

# GaN based RF Power Amplifier (Design and Simulation)

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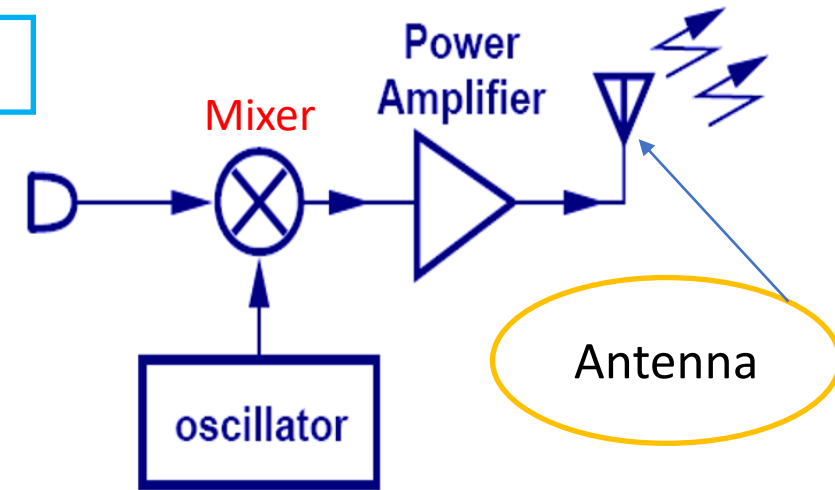
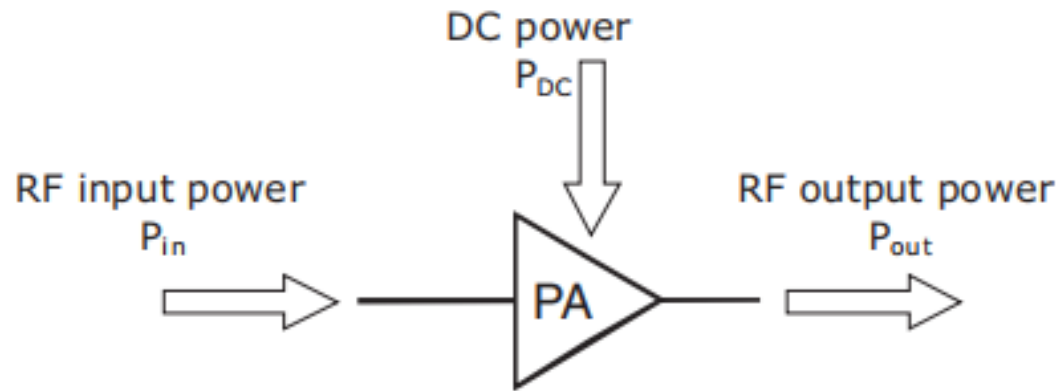
# Outline

- RFPA and their key performance metrics
- Why GaN
- Classes of operation
- PA design steps
- Simulation Results

# What is an RFPA?

Boosts input power (gives a power gain)

Gives high power at RF (things get heated)



*Wireless communication Systems  
(Transmitter side)*

A Power Amplifier (PA) is needed to boost the power before transmission

# Some key specifications

Gain

$$G(f) = \frac{P_{out}(f)}{P_{in}(f)}$$

Efficiency

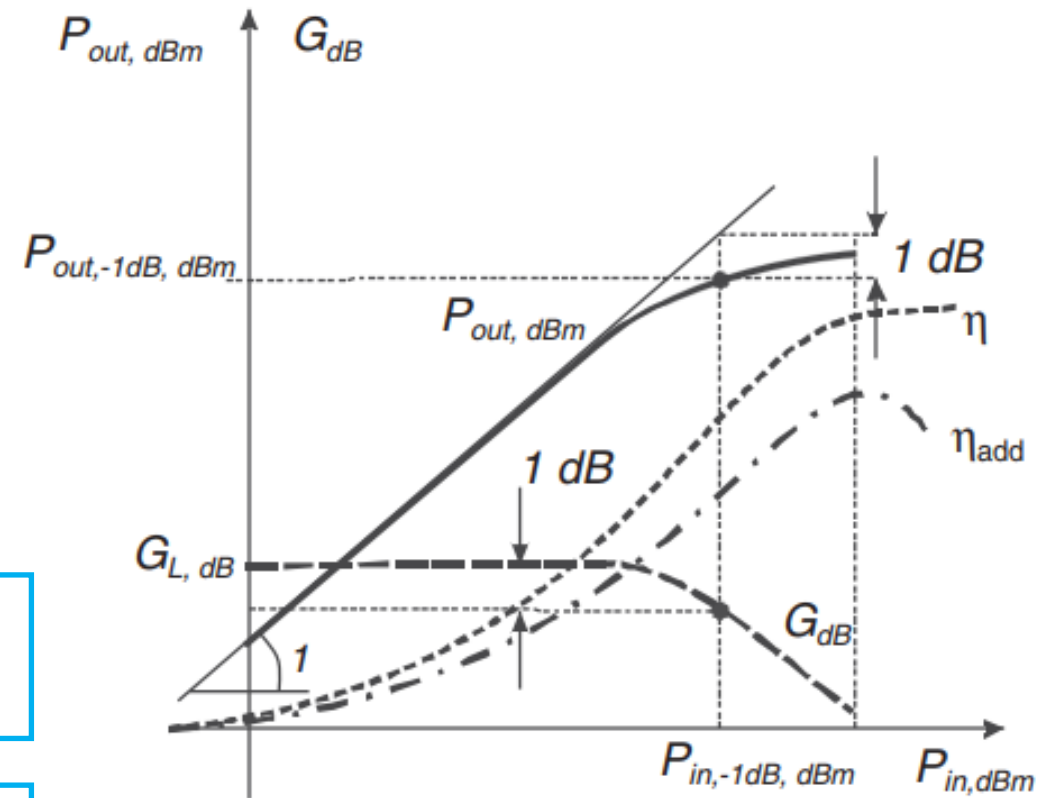
$$\eta = \frac{P_{out}}{P_{DC}}$$

Power-aided  
Efficiency (PAE)

$$\eta_{add} \triangleq \frac{P_{add}}{P_{DC}} = \frac{P_{out} - P_{in}}{P_{DC}}$$

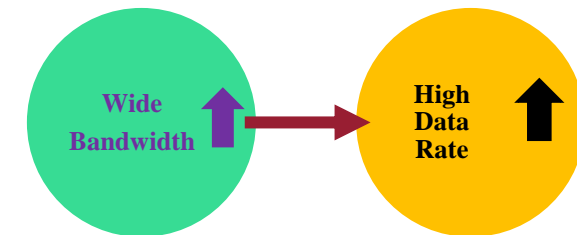
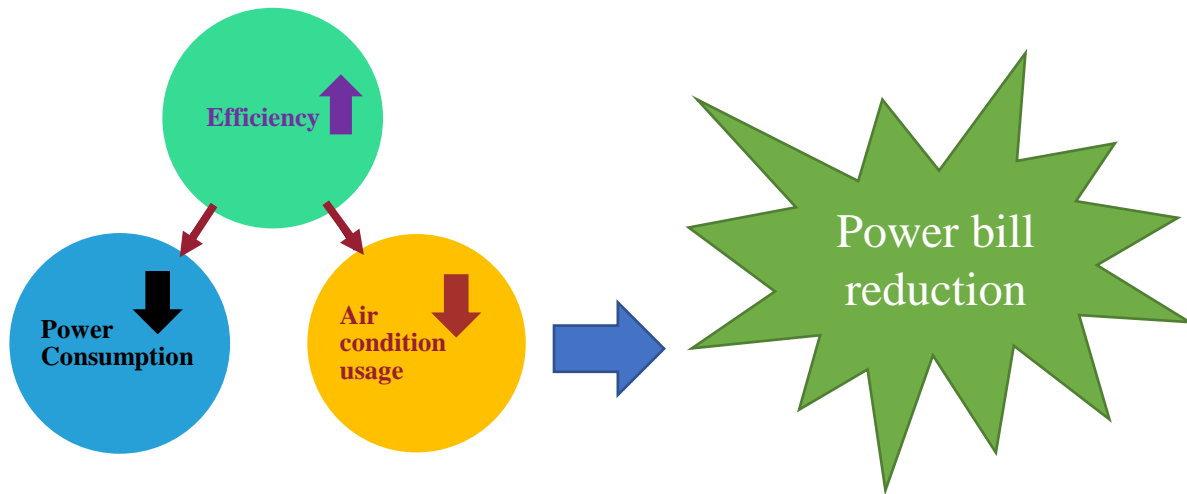
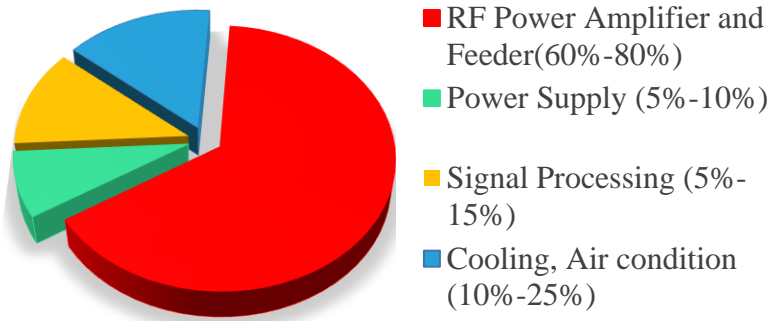
PAE is a more meaningful figure as it subtracts the added RF input power as well.

