

EECS 142



Integrated Circuits for Communication

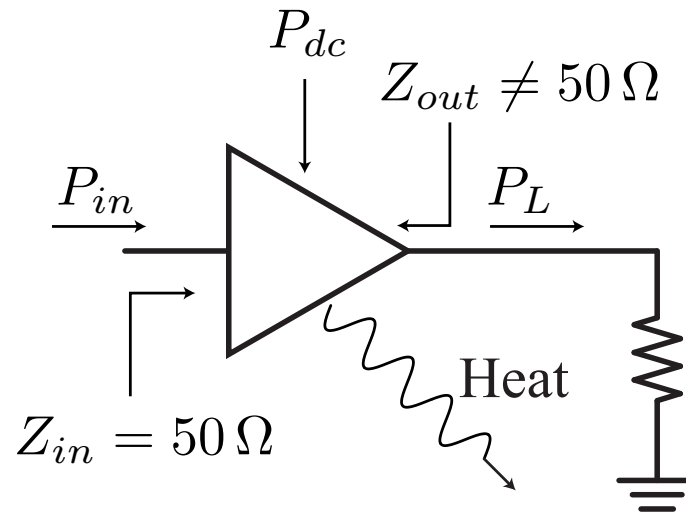
Lecture 26: Power Amplifiers

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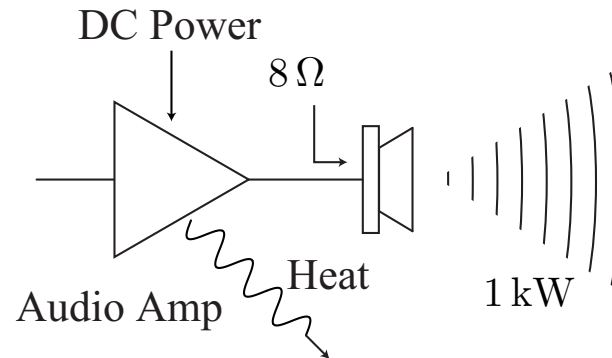
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Introduction to PAs



- Power Amplifiers (PA) deliver power to a given load with maximum efficiency while faithfully transferring the modulation from the input to the output.
- Like small-signal amplifiers, PAs are typically matched at the input. However, the output of the PA is usually unmatched in order to maximize efficiency (which results in lower power gain).

Audio PA Example



- Consider a PA that delivers 1kW of power into 8Ω speakers.
- Assuming a sinusoidal input, the peak voltage and current are

$$V = \sqrt{2RP} = \sqrt{2 \cdot 8 \cdot 1000} = 126V$$

$$I = \frac{2P}{V} = 15.8A$$

- Such large currents and voltages require special techniques and/or technology.

Efficiency

- The *Power Added Efficiency*, or PAE , is a measure of how much power is added to a signal normalized by the DC power consumption

