Chapter 14 Output Stages and Power Amplifiers

- 14.1 General Considerations
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- 14.3 Push-Pull Stage
- 14.4 Improved Push-Pull Stage
- 14.5 Large-Signal Considerations
- 14.6 Short Circuit Protection
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- 14.8 Efficiency
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Why Power Amplifiers?

- Drive a load with high power.
- Cellular phones need 1W of power at the antenna.
- Audio systems deliver tens to hundreds of watts of power.
- Ordinary Voltage/Current amplifiers are not suitable for such applications.
Chapter Outline

Basic Stages
- Emitter Follower
- Push-Pull Stage and Improved Variants

Large-Signal Considerations
- Omission of PNP Transistor
- High-Fidelity Design

Heat Dissipation
- Power Ratings
- Thermal Runaway

Efficiency and PA Classes
- Efficiency of PAs
- Classes of PAs
Experiences low load resistance.

Delivers large current levels.

Requires large voltage swings.

Draws a large amount of power from supply.

Dissipates a large amount of power, therefore gets “hot”.
Power Amplifier Performance Metrics

- Distortion - Linearity
- Power Efficiency
- Voltage Rating – Transistor Breakdown voltage
Emitter Follower Large-Signal Behavior I

As \( V_{in} \) increases \( V_{out} \) also follows and \( Q_1 \) provides more current.

For \( V_{in}=4.8\,V \), \( V_{out}=4.0\,V \), \( I_L=500\,mA \), \( I_{E1}=532.5\,mA \)

\[
A_v = \frac{R_L}{(R_L + 1/g_m)} \\
\text{For } R_L = 8\,\Omega, \\
1/g_m = 0.8\,\Omega, \text{ thus, } I_C = 32.5\,mA
\]
Emitter Follower Large-Signal Behavior II

- For $V_{in}=0.8\,\text{V}$, $V_{out}=0\,\text{V}$, $I_L=0\,\text{mA}$, $I_{E1}=32.5\,\text{mA}$
- For $V_{in}=0.7\,\text{V}$, $V_{out}=-0.1\,\text{V}$, $I_L=12.5\,\text{mA}$, $I_{E1}=20\,\text{mA}$
- When all current (32.5mA) flows to the load, $V_{out}=-0.26\,\text{V}$

However, as $V_{in}$ decreases, $V_{out}$ also decreases, shutting off $Q_1$ and resulting in a constant $V_{out}$.
Example 14.1: Emitter Follower

- \( V_{\text{in}} = 0.5 \text{V}, \ V_{\text{out}} = ? \)

\[
V_{\text{in}} - V_{BE1} = V_{out}, \quad \frac{V_{out}}{R_L} + I_1 = I_{C1}
\]

\[
V_{BE1} = V_T \ln \left( \frac{I_{C1}}{I_S} \right)
\]

\[
V_{\text{in}} - V_T \ln \left[ \left( \frac{V_{out} + I_1}{R_L} \right) \frac{1}{I_S} \right] = V_{out}
\]

For \( V_{\text{in}} = 0.5 \text{ V} \)

\( \Rightarrow V_{out} \approx -211 \text{ mV} \) by a few iterations
Example 14.1: Emitter Follower

For what $V_{\text{in}}$, $Q_1$ carries only 1% of $I_1$?

\[
V_{\text{in}} = V_T \ln \frac{I_{C1}}{I_S} + (I_{C1} - I_1) R_L
\]

For $I_{C1} \approx 0.01 \cdot I_1$

\[
\Rightarrow V_{\text{in}} \approx 390 \text{ mV}
\]
As $V_{in}$ decreases the output waveform will be clipped, introducing nonlinearity in I/O characteristics.
Push-Pull Stage

As \( V_{in} \) increases, \( Q_1 \) is on and pushes current into \( R_L \).

