Design of Linear CMOS RF Power Amplifiers

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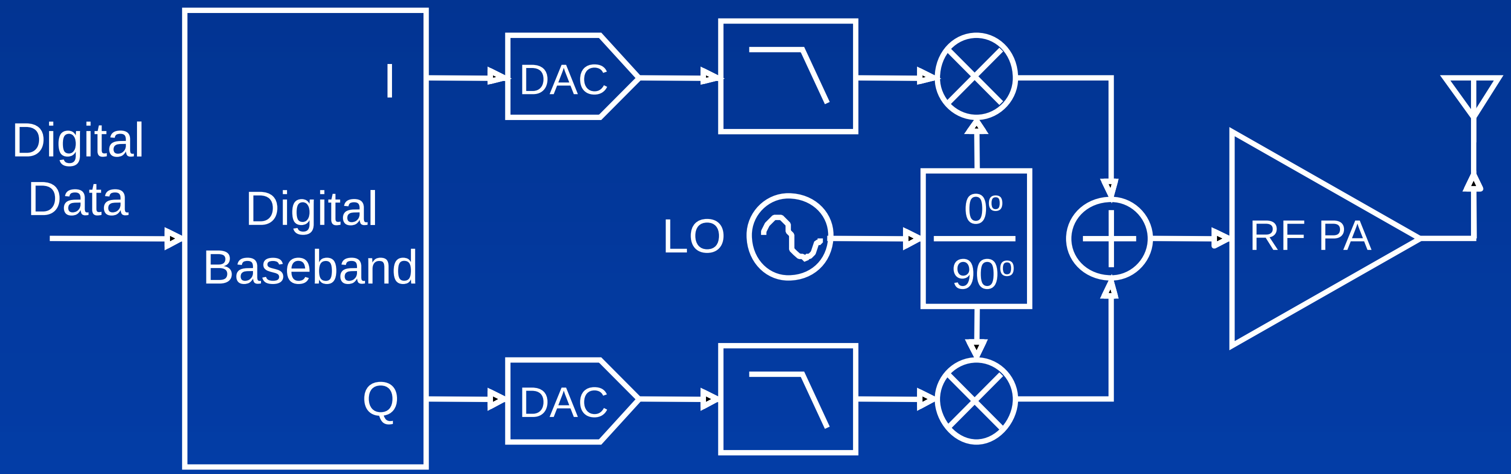
Outline

- Introduction
- Linear Power Amplifier (PA) basics
- Efficiency enhancement: Dynamic Supply
- Conclusion

Introduction

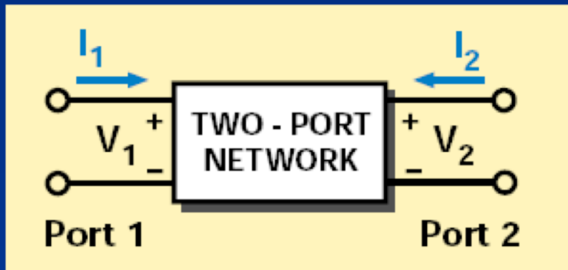
RF
Applications

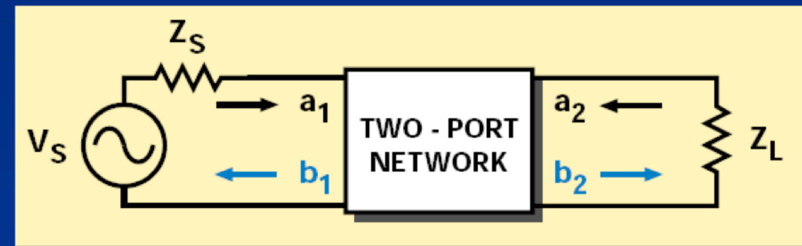
RF Transceiver



Direct conversion transmitter

Two-port representation/S-parameters





Admittance

$$I_1 = y_{11} \cdot V_1 + y_{12} \cdot V_2$$
$$I_2 = y_{21} \cdot V_1 + y_{22} \cdot V_2$$

$$y_{11} = \left.\frac{I_1}{V_1}\right|_{V_2=0}$$

$$y_{12} = \left.\frac{I_1}{V_2}\right|_{V_1=0} \qquad y_{21} = \left.\frac{I_2}{V_1}\right|_{V_2=0} \qquad y_{22} = \left.\frac{I_2}{V_2}\right|_{V_1=0}$$

Scattering

$$b_1 = s_{11} \cdot a_1 + s_{12} \cdot a_2$$
$$b_2 = s_{21} \cdot a_1 + s_{22} \cdot b_2$$

$$s_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$

$$s_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0} \qquad s_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} \qquad s_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$

$$V_1 = z_{11} \cdot I_1 + z_{12} \cdot I_2$$
$$V_2 = z_{21} \cdot I_1 + z_{22} \cdot I_2$$

$$z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0}$$

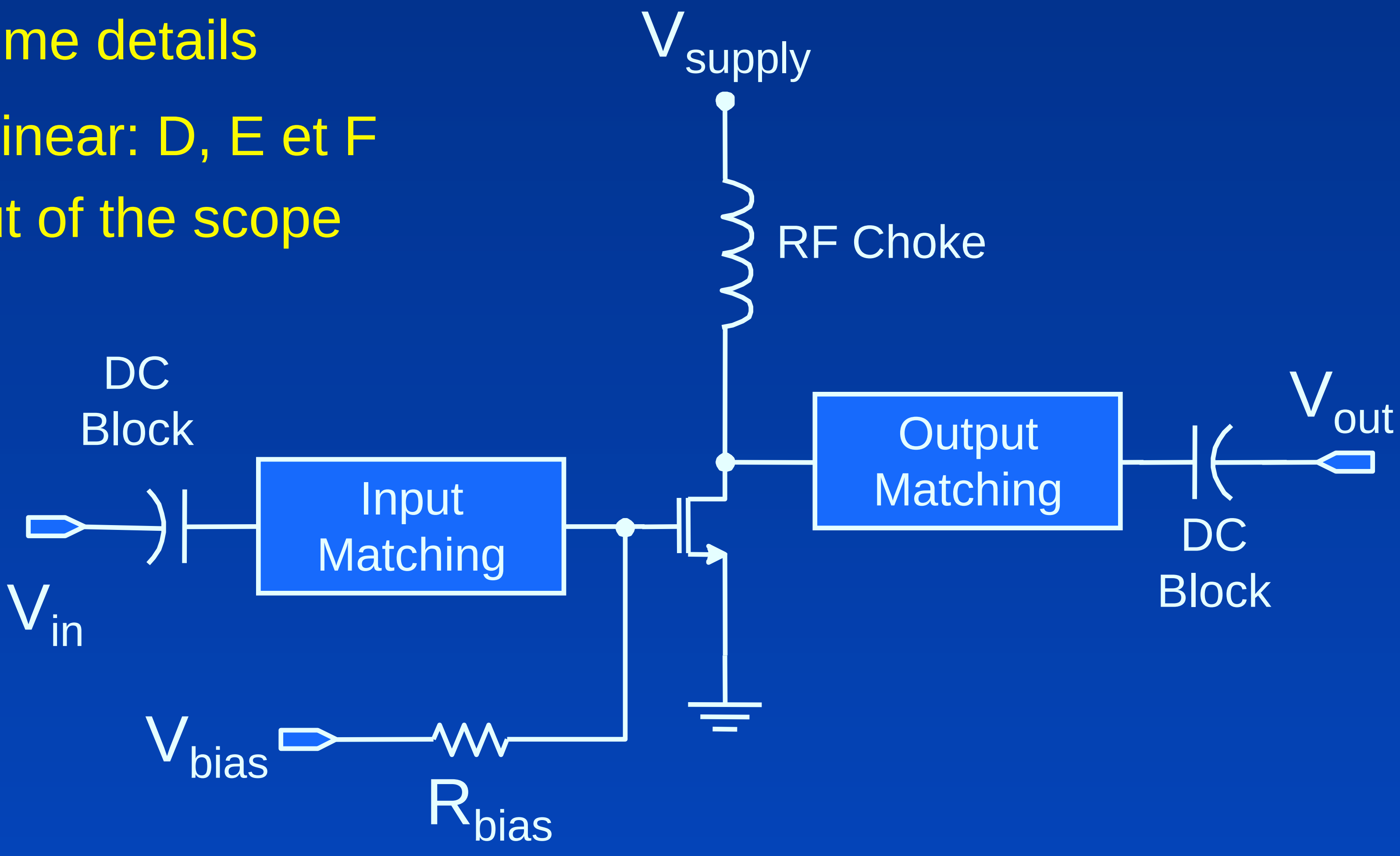
$$z_{12} = \left.\frac{V_1}{I_2}\right|_{I_1=0} \qquad z_{21} = \left.\frac{V_2}{I_1}\right|_{I_2=0} \qquad z_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0}$$

S-parameters are easier to measure. No need of neither short nor open circuits.

Impedance

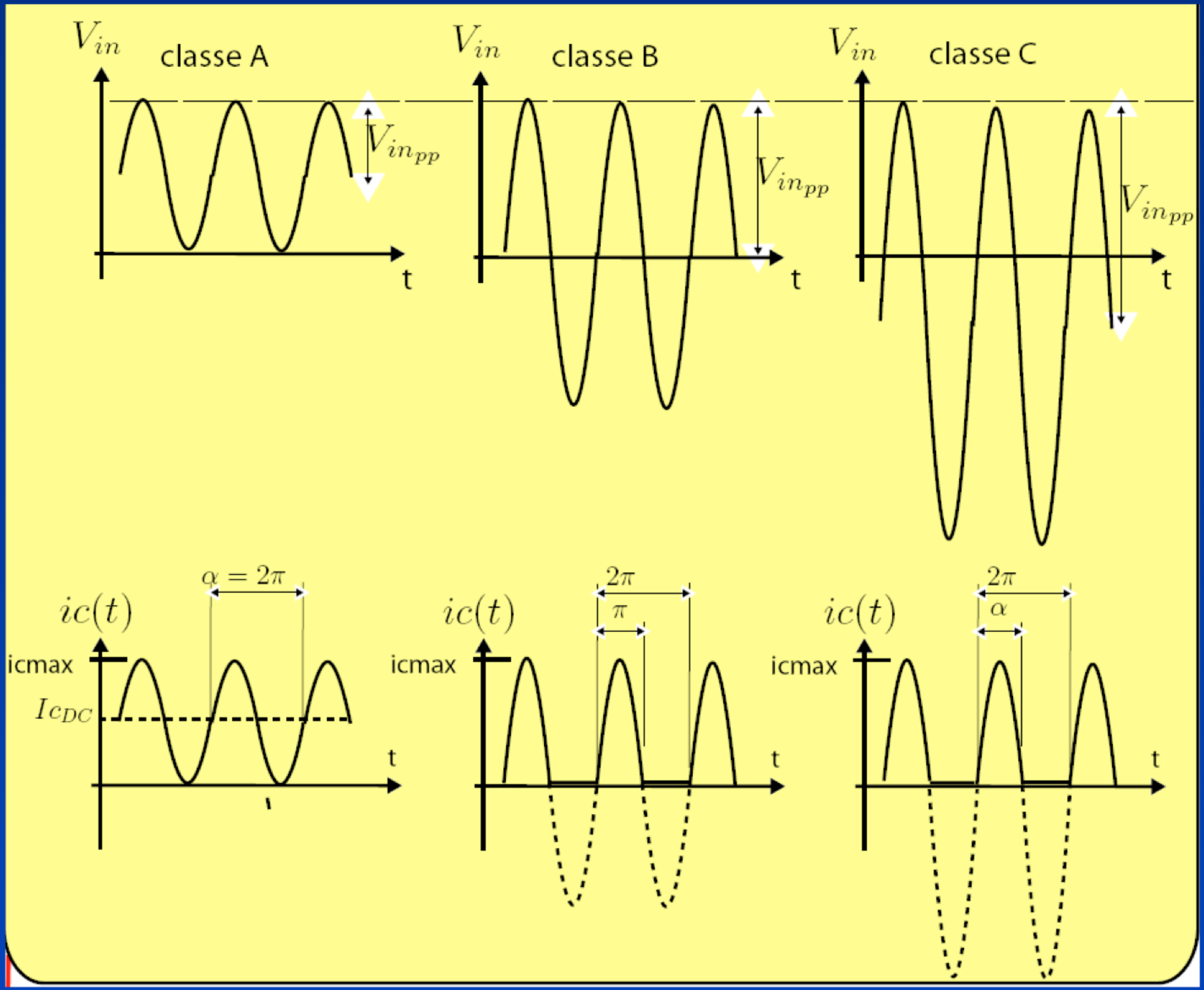
PA Classes

- Linear classes: A, AB, B et C
  - some details
- Non linear: D, E et F
  - out of the scope



Linear classes

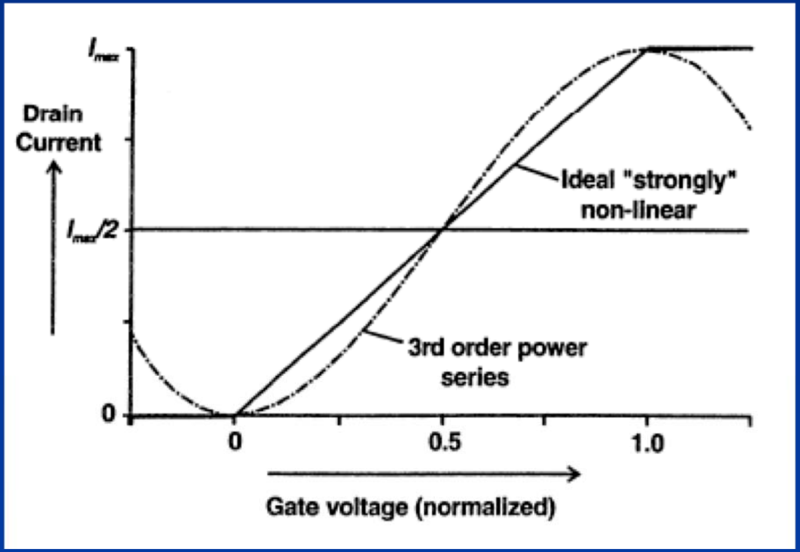
conduction angle α decreases



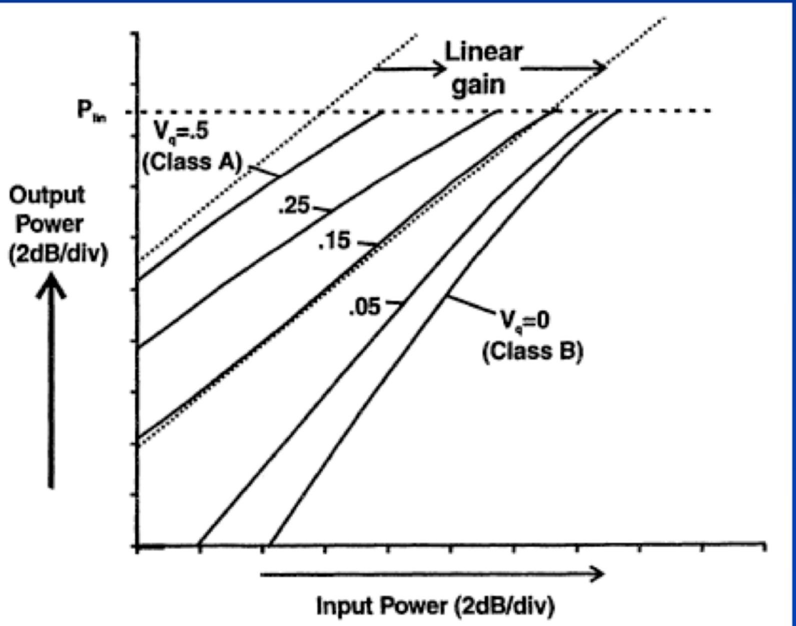
From Schlumpf [1]

Linear classes - comparison

Weak-strong non-linear model*



Gain linearity*

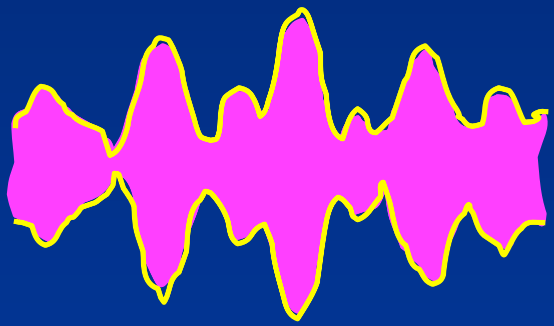


*From Cripps [2]

Class choice according to application

- Constant envelope modulation (GSM):
  - high efficiency PA (switched PA classes)
  - linearity not important
- Variable envelope modulation (IS-95, UMTS, WLAN):
  - linearity very important
    - Linear PA + efficiency enhancement technique
    - high efficiency PA + linearization technique