It is advantageous to operate the PA near saturation to achieve high efficiency.



# Some key specifications

## Base Station Power Consumption



**Bandwidth is also important**

# Solid-State PA (SSPA)

*Microwave tube-based amplifiers*



**A TWT  
Amplifier  
(200W, CW,  
18-26.5 GHz)**

*RF transistor-based amplifiers (SSPA)*



**A cell phone  
uses a  
transistor PA**



# Solid-State PA (SSPA)



Still a choice for very high power applications

## *Microwave tubes limitations*

- Maintenance
- Size
- High voltage

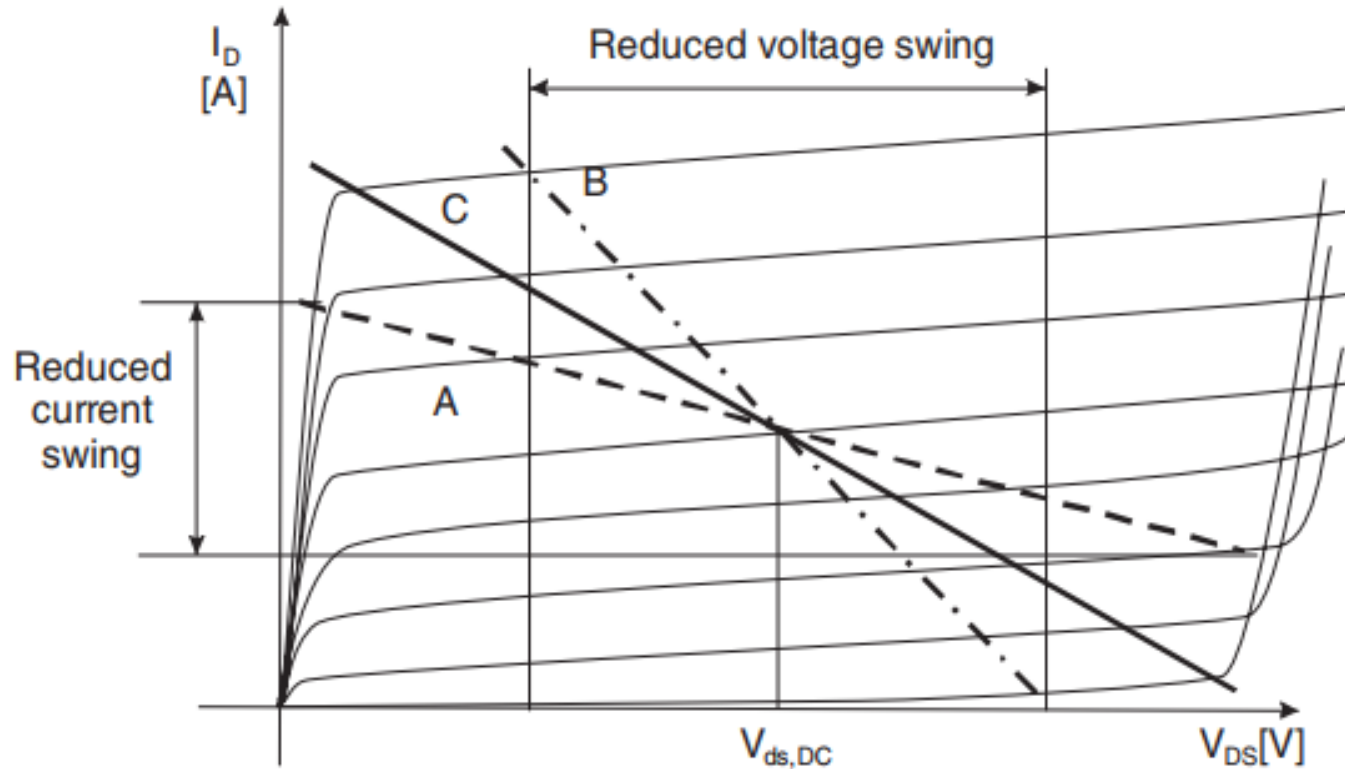


SSPA are replacing the tubes.

## *SSPA advantages*

- Low Maintenance
- Compact
- Greater reliability

# PA power requirement



High voltage and current swings translate into high output power ( $P = V \times I$ ).

In RFPA, complex conjugate matching are not employed at output.



# Why GaN

## Advantages and disadvantages of GaN device

TABLE 1. Comparison of device material properties.

Material	Band Gap Energy eV	Breakdown E Field MV/cm	Mobility cm <sup>2</sup> /V/s	Saturated Velocity cm/s	Thermal Conductance W/cm/°K
Gallium nitride	3.4	3.0	1,500	$2.7 \times 10^7$	1.5
Silicon	1.1	0.3	1,300	$1.0 \times 10^7$	1.5
Gallium arsenide	1.4	0.4	6,000	$1.3 \times 10^7$	0.5

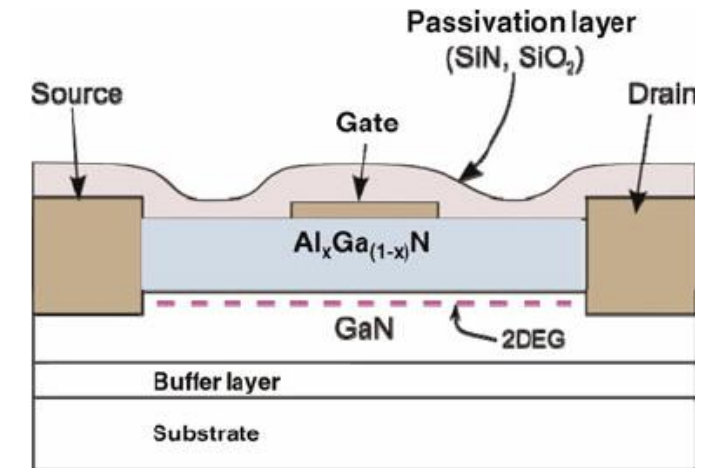
Low mobility partially offset by high saturation velocity

### Advantages:

- High breakdown field enables to be used for high voltage
- High current density: high output power with smaller size
- Outstanding thermal properties with SiC substrate produces less heat
- Higher impedance level: more bandwidth and less loss
- High Efficiency: less source (battery) power required

