ECE 451
Advanced Microwave Measurements

Amplifier Characterization

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Transistor Technology

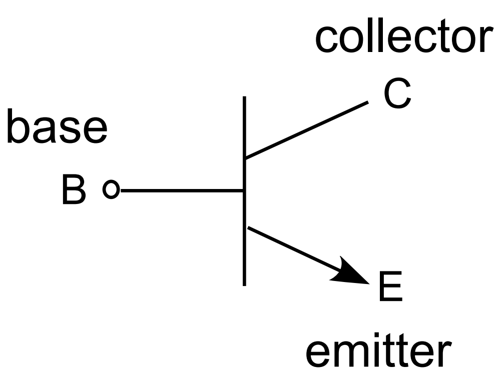
Transistors are semiconductor devices with 3 terminals. They are used to amplify signals and get voltage, current or power gain

- **Tree fundamental types**
  - – Bipolar junction transistors (BJT)
  - – Junction field effect transistors (JFET)
  - – Metal-oxide semiconductor transistors (MOSFET)
- **Technologies**
  - – Silicon
  - – Compound Semiconductors (GaAs, InP, GaN)

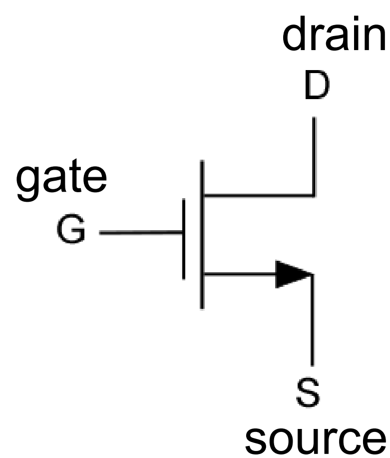
Models for Transistors

- **Polarity**
  - NPN, PNP for BJT
  - NMOS, PMOS for MOSFET
  - CMOS

NPN is favorites for BJT
NMOS is favorite for MOSFET



NPN

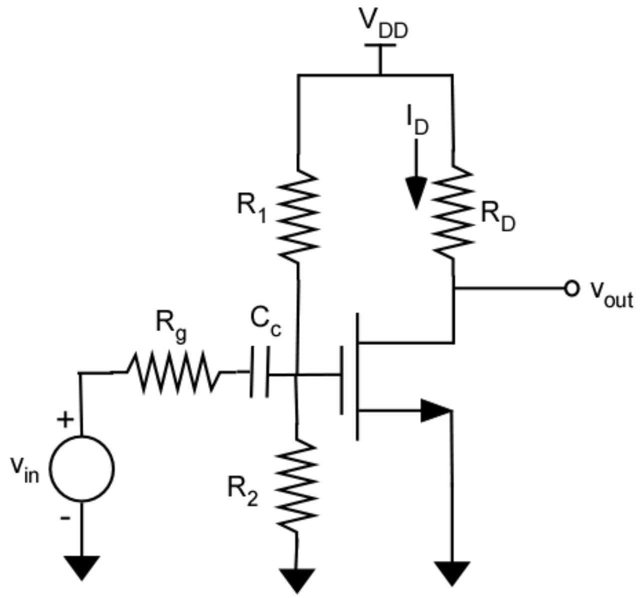


NMOS

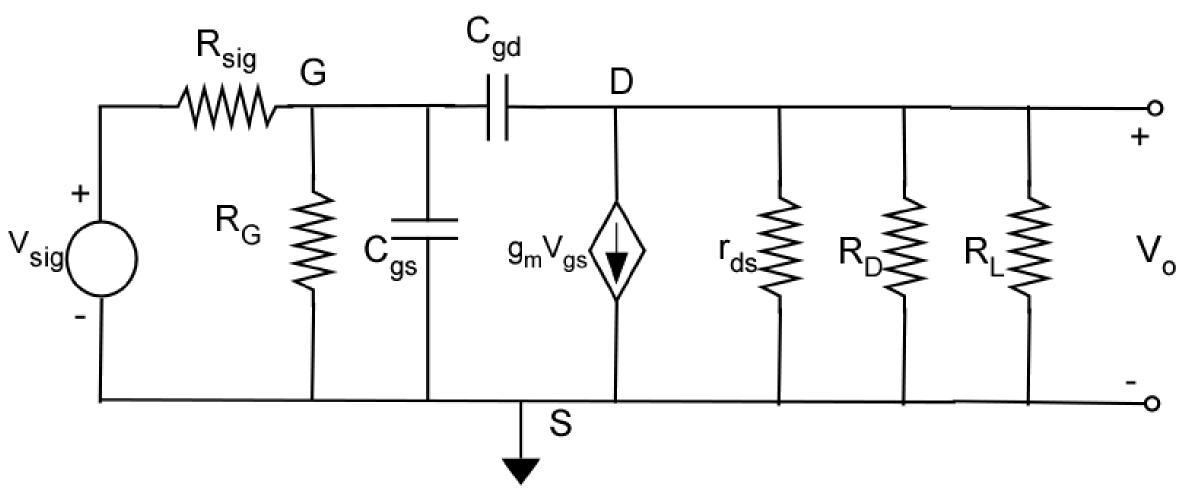
Transistor Models

- **Bipolar**
  - Ebers-Moll
  - Gummel-Poon
- **MOSFET**
  - Shichman-Hodges
  - BSIM

