Doherty Power Amplifier Design

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Introduction

- **Intentions**
  - With high peak to average ratio signals in full use in the commercial world and expanding in the military world, how do we efficiently amplify these signals?

- **Doherty is old news!**
  - PA suppliers are getting very nearly equal results
  - “Optimizations”/“tweaks” are simply exploiting tradeoffs

- **How do we put it all together?**
  - And most importantly, do it quickly…

Doherty Design - Outline

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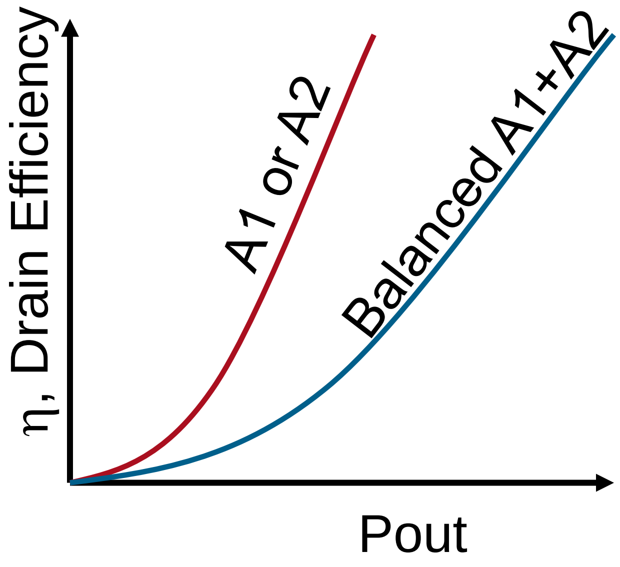
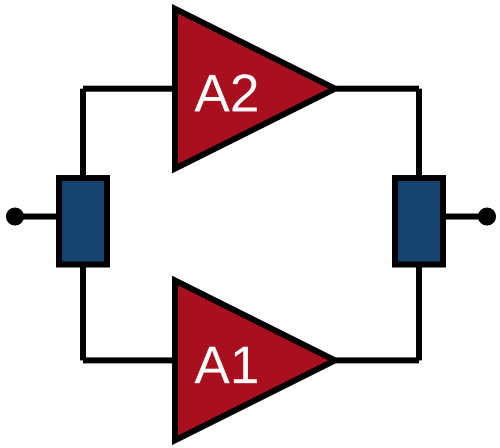
The Traditional Balanced Amplifier

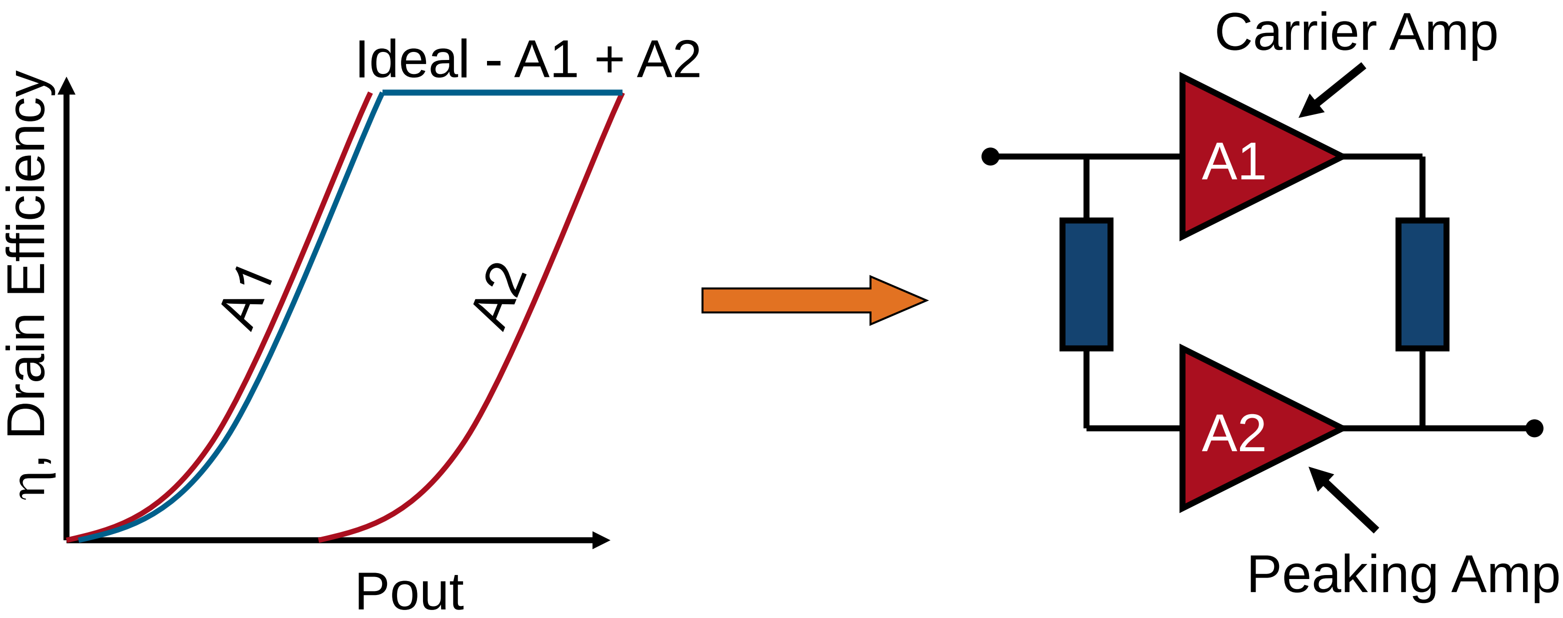
- **Both amplifier A1 and A2 contribute equally to Pout**
- **Both have standard Efficiency vs. Pout characteristics**





The Doherty Amplifier

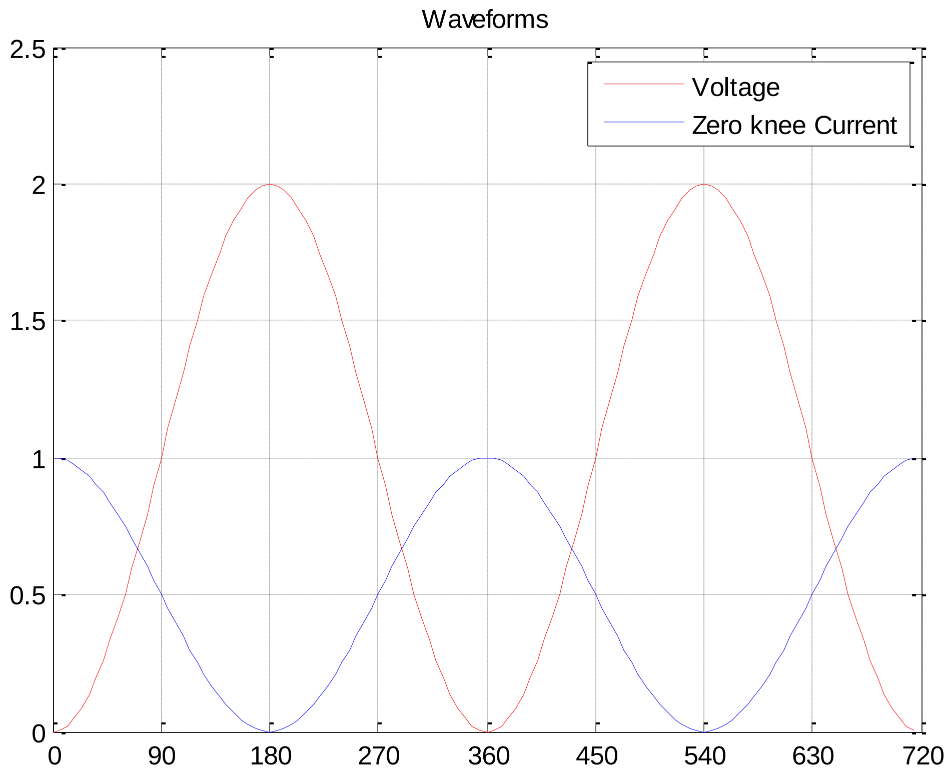
- **A1 operates most of the time - handles average signal**
- **A2 operates only when peak power is needed**
- **A1 and A2's operation is dependent on each other**



Doherty Design - Outline

1. Concept Introductions
2. Operational Fundamentals
3. The Functional Doherty Design – Load Modulation
4. Empirical Doherty Design Example
5. Building the Doherty Amplifier