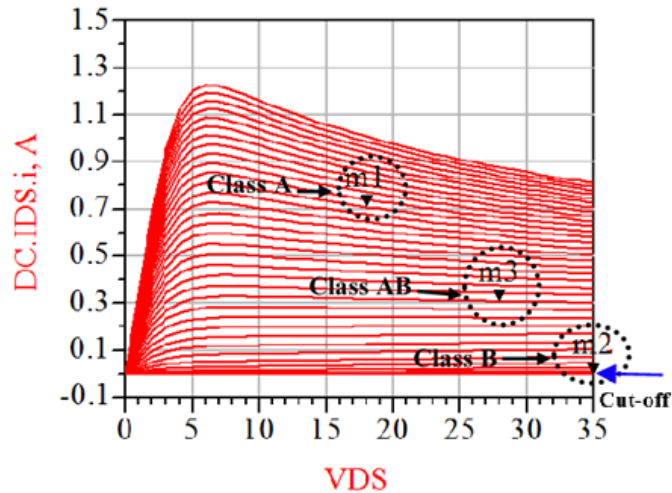
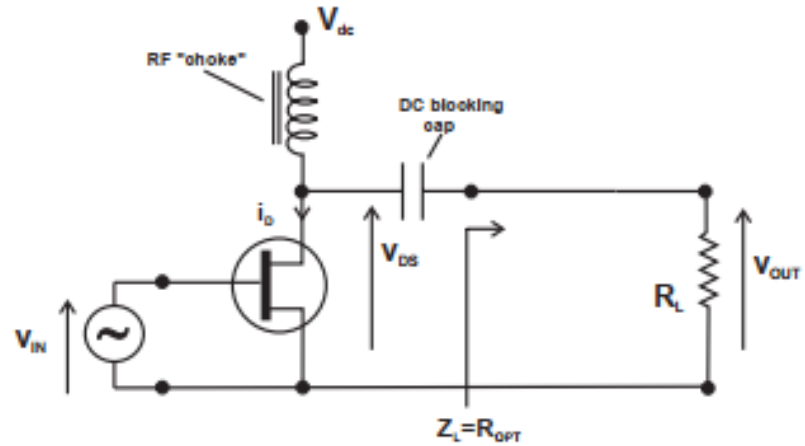
### Disadvantages

- High cost
- Not good linearity compared to GaAs and Si LDMOS
- Not suitable for low power (but maybe possible in future)
- Requires harmonic control for high efficiency PA



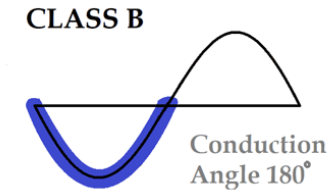
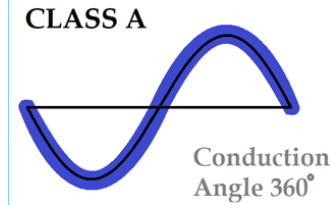
*SiC substrate (GaN-on-SiC) provides excellent thermal conductivity*

# PA classifications



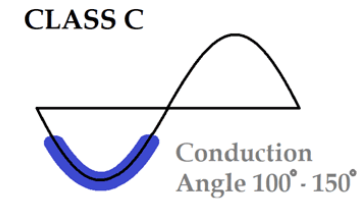
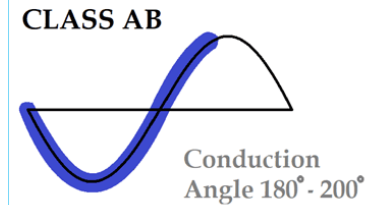
## General classes

$\eta = 50\%$



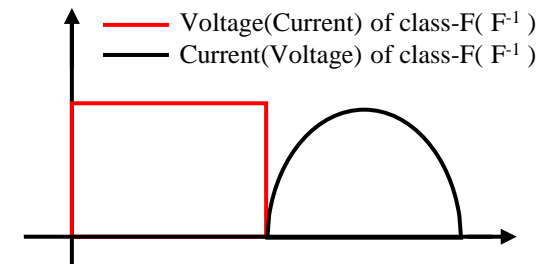
$\eta = 78.5\%$

$50 < \eta < 78.5\%$



$\eta > 78.5\%$

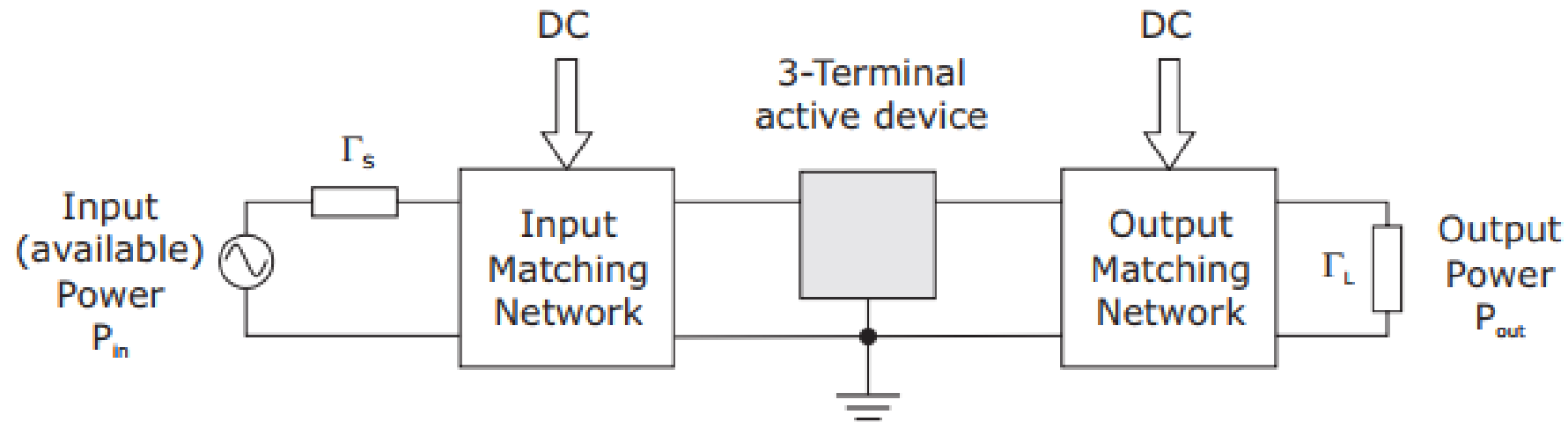
## High efficiency modes, class- F and F<sup>-1</sup>