MOSFET Amplifier

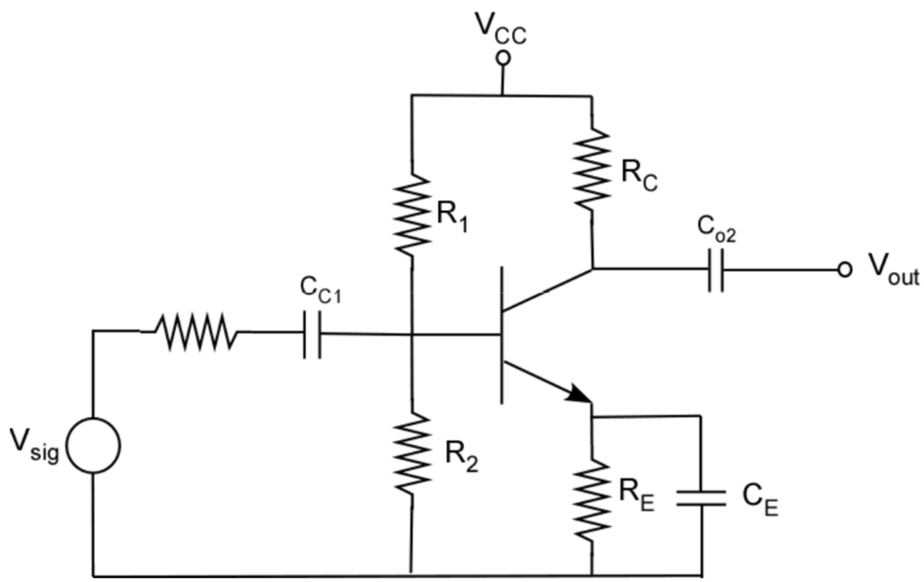


Common Source Topology

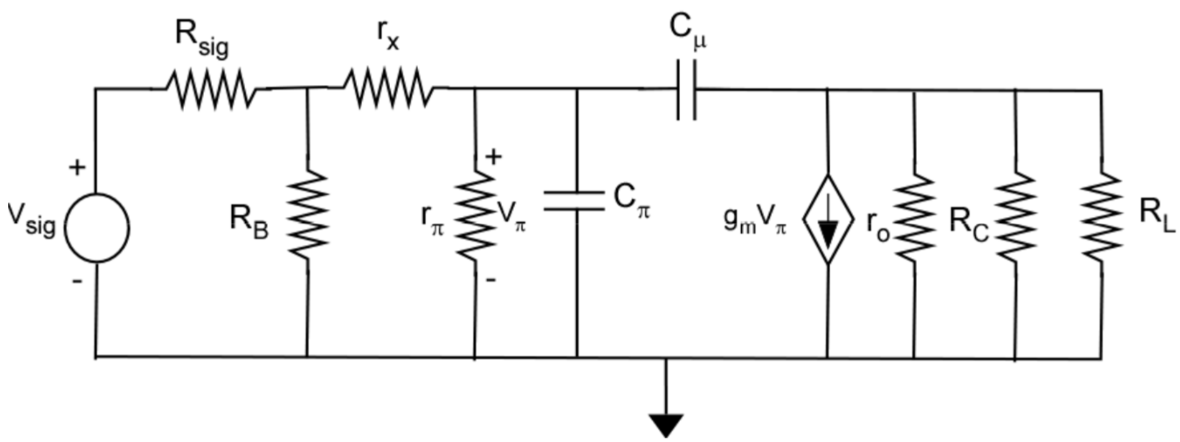


Small-Signal Model

BJT Amplifier

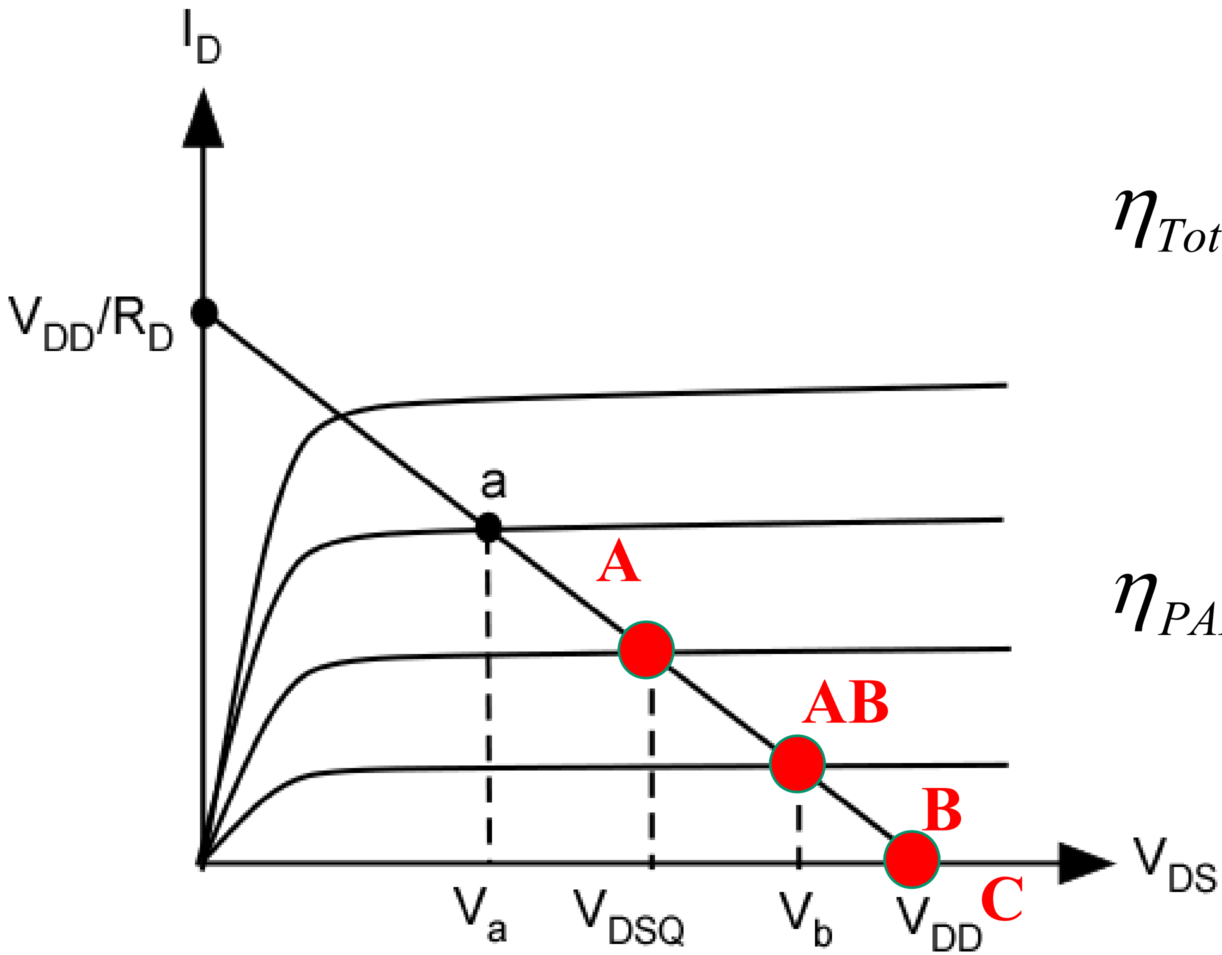


Common Emitter Topology



Small-Signal Model

Amplifier Efficiency



$$\eta_{Total} = \frac{P_{RF,out}}{P_{DC} + P_{RF,in}}$$

$$\eta_{PAE} = \frac{P_{RF,out} - P_{RF,in}}{P_{DC}}$$

Amplifier Efficiency

For high-gain amplifiers, $P_{RF,in} << P_{DC}$ and

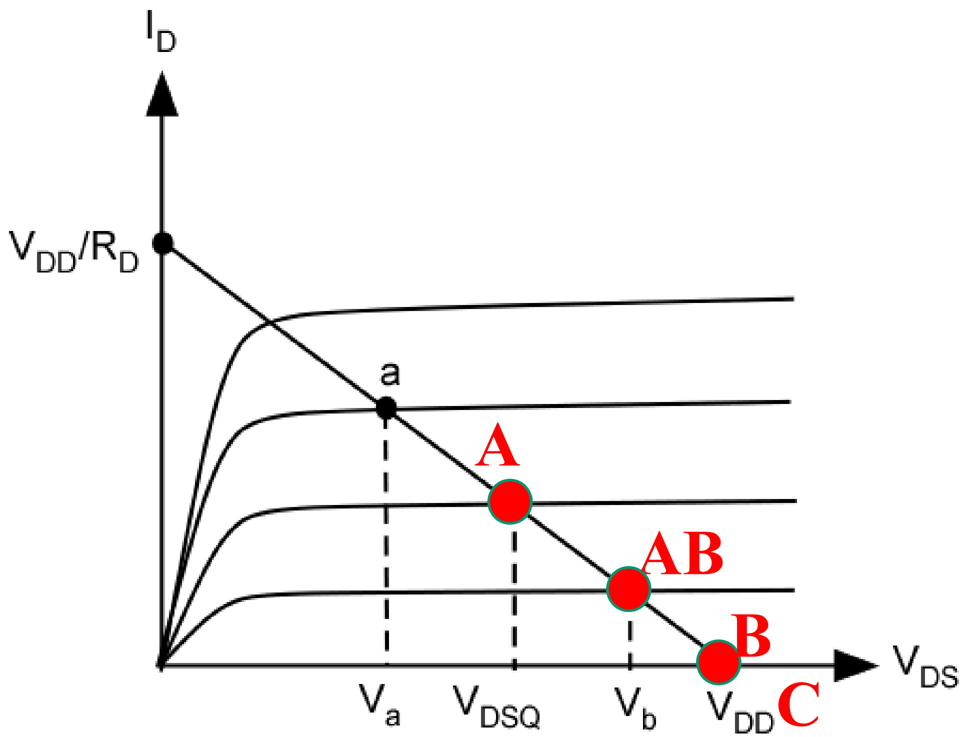
$$\eta_{Total} \simeq \eta_{PAE} \simeq \eta = \frac{P_{RF,out}}{P_{DC}}$$

Efficiencies are typically between 25% and 50%

- **Class A amplifier**
  - Maintain bias so that the transistor is in the middle of the linear range
  - Efficiency is reduced because of DC current
  - Best linearity
  - Choice for small signal (small input) amplification

Amplifier Efficiency

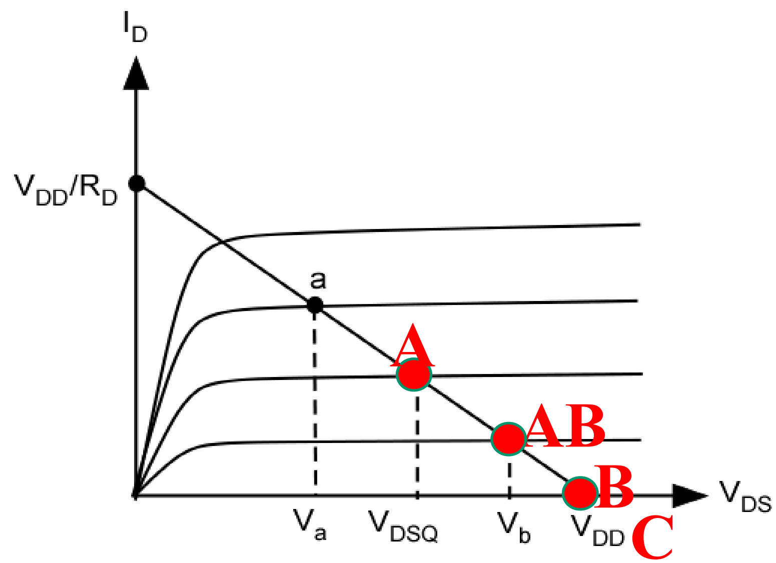
Efficiency is improved by reducing DC power and moving bias point further down the DC load line as in class B, AB and C.



Amplifier Efficiency

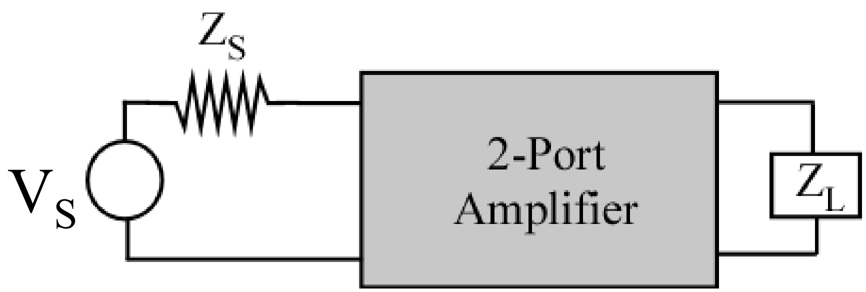
Class B, AB and C present impedance that is a function of the level of the RF signal.

