# Large Signal Modeling of GaN HEMT based Circuits

Ray Pengelly
May 2010
Revision 2

Some examples use latest rev.6 LS models

# Acknowledgement

- None of the material in this tutorial would have been possible without the tremendous work achieved by Bill Pribble who, over many years, has developed large-signal models for Cree's GaN HEMT transistors used within both hybrid and monolithic circuits.

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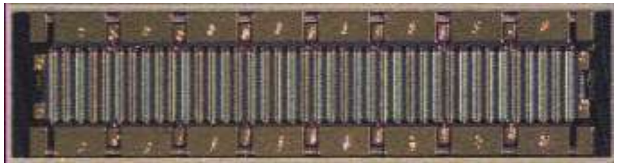
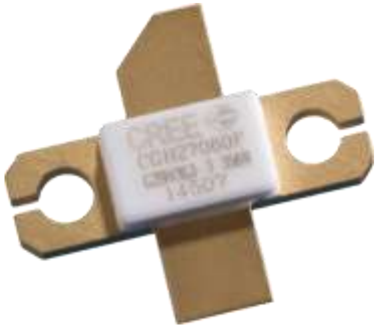
# Contents







# Introduction

- Large signal models are available for all Cree GaN HEMT transistors
  - Agilent's ADS and AWR's Microwave Office are fully supported
- Highly accurate with excellent history of design pass successes
- Enable complete DC and RF simulations
- Models include self-heating (presently single-pole thermal time constant)
- If customer does not have NDA in place with Cree then a simple DMEA (Device Modeling Evaluation Agreement) needs to be signed prior to model library delivery
- Model library is regularly updated
- Many "starter" designs can be provided

# Attributes of GaN HEMTs

- High Voltage Operation
- High power densities – 4 watts/mm at 28 volt operation
- High Frequency Performance – present Cree process has $f_T$ of 25 GHz
- High Efficiency
- Low Quiescent Current
- High Native Linearity
- Low capacitance per peak watt (12% of LDMOS and 21% of GaAs MESFET) – supports broad bandwidths
- Enable new amplifier architectures
- Highly correctable under DPD
- Almost constant $C_{DS}$ as a function of $V_{DS}$ – great for Drain Modulation

Wide Bandgap

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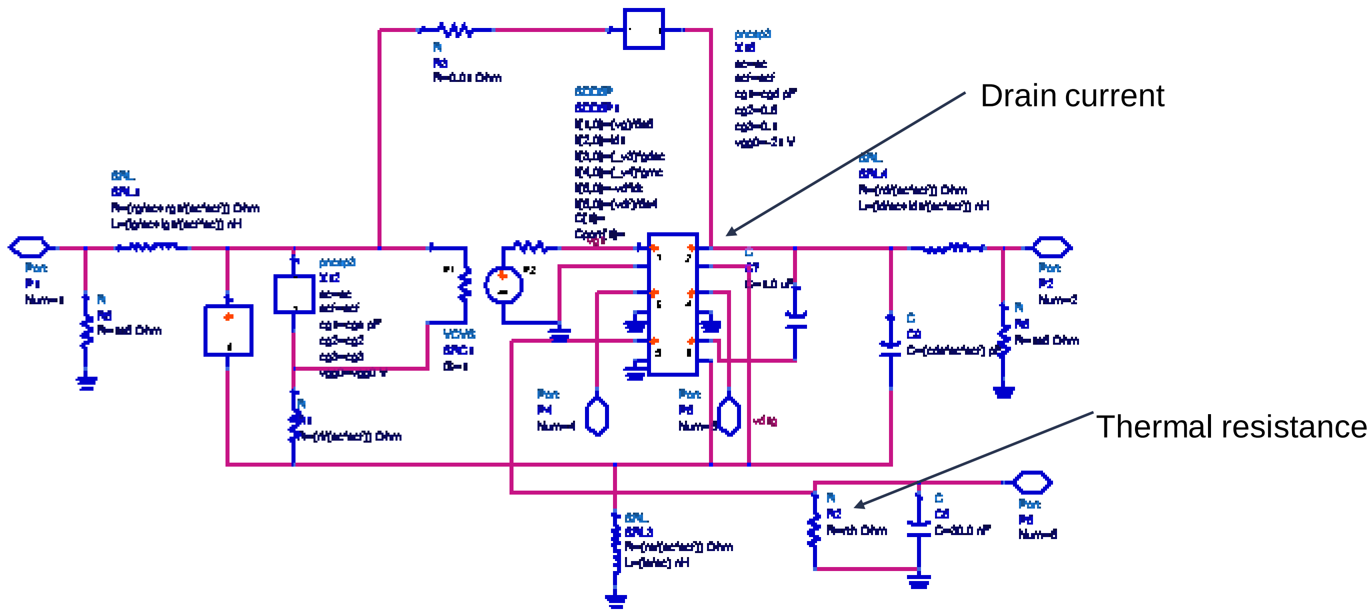
# Models for GaN HEMTs

- Equivalent-circuit based approach
  - Relatively simple extraction
  - Process sensitive based on individual elements
  - Simple implementation using commercial harmonic balance simulators
- Significant historical information for model basis and validation
- Non-linearity introduced as required by element
  - Drain current source is dominant non-linearity
  - Gate current formulation includes breakdown and forward conduction
  - Voltage variations of parasitic capacitances derived from charge formulations
- Model data fit extends over drive, frequency, bias, and temperature
- Many hundreds of successful hybrid and MMIC designs

# Model Schematic



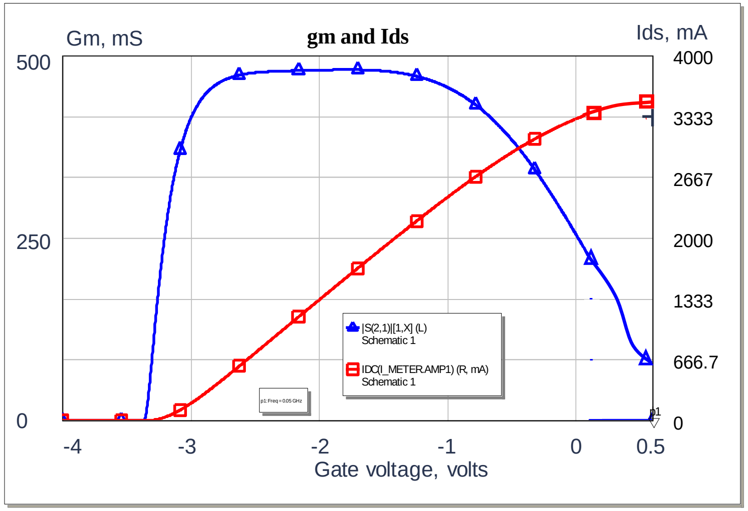

- Based on 13-element MESFET model (Fager-Statz)
- ADS version shown using non-linear equation-based elements
  - Easily changed during design process
  - Speed comparable to C-coded version
- AWR version uses C code with “model wizard”

# More details on Cree GaN HEMT Model

- Most FET models implement a gate current-control characteristic that transitions from the sub-threshold region to the linear gate control region directly, without treating the intermediate region, called the quadratic region. Fager et al. implemented an equation and new parameters to fit the quadratic region. This leads to better agreement with measured IMD and other nonlinear characteristics.
- Gate charge is partitioned into gate-source and gate-drain charge. Each charge expression is a function of both $V_{DS}$ and $V_{GS}$. Using charge partitioning, it is possible to fit most GaN HEMT capacitance functions and observed charge conservation.

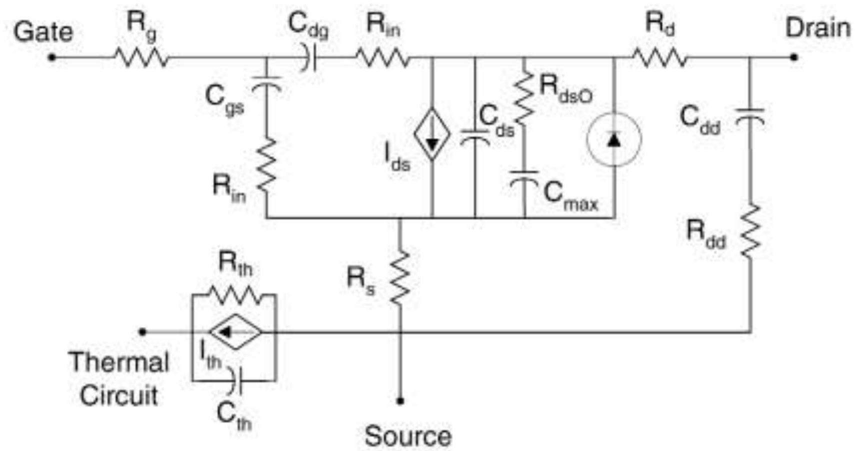
Quad Linear Compression

Sub Threshold



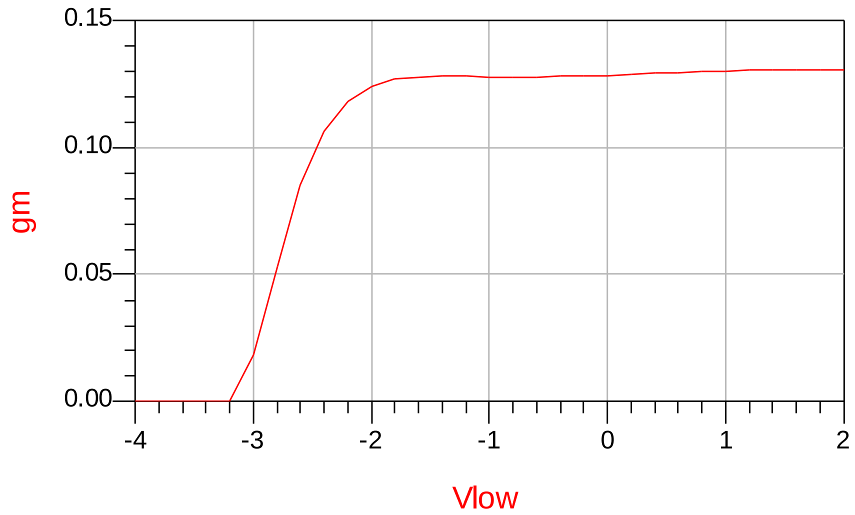

Blue is DC transconductance
Red is drain current

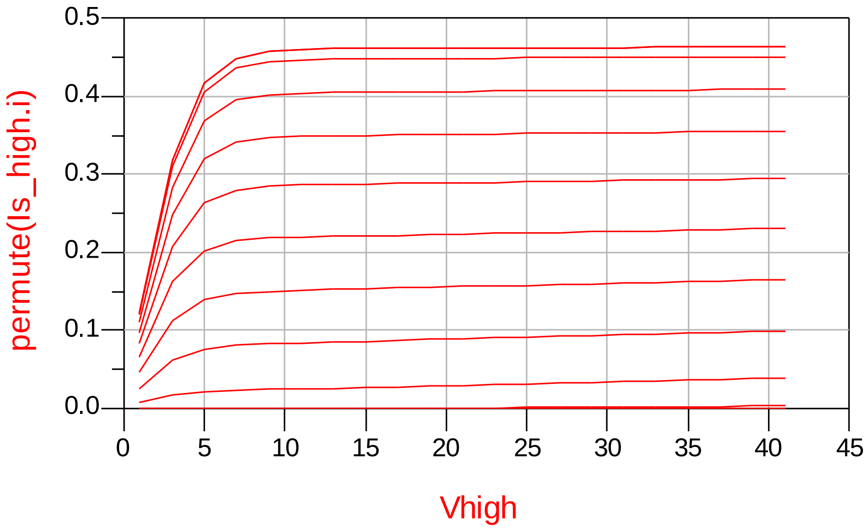
# More details on Cree GaN HEMT Model




- The model includes new capacitance functions as well as modeling of the drain-source breakdown and self heating.
- The model has four ports, with the extra port providing a measure of the temperature rise. The voltage between the external thermal circuit port and the source node is numerically equal to the junction temperature rise in degrees C. This occurs because the current source in the thermal circuit is numerically equal to the instantaneous power dissipated in the FET and the resistance, R_TH is numerically equal to the thermal resistance. The RC product of the thermal circuit is the thermal time constant.
- The model addresses the sharp turn-on knee in GaN HEMTs leading to the accurate prediction of IMD sweet spots in Class A/B operation.

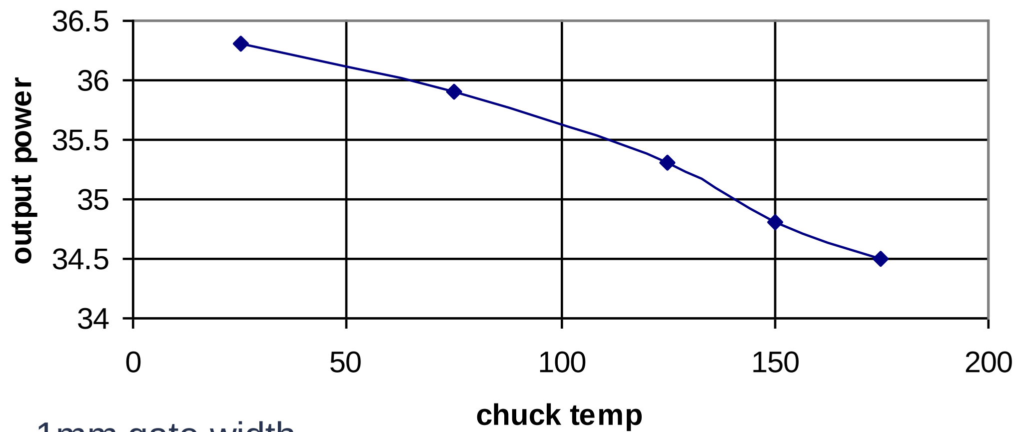
# Drain Current Model




- Transconductance curve fit to Gm from small-signal model fits over bias range
- Output conductance dispersion model
- Peak current and knee voltage fit from load-pull - includes trap effects
- Pinch-off fit from DC IV-characteristics – gives model of drain current
- IV function similar to Statz formulation – good model of pinch-off needed to accurately predict intermodulation distortion

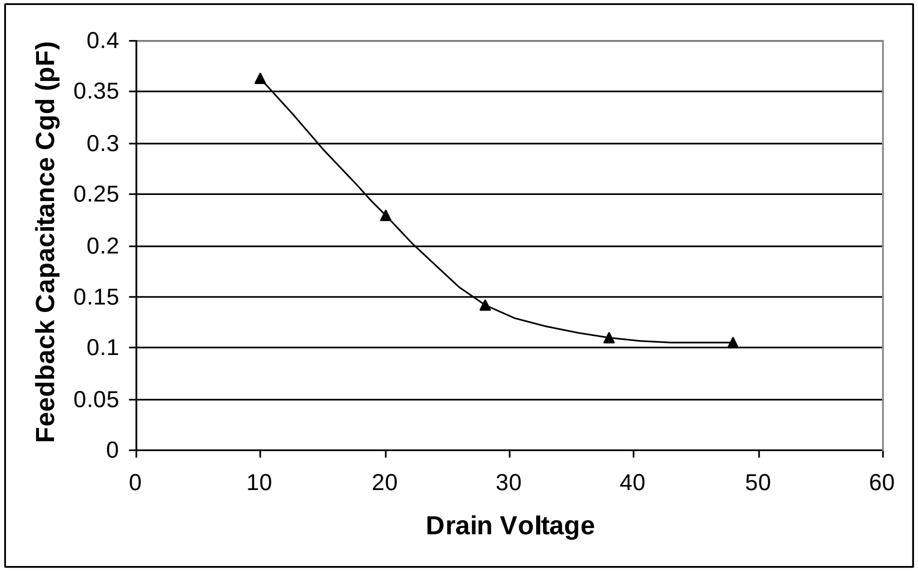
# Temperature Dependence – Self-heating



1mm gate width

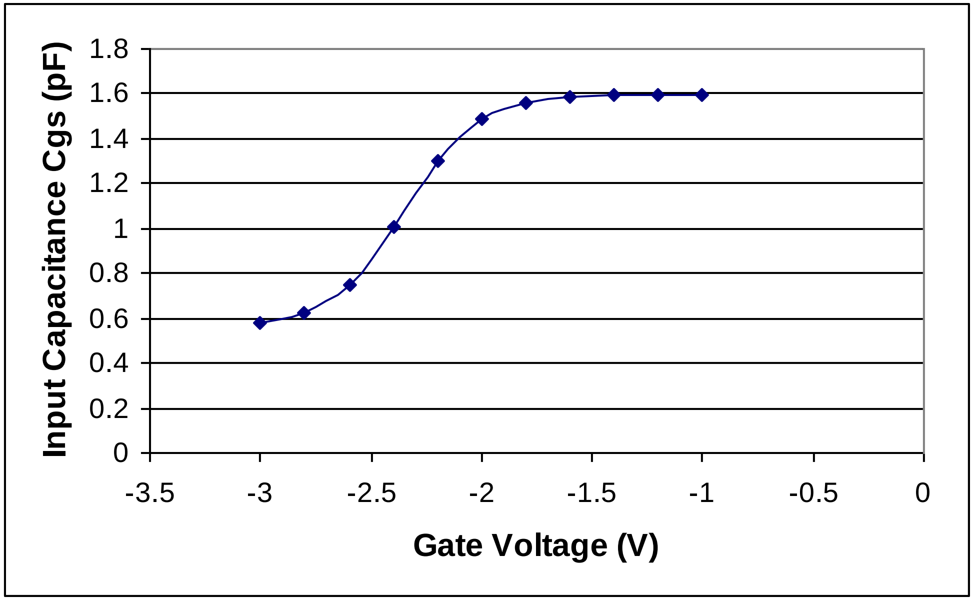
- Drain current is only temperature dependent model element
- Drain current scales to provide -0.1 dB/10$^o$C reduction in power for current-limited load-line
- Self-heating included using a thermal resistance – calculated from finite element analysis of die and package.
- Thermal performance due to package needs to be included where appropriate

# Feedback Capacitance - $C_{GD}$



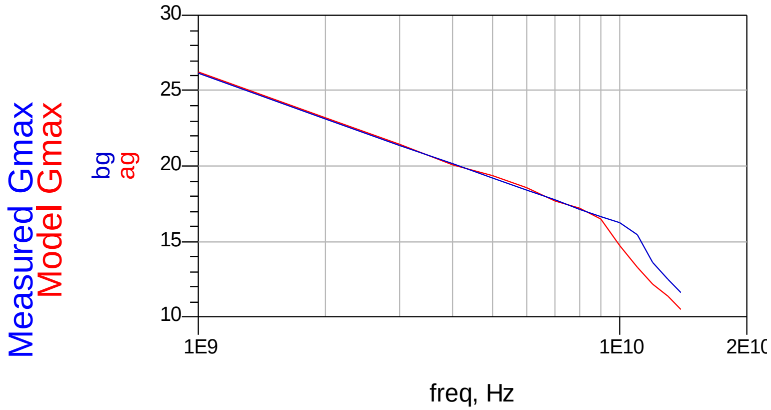

- Feedback capacitance is a strong function of drain voltage
- Inclusion of this effect necessary to fit small-signal data
- Non-linearity changes harmonic generation from the model – effects efficiency and linearity predictions
- Output Capacitance $C_{DS}$ is linear – no voltage dependence (weak anyway)

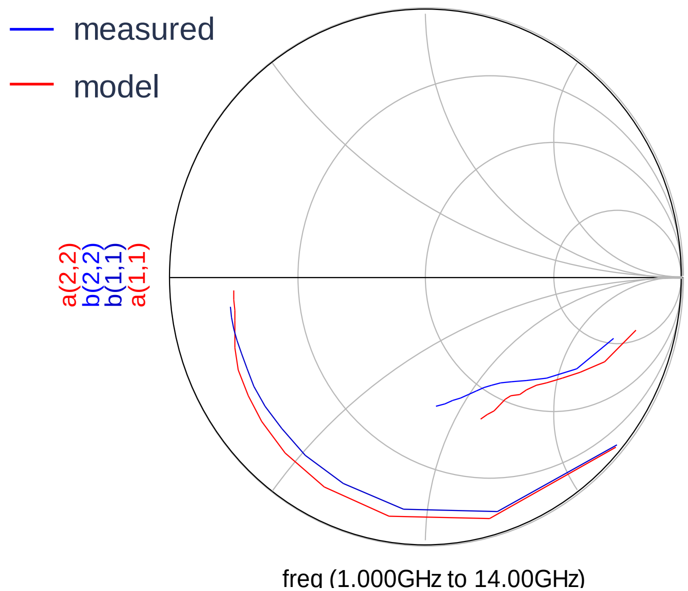
# Input Capacitance - $C_{GS}$




- Input capacitance is a strong function of gate voltage
- $C_{GS}$ is also a function of drain voltage, but this non-linearity is not included at present
- The gate-voltage non-linearity also effects model's harmonic generation

# GaN HEMT Model - Small-Signal

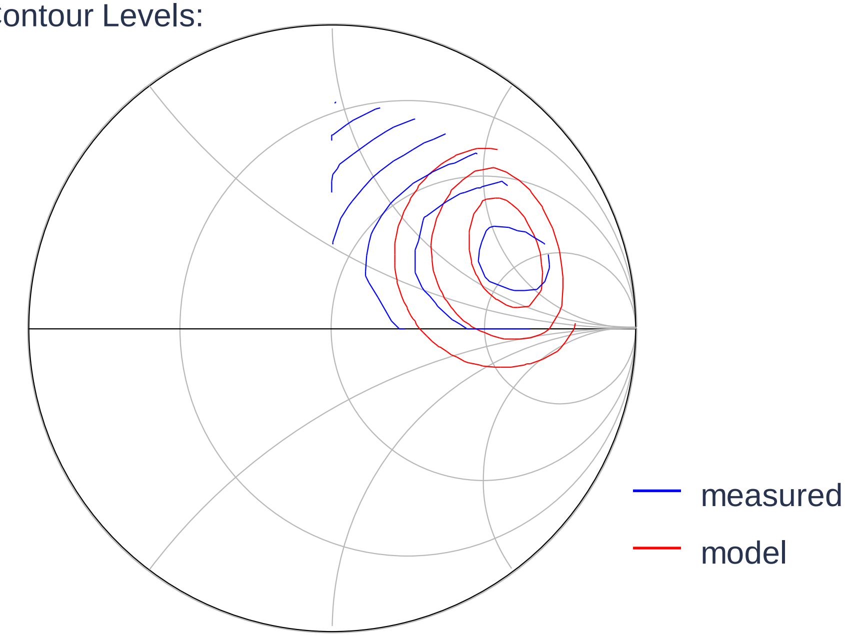



- On-wafer S-parameters of 0.5 mm HEMT – 25$^{O}$C baseplate
- Major challenge of modeling for high power circuits – scaling from reasonable test cell to large periphery output stages – successfully implemented for scaling factors >100:1
- Non-linear model fits small-signal parameters over a range of bias voltages
- All measurements performed using 1% duty cycle, 20μs pulsed bias to control thermal effects

# GaN HEMT Model - Large-Signal

Power Contour Levels:
36 dBm
35 dBm
34 dBm

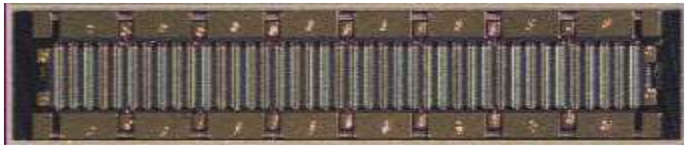


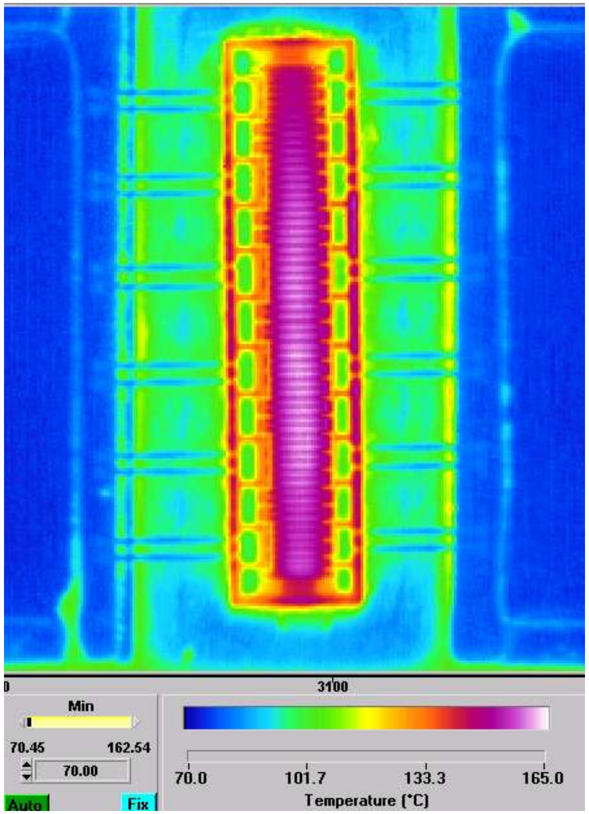

- On-wafer load-pull of 0.5 mm HEMT
- Measured at 3.5 GHz, $V_{DS}$=28V, Id~25%$I_{DSS}$, 25$^{O}$C chuck temperature
- PAE contours not used for modeling due to sensitivity to harmonic loading – PAE verified using hybrid amplifier measurements

# Basic Thermal Features of High Voltage GaN

- 120 Watts CW RF from a 28.8mm HEMT operating at 28 volts drain voltage
- Assume 60% DC to RF conversion efficiency
- 80 watts dissipated heat
- Active chip area is 2.5 sq. mm so heat density is

  > 20 kilowatts per square inch !
- Much emphasis on new amplifier architectures to improve drain efficiencies





# Thermal Modeling

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# Introduction

- Use of Infrared microscopy and finite element analysis are used to produce accurate channel to case temperature differentials
  - Junction to case thermal resistance can then be calculated
- Steady state thermal FEA, using Ansys software, is done where temperature dependence is accounted for in the GaN, SiC and Au materials
- Method has been extended to transient analyses (for pulsed and modulated (DC and/or RF carrier) where the density and specific heat of the materials are also required to calculate time constants
  - Dramatic (and useful!) differences in effective thermal resistances between short pulses and CW – by factors of 4 or more

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# Thermal Conductivities of Relevant Materials

| Material | Thermal Conductivity (W/mK) |
|---|---|
| GaN | 130 |
| AlGaN | 19 |
| SiN (passivation) | 33 |
| SiC | 430 |
| Au | 317 |
| AuSn (die attach) | 57 |
| CuMoCu (package) | 300 |
| Cu (fixture) | 370 |

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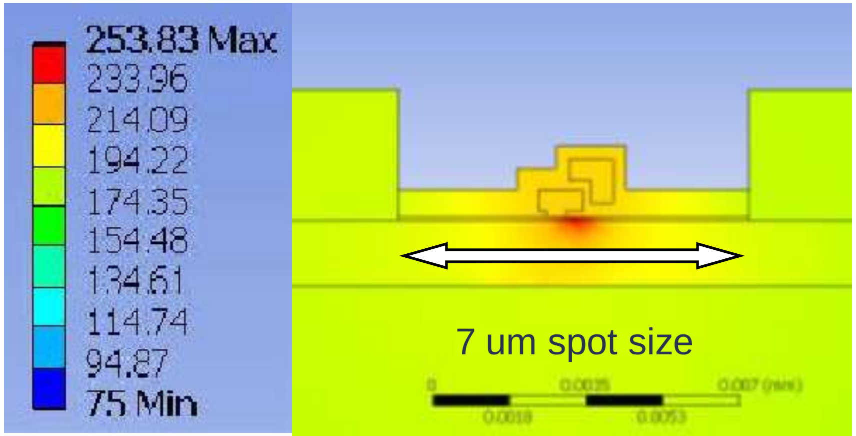
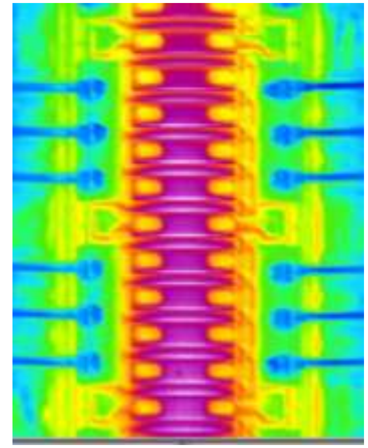
# Thermal Analyses and Measurements



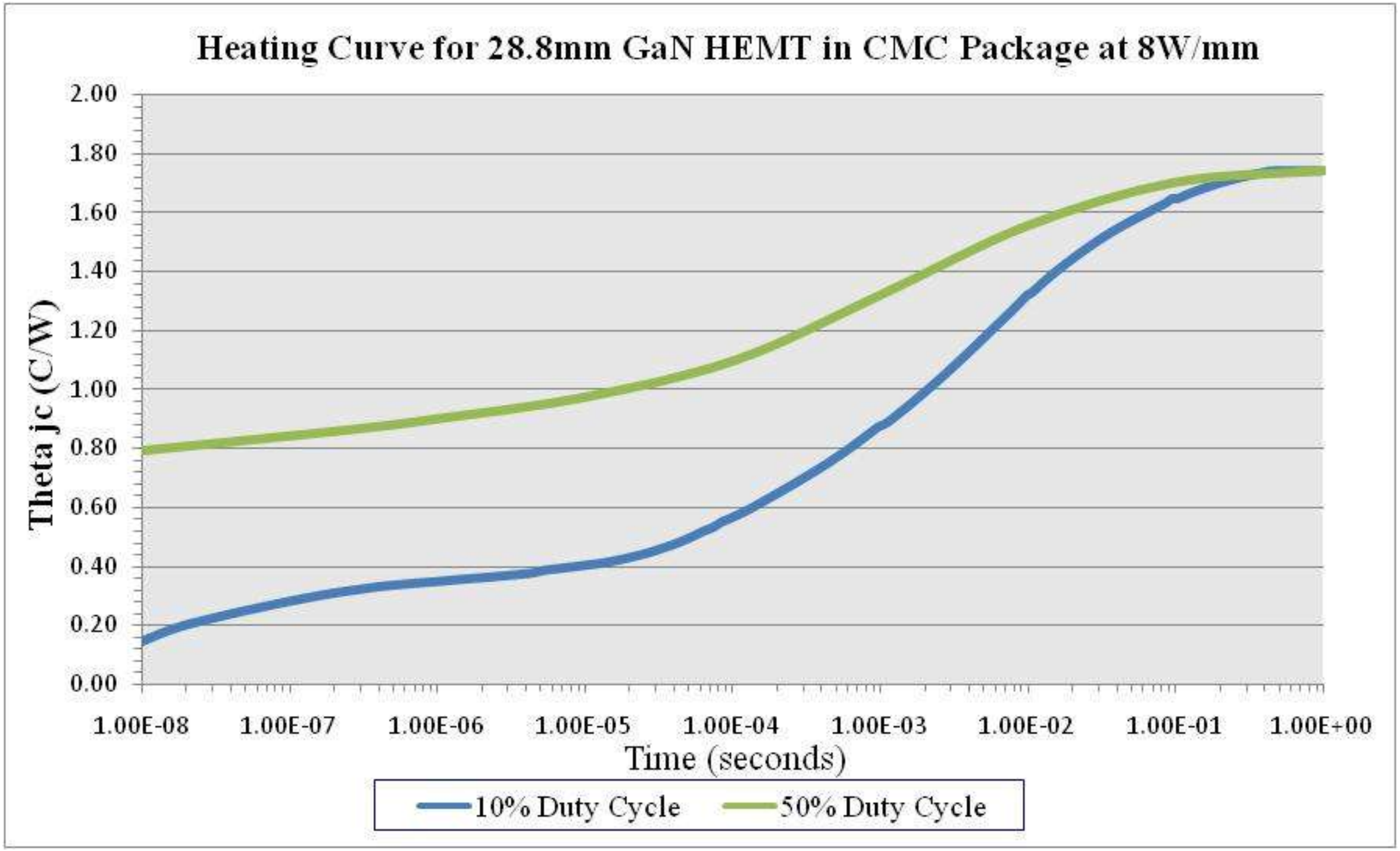
IR Scan

**Confidence Intervals**

| Parameter | Estimate | Lower CI | Upper CI | 1-Alpha |
|---|---|---|---|---|
| Mean | 1.925 | 1.858268 | 1.991732 | 0.950 |
| Std Dev | 0.079821 | 0.052776 | 0.162458 | |

- 4 mil thick 14.4mm GaN HEMT
- 60 mil thick CuMoCu package dissipating 4 watts/mm (58 W)
- Thermal gradient is very high surrounding the heat source 58C drop at a distance of 3.5um from the heat source!
- 38C drop through the AlGaN layer
- 46C drop through the GaN layer
- Accounts for temperature difference between the actual channel and the "average" temperature measured by the IR system (across the spot size)

# Effective Thermal Resistance versus Pulse Width




- Transient Thermal Responses of a 28.8mm GaN HEMT in a 60 mil thick CuMoCu package dissipating 8W/mm at 10% and 50% duty cycles
- Two distinct slopes show the different transient thermal properties of the die and the package

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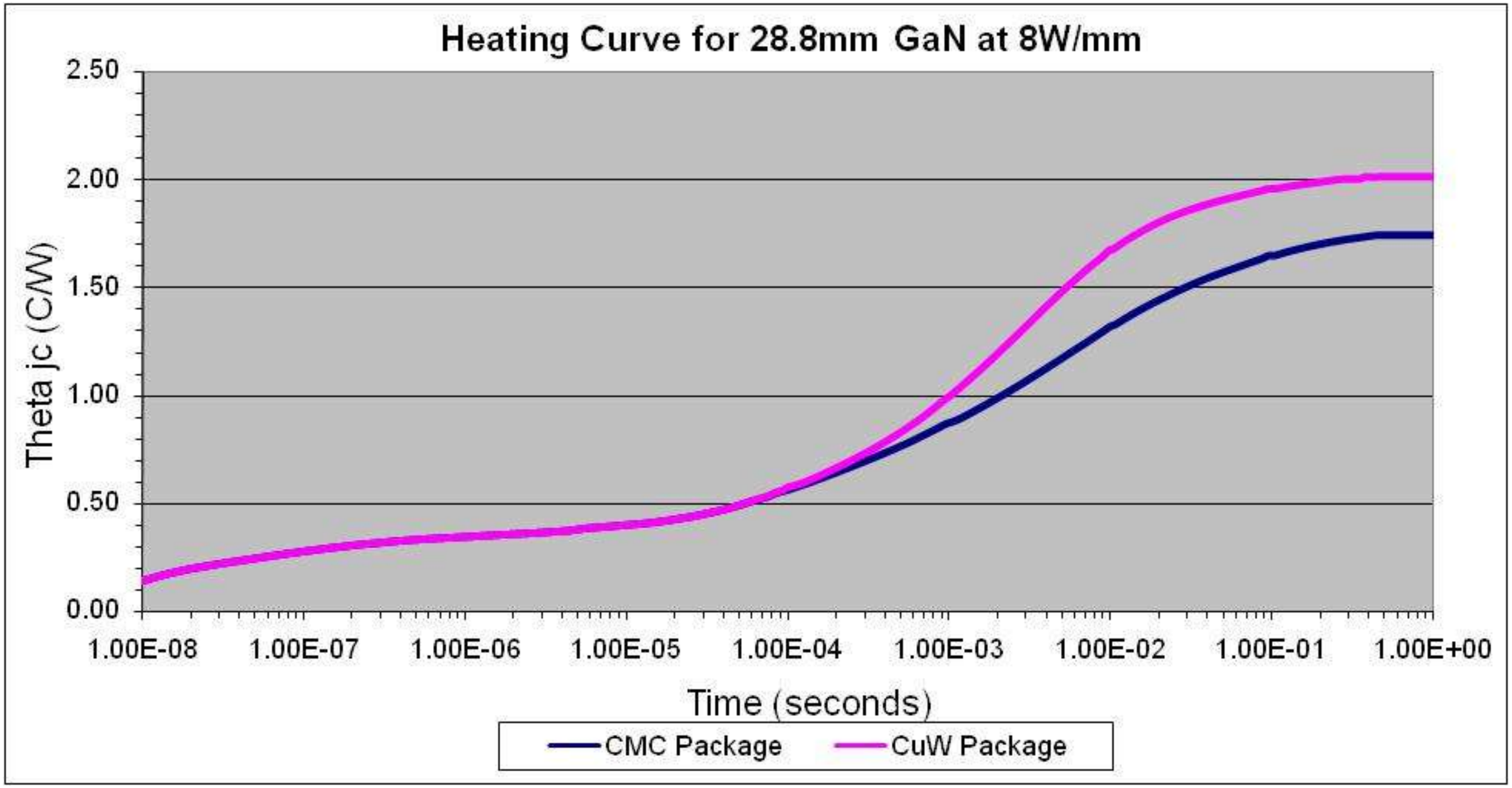
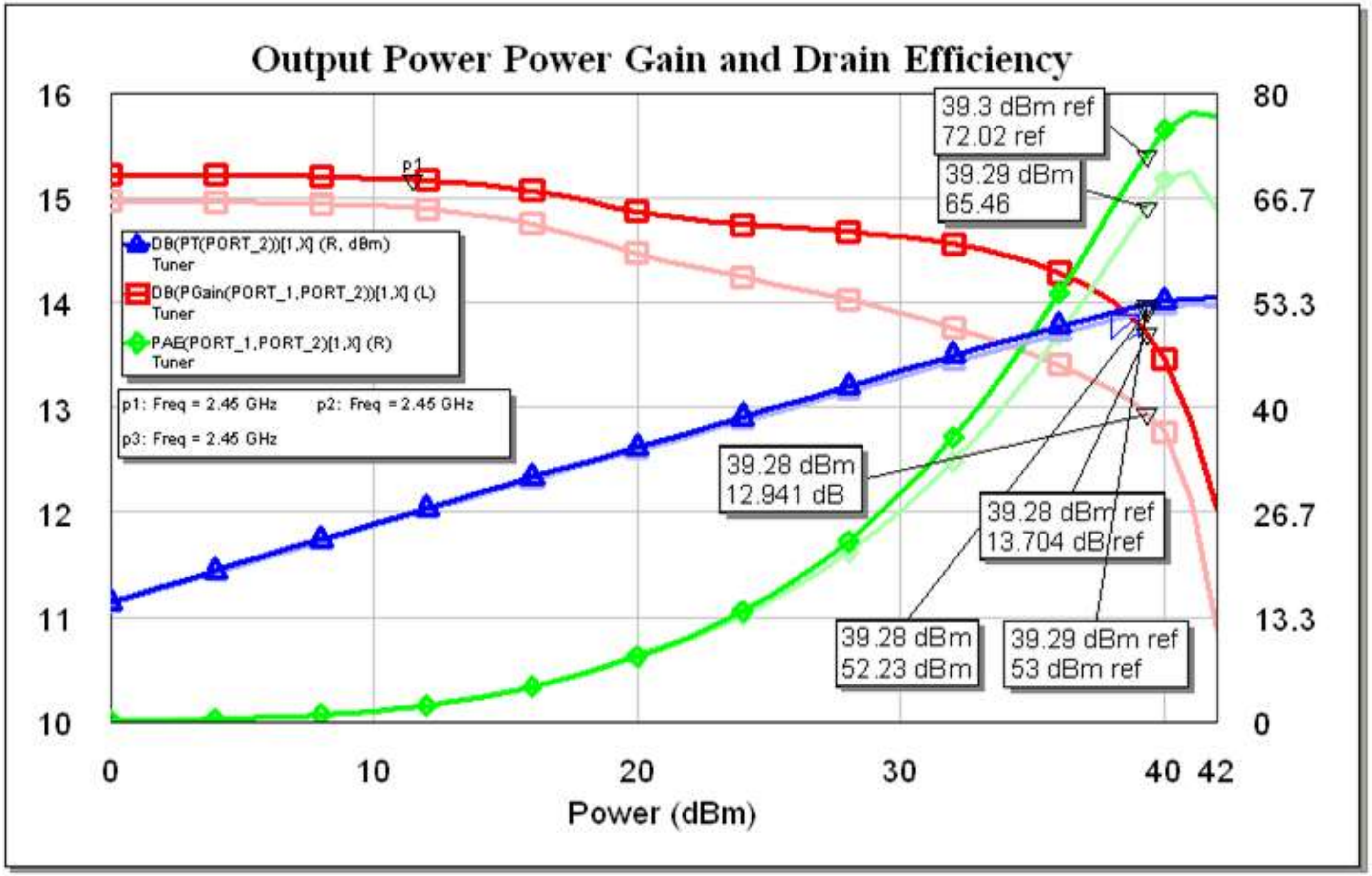
# Effective Thermal Resistance versus pulse width for two different package flange materials



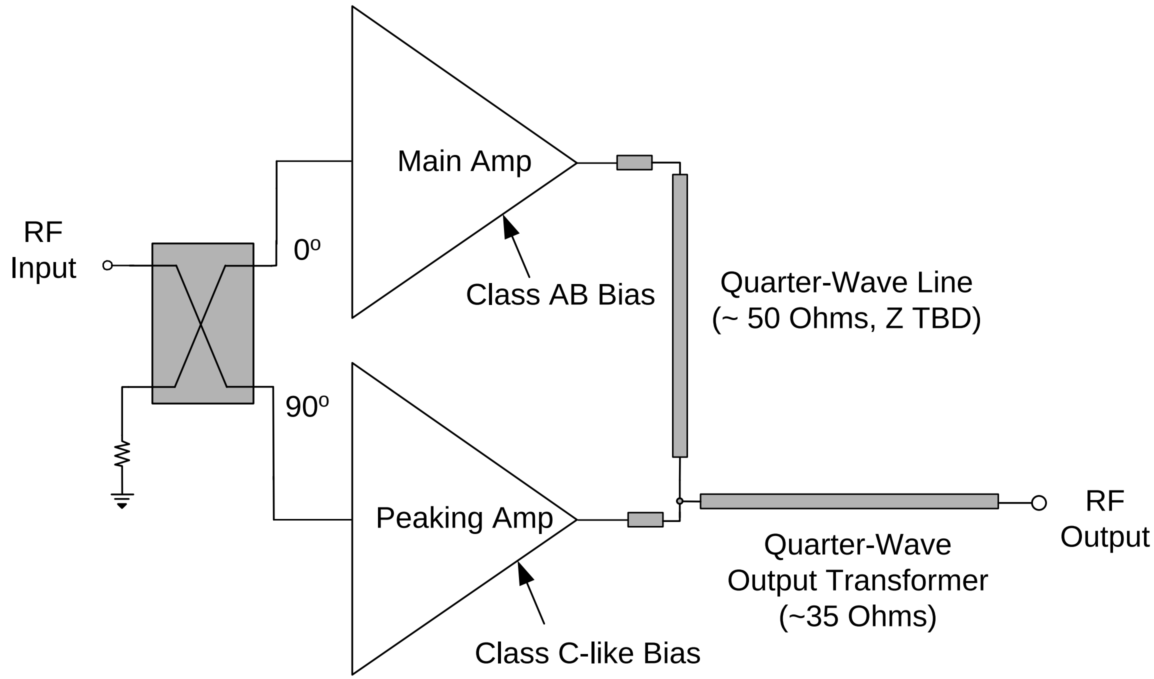

- Difference in thermal resistance of same 28.8mm GaN HEMT mounted in 60 mil thick CuMoCu versus 40 mil thick CuW package
- Note that the thermal resistance up to 100 usec pulse width is same and then effect of package time constant can be seen

# Example of including self-heating model for efficient Class A/B power amplifier




- Operation of 28.8mm GaN HEMT with and without self-heating
  - Bolder colors are without self-heating included in simulations

# Basic Doherty Amplifier Configuration




- The Doherty amplifier configuration is becoming more and more popular as a means of improving overall DC to RF conversion efficiency
- Up to certain input power levels the carrier amplifier saturates earlier than a conventional Class A/B Amplifier because of the load impedance it sees – the peaking amplifier is still OFF
- Above a certain input power level the peaking amplifier turns ON and contributes power as well as altering the load line to the carrier amplifier

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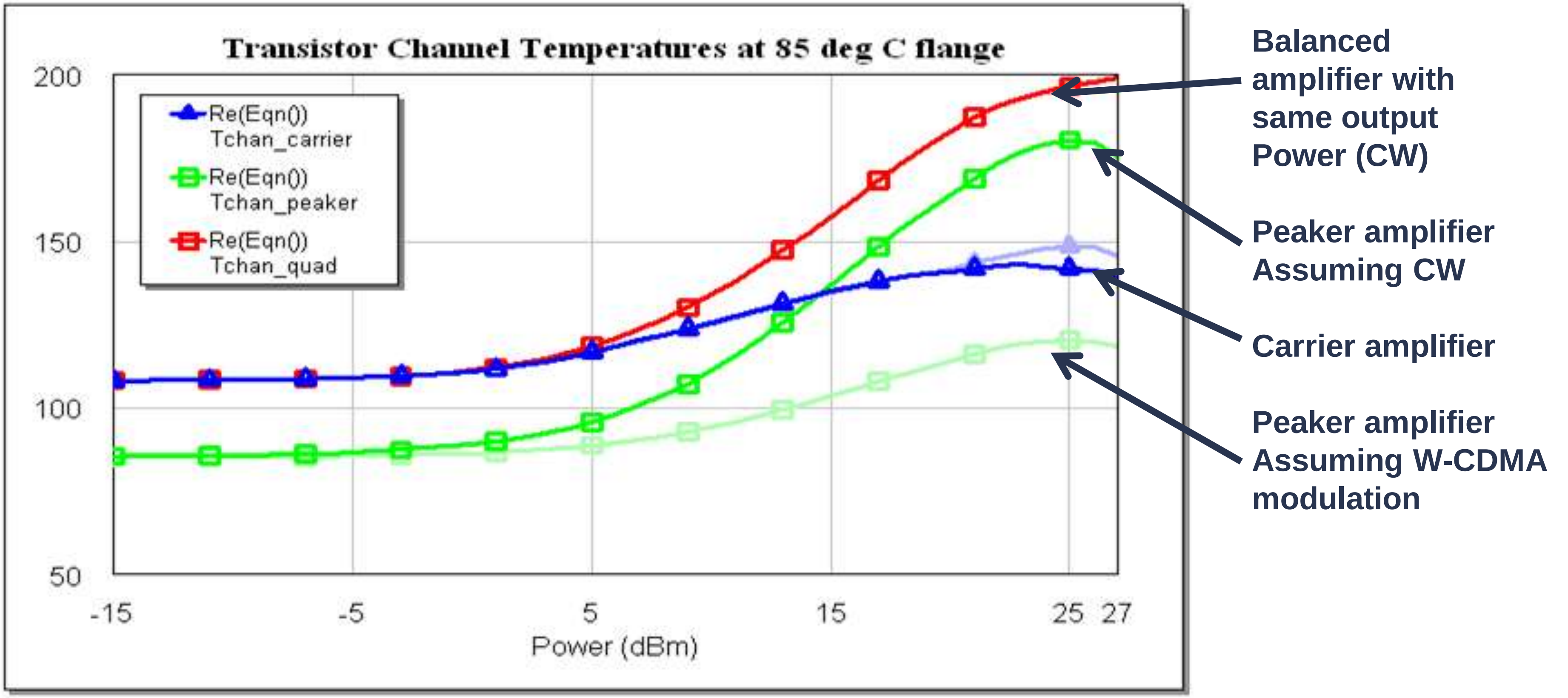
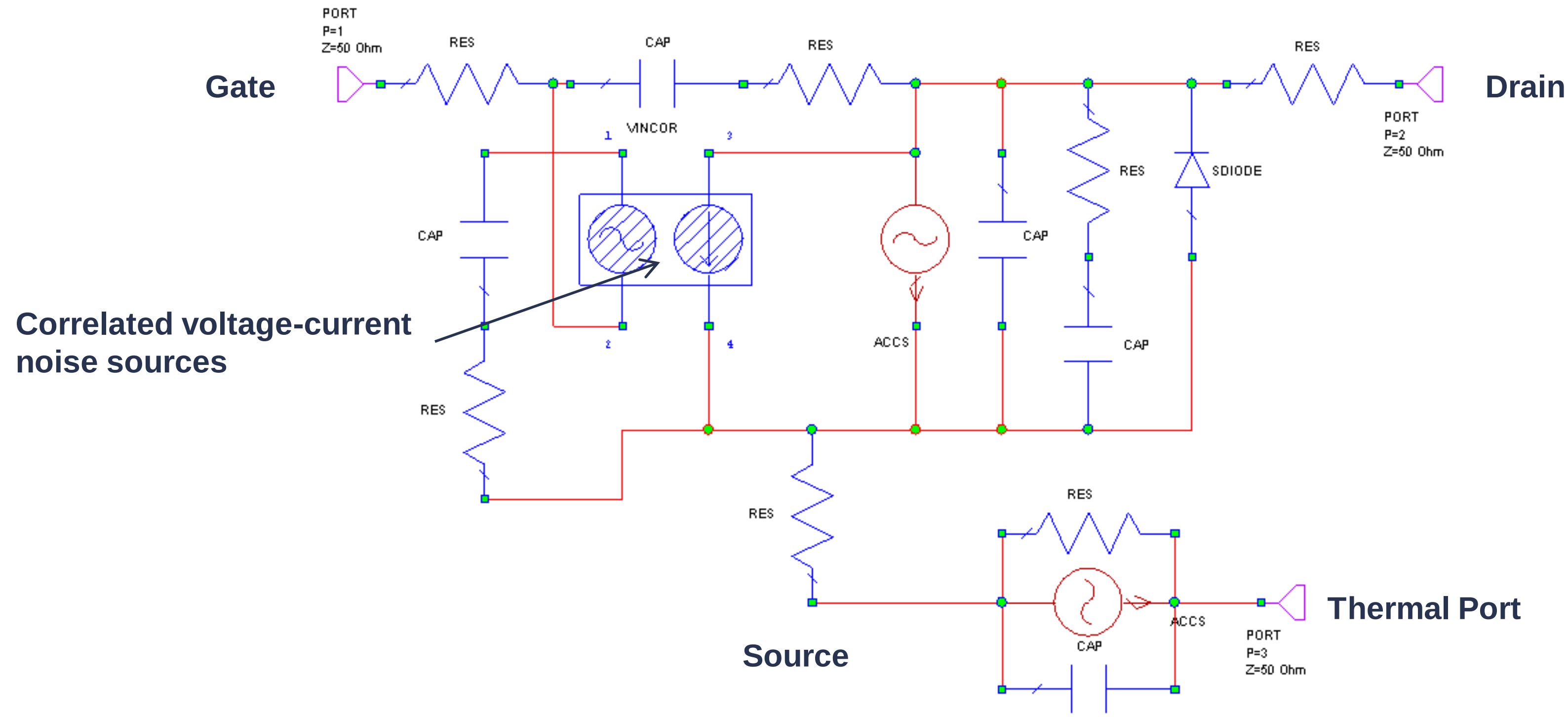
# Example of using self-heating model in a Doherty Amplifier




- Transistors operating at 7 W/mm at peak power
- Bolder colors show channel temperatures if CW is assumed
- lighter traces show channel temperatures when the Doherty
- amplifier is handling W-CDMA

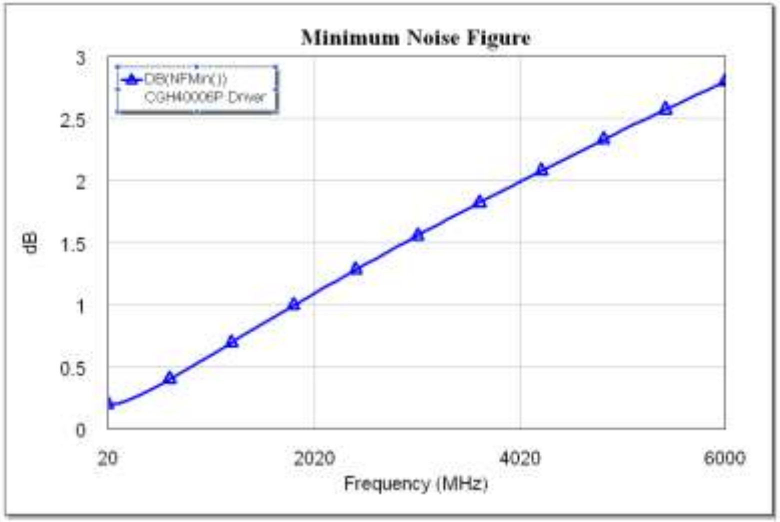
# Noise Modeling

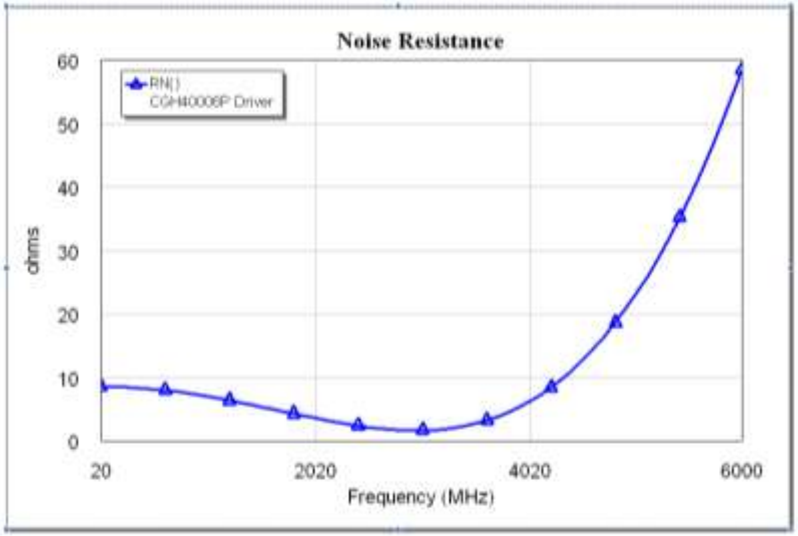
# Simplified Nonlinear HEMT Model including noise

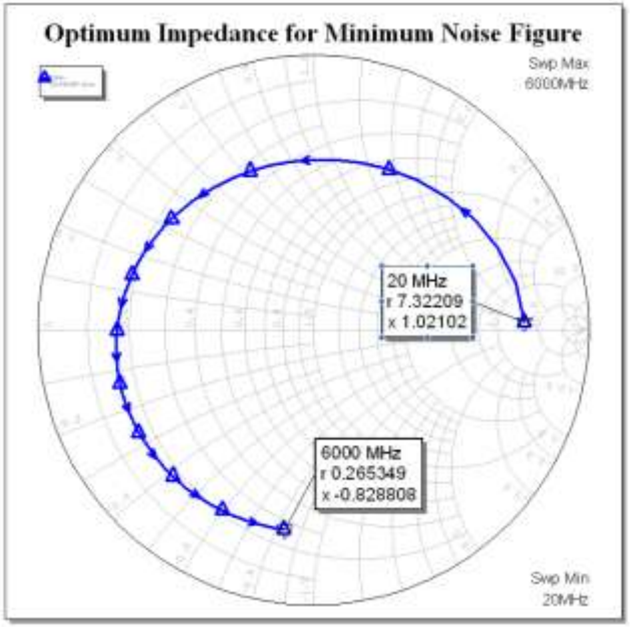



Noise is generated from parasitic resistive elements as well as intrinsic noise sources as shown here. Noise sources are defined by voltage and current noise sources which are correlated.