$\eta = 100\%$

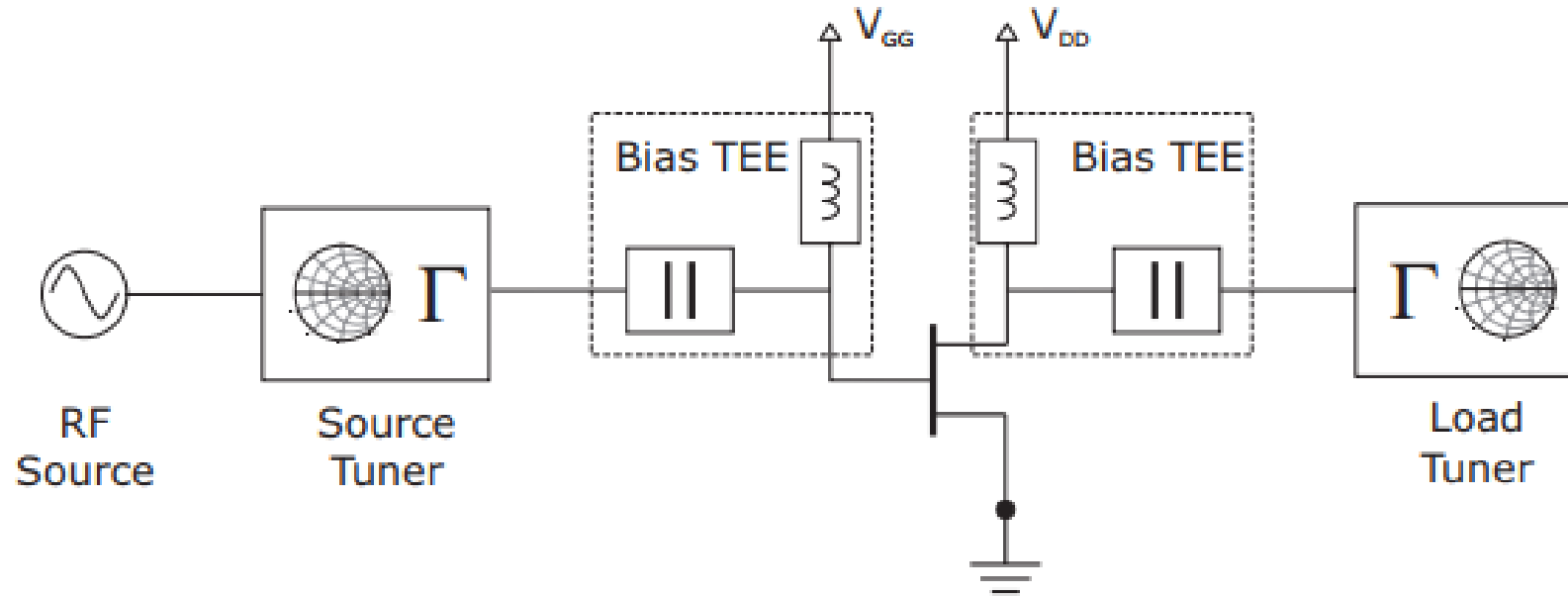
**Class AB is a good compromise between Class A and B with decent linearity and efficiency. Also, employed in Doherty PA.**

# RFPA structure and design method



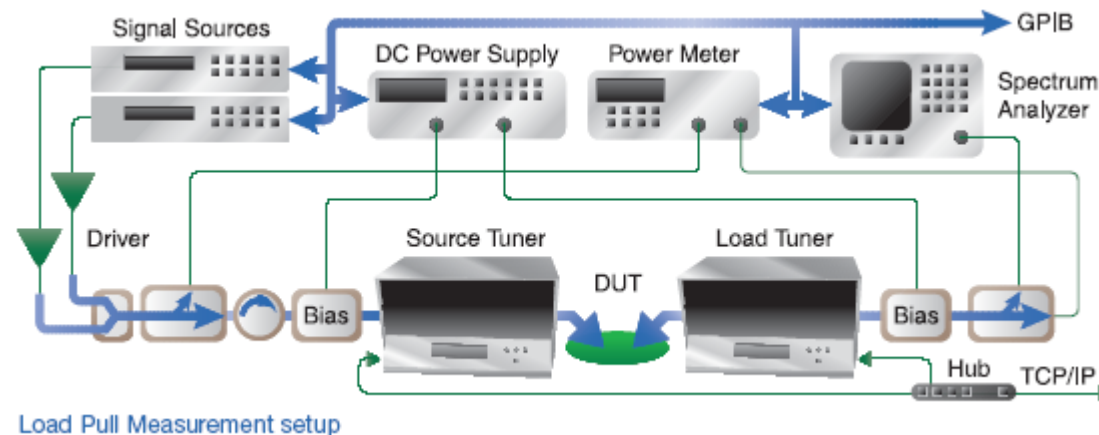
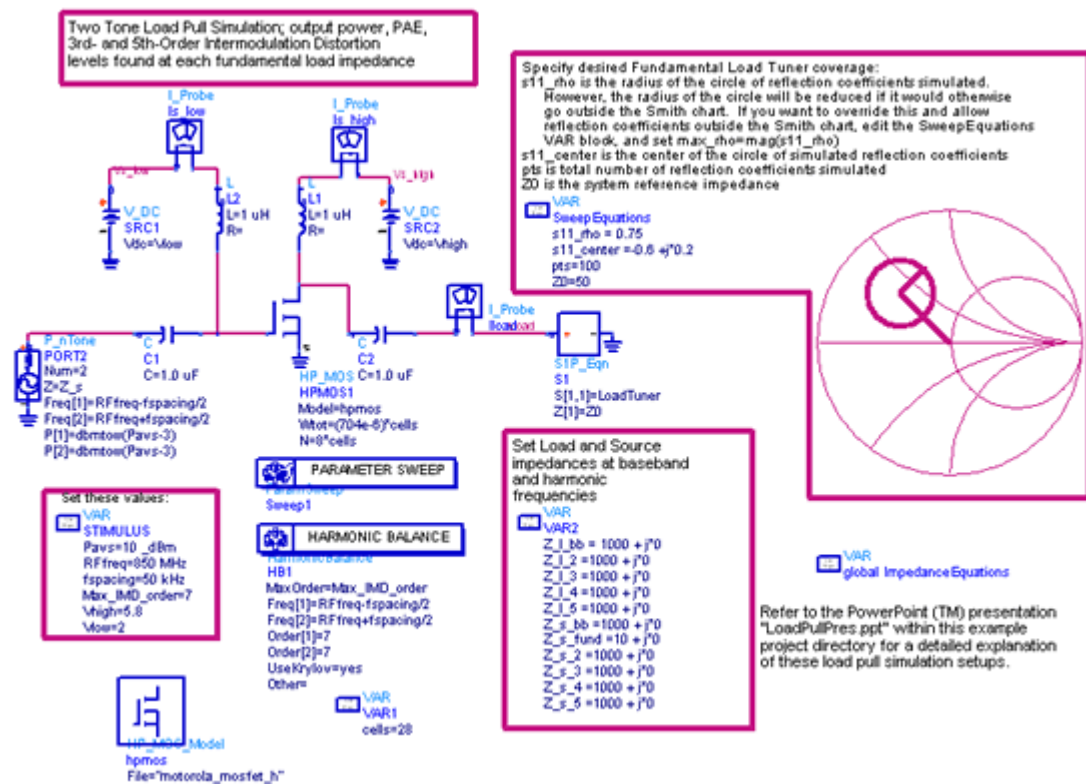
*Impedance matching network design is the main task*

# How to find the optimum load



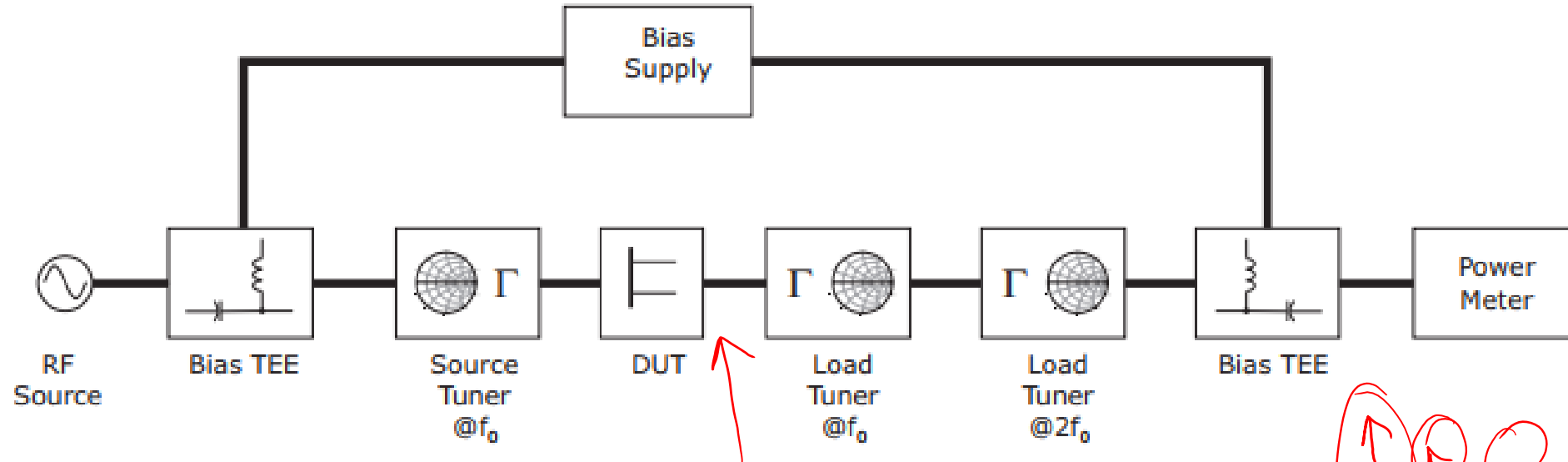
**Loadpull: Tune output load to see at what load the Pout and PAE are maximized**