Class B, AB and C are generally not used for broadband applications because of stability concerns

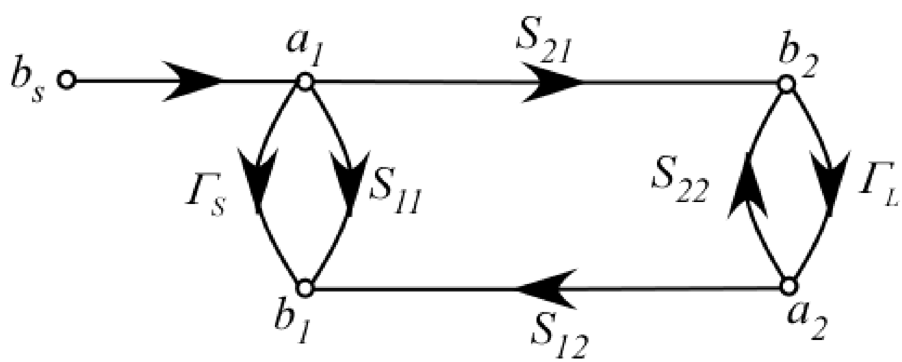


Linear Amplifiers

The transducer power gain is defined as the power delivered to the load divided by the power available from the source.

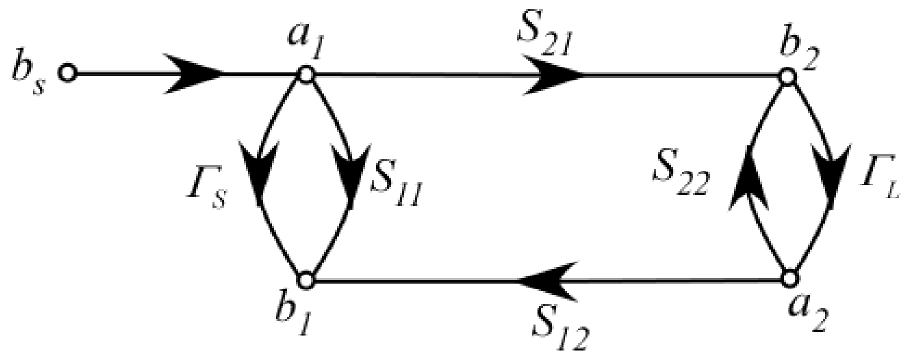


$$P_{avs} = \frac{|b_s|^2}{1-|\Gamma_S|^2}$$



$$b_s = \frac{V_S\sqrt{Z_o}}{Z_S + Z_o}$$

Linear Amplifiers



$$G_T = \frac{P_{del}}{P_{avs}} = \frac{|b_2|^2\left(1-|\Gamma_L|^2\right)}{|b_s|^2 \Big/ \left(1-|\Gamma_S|^2\right)}$$

Non-touching loop rule for power available

$$G_T = \frac{|S_{21}|^2\left(1-|\Gamma_S|^2\right)\left(1-|\Gamma_L|^2\right)}{\left|(1-S_{11}\Gamma_S)(1-S_{22}\Gamma_L)-S_{21}S_{12}\Gamma_S\Gamma_L\right|^2}$$

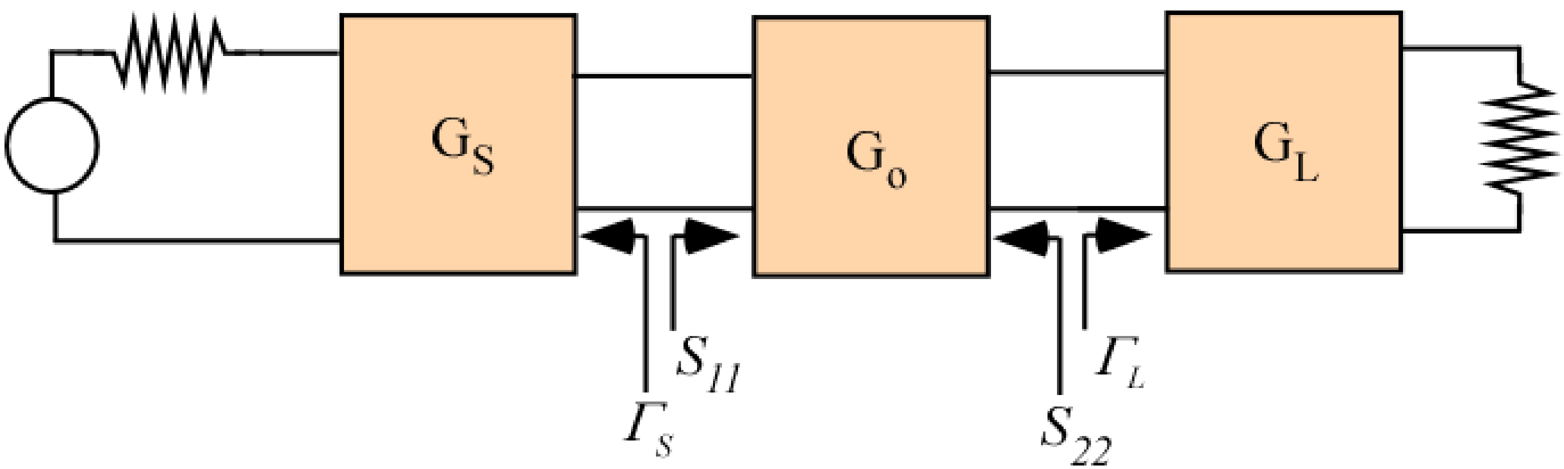
Linear Amplifiers

If we assume that the network is unilateral, then we can neglect S_{12} and get the unilateral transducer gain for $S_{12}=0$.

$$G_{TU} = \left|S_{21}\right|^2 \frac{\left(1-\left|\Gamma_S\right|^2\right)}{\left|1-S_{11}\Gamma_S\right|^2} \frac{\left(1-\left|\Gamma_L\right|^2\right)}{\left|1-S_{22}\Gamma_L\right|^2}$$

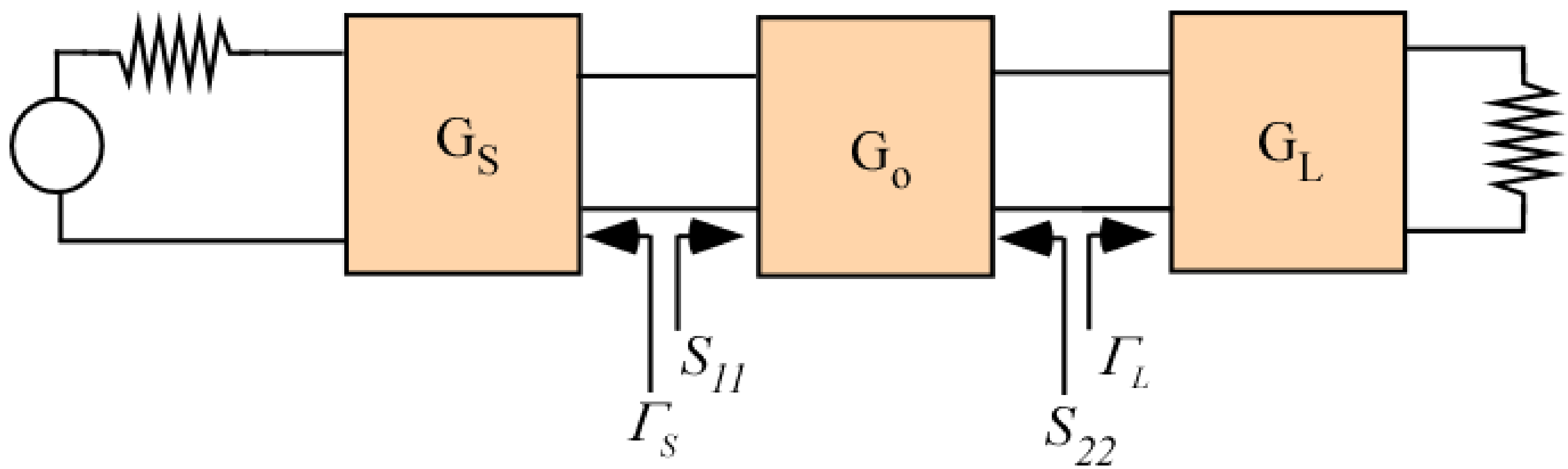
The first term ($|S_{21}|^2$) depends on the transistor. The other 2 terms depend on the source and the load.

Linear Amplifiers



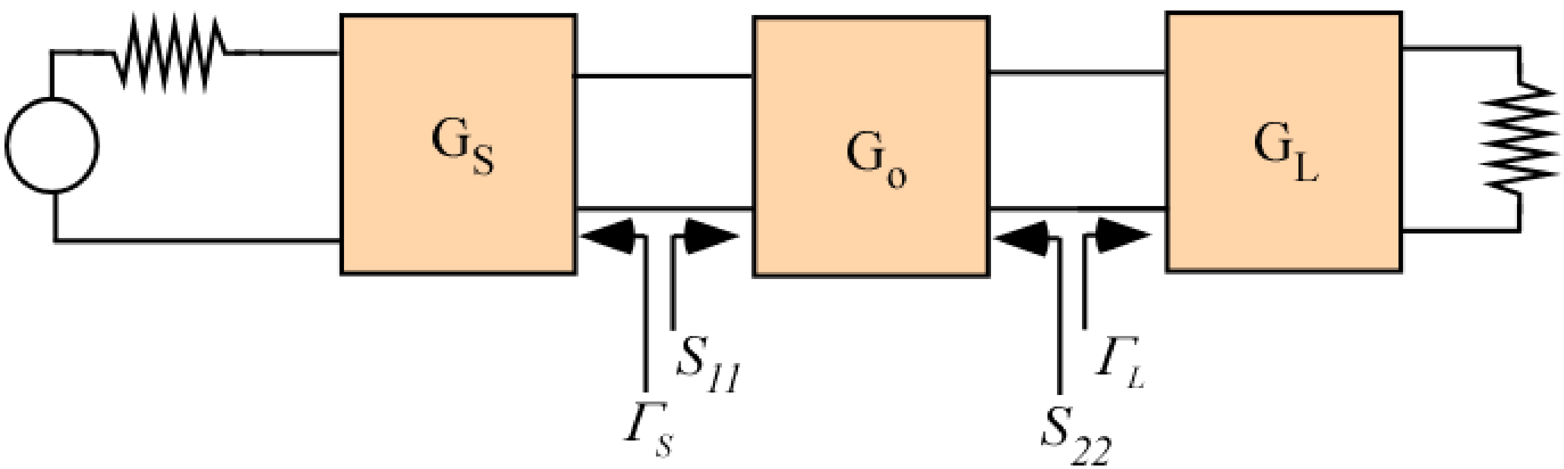
G_s affects the degree of mismatch between the source and the input reflection coefficient of the two-port.