# Noise Parameters

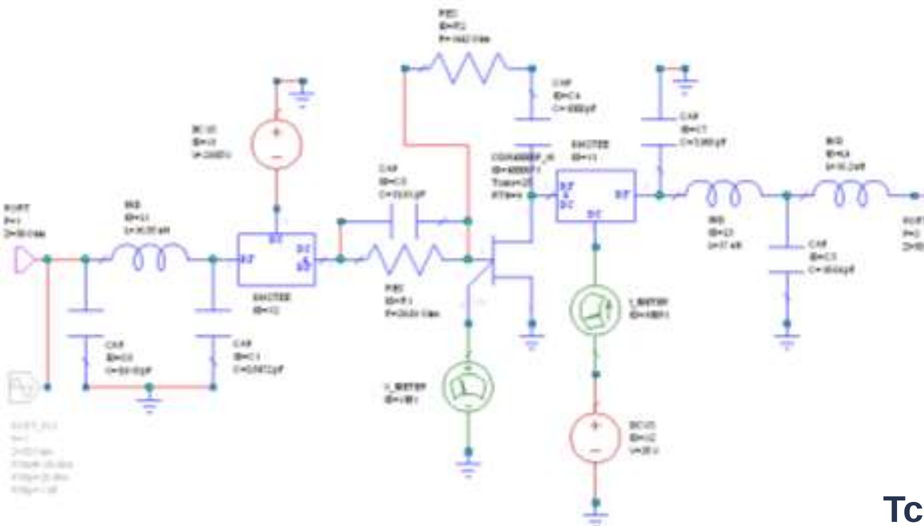


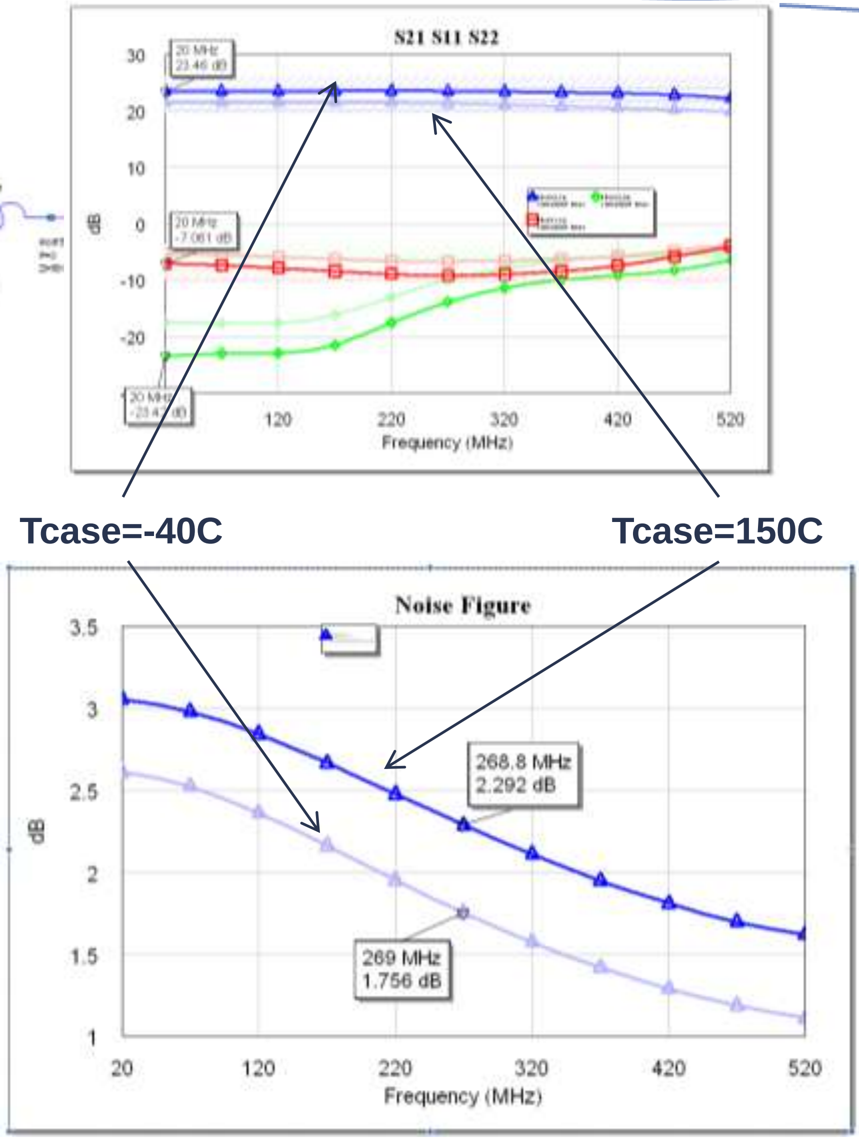




Noise parameters simulated from extracted model are shown for CGH40006P
Conditions are Vdd=28 volts, Idq=65 mA
Frequency Range is 20 to 6000 MHz
Original noise parameters measured “on-wafer” using small gate width transistors. Noise parameters are scaled from these devices to required sizes

# Noise Figure and Temperature






Noise parameters (as well as other Parameters) are temperature dependent as shown aside for a CGH40006P based amplifier operating from 20 MHz to 520 MHz

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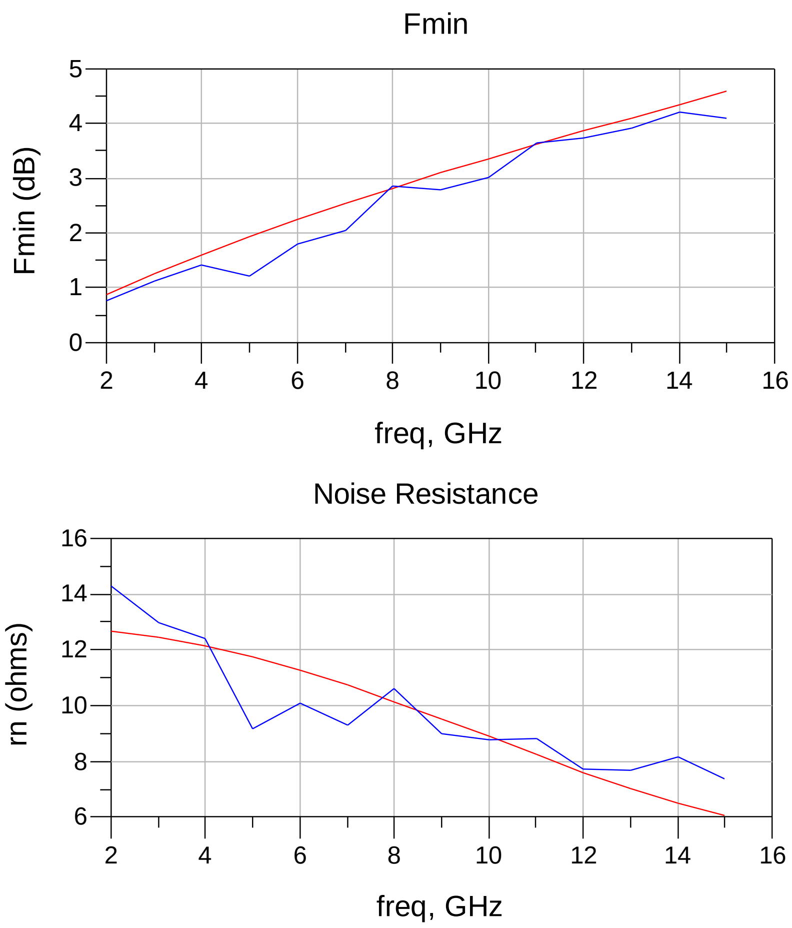
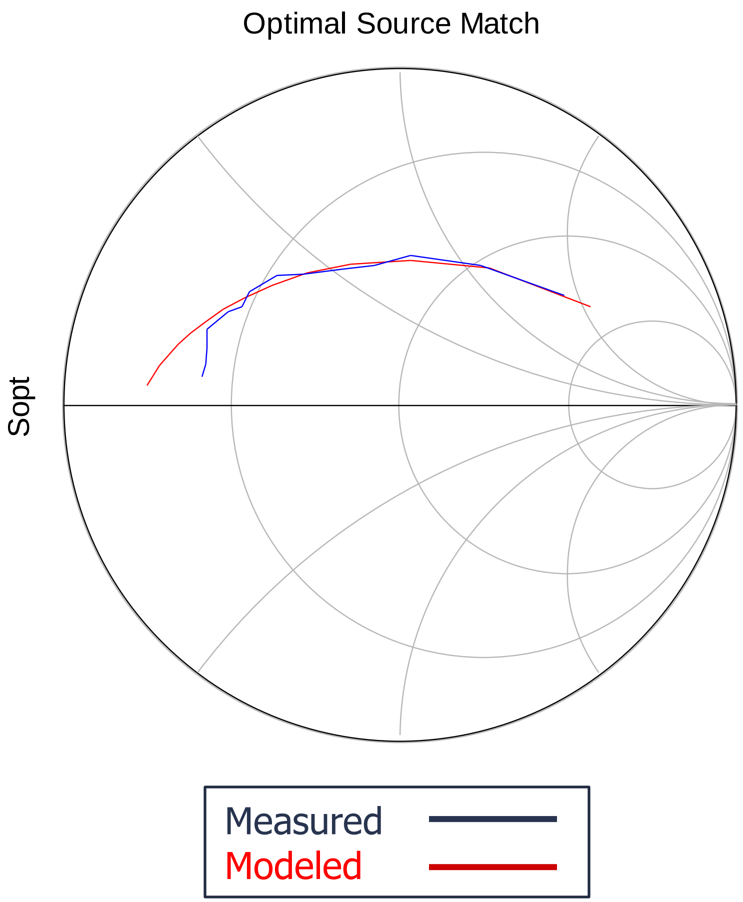
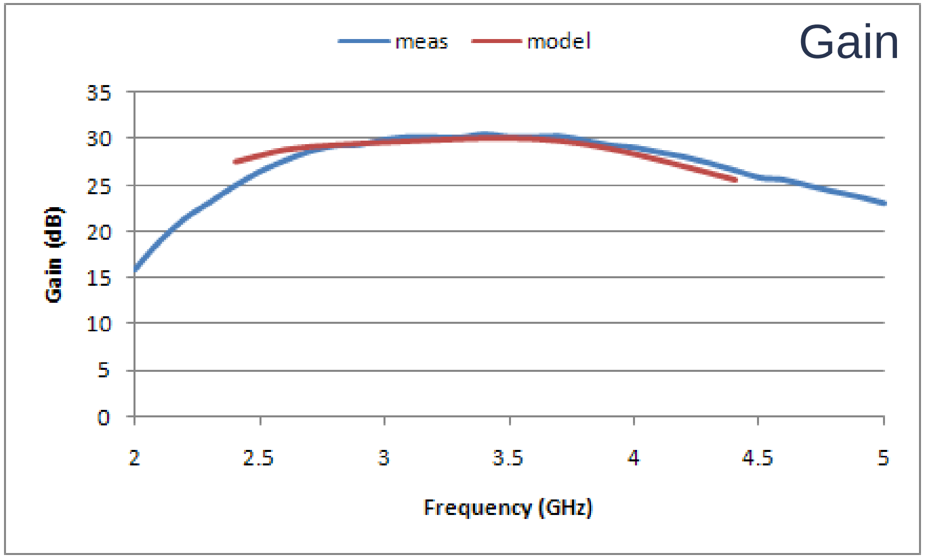
# 0.4um GaN HEMT Noise Model

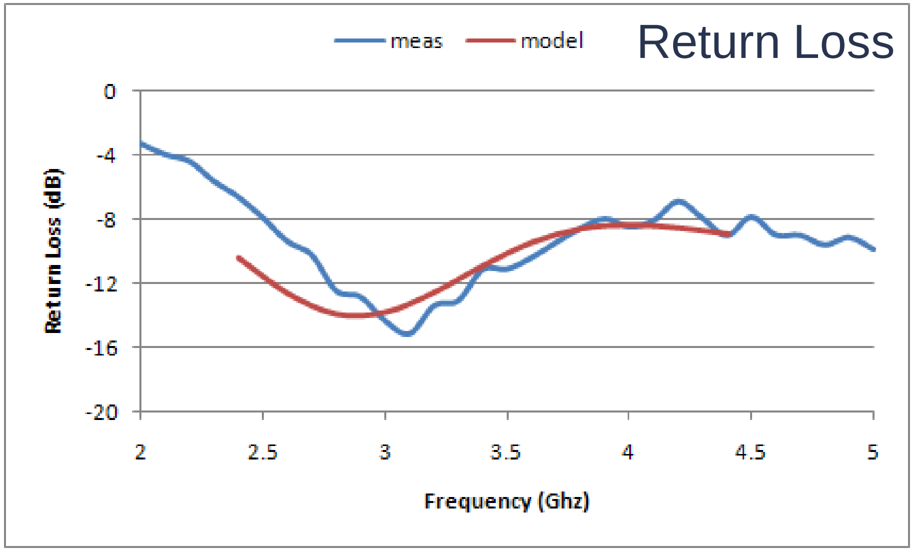


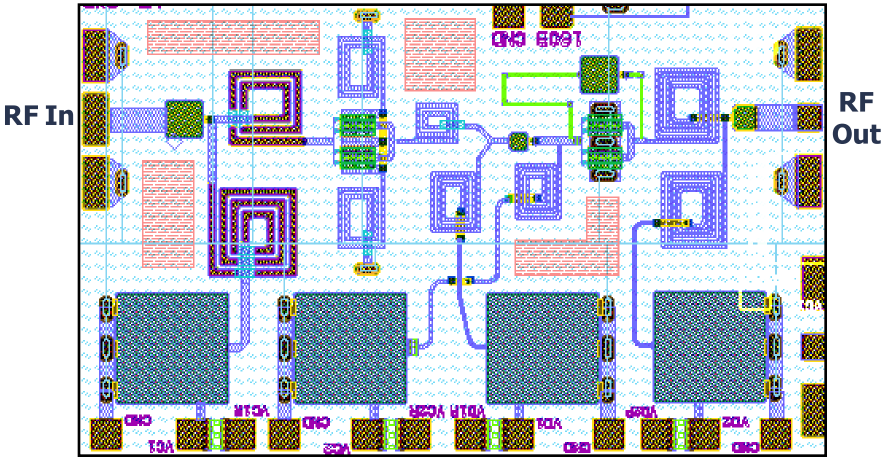




• Good model agreement with measured data

# High Dynamic Range GaN HEMT LNA

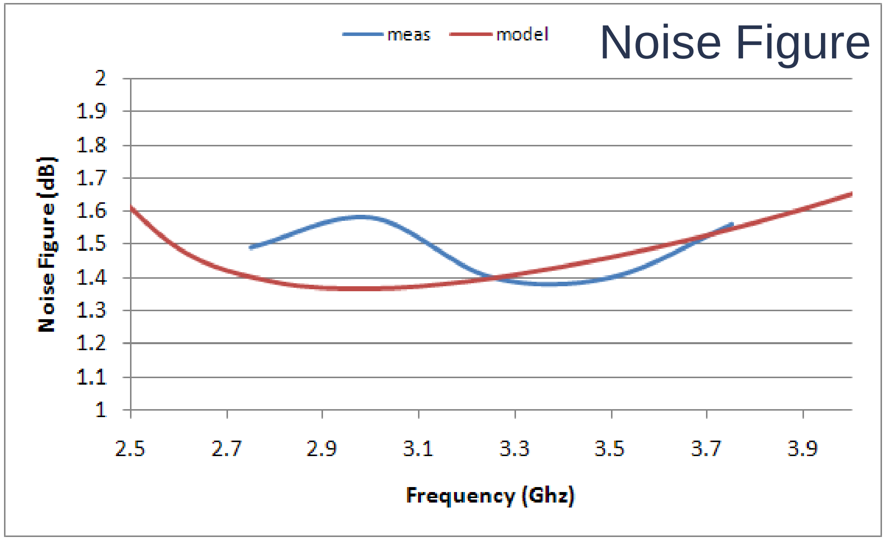


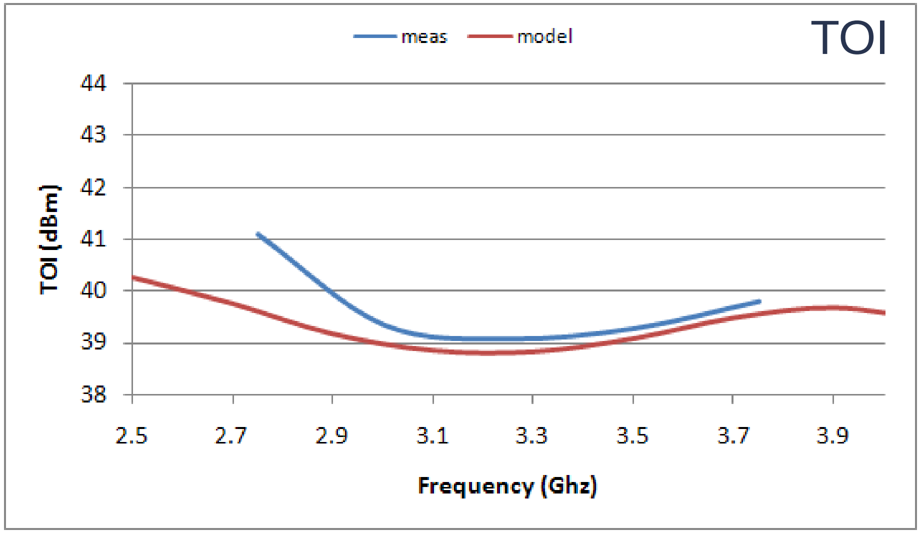



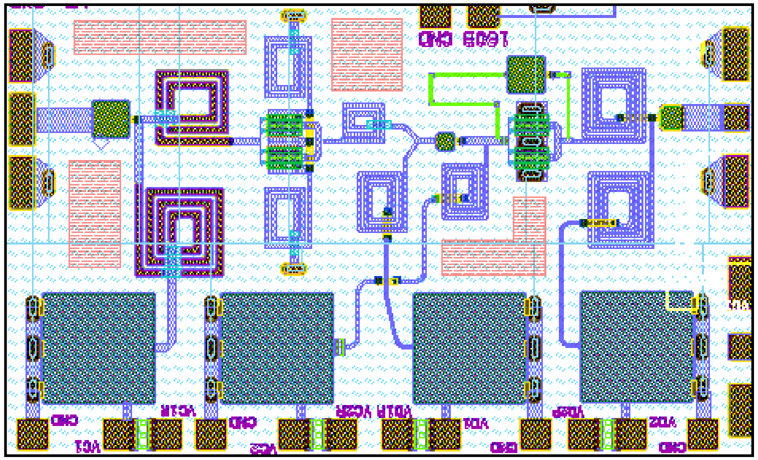

- $V_D$ = 24V
- 2-stage LNA
- 30 dB Gain
- 1.7mm wide by 2.7mm
- Excellent Modeled vs. Measured Performance

# High Dynamic Range GaN HEMT LNA




RF In

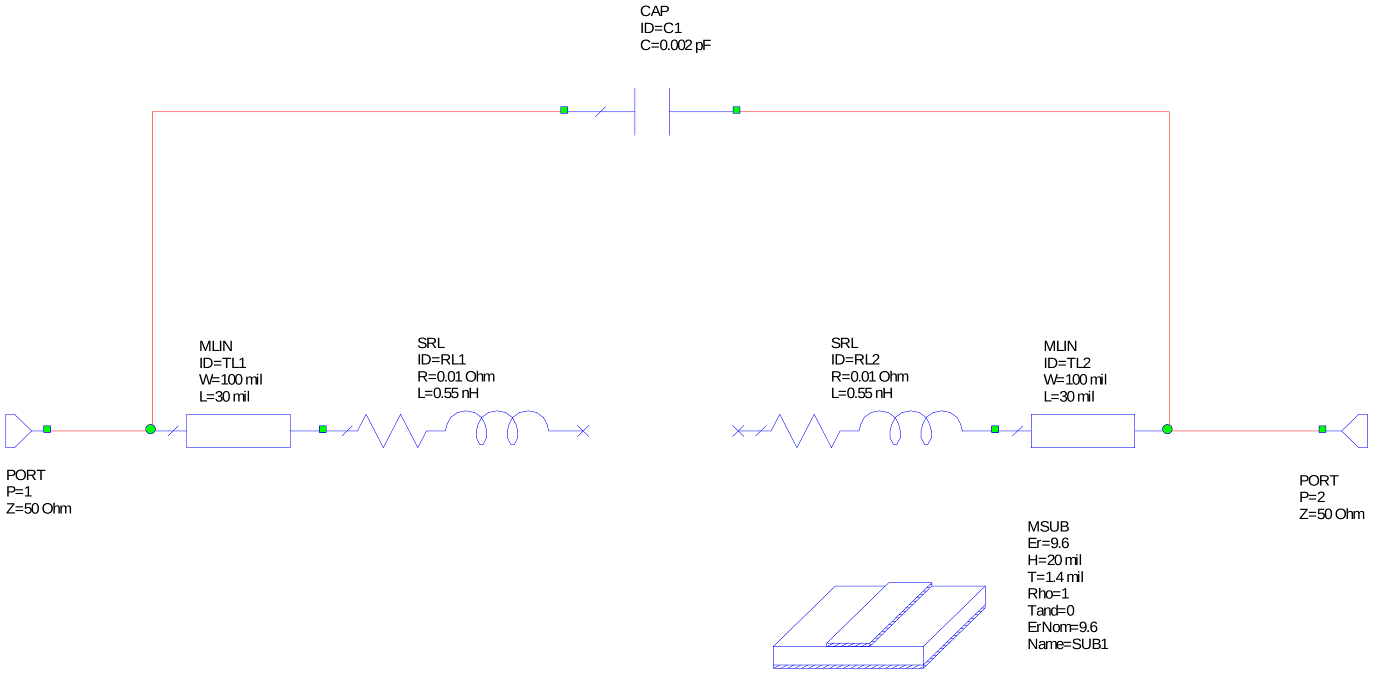


RF Out

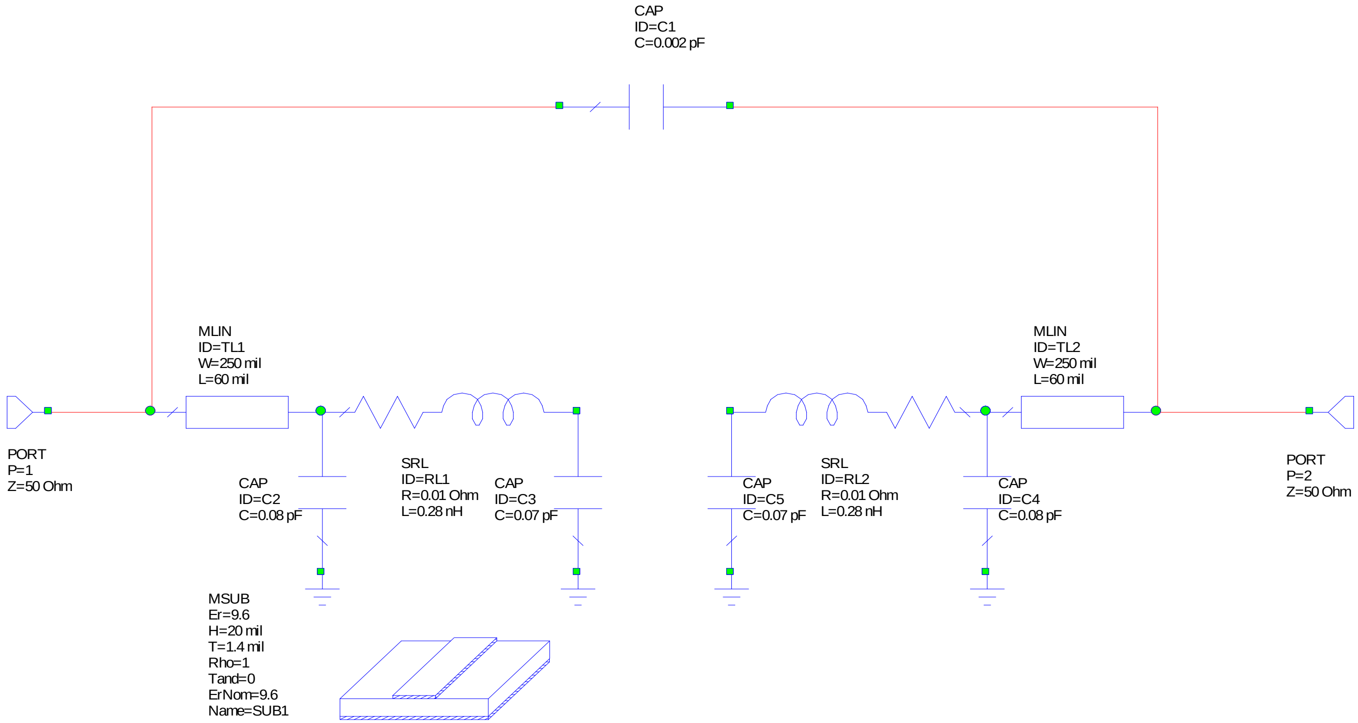
- $V_D$ = 24V
- 2-stage LNA
- High Input TOI ~10 dBm
- 1.7mm wide by 2.7mm

# Examples of Package Models

# 440166 Package Model for CGH40010F



# 440193 Package Model for CGH27060F



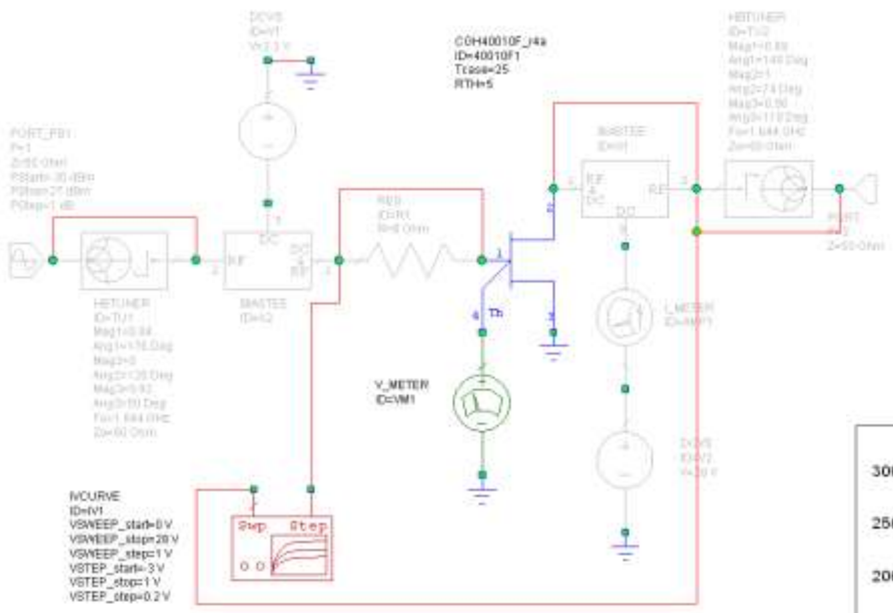
# Design Examples

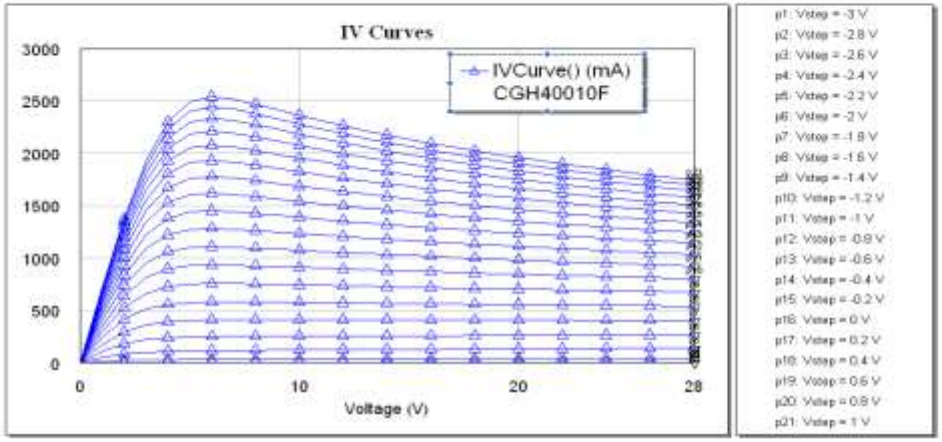
# Example 1
# Basics

# Basic uses for large-signal models

- DC characteristics
- Generation of s-parameters at different bias points
- GMAX, MSG and K factor
- Generation of source and load pull contours
- AM to AM and AM to PM
- Effects of transistor self-heating
- Harmonic terminations and harmonic analysis

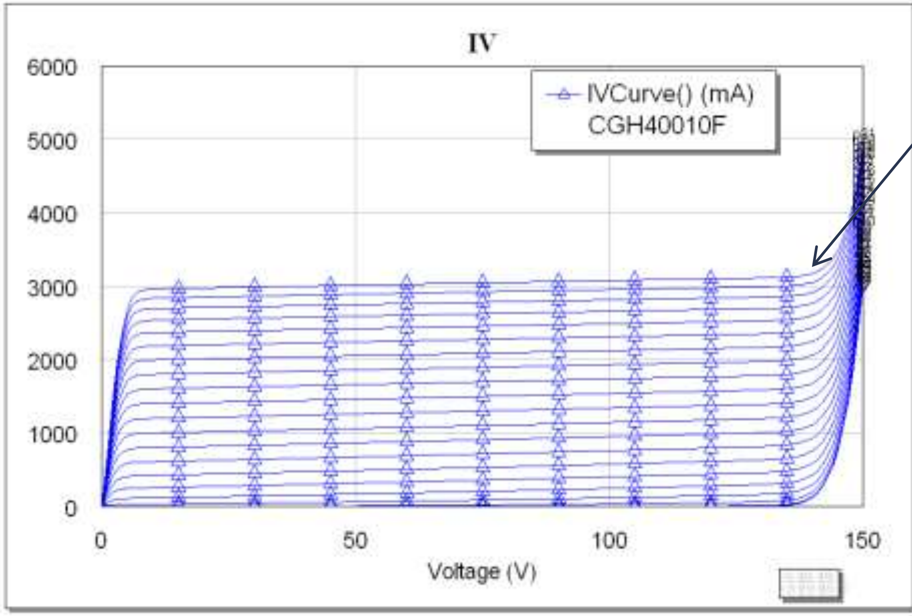
# Generating I-V Curves



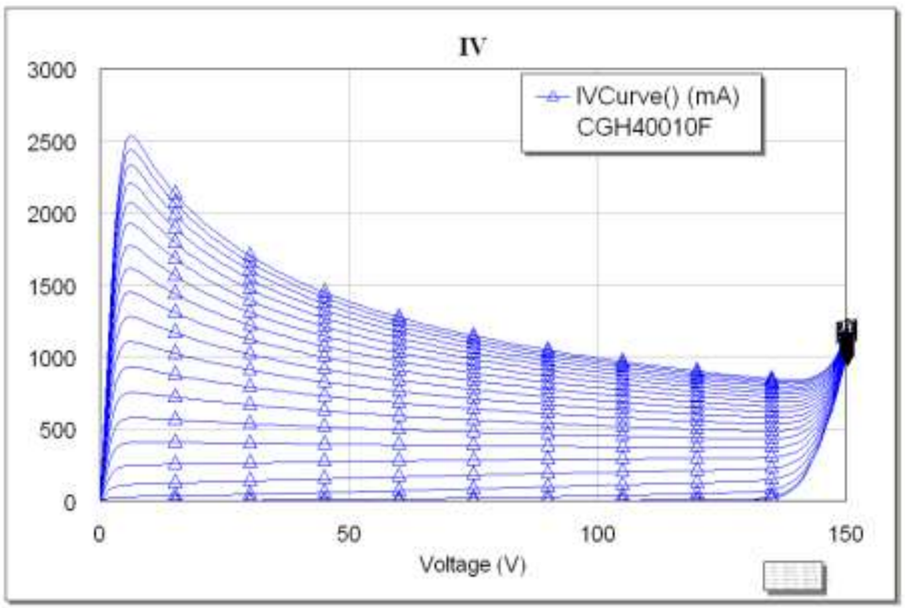



# IV Curves showing Breakdown and Effect of Self-Heating

Drain to source breakdown

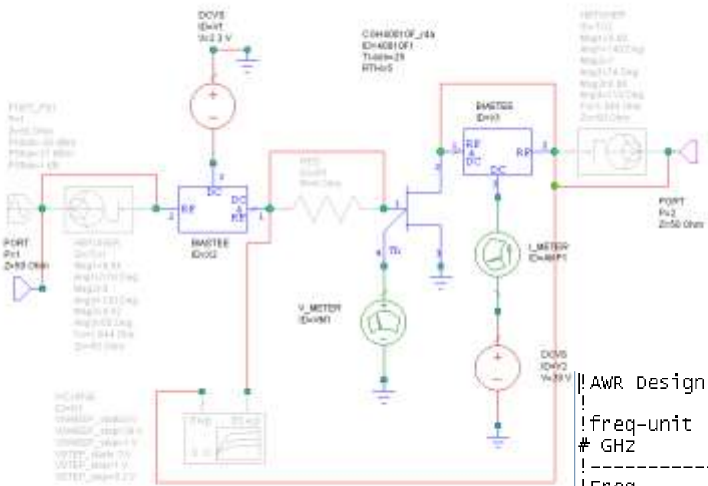



Self-Heating Disabled



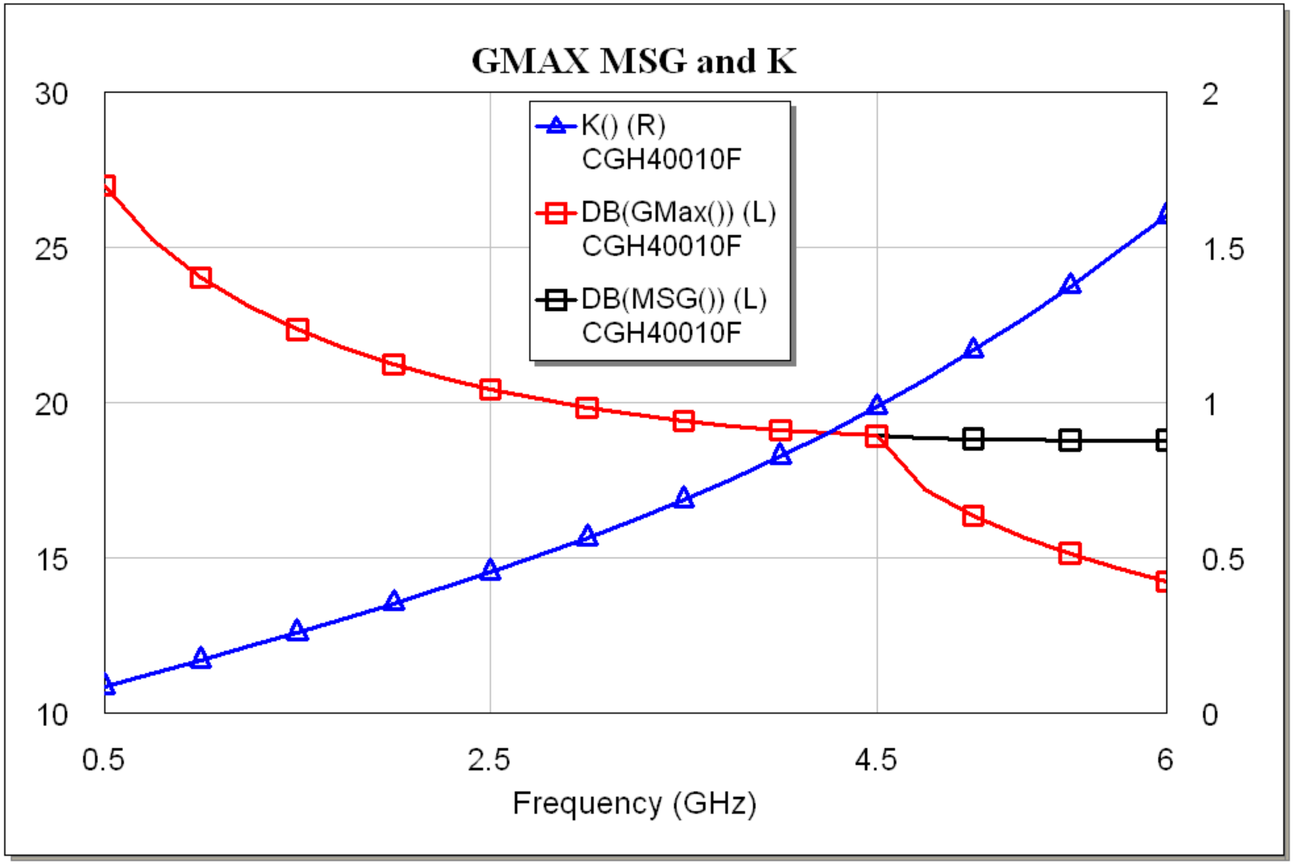

Self-Heating Enabled

# Generating s-parameters

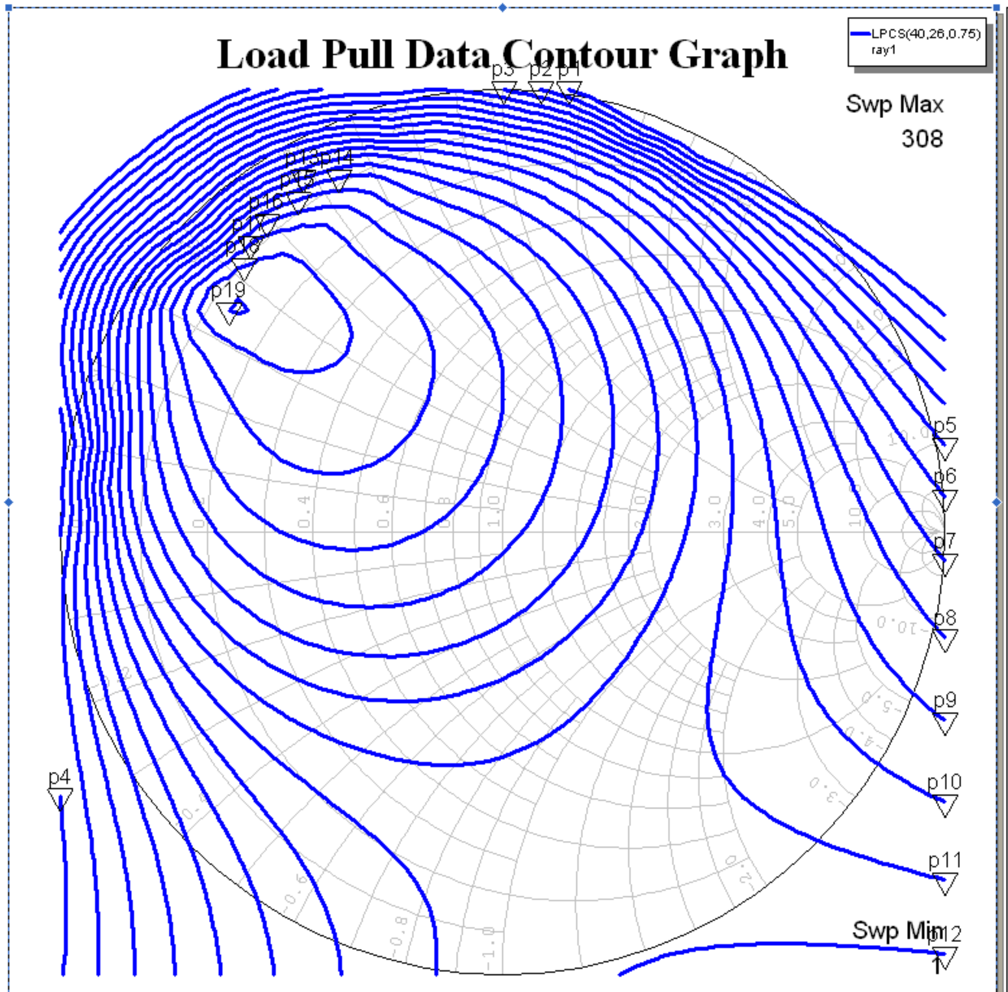



```
!AWR Design Environment (4254) Wed Apr 29 14:40:51 2009
!
!freq-unit  param-type  data-format  keyword  impedance-ohms
# GHz           S            MA          R          50
!----------------------------------------------------------------------------------
!Freq        MagS11     AngS11     MagS21     AngS21     MagS12      AngS12     MagS22     AngS22
 0.5         0.89226    -129.82    17.092     105.62     0.034264    18.391     0.39874    -102.94
 0.75        0.87939    -148.62    12.022     92.777     0.035969    6.9418     0.36438    -120.12
 1           0.87458    -159.87    9.1924     83.586     0.036408    -0.83357   0.35651    -130
 1.25        0.87269    -167.74    7.415      76.034     0.036374    -6.9488    0.36003    -136.39
 1.5         0.87214    -173.85    6.2022     69.352     0.036099    -12.166    0.36933    -141.01
 1.75        0.87226    -178.95    5.3245     63.19      0.035673    -16.827    0.38183    -144.73
 2           0.87278    176.56     4.6613     57.368     0.03514     -21.105    0.3961     -147.98
 2.25        0.87352    172.46     4.1436     51.783     0.034524    -25.095    0.41128    -151
 2.5         0.87438    168.6      3.7292     46.371     0.033841    -28.852    0.42676    -153.93
 2.75        0.87529    164.89     3.3908     41.088     0.033104    -32.409    0.44214    -156.84
 3           0.87619    161.26     3.1102     35.903     0.032322    -35.785    0.45709    -159.77
 3.25        0.87704    157.66     2.8744     30.792     0.031505    -38.99     0.47141    -162.74
 3.5         0.87782    154.07     2.6742     25.734     0.030659    -42.029    0.48492    -165.76
 3.75        0.8785     150.43     2.5029     20.711     0.029792    -44.903    0.49752    -168.86
 4           0.87906    146.74     2.3552     15.707     0.028909    -47.606    0.50913    -172.02
 4.25        0.87949    142.96     2.2272     10.705     0.028018    -50.13     0.51969    -175.27
 4.5         0.87978    139.08     2.1157     5.6904     0.027124    -52.463    0.52917    -178.61
 4.75        0.87992    135.07     2.0182     0.64709    0.026236    -54.59     0.53757    177.95
 5           0.87994    130.92     1.9326     -4.4406    0.025361    -56.489    0.54488    174.41
 5.25        0.87982    126.61     1.8573     -9.5885    0.024511    -58.138    0.55111    170.74
 5.5         0.8796     122.11     1.7908     -14.813    0.023698    -59.511    0.55628    166.93
 5.75        0.87928    117.43     1.7319     -20.13     0.022939    -60.582    0.56042    162.97
 6           0.87892    112.52     1.6793     -25.556    0.022252    -61.331    0.56356    158.84
```

# GMAX, MSG and K Factor

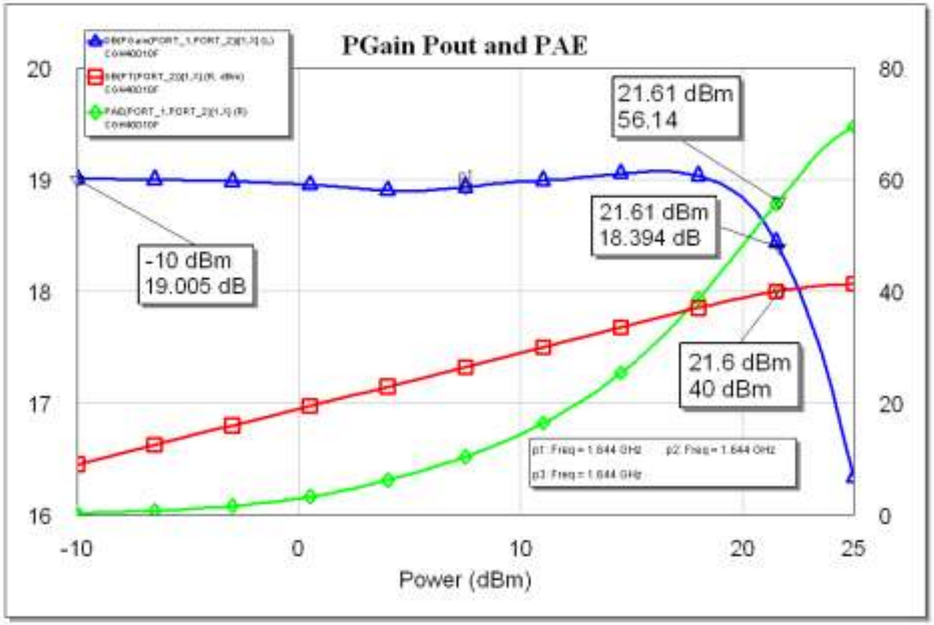


# Generation of source and load pull contours

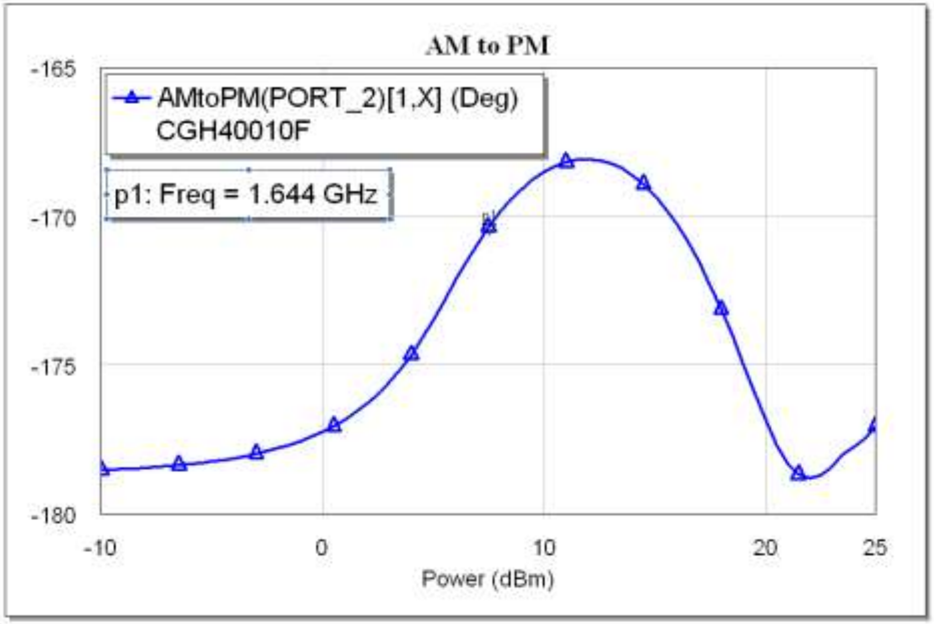



p1: = 25.75
p2: = 26.5
p3: = 27.25
p4: = 28
p5: = 28.75
p6: = 29.5
p7: = 30.25
p8: = 31
p9: = 31.75
p10: = 32.5
p11: = 33.25
p12: = 34
p13: = 34.75
p14: = 35.5
p15: = 36.25
p16: = 37
p17: = 37.75
p18: = 38.5
p19: = 39.25