# How to find the optimum load



**Loadpull either using a model in NI AWR/Keysight ADS  
Or buy dedicated hardware (mechanical setup)**

# How to find the optimum load

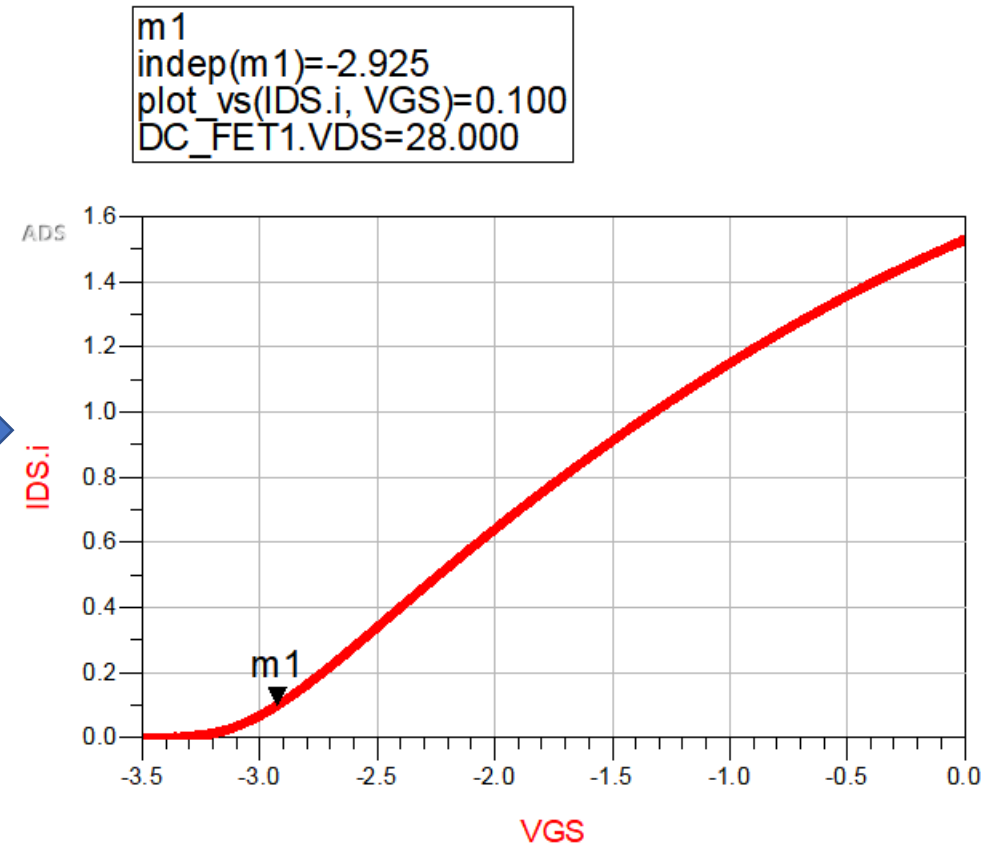
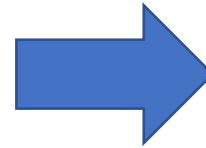
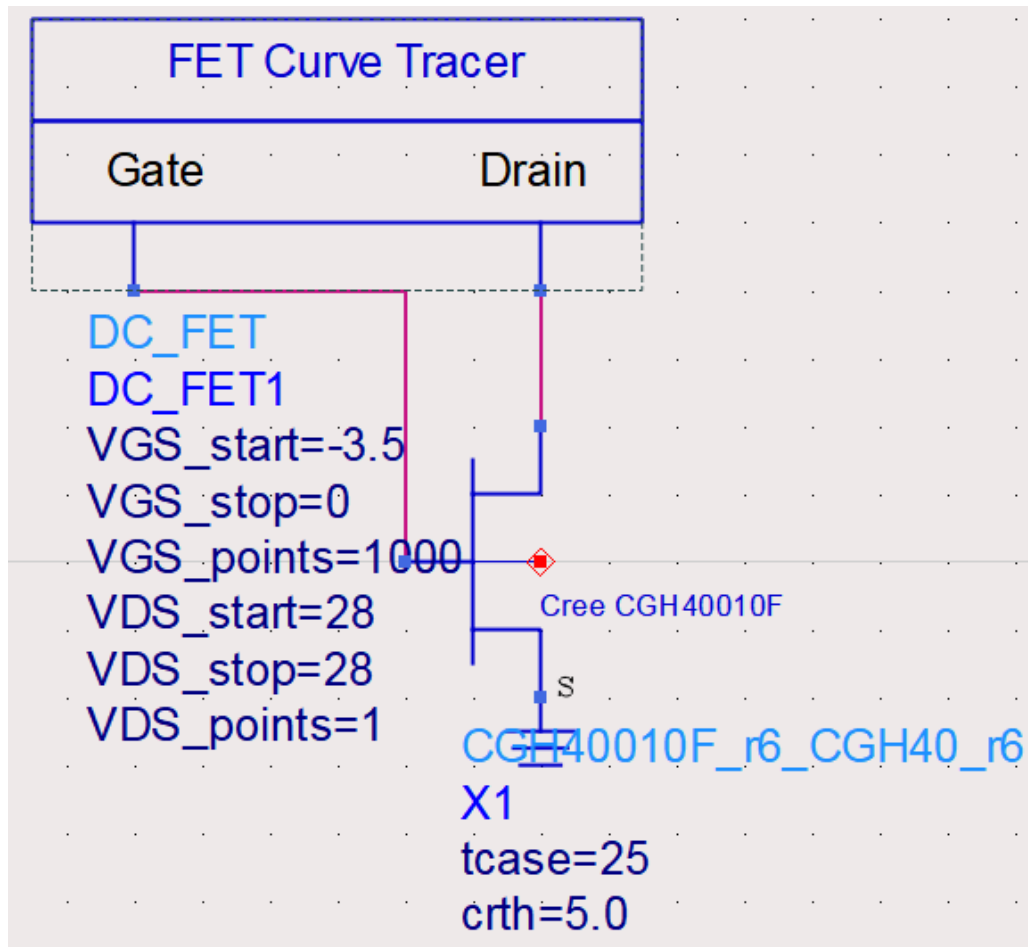


You have to do harmonic loadpull as well



# RFPA Design Steps

Choose a device and perform a DC simulation to plot ID-VGS



Subsequently, we stabilize the device.

# RFPA Design Steps

## Perform a fundamental loadpull simulation

One Tone Load Pull Simulation; output power and PAE found at each fundamental load impedance.

Specify desired Fundamental Load Tuner coverage:  
 $s11\_rho$  is the radius of the circle of reflection coefficients generated. However, the radius of the circle will be reduced if it would otherwise go outside the Smith Chart.  
 $s11\_center$  is the center of the circle of generated reflection coefficients  
 $pts$  is the total number of reflection coefficients generated.  
 $Z0$  is the system reference impedance.

```

VAR
Sweep Equations
s11_rho = 0.95
s11_center = 0.0 + j0.0
pts = 501
Z0 = 50
    
```

$s11\_rho$  is the radius and  $s11\_center$  is the center of the circle. (But this is just a static drawing.)