Linear Amplifiers



G_L affects the degree of mismatch between the load and the output reflection coefficient of the 2-port.

Linear Amplifiers



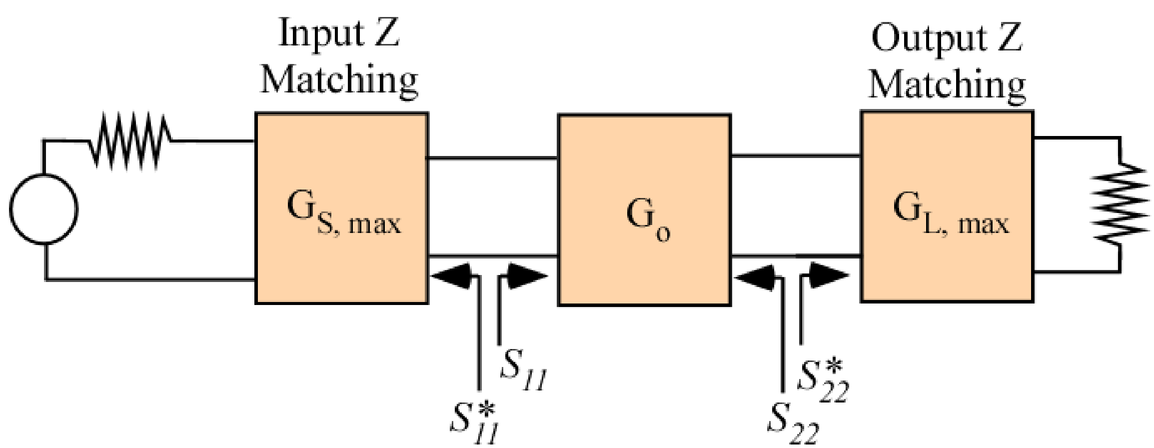
G_o depends on the device and bias conditions

Linear Amplifiers

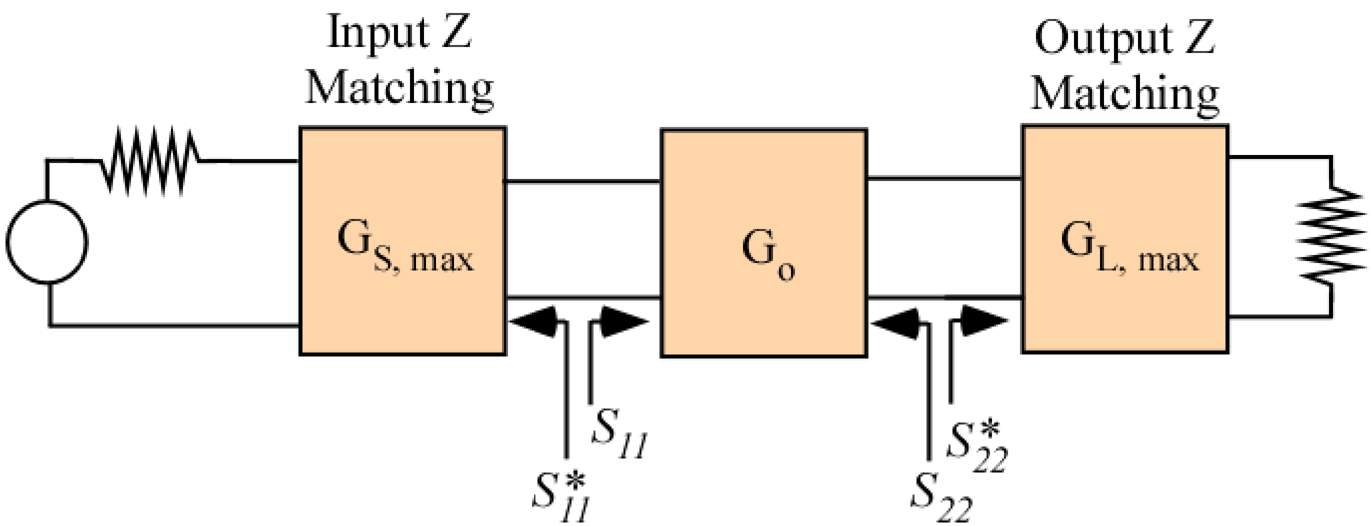
Maximum unilateral transducer gain can be accomplished by choosing impedance matching networks such that.

$$\Gamma_S = S_{11}^* \qquad \Gamma_L = S_{22}^*$$

$$G_{UMAX} = \frac{1}{1-|S_{11}|^2} \cdot |S_{21}|^2 \cdot \frac{1}{1-|S_{22}|^2}$$



Linear Amplifiers



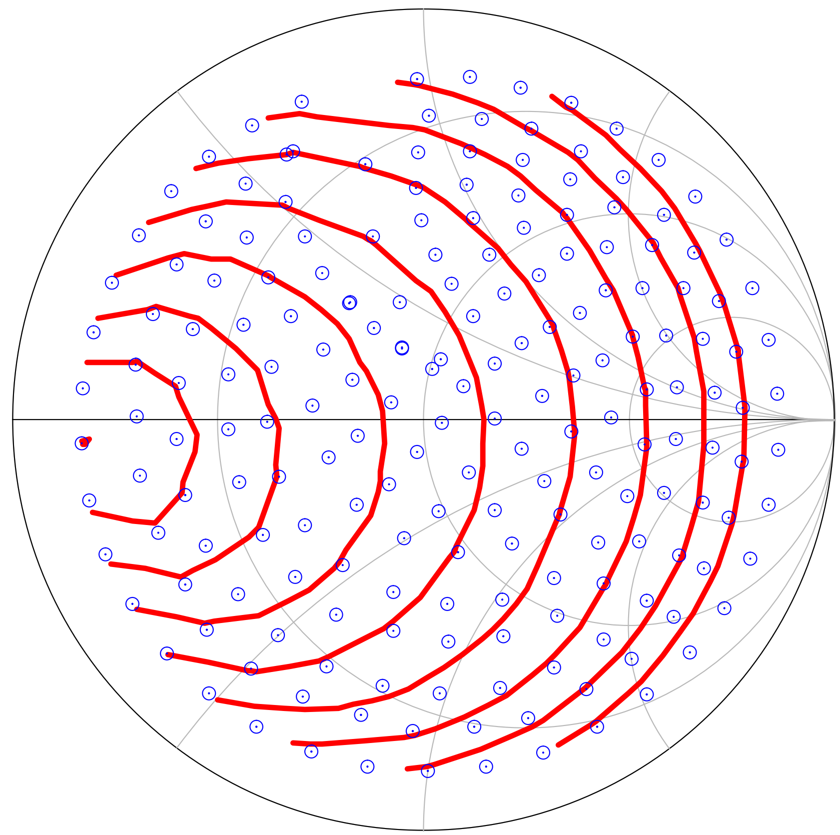
$$G_{UMAX}(dB) = G_{S\max}(dB) + G_o(dB) + G_{L\max}(dB)$$

For $\Gamma_S = S_{11}^*$, **G_S is a maximum**

For $\left|\Gamma_S\right| = 1$, **$G_S$ is 0**

Linear Amplifiers

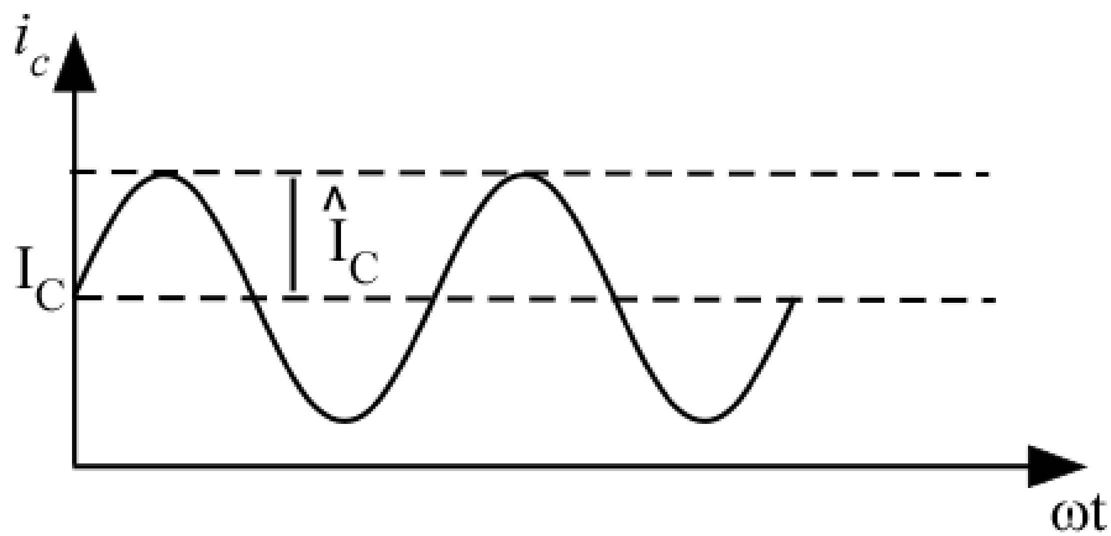
For arbitrary values of G_S between these extremes, the solutions for $|\Gamma_S|$ lies on a circle
➔ Gain circles