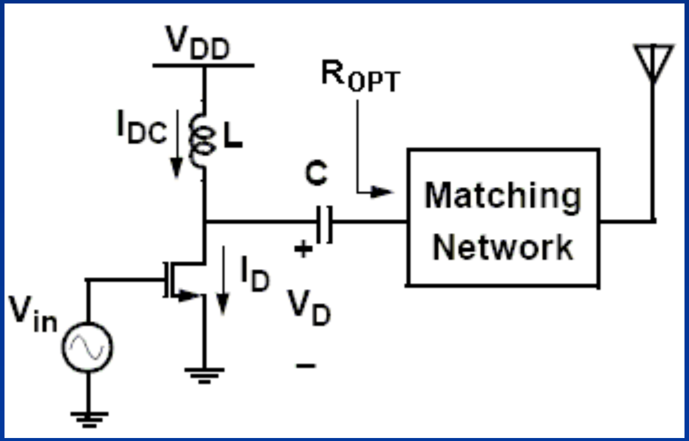
WLAN 802.11a/g

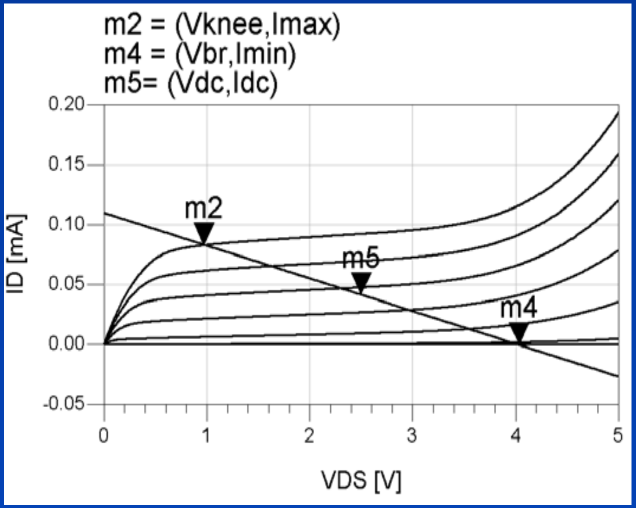


- Enveloppe variable
- large PAPR (17dB, $\sqrt{52}$)
- Requires a high linearity PA

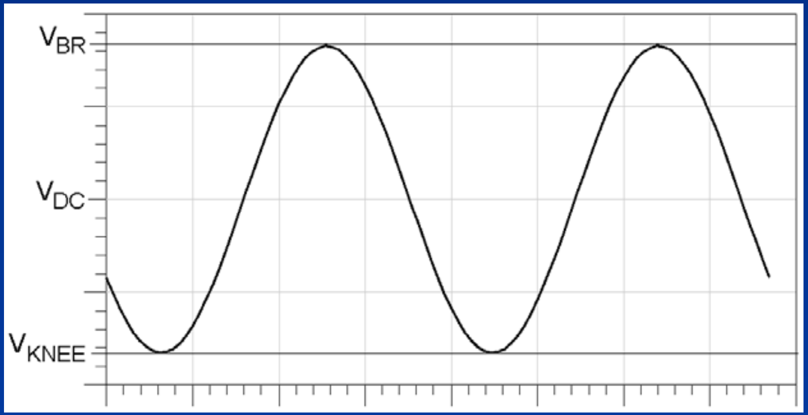
Class A PA

Class A PA

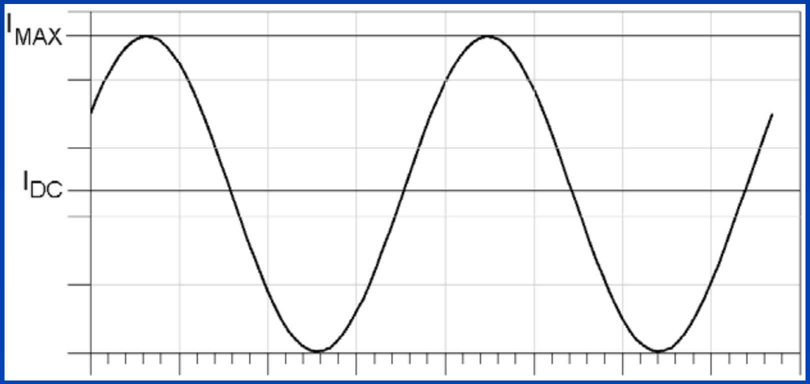




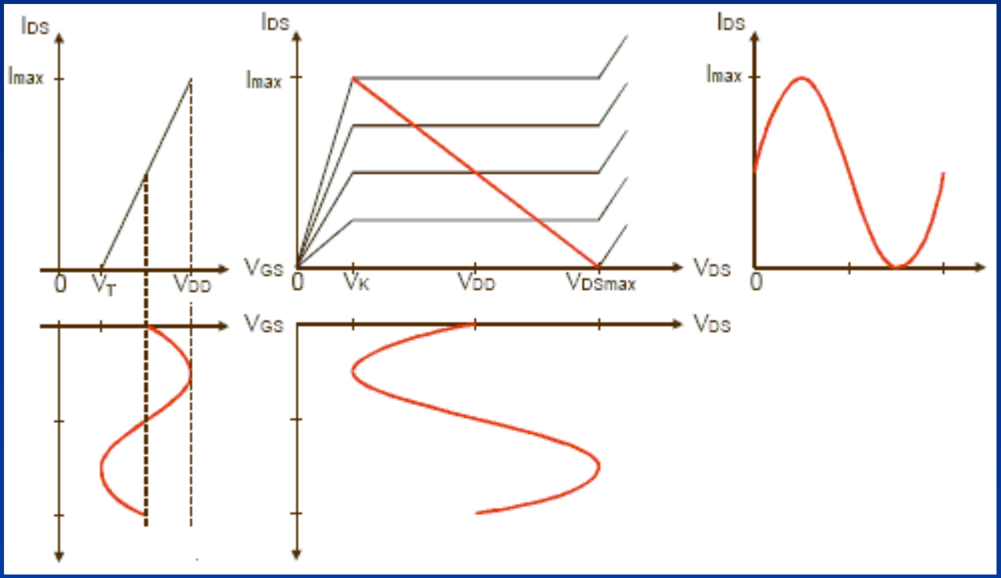
Drain voltage



Drain current



Class A PA – Output Power I



$$V_{DC} = \frac{1}{2}(V_{BR} + V_{KNEE}) \qquad I_{DC} = \frac{1}{2} I_{MAX}$$

If output voltage and R_{OPT} are known:

$$P_{OUT\_MAX} = \frac{V_{eff}^{2}}{R_{OPT}} \qquad V_{eff} = \frac{V_{PP}}{2 \cdot \sqrt{2}}$$

$$P_{OUT\_MAX} = \frac{\left(\frac{V_{PP}}{2 \cdot \sqrt{2}}\right)^2}{R_{OPT}} = \frac{V_{PP}^{2}}{8 \cdot R_{OPT}}$$

$$V_{PP} = V_{BR} - V_{KNEE}$$

$$\boxed{P_{OUT\_MAX} = \frac{1}{8} \cdot \frac{(V_{BR} - V_{KNEE})^2}{R_{OPT}}}$$

It current and R_{OPT} are known:

$$P_{OUT\_MAX} = R_{OPT} \cdot I_{eff}^{2} \qquad I_{eff} = \frac{I_{MAX}}{2 \cdot \sqrt{2}}$$

$$P_{OUT\_MAX} = R_{OPT} \cdot \left(\frac{I_{MAX}}{2 \cdot \sqrt{2}}\right)^2 = R_{OPT} \cdot \frac{I_{MAX}^{2}}{8}$$

Class A PA – Output power II

If output voltage and current are known:

$$P_{OUT\_MAX} = V_{eff} \cdot I_{eff}$$

$$V_{eff} = \frac{V_{PP}}{2 \cdot \sqrt{2}}$$

$$I_{eff} = \frac{I_{MAX}}{2 \cdot \sqrt{2}}$$

$$P_{OUT\_MAX} = \frac{V_{PP}}{2 \cdot \sqrt{2}} \cdot \frac{I_{MAX}}{2 \cdot \sqrt{2}} = \frac{V_{PP} \cdot I_{MAX}}{8}$$

$$\begin{cases} P_{OUT\_MAX} = \frac{1}{8} \cdot (V_{BR} - V_{KNEE}) \cdot I_{MAX} \\ P_{OUT\_MAX} = \frac{1}{4} (V_{BR} - V_{KNEE}) \cdot I_{DC} \\ P_{OUT\_MAX} = \frac{1}{4} (V_{DC} - V_{KNEE}) \cdot I_{MAX} \\ P_{OUT\_MAX} = \frac{1}{2} (V_{DC} - V_{KNEE}) \cdot I_{DC} \end{cases}$$

Expressions for R_{OPT}:

$$R_{OPT} = \frac{(V_{DC} - V_{KNEE})}{I_{DC}}$$

$$R_{OPT} = \frac{(V_{DC} - V_{KNEE})^2}{2 \cdot P_{OUT\_MAX}}$$

$$R_{OPT} = \frac{V_{BR} - V_{KNEE}}{I_{MAX}}$$

$$\boxed{R_{OPT} = \frac{1}{8} \cdot \frac{(V_{BR} - V_{KNEE})^2}{P_{OUT\_MAX}}}$$

Considerations on R_{OPT}

- It is necessary to guarantee that the desired maximum output power can be delivered to the load:
  - limited supply voltage
  - transistor non idealities

Transistor sizing

For a given output power, if V_{BR} and V_{KNEE} of the transistor are known:

1. Determine R_{opt} → $$R_{OPT} = \frac{1}{8} \cdot \frac{(V_{BR} - V_{KNEE})^2}{P_{OUT\_MAX}}$$
2. Calculate necessary I_{MAX} → $$I_{MAX} = \frac{(V_{BR} - V_{KNEE})}{R_{OPT}}$$
3. The transistor must be designed for I_{MAX} → $$I_D = \frac{1}{2} \cdot k' \cdot \frac{W}{L} \cdot (V_{GS} - V_T)^2$$
4. Calculate W/L → $$\frac{W}{L} = \frac{2 \cdot I_{MAX}}{k' \cdot (V_{GS} - V_T)^2}$$
5. Verification with simulator

Choice of VGS and W/L

- Case 1 – integrated transceiver
  - input capacitance
  - input signal swing
- Case 2 – stand-alone PA
  - No constraints, VGS and W/L can be chosen so as to maximize linearity or efficiency

PA stability

Stability circles

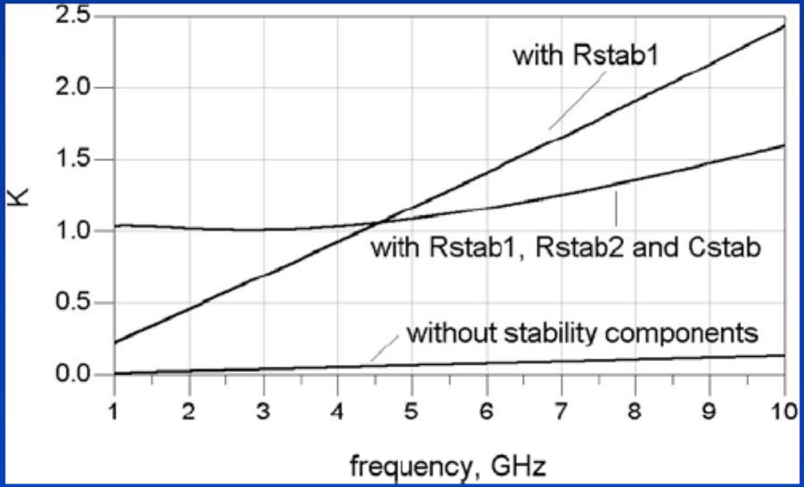
K factor > 1 (Rollet [3])

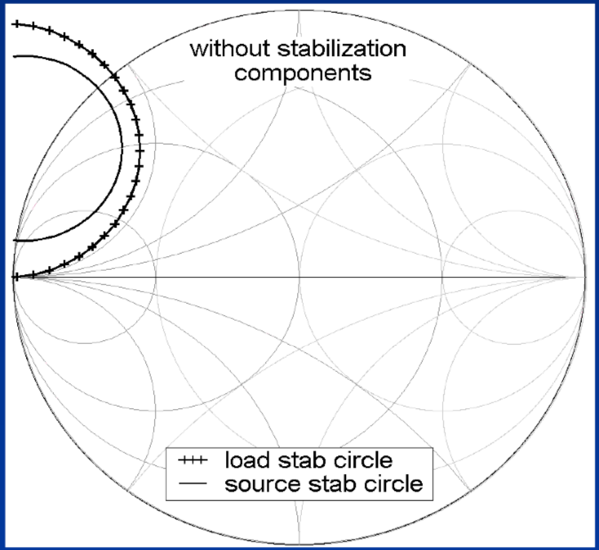
$$K = \frac{1 + |D|^2 - |s_{11}|^2 - |s_{22}|^2}{2|s_{12}s_{21}|}$$

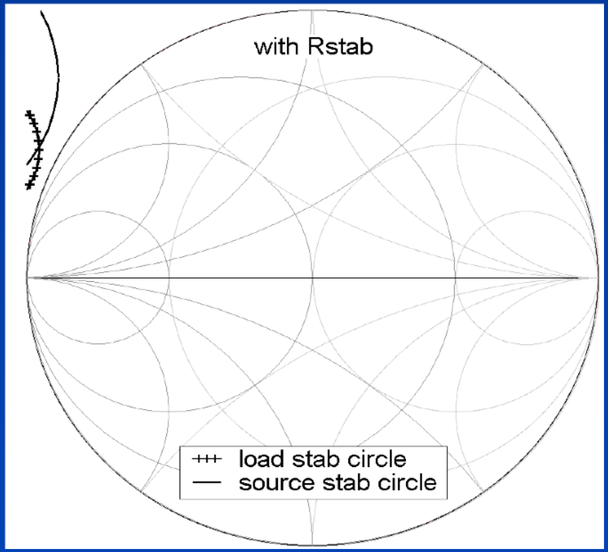
$$D = s_{11}s_{22} - s_{12}s_{21}$$

B1 > 0 (Bodway [3])

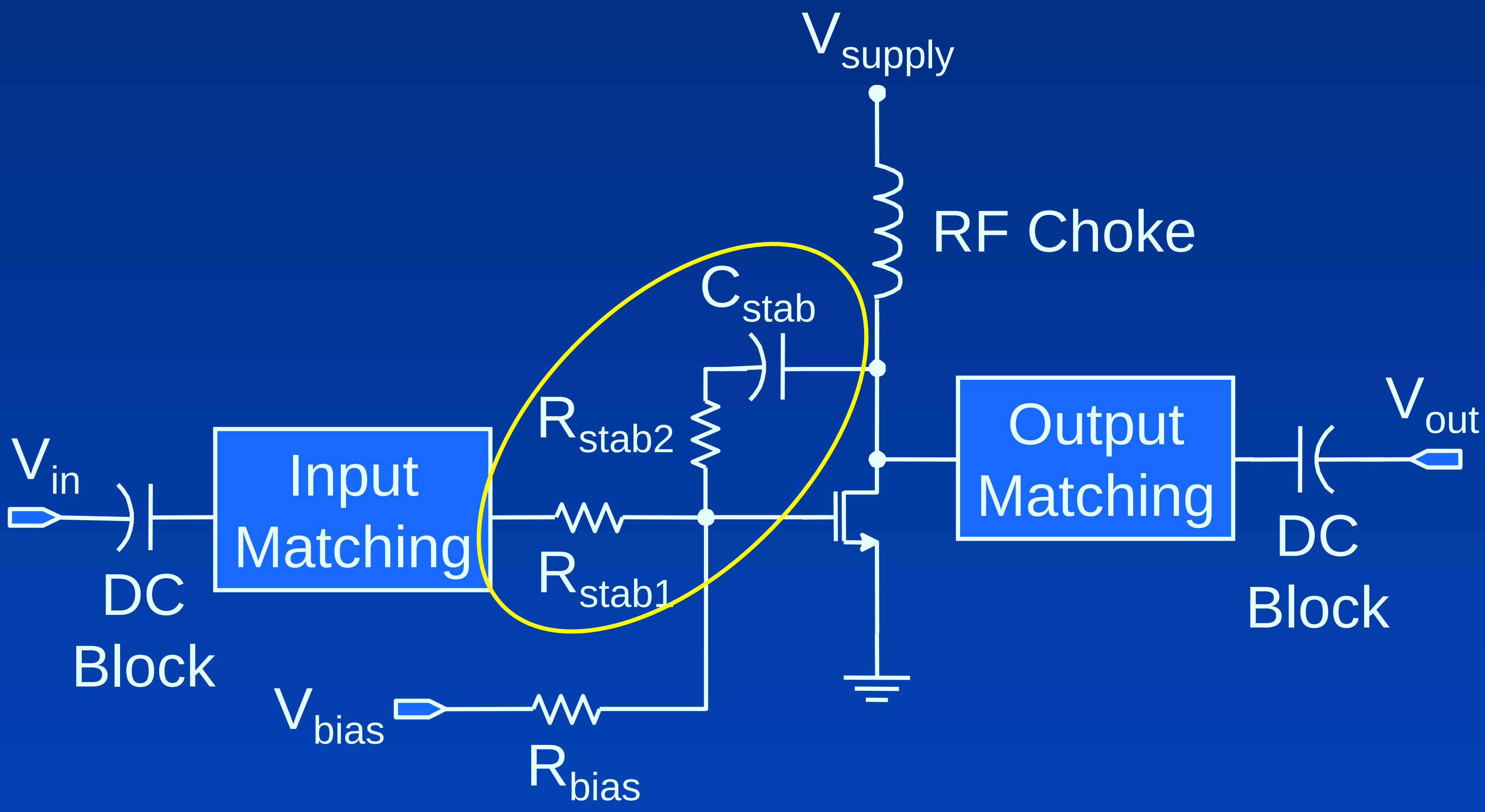
$$B_1 = 1 + |s_{11}|^2 - |s_{22}|^2 - |D|^2$$