Set Load and Source impedances at harmonic frequencies

```

VAR
VARZ
Z_s_1 = 0.1 + j0
Z_s_2 = 0 + j20
Z_s_3 = 10 + j0
Z_s_4 = 10 + j0
Z_s_5 = 10 + j0
Z_s_fund = 8.6 + j19
Z_s_2 = 10 + j0
Z_s_3 = 10 + j0
Z_s_4 = 10 + j0
Z_s_5 = 10 + j0
    
```

Refer to the data display file "ReflectionCoeffUtility" for help in setting  $s11\_rho$  and  $s11\_center$ . Also, refer to the example design file: examples/RF\_Board/LoadPull\_prj/HB1Tone\_LoadPull\_eqns for details about how this simulation is run.

```

VAR
ImpedanceEquations
    
```

NETLIST INCLUDE

```

muRataLibWeb_include
muRata
    
```

Set these values:

```

VAR
STIMULUS
Pav = 25_dBm
RFreq = 2000 MHz
Vhigh = 28
Vlow = 2.525
    
```

PARAMETER SWEEP

```

ParamSweep
Sweep1
    
```

HARMONIC BALANCE

```

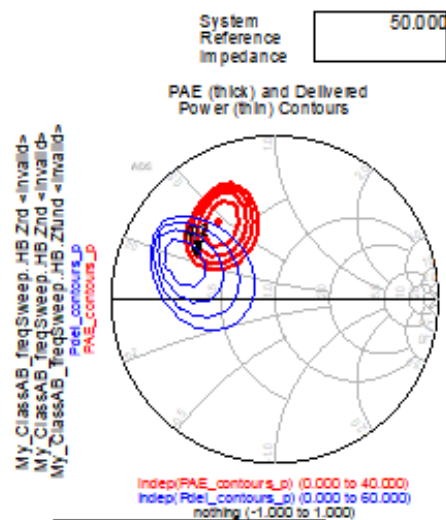
HarmonicBalance
HB1
Freq[1] = RF freq
Order[1] = 5
    
```



# RFPA Design Steps

## Choose an optimum load impedance

See the Load Pull DesignGuide for improved and enhanced load pull simulation displays.

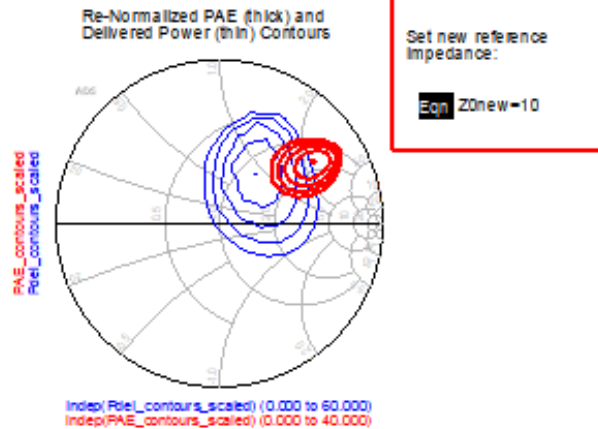


Set Delivered Power contour step size (dB) and PAE contour step size (%), and number of contour lines

- Eqn PdeI\_step=0.5
- Eqn PAE\_step=2
- Eqn NumPAE\_lines=5
- Eqn NumPdeI\_lines=5

Maximum Power-Added Efficiency, %: 77.41

Maximum Power Delivered, dBm: 41.80

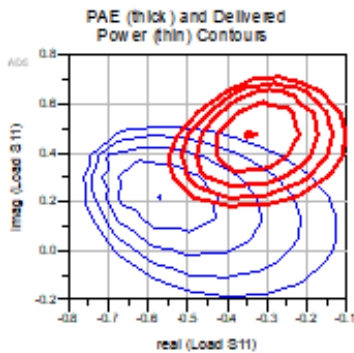


Set new reference impedance:  
Eqn Z0new=10

m1  
Index(m1)=11  
PAE\_contours\_p=0.545 / 151.183  
level=71.309, number=1  
Impedance = Z0 \* (0.312 + j0.233)

m2  
Index(m2)=16  
PdeI\_contours\_p=0.559 / 147.178  
level=41.285, number=1  
Impedance = Z0 \* (0.305 + j0.269)

Equations are on the "Equations" page.



Simulated Load Impedances and Input Reflection Coefficients

Move Marker m3 to select load impedance value. Corresponding PAE, delivered power, input reflection coefficient and impedance values will be updated.

Impedance at marker m3: 15.189 + j13.417

PAE, %: 72.94

Power Delivered (dBm): 41.30

Input Reflection Coefficient: 0.73 / -1.37E2

Input Impedance: 9.02 - j19.34

m3  
real\_Index(m3)=-0.472  
surface\_sample=0.981 / 147.291  
imag\_Index(m3)=0.323  
impedance=Z0 \* (0.304 + j0.289)

real\_Index(m1) (-0.949 to 0.949)

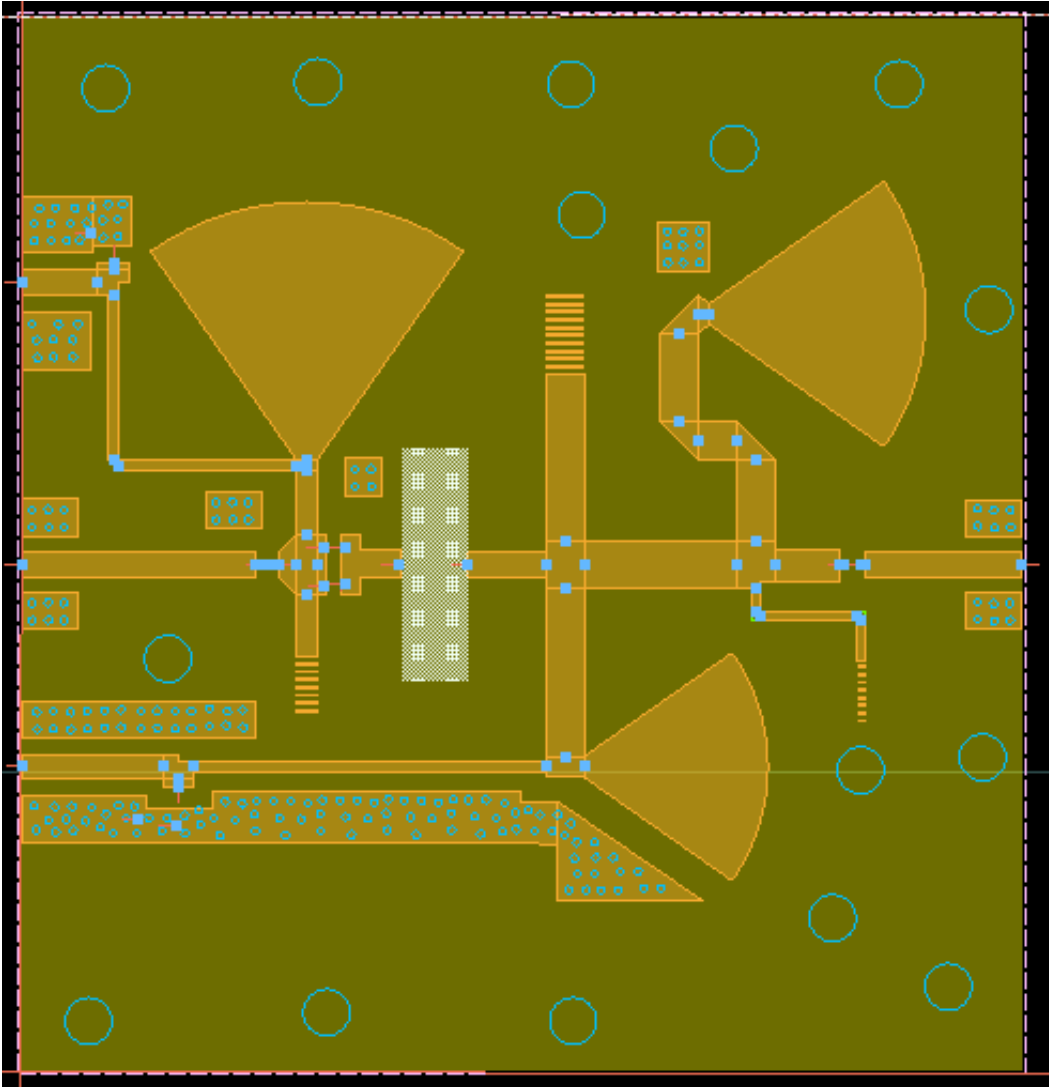
Rho\_in\_Func[imag\_Index(real\_Index)]  
Rho\_in\_Func[surface\_Samples]