# AM to AM and AM to PM

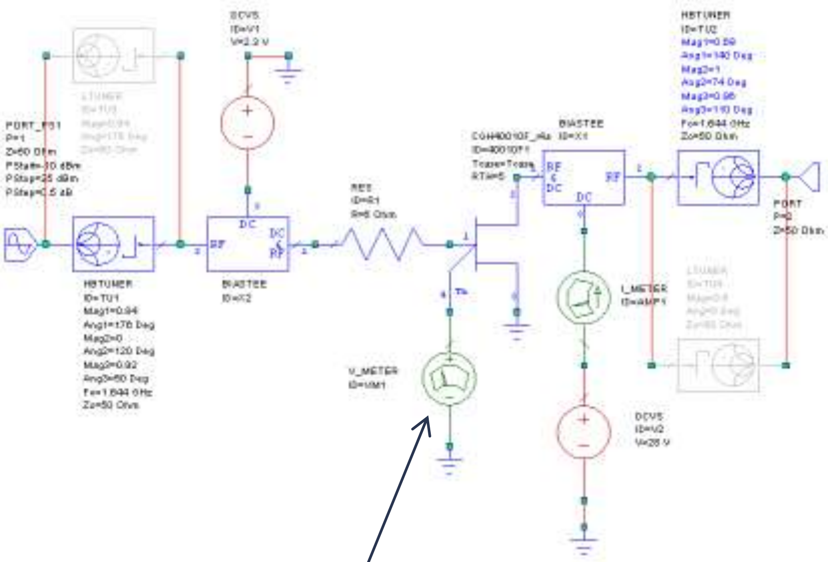



AM to AM Performance

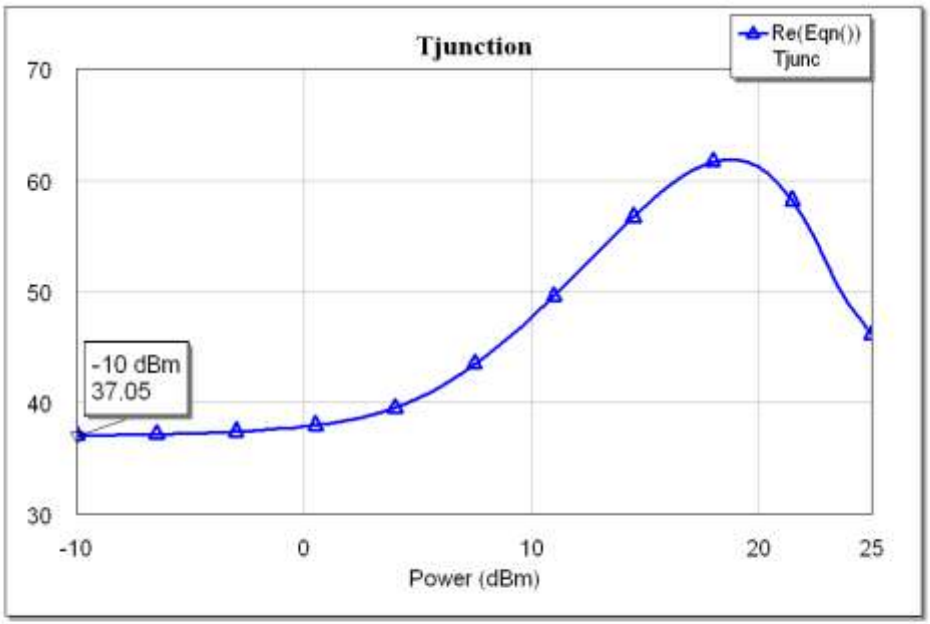



AM to PM Performance

# Effects of transistor self-heating

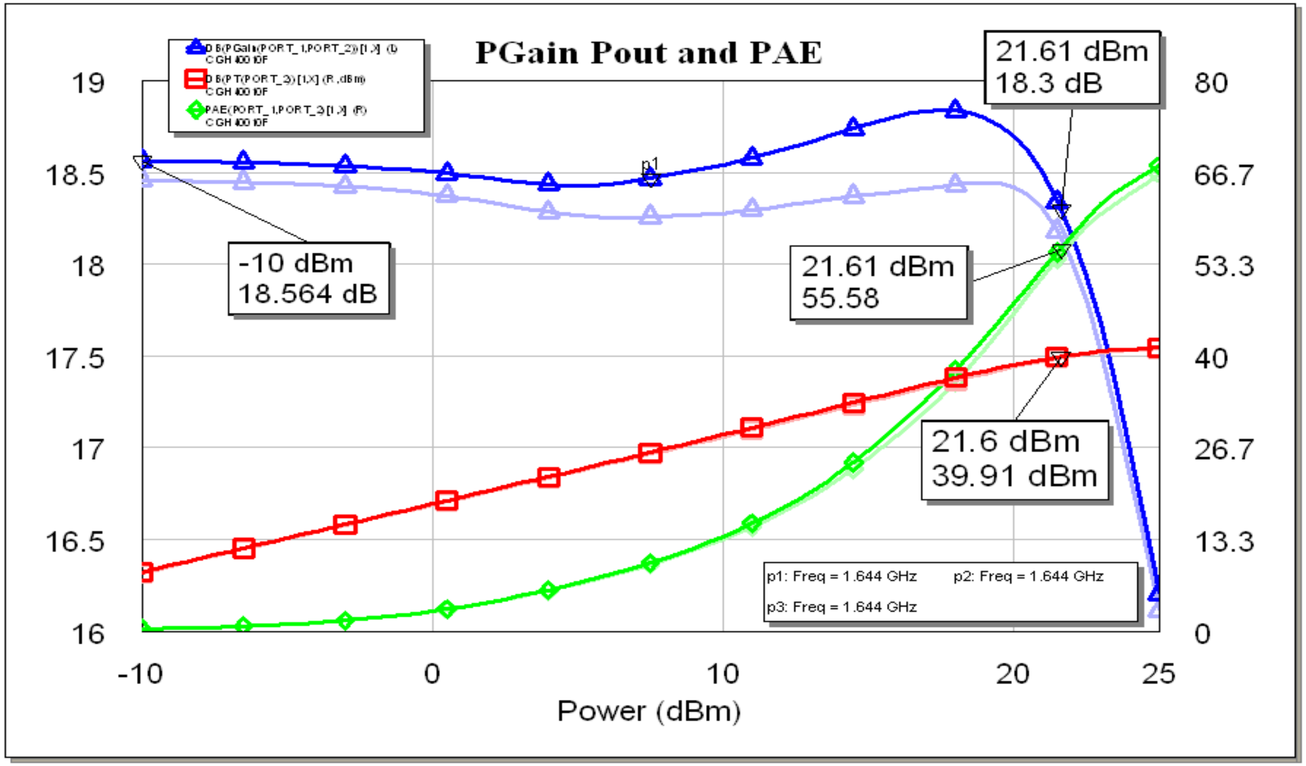


Thermometer



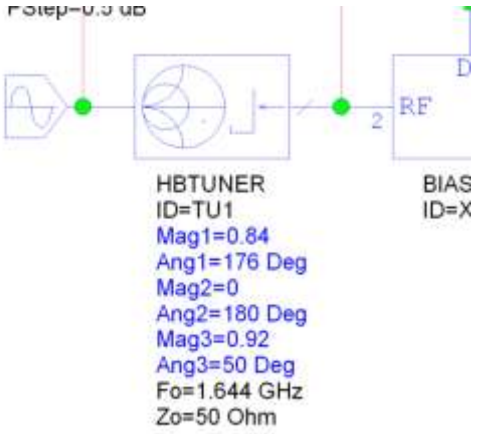

Tjunction = Trise+Tcase
Tcase set to 25 C

# Effect of Self-heating engine in model

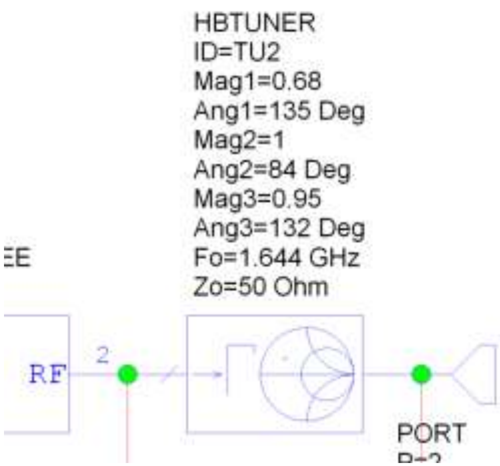



Bold plots are with self-heating turned off

# Harmonic Terminations

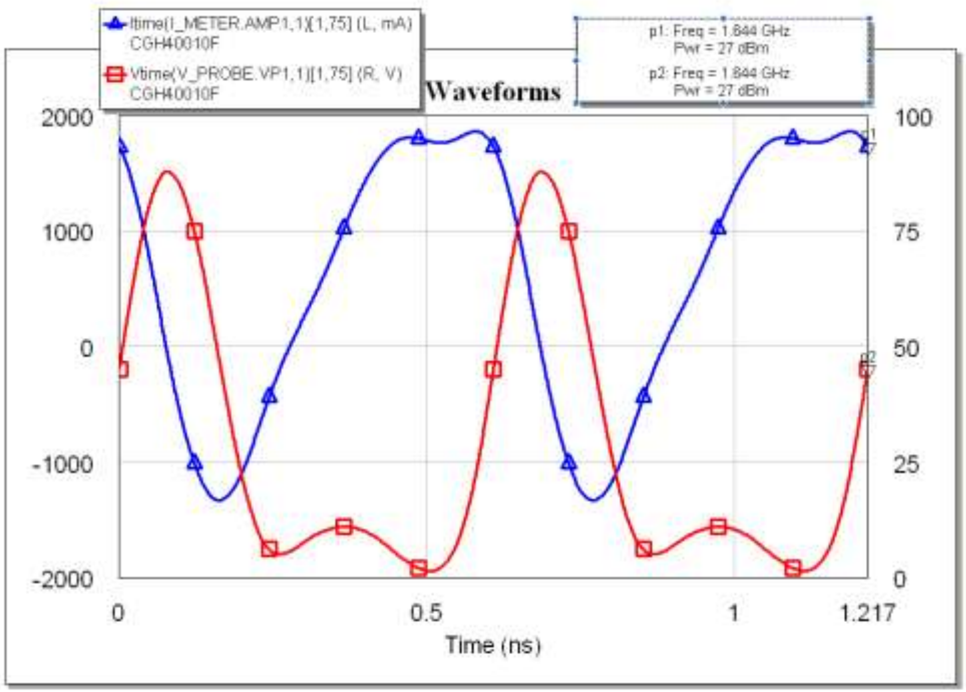



Gate termination



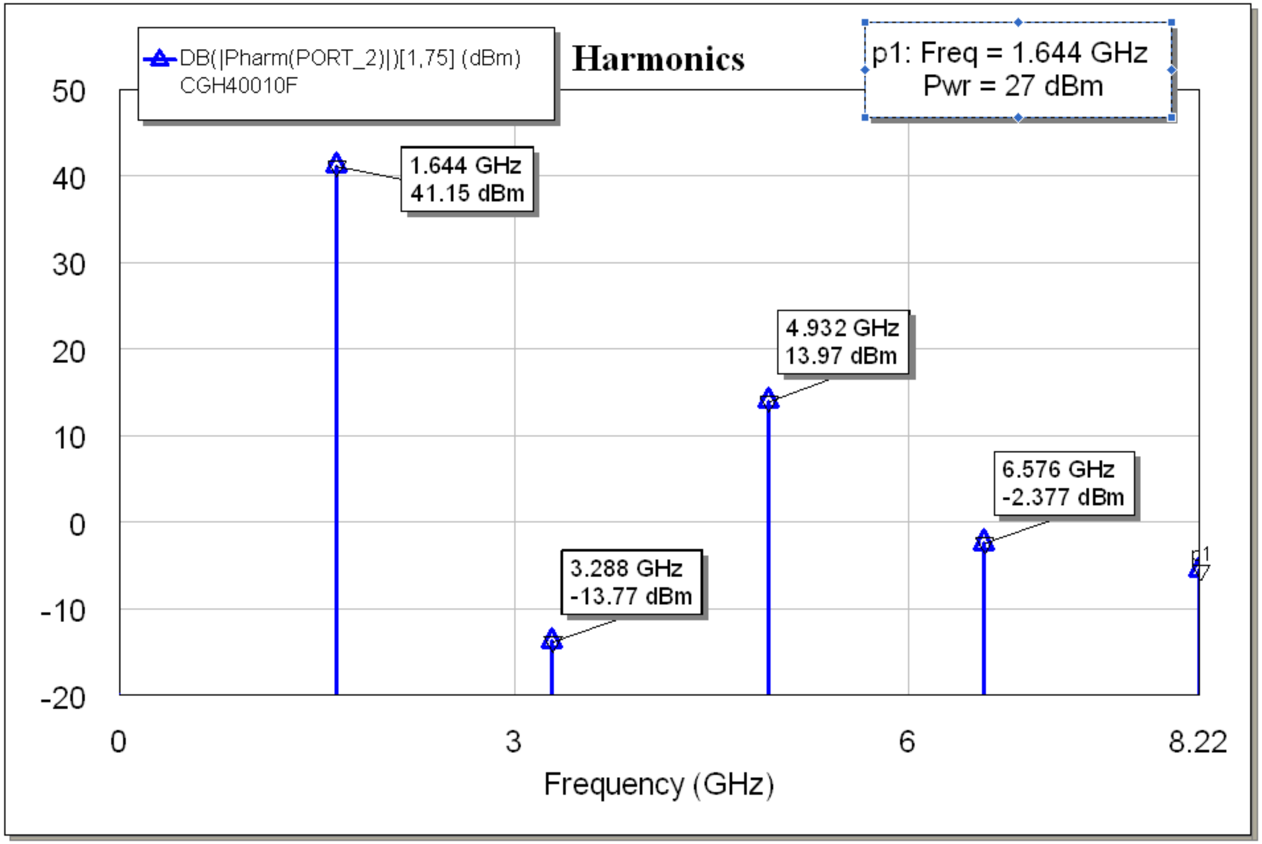

Drain termination

$P_{out}$ = 41 dBm
4.5 dB into compression
Drain Efficiency = 75%




Red is drain voltage; Blue is drain current

# Output Signal Harmonic Analysis



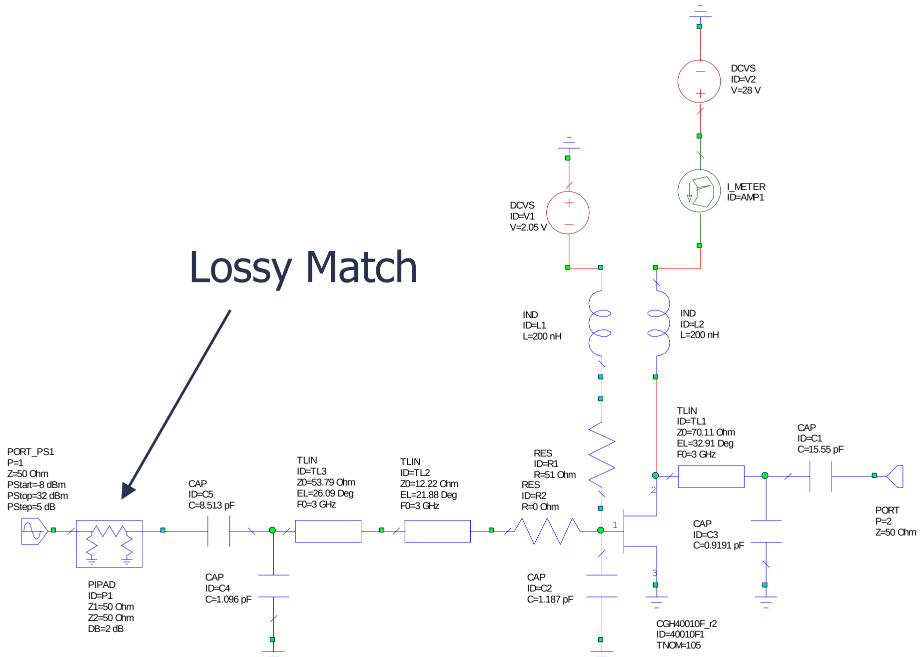

The plot illustrates the frequency spectrum at the output of the amplifier, captured from DC to 8.22 GHz. The harmonic suppressions at the output for the 2nd and 3rd harmonics are -55dBc and -27dBc respectively, indicating that most of the harmonics are re-injected into the PA as expected.

# Example 2

# 500 to 2700 MHz Amplifier using Cree CGH40010F

# 500 to 2700 MHz Amplifier using Cree CGH40010F

Lossy Match




PRELIMINARY

CREE

**CGH40010**

**10 W, RF Power GaN HEMT**

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 4 GHz Operation
- 16 dB Small Signal Gain at 2.0 GHz
- 14 dB Small Signal Gain at 4.0 GHz
- 13 W typical $P_{3dB}$
- 65 % Efficiency at P3dB
- 28 V Operation

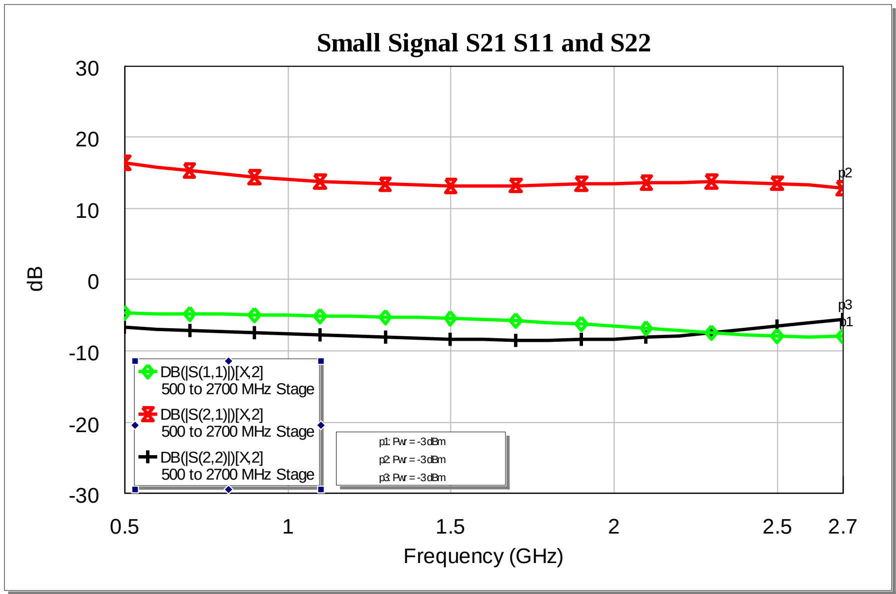
**APPLICATIONS**

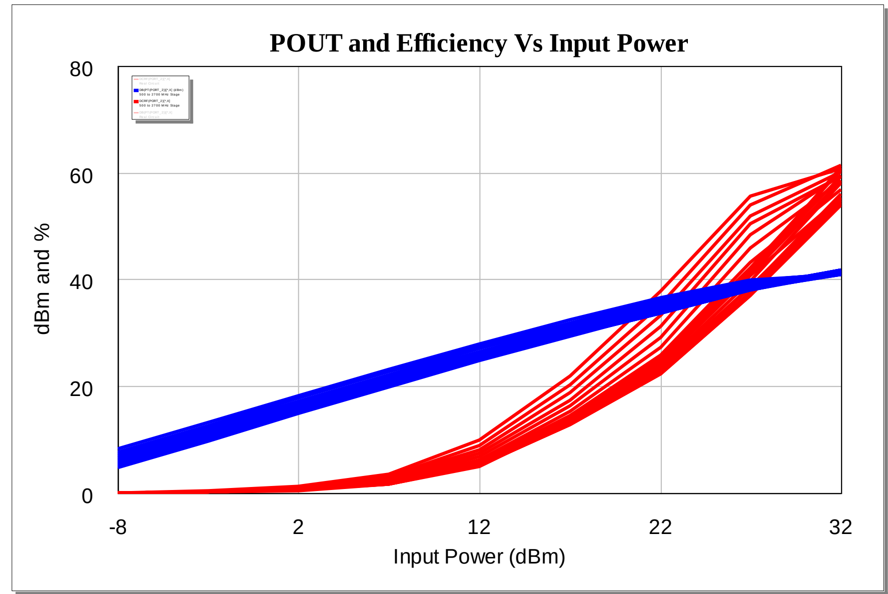
- 2-Way Private Radio
- Broadband Amplifiers
- Cellular Infrastructure
- Test Instrumentation
- Class A, AB, Linear amplifiers suitable for OFDM, W-CDMA, EDGE, CDMA waveforms

RoHS COMPLIANT

Courtesy: L3 Communications
TRL Technology UK

# Simulated Performance of 500 to 2700 MHz GaN HEMT PA



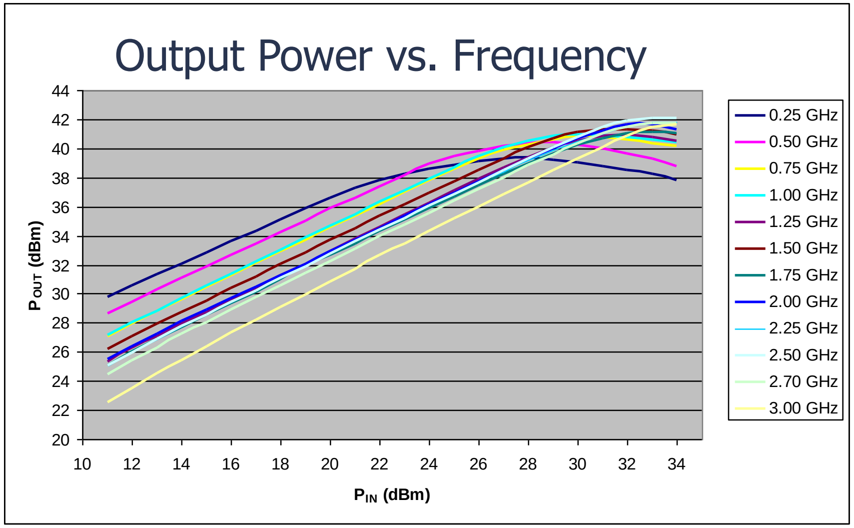



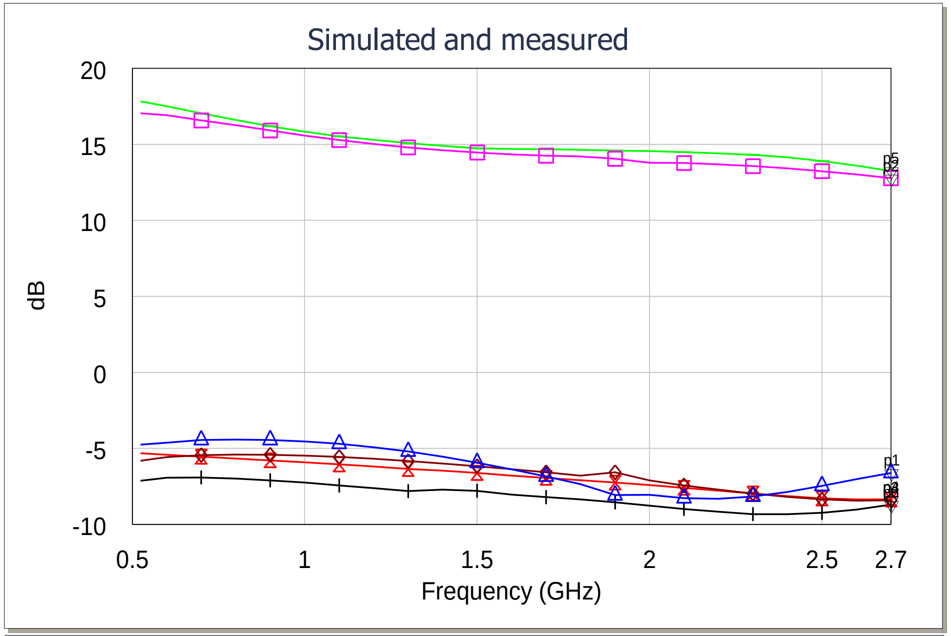

- Worst Case Heat Dissipation is 9 watts
- Theta-jc of packaged transistor is 5 deg C/watt
- Max. channel temperature at 85 deg C case is 130 deg C.

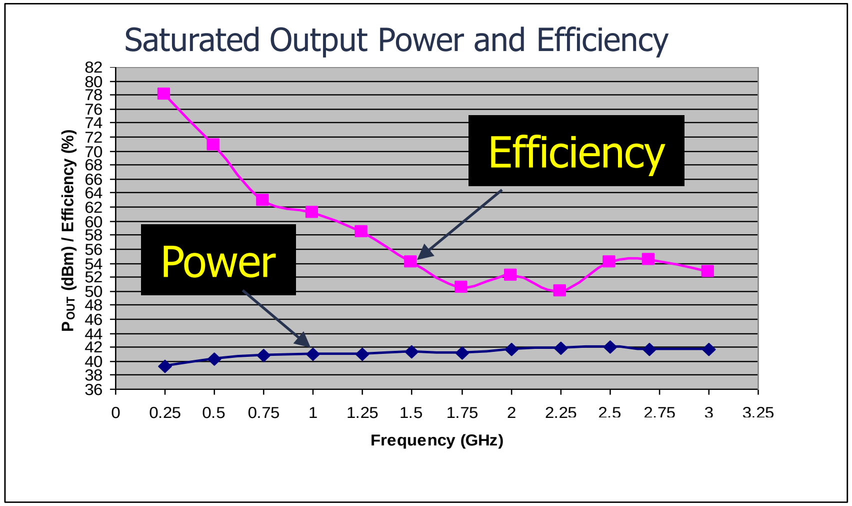
CREE

# Measured Performance of 500 to 2700 MHz GaN HEMT PA

- Excellent agreement between simulations and measurements
- Measured efficiencies between 50 and 78% over the band



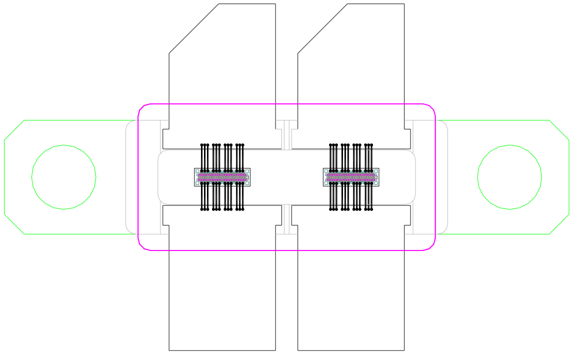




Courtesy: L3 Communications
TRL Technology UK

# Example 3
# Various Broadband Amplifier Design Approaches

# Broadband Amplifier Performance Trade-Off Analysis - Background

- Broadband (0.8 to 2.2 GHz) push-pull amplifier to provide 100 watts peak power
- Two GaN HEMT die in "Gemini" package
  - HEMTs attached to composite material shims within Cu-Mo-Cu package
- Study drain efficiencies over the band and impact on thermal management
  - Comparison of different matching approaches and termination impedances

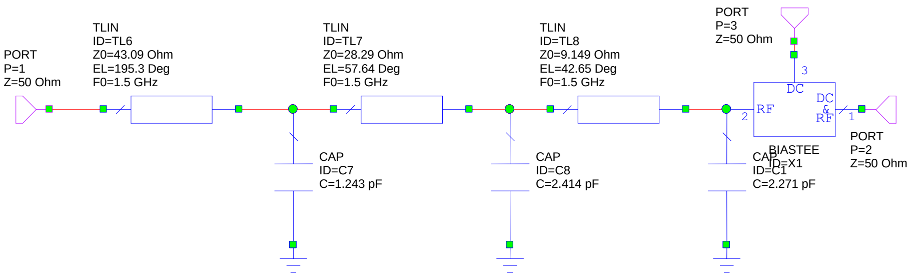


Theta-jc is 1.1 deg C/watt

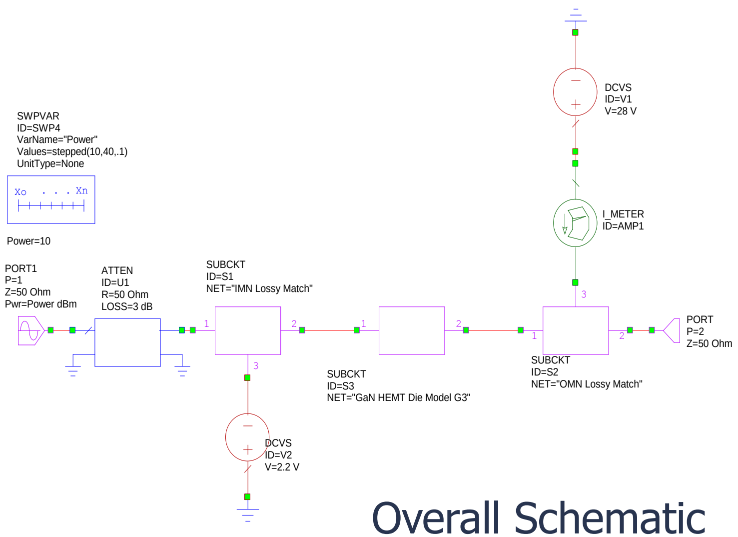
# Basic Amplifier

- Different matching topologies
  - Drain-to-Gate Feedback
  - Lossy Match
  - Multi-section reactive
  - Lossy Match with Feedback

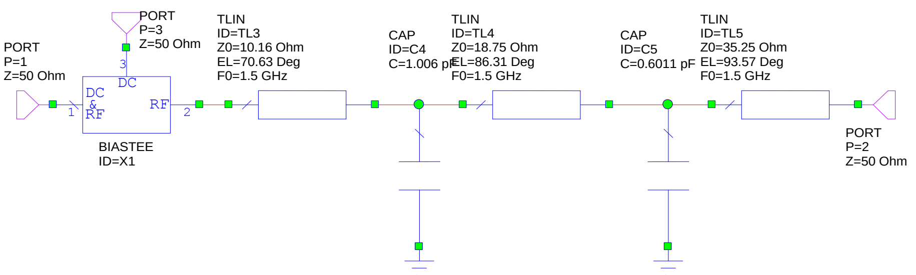
- Concentrate on Lossy Match case




Input Match Schematic

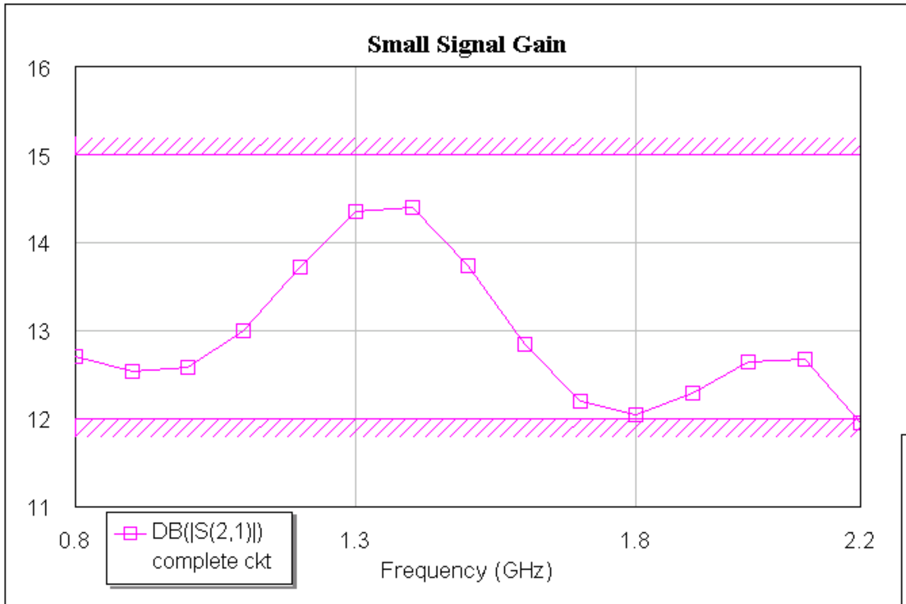



Overall Schematic



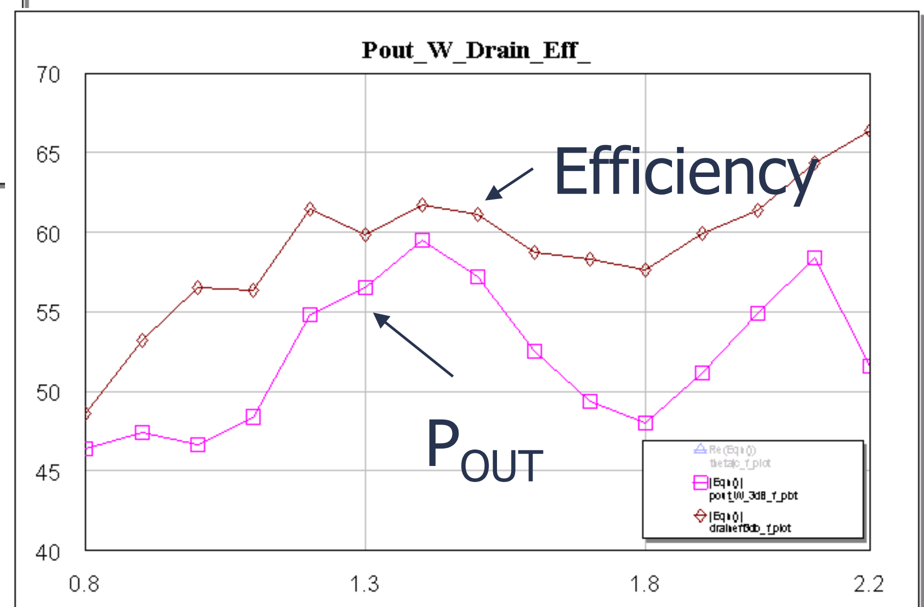

Output Match Schematic

# Simulated Amplifier Performance




Small Signal Gain

Output Power at $P_{3dB}$ and Drain Efficiency

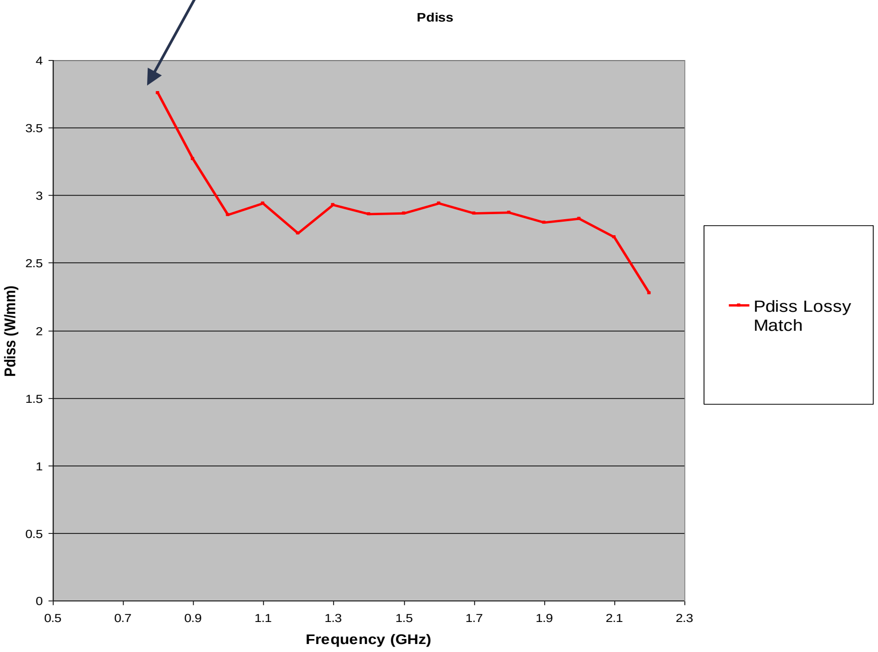



Gain = 13.2 dB ± 0.8 dB
$P_{OUT}$ = 46 to 59 watts
Drain Efficiency = 49 to 66%
Worst Case Dissipated Heat is 54 watts (per transistor)

# Thermal Performance

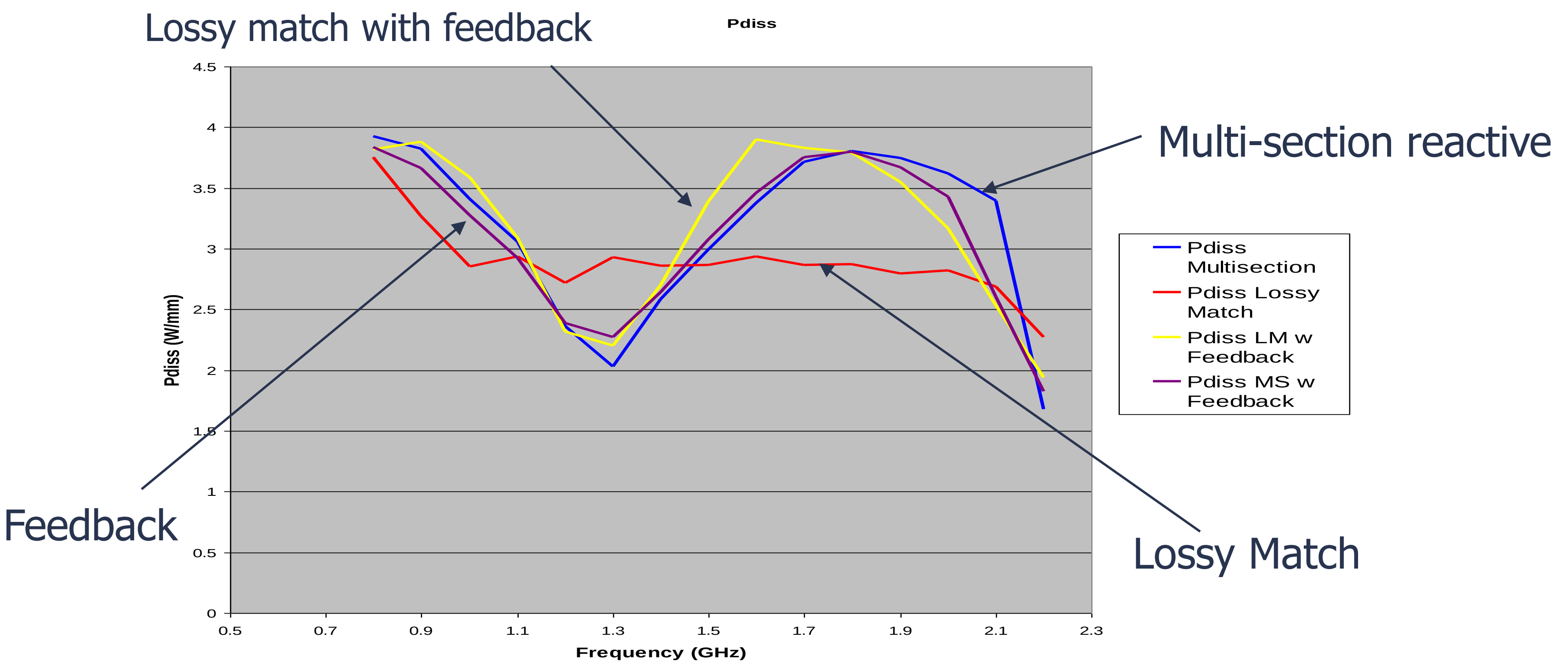
- Assuming $T_J$ limit of 200°C, maximum dissipated heat of 108 watts and theta-jc of 1.1 deg C/Watt leads to a maximum case temperature of 81 deg C
- The thermal characteristics of the die and the package are very important
  - The design requires a composite material shim such as silver-diamond (theta jc =550 W/mK) mounted on a Super-CMC package flange (theta jc = 370 W/mK)
- Before full electrical design is completed broadband amplifiers require thermal design even with GaN HEMTs!

3.75 W/mm dissipated
54 watts per transistor



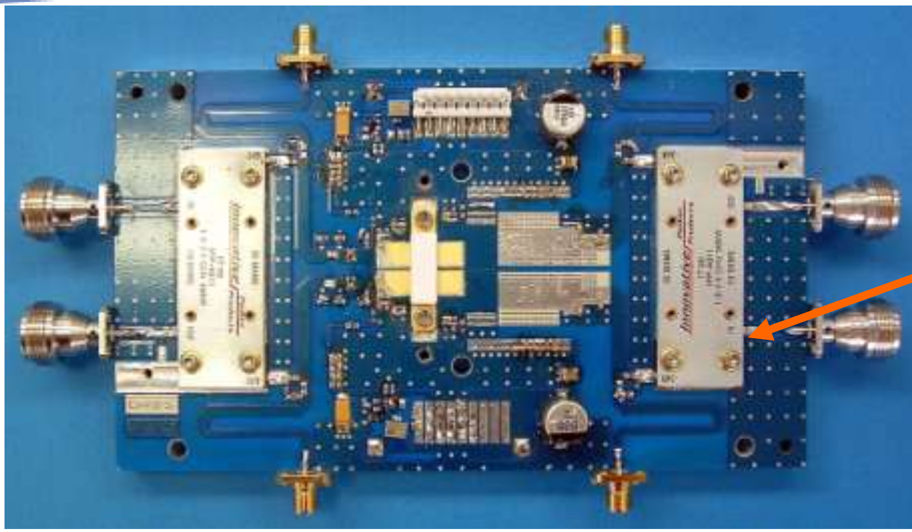

Dissipated Power as a function of frequency

# Comparison of Dissipated Power vs. Frequency for 4 Amplifier Approaches

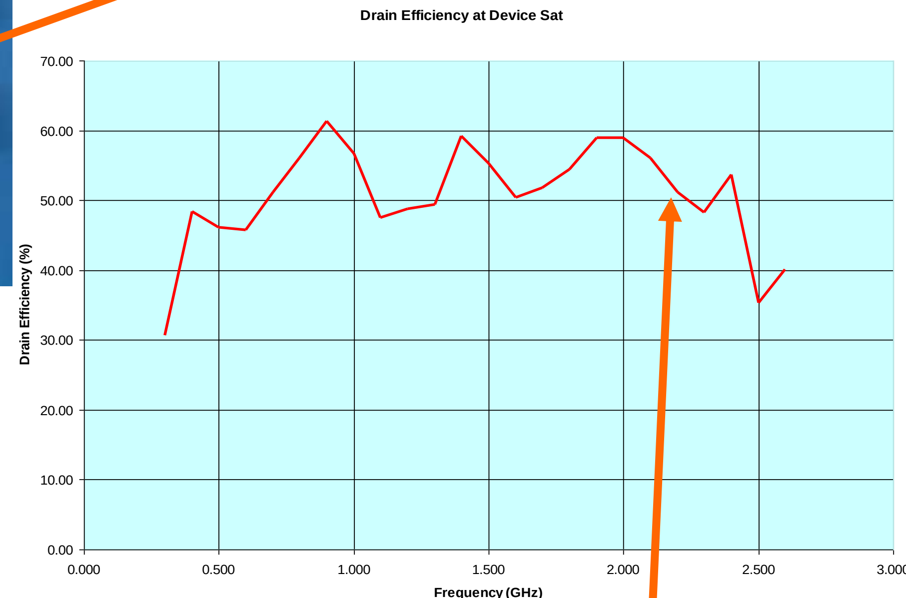


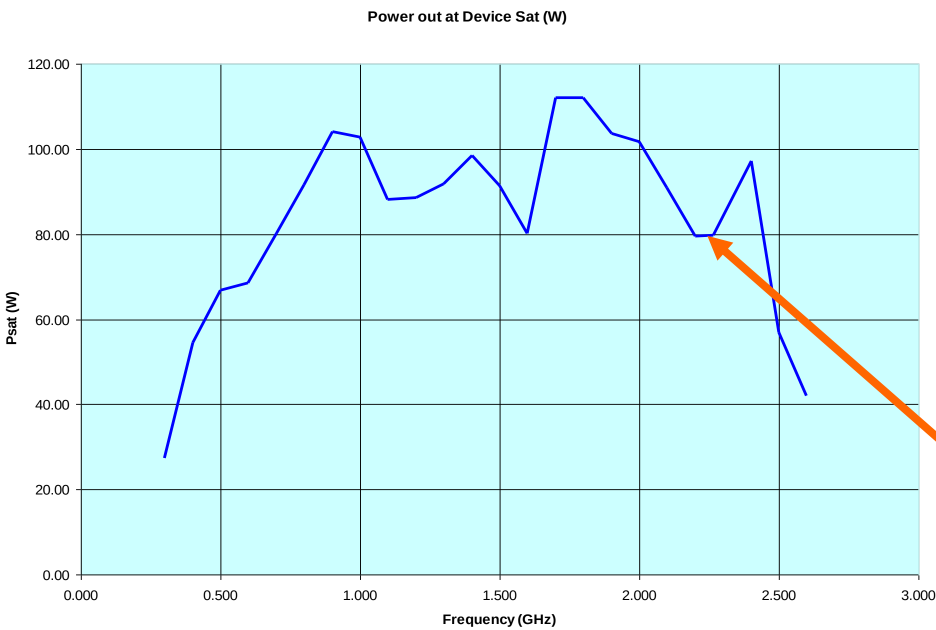

- Large-Signal Modeling of Broadband Amplifiers invaluable in selecting optimum topology for both electrical and thermal performance

# Measured 0.5 to 2.5 GHz Push-Pull Amplifier Performance



25 to 50 ohm coupler



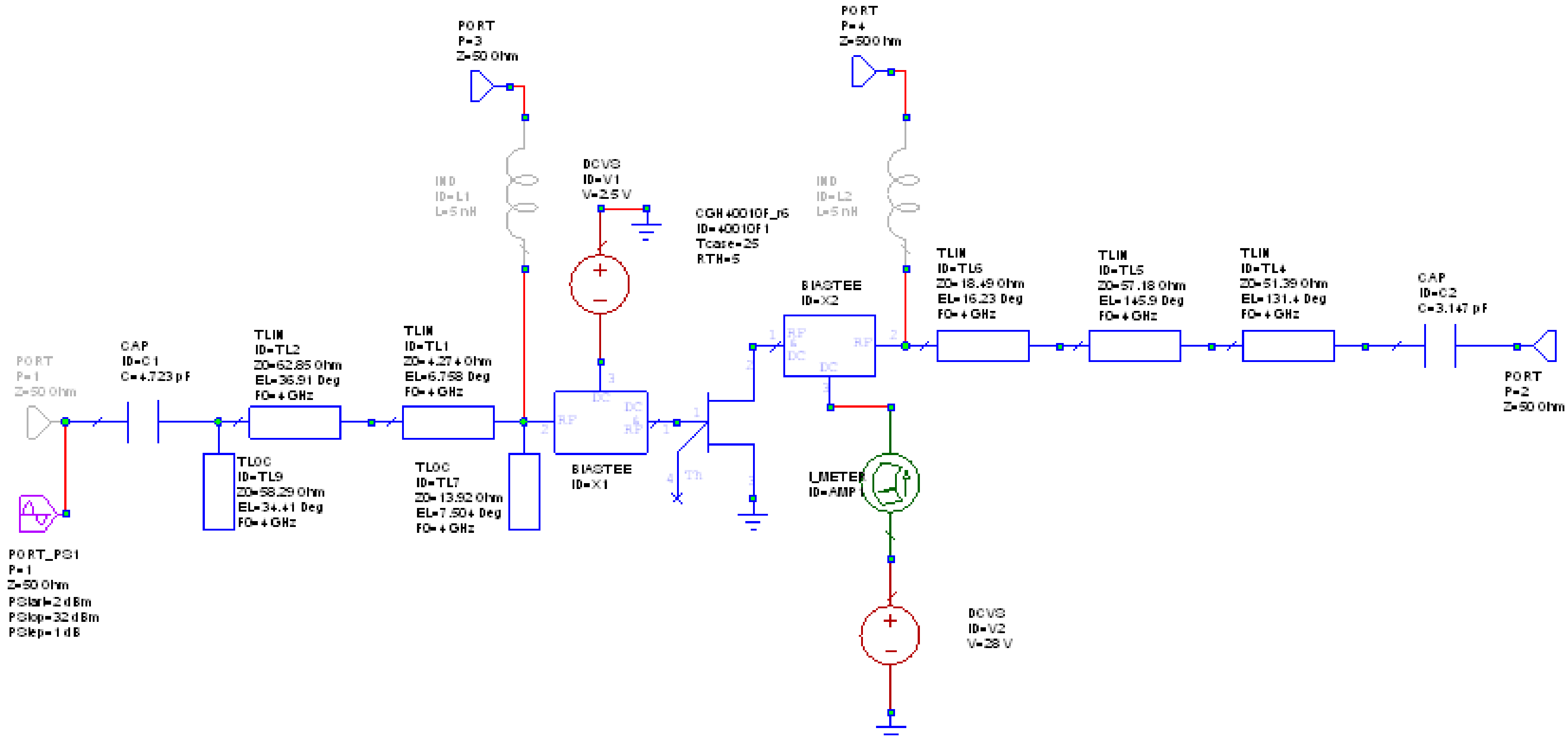

Full amplifier with
coupler insertion losses
Average Gain = 15 dB
Psat > 80 watts and
Drain Efficiencies > 45%

# Example 4
# 2 to 6 GHz Broadband PA using CGH40010F

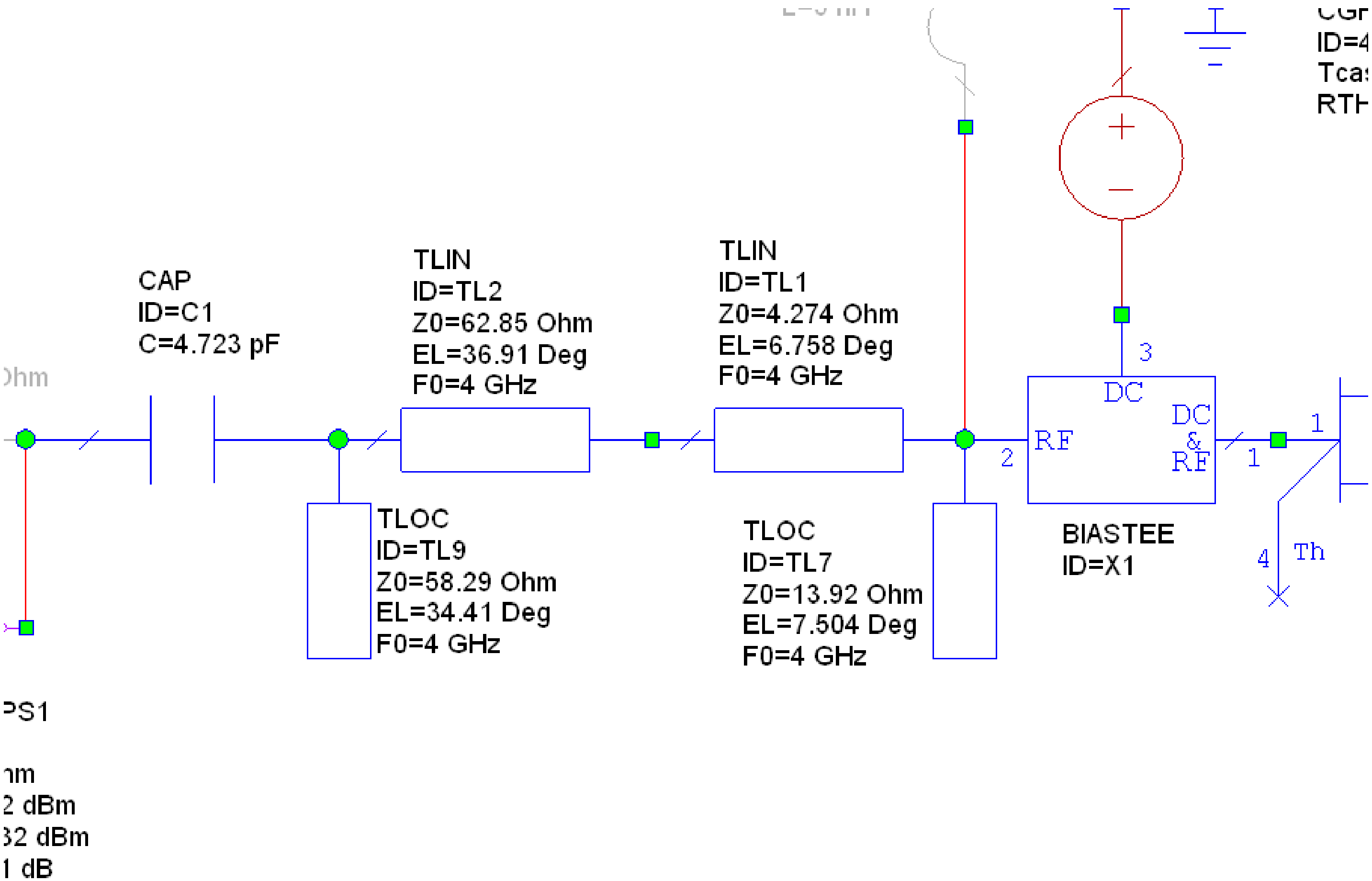
# Summary

- 2000 to 6000 MHz amplifier using packaged CGH40010F GaN HEMT transistor
- Design uses GaN HEMT Transistors operating at nominal drain to source rail of 28 volts
- Amplifier designs use transmission lines, open-circuit stubs and capacitors
- Matched to 50 ohm input and output impedances