Stabilized PA

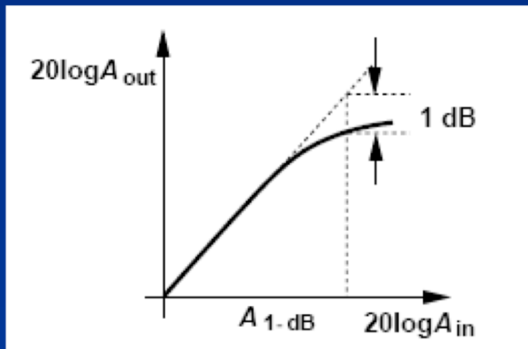


Impedance matching networks

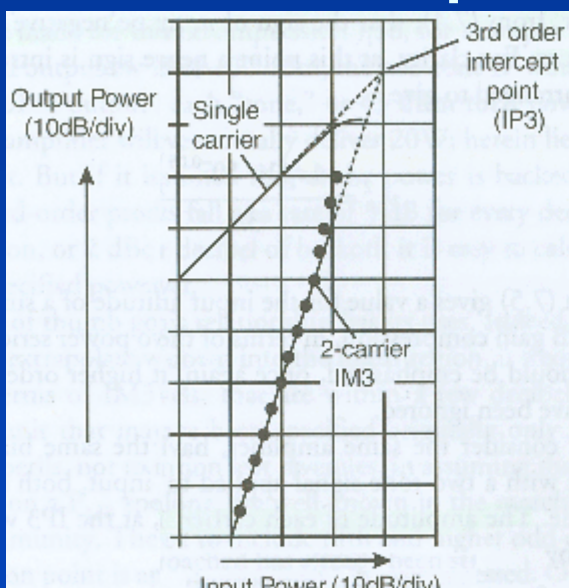
- For the determined R_{OPT} , find correspondent Γ_{IN} and choose $\Gamma_S = \Gamma_{IN}^*$
- Choose a matching network for the output, in general low-pass (to attenuate harmonics), to transform the antenna impedance into R_{OPT} (Smith Chart [4])
- Choose a convenient matching network for the input so that the desired matching can be attained

Linearity I – 2tone

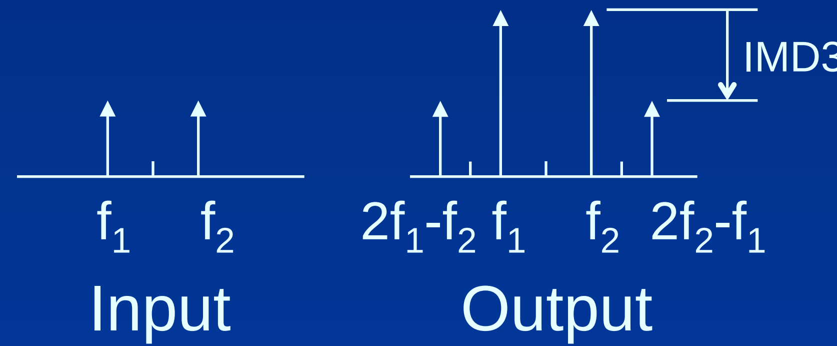
1-dB Compression Point

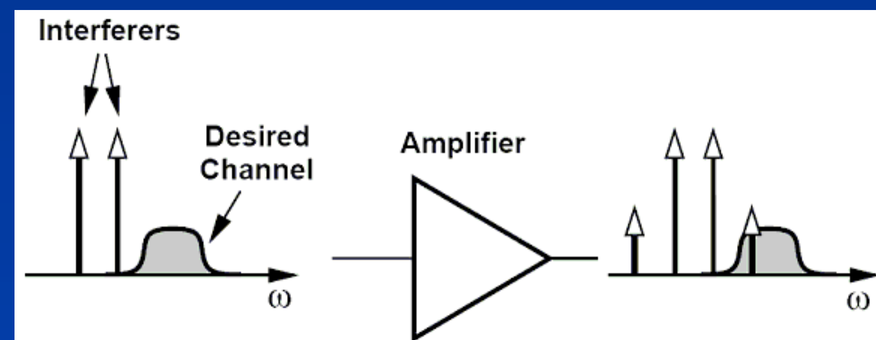


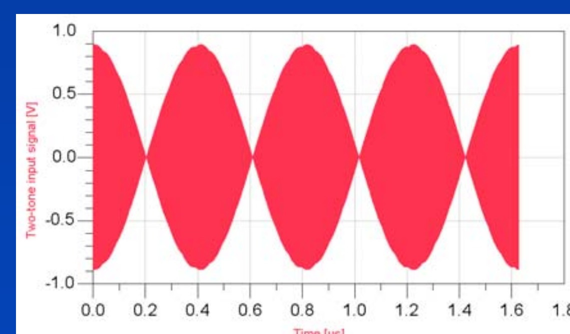
3rd Order Intercept Point



3rd Order Intermodulation Distortion (IMD3)

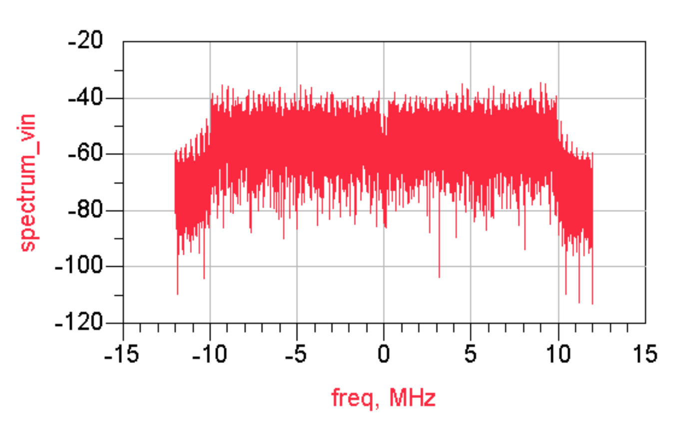




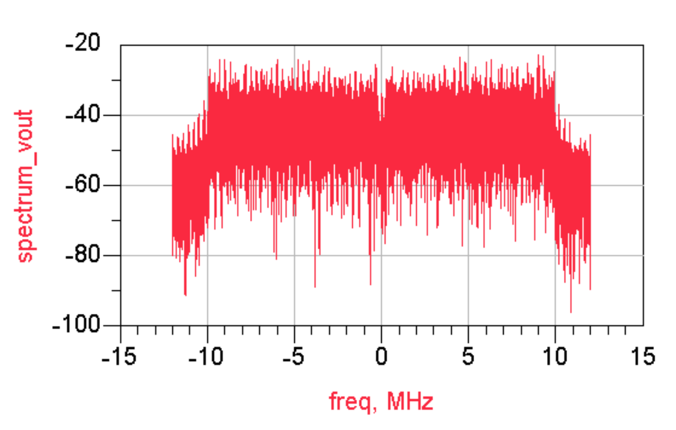


Linearity II - OFDM

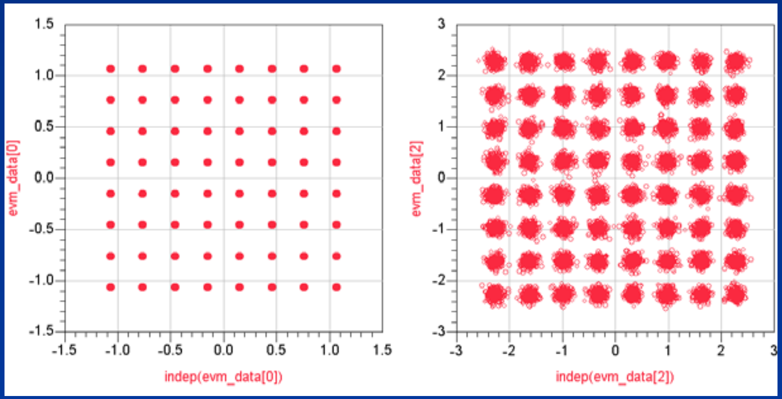
Input OFDM spectrum

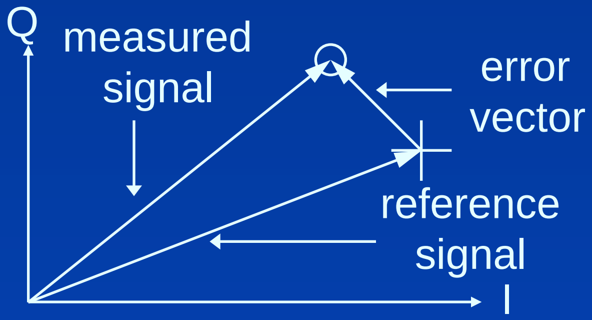


Output OFDM spectrum



Error Vector Magnitude



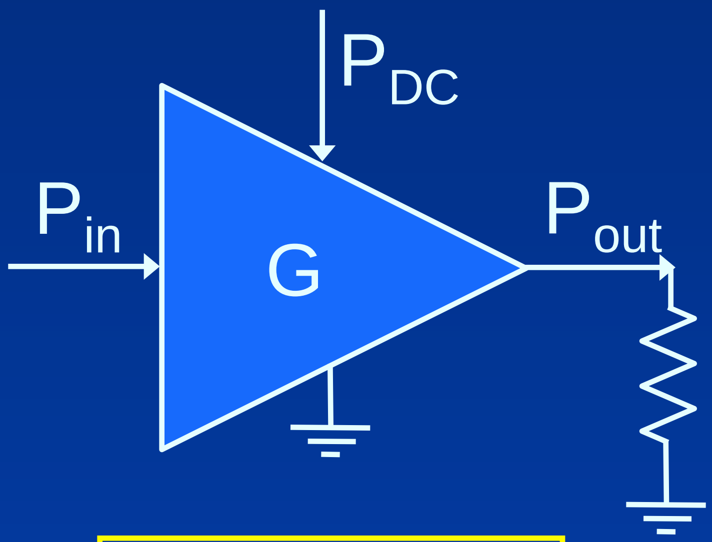


IEEE802.11a – EVM < -25dB (5.6%)

OFDM, 64QAM, 54Mbps

In general, EVM < 3%

Efficiency



$$PAE = \frac{P_{OUT} - P_{IN}}{P_{DC}}$$

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

$$P_{OUT} = G \cdot P_{IN}$$

$$PAE = \eta_D \cdot \left(1 - \frac{1}{G}\right)$$

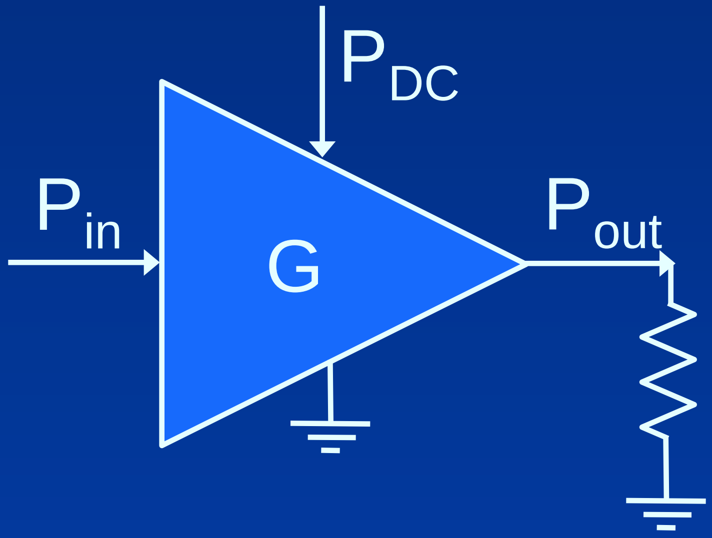
Class A PA:

- Max efficiency with P_{OUT_MAX}
- Consumes power even without input signal
- Efficiency depends also on gain

Scenario

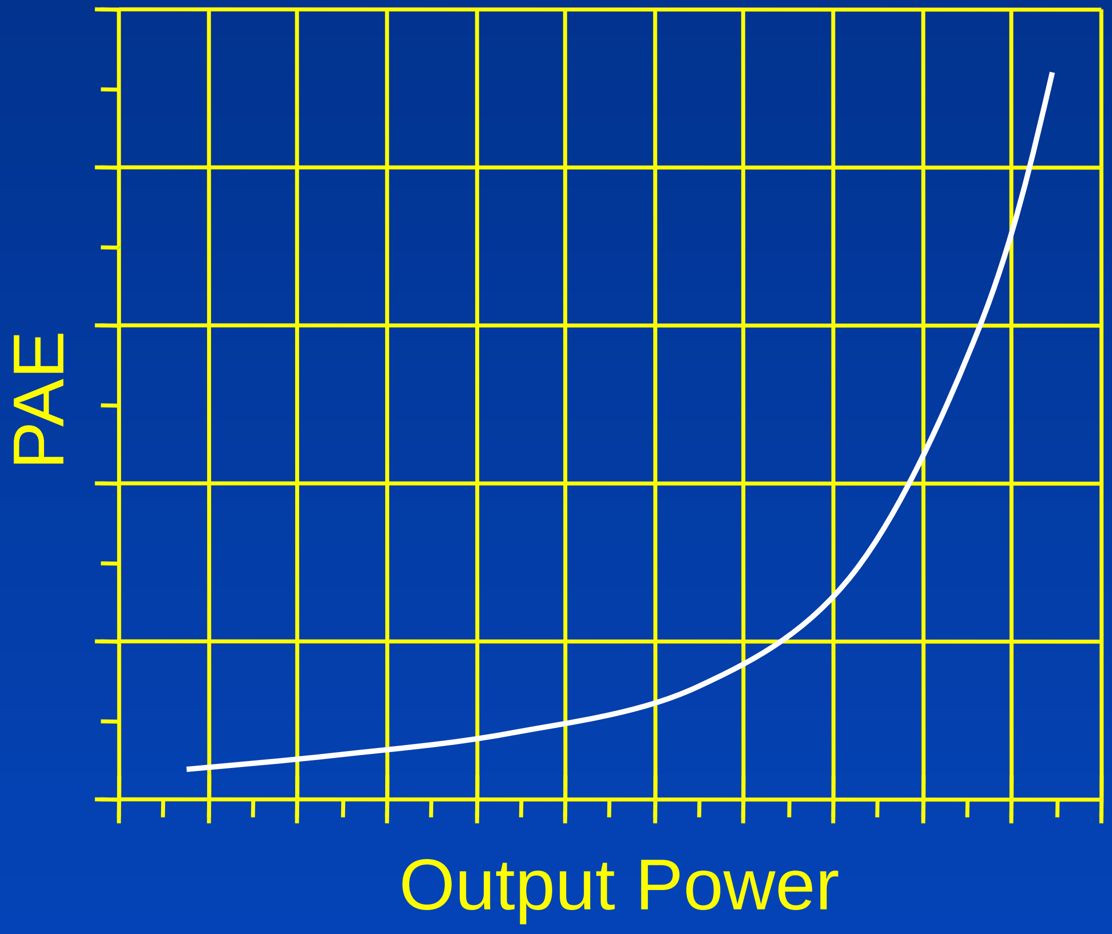
- Mobile devices require high efficiency circuits
- Applications such as WLAN (variable envelope) requires high linearity PAs
- RF power amplifiers are power hungry devices
- High efficiency PA means low linearity PA

Improving efficiency…



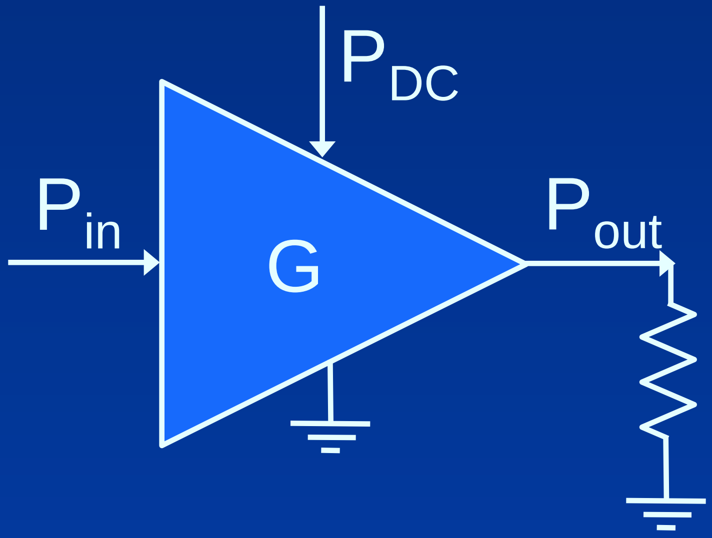
$$PAE = \frac{P_{OUT} - P_{IN}}{P_{DC}}$$

$$P_{DC} = V_{DD} \cdot I_{DD}$$




What if …?