Classification of Amplifiers

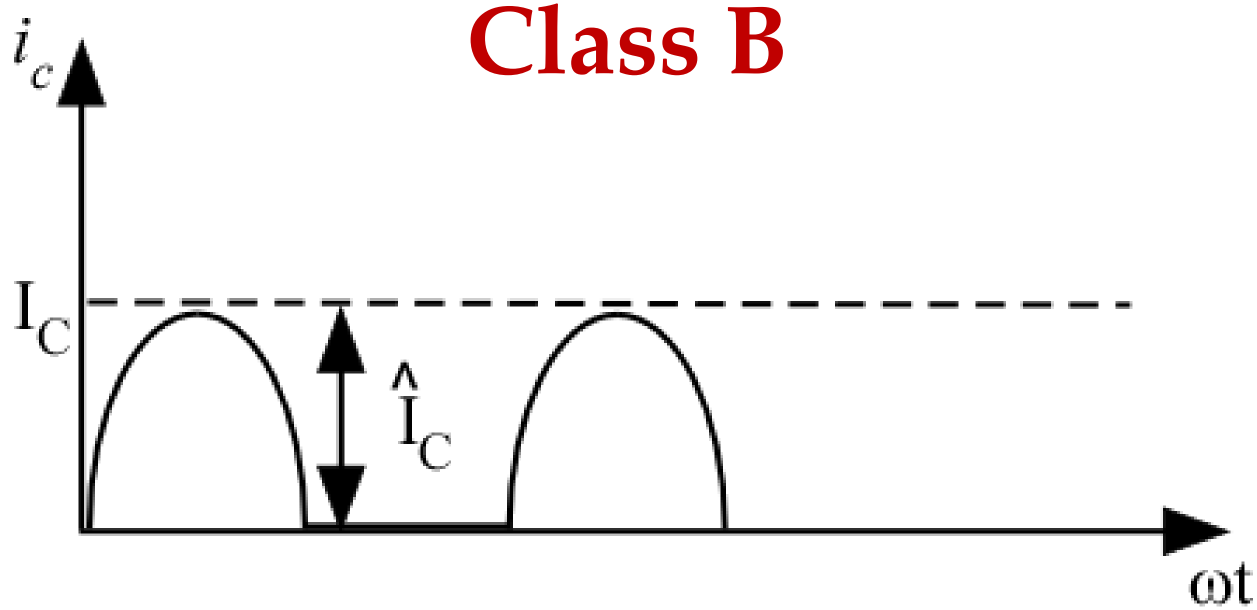
Class A - Amplifier is biased at current I_C greater than the amplitude of the signal. Transistor conducts for the entire cycle of the signal → conduction angle = 360º.

Class A



Classification of Amplifiers

Class B



In class B stage, the transistor is biased for zero dc current

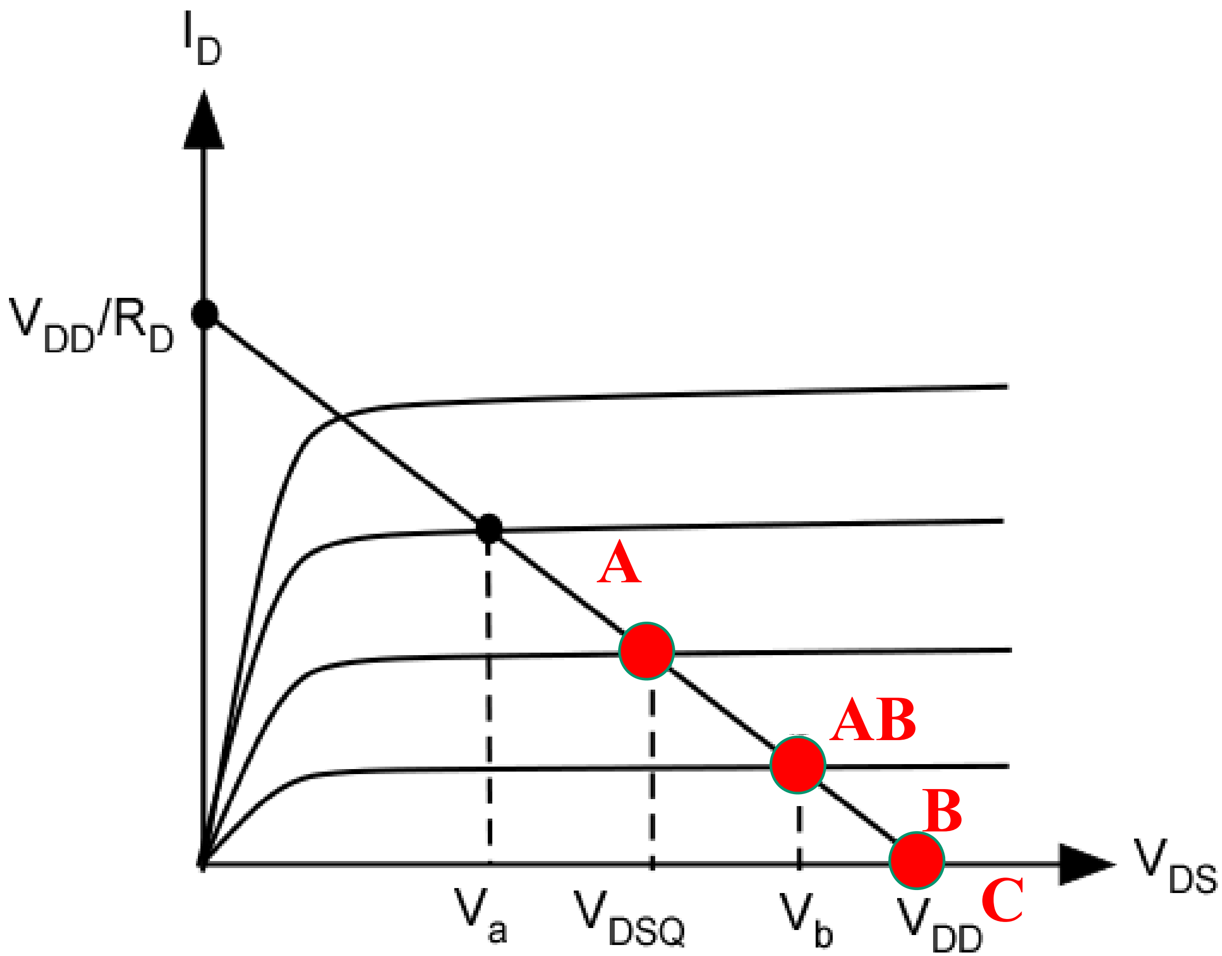
Classification of Amplifiers

The amplifier conducts for only half of the cycle of the input sine wave. Conduction angle = 180° Negative halves supplied by another transistor operating in class B

An intermediate class between A and B is called class AB

AB involves biasing the transistor at a nonzero DC current much smaller than the peak current

Classification of Amplifiers

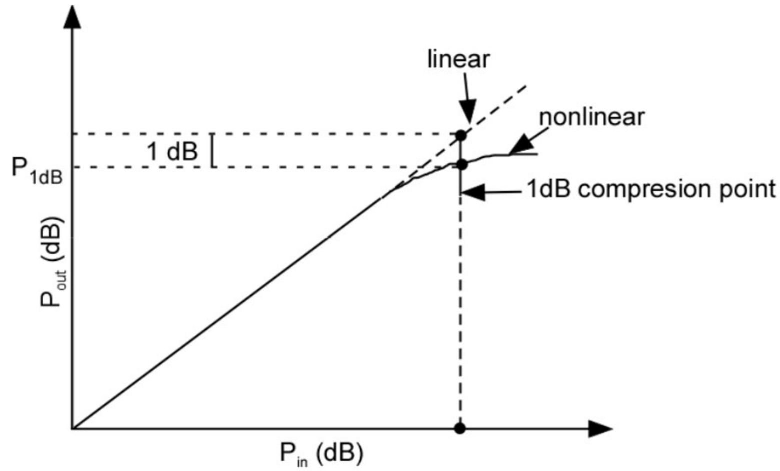


Distortion and Nonlinearities

Distortion occurs when the output signal from an amplifier approaches the extremes of the load line and the output is no longer an exact replica of the input.