$$PAE = \eta = \frac{P_L - P_{in}}{P_{dc}}$$

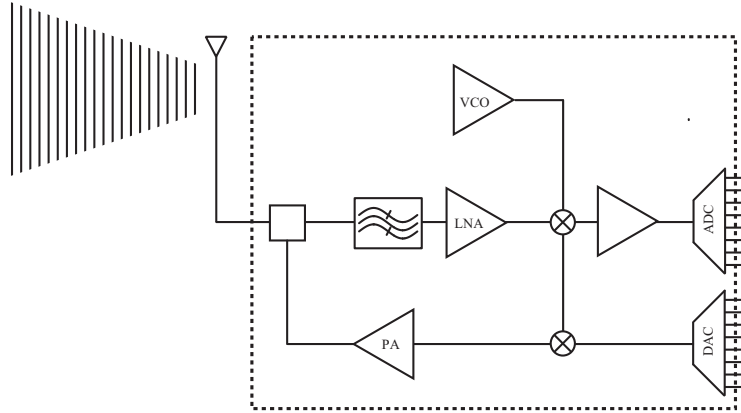
- If the power gain is large

$$PAE = \frac{P_L(1 - G_p^{-1})}{P_{dc}} \approx \frac{P_L}{P_{dc}}$$

- The drain or collector efficiency is defined as

$$\eta_{c|d} = \frac{P_L}{P_{dc}}$$

Mobile Phone Example



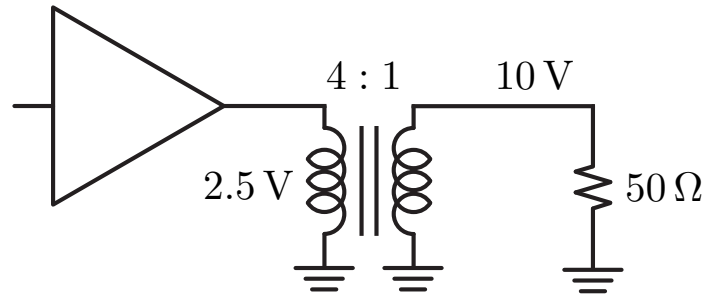
- Consider a typical mobile phone that delivers 1W in to a 50Ω antenna. Here we find that

$$V_0 = \sqrt{2PR} = \sqrt{2 \cdot 50} = 10V$$

$$I_0 = 2/10 = 0.2A$$

- Most high-frequency Si transistors cannot handle 10V due to breakdown. Thus we need to transform the voltage down to a safe value.

High Voltage/Current



- Note that in the process of transforming the voltage down, the current transforms up, $I = 0.8\text{A}$. This requires careful layout to minimize “series” parasitic loss. For a 1Ω parasitic loss, we throw away nearly $1/3$ of the power to the load

$$P_{L,s} = \frac{1}{2} I^2 R = 320\text{mW}$$

Effect of Loss

- If the core amplifier efficiency is say 50%, then this external loss cuts the efficiency to

$$P_{loss} = 320\text{mW} + \frac{P_L}{\eta} = 2.32\text{W}$$

$$\eta = \frac{1}{2.32} = 43\%$$

- If the transformer has 2 dB of insertion loss, then the efficiency drops to

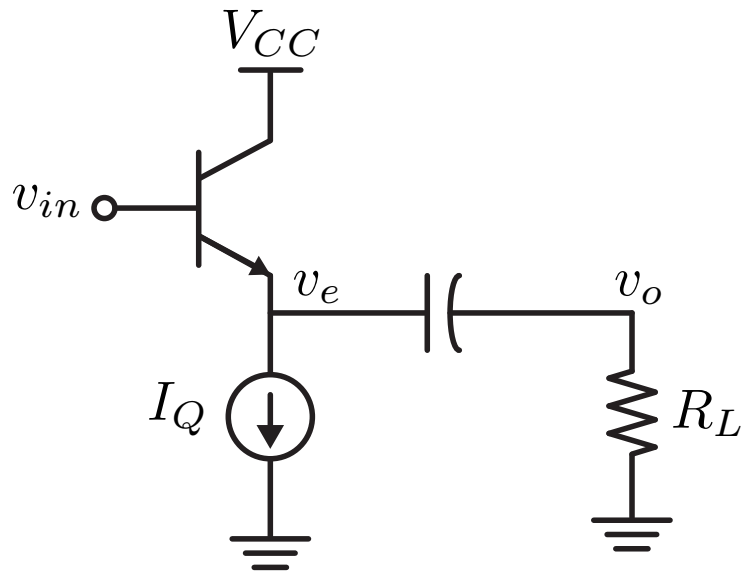
$$\eta = \frac{0.63 \times P_L}{P_{dc} + .27 \times P_L} = 24\%$$

Power Amplifier Considerations

- PAs drive large voltages/currents into small load impedances. Thus matching networks are critical. Any loss in the matching network has a severe impact on the efficiency of the amplifier.
- Heat generation is high. We need to carefully provide heat sinks to keep the junction temperatures as low as possible.
- Due to the interface with the external “off-chip” world, packaging and board parasitics are very important.
- The spectral “leakage” and harmonic generation in a PA must be kept to the a minimum in order to minimize interference to other users.

