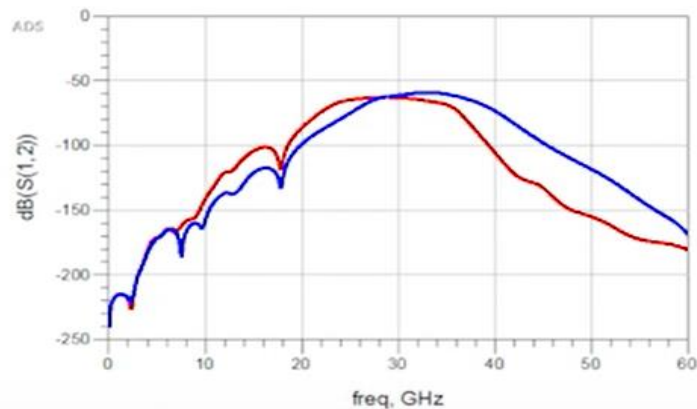
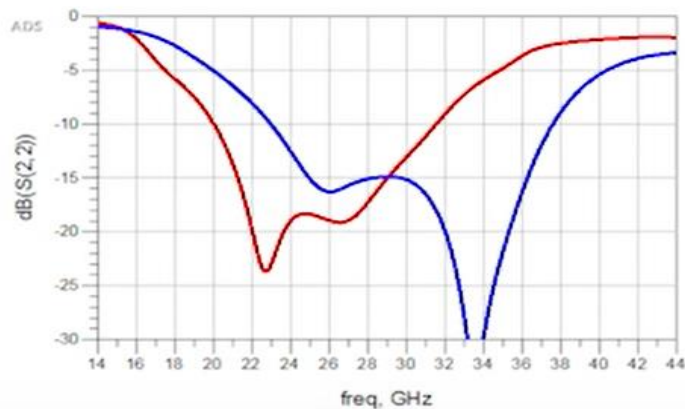
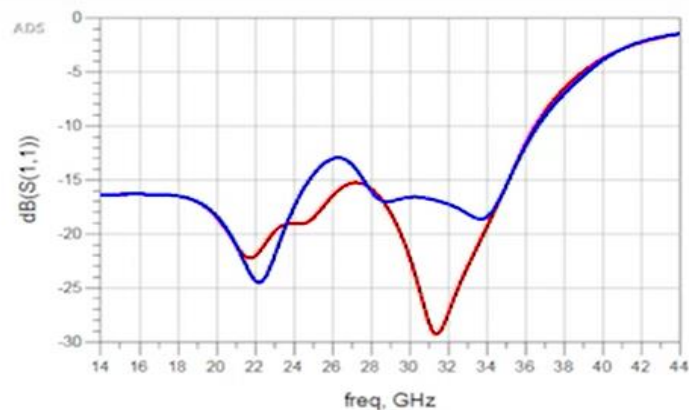
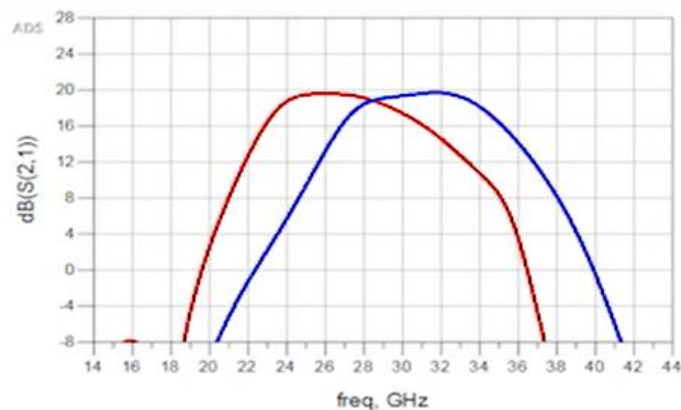
Dual Band PA – Design Strategy

- 1st Design 2 single band PAs, one for each band
 - Use multiple power combined transistors to achieve gain and power at mm-wave frequencies
 - Use common topology, transistor sizes and bias point
- Convert the two individual PAs into a single switched design
 - Key RF elements switched in and out of circuit:
 - Lengths of transmission line
 - Capacitors
- Switches realized by PHEMT transistors
 - OFF capacitance problematic at mm-wave!

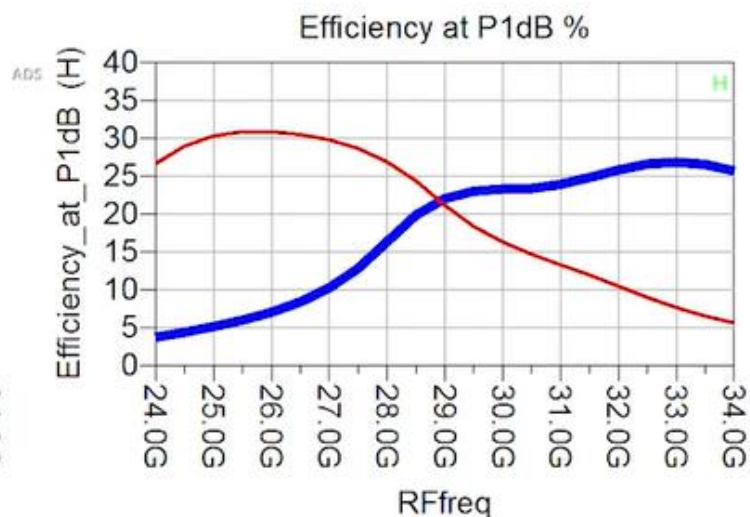
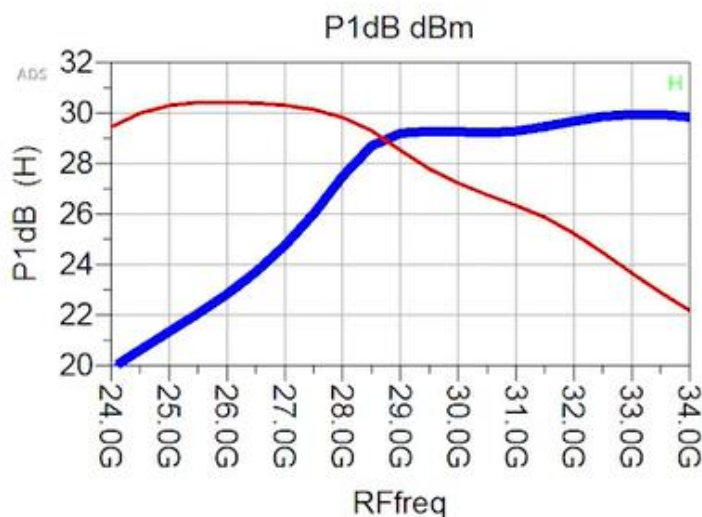




Dual Band PA – Simulated Small Signal



Dual Band PA – Simulated Large Signal



More details: <https://www.plextekrfi.com/mm-wave/mm-wave-5g/>

Conclusions

- Much work is currently underway in the development of mm-wave components targeting the expected 5G mm-wave bands
- Operating bands still to be confirmed, Ka-band looking likely but a single allocation worldwide is not realistic.
- Four mmWave 5G PA design examples presented:
 1. 28GHz PA in plastic overmoulded QFN package
 2. 39GHz PA in air-cavity plastic
 3. 26GHz PA in custom laminate dual-channel package
 4. Dual-band PA (26GHz and 32GHz bands)
- For more details, see: www.PlextekRFI.com