Operational Fundamentals – Class A



Under basic loadline condition

$$i_D(t) = I_P \cdot \cos(\omega t)$$

$$v_{DS}(t) = V_P \cdot \cos(\omega t + \varphi)$$

$V_{knee} = 0$

$V_{DC} = 1.0$

$V_{signal(fund)} = 1.0$

$I_{bias} = 0.5$

$I_{signal} = 0.5$

*Reference [1]

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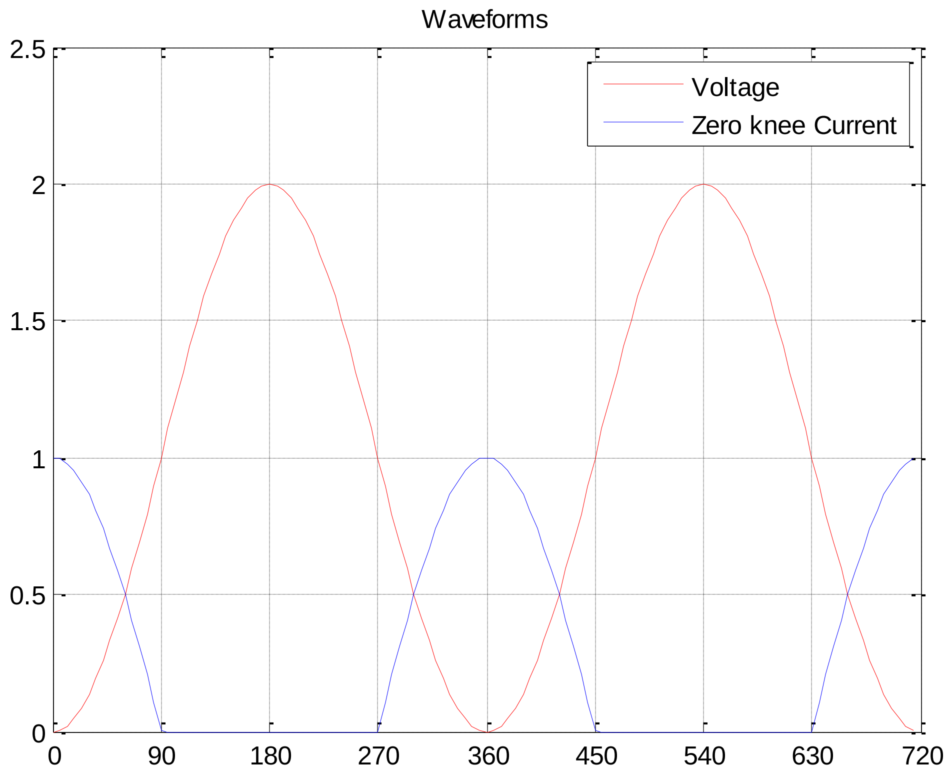
Operational Fundamentals – Class B



$V_{knee} = 0$

$V_{DC} = 1.0$

$V_{signal(fund)} = 1.0$

$I_{bias} = 0$

$I_{signal} = 1.0$

*Reference [1]

Load Resistor – R_L

Adjust Input Drive for Max V

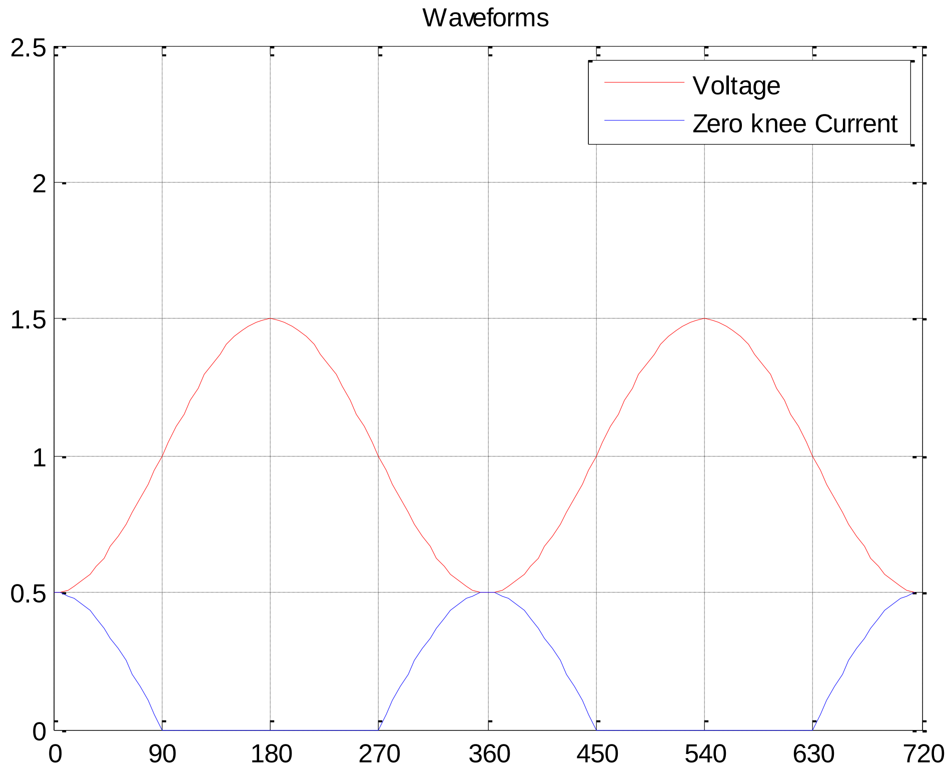
The output waveforms must be expanded into its Fourier series components

$$i_D(t) = I_0 + I_1 \cdot \cos(\omega t) + I_2 \cdot \cos(2\omega t) + I_3 \cdot \cos(3\omega t) + \cdots$$

Vds is simplified due to short circuited harmonics

$$v_{DS}(t) = V_{DC} - V_1 \cdot \cos(\omega t)$$

Operational Fundamentals – Class B at half power



$V_{knee} = 0$
$V_{DC} = 1$
$I_{bias} = 0$

Drive Signal → -6dB
Efficiency Drops by 2

*Reference [2]

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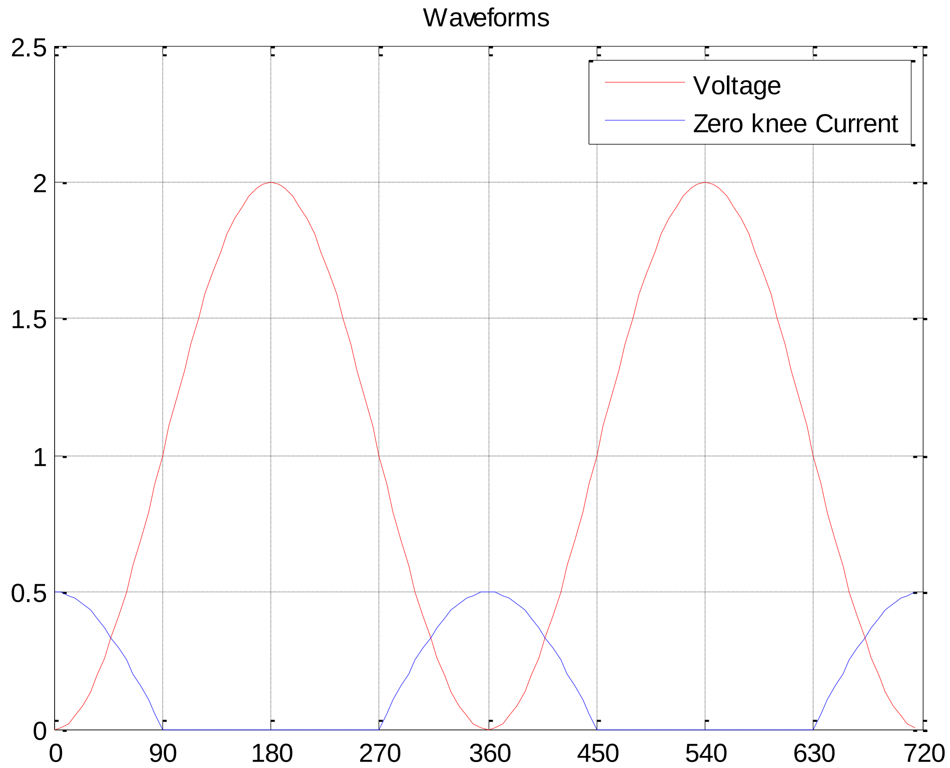
Operational Fundamentals – Class B (Load Modulation)