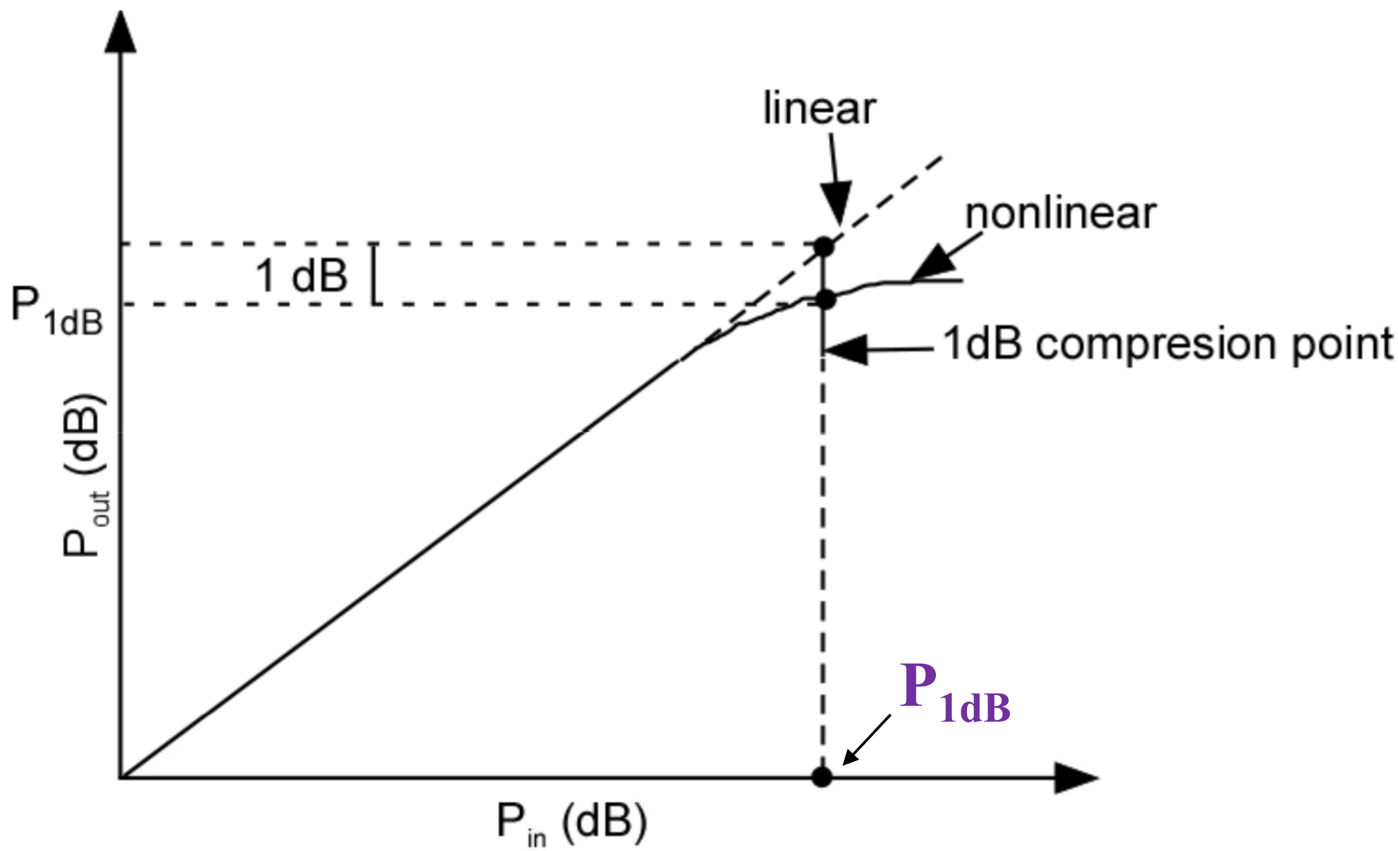
The ideal amplifier follows a linear relationship. Distortion leads to a deviation from this linear relationship

Distortion and Nonlinearities



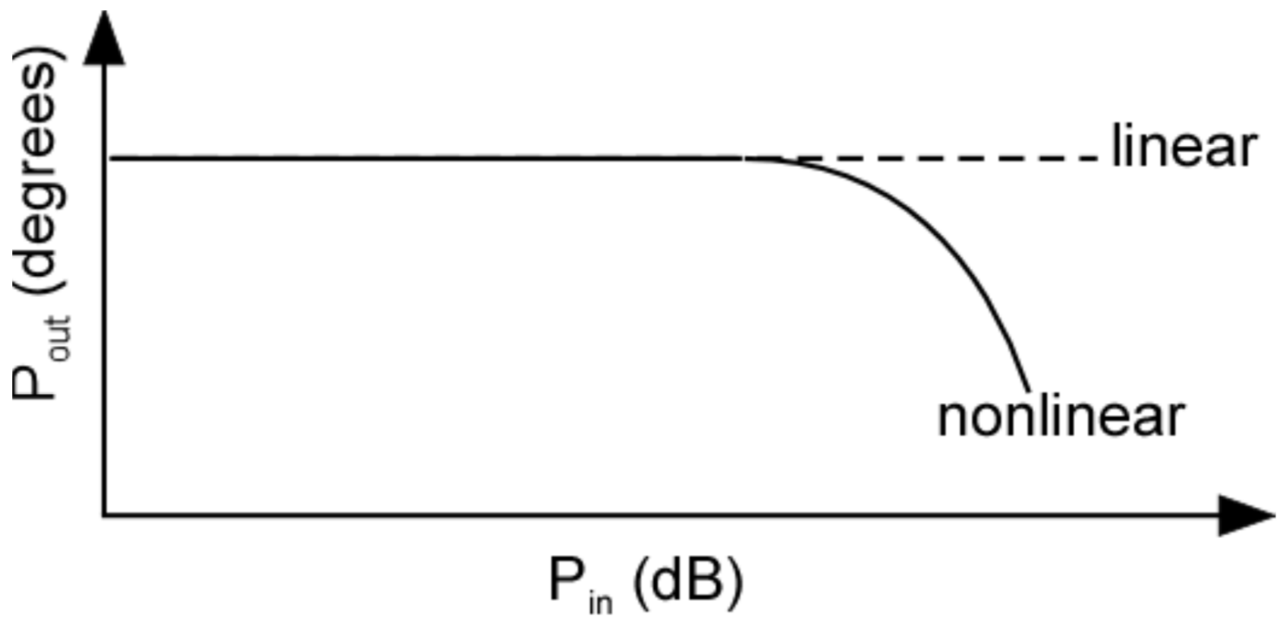
The *1dB compression point* is the point where the difference between the extrapolated linear response exceeds the actual gain by 1dB. P_{1dB} is the power output at the 1dB compression point and is the most important metric of distortion.

Distortion and Nonlinearities



AM-AM Distortion

Distortion and Nonlinearities



AM-PM Distortion

Distortion and Nonlinearities

AM-AM distortion is generally more significant

Distortion is a result of nonlinearities in the response of an amplifier. One possible model for the response is:

$$v_o = k_1 v_i + k_2 v_i^2 + k_3 v_i^3 + \dots$$

When the input signal is large enough the higher order terms become significant.

Single-Tone Excitation

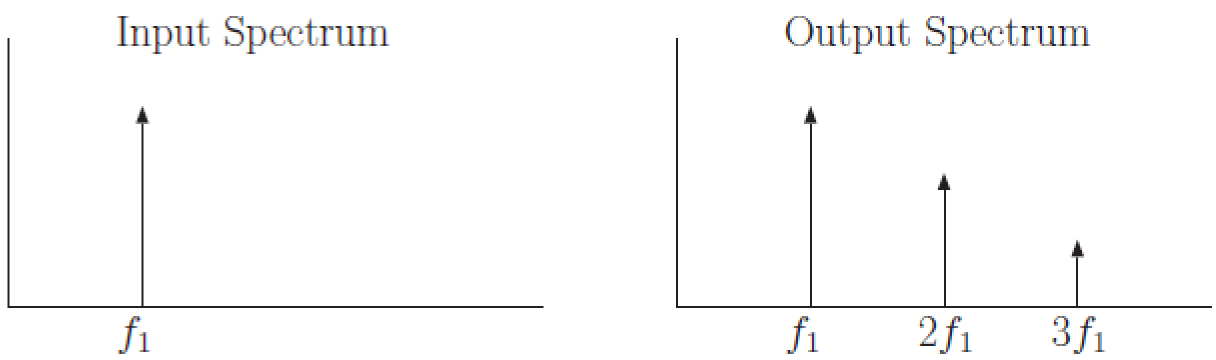
$$v_o = k_1 v_i + k_2 v_i^2 + k_3 v_i^3$$

$$v_i(t) = a_1 \cos \omega_1 t$$

$$v_o(t) = \frac{1}{2} k_2 a_1^2 + \left(k_1 a_1 + \frac{3}{4} k_3 a_1^2 \right) \cos \omega_1 t +$$

$$\frac{1}{2} k_2 a_1^2 \cos 2\omega_1 t + \frac{1}{4} k_3 a_1^3 \cos 3\omega_1 t$$

Single-Tone Excitation



Single-tone excitation produces harmonics of input frequency

Distortion and Nonlinearities

If the input is a sine wave, the output will contain harmonics of the input. That is the output will have frequency components that are integer multiples of the fundamental (CW) sine wave input signal

When the input signal is a two-tone signal (modulated signal), additional tones will appear at the output and we say that the distortion produces intermodulation products (IMP)