Emitter Follower “PA”

- The emitter follower is a popular output stage. It does not have any voltage gain but it has a power gain. What's the efficiency of such an amplifier?



$$P_L = \frac{v_o^2}{2R_L}$$

$$P_{dc} = V_{CC}I_Q$$

$$\eta_c = \frac{P_L}{P_{dc}} = \frac{1}{2} \frac{v_o}{R_L} \frac{v_o}{V_{CC}I_Q}$$

$$\eta_c = \frac{1}{2} \left(\frac{i_o}{I_Q} \right) \left(\frac{v_o}{V_{CC}} \right) = \frac{1}{2} \bar{i} \bar{v}$$

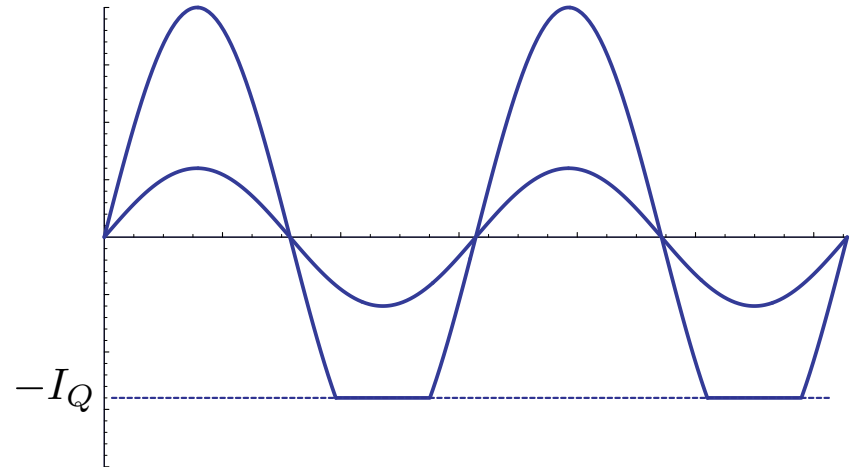
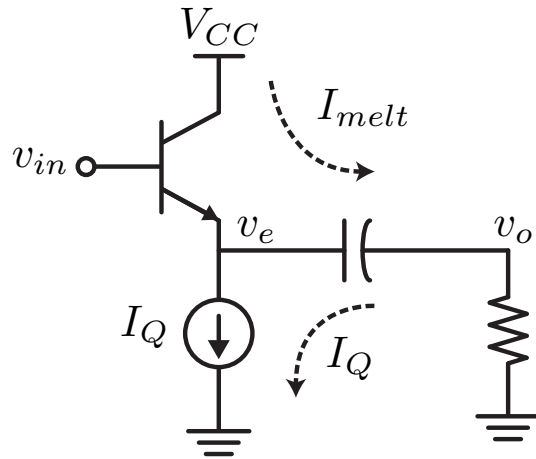
Normalized Current/Voltage Swing

- Apparently in order to maximize the efficiency of the follower stage, we must maximize the normalized current swing \bar{i} and the voltage swing \bar{v} .
- Of course the current and voltage swing are related by the load impedance, so if it is fixed, we cannot independently change both.

$$R_L = \frac{v_o}{i_o}$$

- An impedance matching network, therefore, adds one more degree of freedom to the optimization problem, allowing us to maximize \bar{i} and \bar{v} independently.