$V_{knee} = 0$
$V_{DC} = 1$
$I_{bias} = 0$

$R_L \rightarrow 2xR_L$

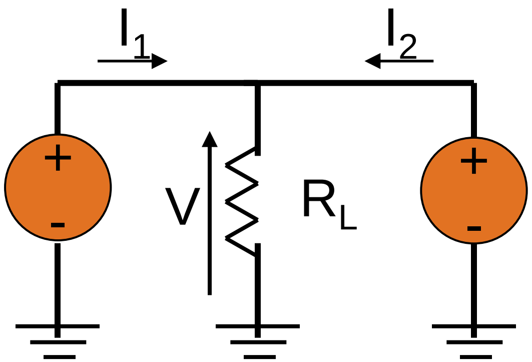
Efficiency Restored

*Reference [2]

Doherty Design - Outline

Textbook Load Modulation

$$Z_1 = R_L\left(1 + \frac{I_2}{I_1}\right)$$



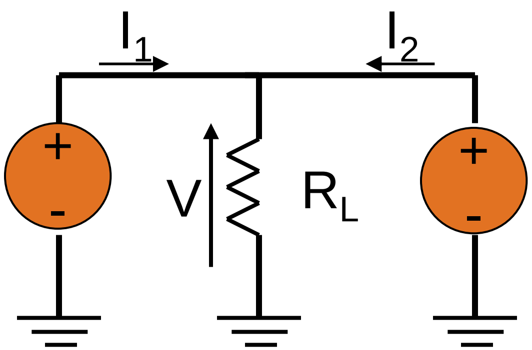
- **Doherty achieves Load modulation by using the principle of “load pulling” using two devices***

*Reference [3]

Textbook Load Modulation

Case I

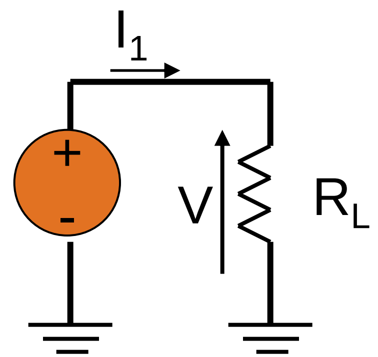
Both amplifiers contributing equally



$$Z_1 = Z_2 = 2R_L$$

Case II

Peaking amp off



$$I_2 = 0$$

$$Z_1 = R_L$$

*Reference [3]

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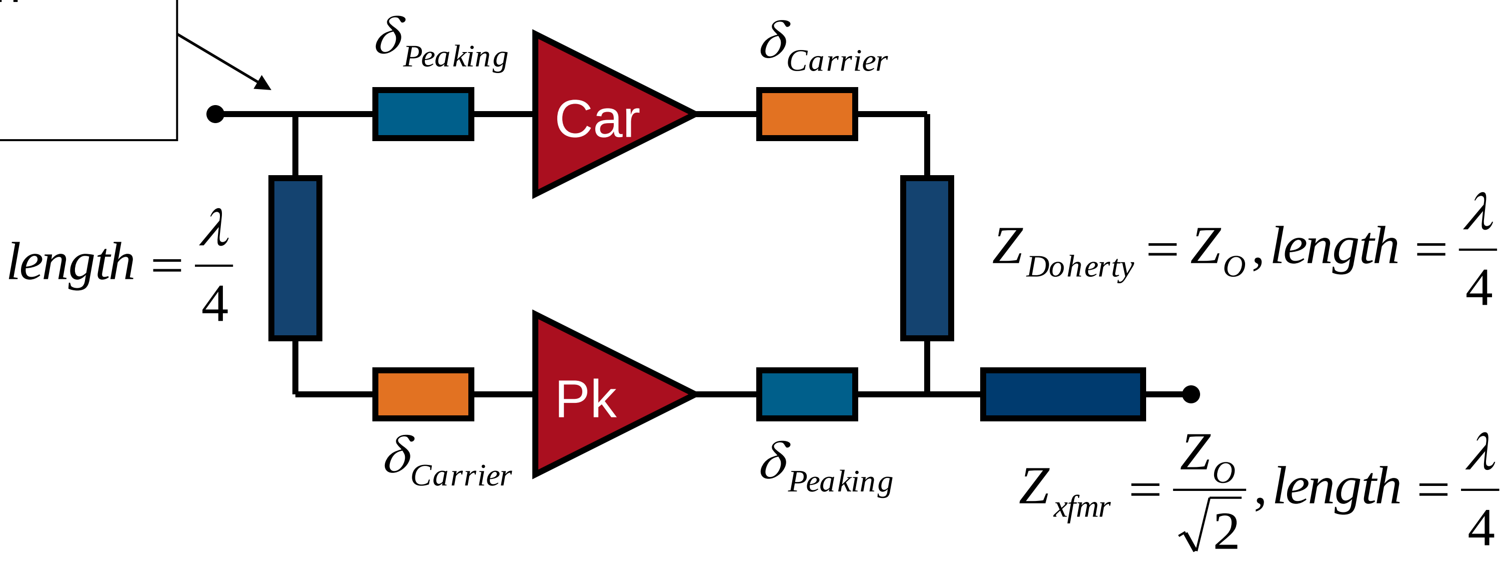
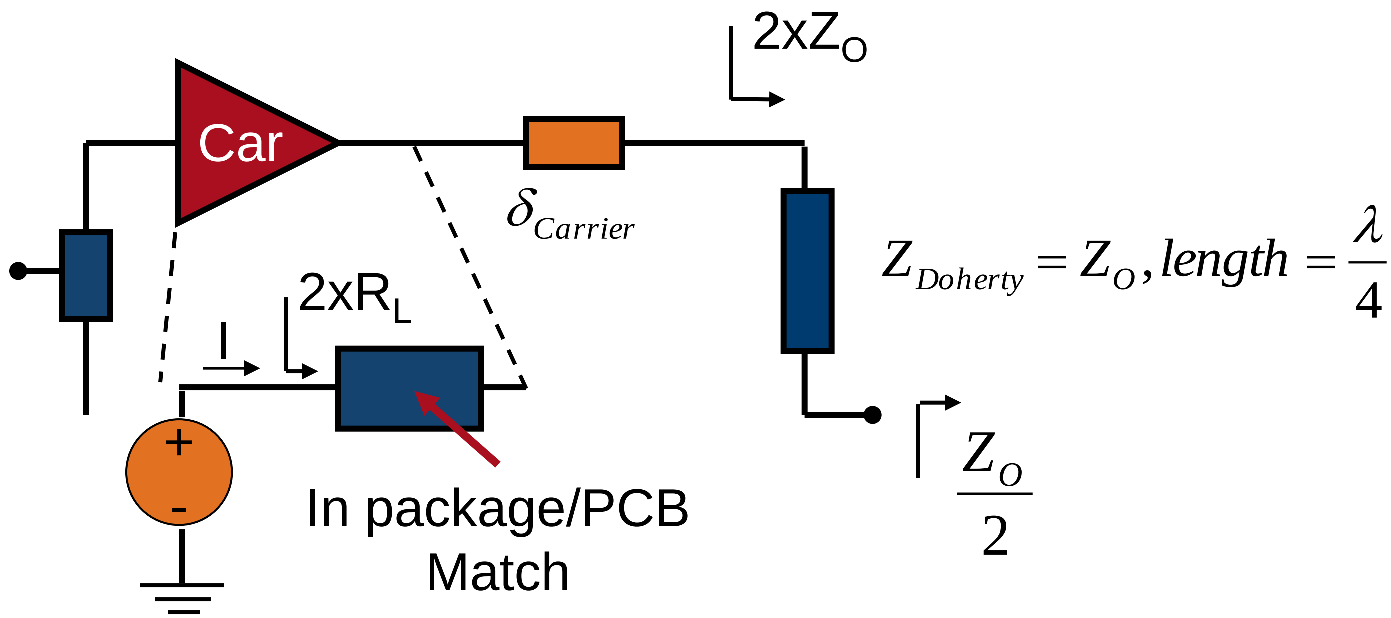
Doherty Topology – Definitions