Two-Tone Excitation

$$v_o = k_1 v_i + k_2 v_i^2 + k_3 v_i^3$$

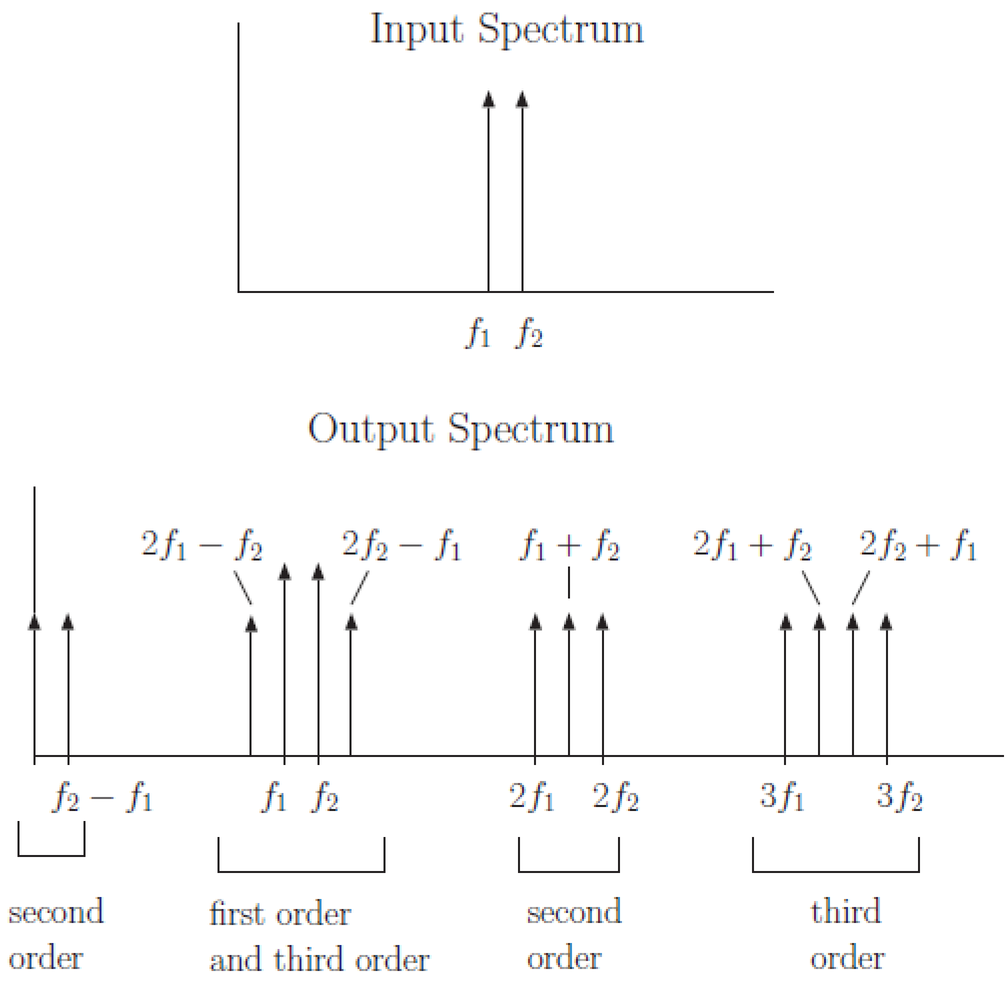
$$v_i(t) = a_1 \cos\omega_1 t + a_2 \cos\omega_2 t$$

$$v_o(t) = k_1\left[a_1 \cos\omega_1 t + a_2 \cos\omega_2 t\right] +$$

$$k_2\left[\begin{array}{l}\frac{1}{2}\left(a_1^2 + a_2^2\right) + \frac{1}{2}a_1^2 \cos 2\omega_1 t + \frac{1}{2}a_2^2 \cos 2\omega_2 t \\ + a_1 a_2 \cos\left(\omega_1 + \omega_2\right)t + a_1 a_2 \cos\left(\omega_1 - \omega_2\right)t\end{array}\right] +$$

$$\frac{1}{4}k_3\left[\begin{array}{l}\frac{1}{4}a_1^3 \cos 3\omega_1 t + \frac{1}{4}a_2^3 \cos 3\omega_2 t \\ + \frac{3}{4}a_1 a_2^2\left(\cos\left(2\omega_2 - \omega_1\right)t + \cos\left(2\omega_2 + \omega_1\right)\right) \\ + \frac{3}{4}a_1^2 a_2\left(\cos\left(2\omega_1 - \omega_2\right)t + \cos\left(2\omega_1 + \omega_2\right)\right)\end{array}\right]$$

Two-Tone Excitation



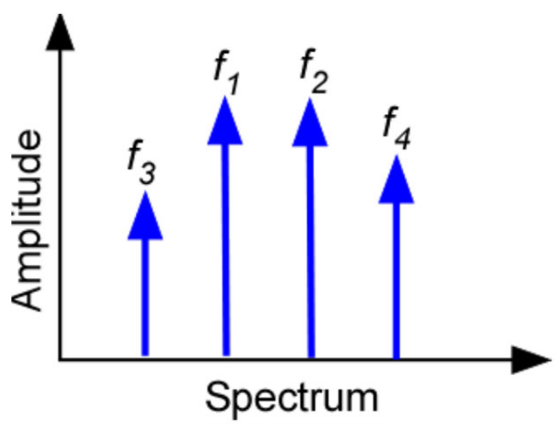
Two-tone excitation produces intermodulation

Distortion and Nonlinearities

If f_1 and f_2 are the frequencies associated with the two signals, the output will have components at f_3 and f_4 where

$$f_3 = 2f_1 - f_2 \quad \textbf{and} \quad f_4 = 2f_2 - f_1$$

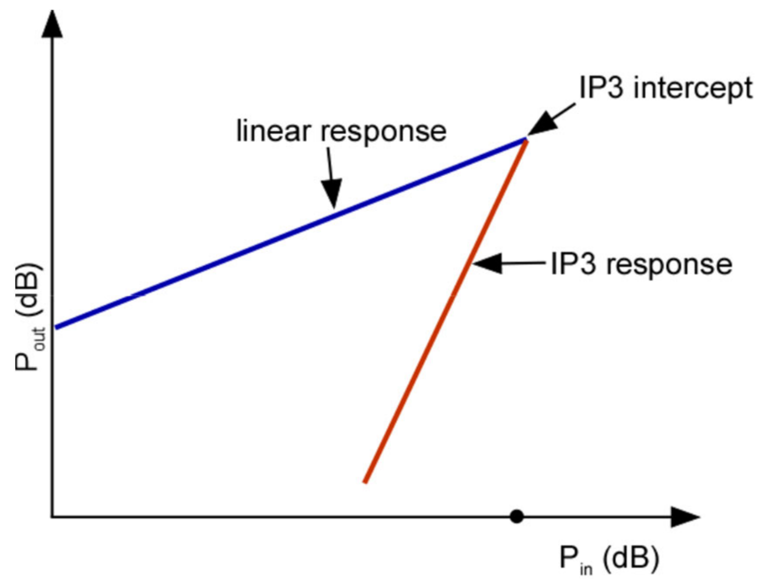
are known as the lower and upper IM3 respectively.



Distortion and Intermodulation

At low power, before compression the fundamental has a response with 1:1 slope with respect to the input

The IP3 response varies as the *cube* of the level of input tones. The IP3 has a 3:1 logarithmic slope with respect to the input.