Current Swing

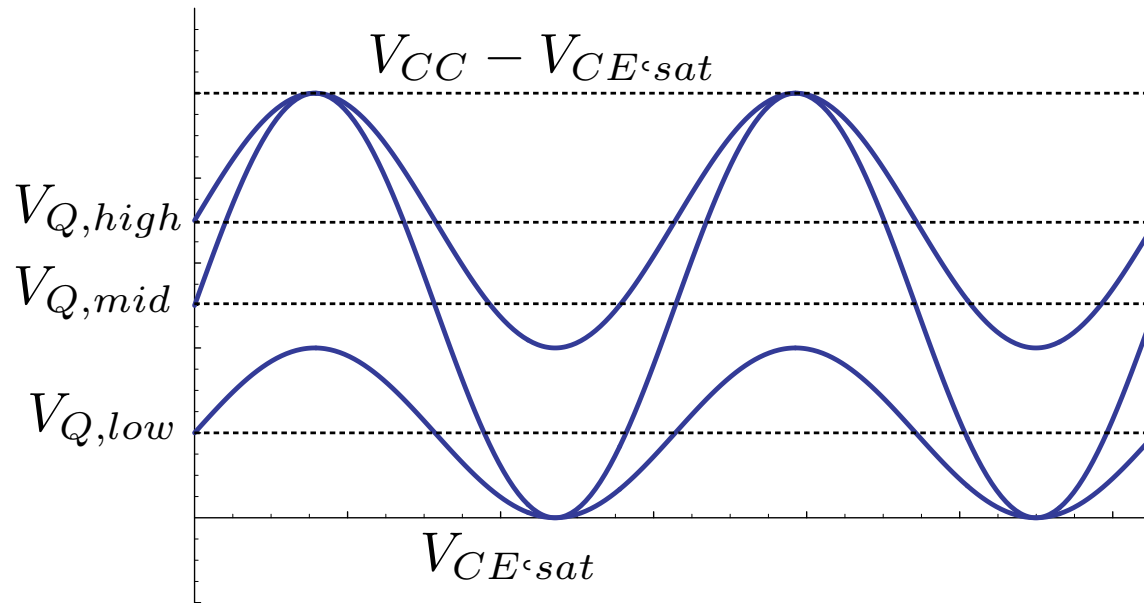


- Consider the output current i_o . The BJT can supply an unlimited current to the load during positive excursions of the input drive but the negative excursion is limited by the current source I_Q .
- In order to avoid clipping the waveform, therefore, $i_o \leq I_Q$ and therefore $\bar{i} \leq 1$.

Voltage Swing

- The maximum positive output voltage certainly cannot exceed the power supply voltage V_{CC} . Also, if the follower transistor remains active during the entire cycle, then the maximum voltage is set by the input bias level minus V_{BE} .
- If the input voltage exceeds the supply, the transistor base-collector junction forward biases. Under “saturation”, the maximum voltage is therefore given by $v_{Omax} = V_{CC} - V_{CE,sat}$. In reality, we would never push our transistor this hard because it would generate a lot of distortion.
- Likewise, the minimum voltage occurs when we saturate our current source, at a value of $v_{Omin} = V_{CE,sat}$

Voltage Swing (cont)



- To maximize the swing, we would bias the output at the midpoint

$$V_Q = \frac{V_{CC} - 2V_{CE,sat}}{2}$$

Follower Efficiency

- For a follower we see that $\bar{i} \leq 1$ and \bar{v} depends heavily on the supply voltage. Let's take $V_{CC} = 3V$. Then

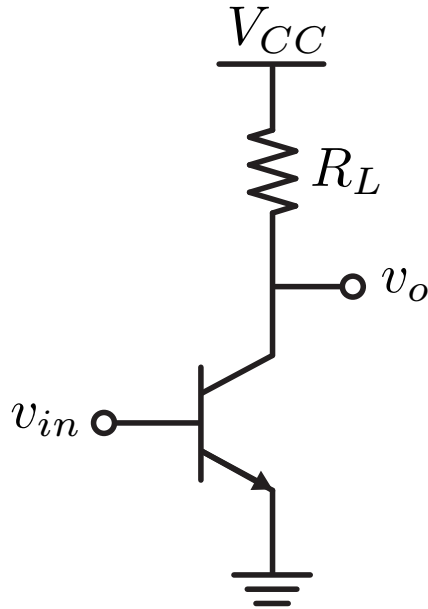
$$\bar{v} = \frac{V_{CC} - 2V_{CE,sat}}{2V_{CC}} = \frac{1}{2} - \frac{V_{CE,sat}}{V_{CC}}$$