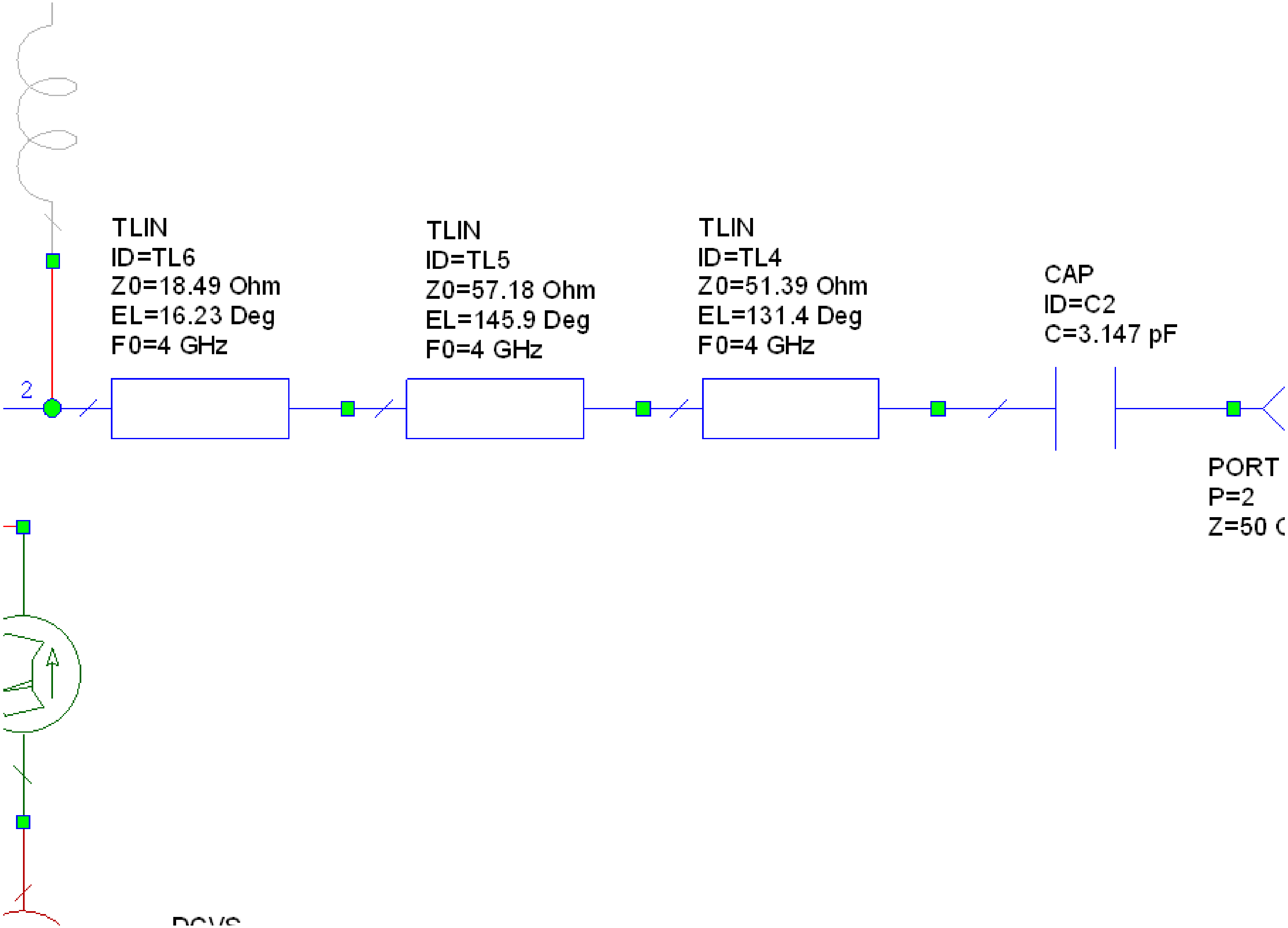
# Amplifier Schematic



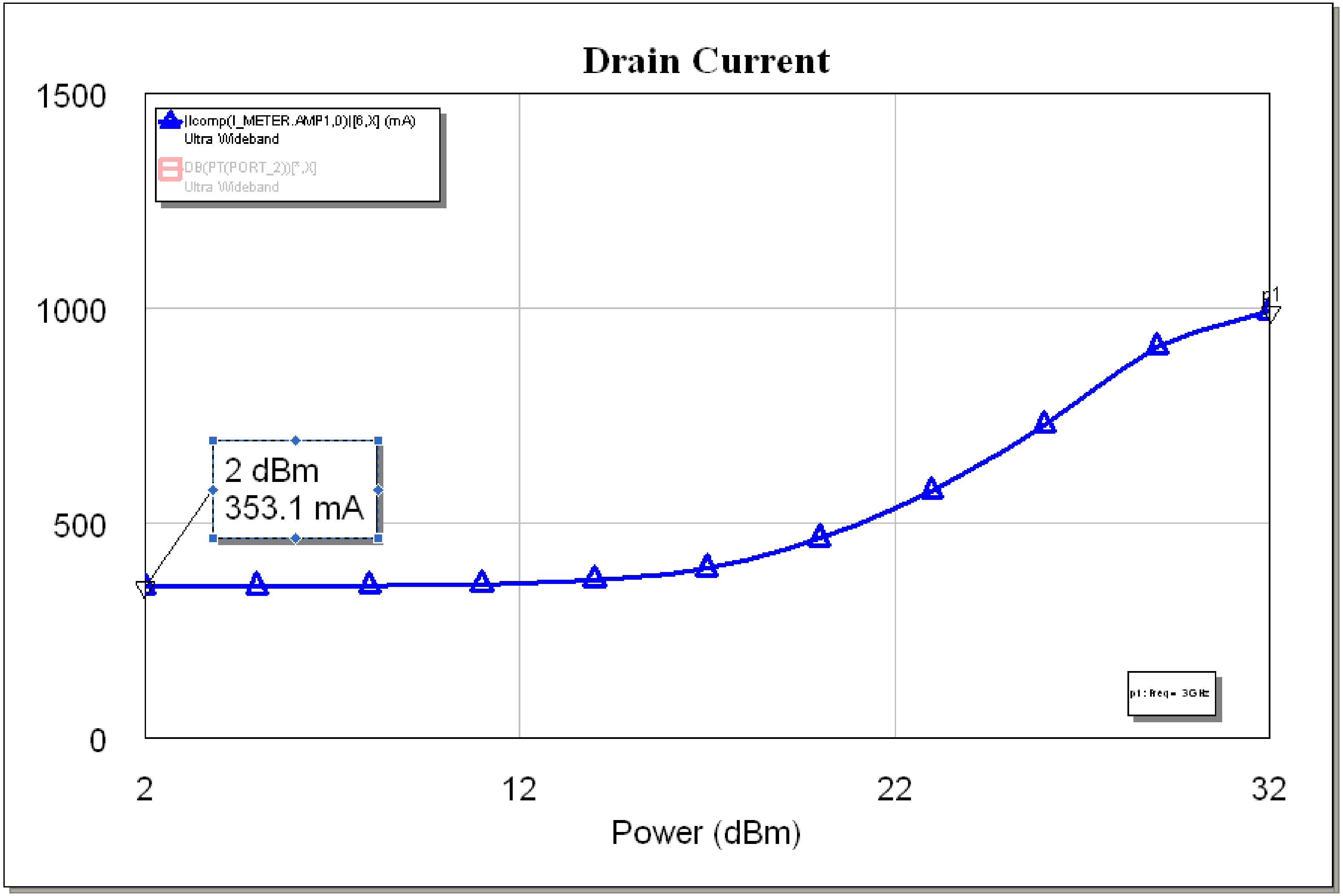
# Detail of Input Match



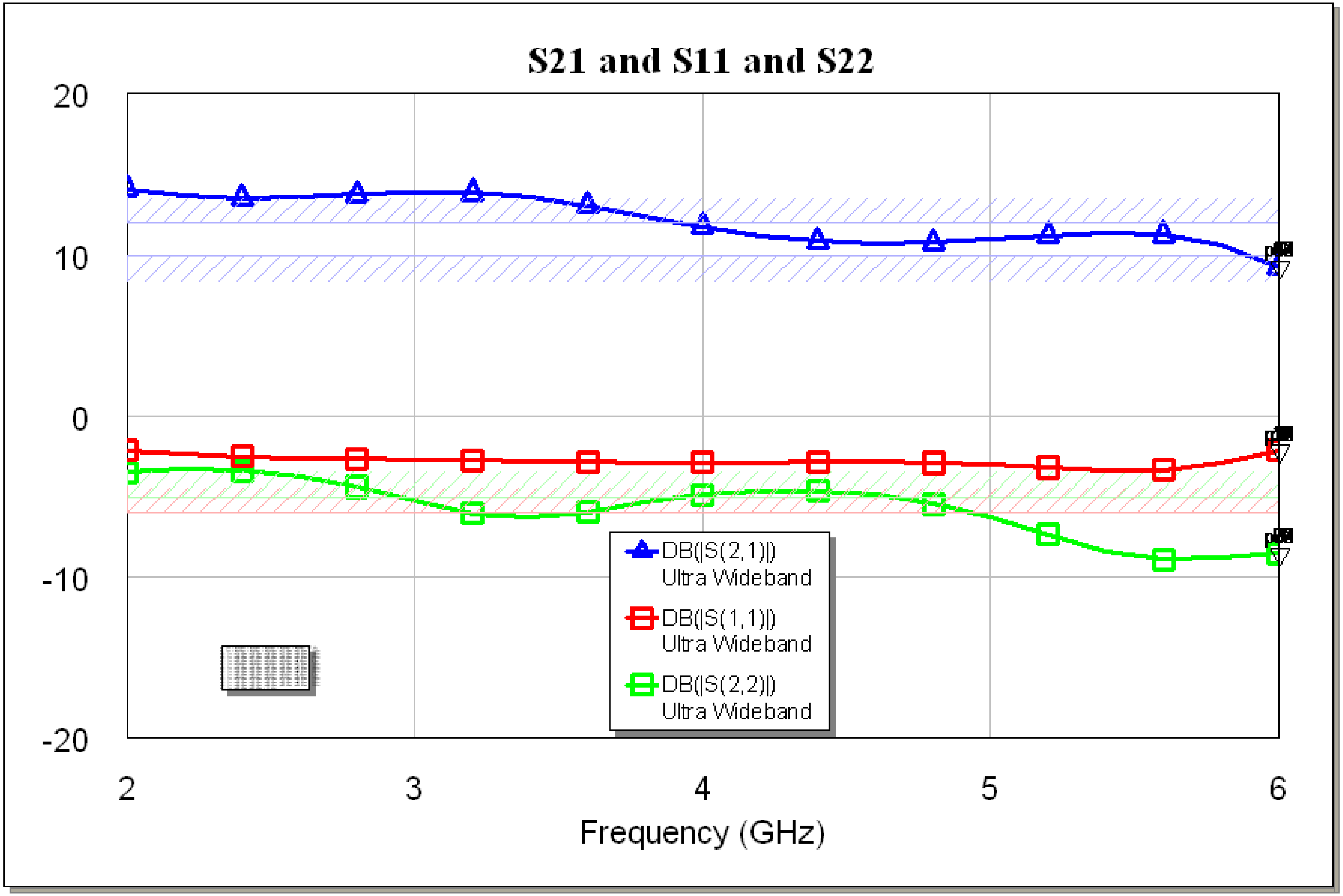
# Detail of Output Match



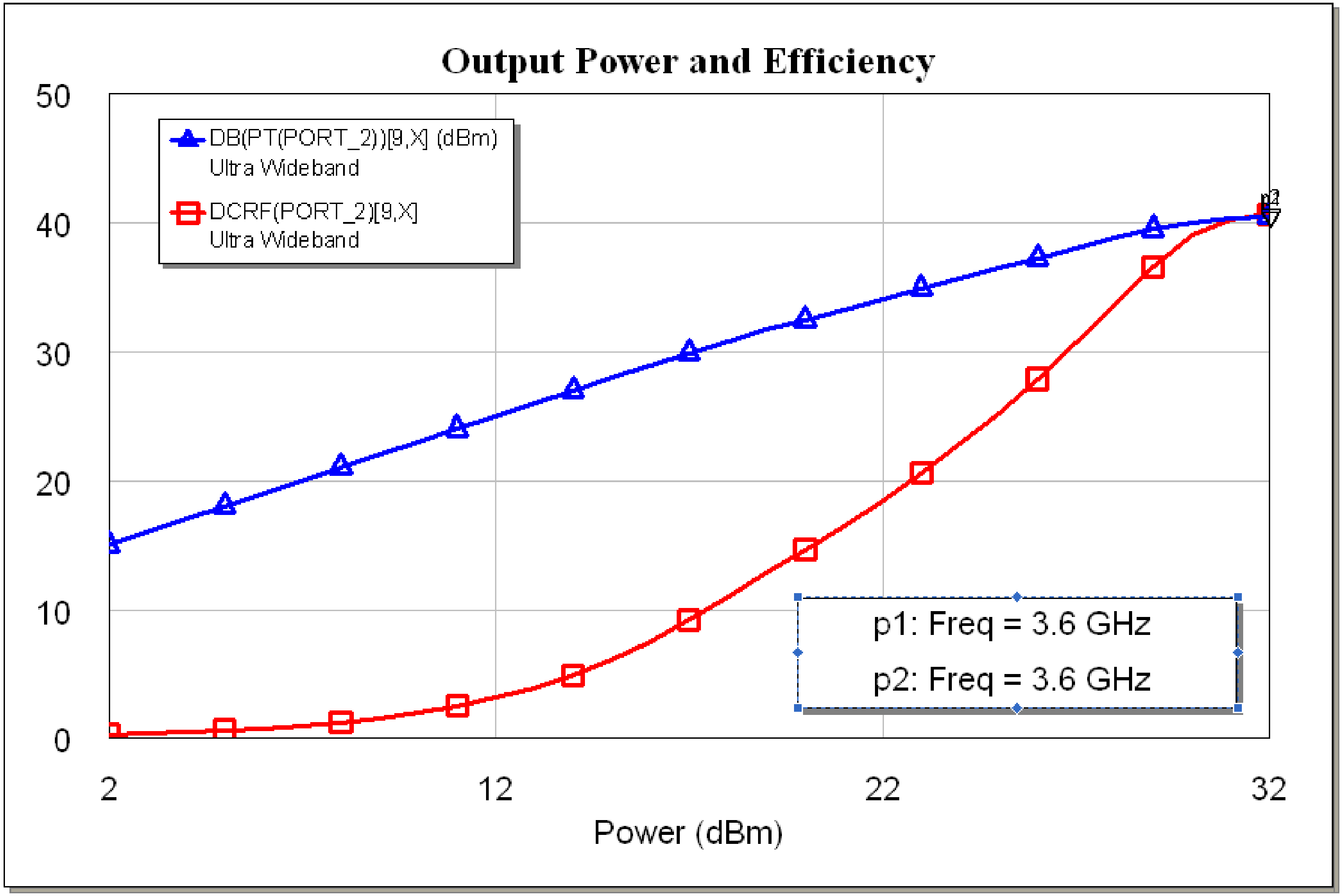
# DC Current versus Input RF power at 3 GHz



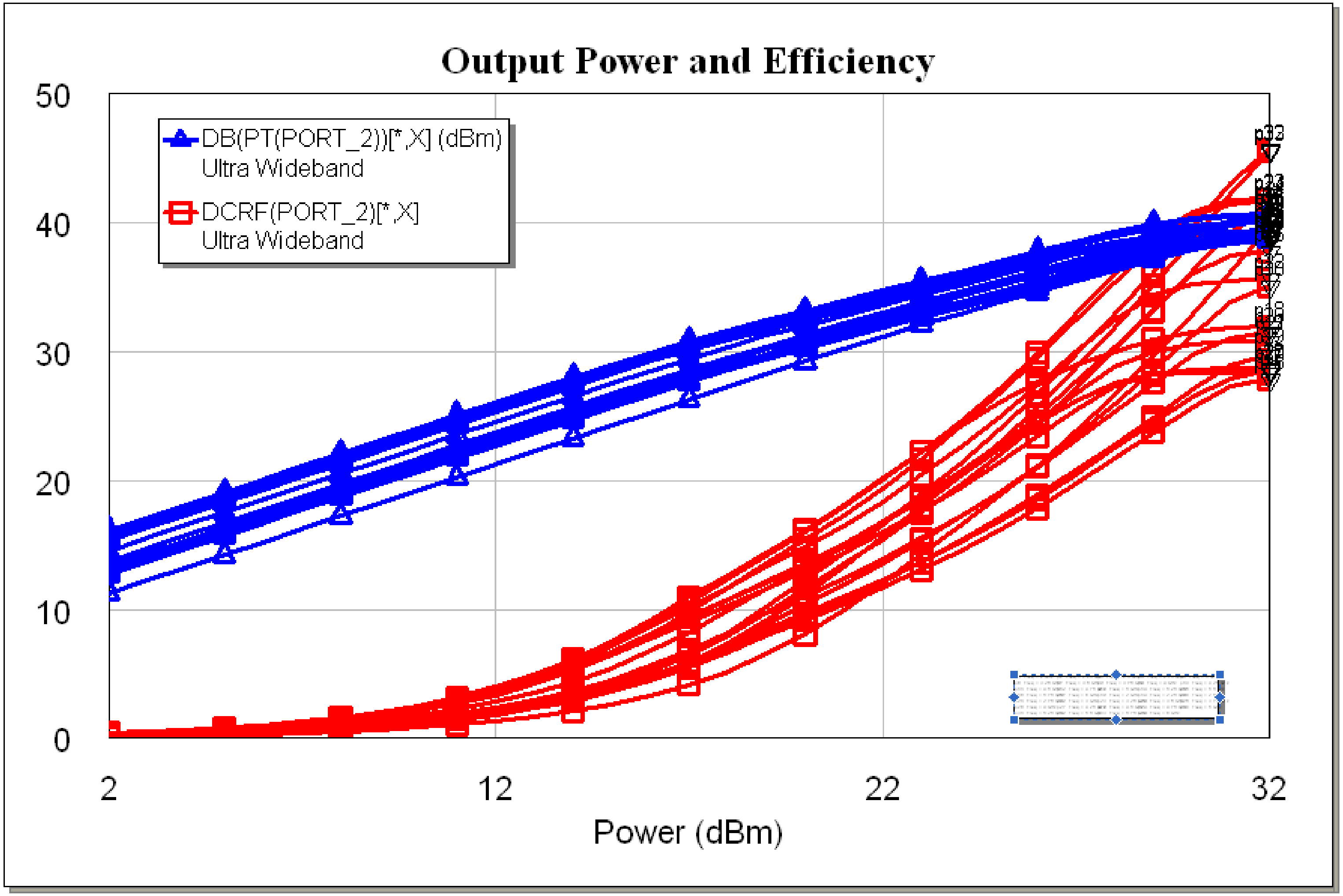
# Small signal gain, input and output return losses



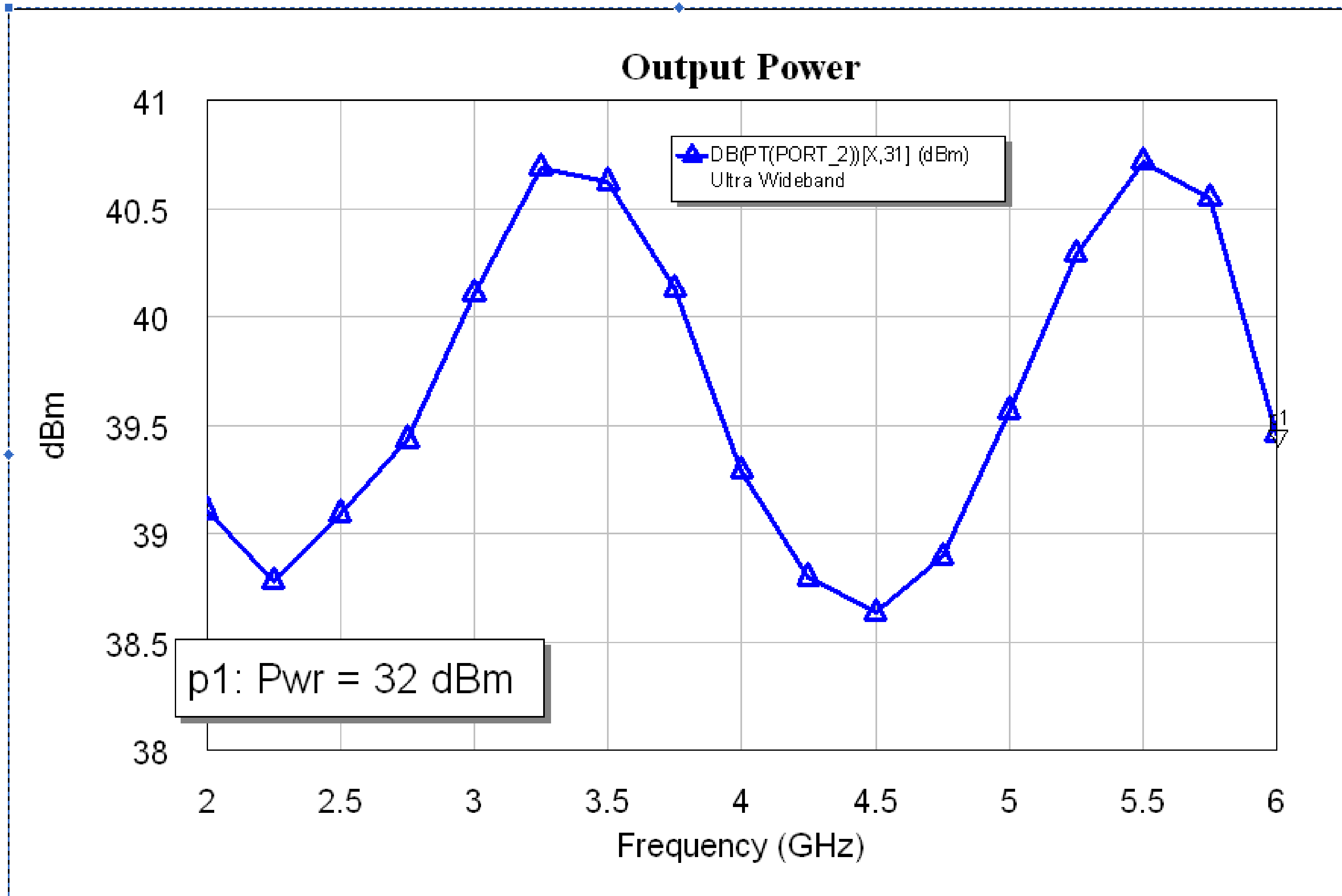
# Output Power and Efficiency at 3.6 GHz



# Output Power and Efficiency versus Frequency



# Saturated Output Power versus Frequency

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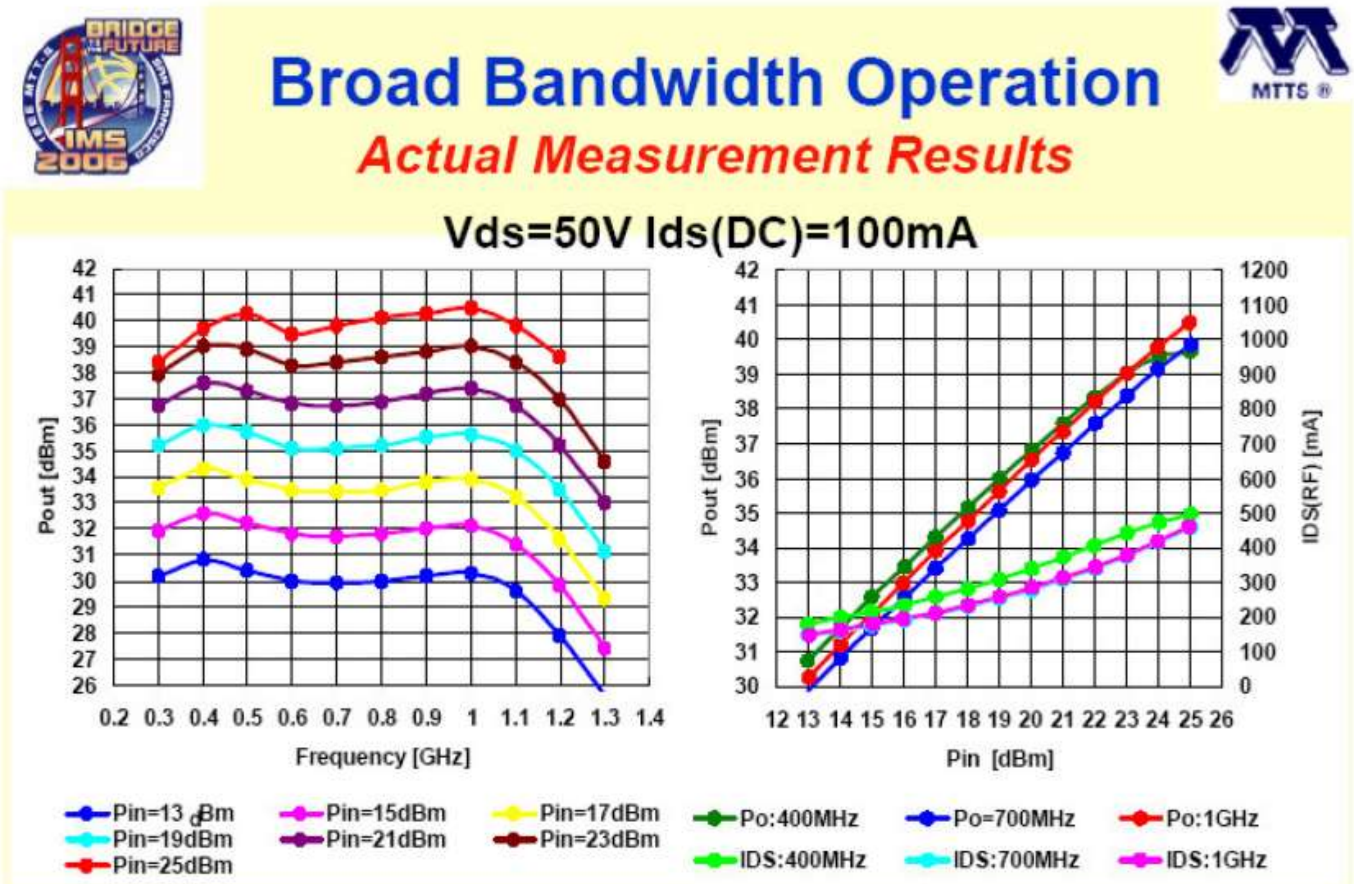
# Cree versus Eudyna!

# Eudyna 10 watt GaN HEMT




Eudyna

0.3 to 1 GHz 10 Watt Amplifier 21

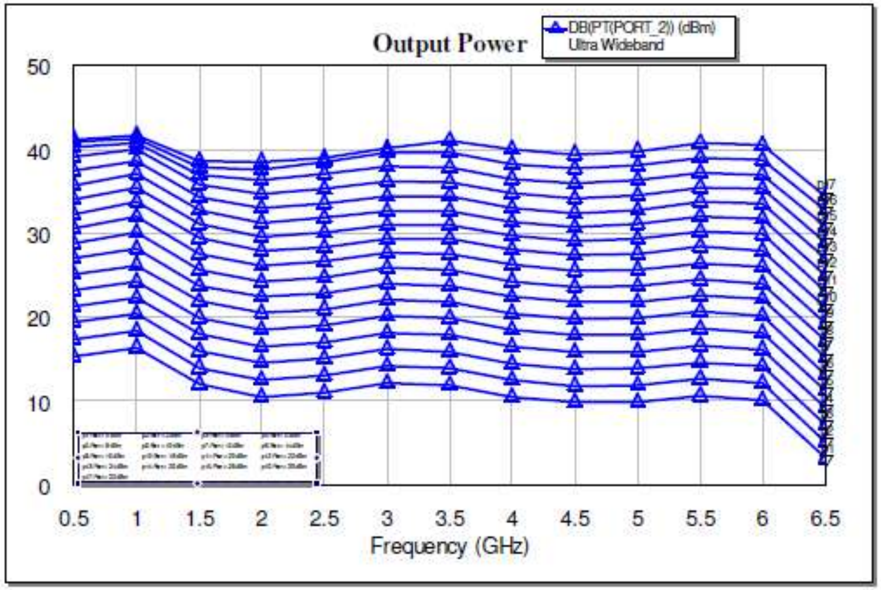
17 dB small-signal gain

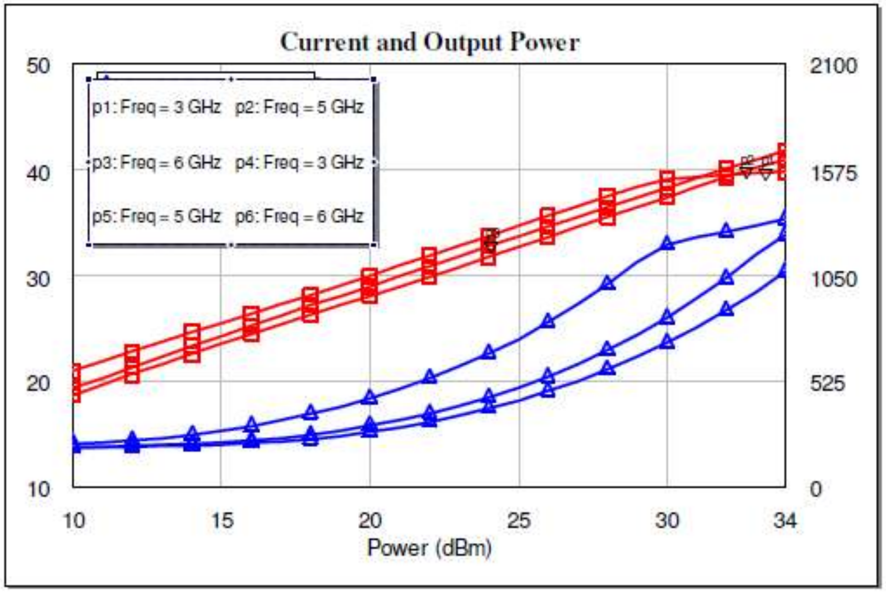
40% drain efficiency at 10 watts RF output power

CREE

# Cree 10 watt GaN HEMT

$V_{DS}$ = 28 volts $I_{DQ}$ = 200 mA




Pin is 0 to 32 dBm in steps of 2 dBm

## Cree 0.5 to 6 GHz 10 Watt Amplifier

10 to 14 dB small-signal gain

30 to 40% drain efficiency at P-1dB RF Output Power

Direct consequence of Cree's higher power density and lower capacitance per Watt!

# Example 5
# Linear WiMAX Amplifier
# Simulation versus Measured Data
# for the CGH27060F

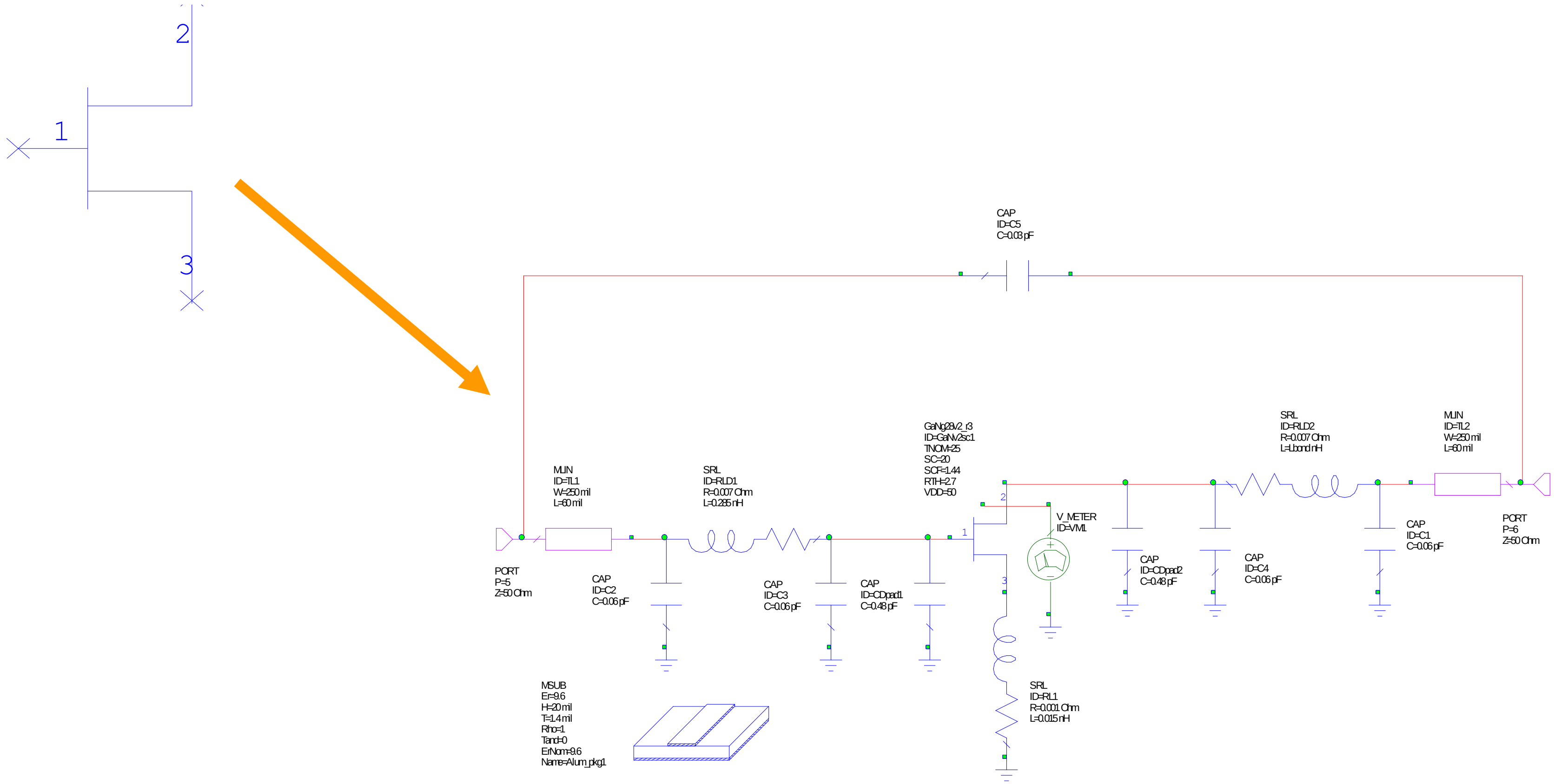
# Linear WiMAX Amplifier Simulation versus Measured Data

- 60 Watt, 2.3 to 2.8 GHz linear amplifier design
- Developed an accurate packaged transistor model using the Cree GaN HEMT scale-able die model
- Circuit developed to address Fixed and Mobile Access WiMAX applications such as
  - 802.16-2004
  - 802.16e
  - WiBro
- The design targets were as follows:
  - Average Output Power > 8W
  - EVM < 2.5%
  - Drain Efficiency > 25% (under WiMAX stimulus)

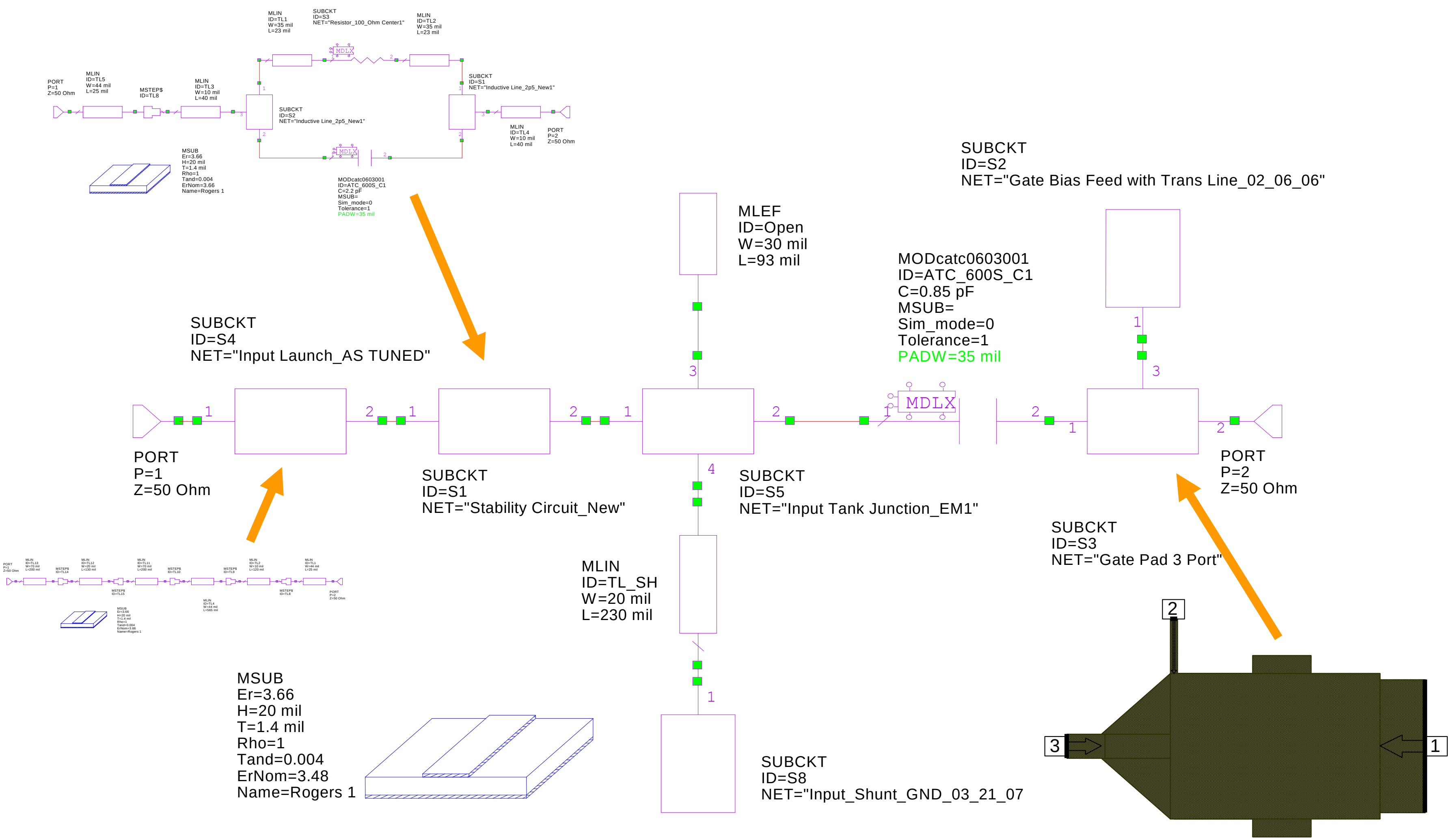
CREE

# CGH27060F Packaged Device Model

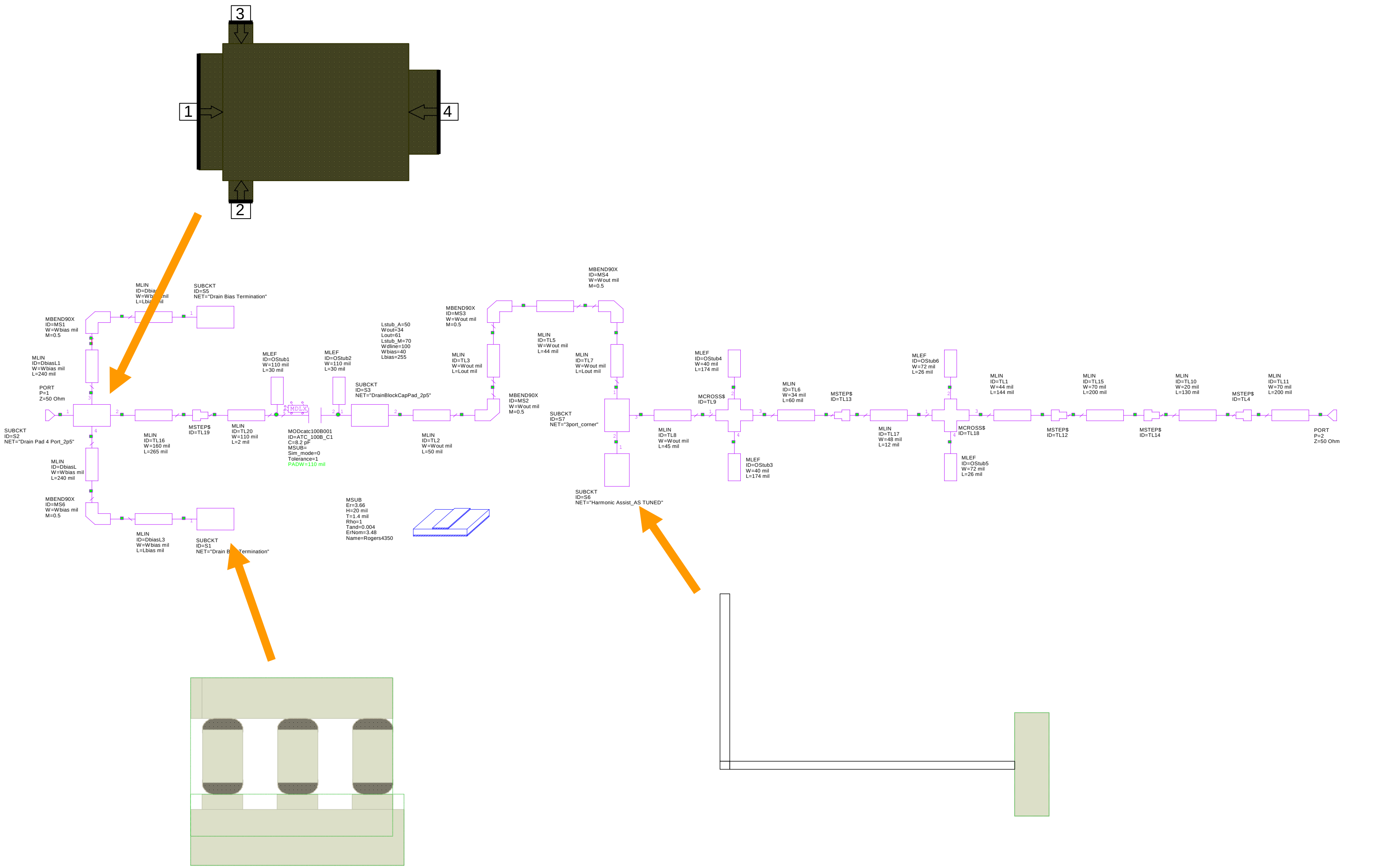
ID=CGH27060
TNOM=25



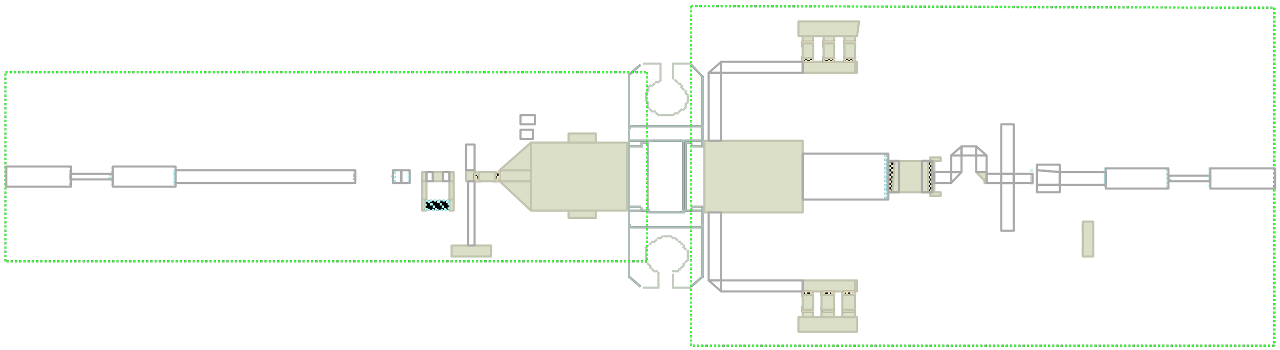
# Input Circuit Model

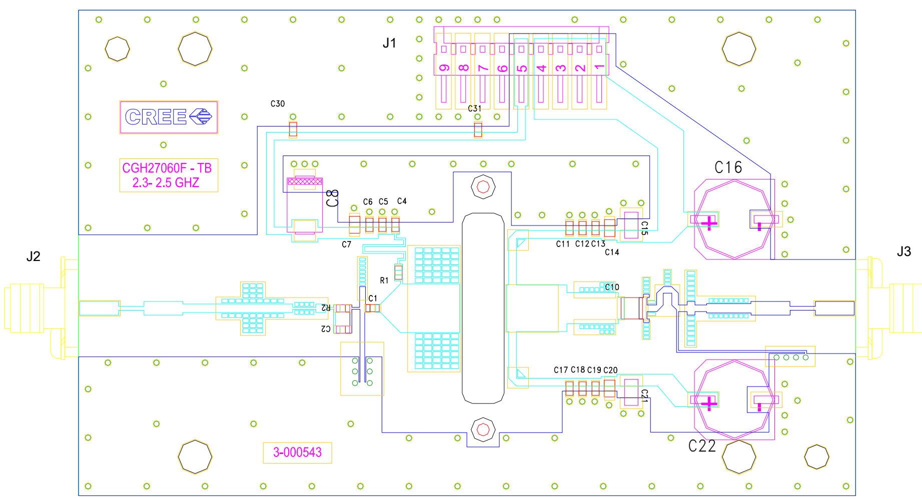


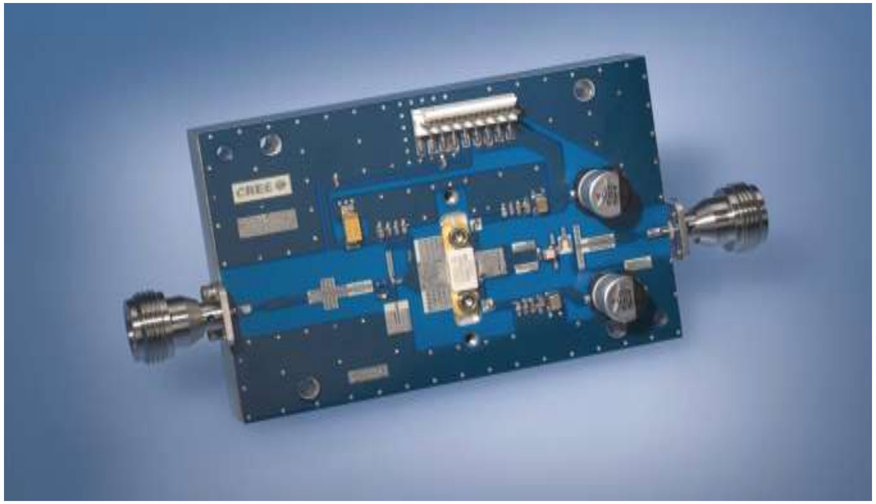
# Output Circuit Model



# Fully Modeled Layout of Amplifier

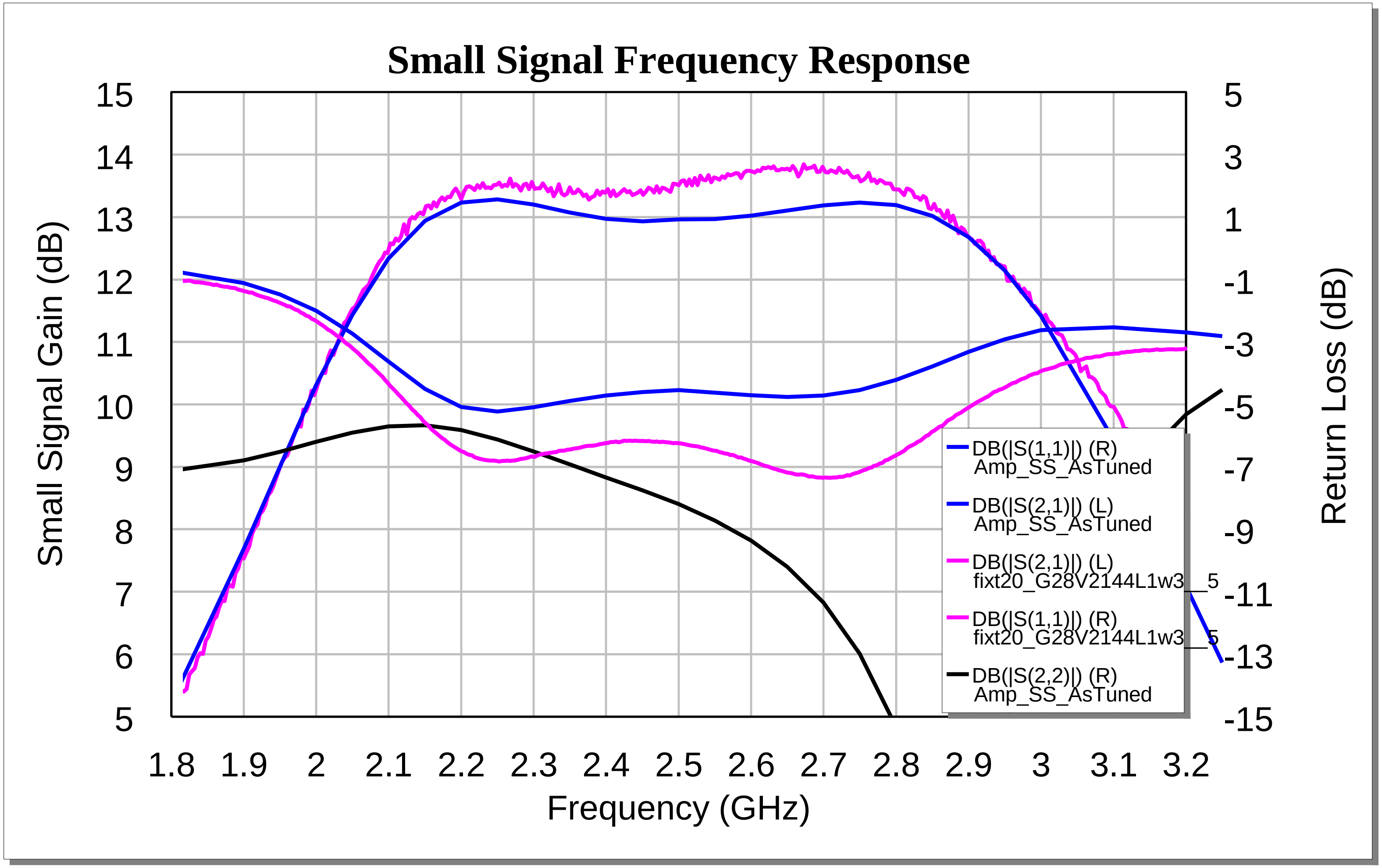




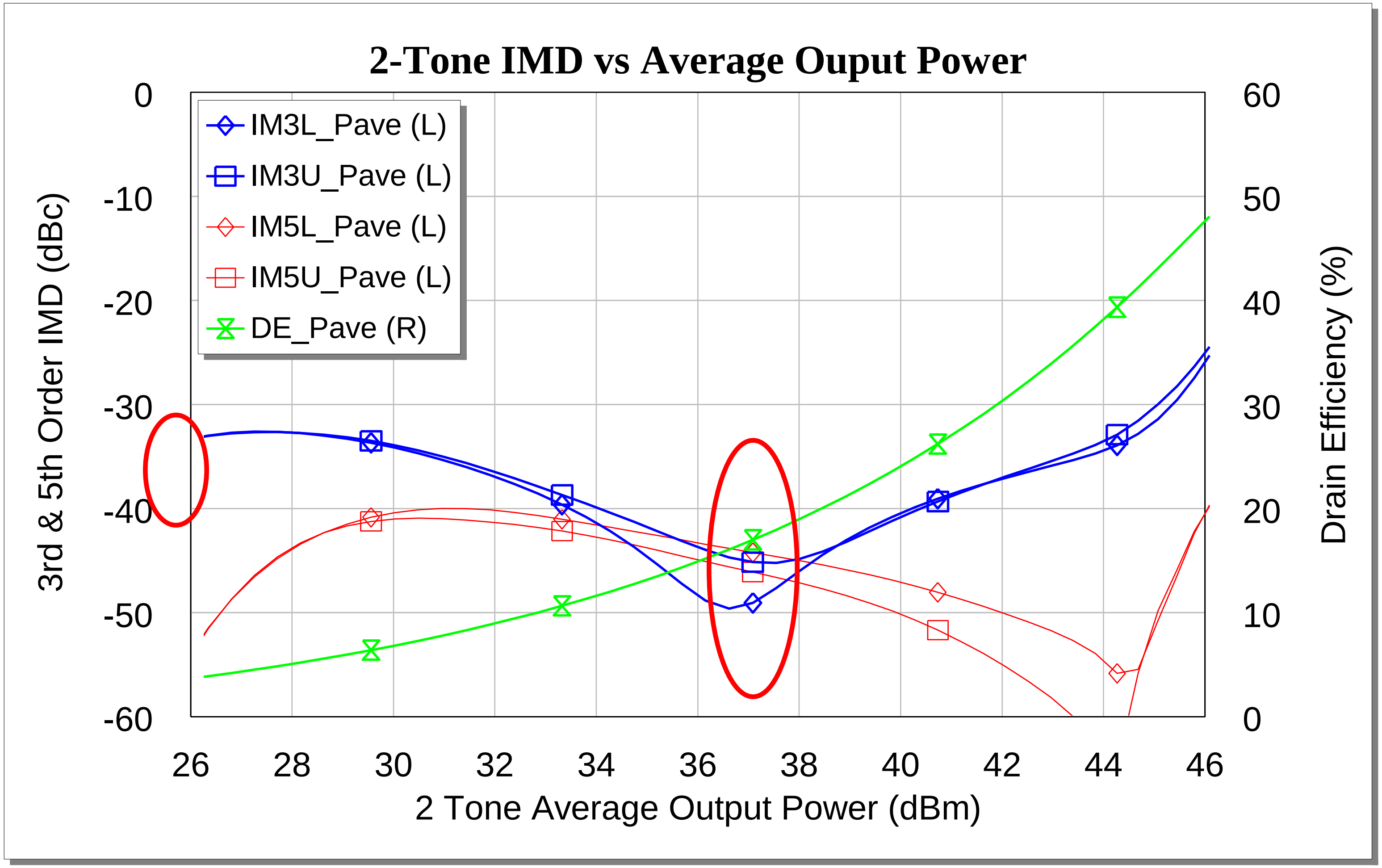



Actual Printed Circuit Board

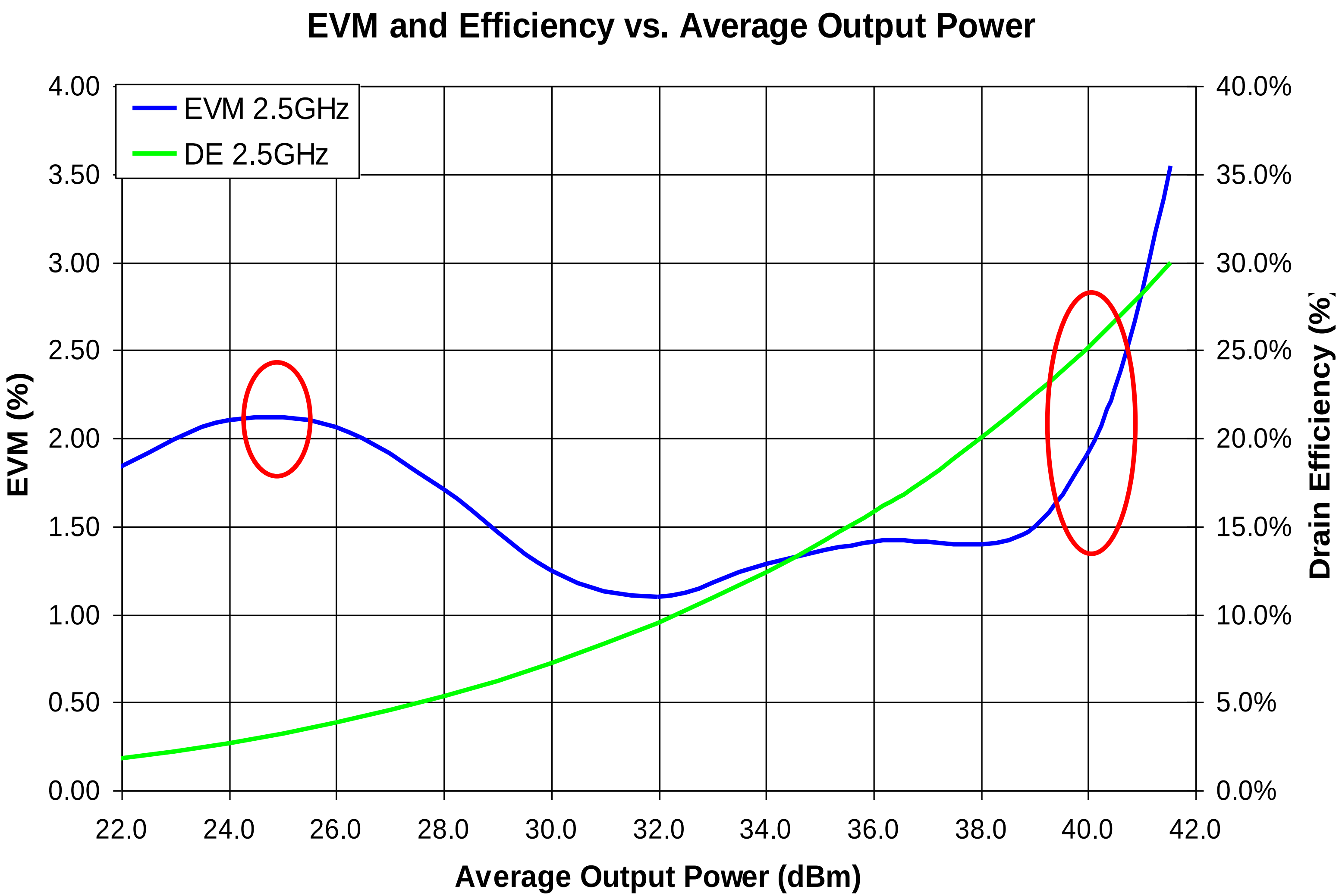
# Simulated and Measured Amplifier



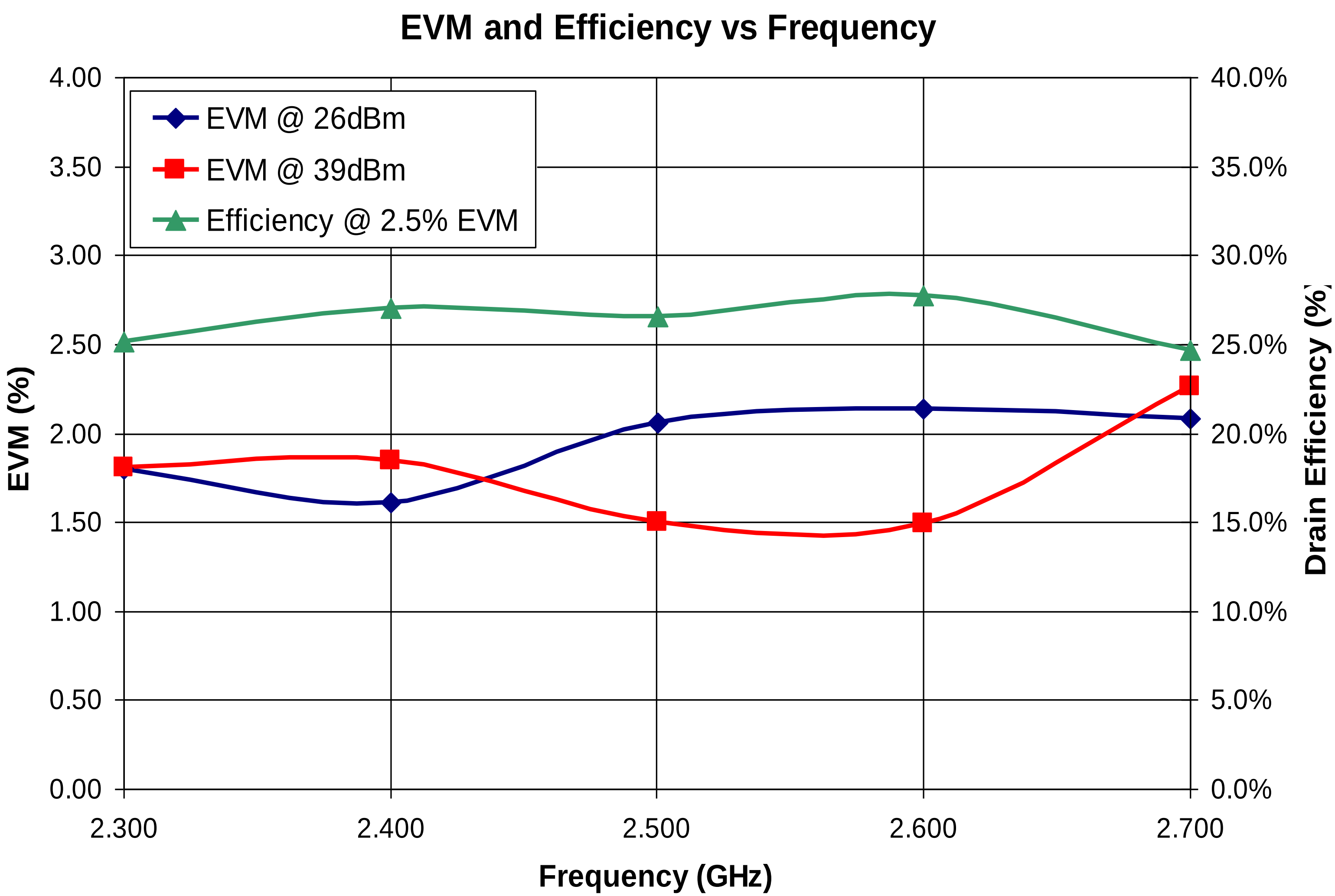
# Simulated Linearity of Amplifier



# Measured Linearity of Amplifier



# Measured Linearity of Amplifier



# Example 6
# 6 GHz Linear Amplifier using CGH55015F Transistor suitable for OFDM

# Summary

CGH55015F is electrically “short”