What if….?

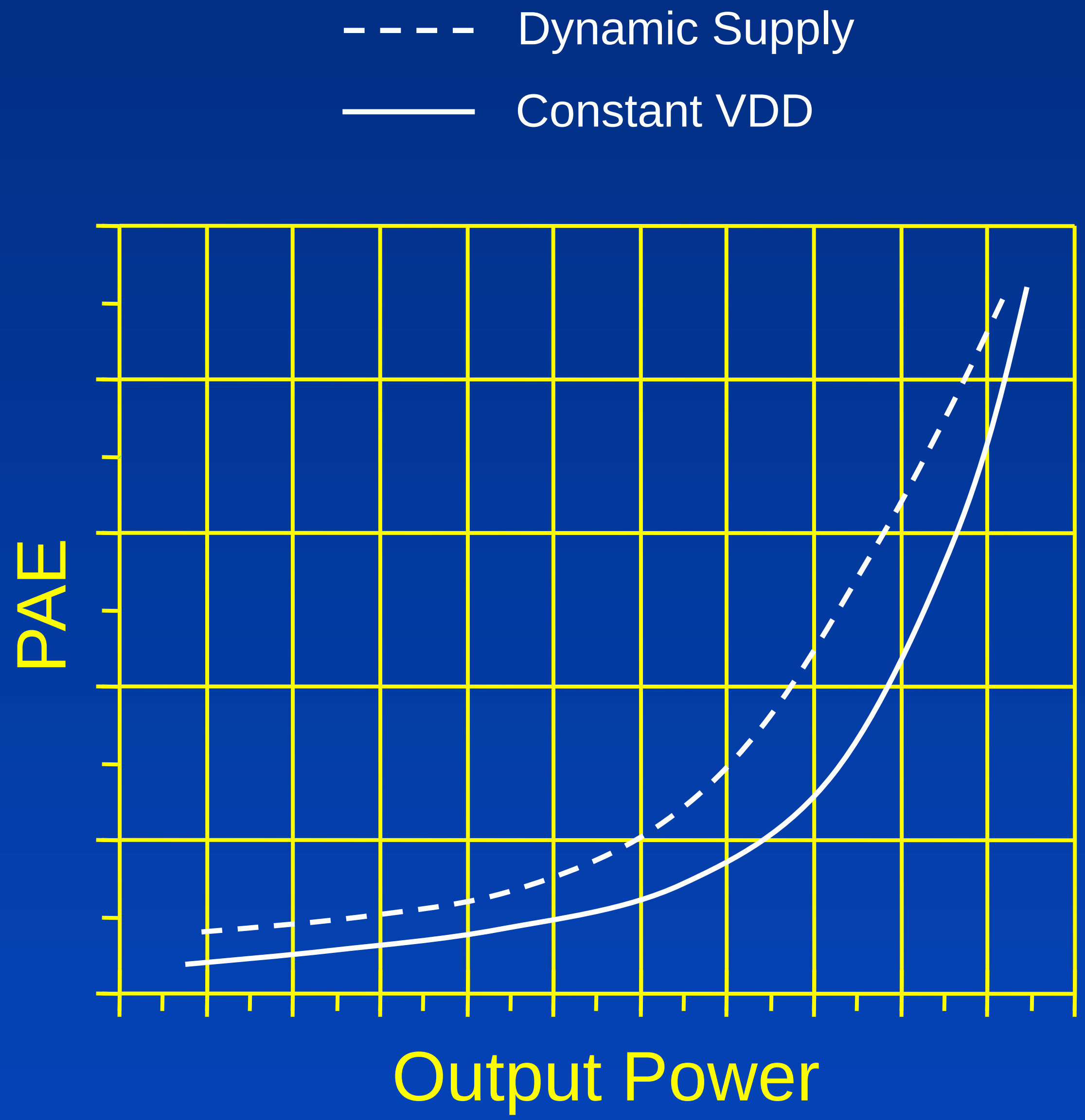


$$PAE = \frac{P_{OUT} - P_{IN}}{P_{DC}}$$

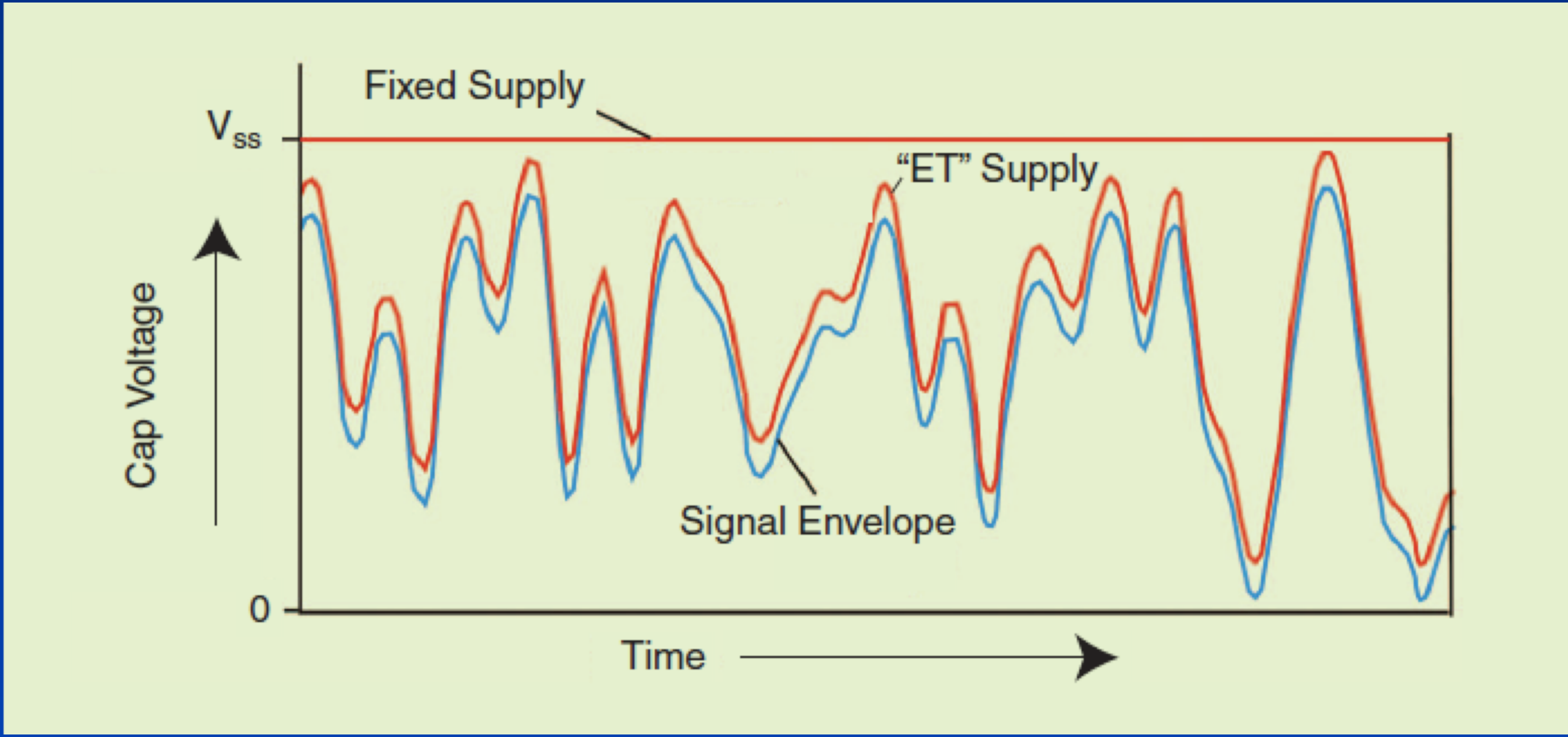
$$P_{DC} = V_{DD} \cdot I_{DD}$$

Low output power: V_{DC} ↓

High output power: V_{DC} ↑



Dynamic Supply

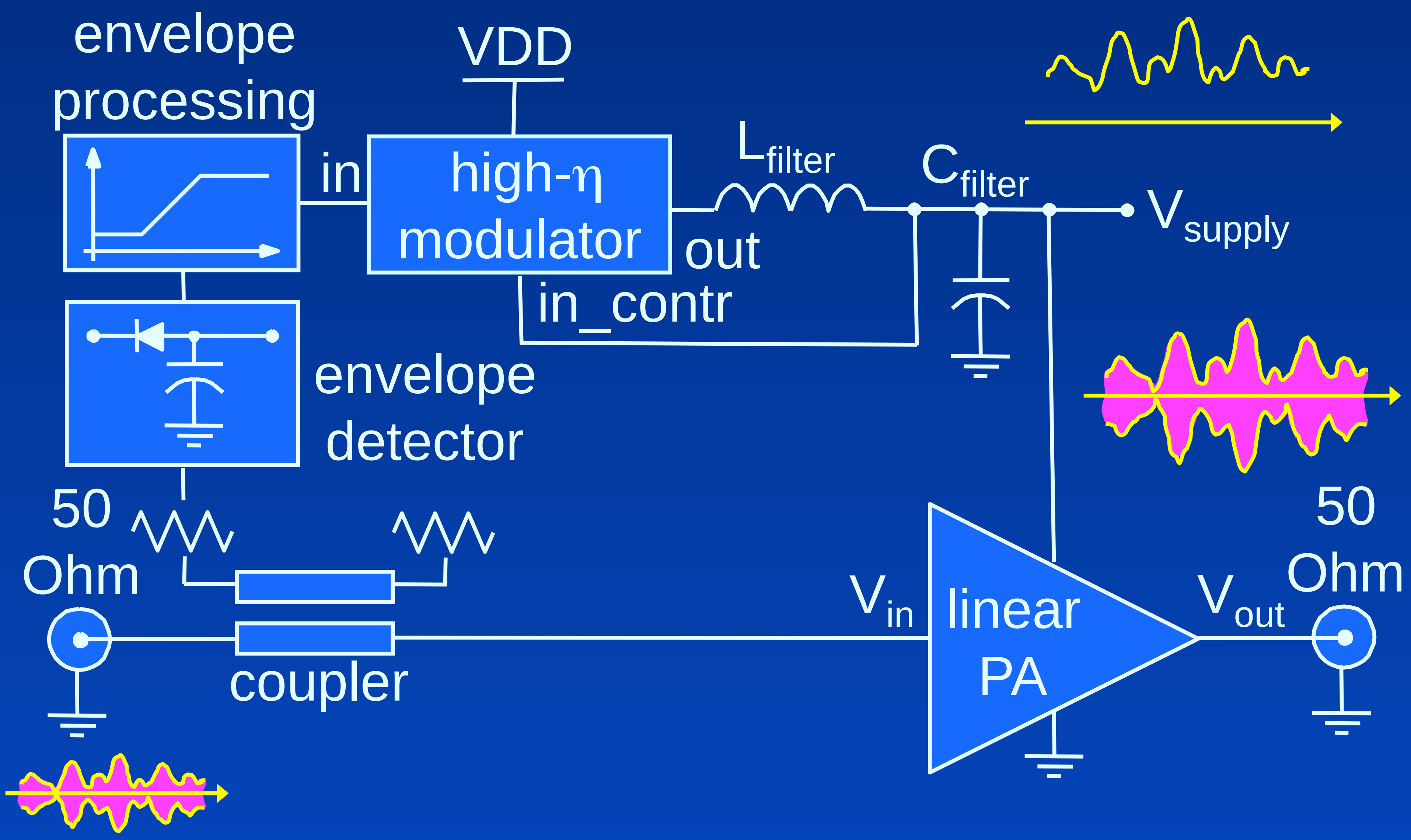


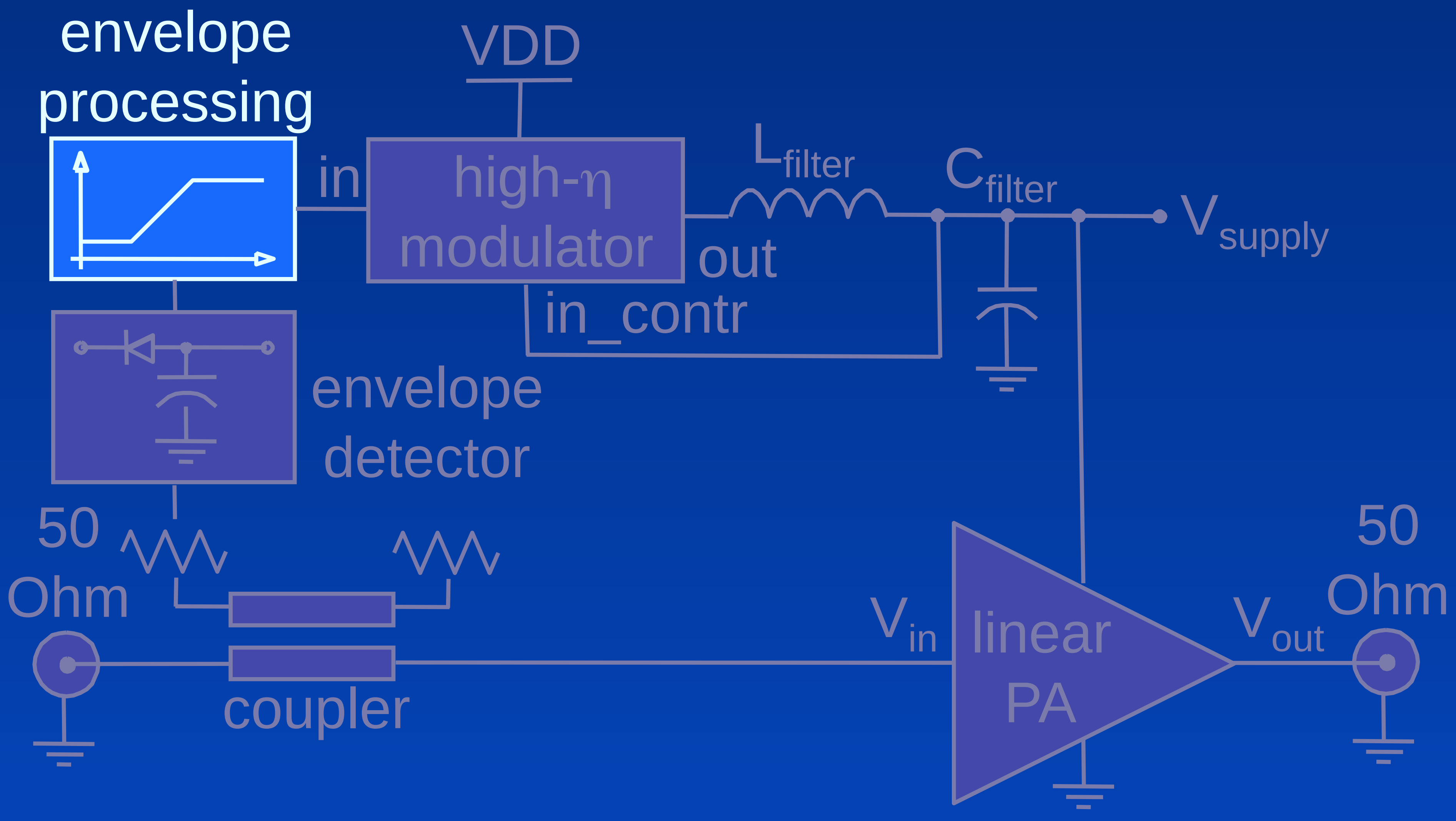
From Cripps, Microwave Magazine Oct-2010

Articles about enhancement techniques

- Dynamic Supply:
  – Hanington [5], 1999 (T-MTT)
  – Schlumpf [1], 2004 (JSSC)
  – Minnis [7], 2009 (T-CAS-1)
  – Larson [10], 2008 (CICC)
  – Jeong [9], 2009 (T-MTT)
- EER:
  – Chen [6], 2004 (MTT-S)