- Typically $V_{CE,sat} \approx 300\text{mV}$, and say $V_{CC} = 3V$. Then

$$\bar{v} = \frac{1}{2} - \frac{1}{10} = 0.4$$

$$\eta \leq 20\%$$

CE/CS Power Amplifier

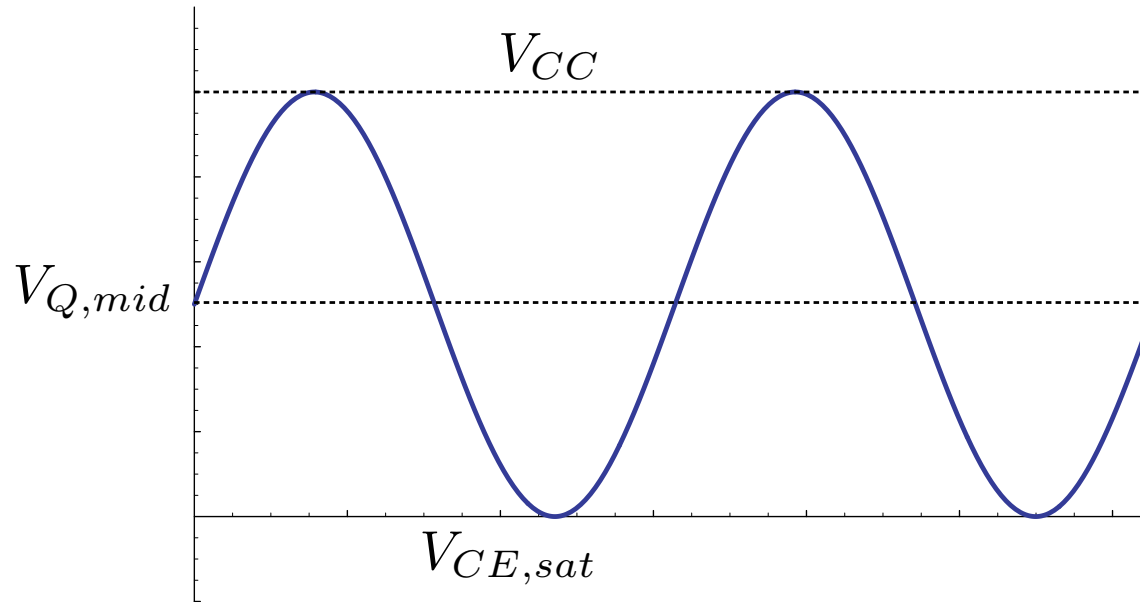


- The CE amplifier has the advantage of higher power gain (there is voltage gain and current gain). The collector efficiency is given by

$$\eta_c = \frac{P_L}{P_{dc}} = \frac{\frac{1}{2}v_o i_o}{V_{CC} I_Q} = \frac{1}{2} \bar{v} \times \bar{i}$$

- As before, the efficiency is maximized if we can set the voltage swing and current swing independently.

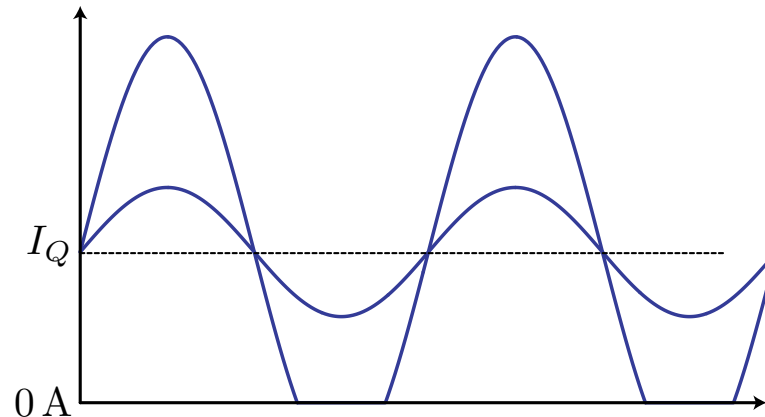
Voltage Swing Waveforms



- We see that to avoid clipping, we should bias the transistor at the midpoint between V_{CC} and $V_{CE,sat}$. Thus

$$v_o \leq \frac{V_{CC}}{2}$$

Current Swing Waveforms



- The current in the transistor cannot go negative. Therefore, the maximum current is set by the bias current.