– Suitable for operation up to 6 GHz for linear applications

– Maximum available gain will be traded for linearity

– Use IM3 as a figure of merit for acceptable EVM

• Better than 40 dBc IM3 is equivalent to < 2.5% EVM

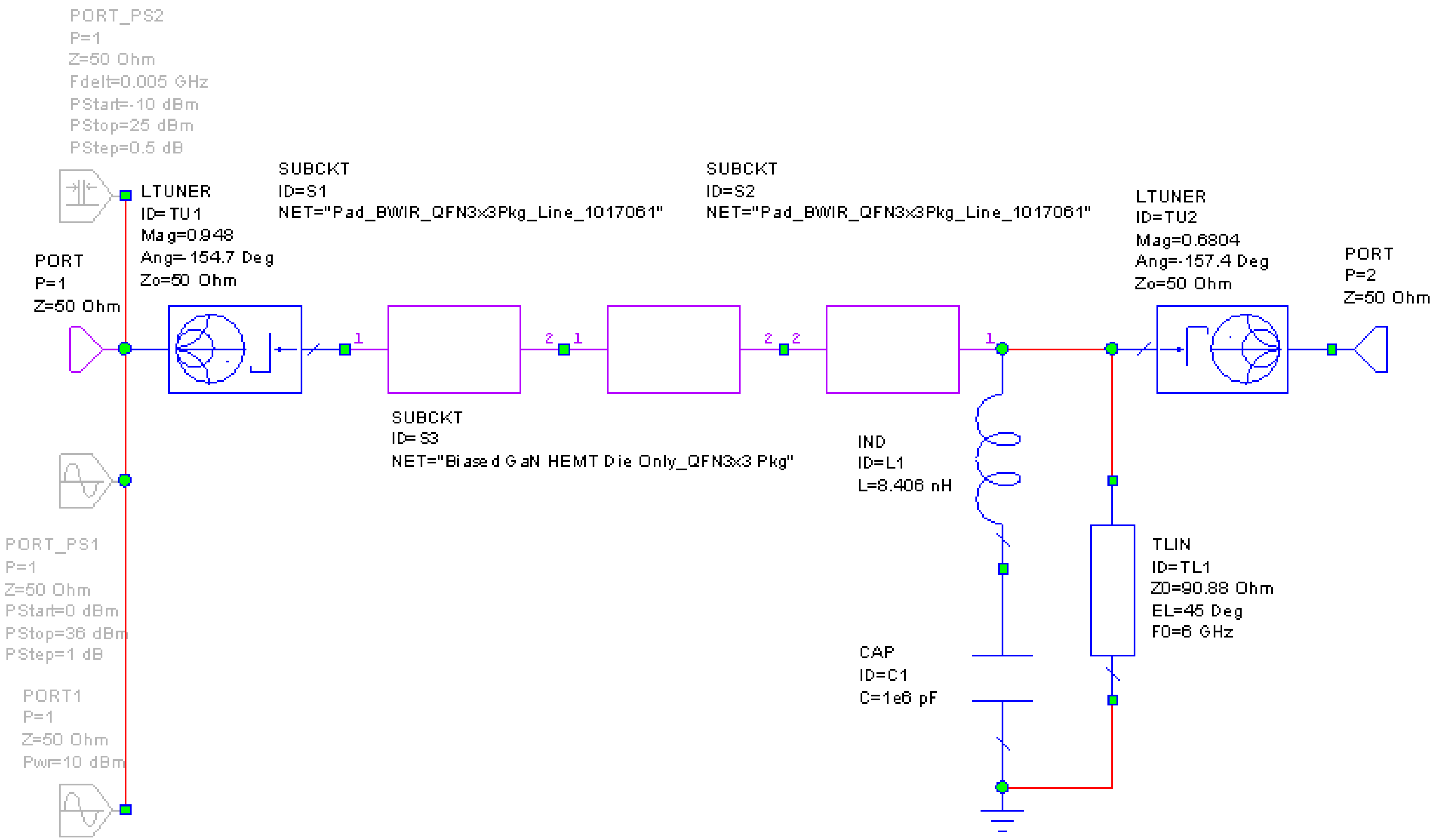
• Needed at both 2 watts $P_{AVE}$ under OFDM and over 15 dB back-off power dynamic range

• Video “short” used in design to assure low IM3’s

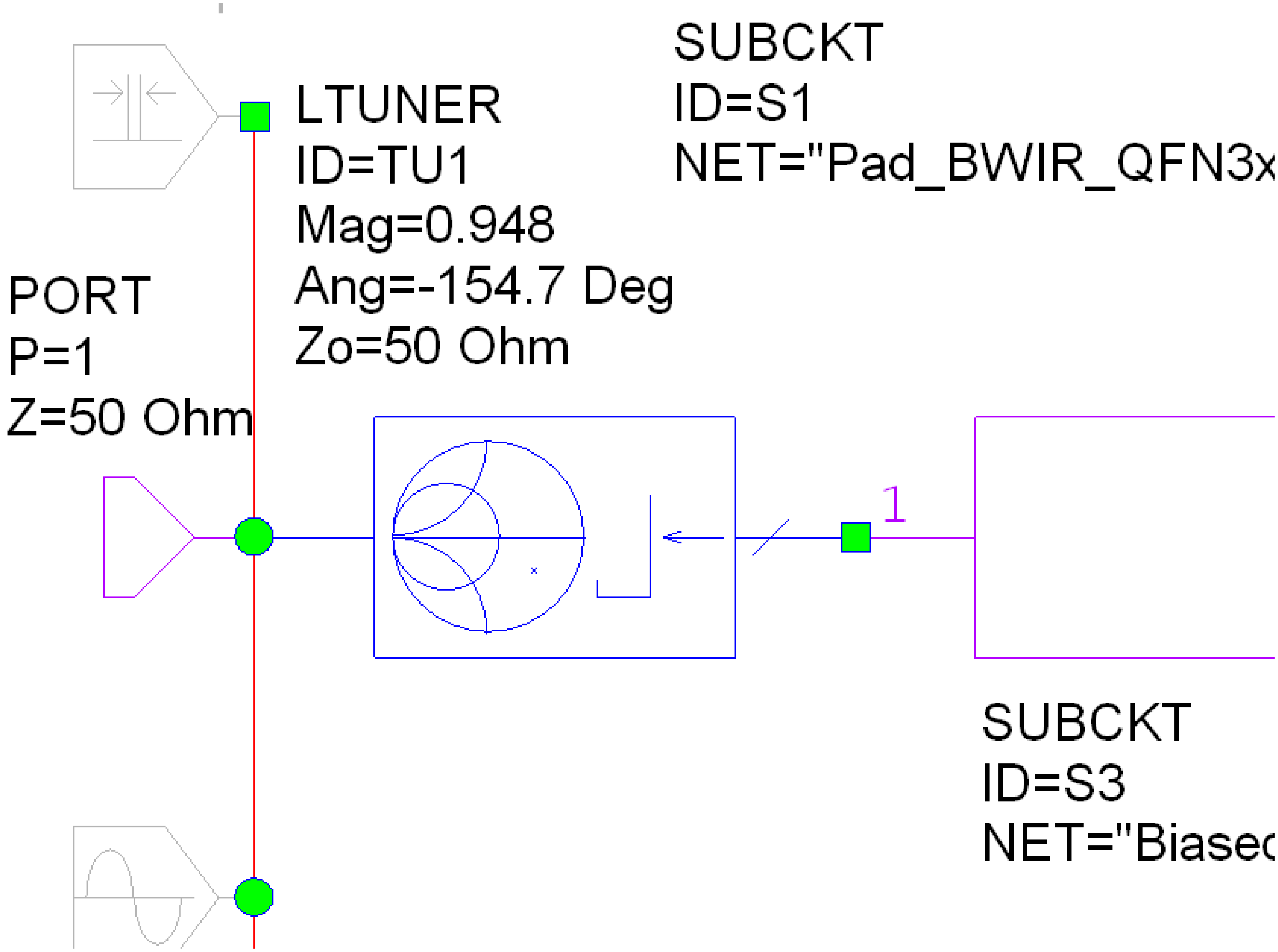
• 2nd harmonic short used on transistor output to improve linearity

• $I_{DQ}$ adjusted to 60 mA – value used for linear amplifiers at 2.5 and 3.5 GHz

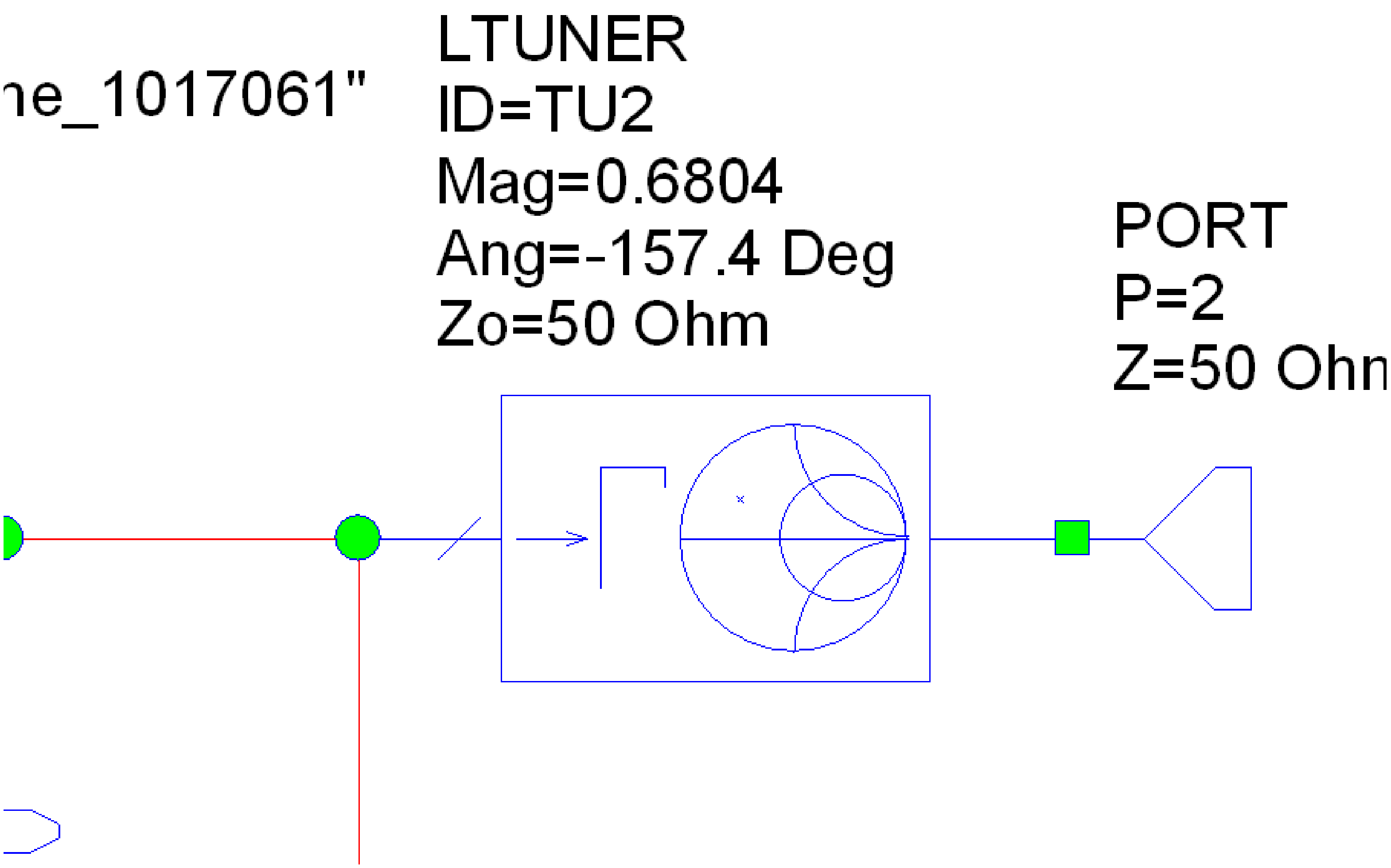
# PA Schematic



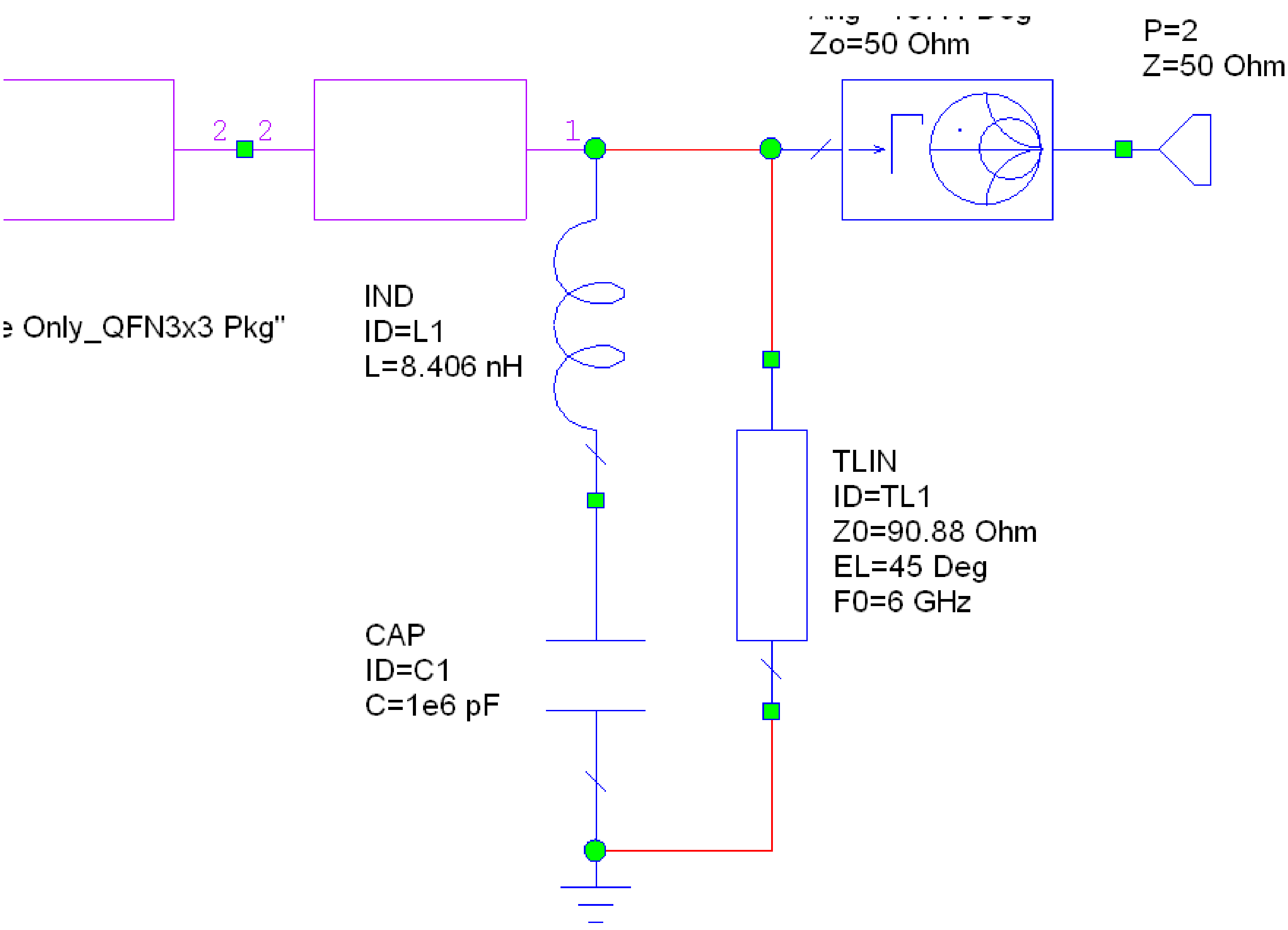
# Source Pull Value at 6 GHz



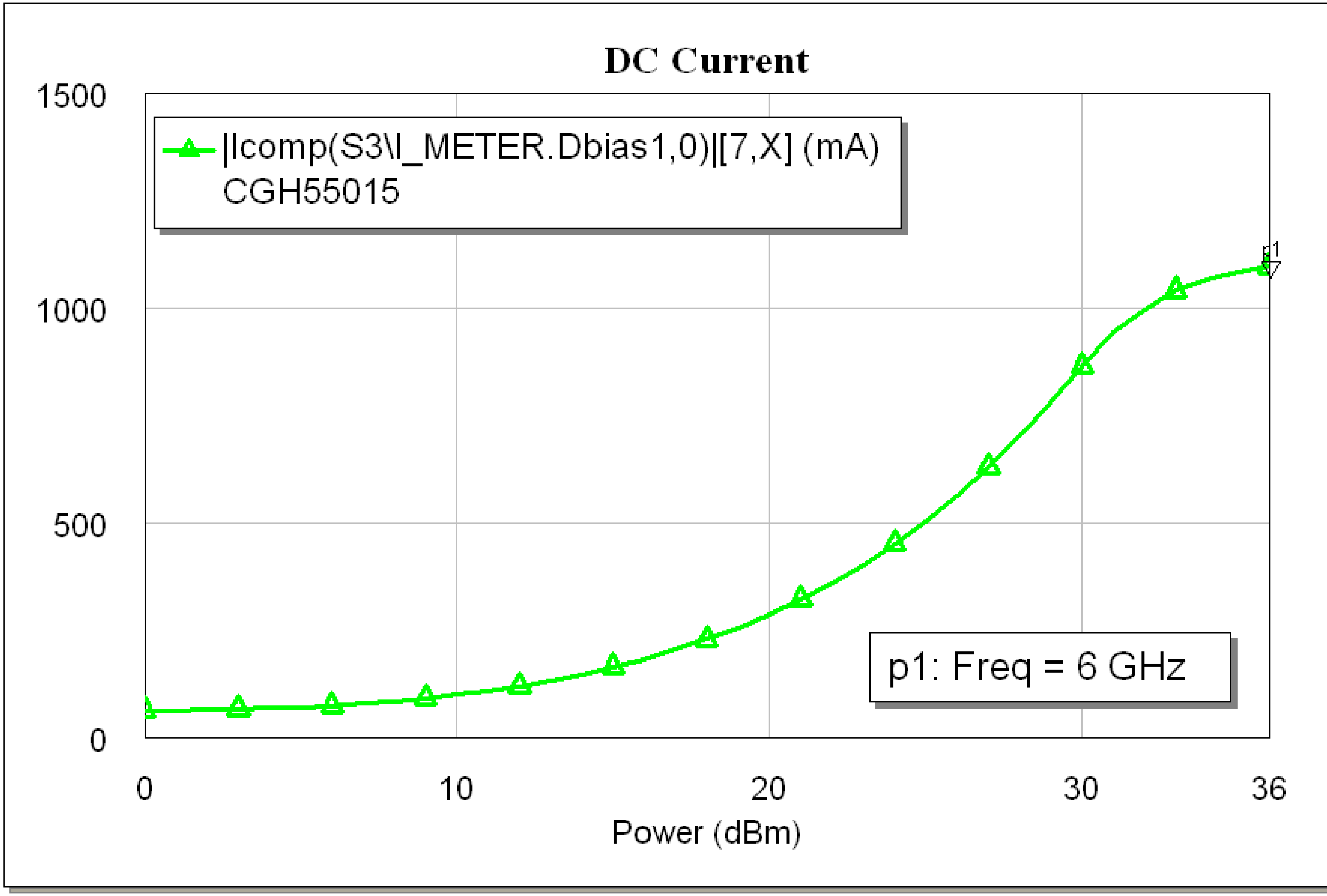
# Load Pull Value at 6 GHz



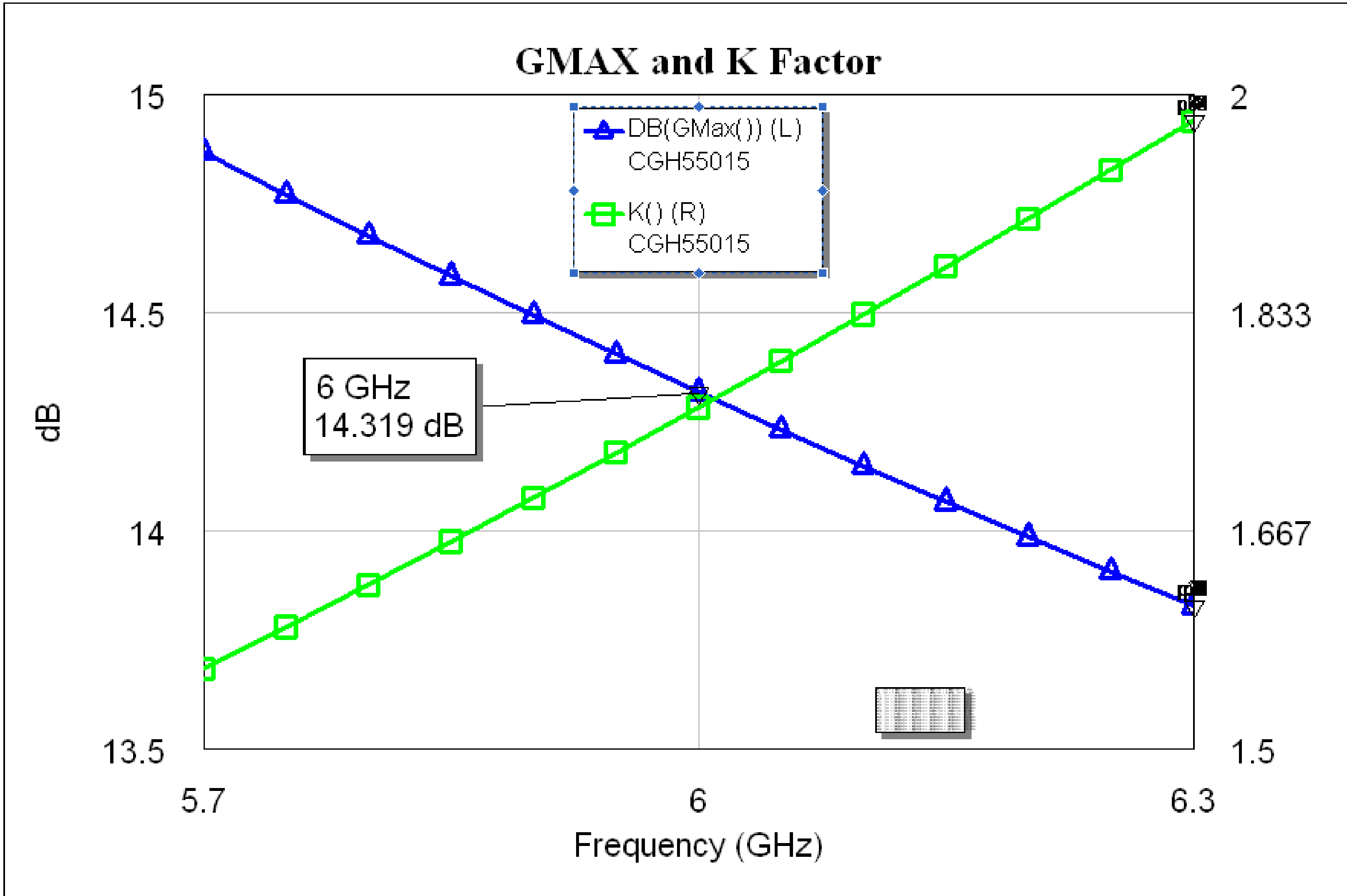
# Video Return and 2nd Harmonic Short



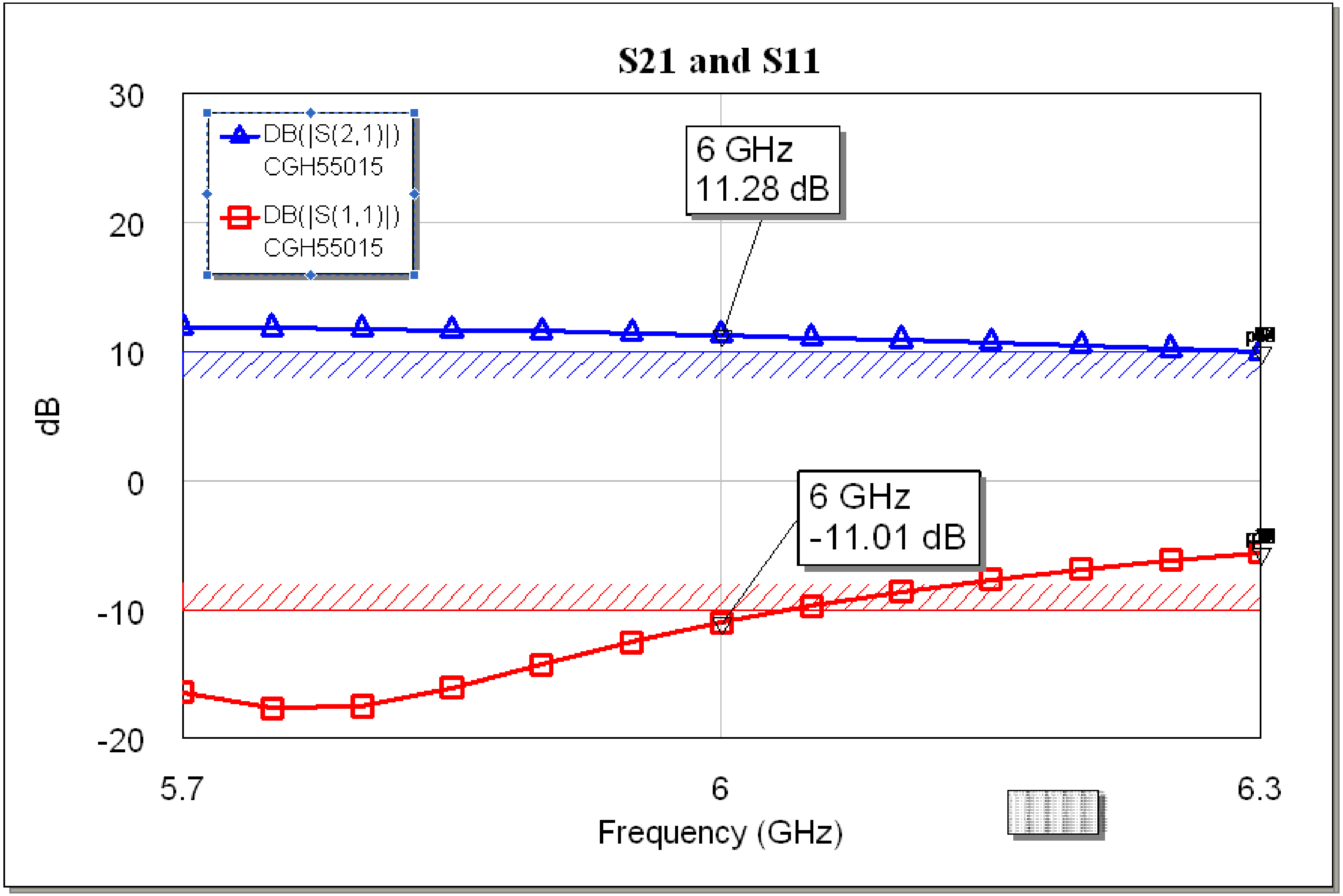
# DC Current versus RF Drive Level



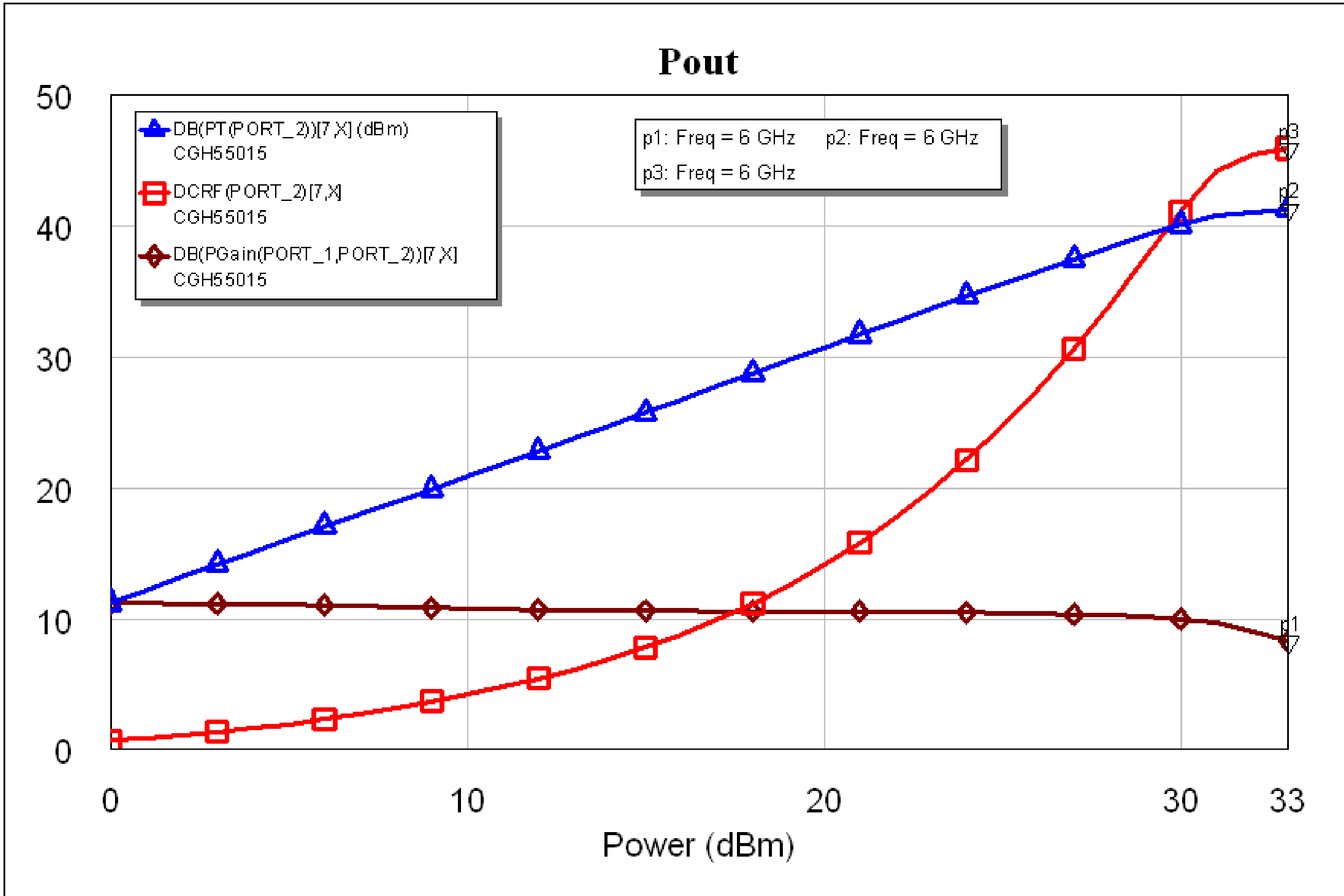
# Maximum Available Gain of CGH55015



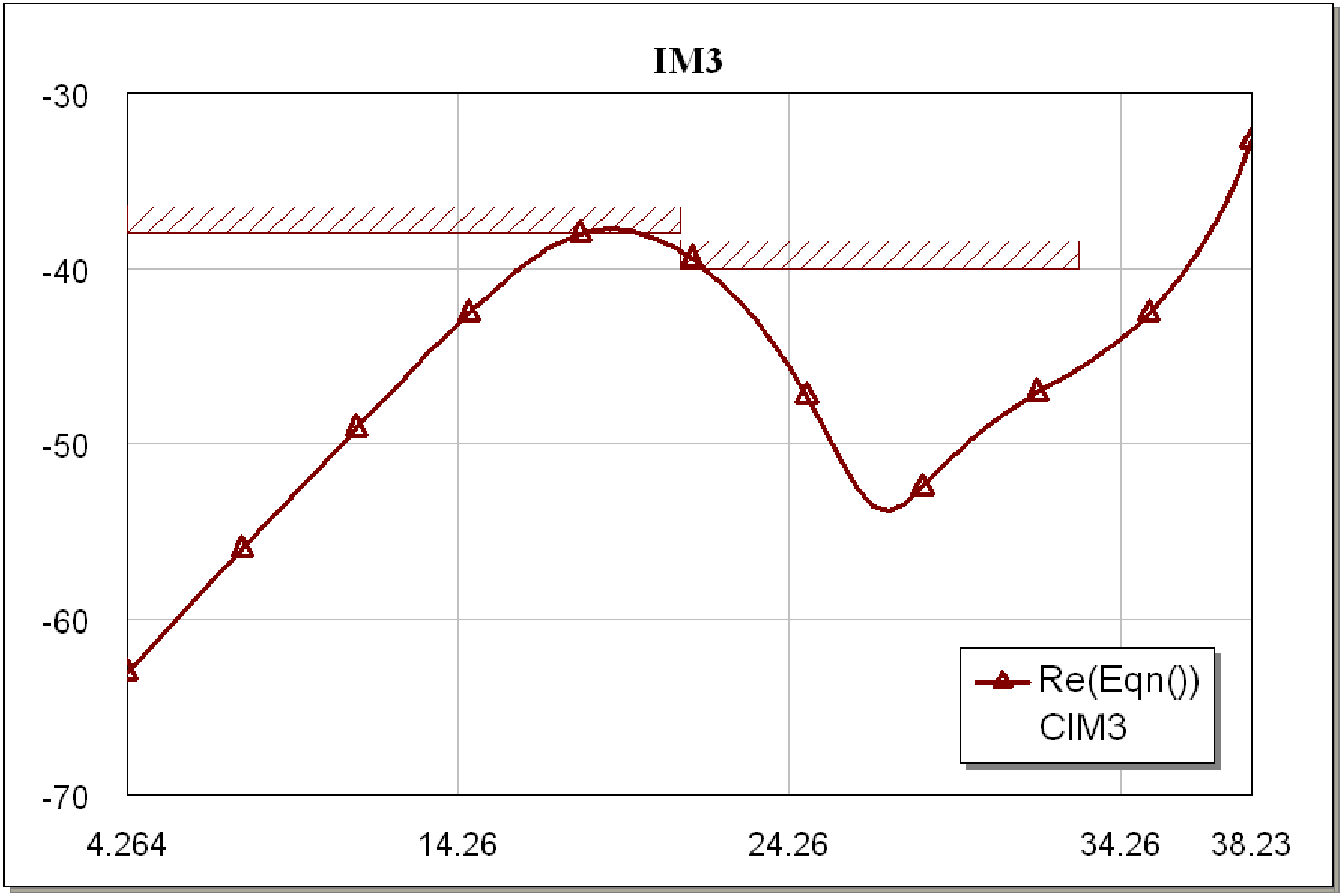
# Small-Signal Gain and Input return loss over 5.7 to 6.3 GHz



# Single-Tone CW RF Output Power, Power Gain and Drain Efficiency versus RF Input Power



# 2-Tone IM3 versus Input Power

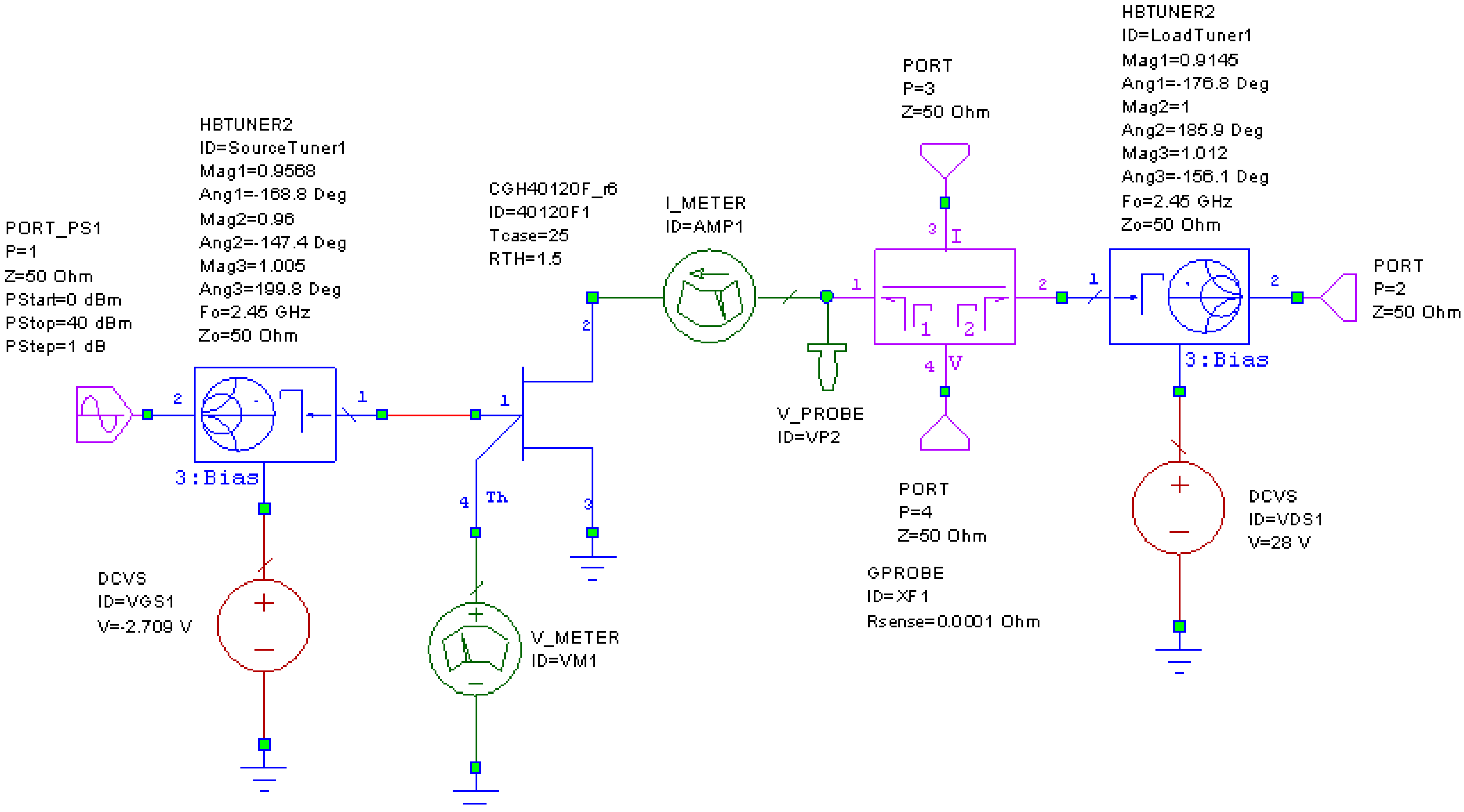


# Example 7
# High Efficiency Waveform Engineered Amplifier

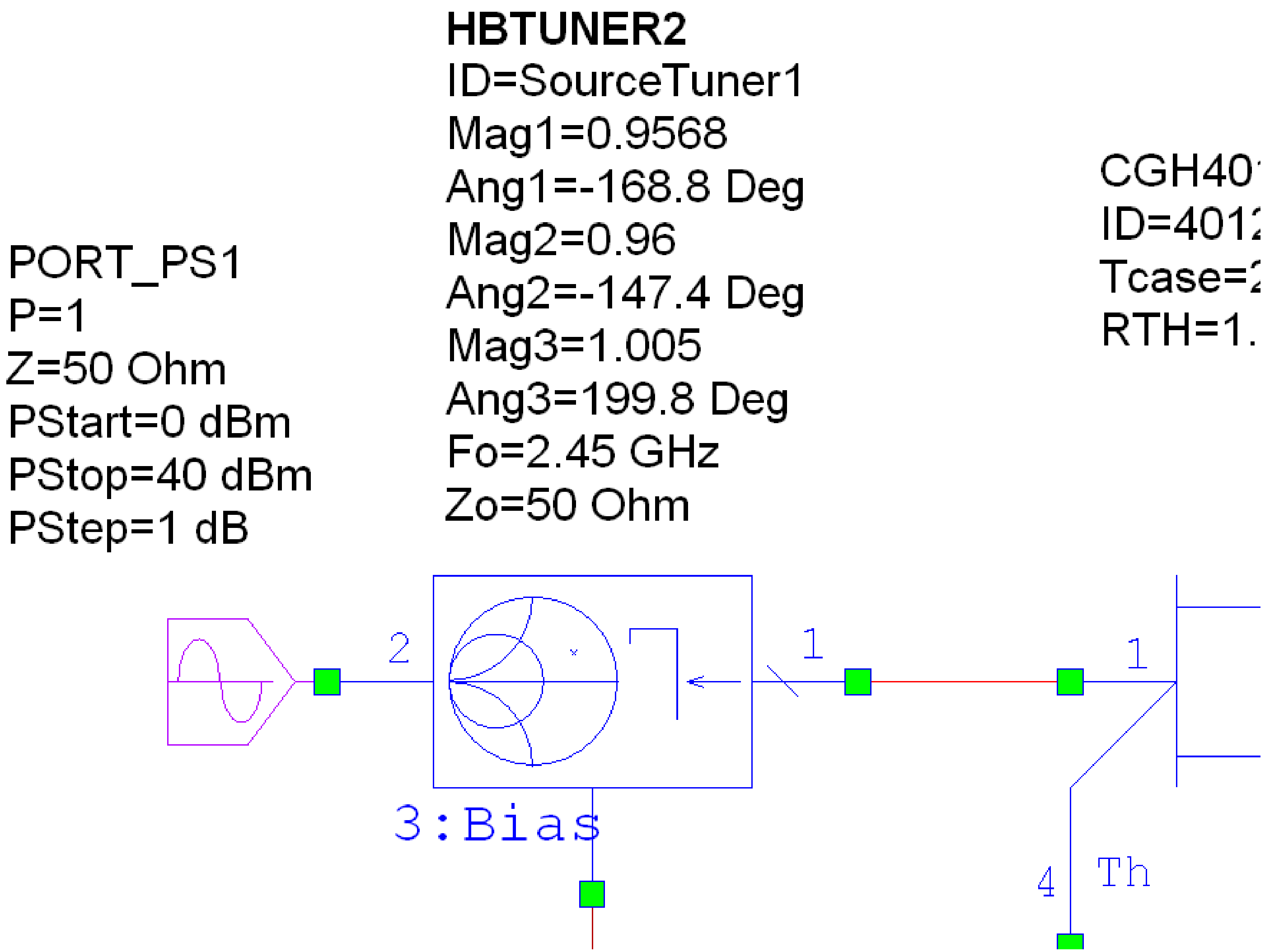
# Summary

- CGH40120F operating at 28 volts
- Fundamental tuning as well as 2nd and 3rd harmonic terminations to improve efficiency
- 2.45 GHz application where high efficiency is key

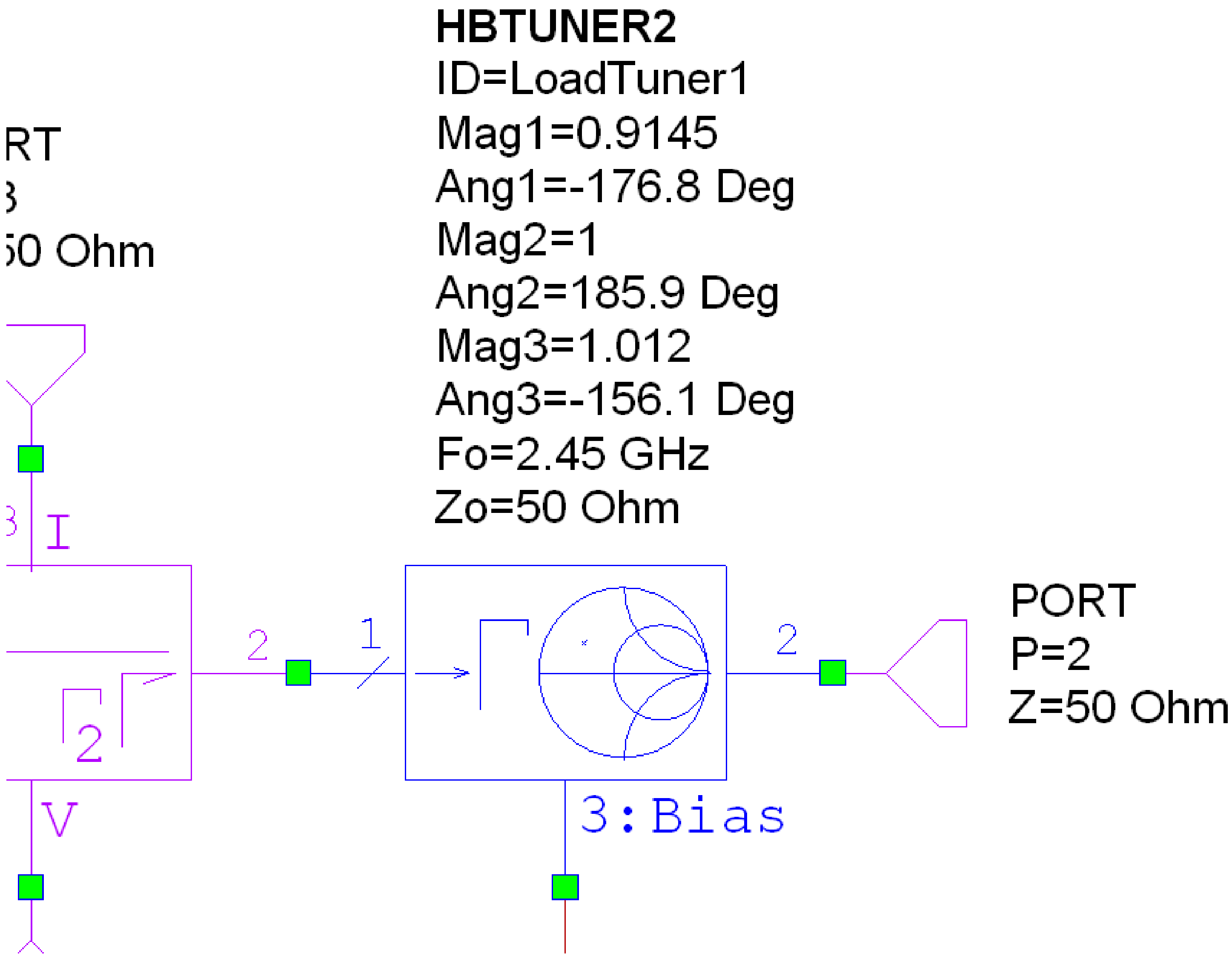
# Amplifier Schematic



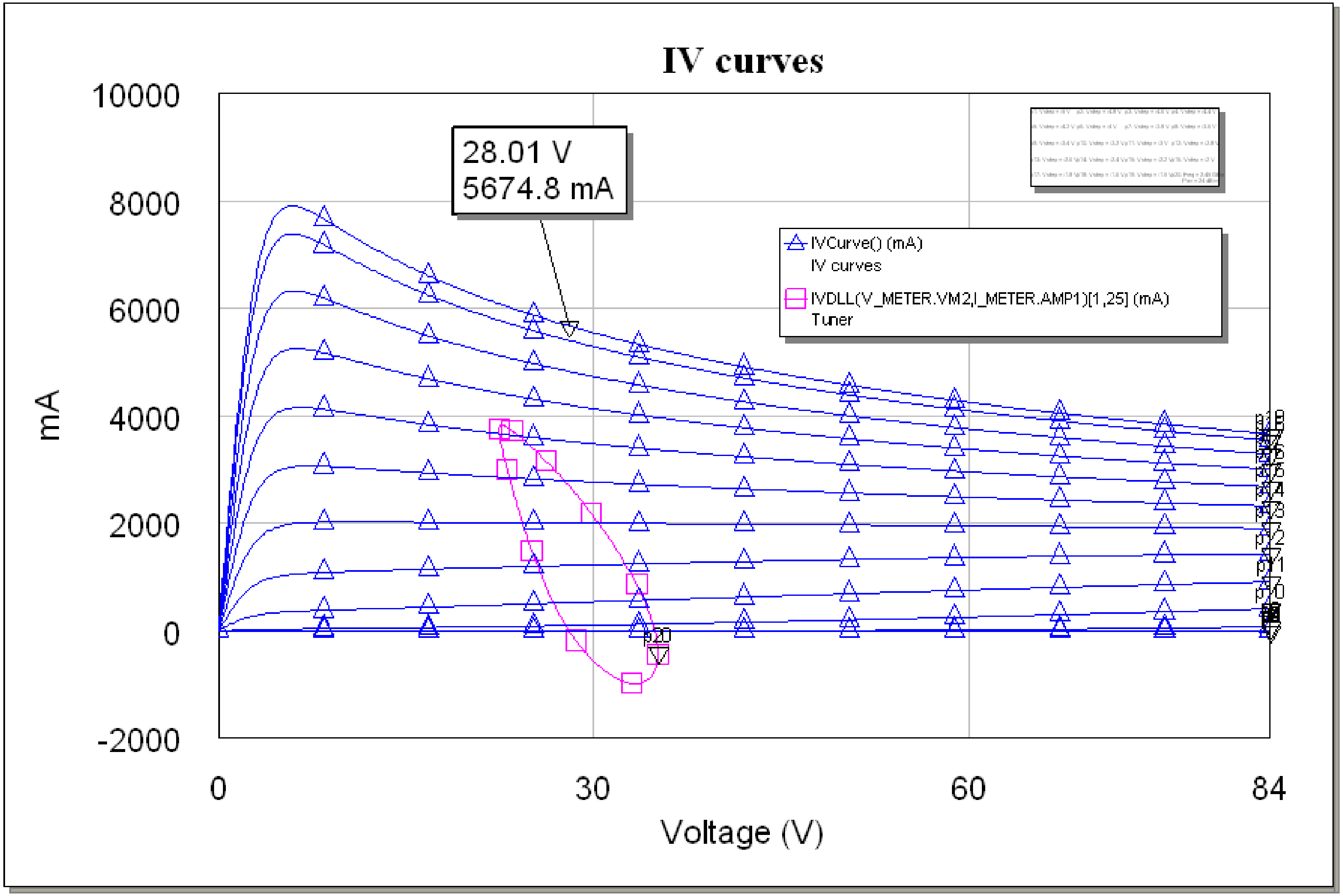
# Gate fundamental and harmonic terminations