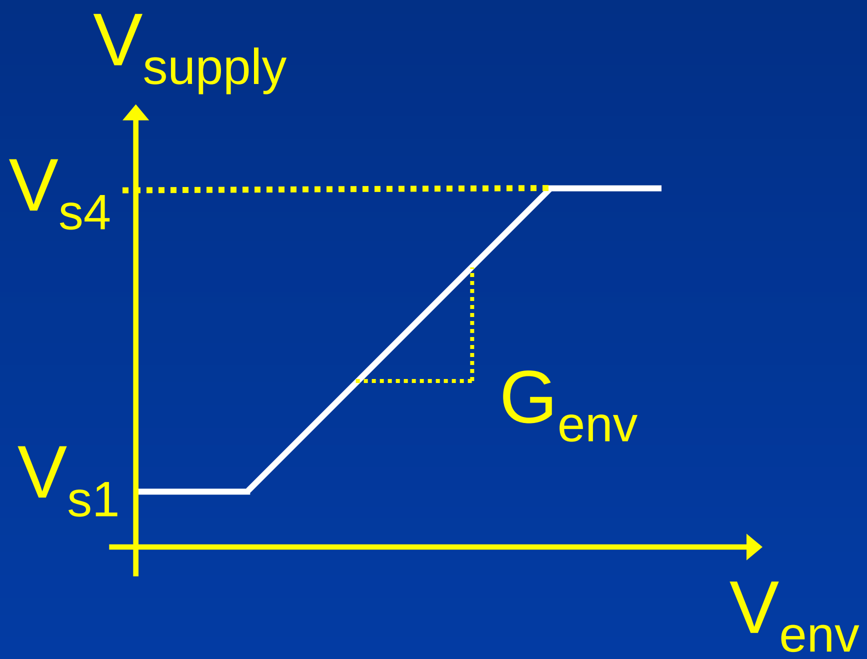
Dynamic Supply PA Block Diagram

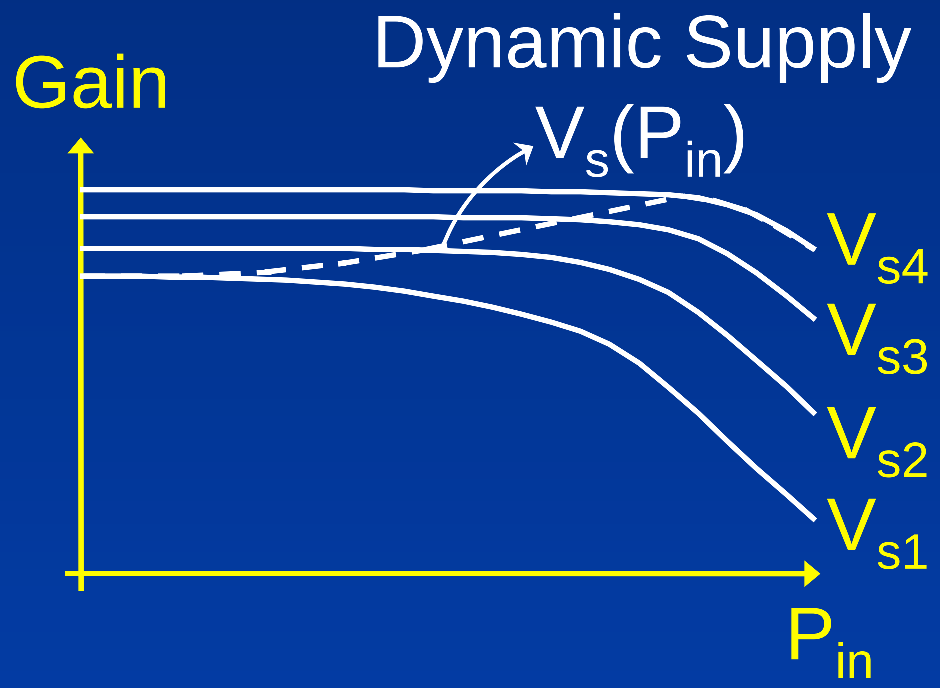




envelope processing
VDD
in
high-η modulator
L_{filter}
C_{filter}
V_{supply}
out
in_contr
envelope detector
50 Ohm
coupler
V_{in}
linear PA
V_{out}
50 Ohm

Envelope processing

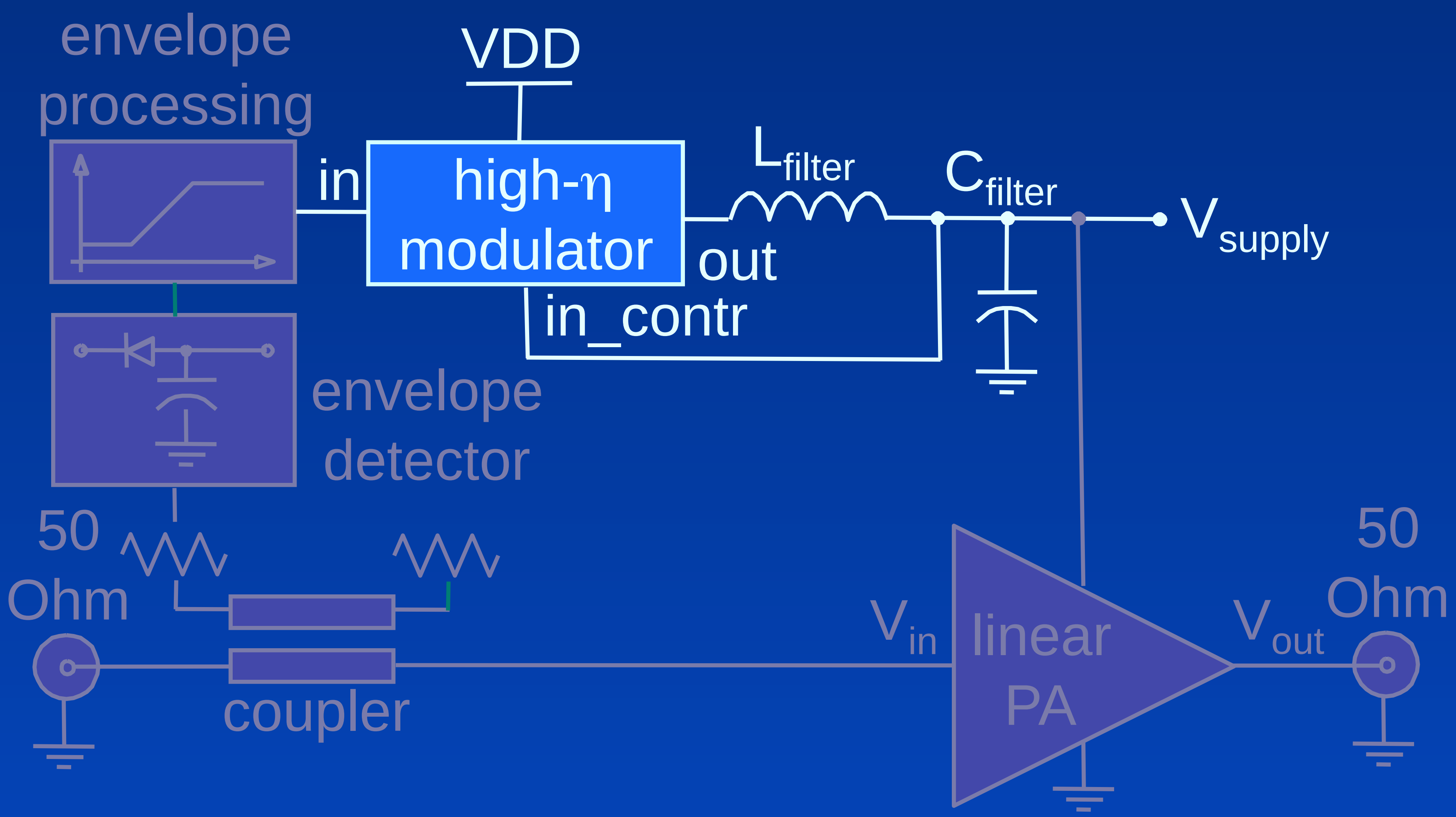




$$G_{env} \cdot |V_{in}| + V_{knee} < V_{s1} \rightarrow V_s(P_{in}) = V_{s1}$$

$$V_{s1} \leqslant G_{env} \cdot |V_{in}| + V_{knee} \leqslant V_{s4} \rightarrow V_s(P_{in}) = G_{env} \cdot |V_{in}| + V_{knee}$$

$$G_{env} \cdot |V_{in}| + V_{knee} \geqslant V_{s4} \rightarrow V_s(P_{in}) = V_{s4}$$

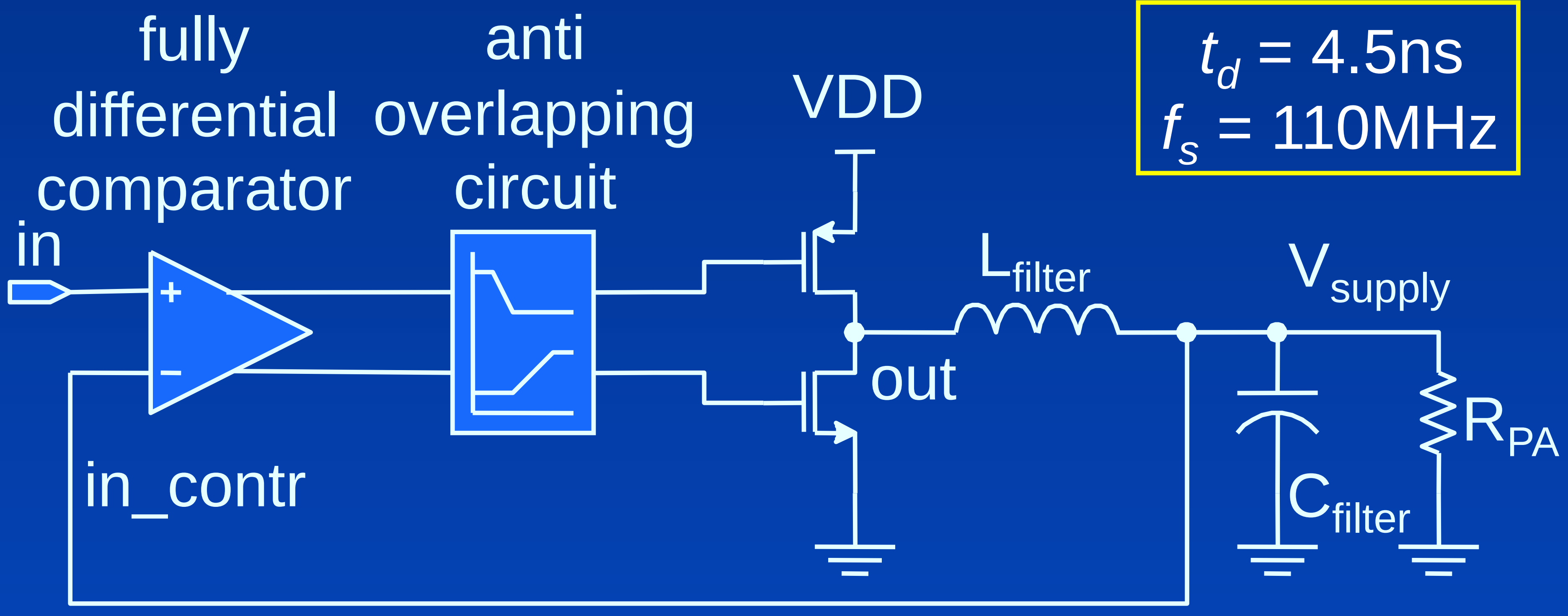

envelope
processing
VDD
in
high-η
modulator
L filter
C filter
V supply
out
in_contr
envelope
detector
50
Ohm
coupler
V in
linear
PA
V out
50
Ohm

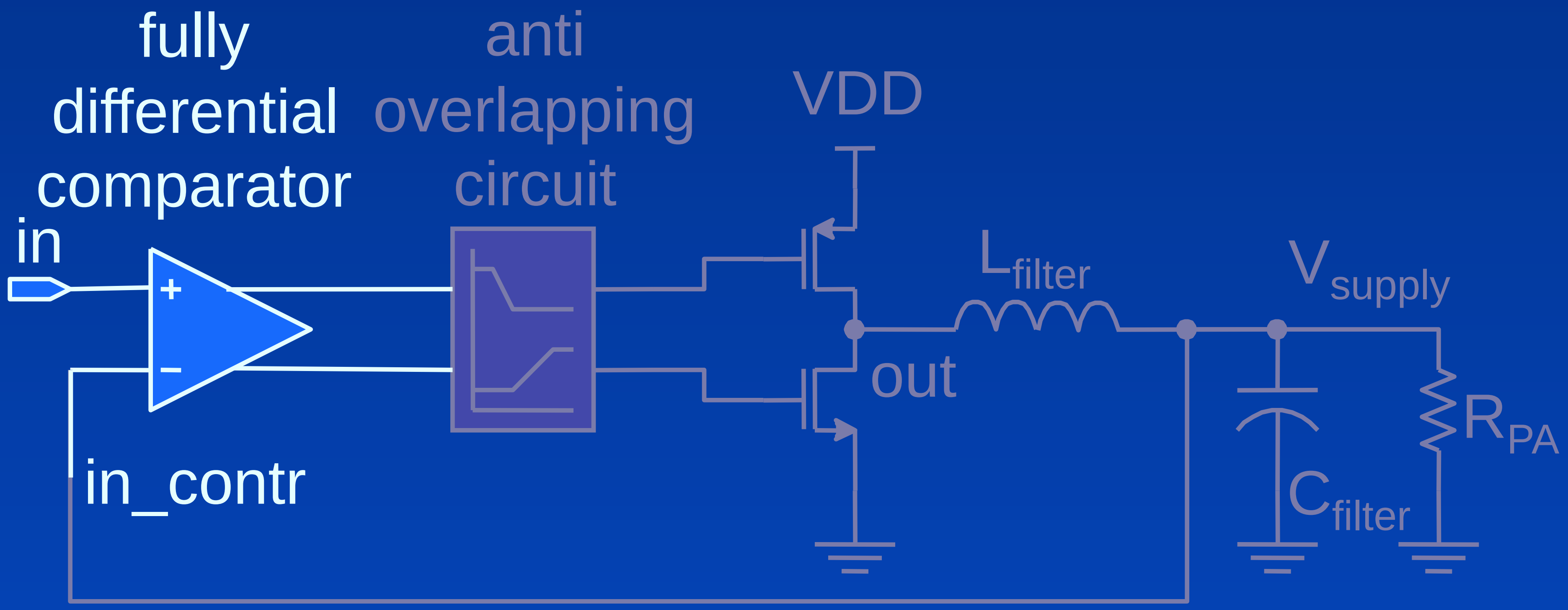
High-Efficiency Modulator

$\eta = 86\%$

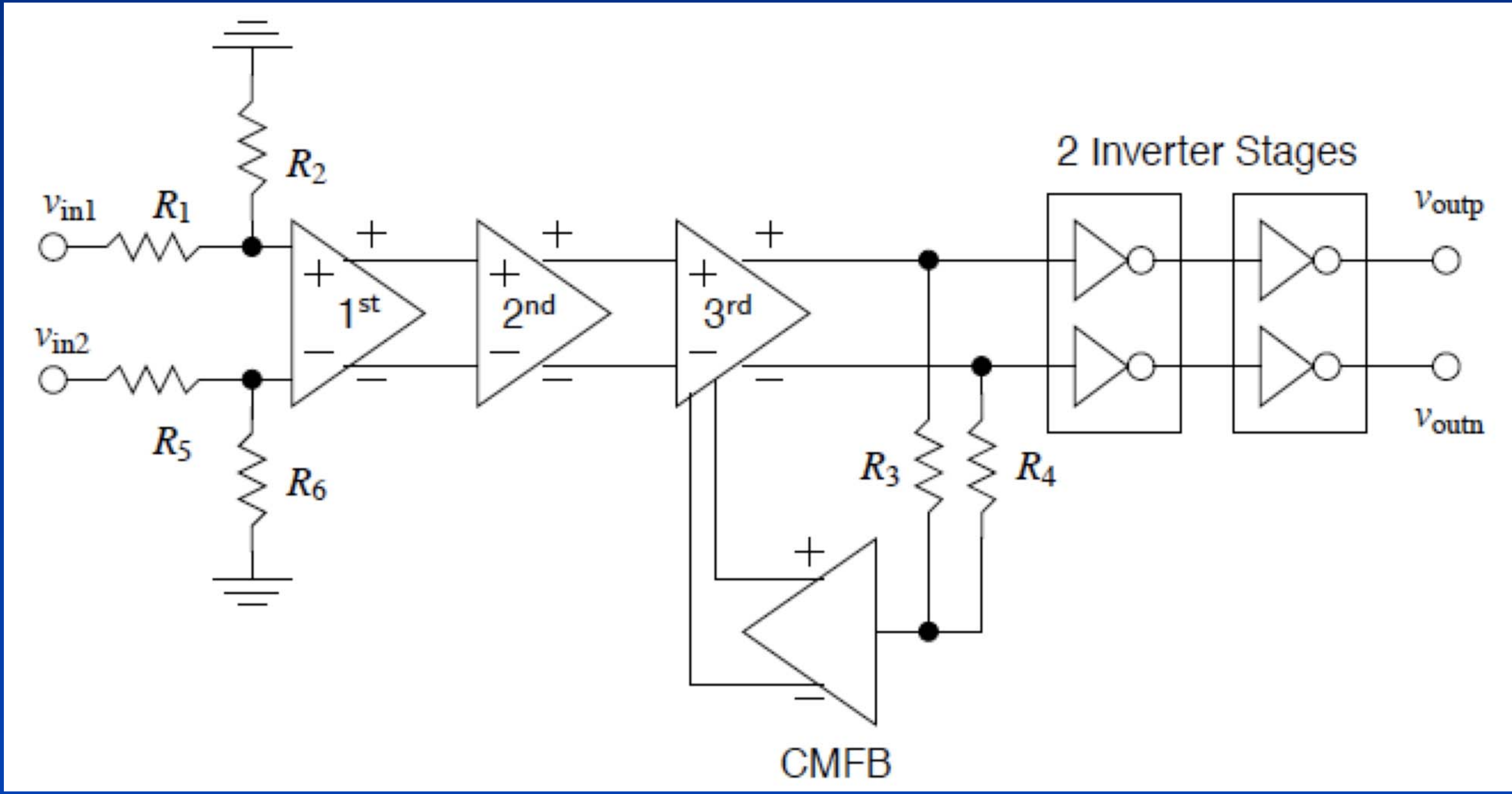
$f_s \cdot t_d \cdot 360° + \varphi_{LC}(f_s) = 180°$