$$i_o \leq I_Q$$

- The efficiency is therefore still limited to 25%

$$\eta \leq \frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$$

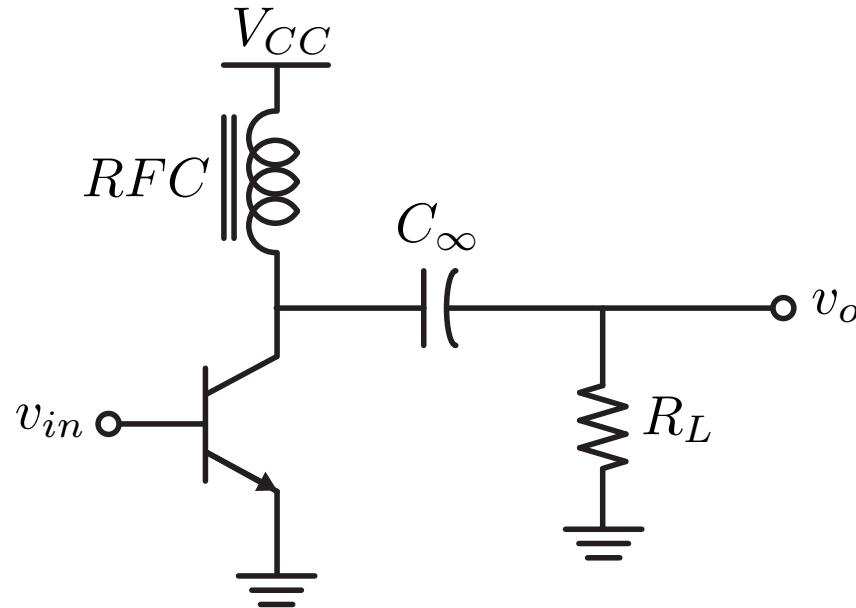
Optimum Load

- It's important to note that to achieve these optimum efficiencies, the value of the load resistance is constrained by the current and voltage swing

$$R_{opt} = \frac{v_o}{i_o} = \left(\frac{\bar{v}}{\bar{i}} \right) \left(\frac{V_{CC}}{I_Q} \right)$$

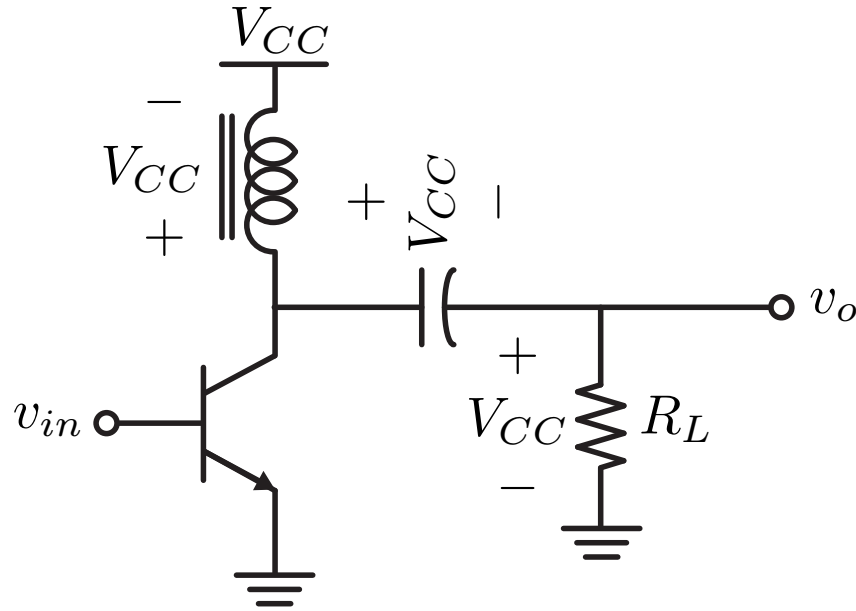
- Since the load resistance is usually fixed (e.g. antenna impedance), a matching network is required to present the optimum load to the amplifier.