Create a splitter
- Wilkinson
- Gysel
- Hybrid



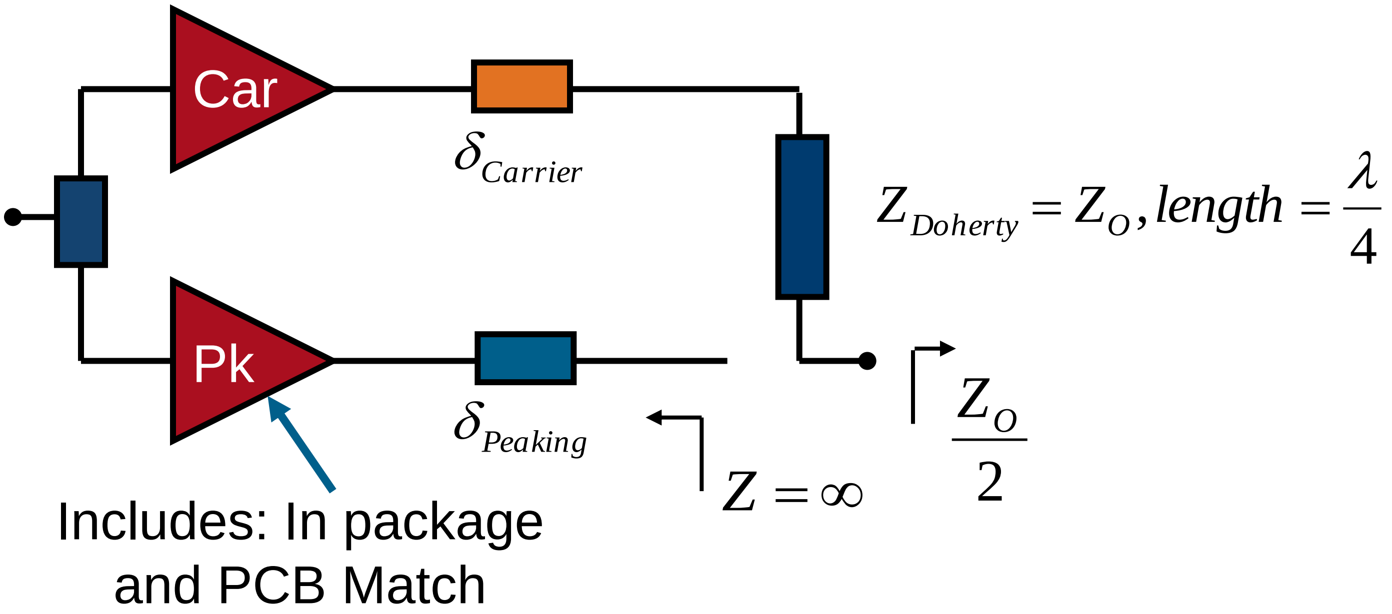
Practical Circuit Load Modulation



High Power Low Power

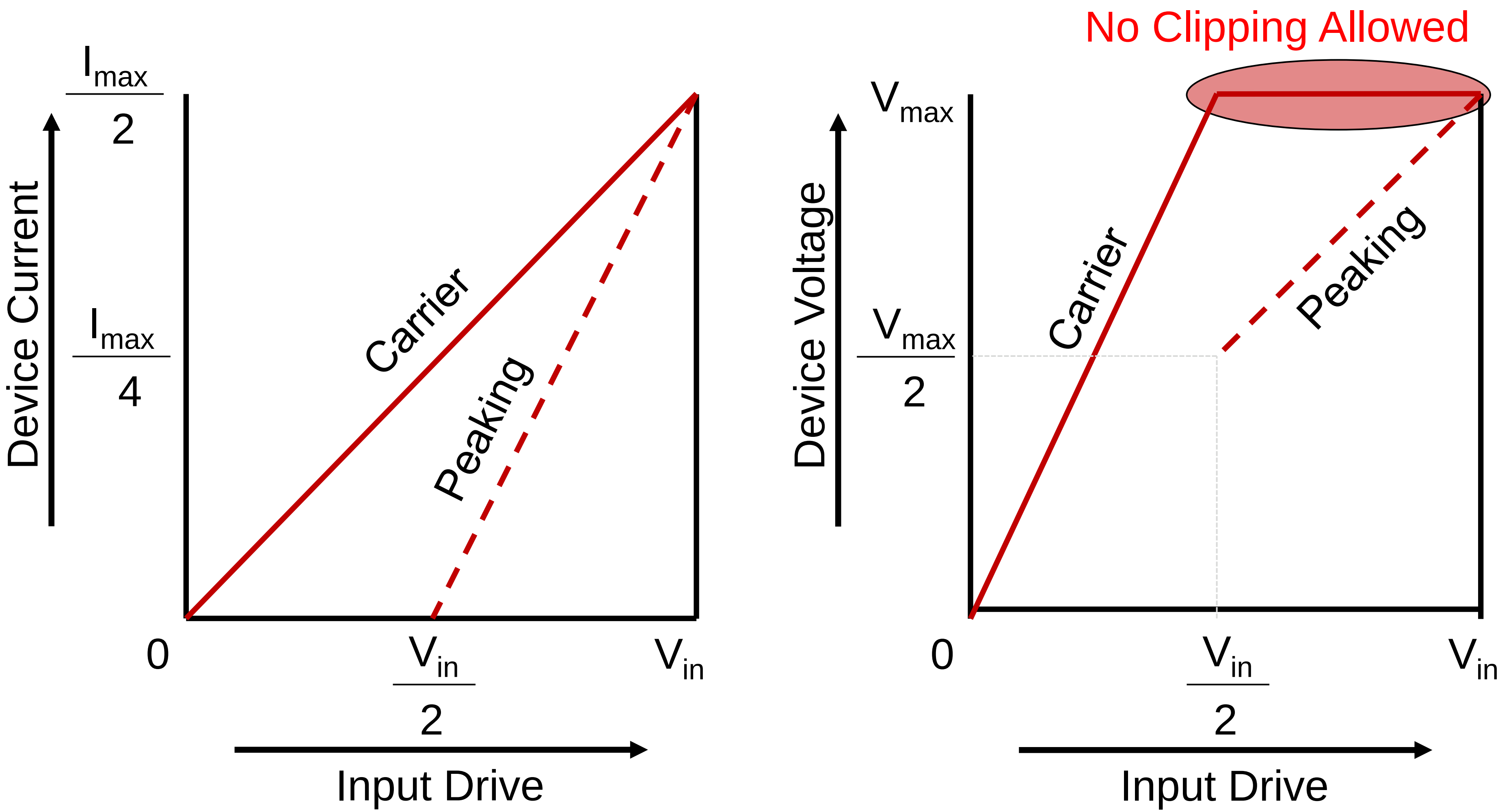
- **The real implementation modulates $Z_o \rightarrow 2xZ_o$**
  - At the current source plane we want $R_L \rightarrow 2xR_L$
- **How do we get this?**

Designing the Doherty – Peaking off state



- **At the combiner node, we want $Z_{pk} = \infty$**
  - When the peaking amp is off
- **An additional phase shift can create this, $\delta_{Peaking}$**

Doherty – The Key to Operation or Why Doesn't it Work?



*Reference [3]

Doherty Topologies

- **There is no differentiation between standard and inverted Doherty topologies**
- **The Point of a Doherty amplifier is load modulation**
  - how you achieve target impedances is irrelevant

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4. **Empirical Doherty Design Example**
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GaN Device used for Design Example

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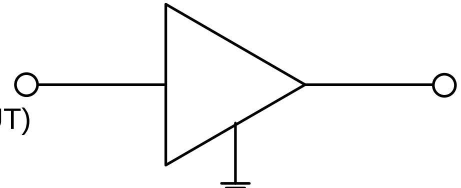
RFG1M09180