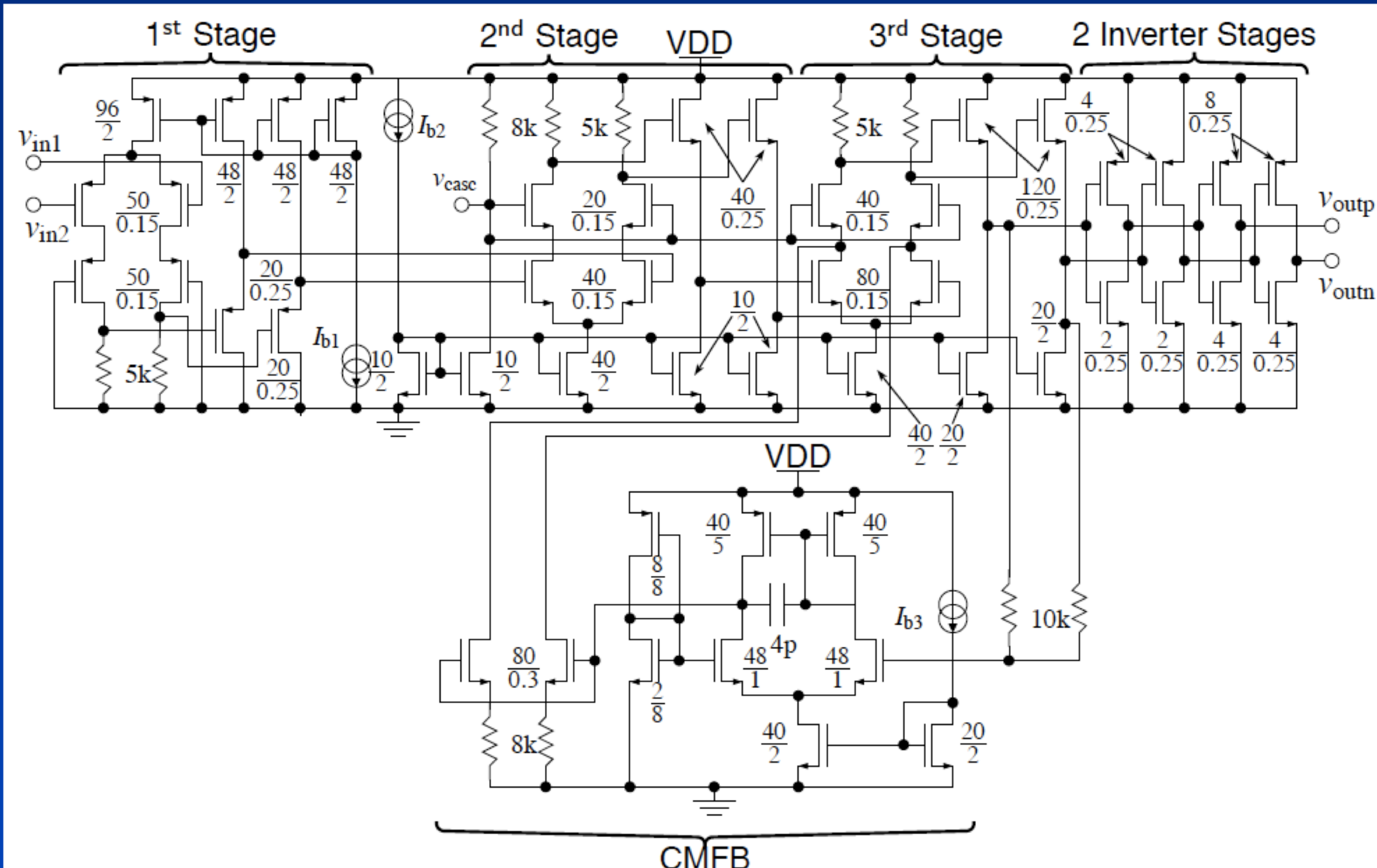
$t_d = 4.5\text{ns}$
$f_s = 110\text{MHz}$

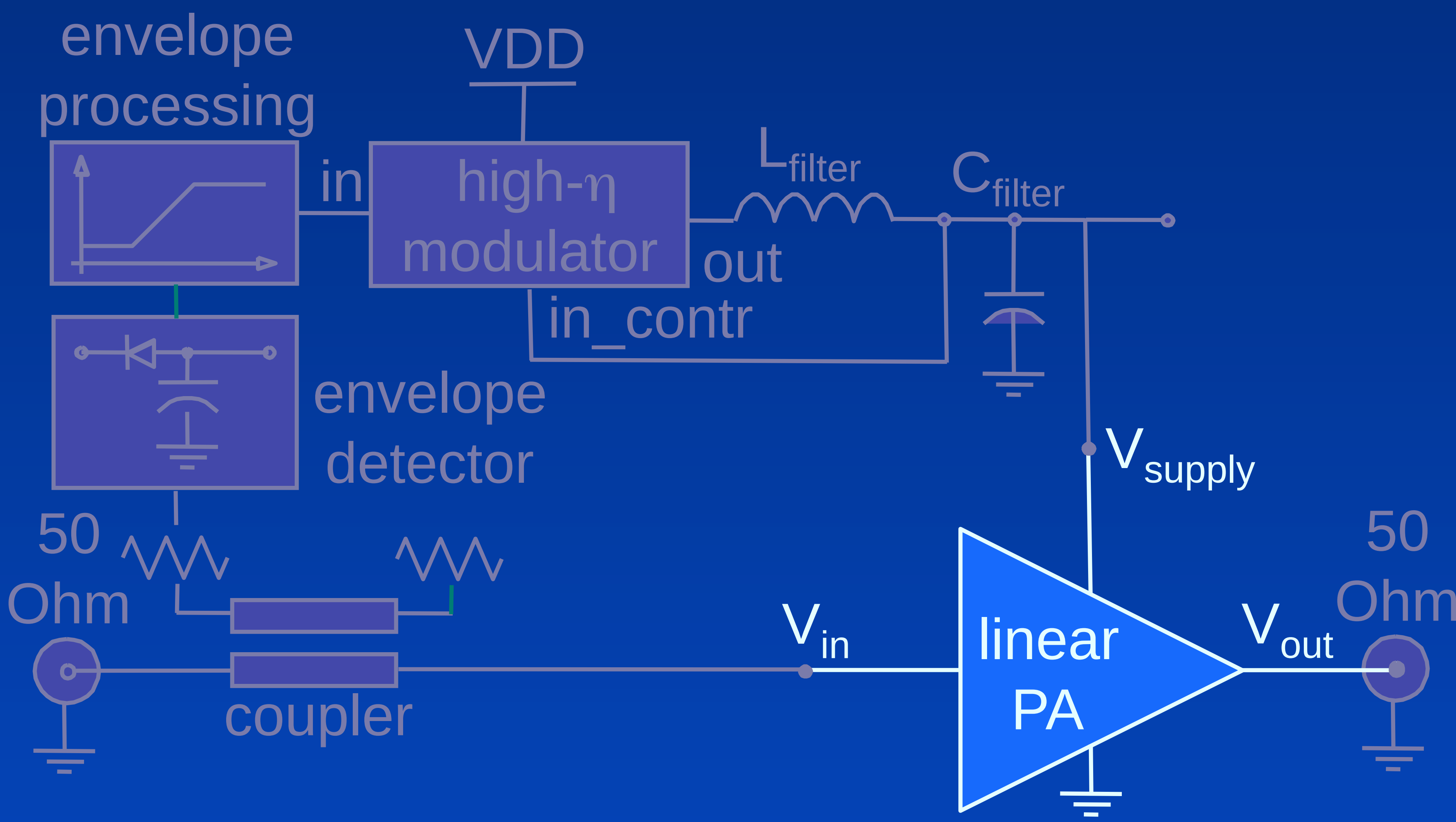



fully differential comparator
anti overlapping circuit
VDD
in
+
−
in_contr
out
Lfilter
Vsupply
Cfilter
RPA

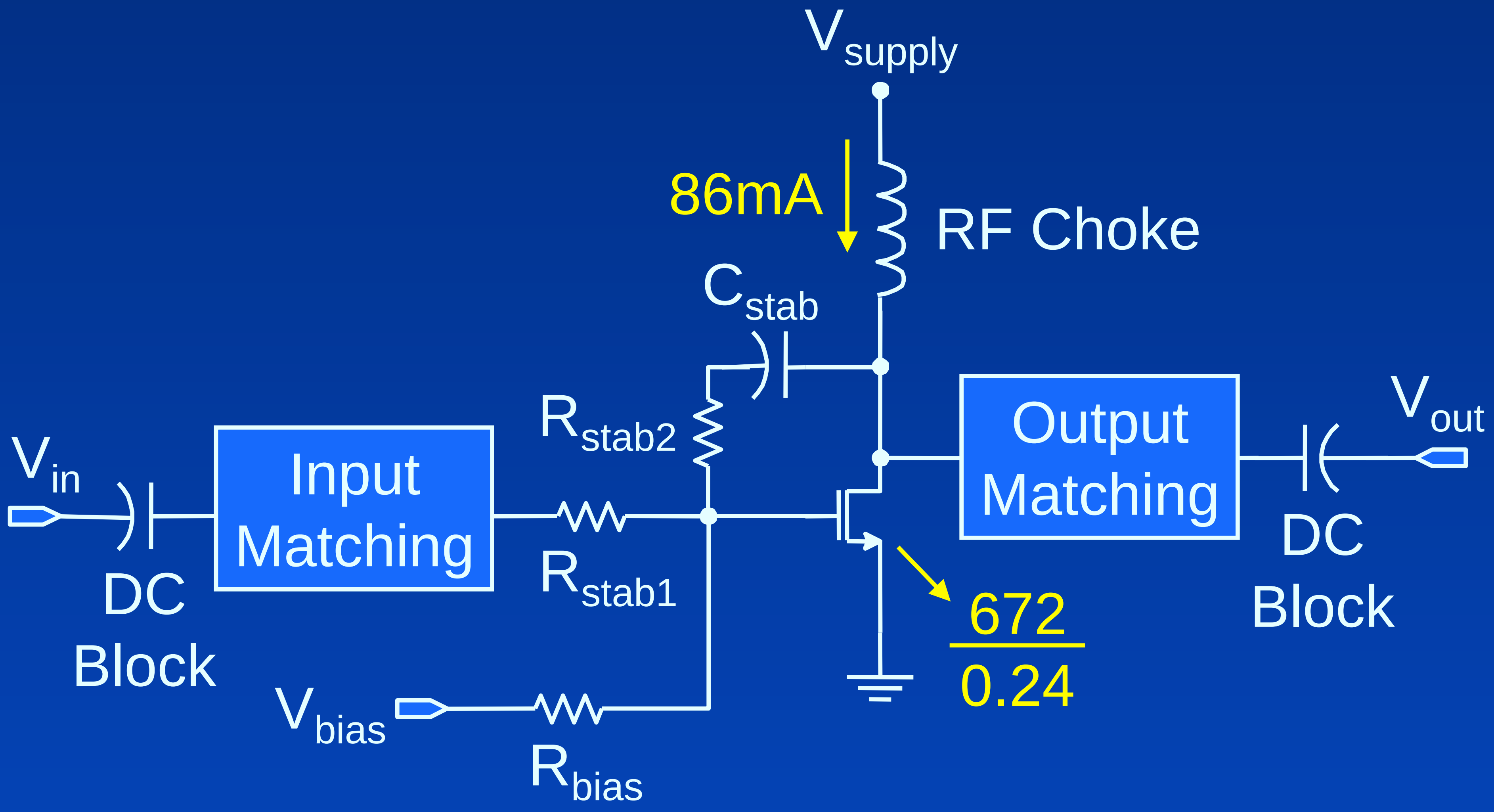
High-Speed Comparator



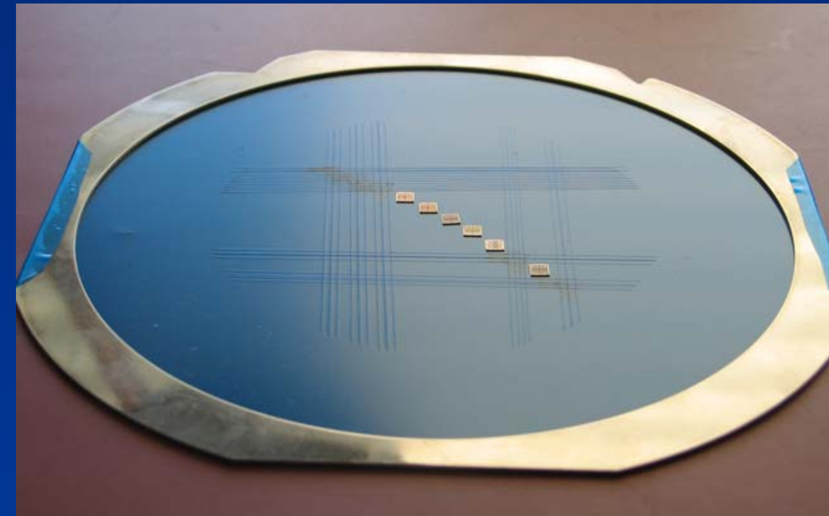

1st Stage
2nd Stage
VDD
3rd Stage
2 Inverter Stages
vin1
vin2
Ib2
vcasc
Ib1
8k
5k
5k
5k
10k
8k
4p
Ib3
voutp
voutn
VDD
CMFB

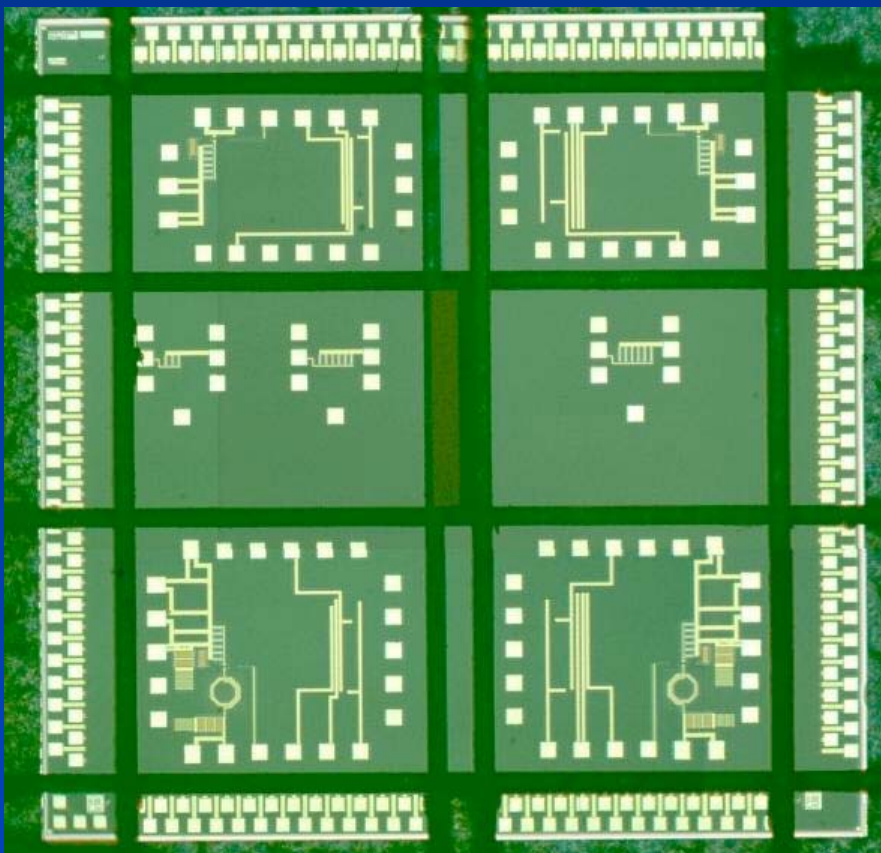

envelope
processing
VDD
in
high-η
modulator
L
filter
C
filter
out
in_contr
envelope
detector
V
supply
50
Ohm
50
Ohm
V
in
linear
PA
V
out
coupler