Inductor Loaded Amplifier



- If we AC couple a load R_L to the amplifier, then the Q point of the amplifier collector voltage is set at V_{CC} through the choke inductor.
- The maximum swing is now nearly twice as large. Notice that the collector voltage can swing *above* the supply rail.

Inductor Voltage



- Does this bother you? Recall that the voltage polarity across the inductor is given by dI/dt , which can go negative. Thus the collector voltage is equal to the supply minus or *plus* the absolute voltage across the inductor.

Collector Inductor Efficiency

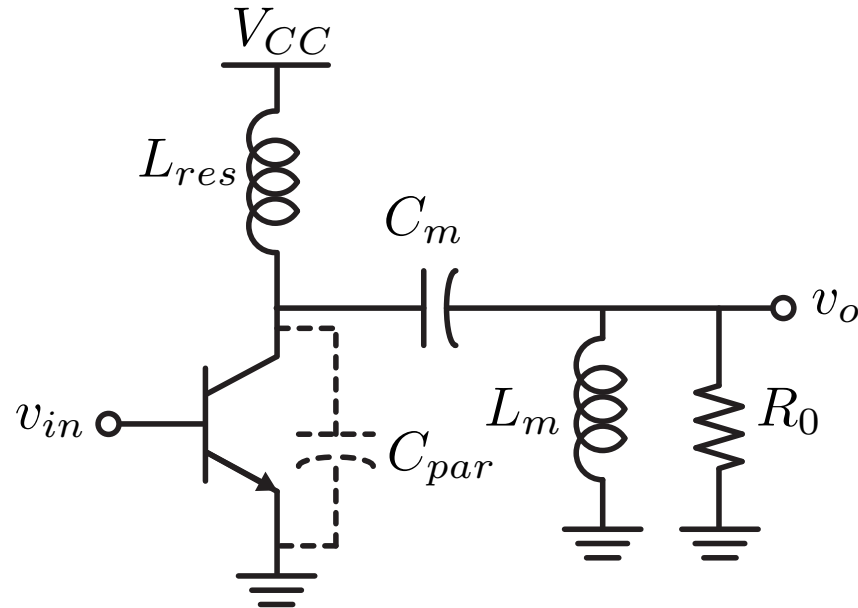
- Since the swing is almost double, the efficiency now approaches 50%

$$v_o \leq V_{CC}$$

$$\eta = \frac{1}{2} \frac{i_o v_o}{I_Q V_{CC}} \leq \frac{1}{2}$$

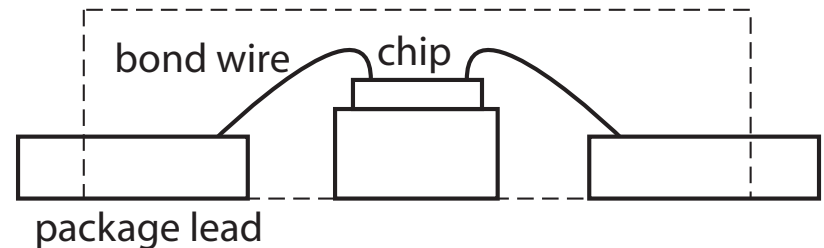
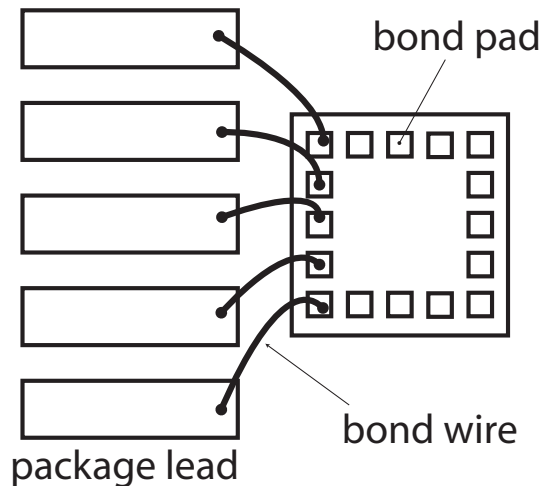
- In practice, due to losses in the components and back-off from maximum swing to minimize distortion, the actual efficiency can be much lower.
- Package parasitics (see later slides) also limit the voltage swing.