# Drain fundamental and harmonic terminations

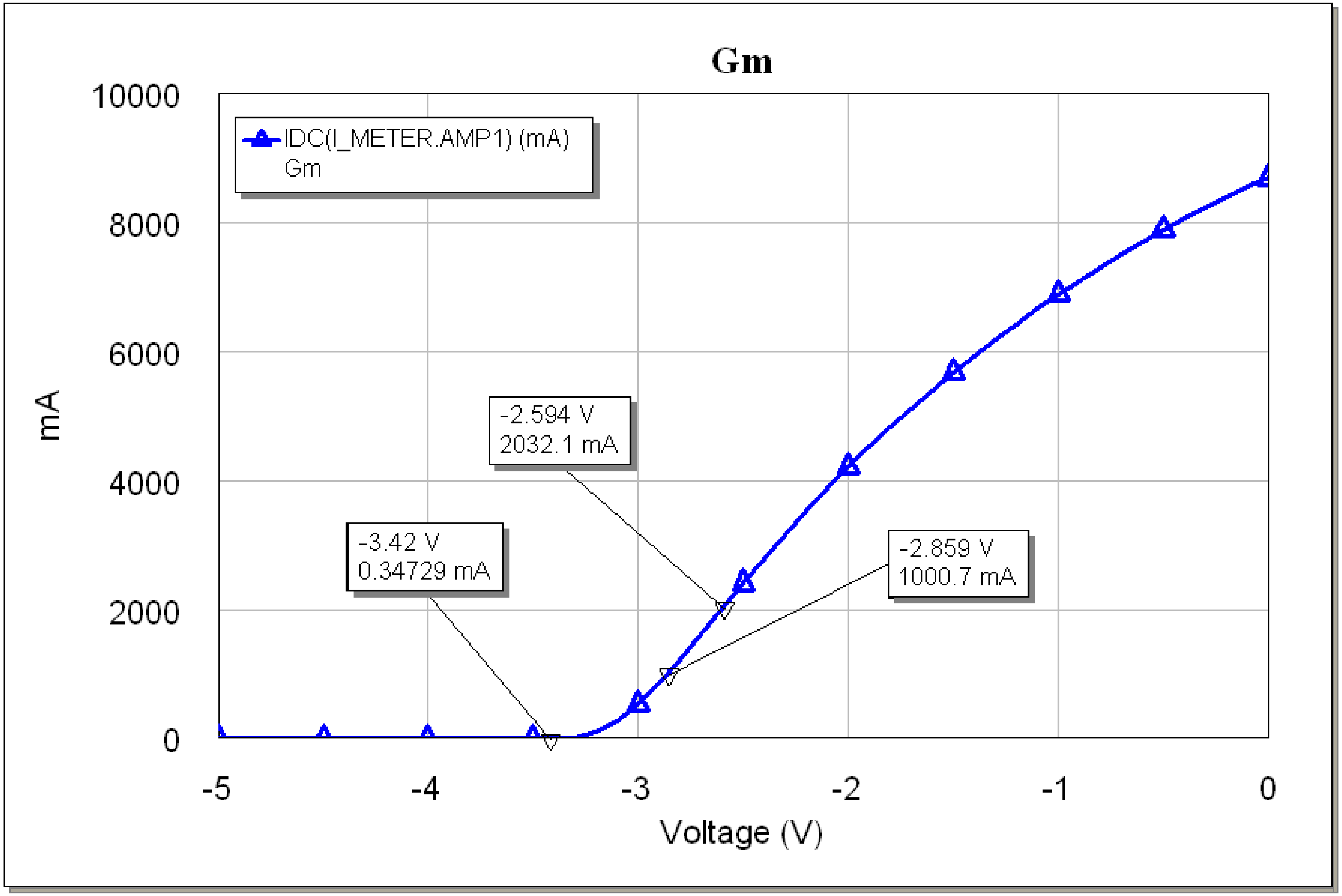


# I-V Curves showing effect of self heating (CW)

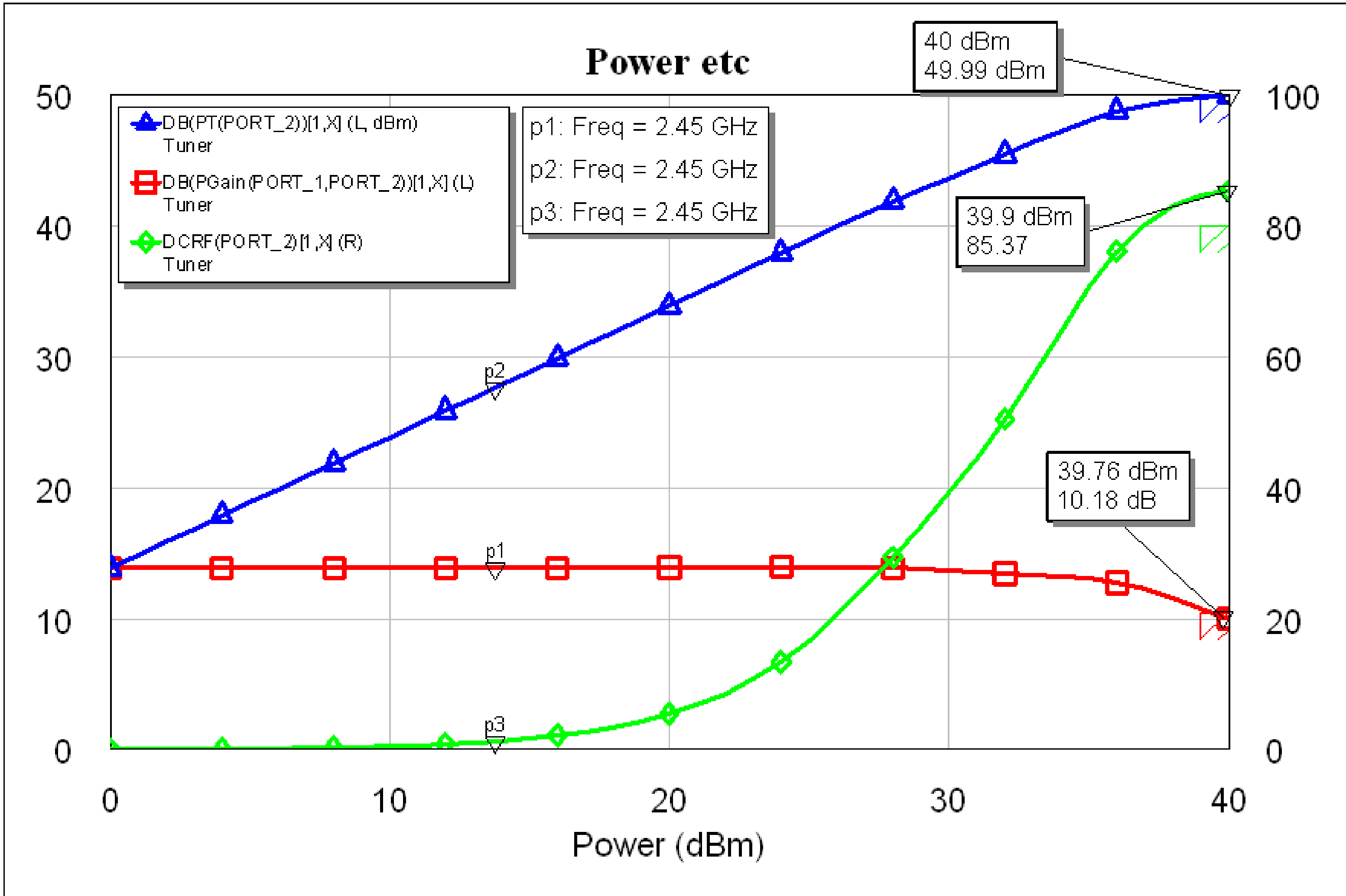



Also shown is dynamic load line

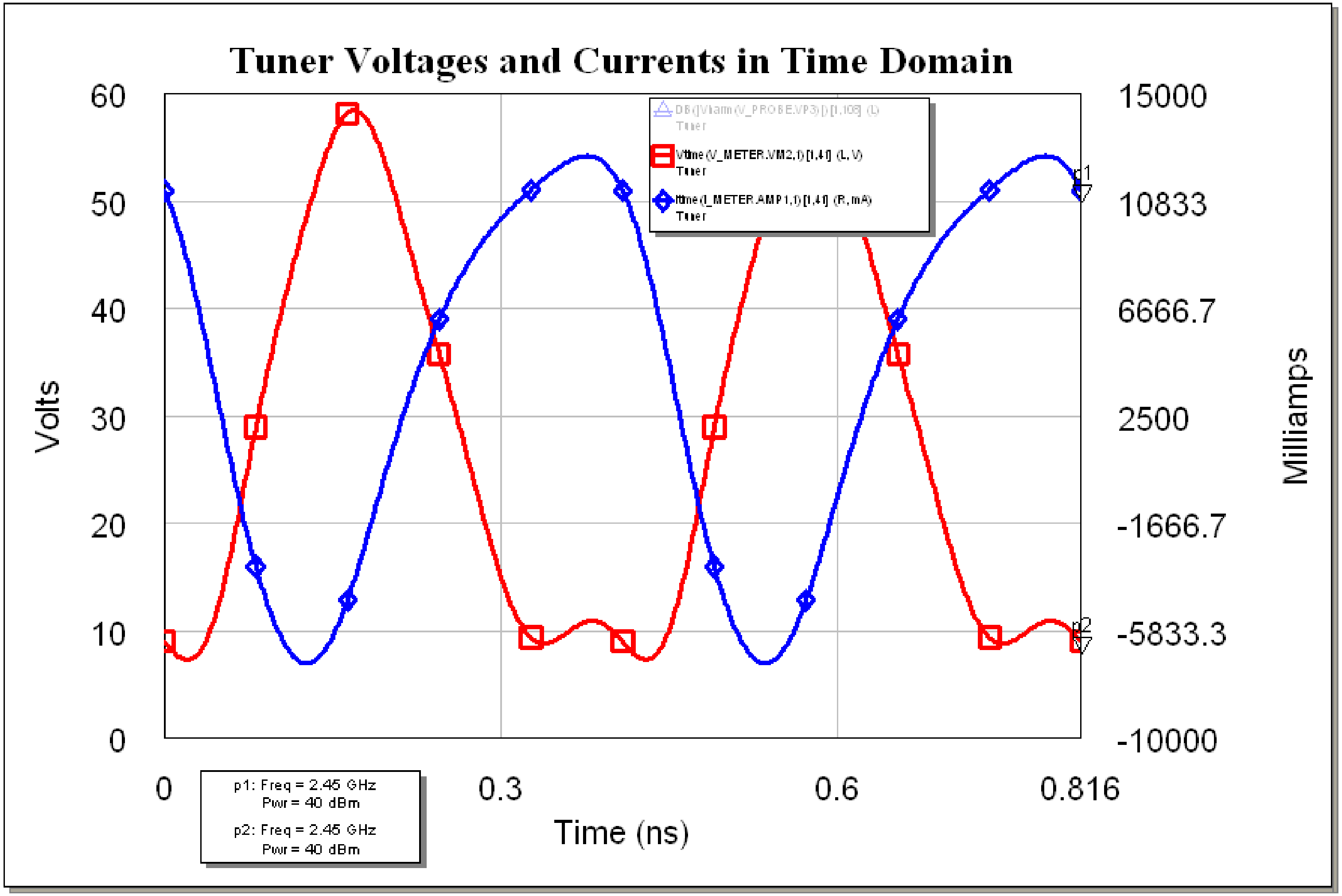
# Simulation showing pinch-off of transistor



# Output Power, Power Gain and Drain Efficiency

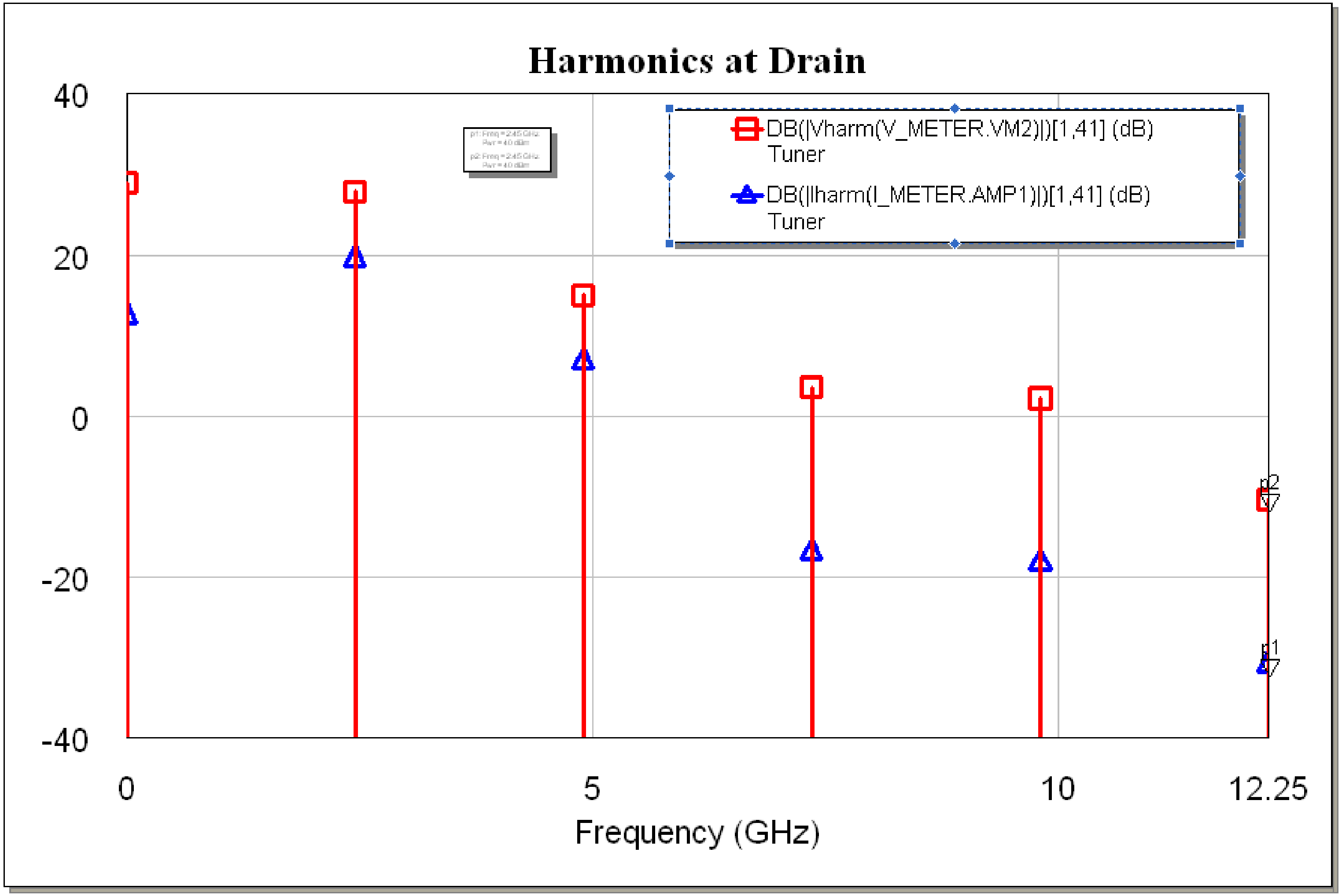


# Drain Voltage and Current Waveforms




Pin = 40 dBm

# Current and Voltage harmonics at Drain – 3dB compression



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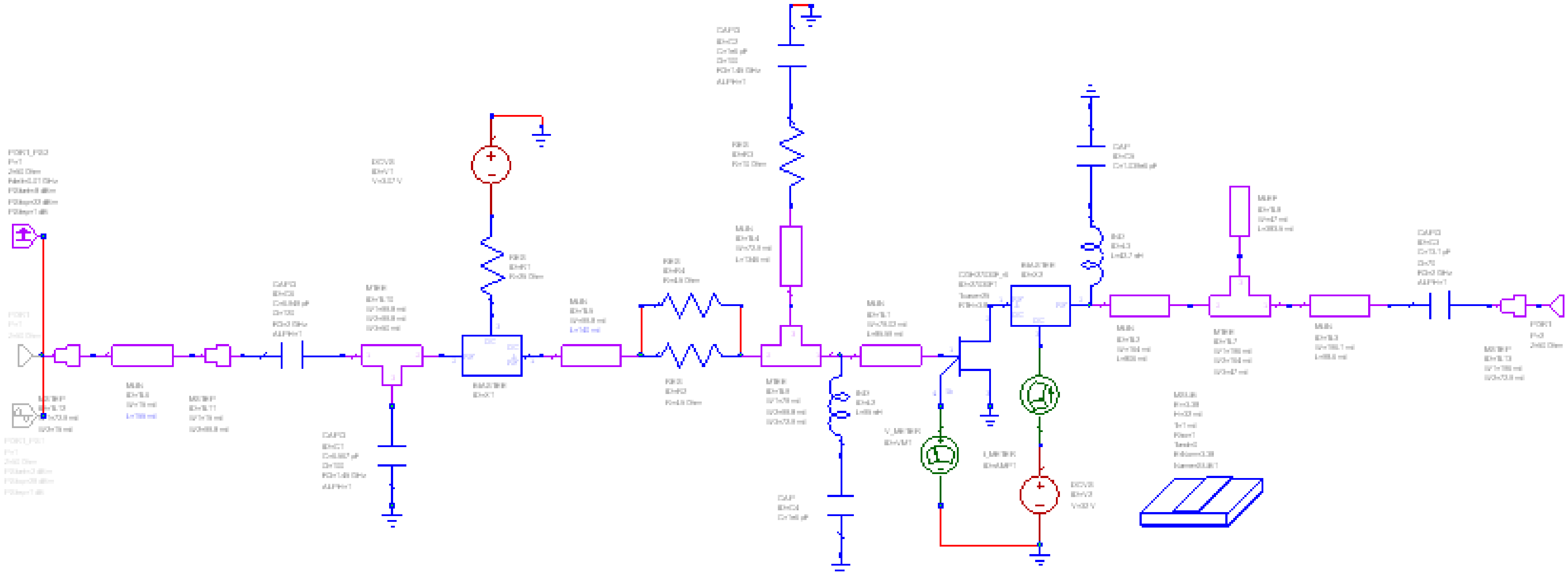
# Example 8
# CGH27030 Linear Driver Amplifier for the 1.45 to 1.492 GHz DVB-H Band

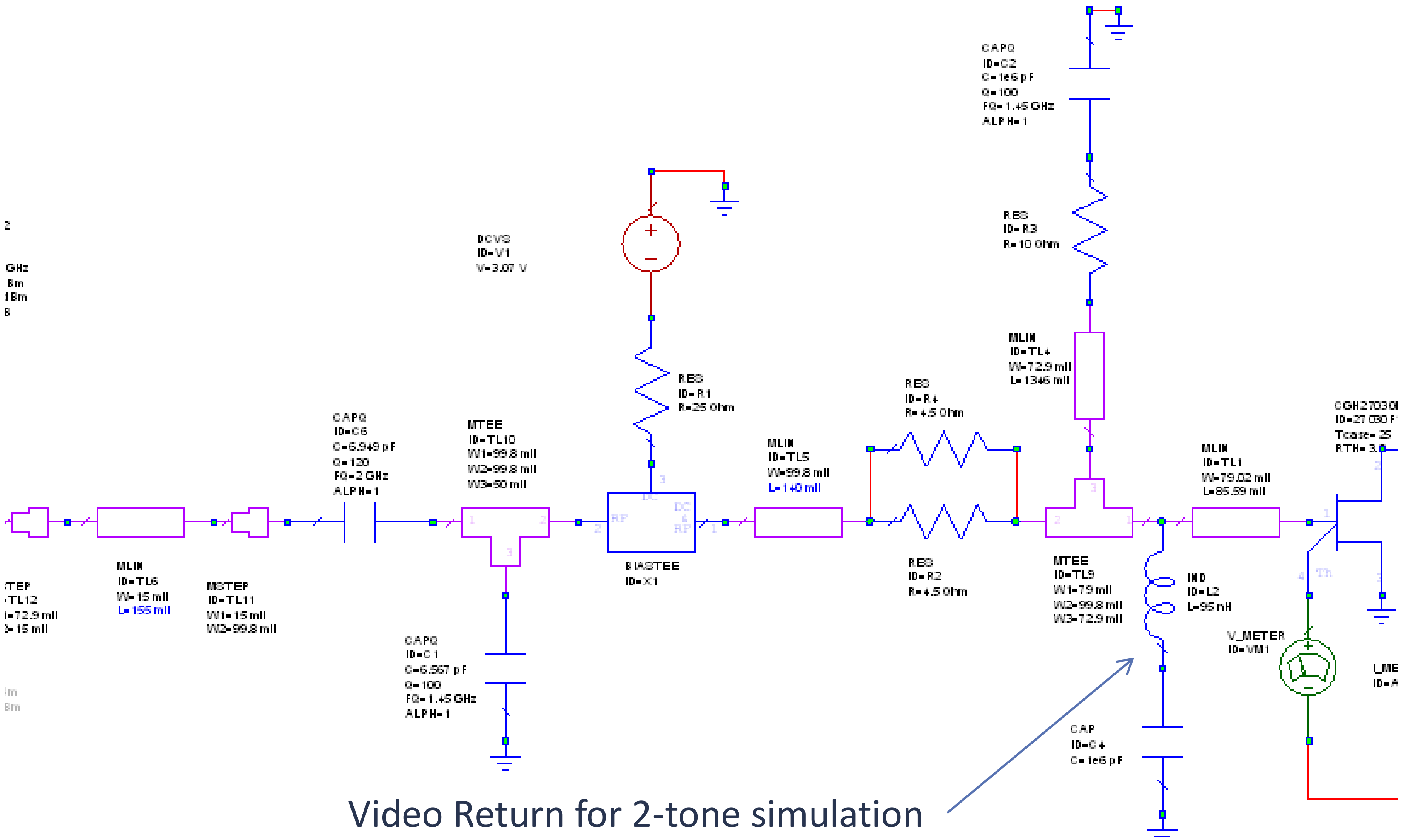
# Summary

- PCB material assumed to be 32 mil thick Rogers 4003 with dielectric constant of 3.38
- Simple design using a few transmission lines and chip components using CGH27030F GaN HEMT transistor in Cree 440166 package
- Drain voltage set at 32 volts and Idq set to 100mA
- Microstrip used with finite Q capacitors and inductor in simulation
- Goals
  - > 18 dB stable small-signal gain
  - IM3's at Pave and back-off hill to be better than 42 dBc and 35 dBc respectively
  - Psat > 25 watts
  - Input Return Loss > 15 dB

# Schematic of Amplifier



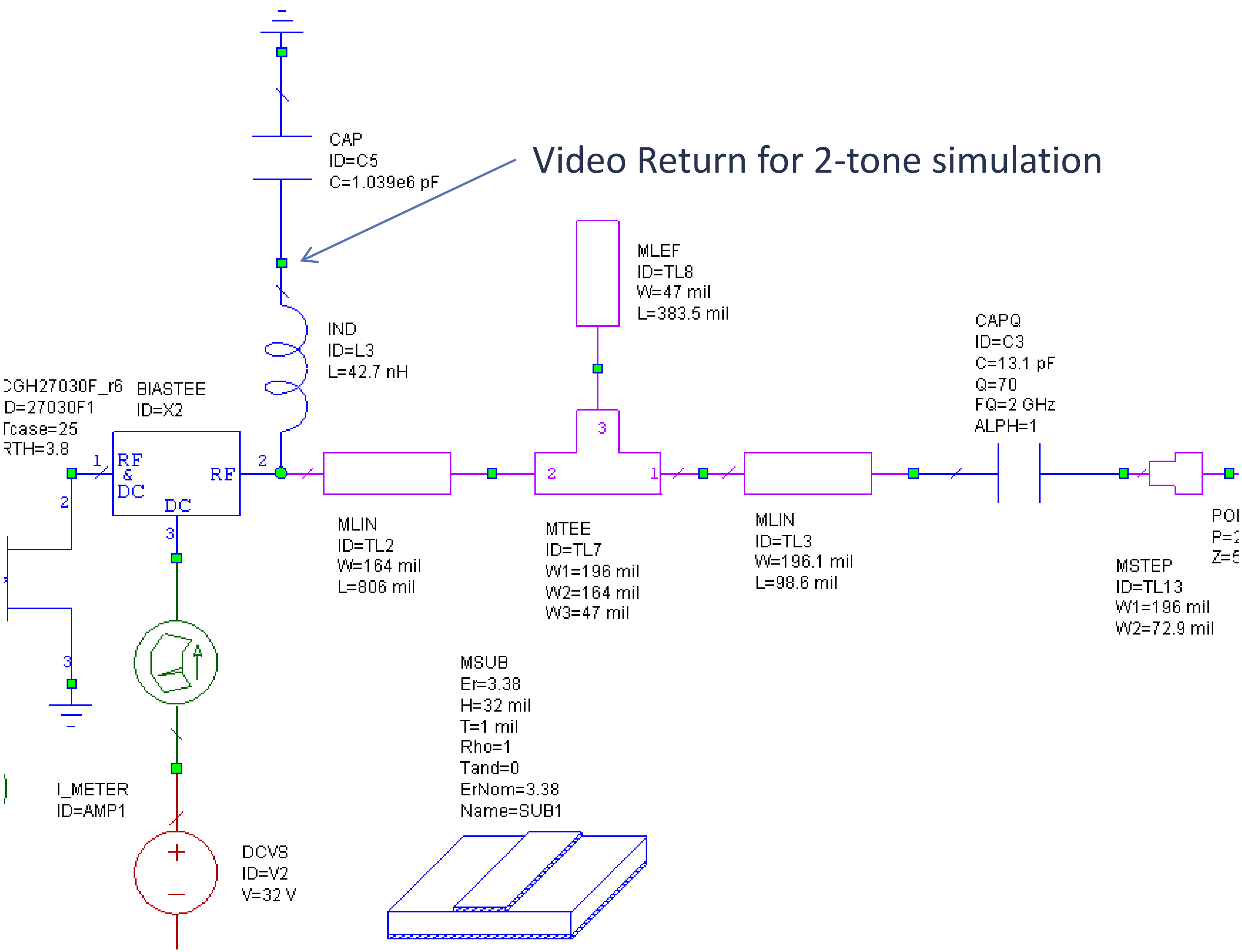
# Detail of Input Match




Video Return for 2-tone simulation

# Detail of Output Match

Video Return for 2-tone simulation

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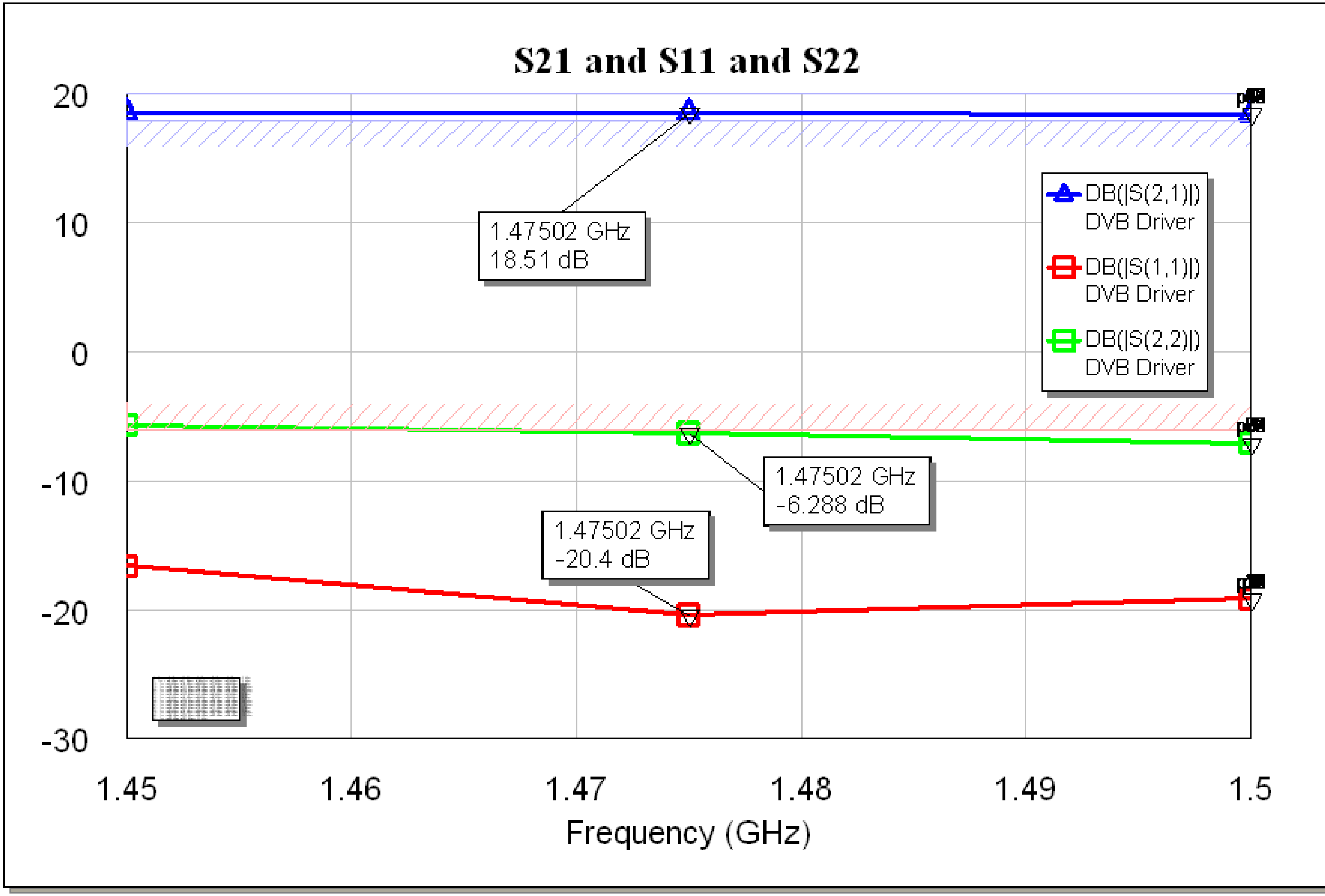
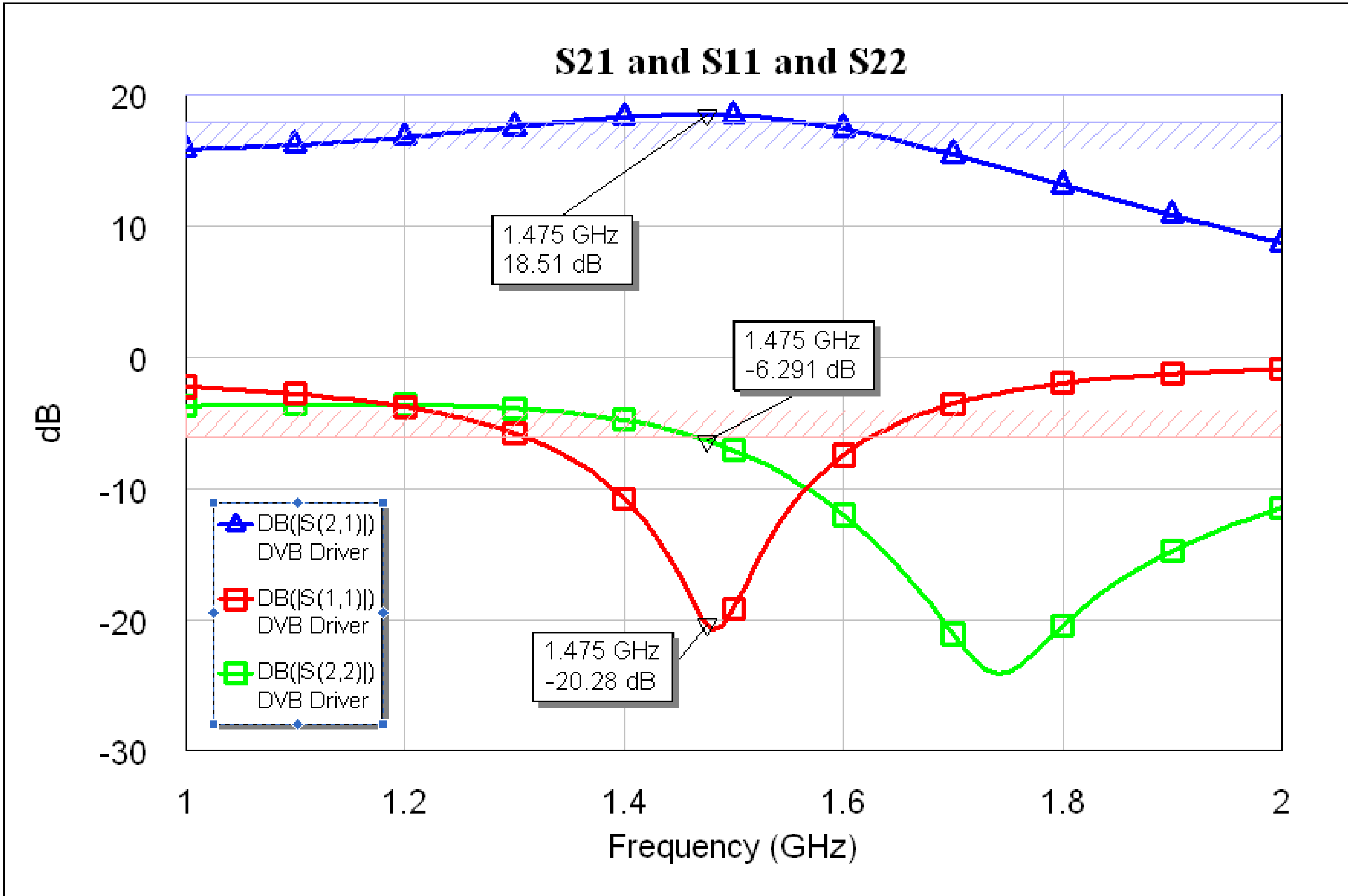
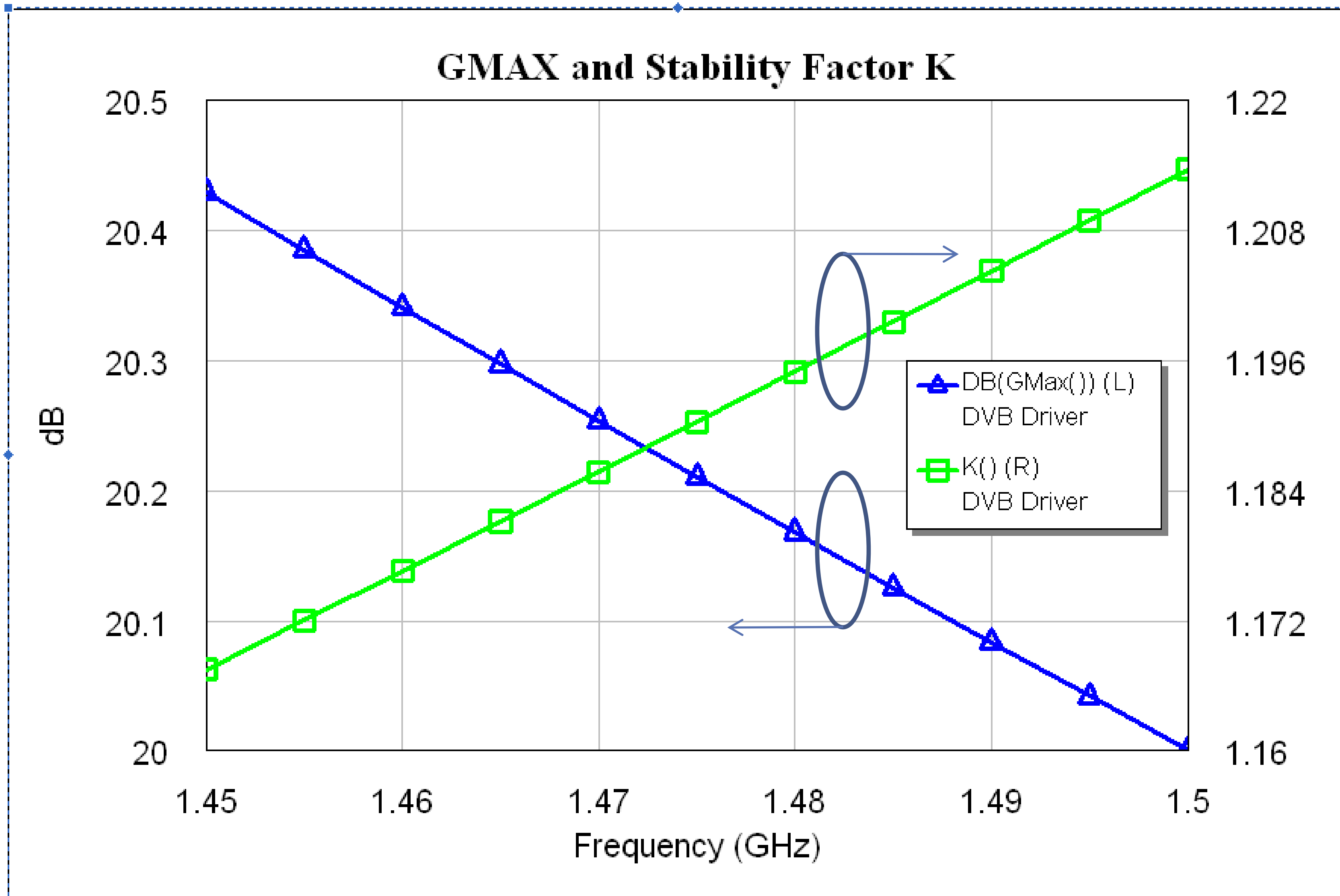
# Small Signal Characteristics



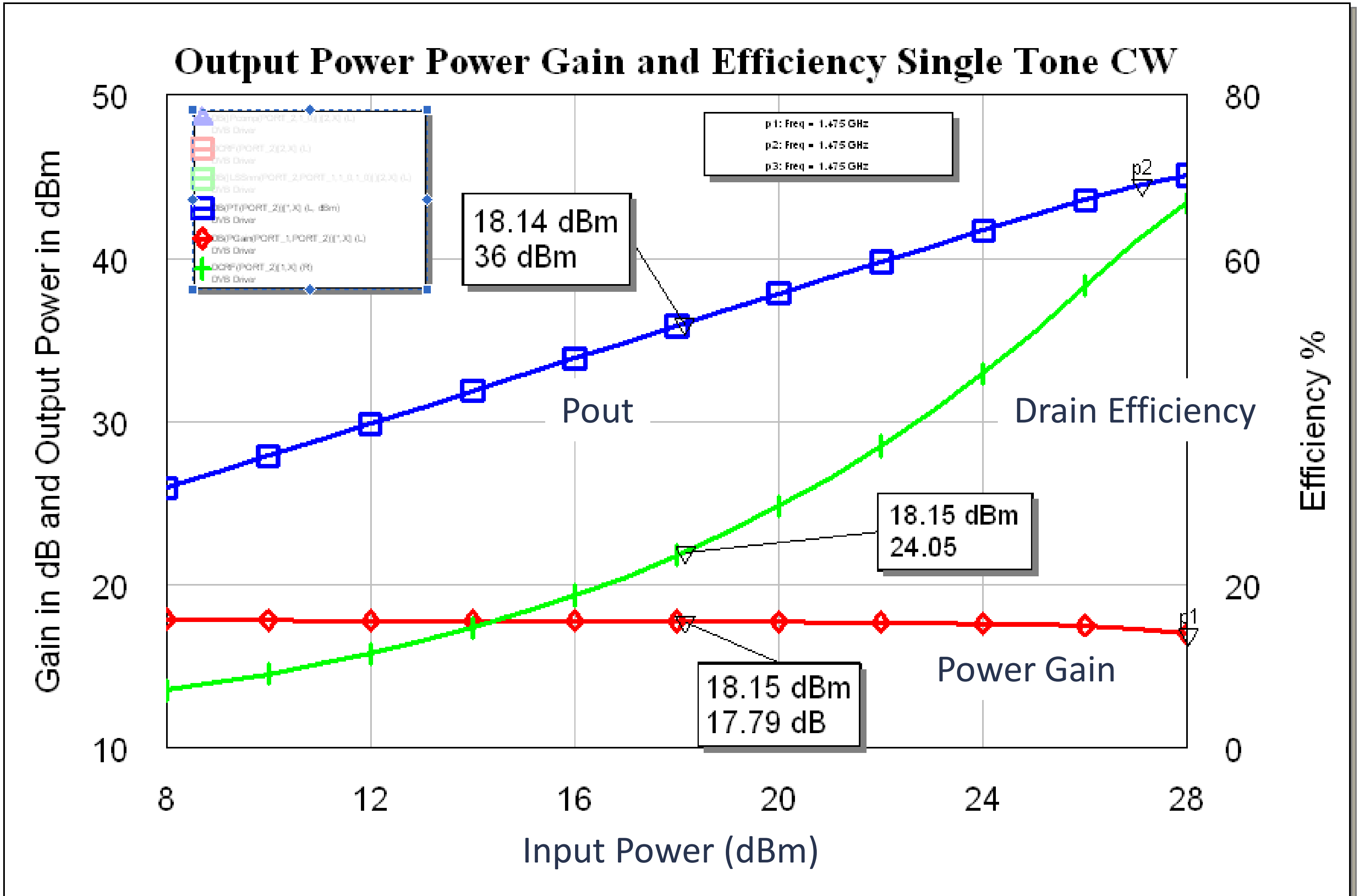
# Wideband Small Signal Characteristics



# Maximum Gain and Stability Factor K



# Power Characteristics (1.475 GHz)

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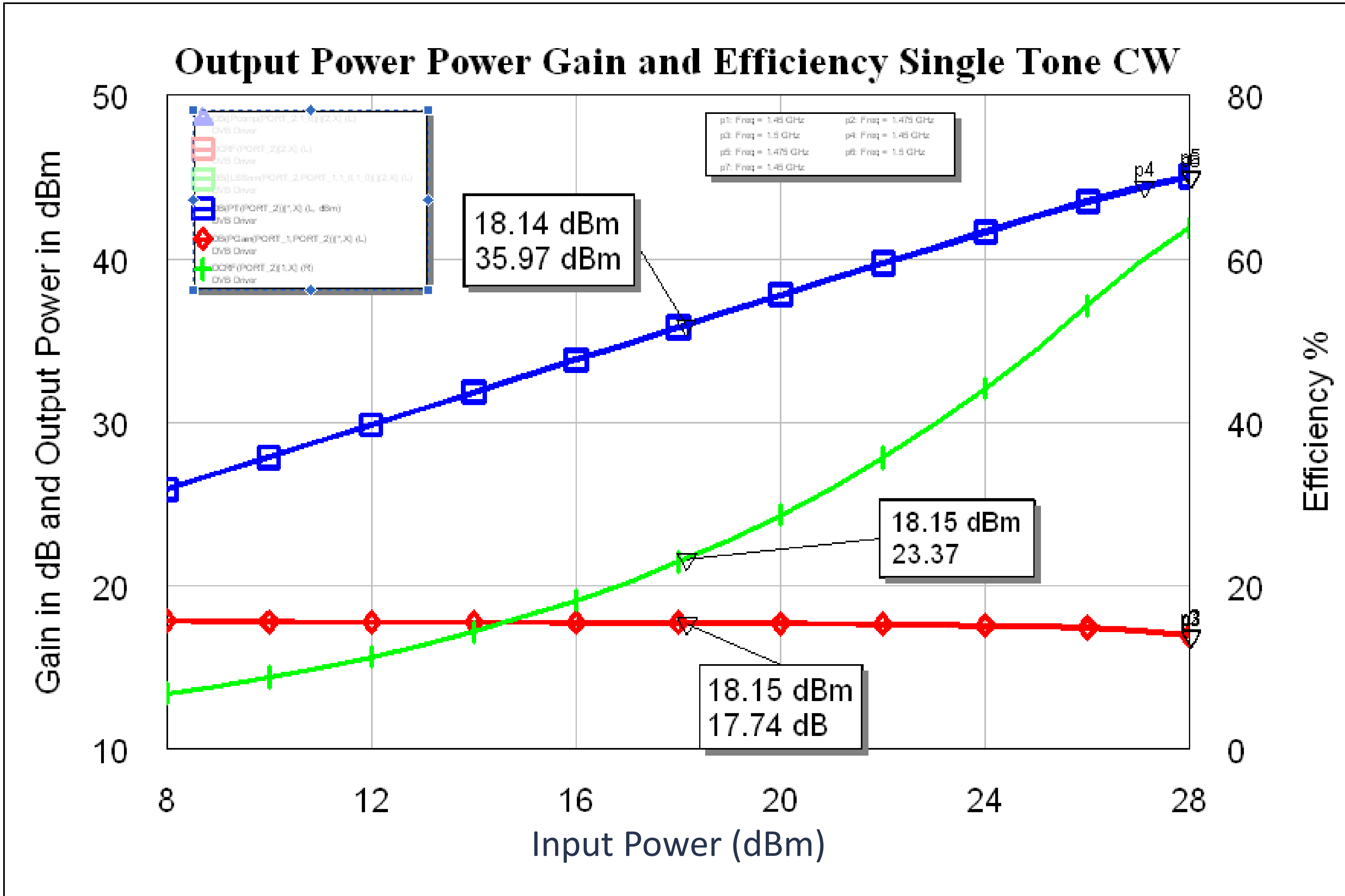
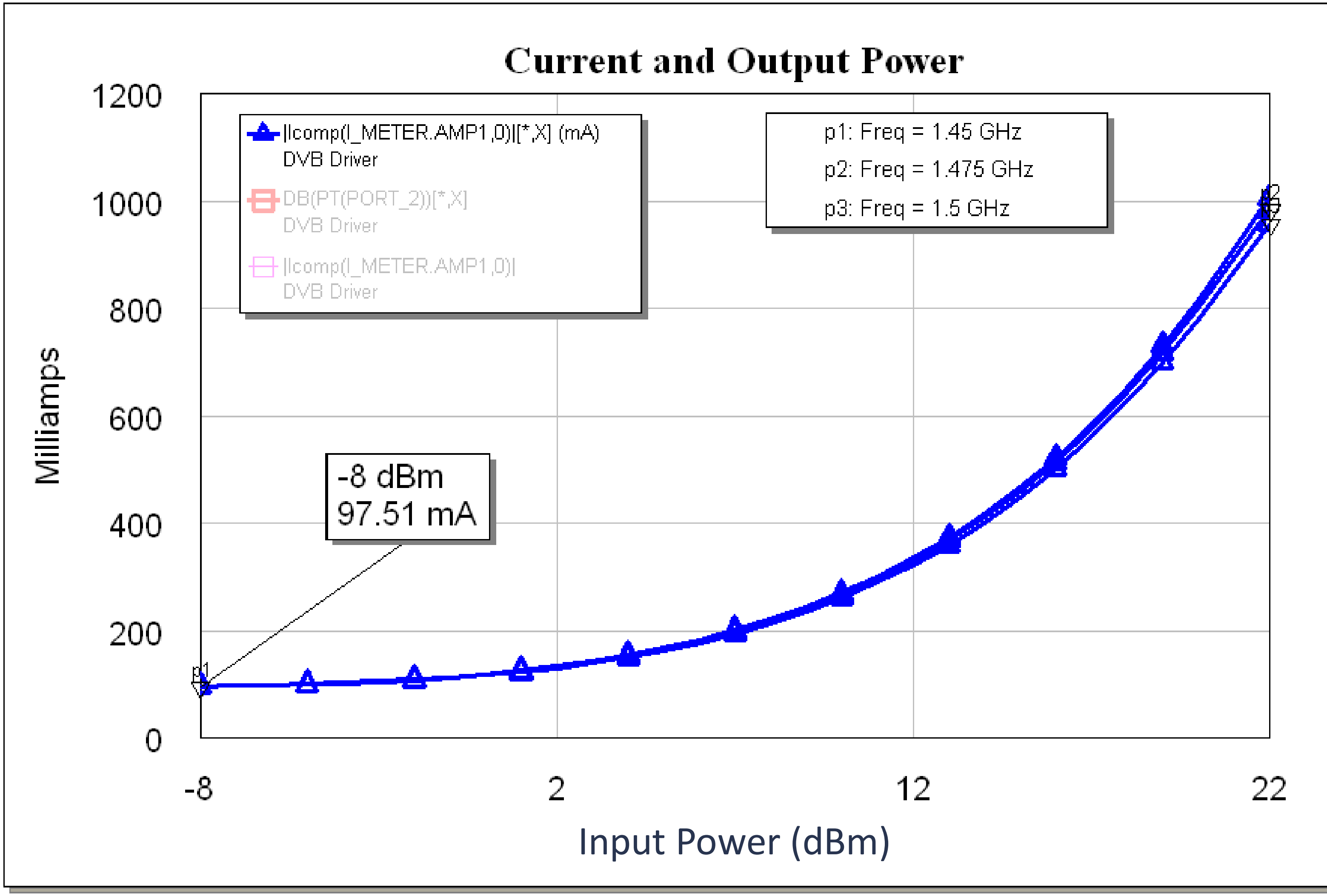
# Power Characteristics at Band Center and Edges

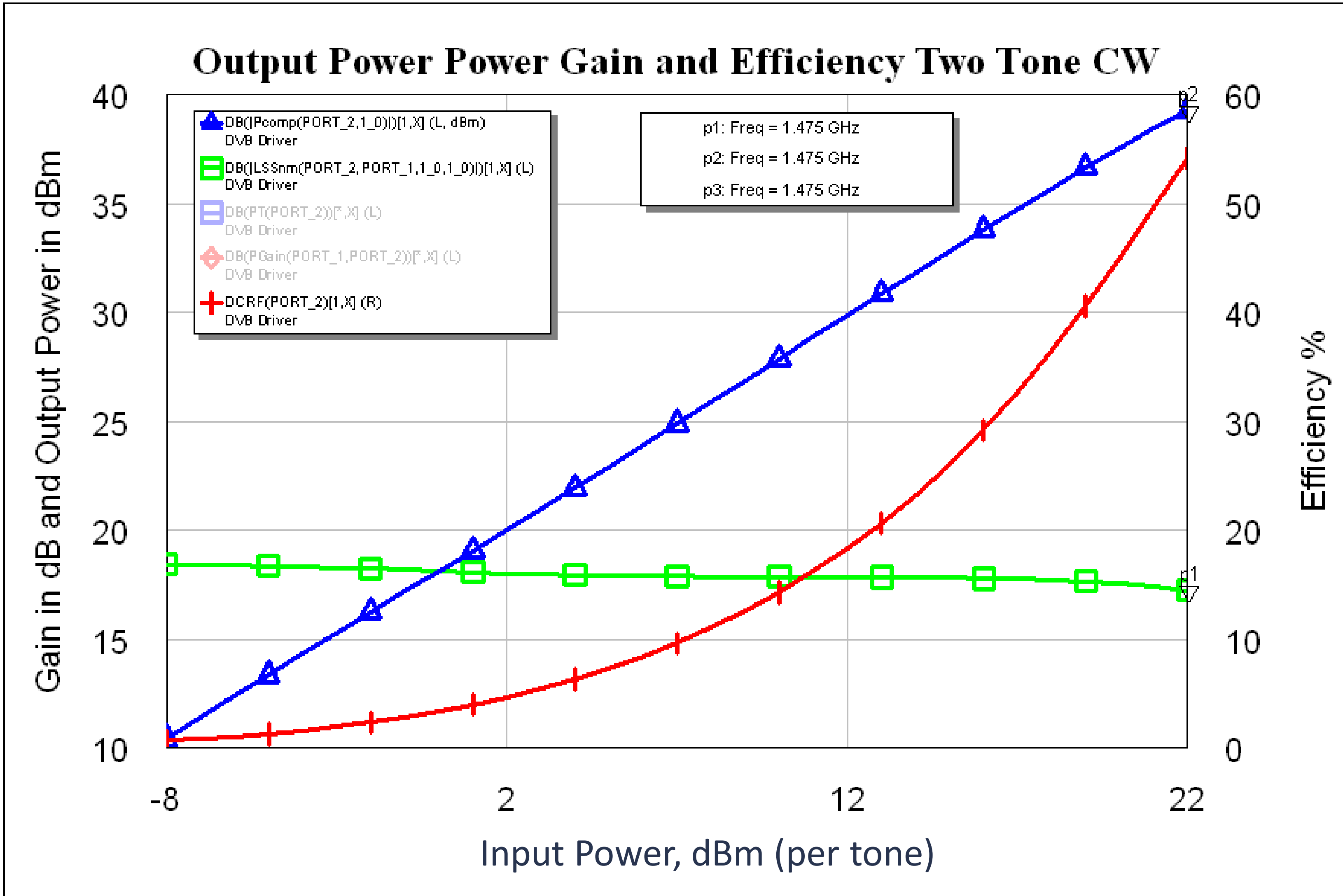


# DC Current versus RF Drive level (2-tone)

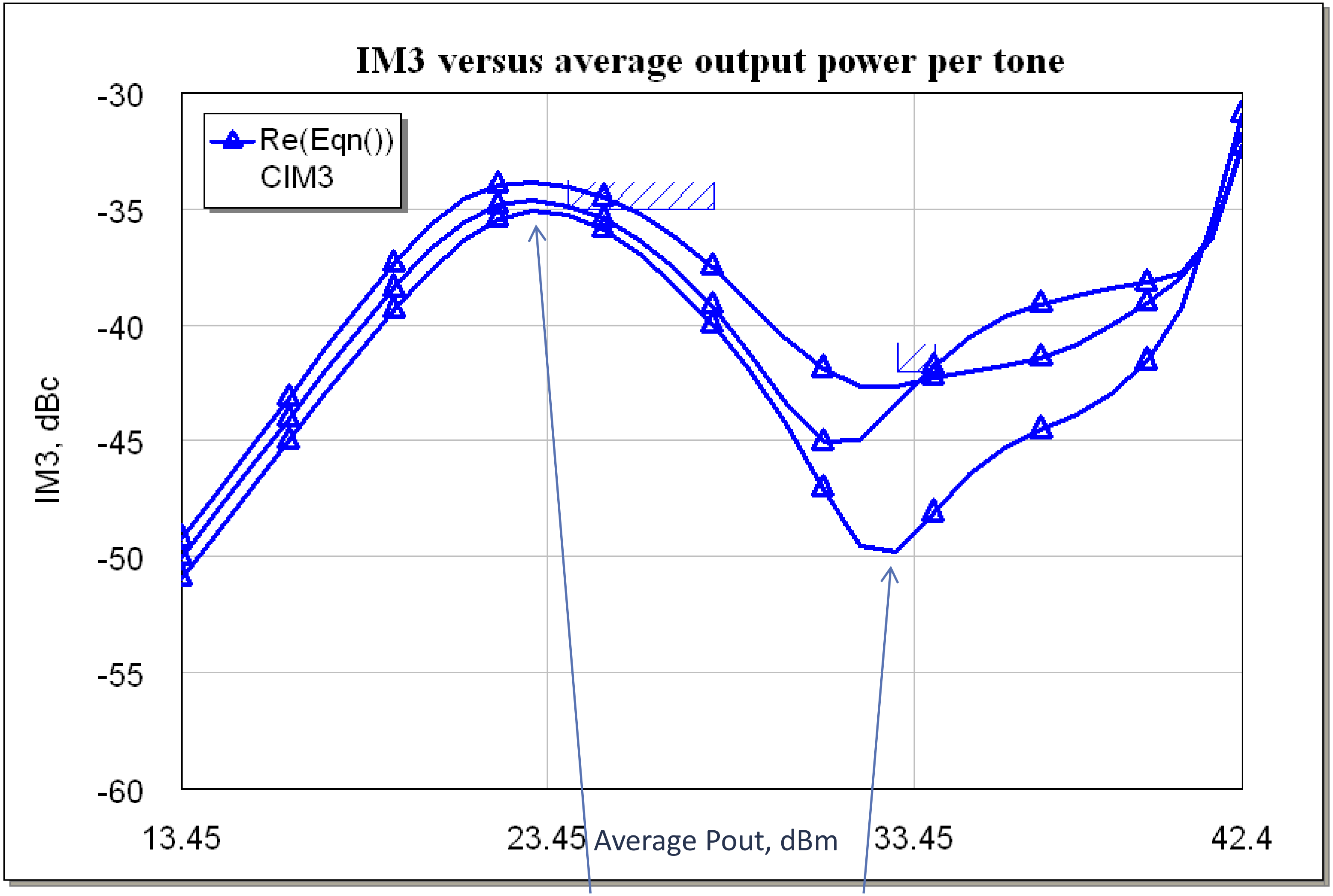



Vdd = 32 volts and Idq set to 100 mA

# 2 Tone Power Characteristics (1.475 GHz)



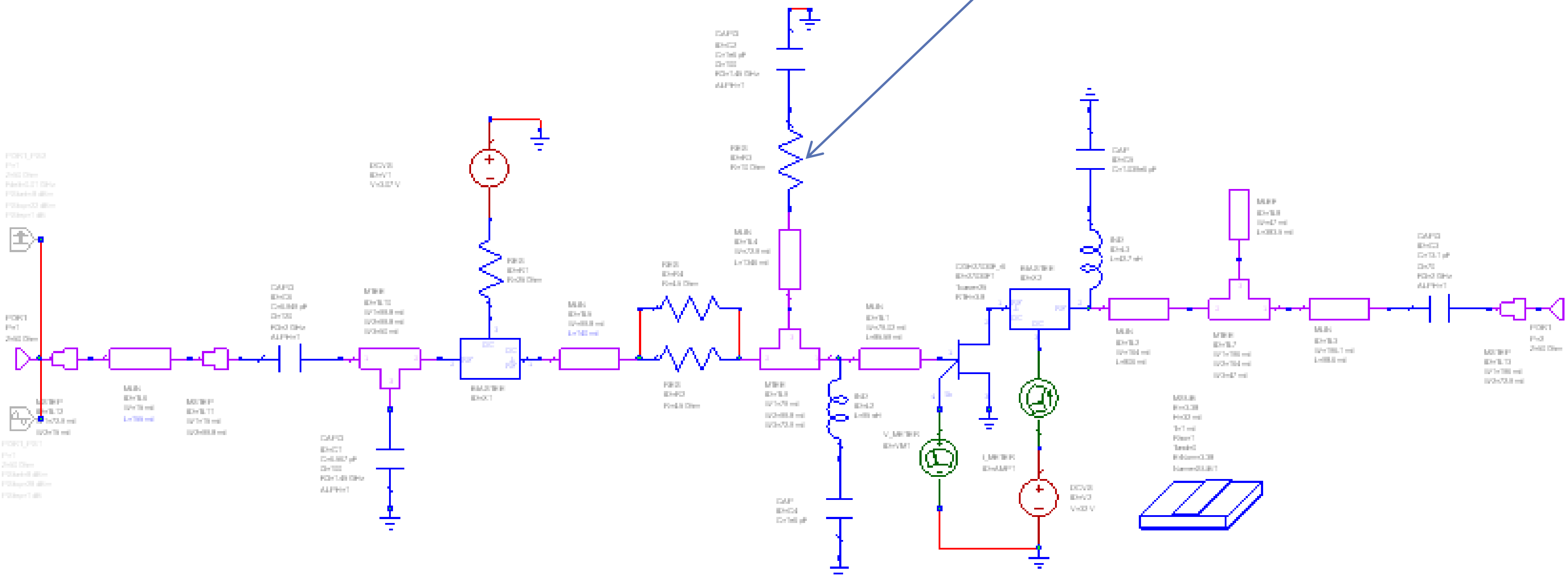
# 3rd order intermodulation products at band center and band edges