The RF Power Amplifier

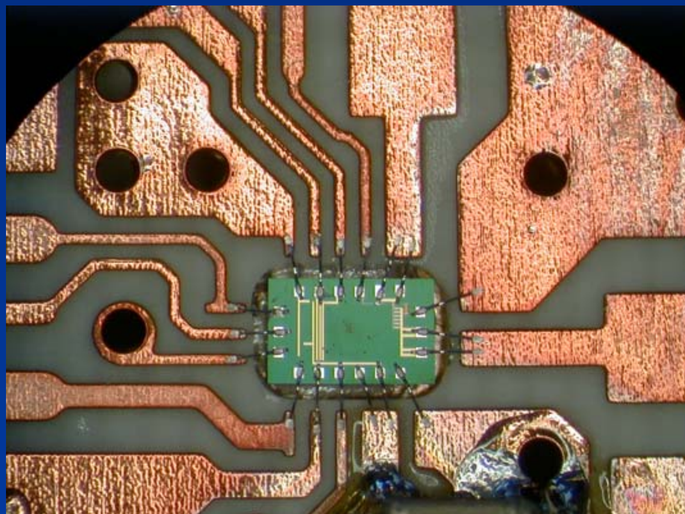


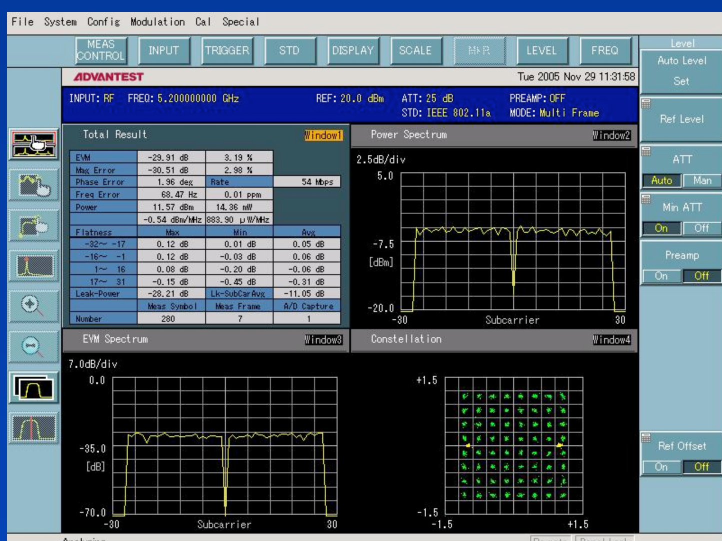
Measurements I

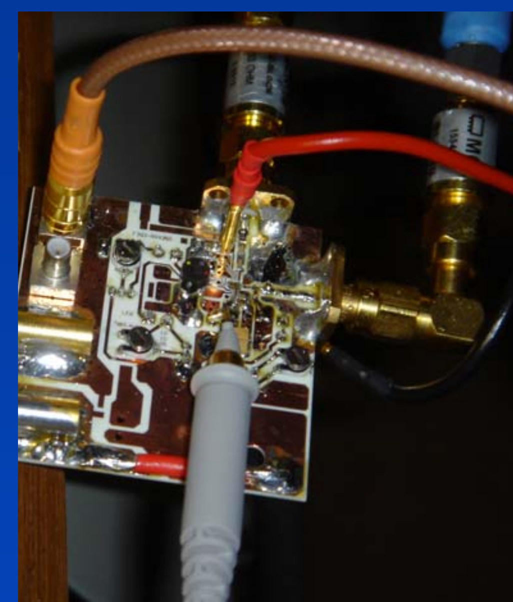




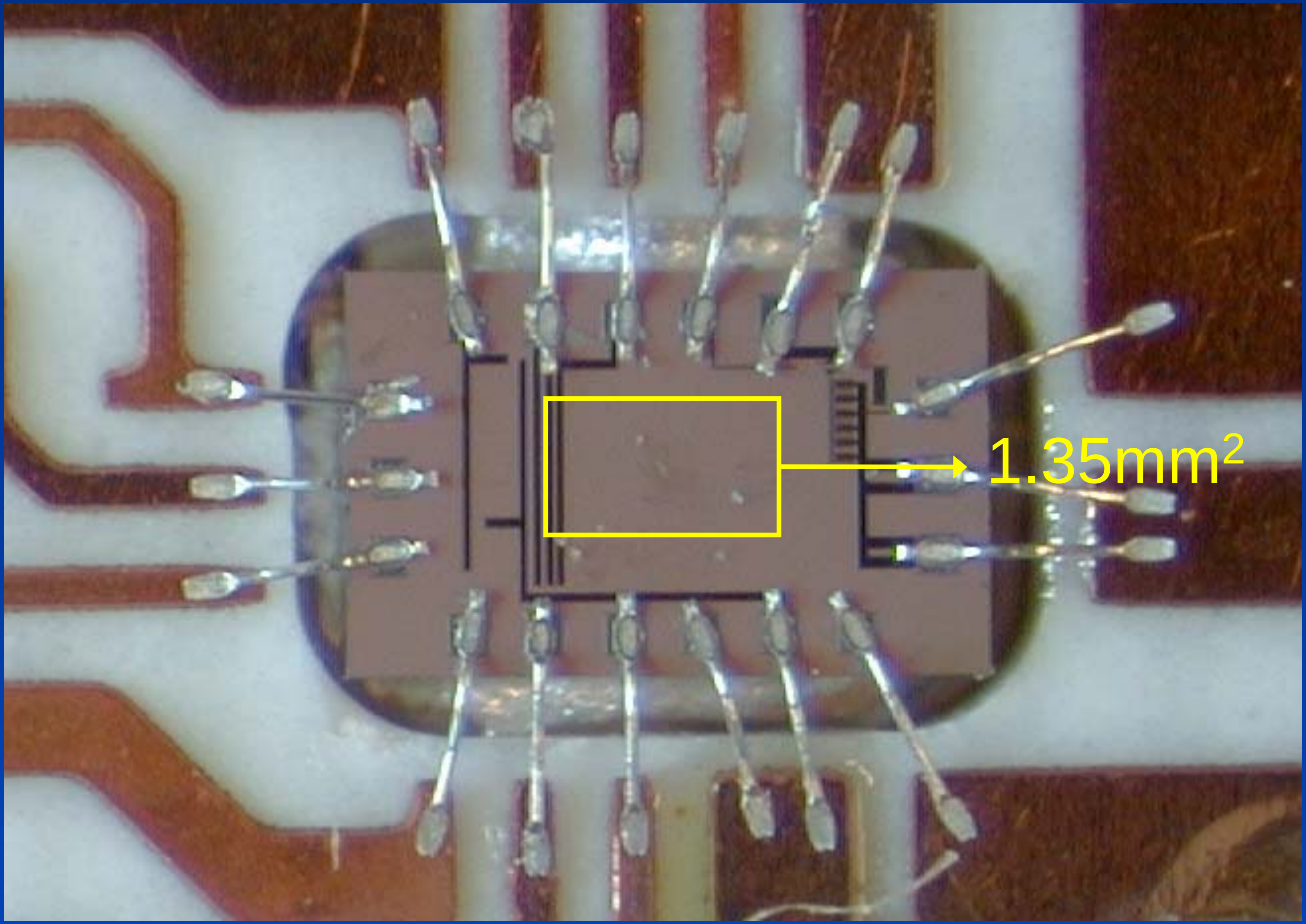
Measurements II



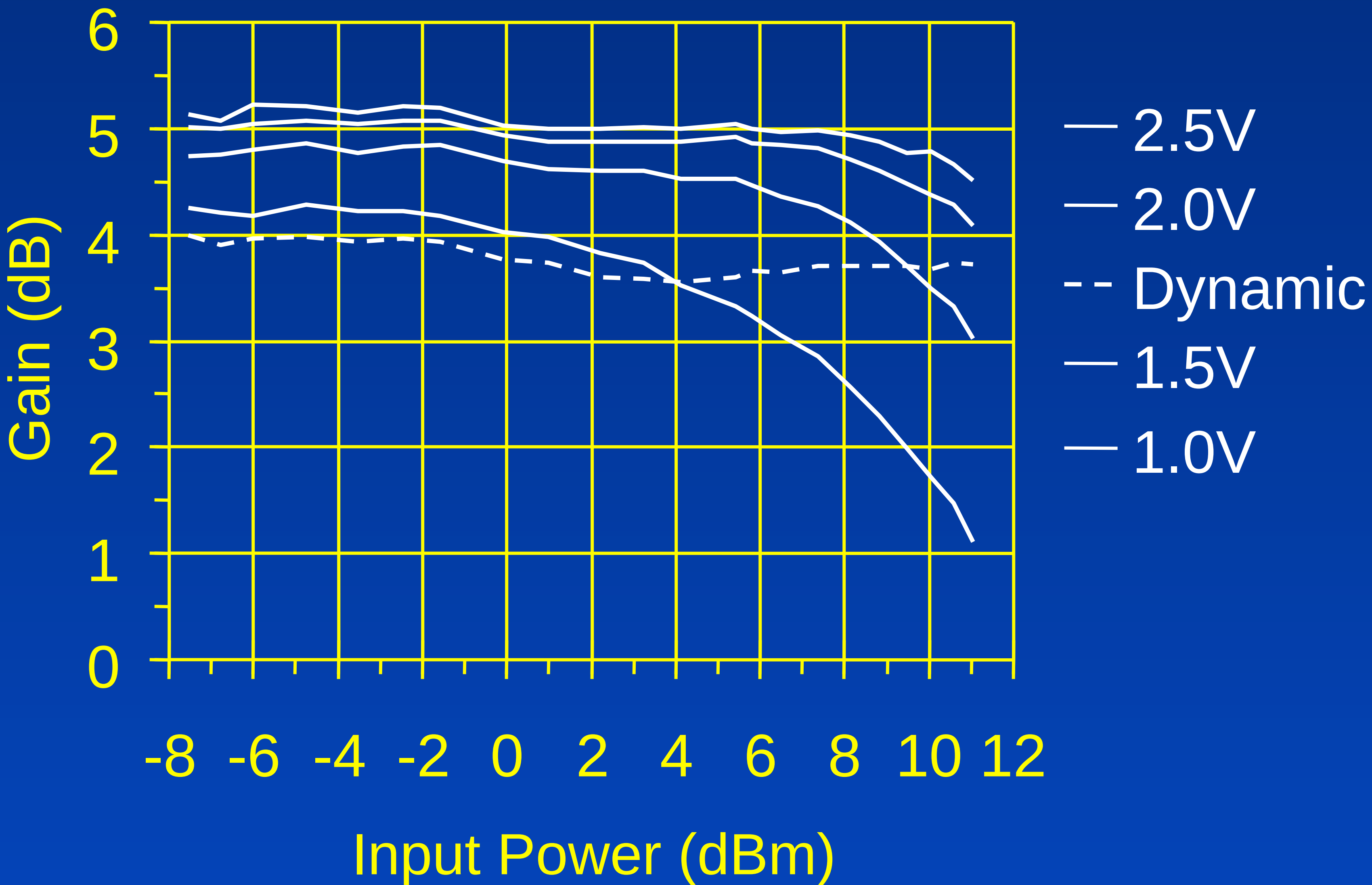




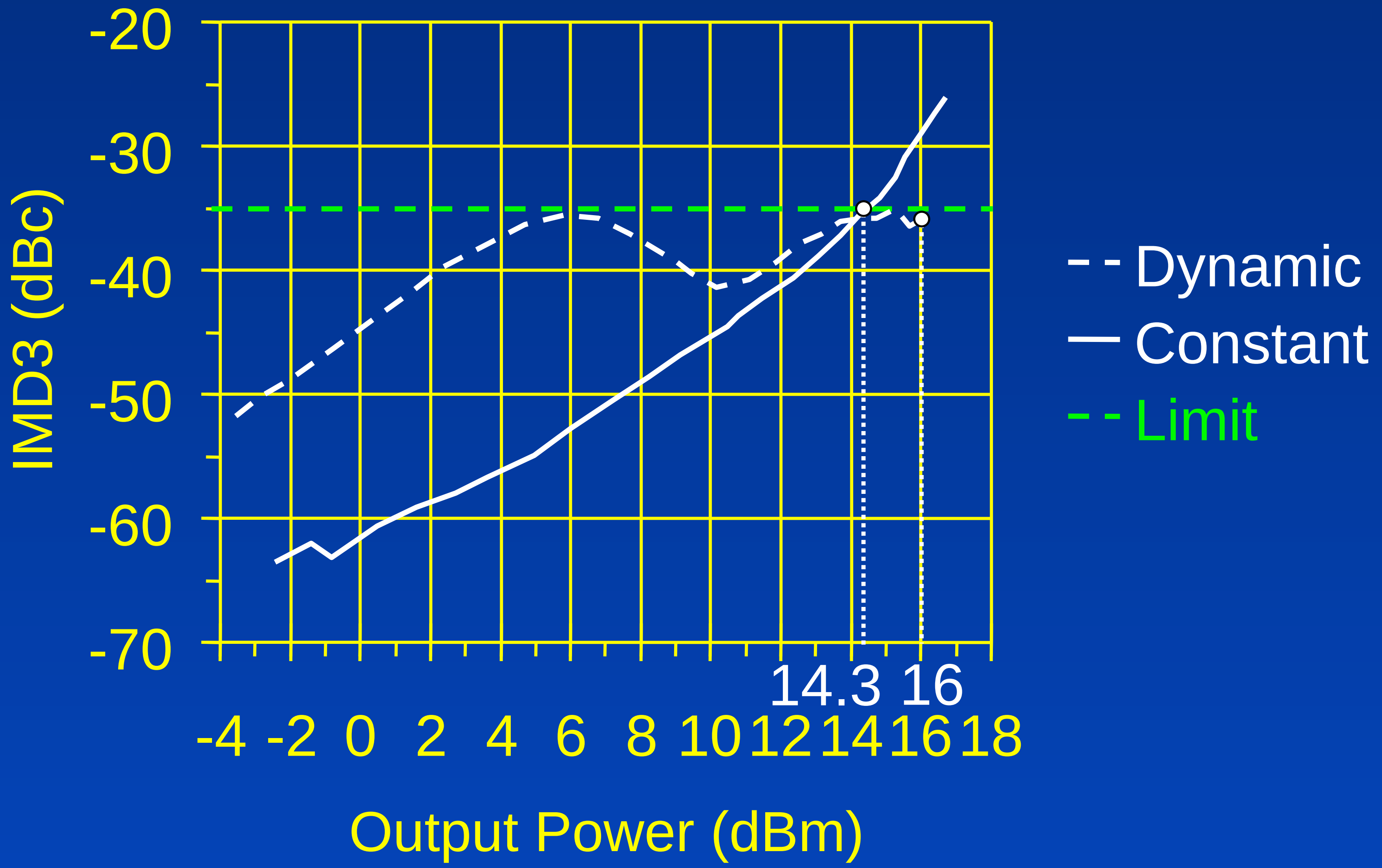
Measurement Results [8]