Complete PA



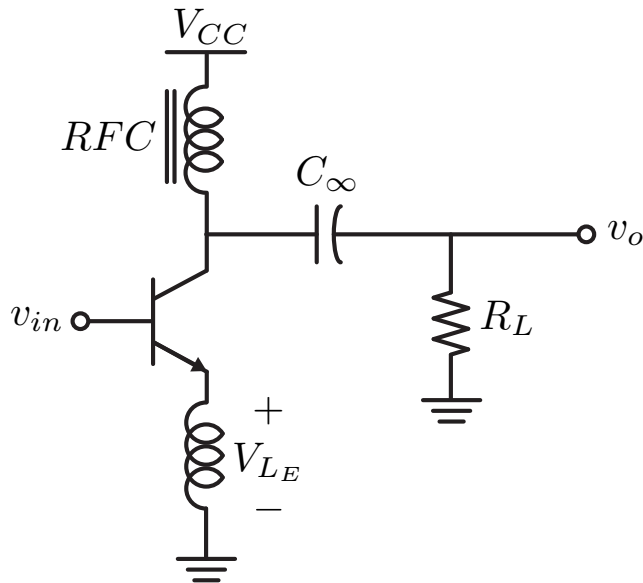
- In practice the collector inductor can double as a resonant element to tune out the collector parasitics. The coupling capacitor C_c can be replaced by a matching capacitor C_m .

Package Parasitics



- In a normal inexpensive package, the pads of the chip are wire-bonded to the chip leads. Since the aspect ratio of the leads is much larger than the pad pitch, long bond wires are required to make the connections, leading to large inductance.
- The model of the package/chip should include the pads, the bond wires, as well as the package leads.

Emitter Degeneration

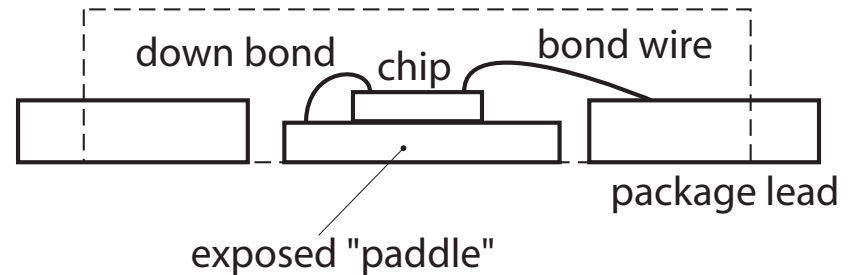
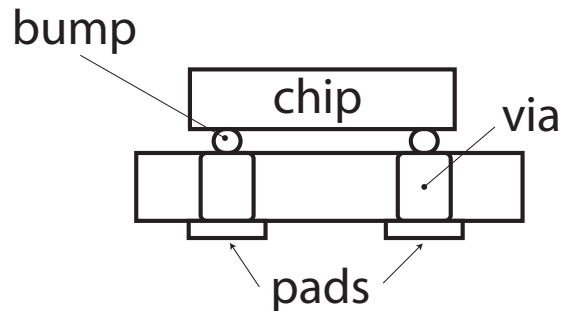


- Emitter inductance has a detrimental effect on PA efficiency since it reduces the swing. The voltage across the emitter is given by

$$V_E = j\omega L_E i_o$$

- For a current swing of 1 A at 1 GHz, a typical parasitic inductance of 1 nH will “eat” up 6.28 V of swing! We need to reduce L_E or to use a much higher V_{CC} .
- In practice both approaches are taken. We choose a technology with the highest breakdown voltage and the package with the lowest L_E .

Advanced Packaging



- In flip-chip technology, the chip is flipped and “bumped” onto a carrier substrate (on onto the board directly). This results in small inductance connections.
- In an exposed “paddle” package, there is a ground plane inside the package. We use conductive glue to mount the chip onto the package. Short down-bonds then create low inductance ground connections.
- In the extreme case, we can use several down-bonds in parallel surrounding the chip in addition to thinning the die.