700MHZ TO 1000MHZ 180W GAN POWER AMPLIFIER

Features

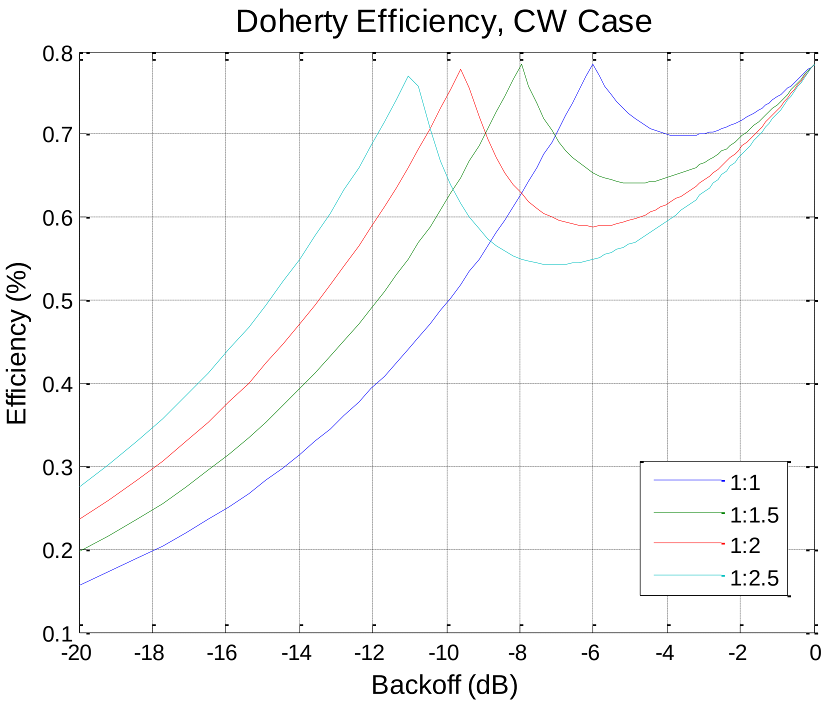
- Advanced GaN HEMT Technology
- Peak Modulated Power > 240W
- Single Circuit for 865 – 960MHz
- 48V Operation Typical Performance
    - Pout 47dBm
    - Gain 20dB
    - Drain Efficiency 39%
    - ACP -31.5dBc
    - Linearizable to -55dBc with DPD
- Optimized for video bandwidth and minimized memory effects
- RF tested for 3GPP performance
- RF tested for peak power using IS95
- Large signal models available

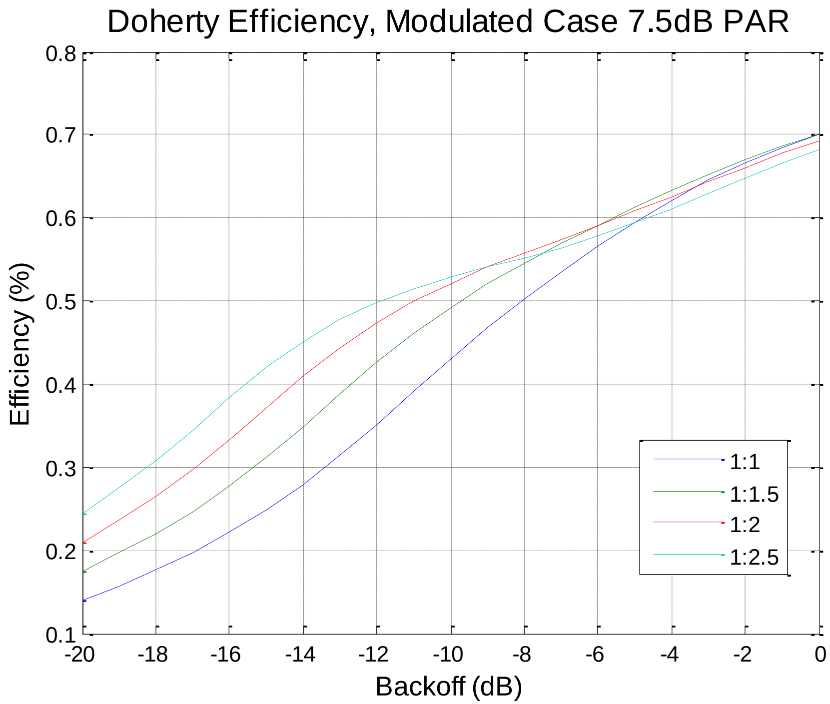
Package: Flanged Ceramic, 2 pin, RF400-2



Being Statistically Realistic

CHALLENGE: Design a symmetric Doherty Amplifier for αdBm average power operation with πdB peak to average ratio





Choosing the Load Conditions

CHALLENGE: Design a symmetric Doherty Amplifier for αdBm average power operation with πdB peak to average ratio

- **To achieve the best efficiency, we need:**
  - Pout = $\alpha+\pi$dBm composite power (full peak power)
    - Full contribution of peak power from each amplifier
  - Pout = $(\alpha+\pi-6)$dBm
    - Carrier amplifier is fully saturated
    - Peaking amplifier is just about to turn on
  - $(\alpha+\pi-6)$dBm > Pout > $(\alpha+\pi)$dBm
    - Carrier amplifier maintains saturation without clipping
    - Peaking amplifier is "load modulating" the carrier amplifier

Choosing the Load Conditions

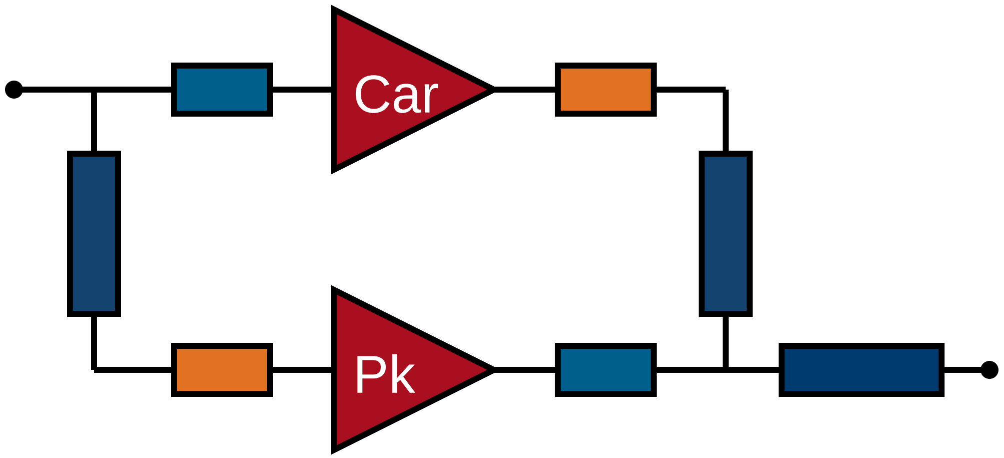
CHALLENGE: Design a symmetric Doherty Amplifier for αdBm average power operation with πdB peak to average ratio

- **Break the challenge into two static cases**
  - At αdBm composite power
    - Each amplifier is functioning at $(\alpha - 3)$dBm
    - Full addition of power from carrier and peaking amp recreating all peaks
    - Amplifier must not clip
  - At slightly < αdBm composite power
    - If π is 6dB
      - Carrier amplifier is functioning < αdBm and is fully saturated (high efficiency)
      - If the peaking amplifier is off, this represents the best case efficiency
    - Be careful if π is ≠6dB (for the symmetric case)