# RFPA Design Steps

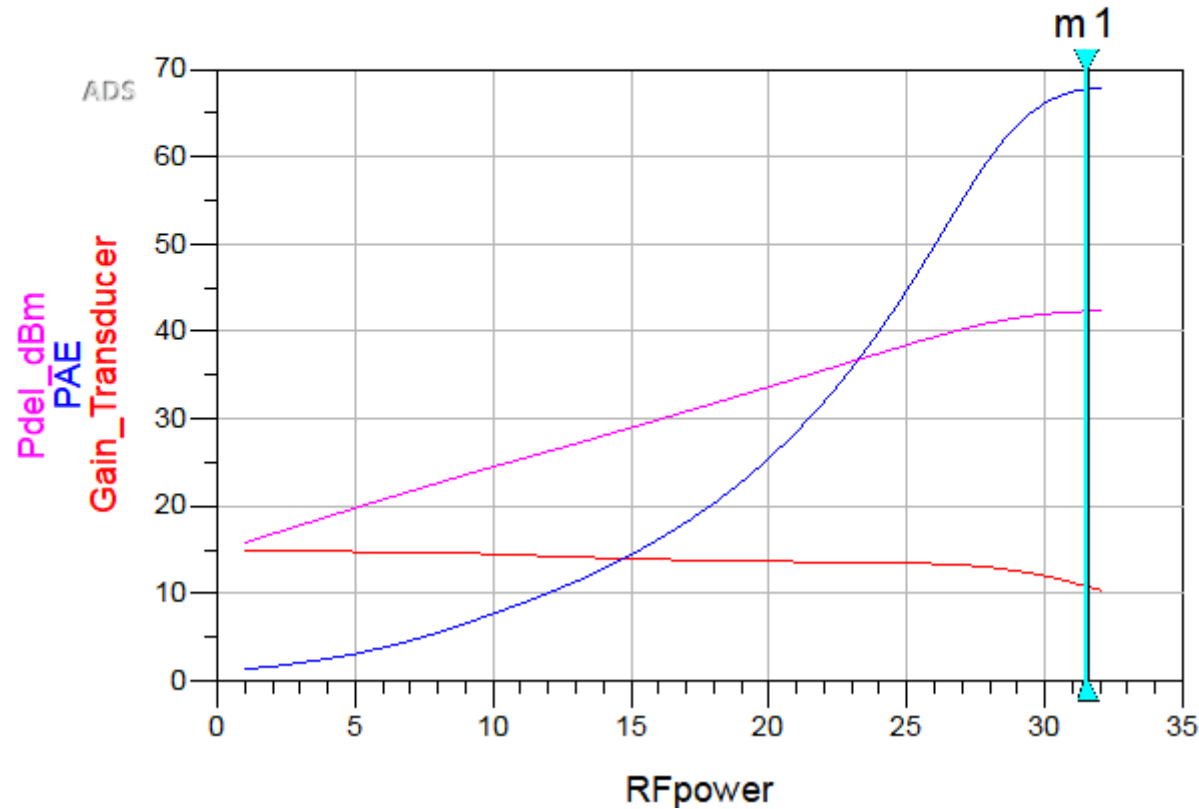
**Final optimized design**



# RFPA Design Steps

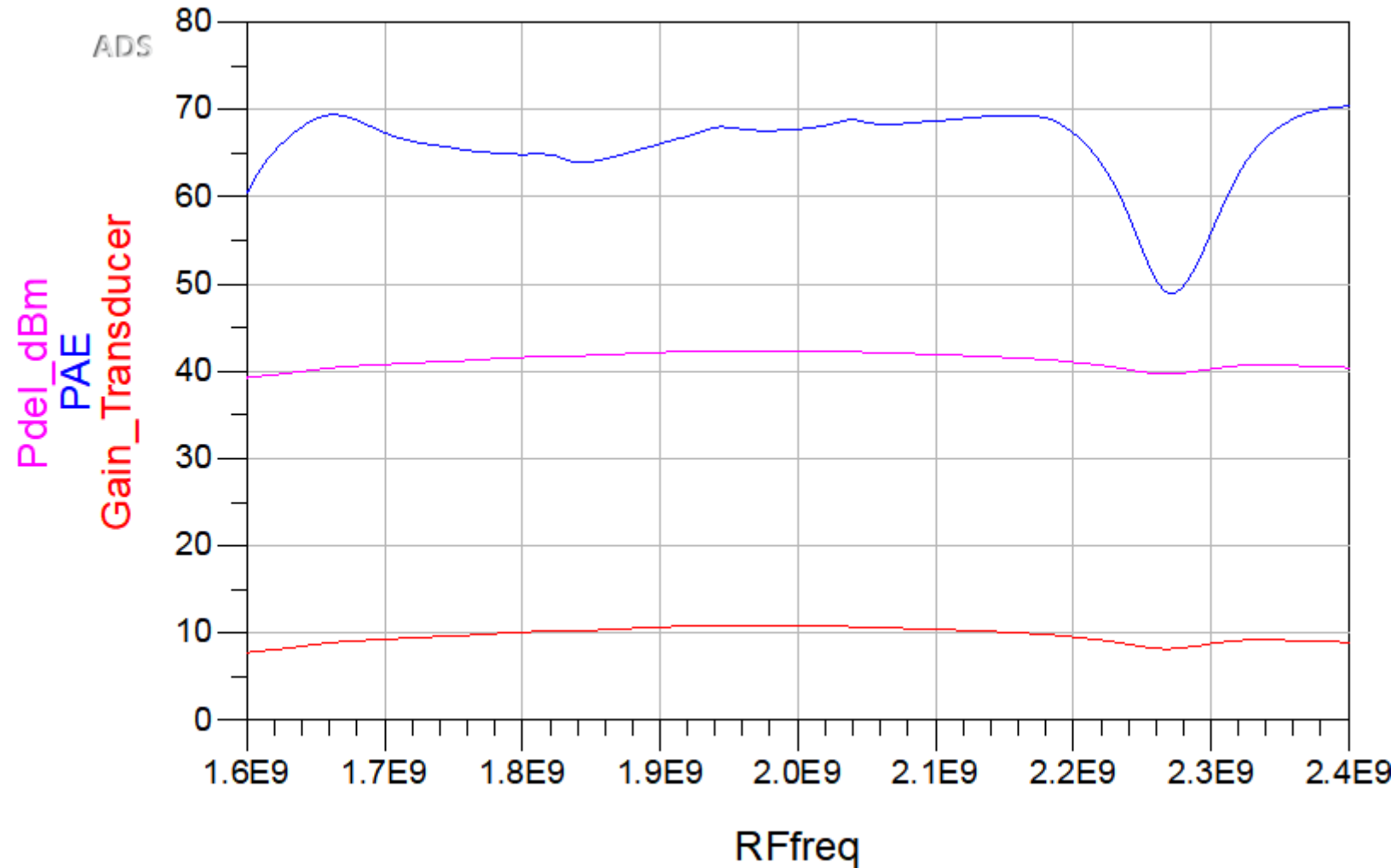
## Simulated results of Final PA: Power sweep