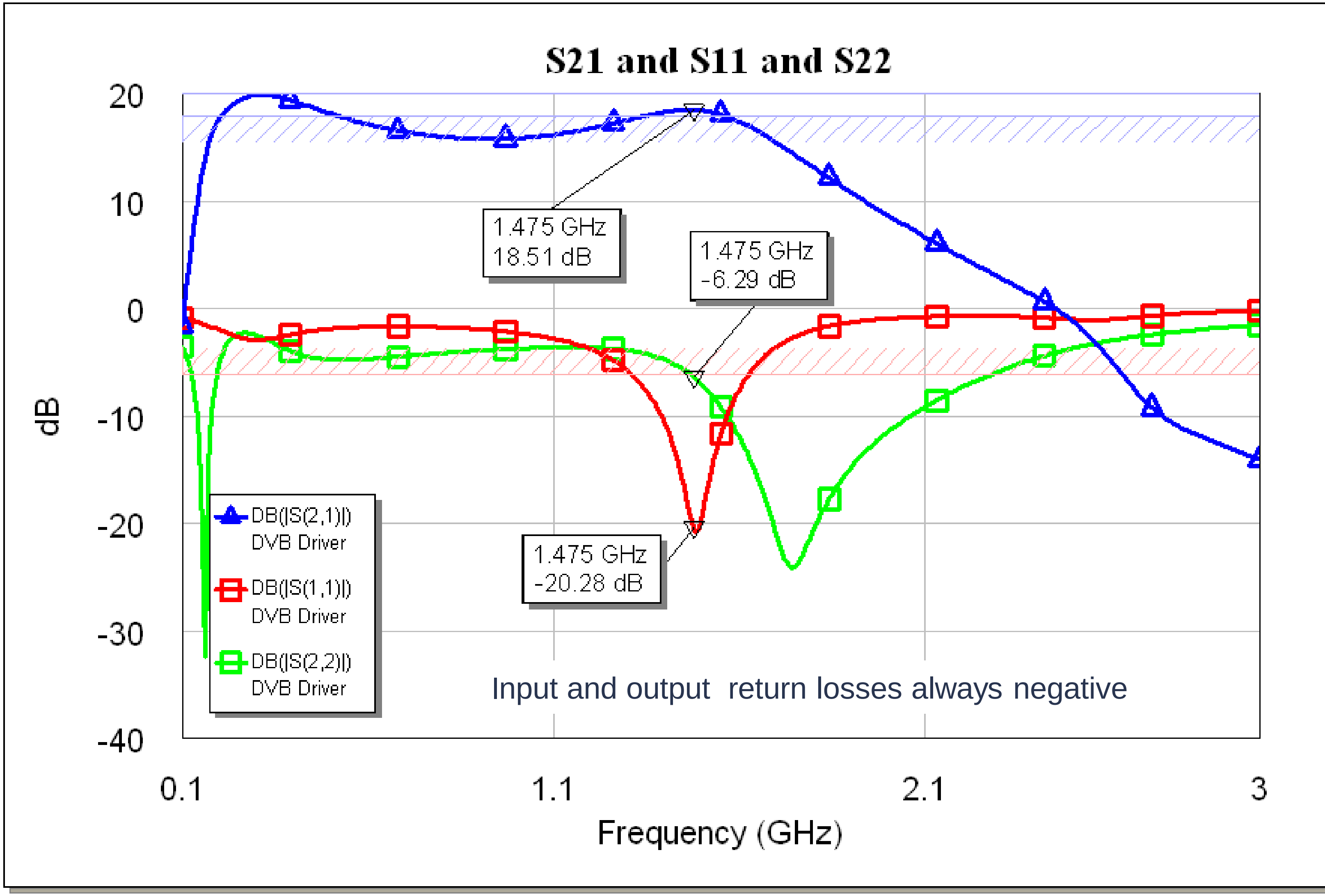

"Classic" back-off hill and sweet spot

# Very low frequency stability

Additional 90 degree 50 ohm line at 1.45 GHz loaded with 10 ohm “de-Qing” resistor



# Ultra wideband small signal characteristics

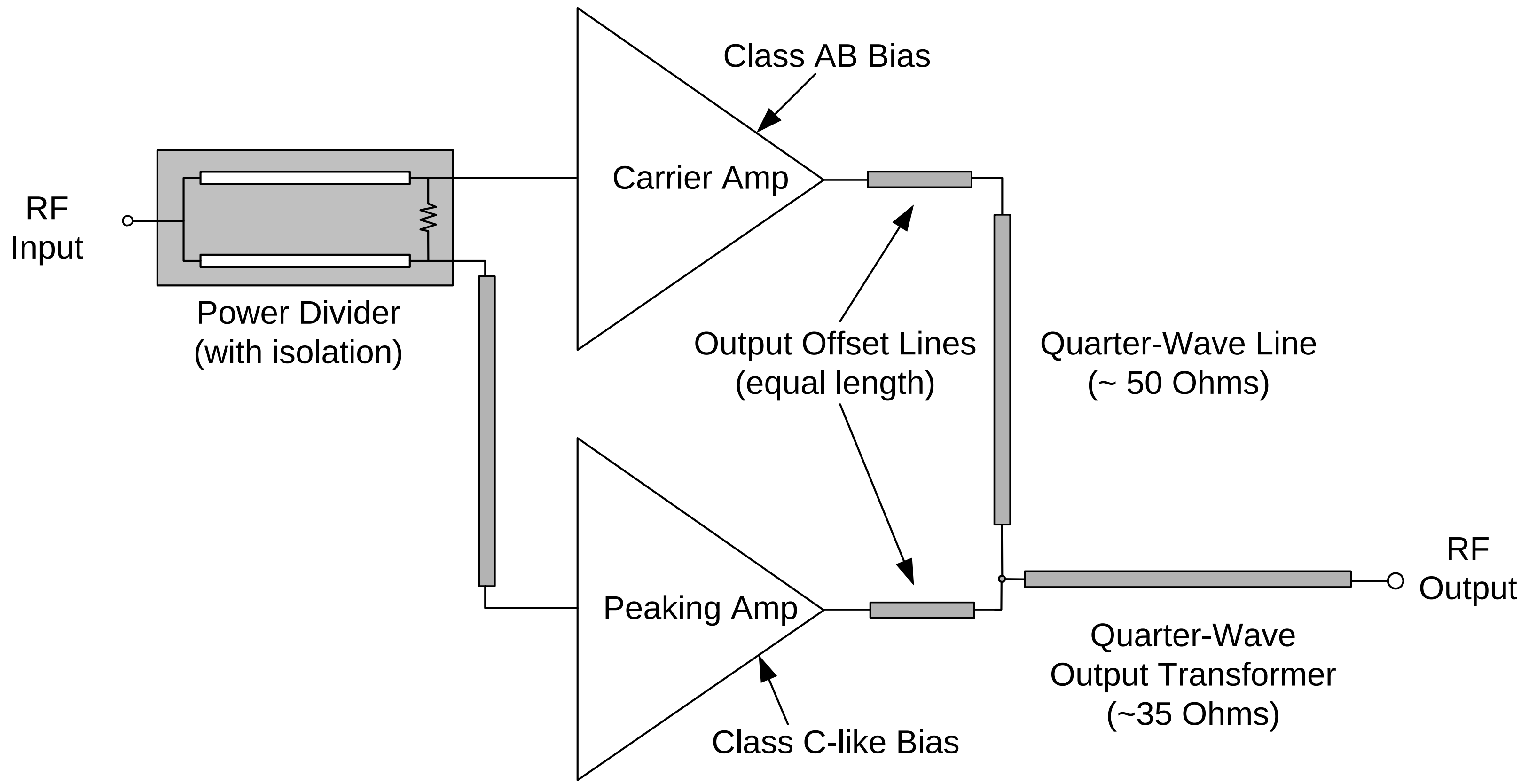


# Example 9
# Doherty Amplifier Example
# (CDPA21480)

# Summary

- Operating Frequency: 2.11 to 2.17 GHz (aim to have 200 MHz bandwidth)
- Modulation Signal: 3 GPP W-CDMA
- Gain: > 14 dB
- Peak Output Power: 480 Watts
- Average Output Power: 80 Watts
- Drain Efficiency at $P_{AVE}$: 50%
- DPD Corrected ACLR1: -50 dBc
- Operating Voltage: 28 volts
- Uses 2 x CGH21240F pre-matched transistors

# Two-way Doherty Amplifier Block Diagram

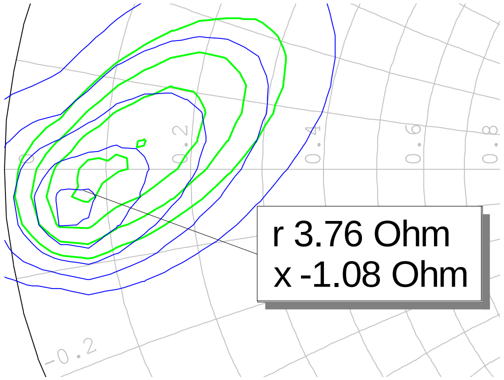


# Design Considerations

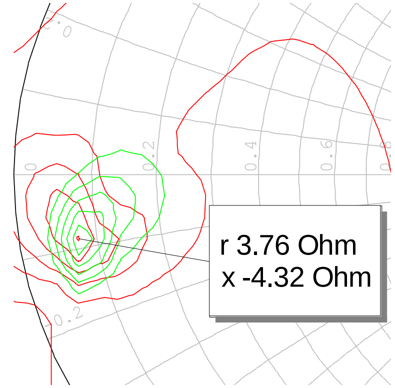
- Doherty Amplifier Design has many design aspects:
  - Input divider coupling ratio
  - Source impedances for carrier and peaking amplifiers (including harmonics)
  - Load impedances for carrier and peaking amplifiers (including harmonics)
  - Output offset line lengths
  - “Quarter wave” input and output line lengths
  - Output transformer impedance
  - Carrier and peaking amplifier quiescent bias levels
- 2-tone intermodulation products need to be < -25 to -30 dBc to meet SEM requirements after DPD

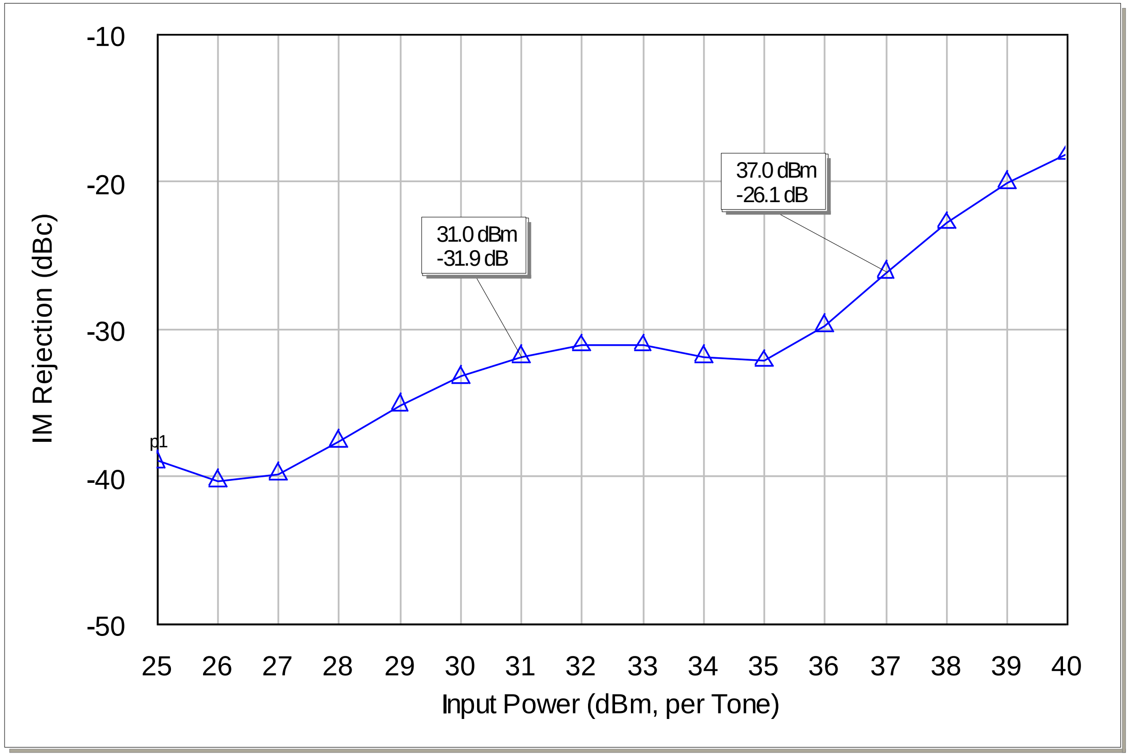
# Simulations of Doherty Amplifier 2-tone Intermodulation rejection

Source Pull of Peaking Amplifier at $P_{IN}$=37 dBm

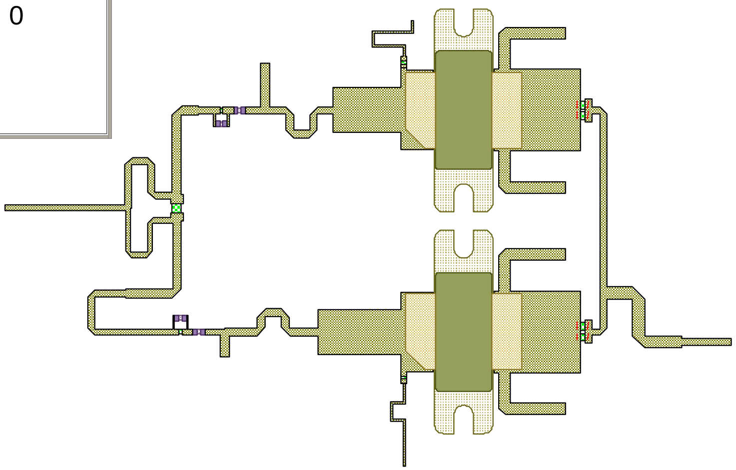



Source Pull of Peaking Amplifier at $P_{IN}$=31 dBm

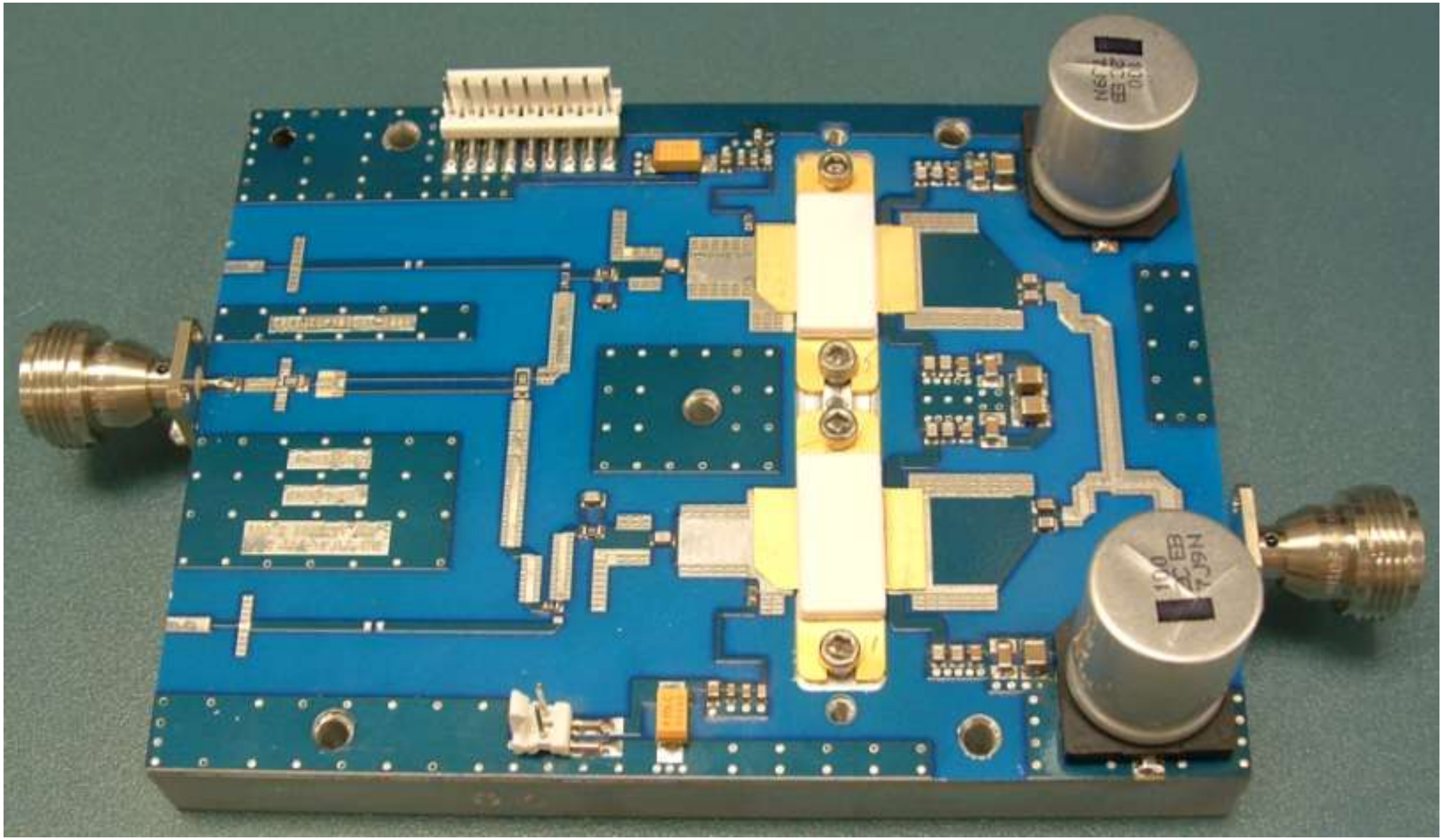


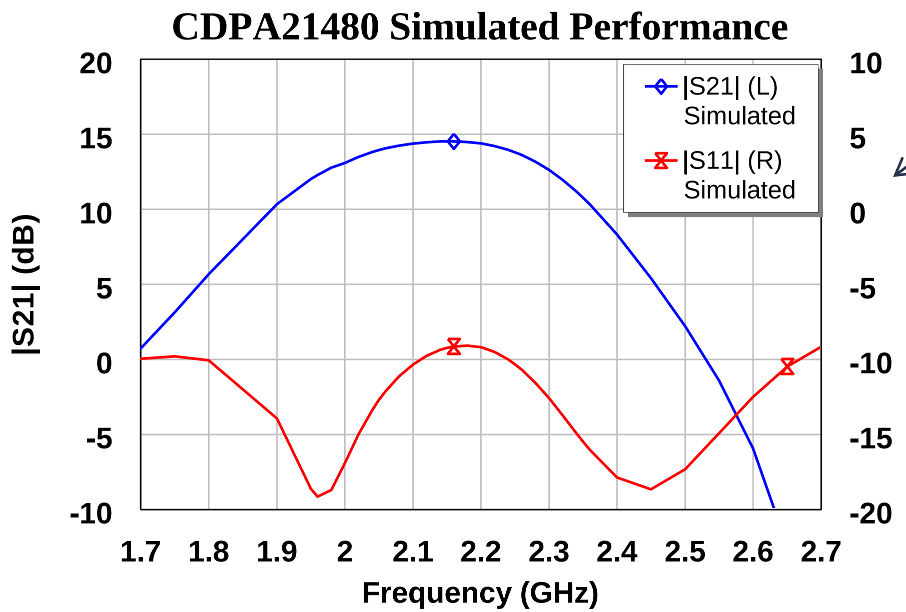
# Further simulation of Doherty 2-tone IM rejection and Efficiency versus lengths of output offset lines

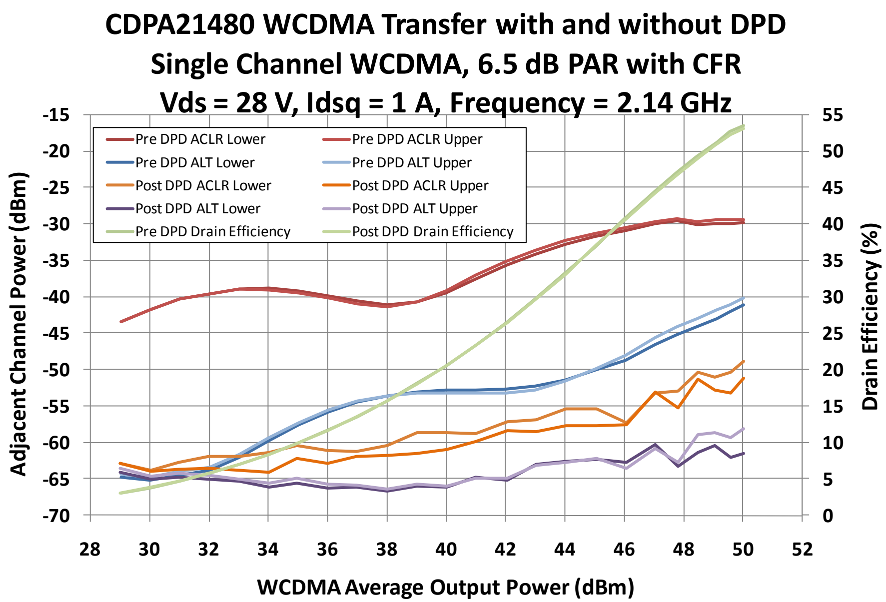
# UMTS 480 watt peak power DPA hardware



# Simulated and Measured Performance of CDPA21480

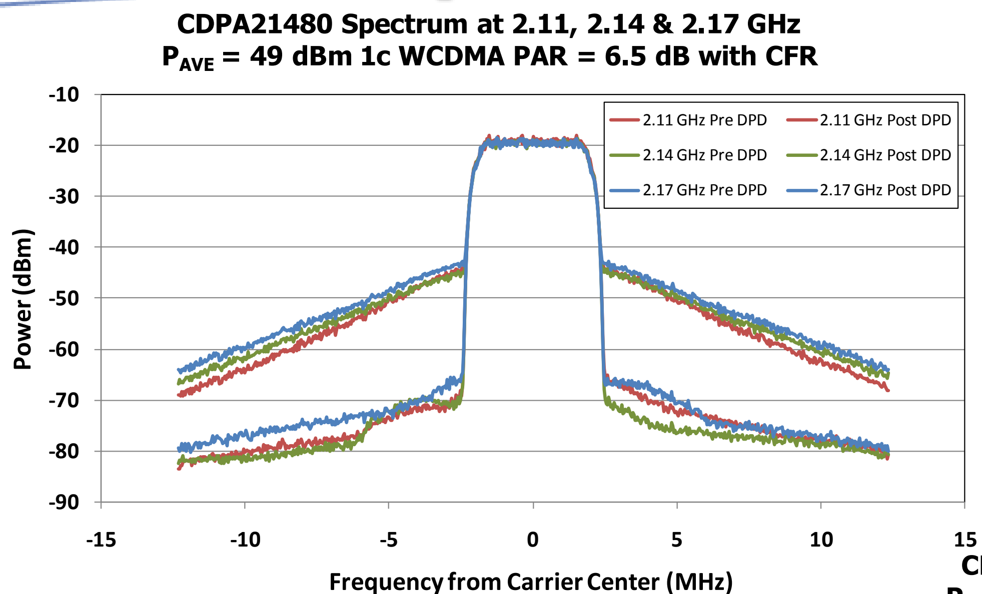


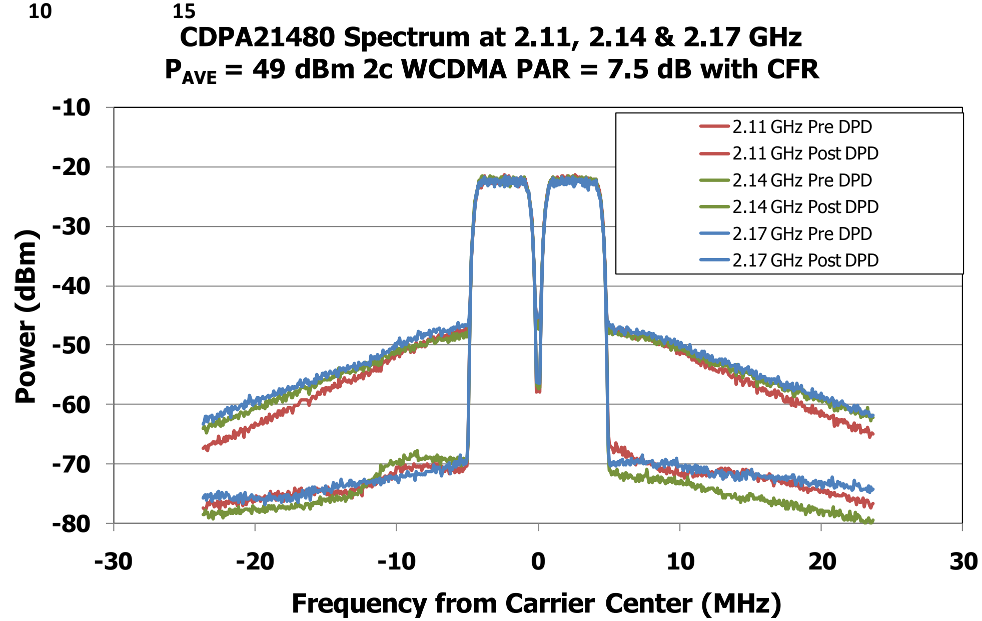

Simulated Small Signal Response




Measured W-CDMA Transfer Curves

# Single and 2 carrier W-CDMA Output Spectra (with and without DPD)



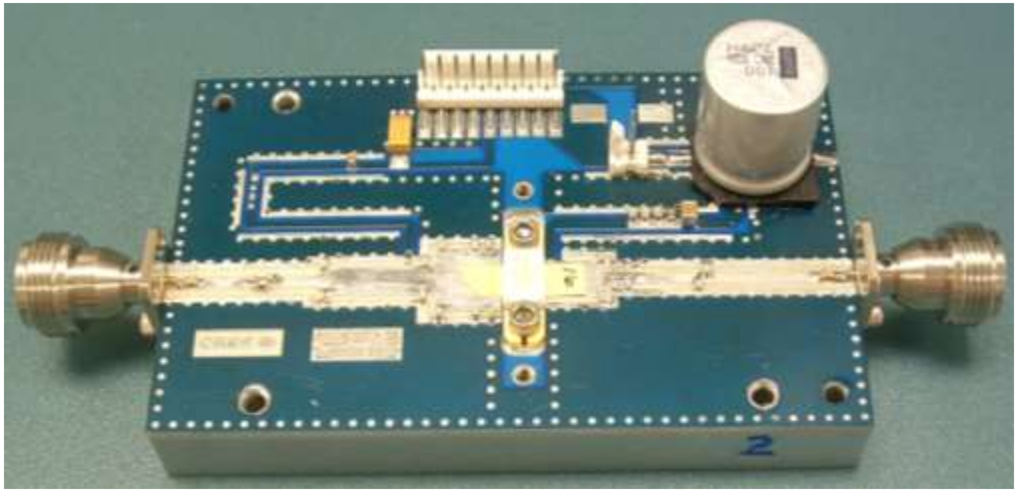
# Example 10
# Comparing Balanced Amplifier and Doherty Performances

# Summary

- CGH09120F transistor used in single-ended PA design
  - That design applied to a balanced amplifier as well as a Doherty amplifier to compare back-off efficiencies

Single-ended amplifier performance:

| *Parameter* | |
|---|---|
| Operating Frequency | 700 to 950 MHz |
| Modulation signal (for testing purposes) | 2 carrier W-CDMA with 10 MHz bandwidth and PAR of 7.5 dB |
| Output Power (average) | 20 Watts |
| Drain efficiency | 35% |
| DPD corrected ACLR1 | -50 dBc |
| Operating Voltage | 28 volts |





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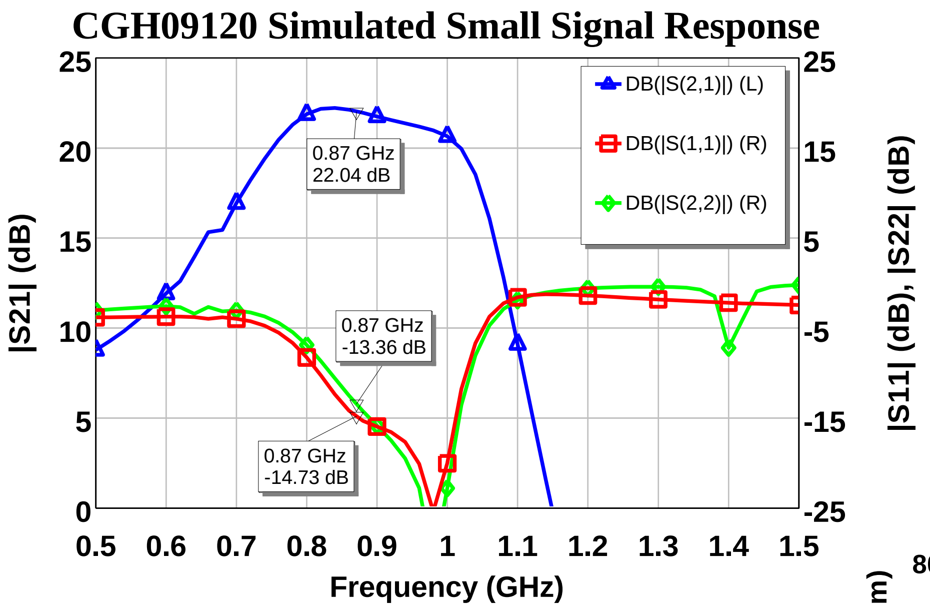
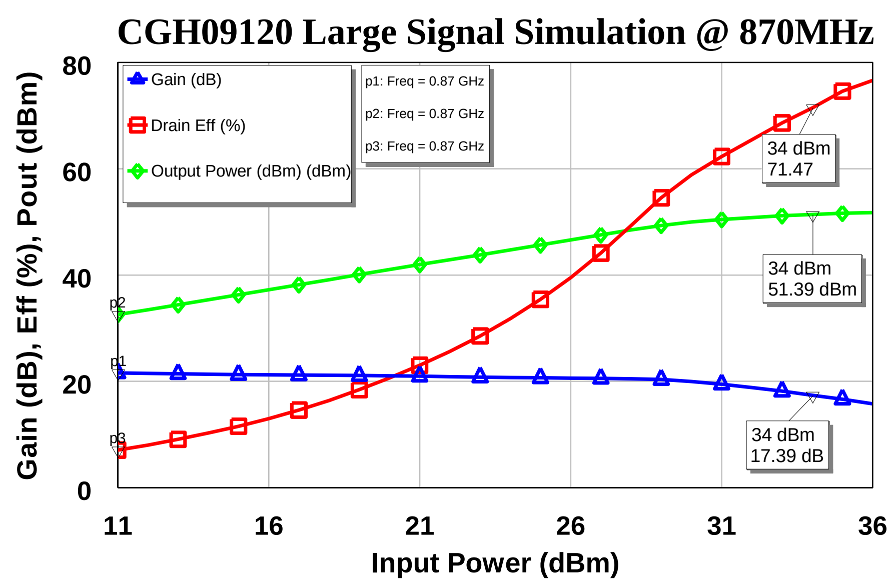
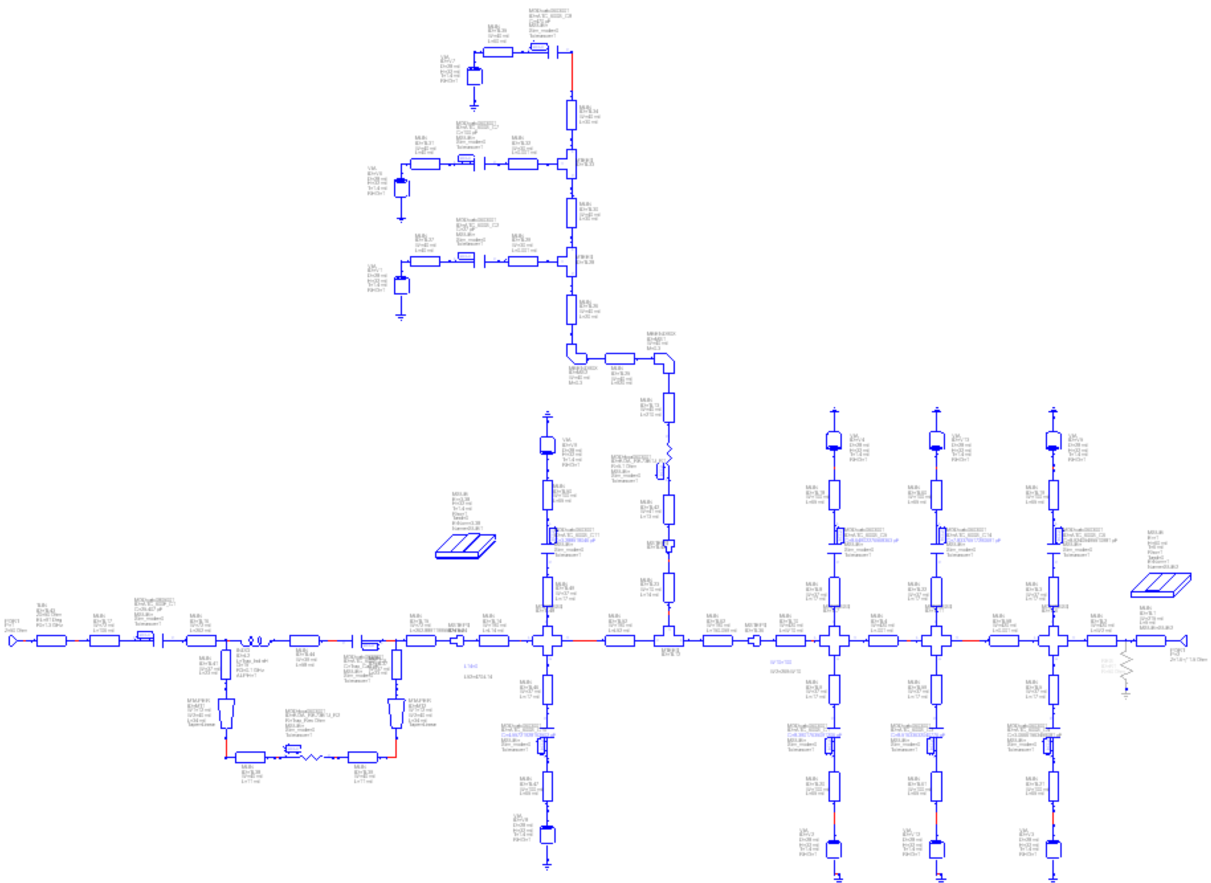
# Simulated Small and Large signal performance of CGH09120F demonstration amplifier

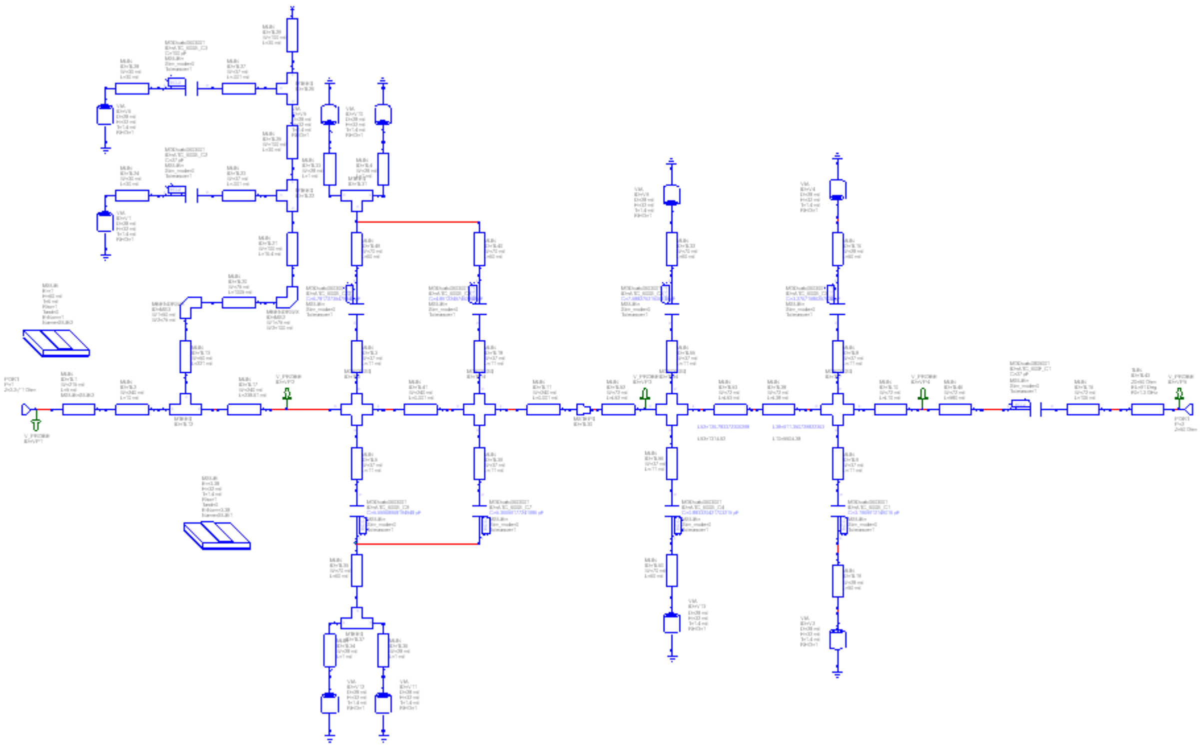


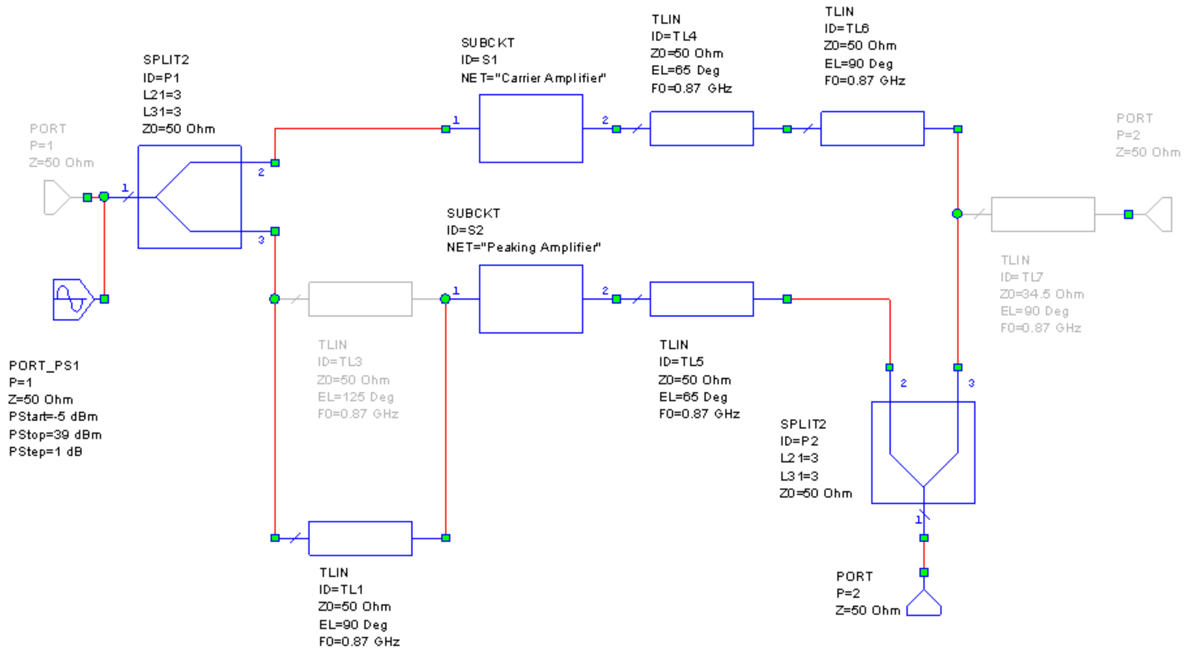
# Input Matching Network of Single-Ended PA



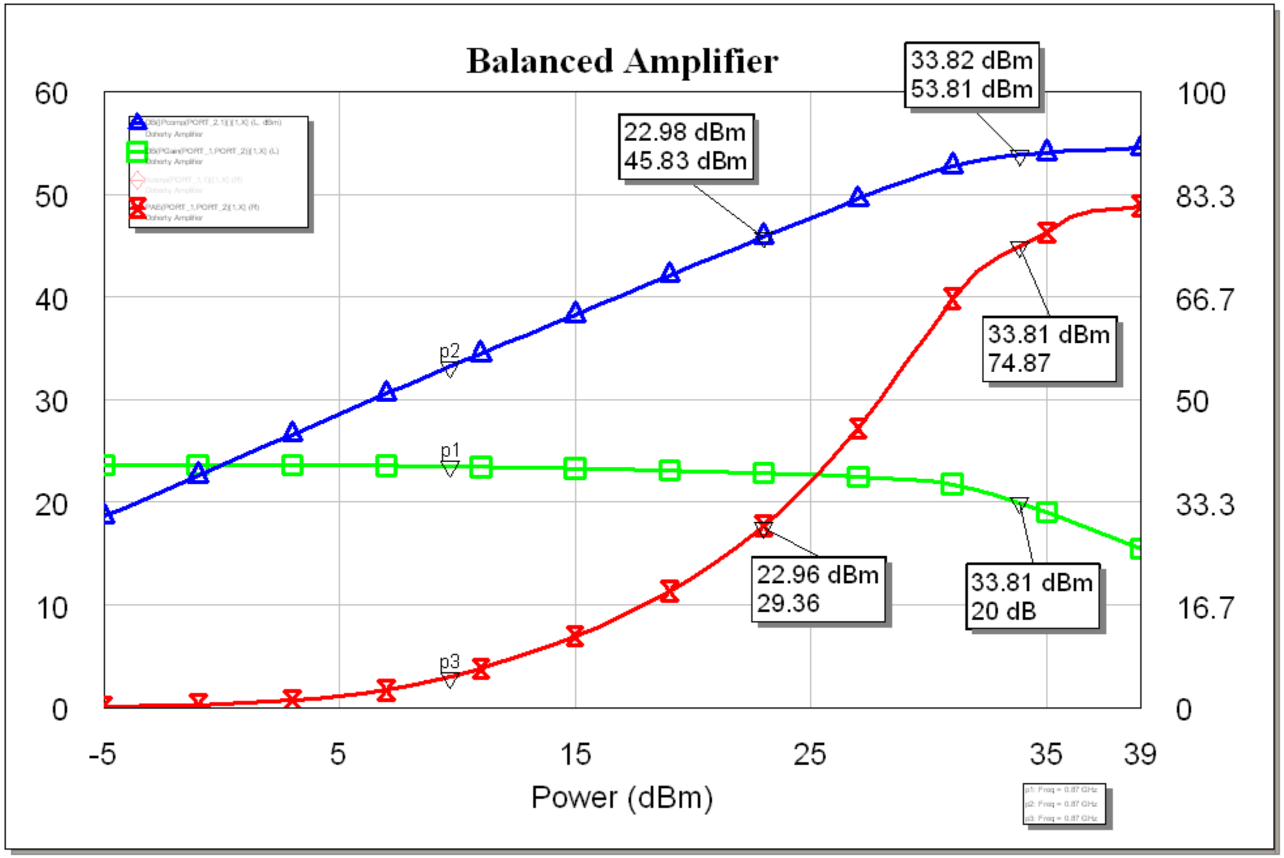
# Output Matching Network of Single-Ended PA



# Top Level Schematic set up as balanced PA



# Simulation of Large-Signal Performance of Balanced Amplifier




Note the marker values at Peak Power and 8 dB Back-off



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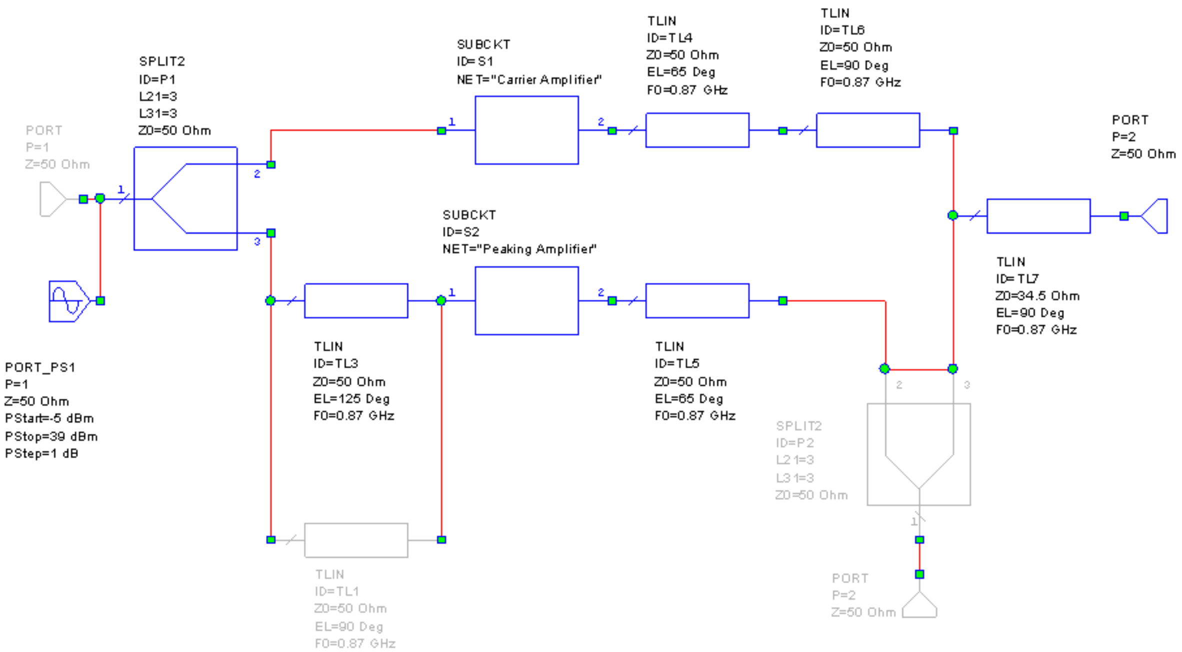
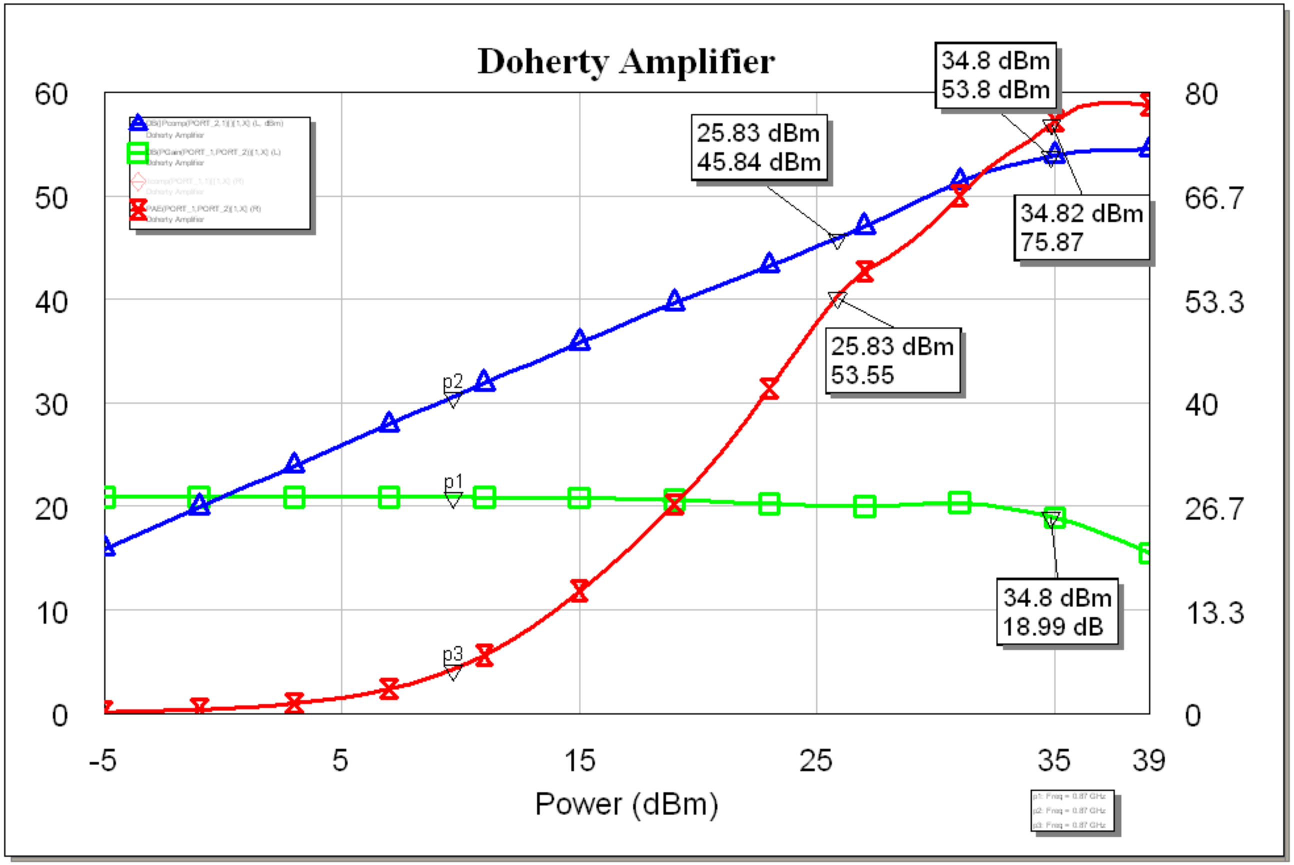
# Top level schematic set up as Doherty PA



# Simulation of Large-Signal Performance of Doherty Amplifier




Note the marker values at Peak Power and 8 dB Back-off



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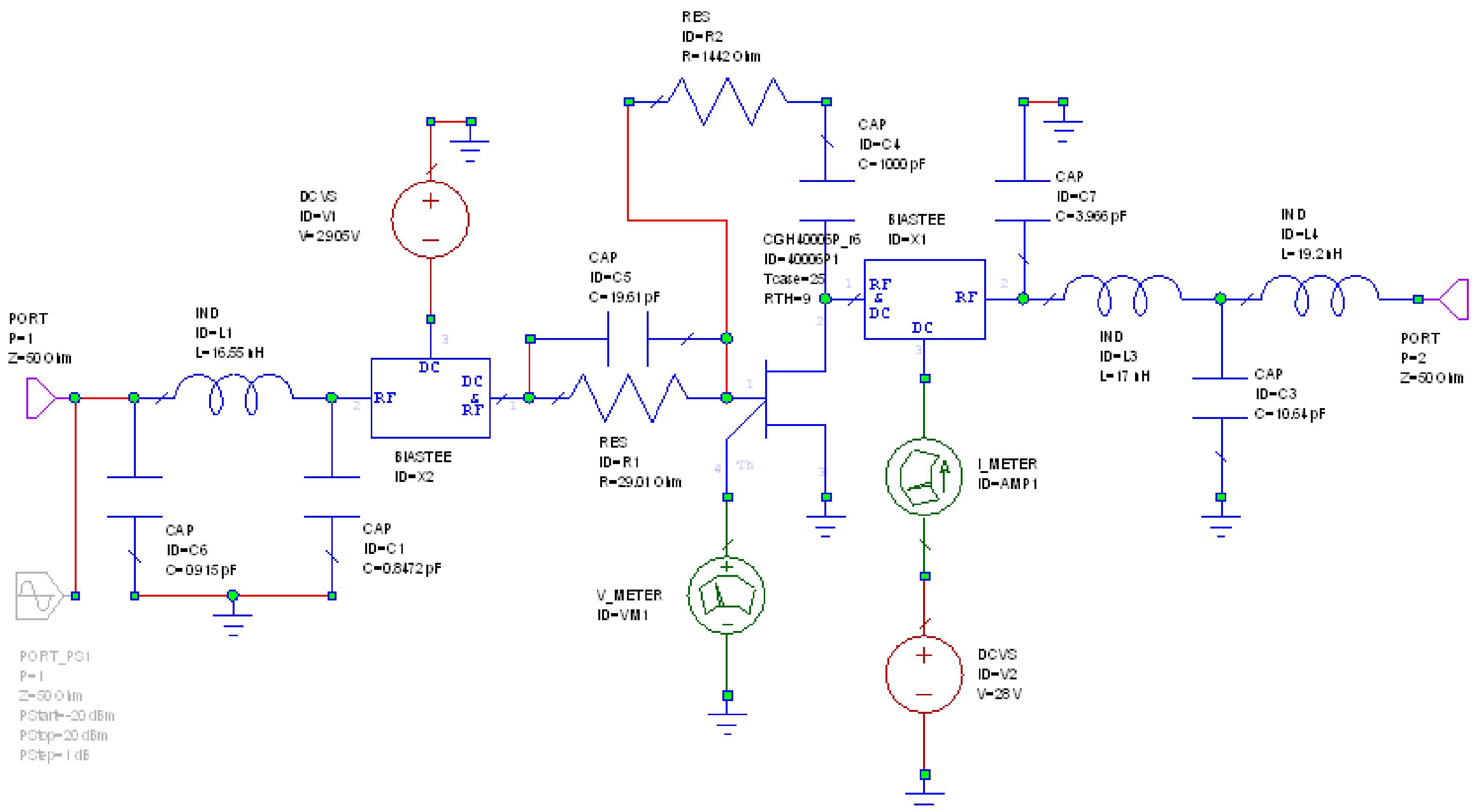
# Example 11
# Using the CGH4006P over 20 to 520 MHz