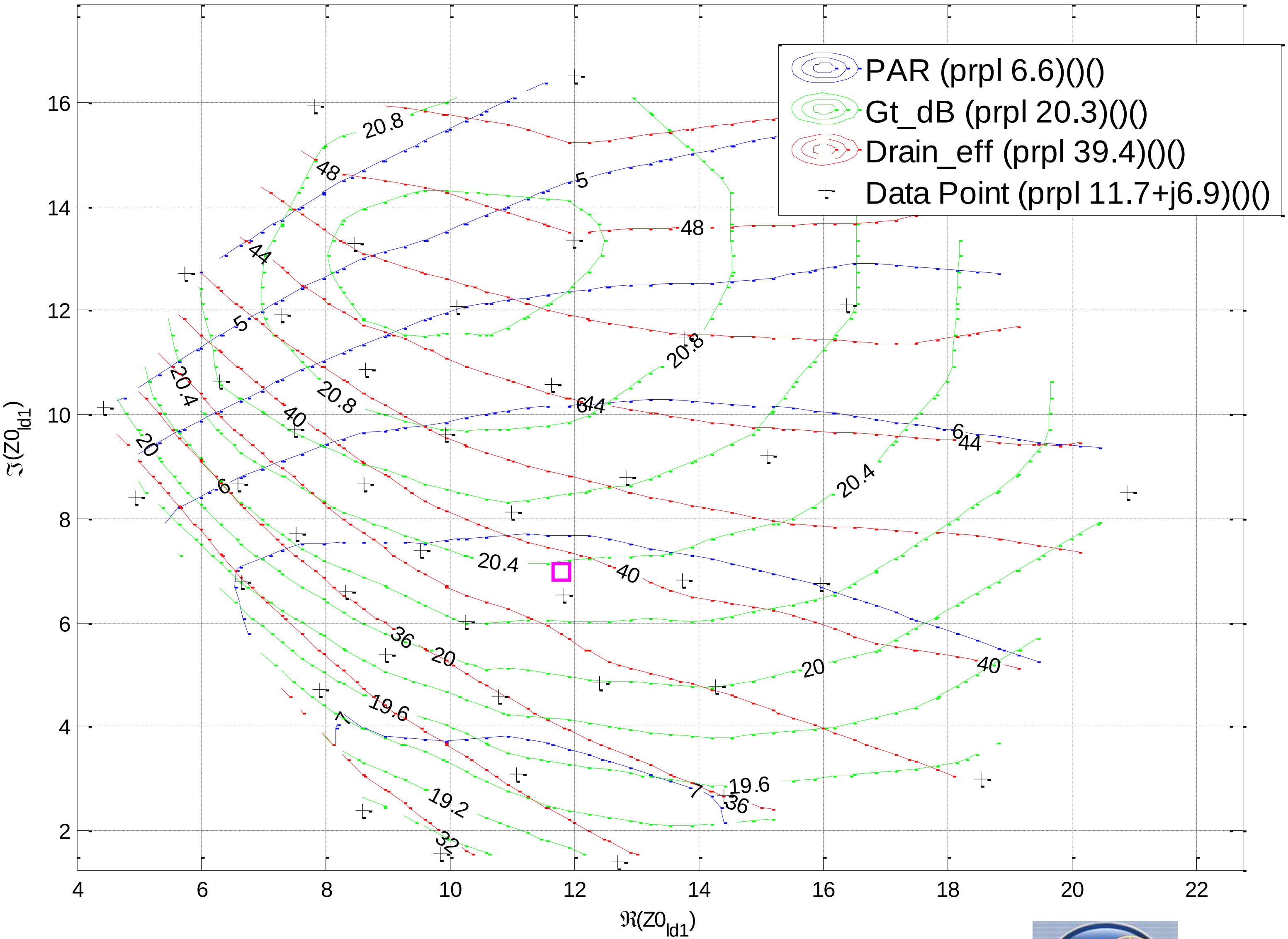
Choosing the Load Conditions

Composite Power α**dBm**

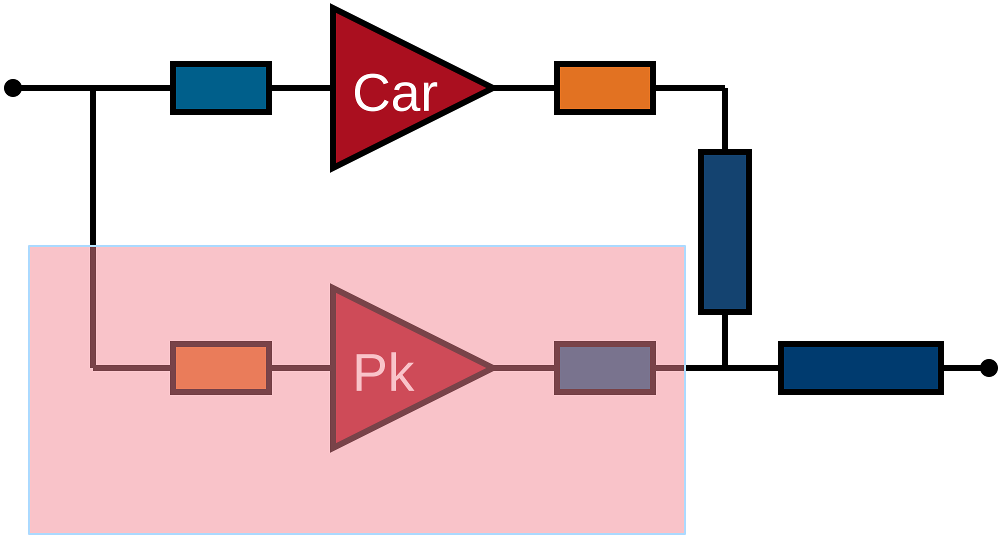
Power from each amp $(\alpha-3)$dBm



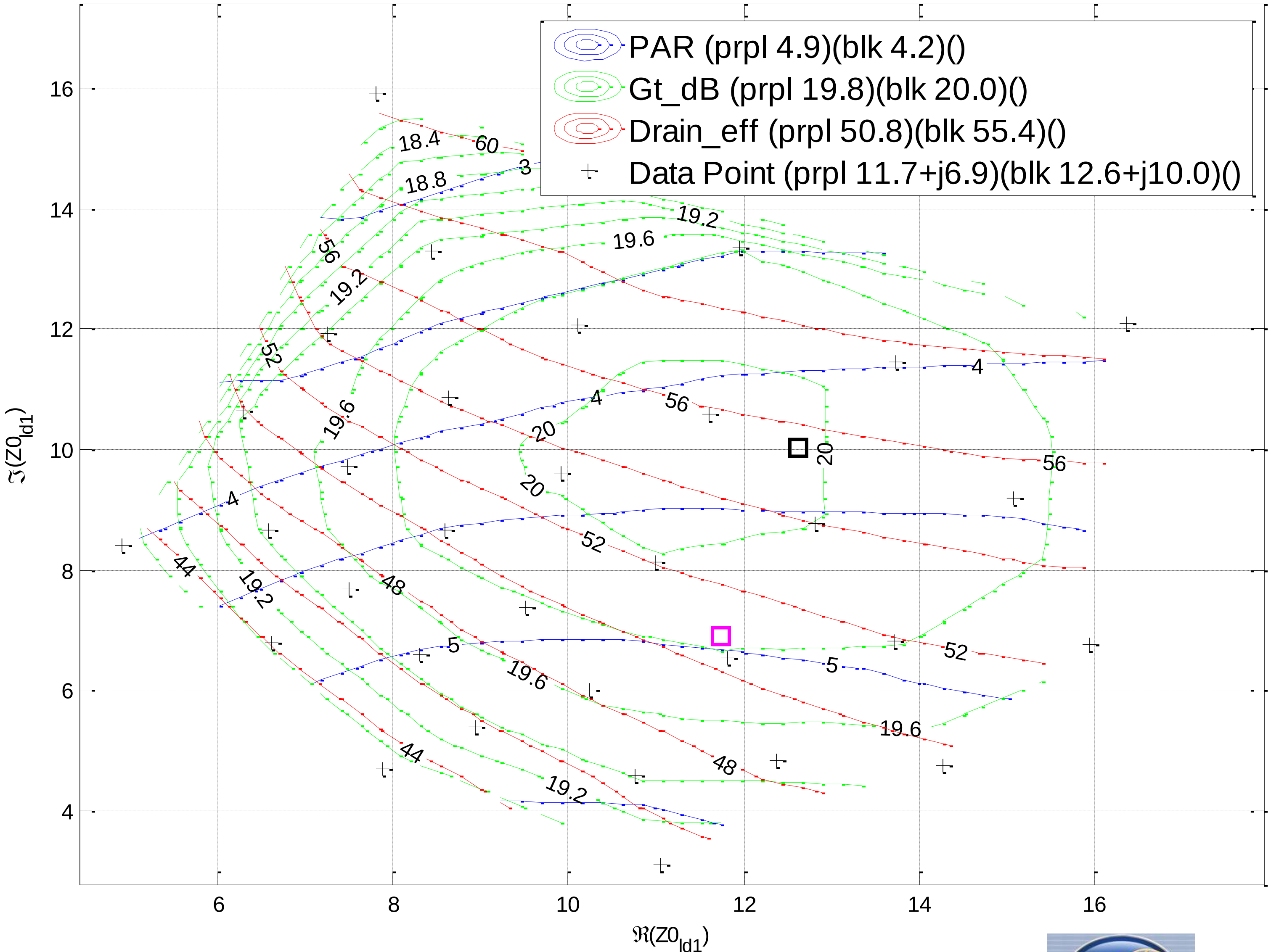
Load Contours: (α–3)dBm



Power from Carrier amp: αdBm

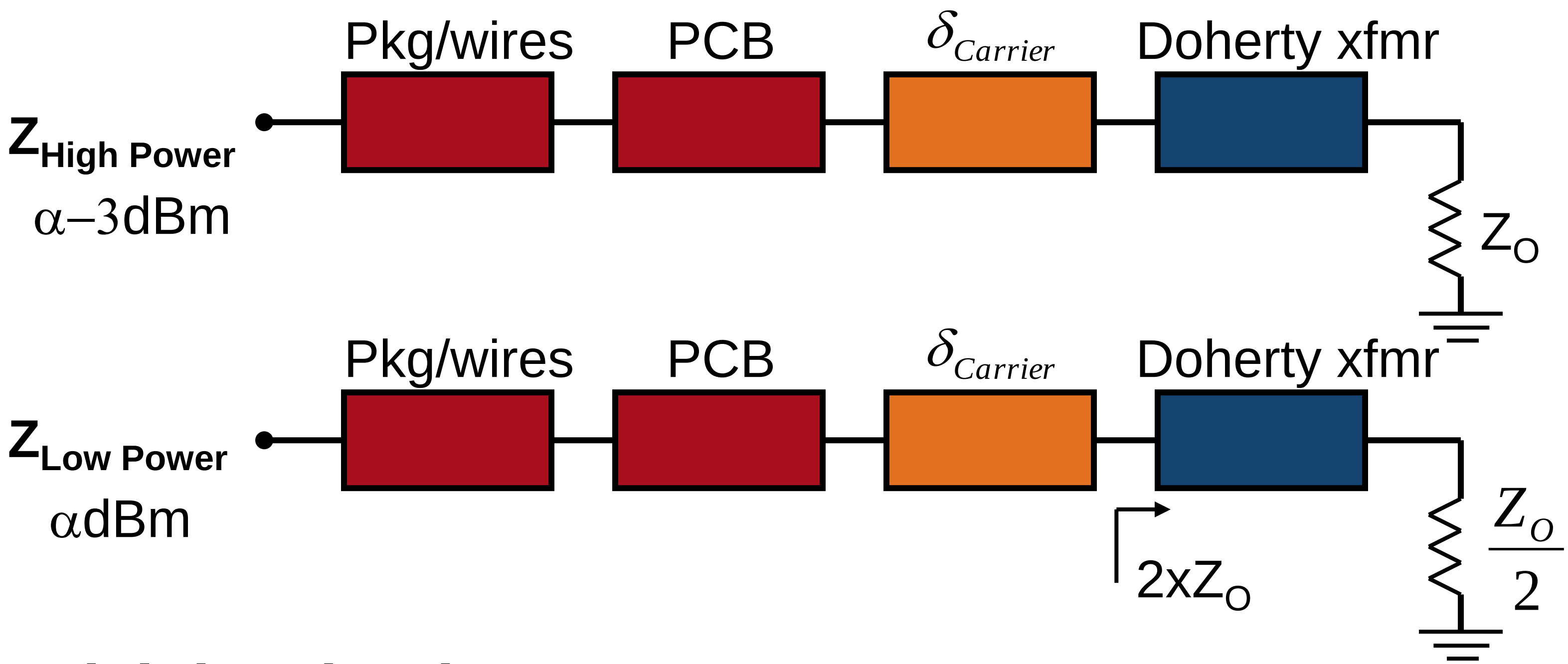


Load Contours: αdBm



Doherty Design - Outline

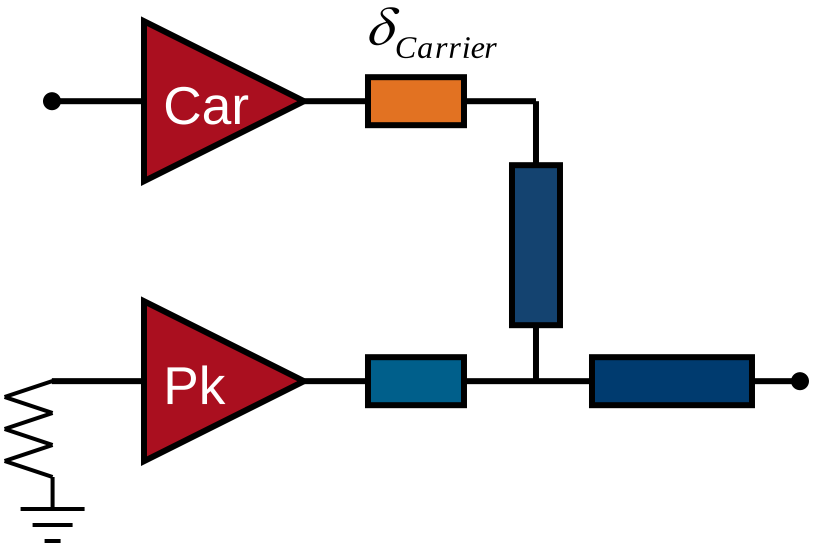
Static Tuning – Reality sets in



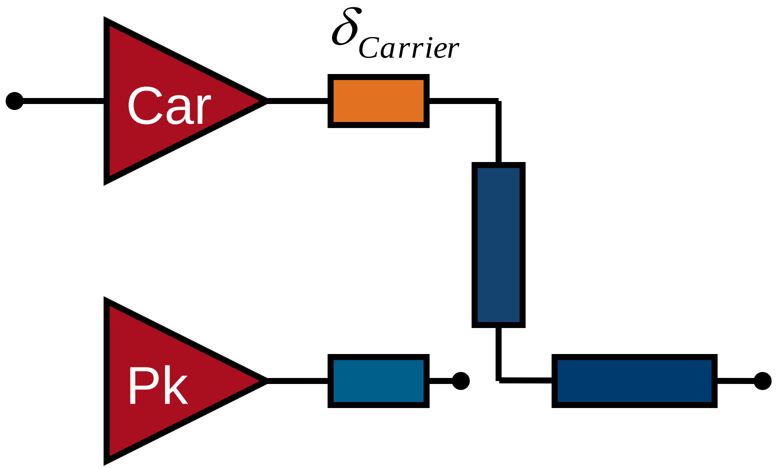