m 1  
RFpower=31.500  
Gain\_Transducer=10.792  
PAE=67.742  
Pdel\_dBm=42.292



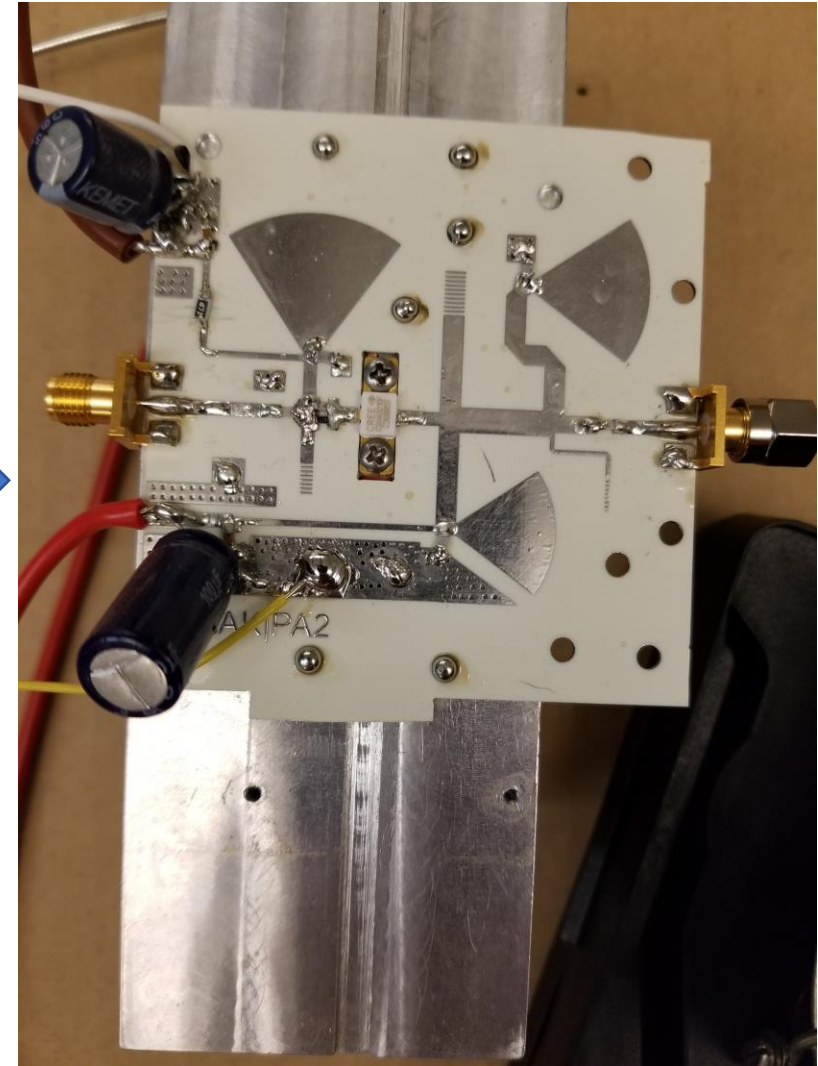
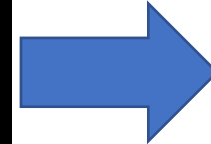
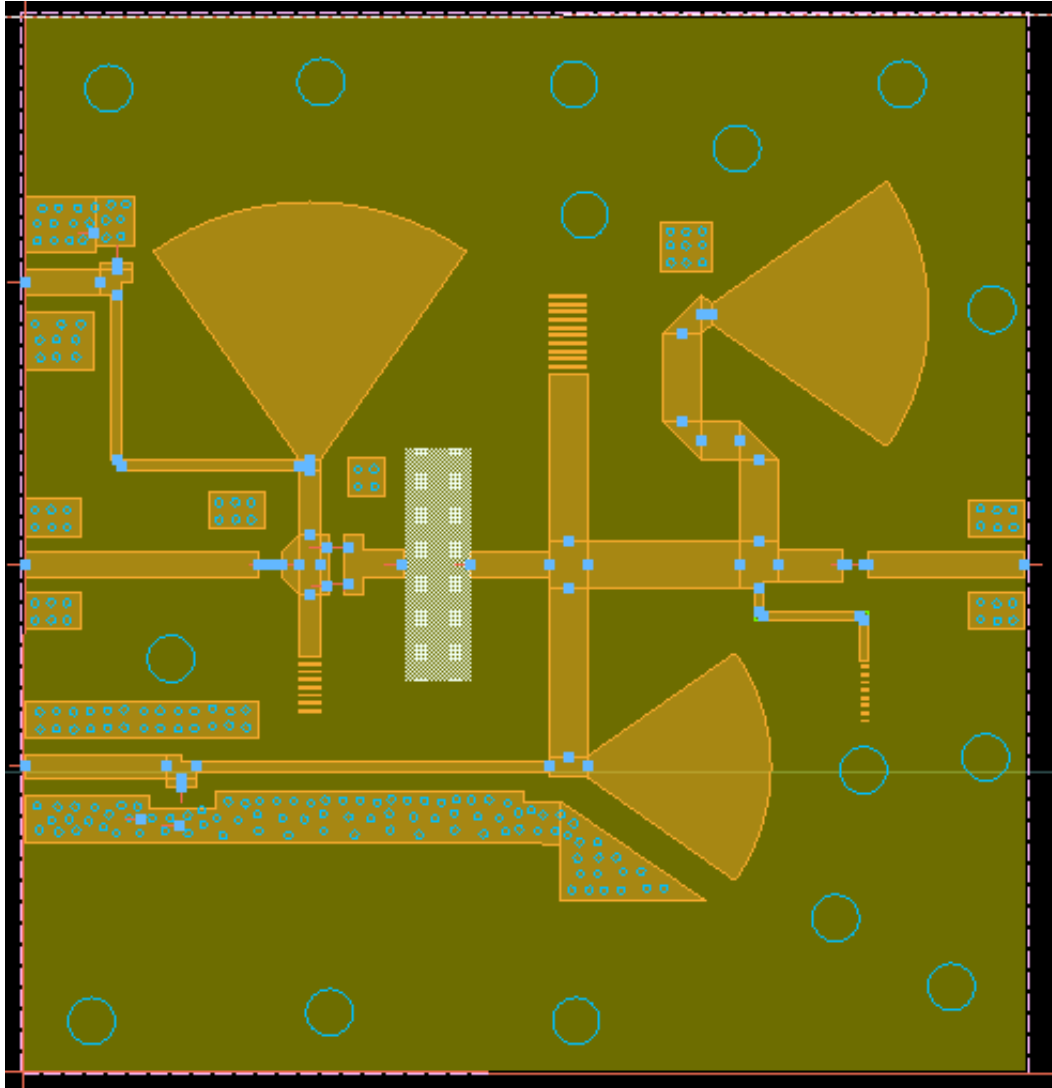
# RFPA Design Steps

## Simulated results of Final PA: Frequency Sweep



# RFPA Design Steps

Final optimized design



# Conclusion

**RFPA design employing a GaN device is a very current topic**

**RFPA design involves a great deal of time on simulation, a good device model and an EDA tool are quite helpful.**

**One needs to perform a number of simulations and optimization at different level.**

**Our RFPA design using a Wolfspeed 10W GaN device shows an excellent performance in simulation.**

**The measurement results of prototype will be shared once the measurements are complete.**

**If you have any questions or would like to collaborate with me, please feel free to drop me an email at [mohammad.maktoomi@scranton.edu](mailto:mohammad.maktoomi@scranton.edu).**



# References

- (1) S. C. Cripps, RF Power Amplifiers for Wireless Communications. Norwood, MA, USA: Artech House, 2006
- (2) P. Colantonio, F. Giannini and E. Limiti, High Efficiency RF and Microwave Solid State Power Amplifiers, New York:Wiley, 2009

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