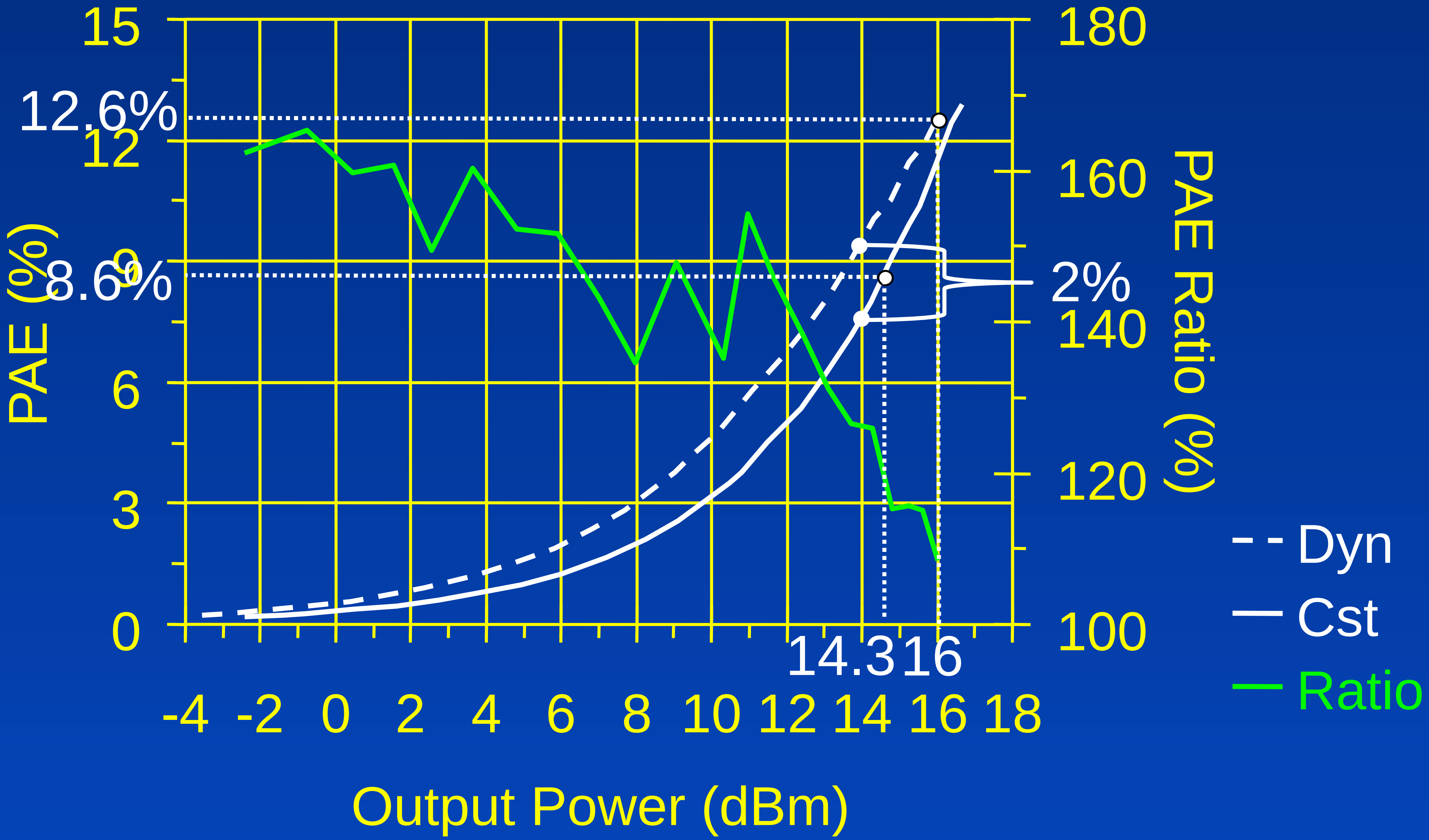
Gain vs. Input Power 5.2GHz



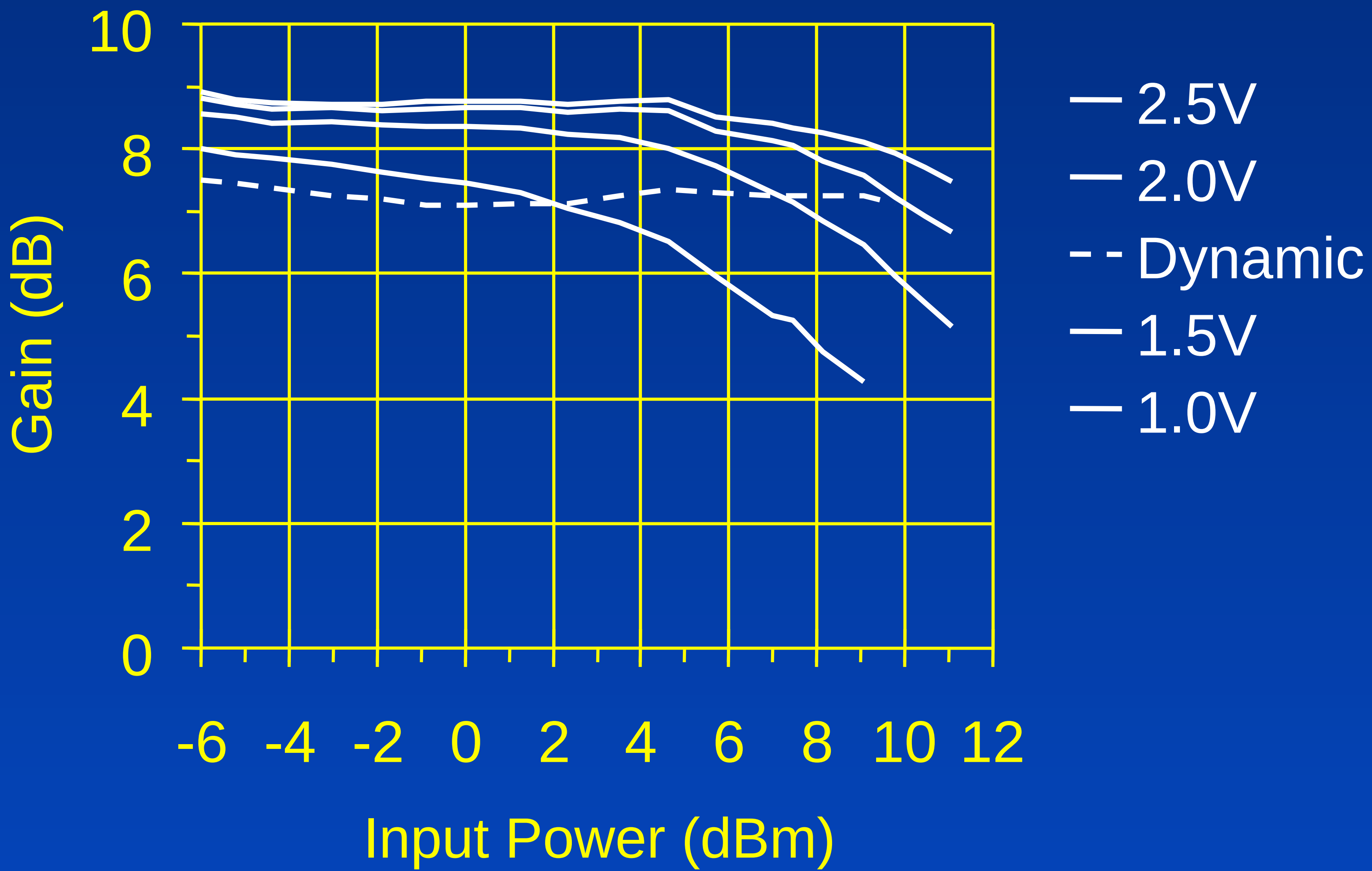
IMD3 vs. Output Power 5.2GHz



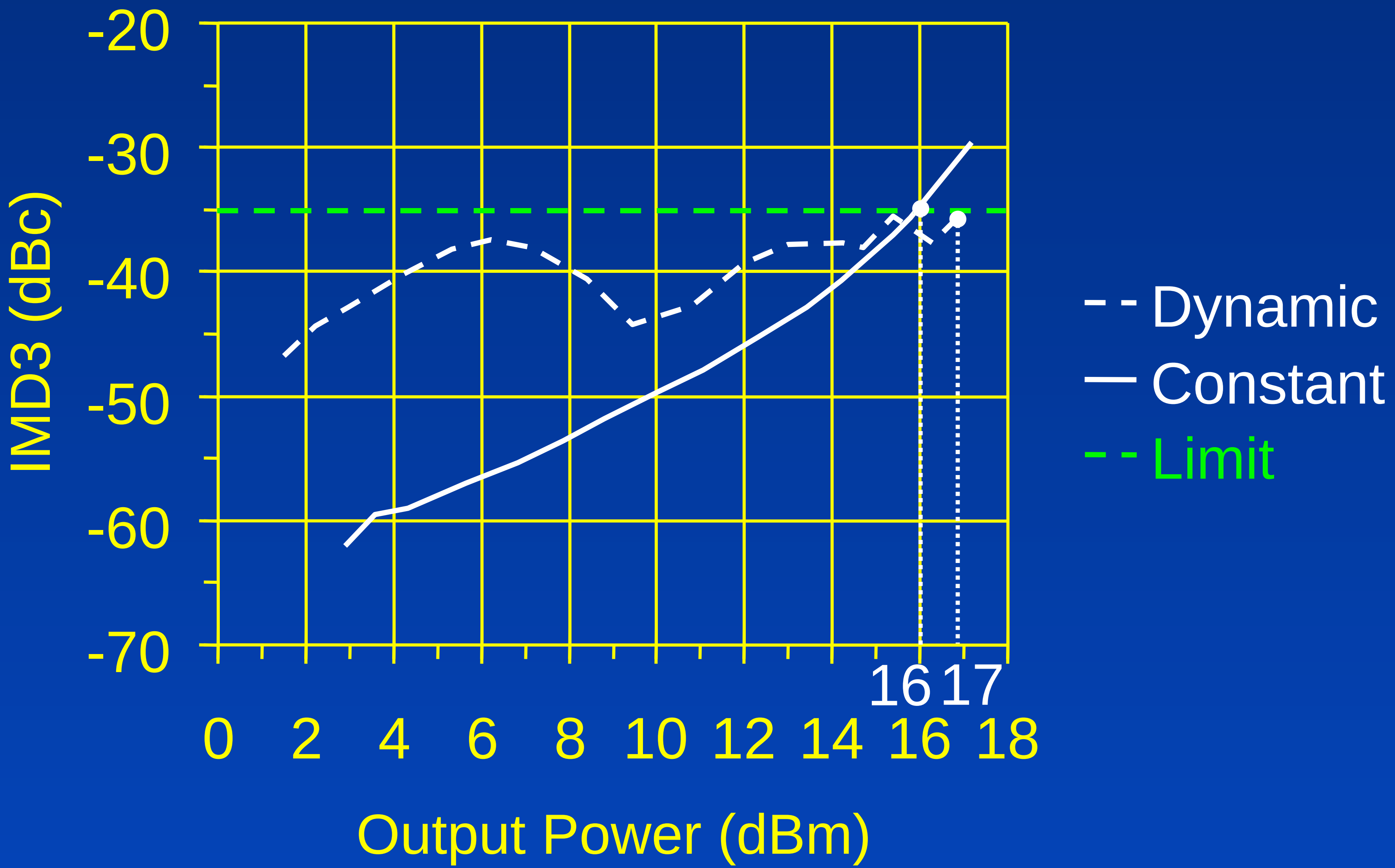
Efficiency vs. Output Power 5.2GHz



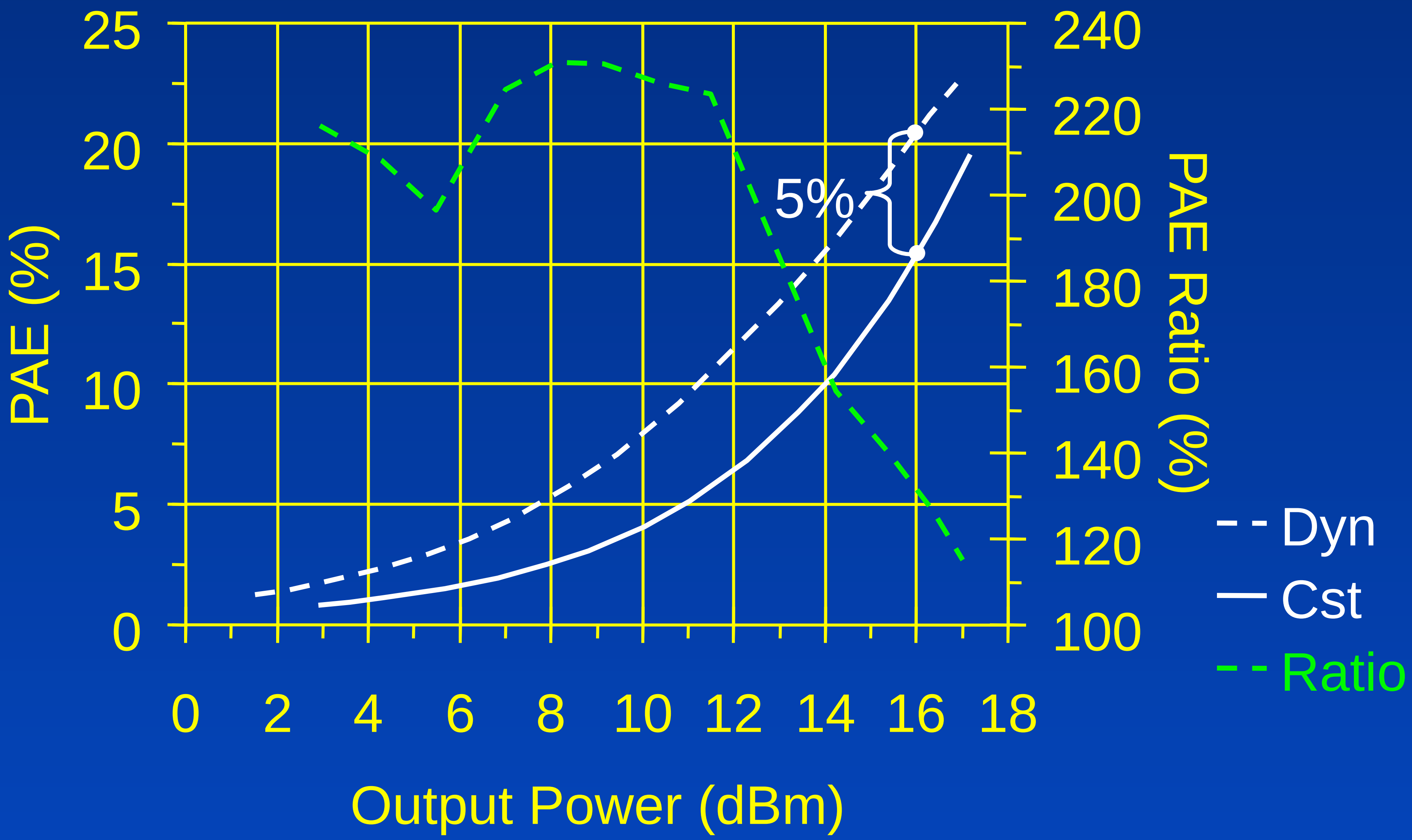
Gain vs. Input Power 2.4GHz



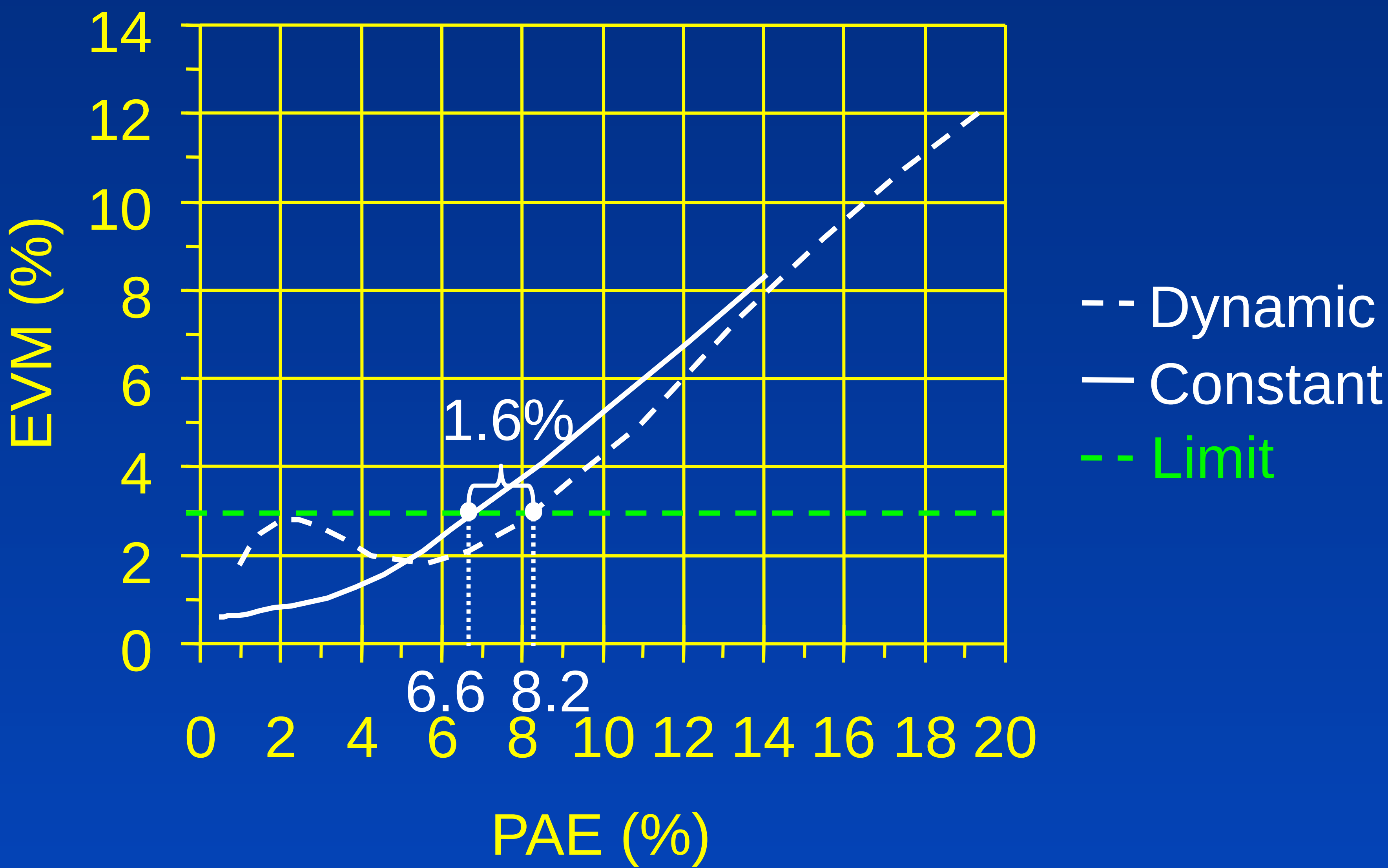
IMD3 vs. Output Power 2.4GHz



Efficiency vs. Output Power 2.4GHz



EVM vs. Efficiency 2.4GHz



Summary & Conclusion

- RF power amplifier basics
- Dynamic supply principle
- Modulator and PA circuits
- Improvement needed for WLAN application
- Efficiency enhancement verified through measurement results at 2.4 and 5.2GHz

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