- **Model the circuit**
- **Tune under static conditions**
- **Assume load modulation**

Tuning Tips – Carrier Amp

Option 1 – Peaking Amp in place

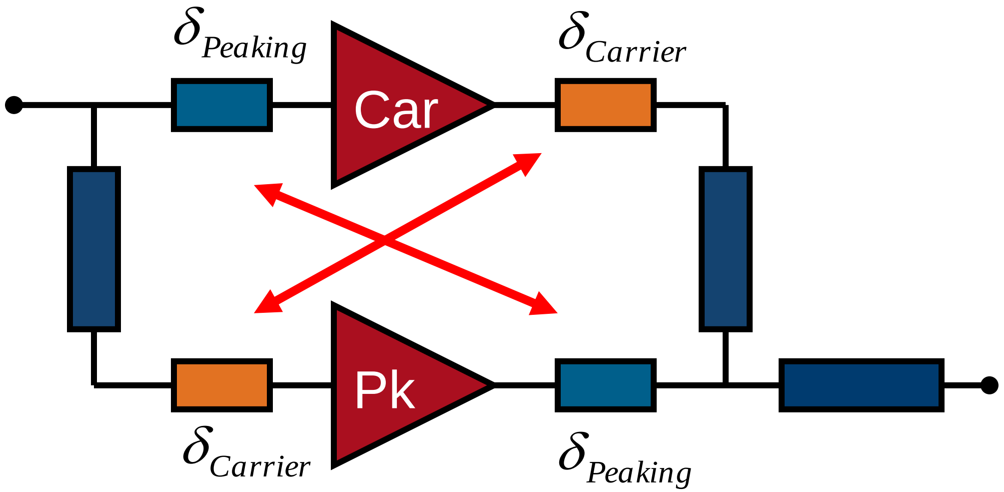


Option 2 – Peaking Amp removed



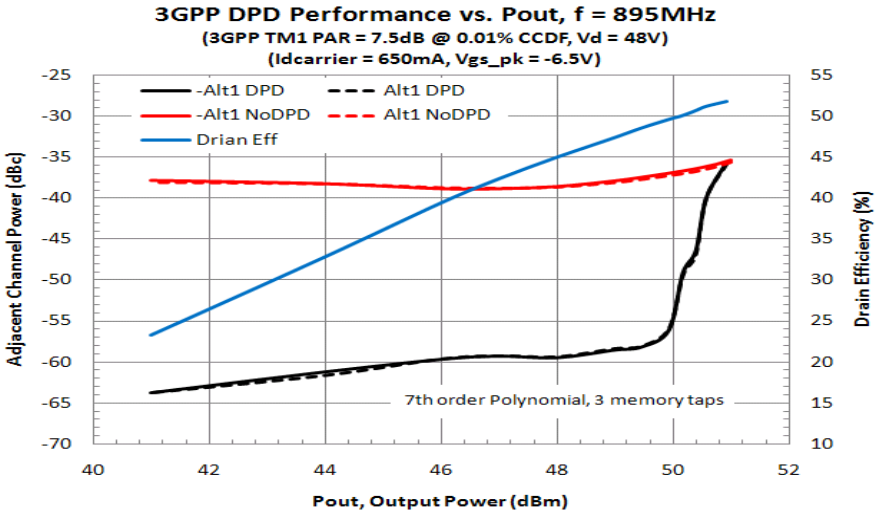
- **The Carrier Amp is where it all happens!**
  - We want no Clipping at full power with Zo impedance
  - Saturation with peaking amplifier off
    - Must make assumptions about peaking amp and its ability to load modulate