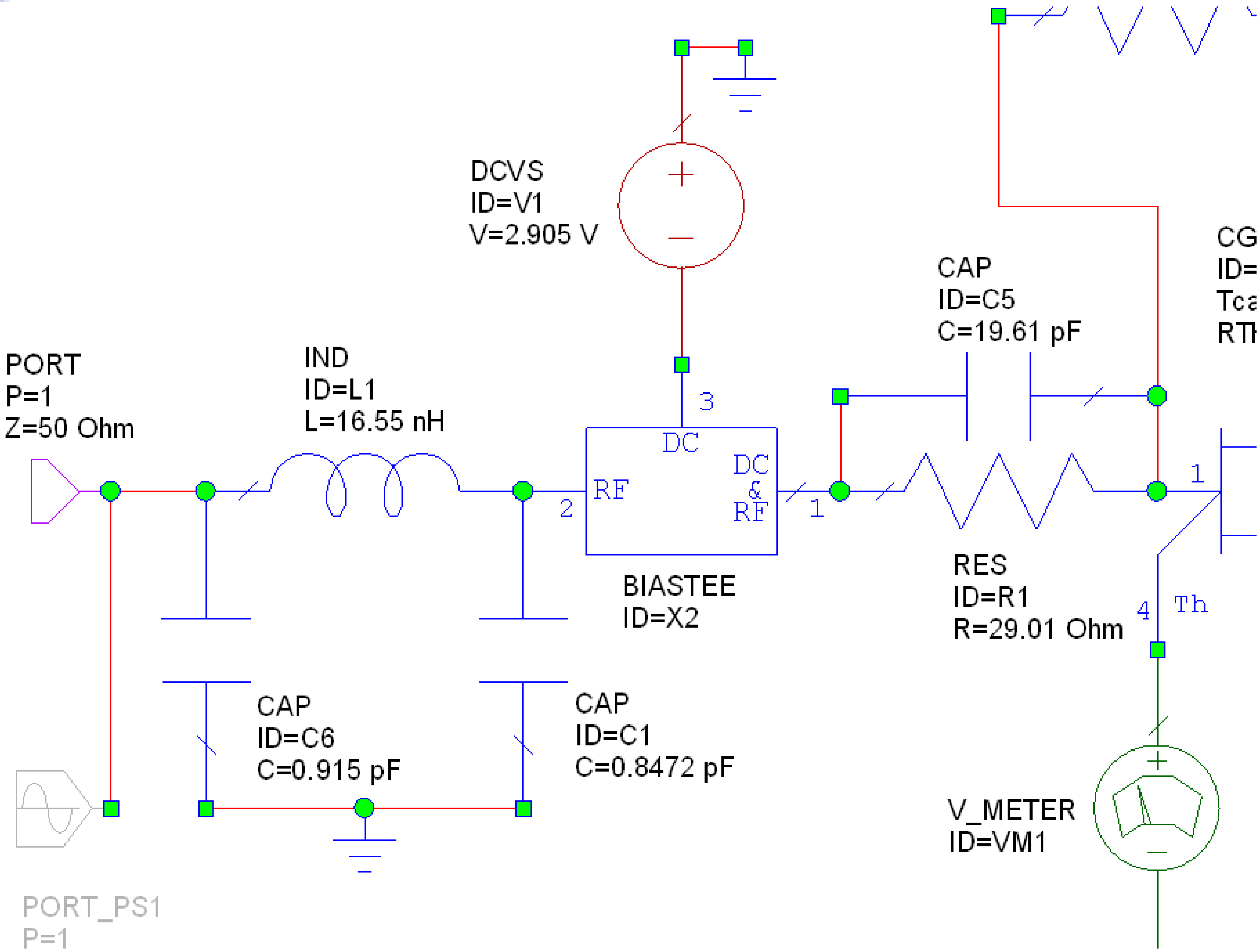
# Summary

- The CGH40006P consists of a 2.16mm GaN HEMT in a small ceramic/metal pill package. The device is capable of providing 8 watts CW power
  - Microwave Office has been used to design a gate-to-drain feedback amplifier with additional reactive matching provided by lumped elements in a 50 ohm characteristic impedance;
  - Drain voltage set at 28 Volts; Idq for the transistor set at 65 mA
- Drain Efficiencies between 42 and 66% at Psat of 8 watts over 20 MHz to 520 MHz obtained
- Noise Figure Analysis of the PA also performed

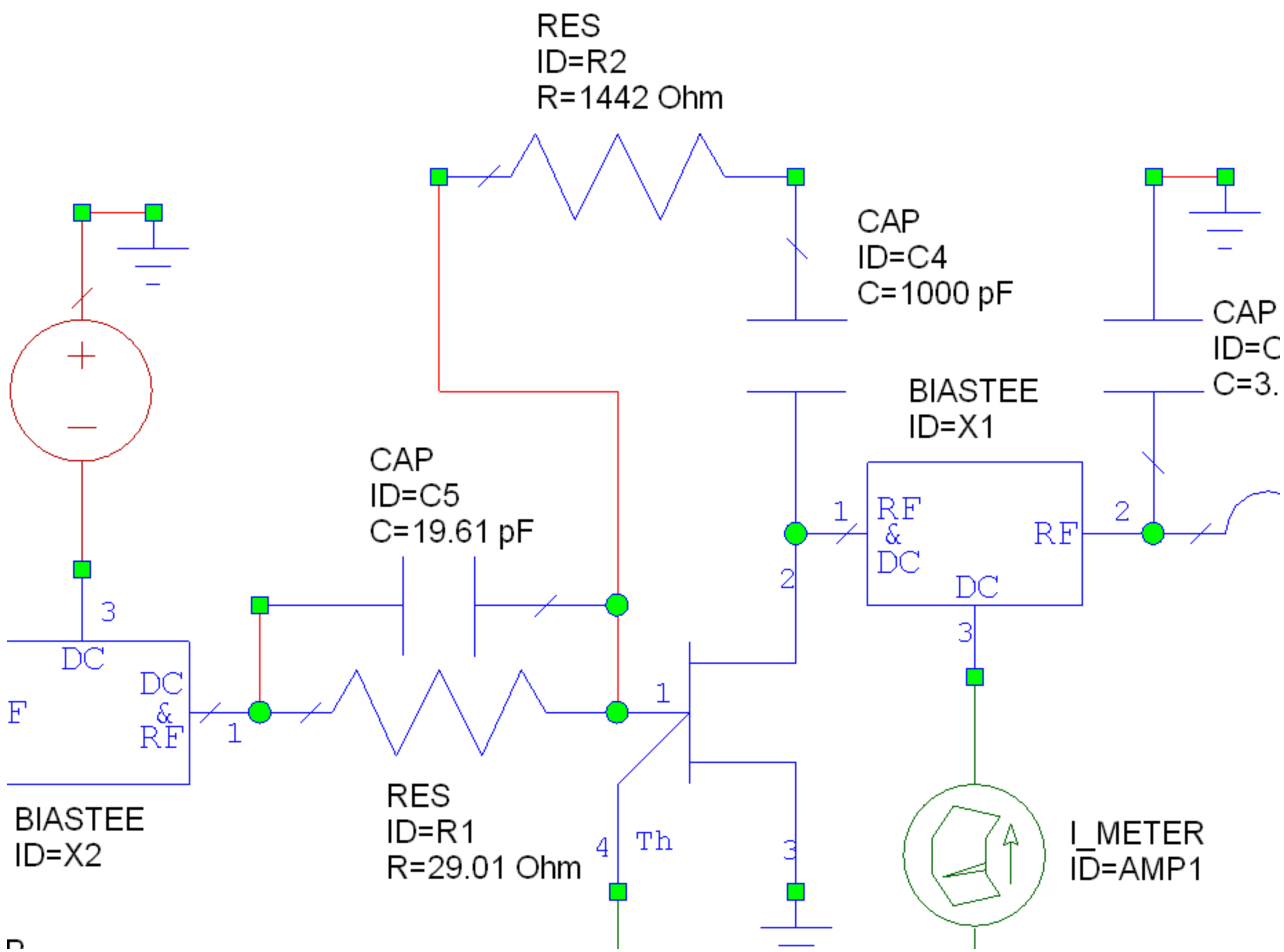
# Schematic of PA



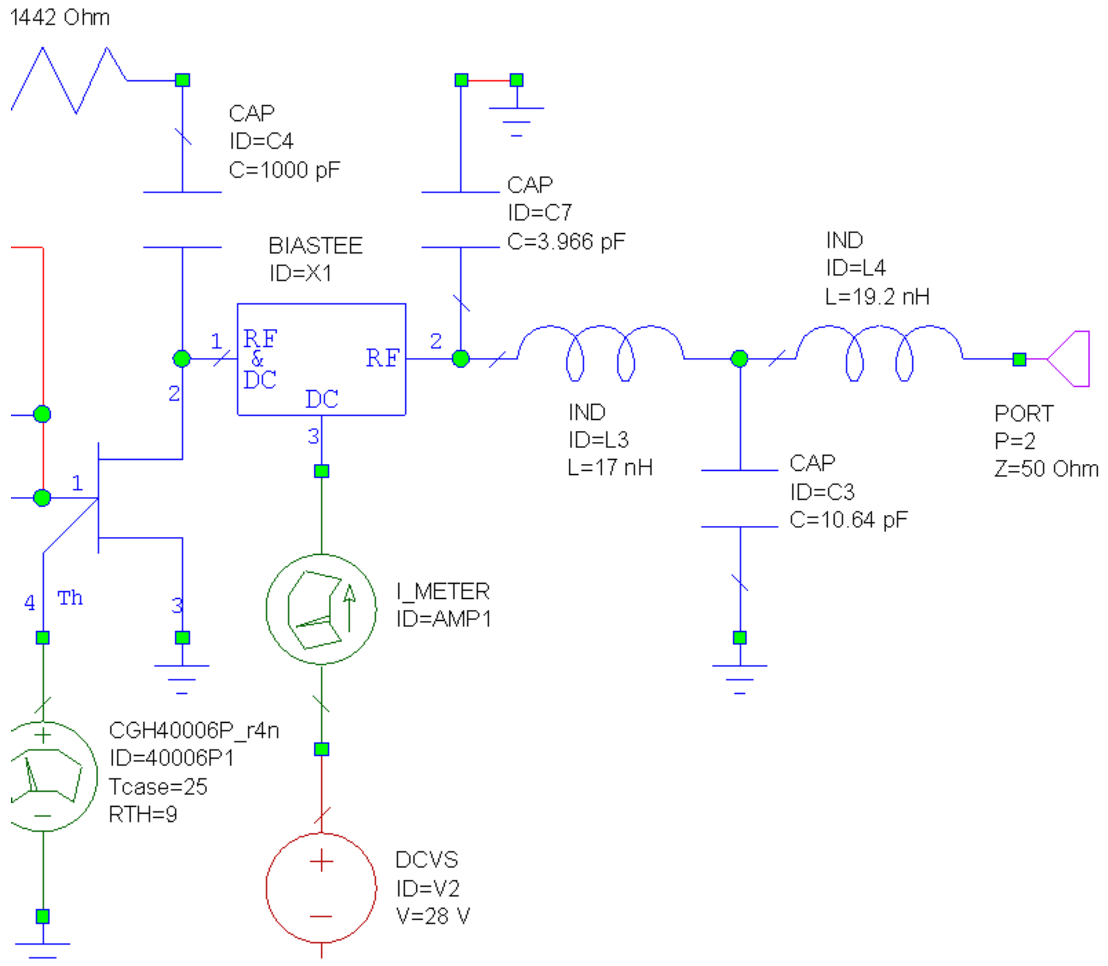
# Input Matching Network



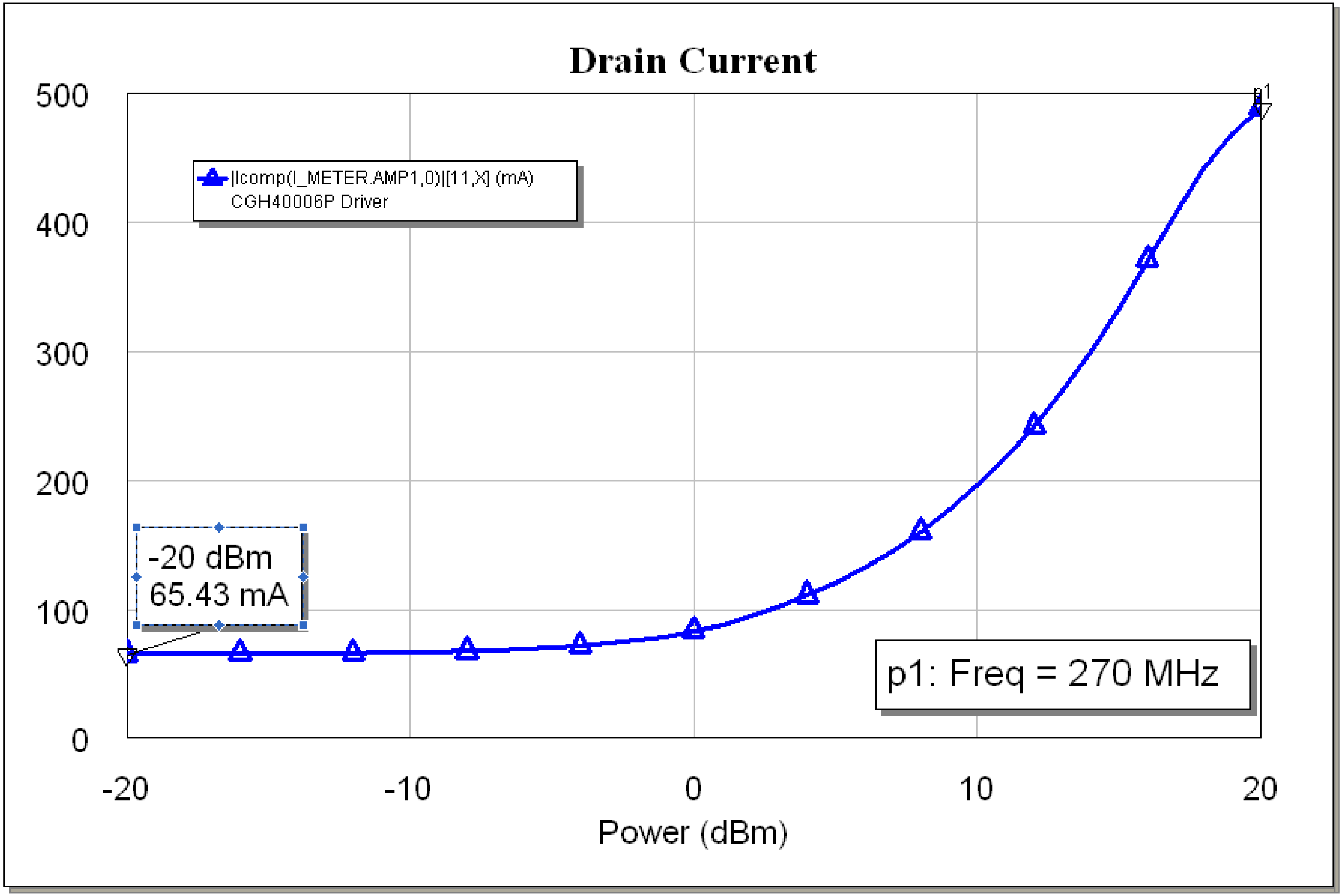
# Feedback Network



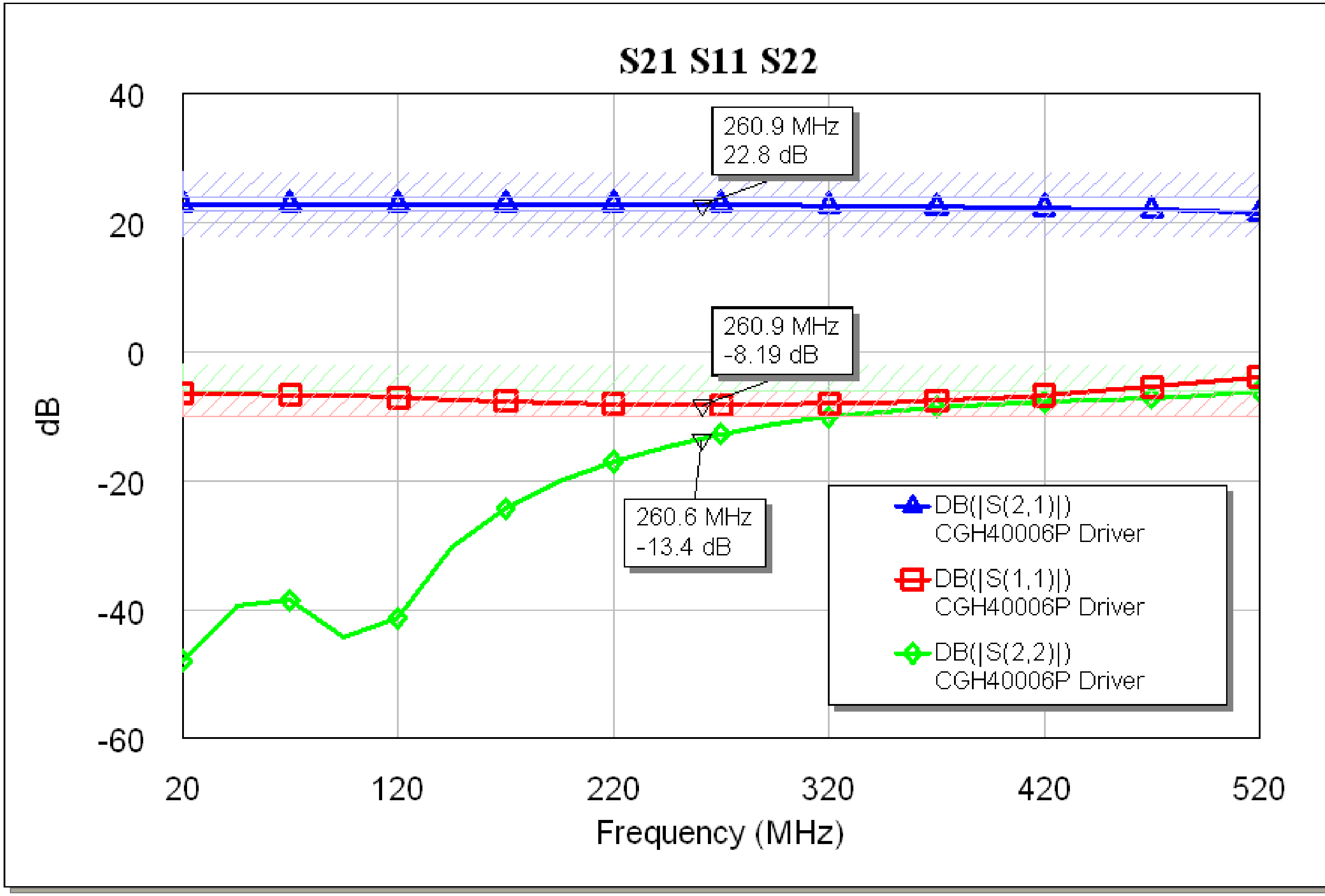
# Output Matching Network



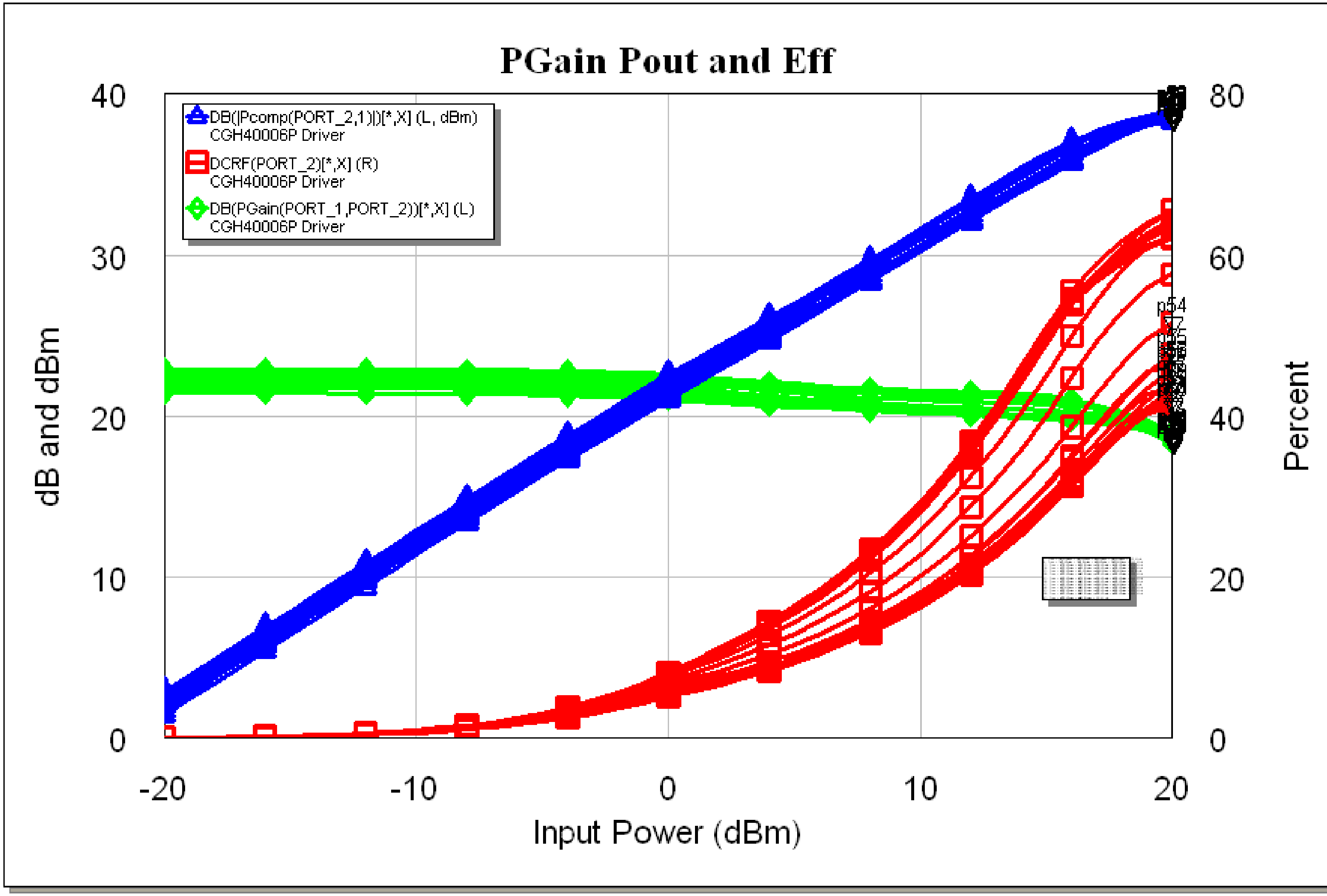
# Typical Drain Current versus Input Power



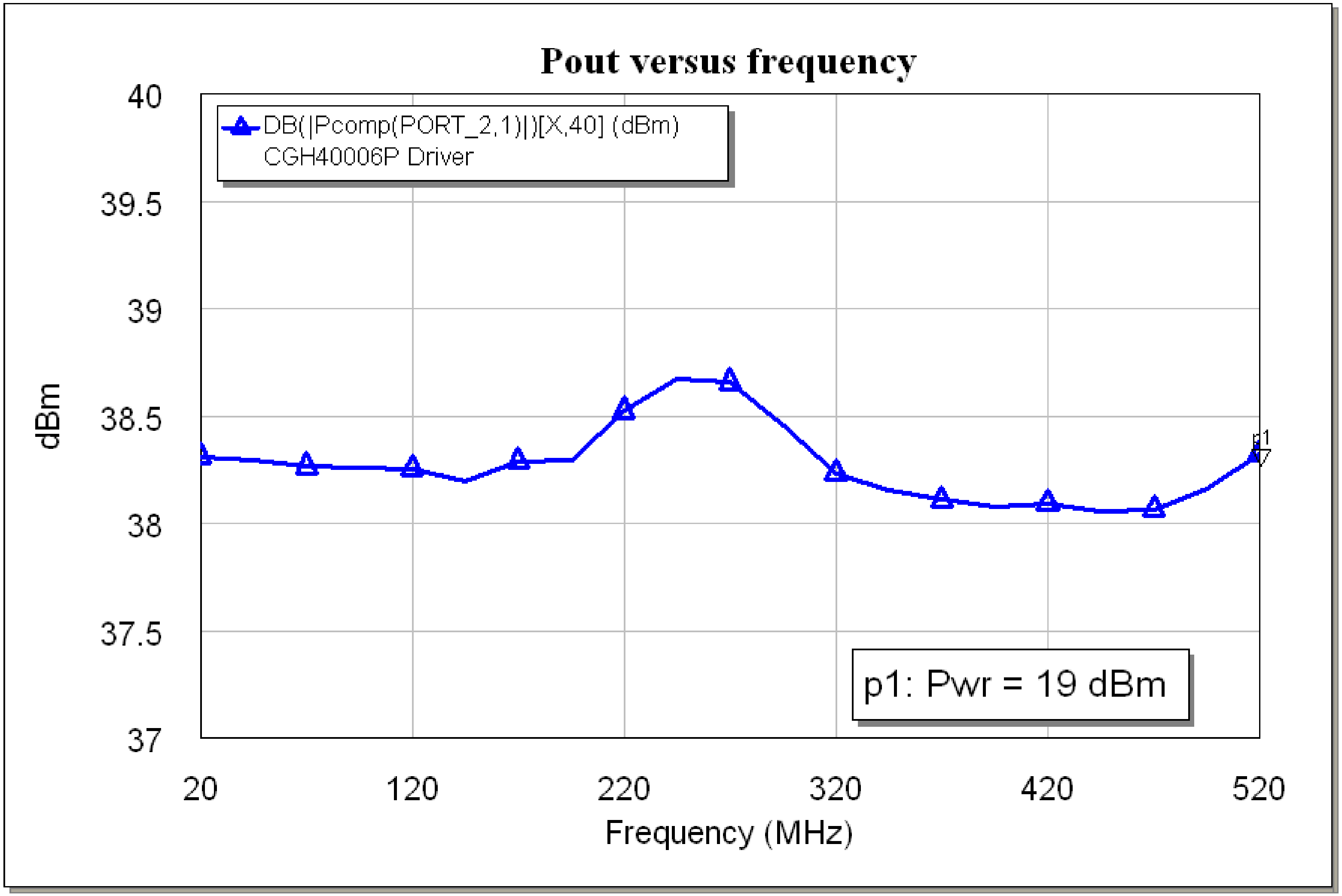
# Small signal gain, input and output return losses



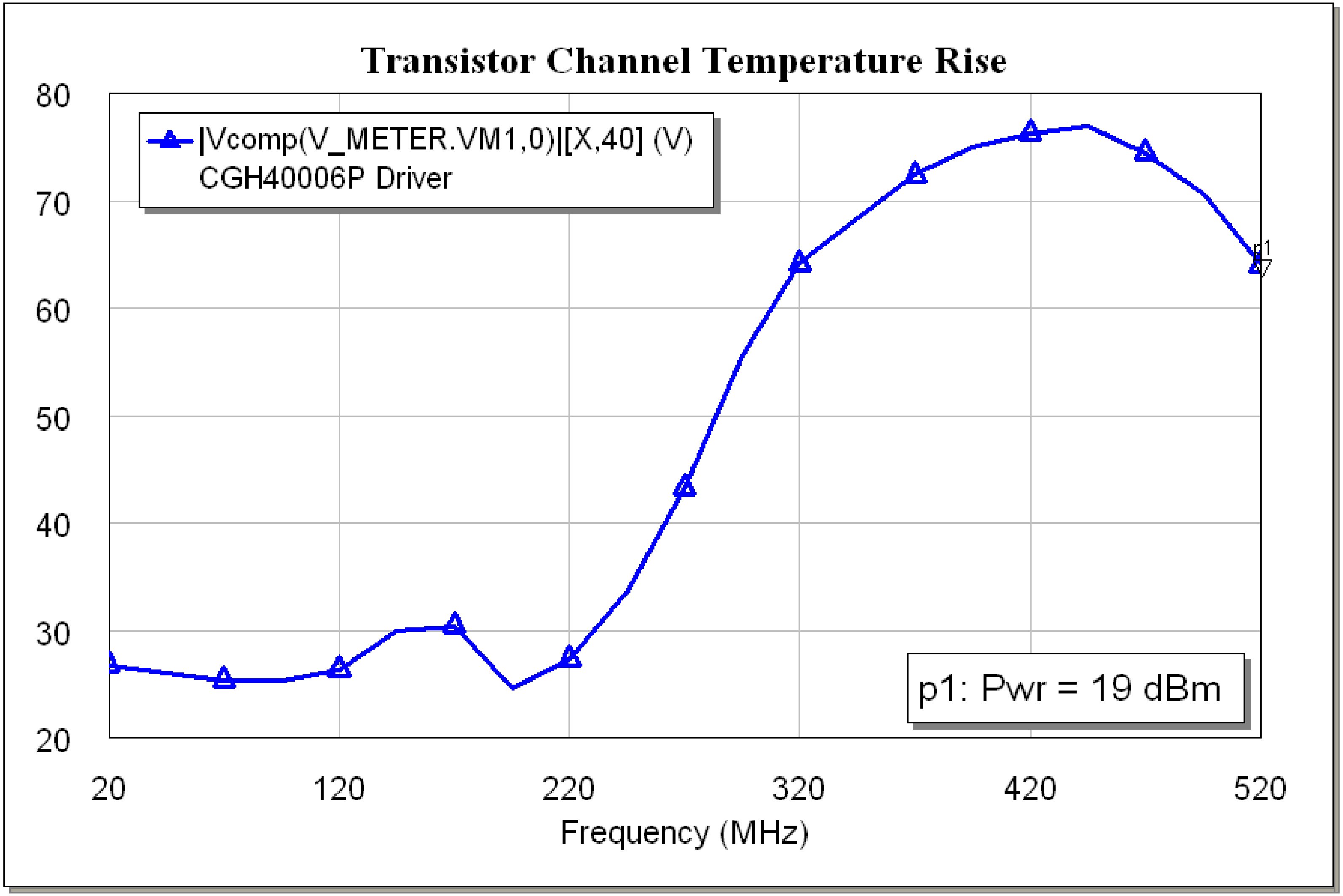
# Gain, Drain Efficiency and Output Power versus Input Power



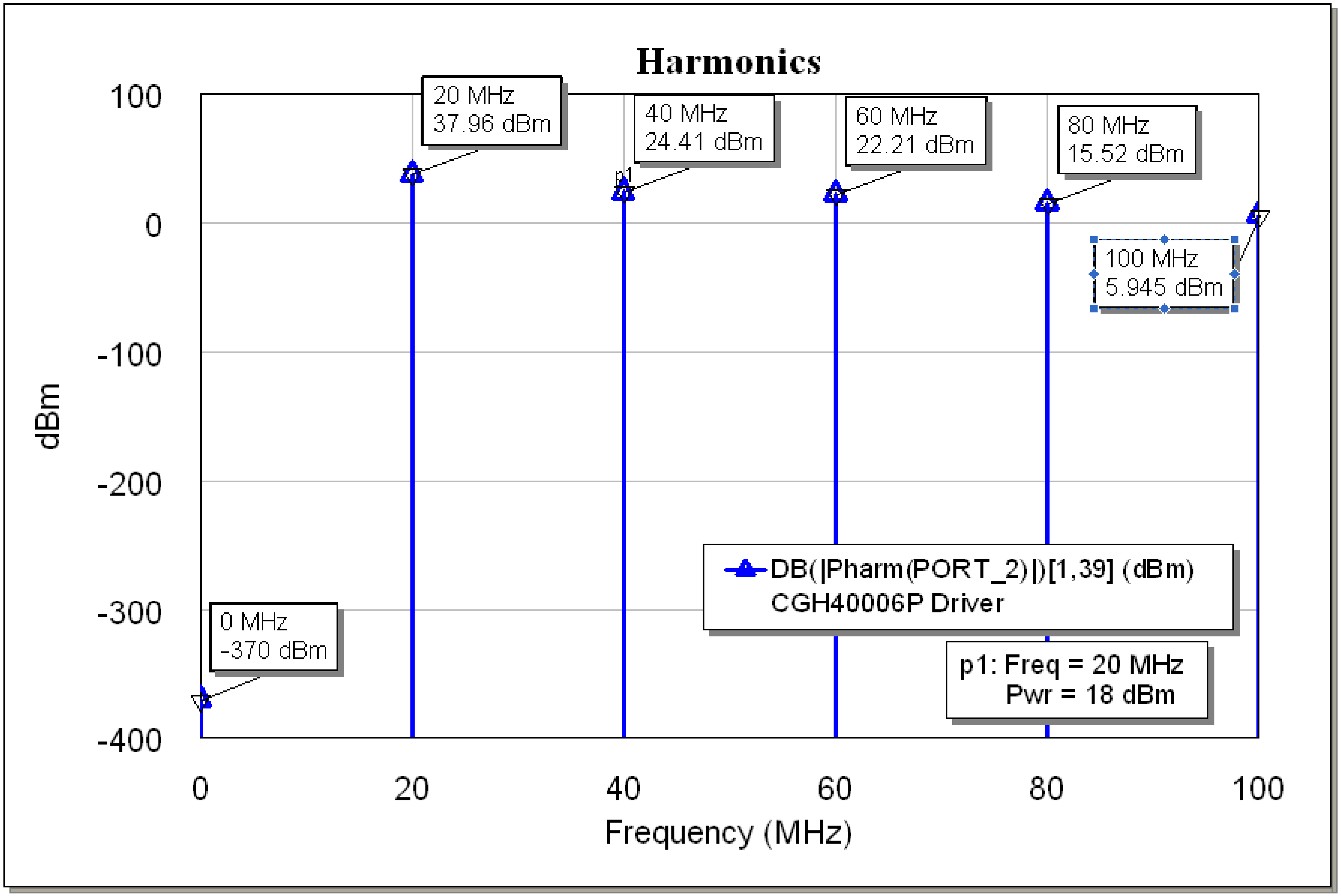
# Output Power versus Frequency at Pin=19 dBm



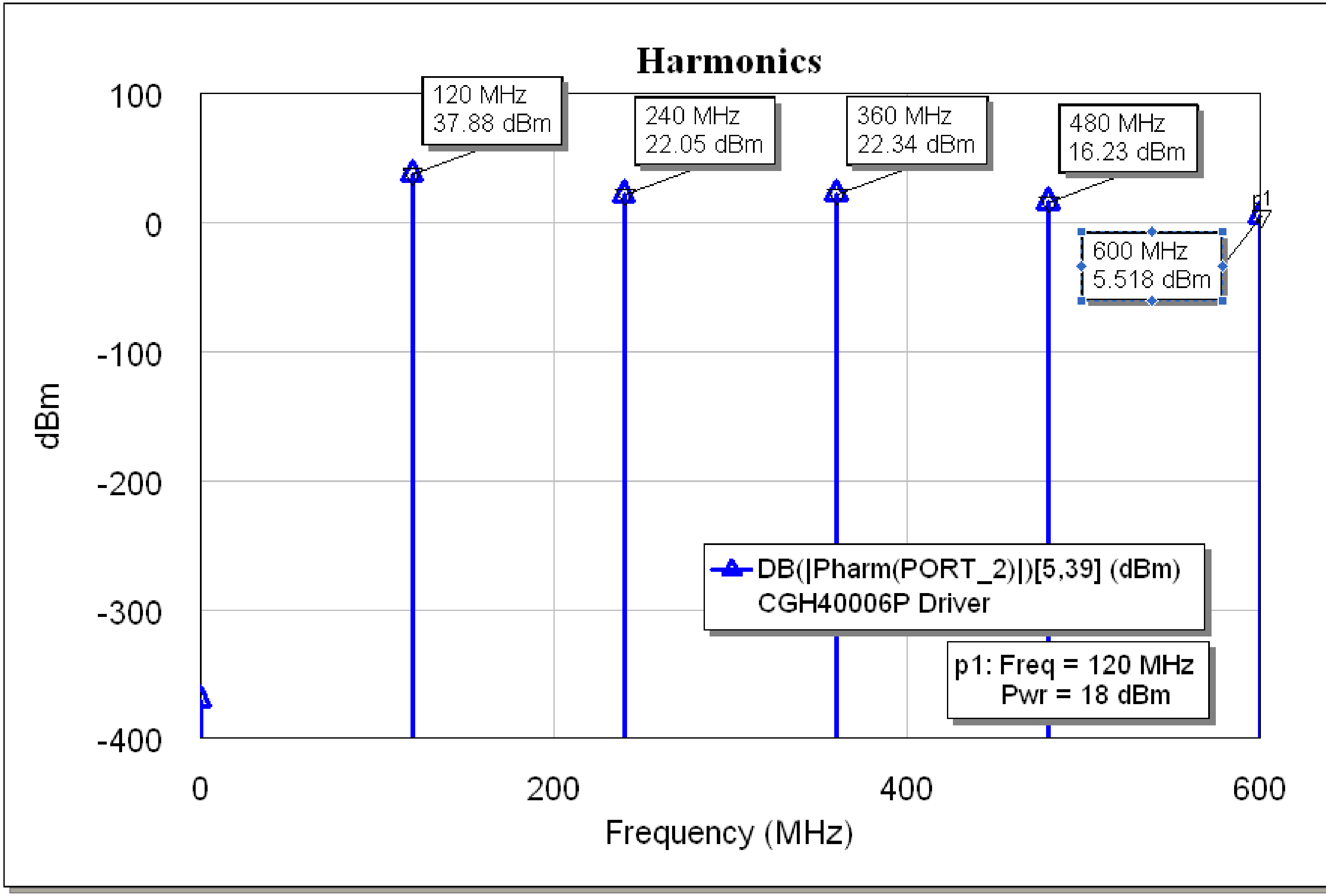
# Transistor Temperature Rise at Pin= 19dBm



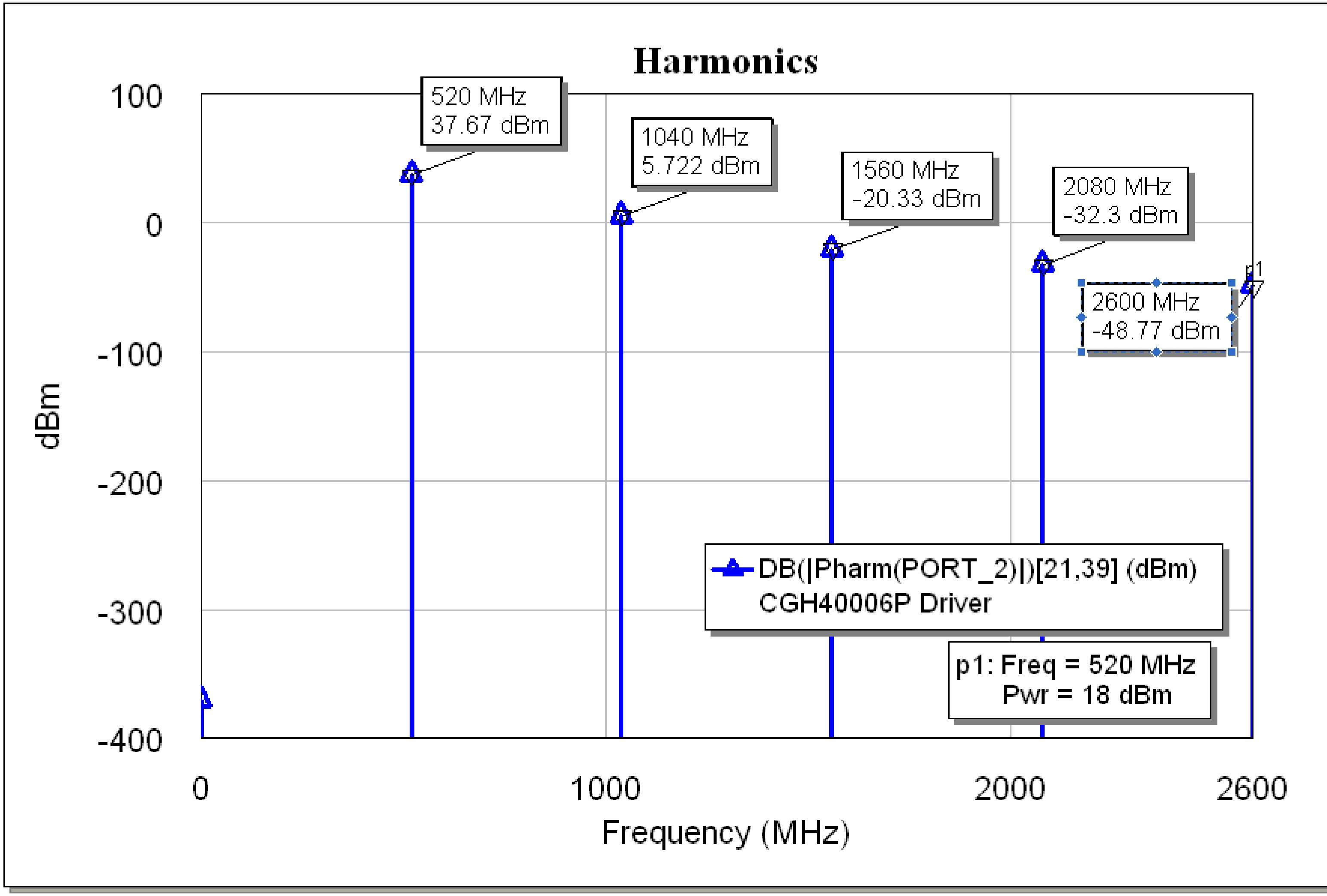
# Harmonics of PA (f=20 MHz) at Pin=18 dBm



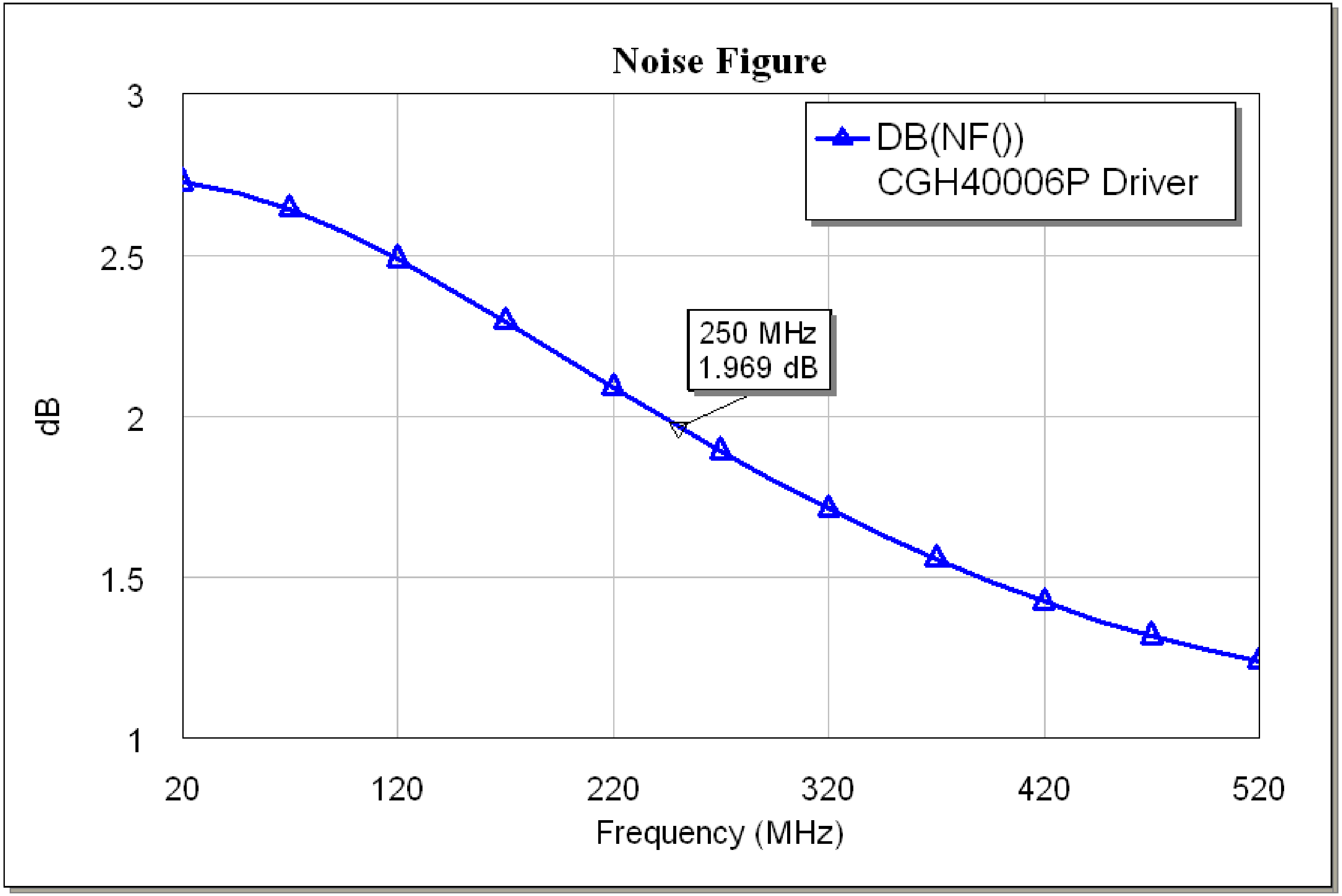
# Harmonics of PA (f=120 MHz) at Pin = 18 dBm



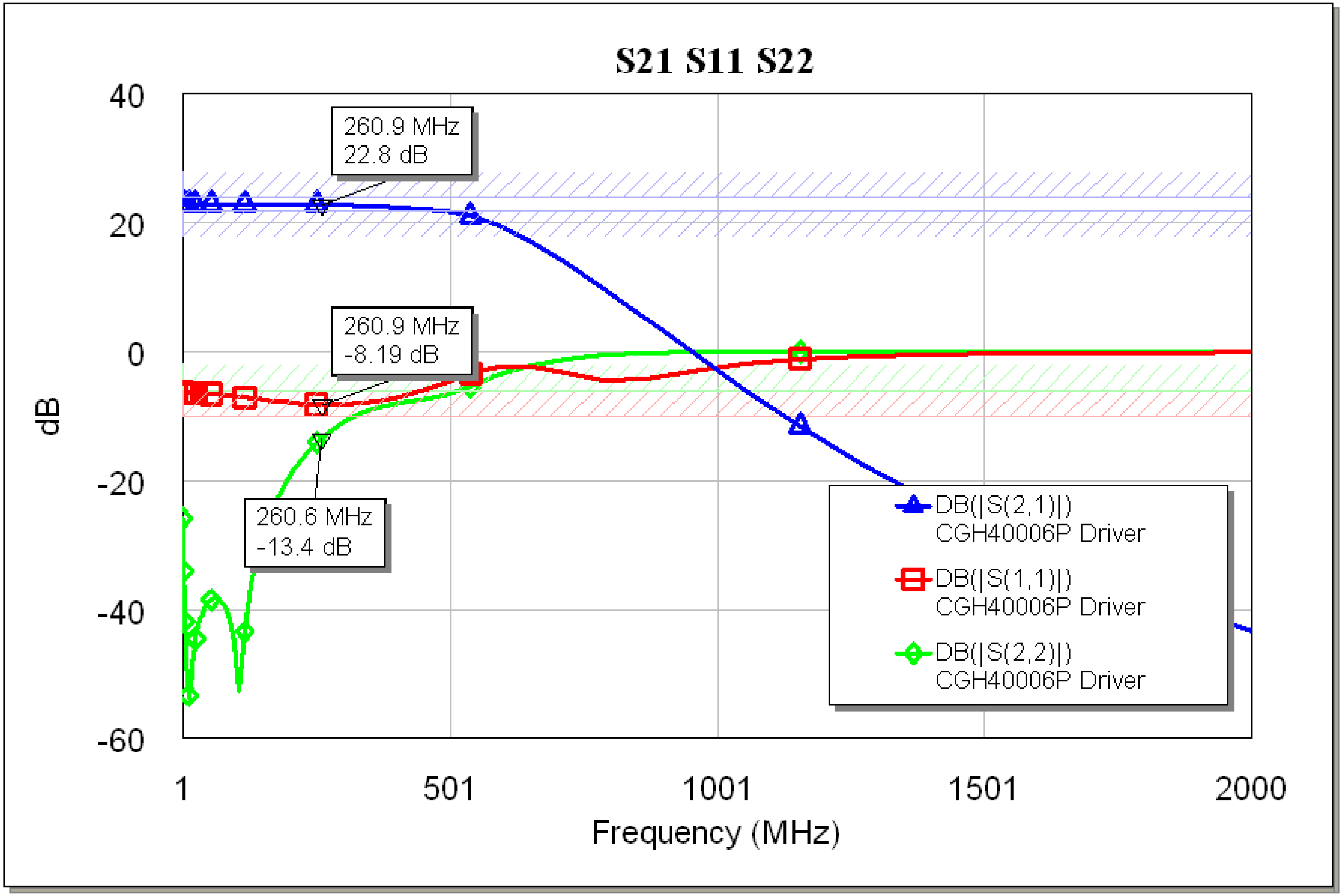
# Harmonics of PA (f=520 MHz) at Pin=18 dBm



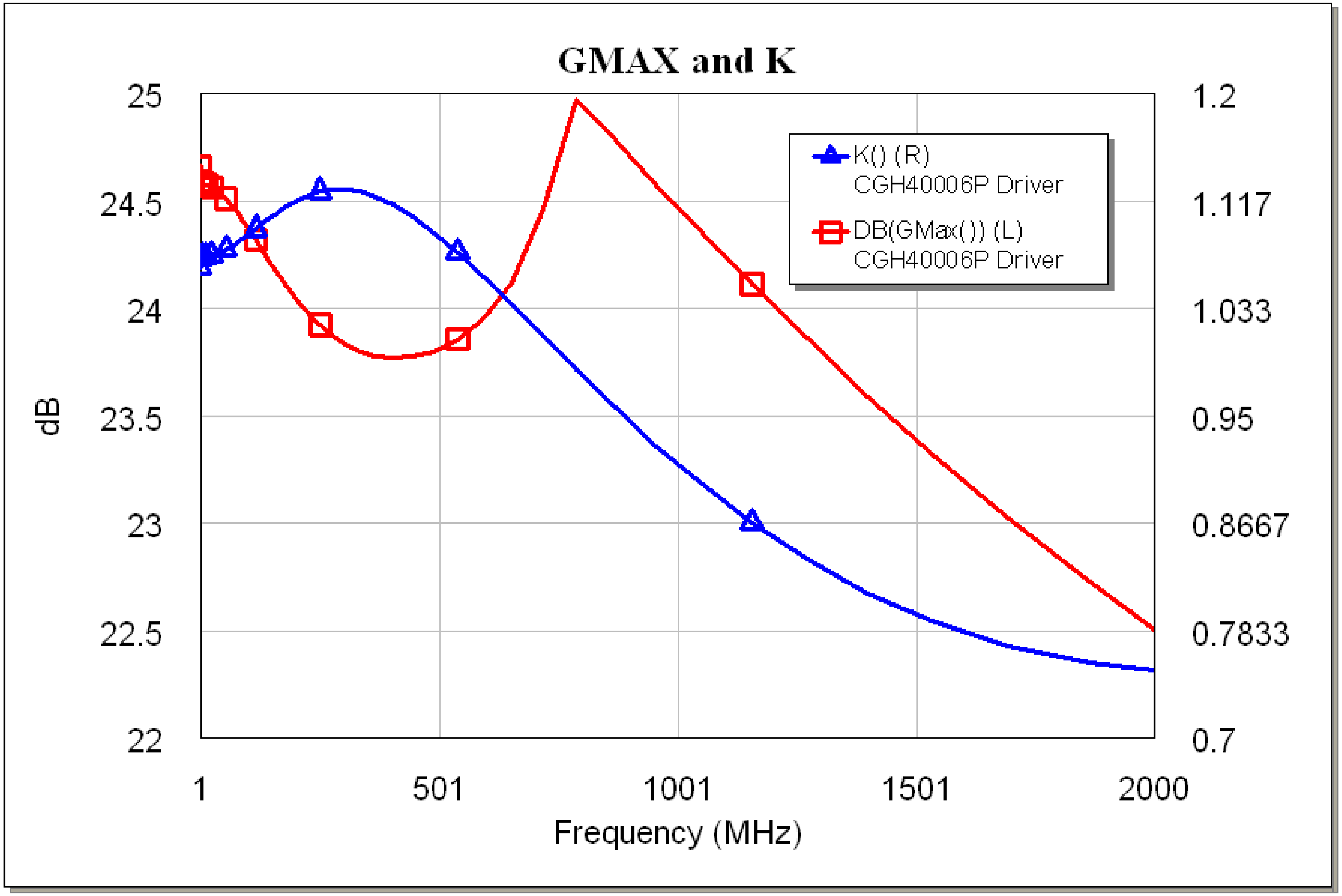
# Noise Figure of PA



# Ultra-Broadband Performance of PA



# Ultra-Broadband GMAX and K Factor of PA



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