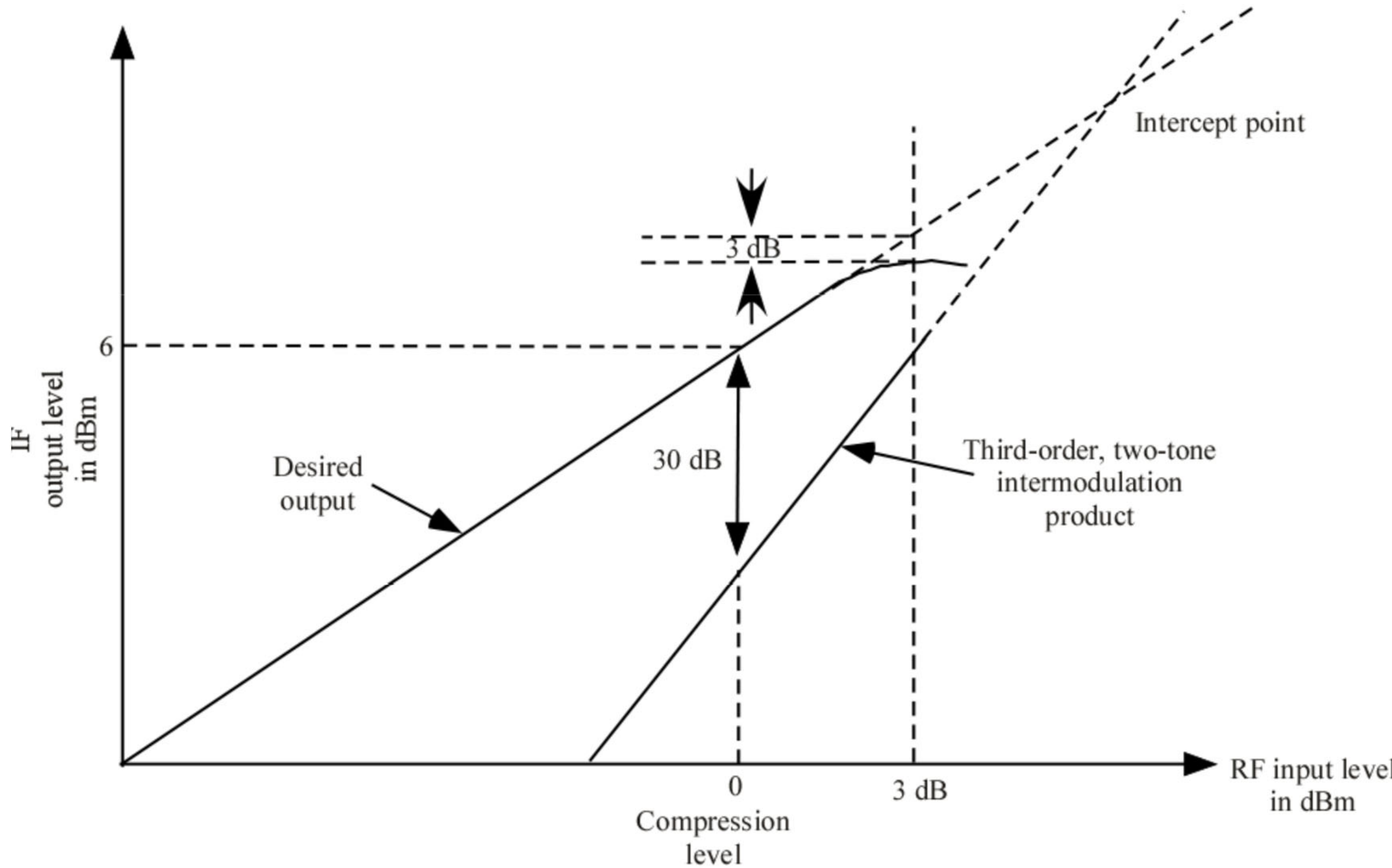


Distortion and Intermodulation

The point of intersection of the extrapolated linear output (of power P_o) and third order (IP3) of power P_{IP3} is called the third-order intercept point which is a key parameter

- Harmonics can be filtered out by filters
- Intermodulation distortion cannot be filtered out because they are in the main passband

Distortion and Intermodulation



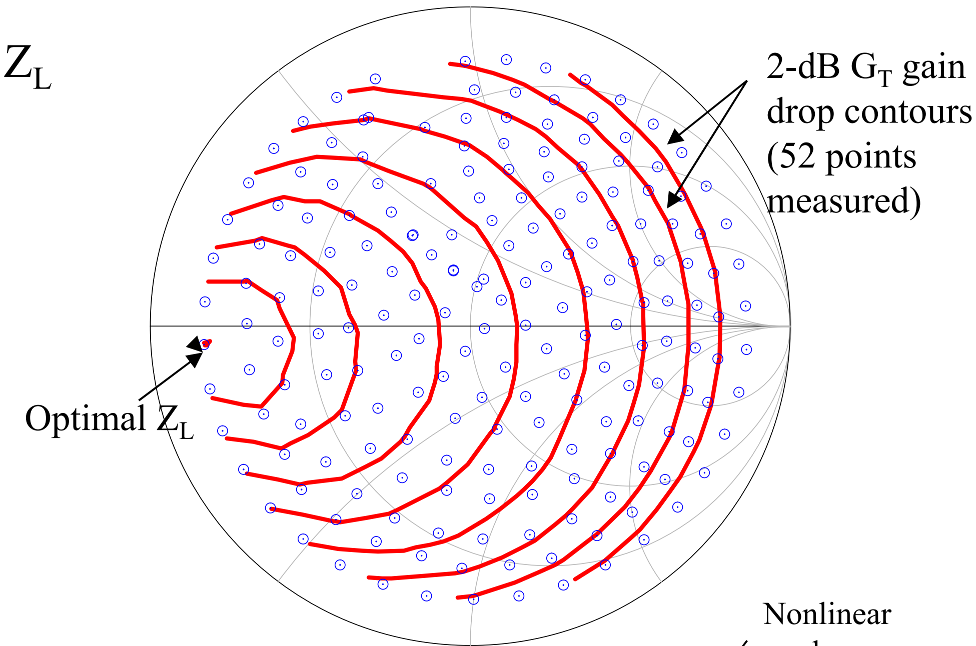
Power Transistor Characterization

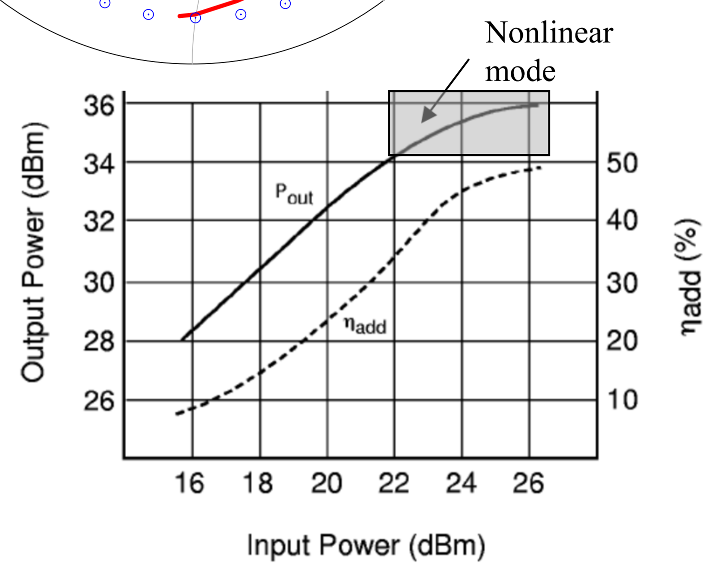
Because of nonlinearities, scattering parameters cannot be used to characterize power devices. Other techniques must be used.

- **Methods**
  - Load Pull
  - X-Parameters

Load-Pull Measurements

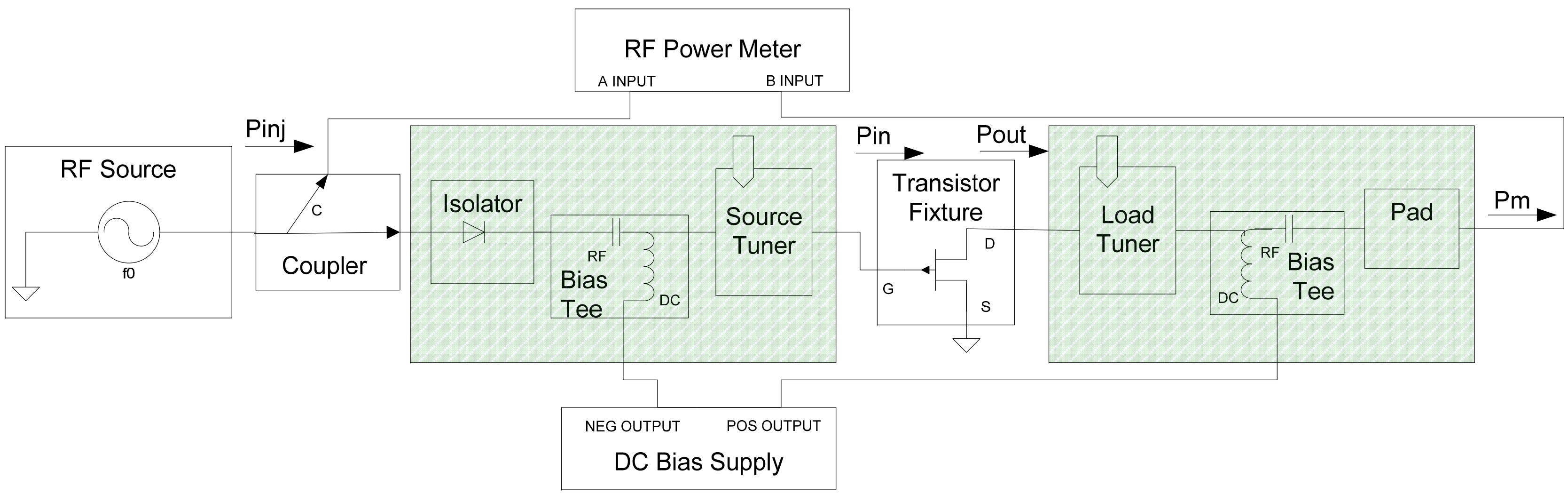
- Varying ("pulling") load impedance Z_L seen by an active device under test
- Measuring performance metrics of DUT at each Z_L point:
  - Transducer Gain (as shown)
  - Power-added Efficiency
  - 1-dB Gain Compression Point
  - Noise Figure
  - …
- Not needed for linear devices
  - Performance with any Z_L determined by measuring small-signal S-parameters
- Important for characterizing devices operating in large-signal (nonlinear) mode
  - Operating point (and thereby performance) may change for different loads





Manual Load-Pull Setup

- First set up source tuner for maximum gain, then fix its position
- For each (X,Y) position of the load tuner:
  1. Measure injected power P_{inj}, delivered power P_m
  2. Measure S-parameters of source and load circuitry (shaded boxes)
  3. Move the reference plane to the DUT input and output:
  - Calculate input and output power loss (due to mismatch) from measured S-parameters
  - Obtain P_{in}, P_{out} by correcting P_{inj}, P_m for power losses
  4. Solve for transducer gain $G_T=P_{out}/P_{in}$



- Done at a constant input frequency f_0 - harmonic measurements also possible
- Large number of points needed for each frequency
  - Measurements are usually automated