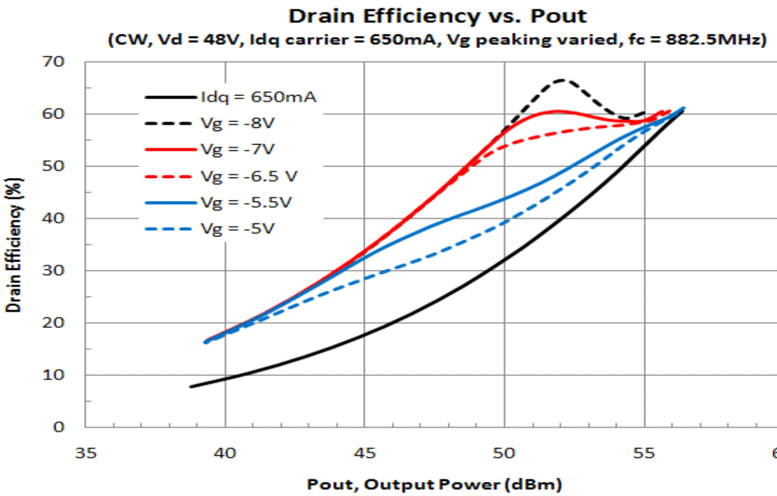
Tuning Tips – Peaking Amp



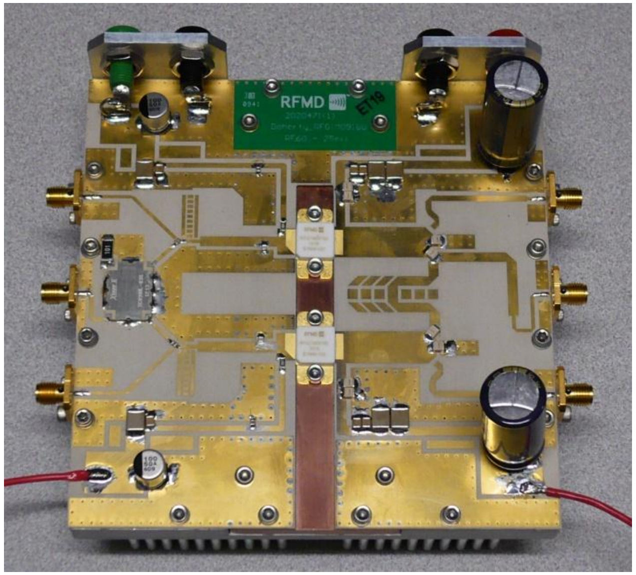
- **Set the off-state Z of peaking amp with $\delta_{Peaking}$**
  - Is this really so important
  - Can we find some advantage not to set the off-state to ideal?
- **Conventional wisdom says equal phase in each branch**
  - – Class-C peaking amp has large AM-PM component
  - – Where do we want phase alignment?

Tuning Tips – Putting it all together



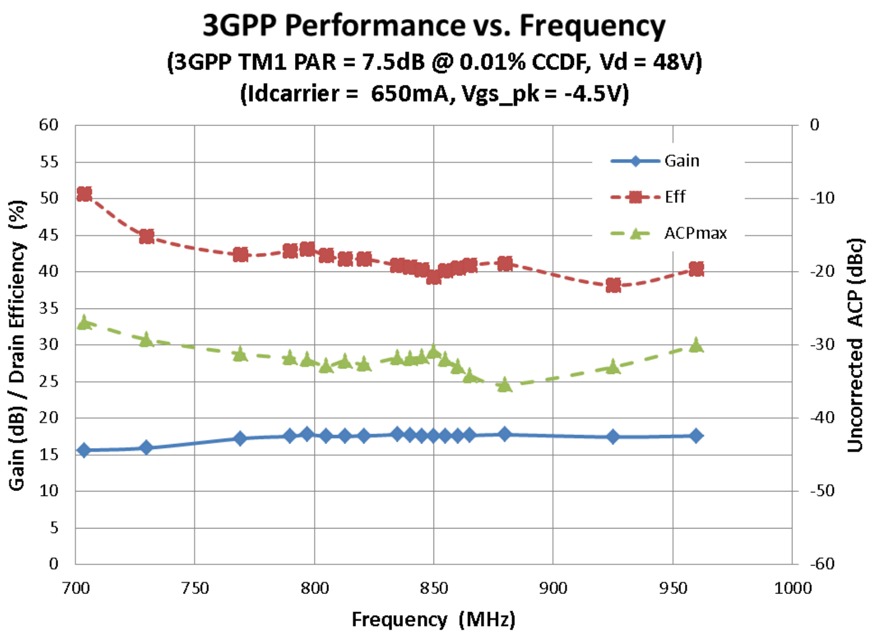


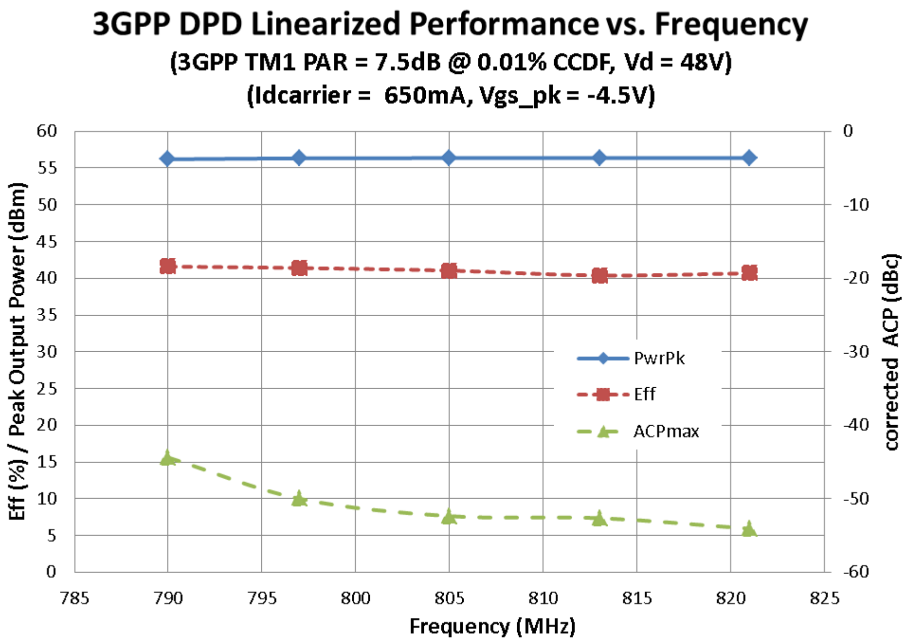
- 50% Drain Efficiency
- (7.5dB PAR @ 0.01% CCDF)
- Fully Linearizable with peak power recovery
- 15% bandwidth



Broadband Performance and Reality

- **Performance is only as good as your load modulation “bandwidth”**





Summary

- The Doherty Amplifier topology can provide efficiency benefits
- Implementation is full of pitfalls
- Variants are many, based on the same concept

Do You Have Any Questions?

References

[1] Colantonio, Giannini, Limiti, *High Efficiency RF and Microwave Solid State Power Amplifiers*, Wiley and Sons, 1999, p 49-82

[2] Cripps, S., "Doherty RF Power Amplifiers, Theory and Practice", *Short Course SC-4, 2009 International Microwave Symposium*, Boston

[3] Cripps, S., *RF Power Amplifiers for Wireless Communications*, Artech House, 1999, p 225-235