As \( V_{in} \) decreases, \( Q_2 \) is on and pulls current out of \( R_L \).
Example 14.2: I/O Characteristics for Large $V_{\text{in}}$

- For positive $V_{\text{in}}$, $Q_1$ shifts the output down and for negative $V_{\text{in}}$, $Q_2$ shifts the output up.

\[
V_{\text{out}} = V_{\text{in}} - V_{\text{BE1}} \quad \text{for large } +V_{\text{in}}
\]
\[
V_{\text{out}} = V_{\text{in}} + |V_{\text{BE2}}| \quad \text{for large } -V_{\text{in}}
\]
However, for small $V_{in}$, there is a “dead zone” (both $Q_1$ and $Q_2$ are off) in the I/O characteristic, resulting in gross nonlinearity.
Example 14.3: Small-Signal Gain of Push-Pull Stage

- The push-pull stage exhibits a gain that tends to unity when either $Q_1$ or $Q_2$ is on.
- When $V_{in}$ is very small, the gain drops to zero.
Example 14.4: Sinusoidal Response of Push-Pull Stage

- For large $V_{in}$, the output follows the input with a fixed DC offset, however as $V_{in}$ becomes small the output drops to zero and causes "Crossover Distortion."
Improved Push-Pull Stage

With a battery of $V_B$ inserted between the bases of $Q_1$ and $Q_2$, the dead zone is eliminated.

$V_B = V_{BE1} + |V_{BE2}|$
Since $V_B = V_{BE1} + |V_{BE2}|$, a natural choice would be two diodes in series.

$I_1$ in figure (b) is used to bias the diodes and $Q_1$. 
Example 14.6: Current Flow I

\[ I_{in} = I_1 - I_{B1} + |I_{B2}| \]

Usually \( I_{B1} \neq |I_{B2}| \) unless \( V_{out} = 0 \)

\( I_{in} \) flows even when \( V_{out} = 0 \).
Example 14.8: Current Flow II

\[ V_{D1} \approx V_{BE} \rightarrow V_{out} \approx V_{in} \]

\[ I_{in} = 0 \text{ when } V_{out} = 0 \text{ if } I_1 = I_2 \]
A CE stage (predriver) is added to provide voltage gain from the input to the bases of $Q_1$ and $Q_2$. 
For bias point analysis for $V_{out}=0$, the circuit can be simplified to the one on the right, which resembles a current mirror.

$$I_{C1} = \frac{I_{S,Q1}}{I_{S,D1}} \cdot |I_{C3}|$$
Assuming $2r_D$ is small and $(g_{m1}+g_{m2})R_L$ is much greater than 1,

$$A_v = -g_{m4} \left[ (r_{\pi1} \parallel r_{\pi2}) + (\beta + 1)R_L \right]$$

$$= -g_{m4} \left[ (r_{\pi1} \parallel r_{\pi2}) + \left\{ (r_{\pi1} \parallel r_{\pi2})(g_{m1} + g_{m2}) + 1 \right\} R_L \right]$$

$$\approx -g_{m4} \left( r_{\pi1} \parallel r_{\pi2} \right) (g_{m1} + g_{m2}) R_L$$
Example 14.9: Output Resistance Analysis

\[ R_{out} \approx \frac{1}{g_{m1} + g_{m2}} + \frac{r_{O3} \parallel r_{O4}}{(g_{m1} + g_{m2})(r_{\pi1} \parallel r_{\pi2})} \]

- If β is low, the second term of the output resistance will rise, which will be problematic when driving a small resistance.
Compute the required bias current.

Predriver (CE stage): $A_V = 5$

Output Stage: $A_V = 0.8$ for $R_L = 8 \, \Omega$

$\beta_{nnp} = 2 \beta_{pnp} = 100$, $I_{C1} \approx I_{C2}$

Thus, $I_{C1} \approx I_{C2} \approx 6.5 \, \text{mA}$

$g_{m1} + g_{m2} = \left(2 \, \Omega\right)^{-1} \Rightarrow g_{m1} \approx g_{m2} \approx \left(4 \, \Omega\right)^{-1}$

$r_{\pi1} \parallel r_{\pi2} = 400 \, \Omega \parallel 200 \, \Omega = 133 \, \Omega$

$g_{m4} \cdot (r_{\pi1} \parallel r_{\pi2}) \cdot \left[1 + (g_{m1} + g_{m2}) \cdot R_L\right] = 4$

$\Rightarrow g_{m4} = \left(133 \, \Omega\right)^{-1} \Rightarrow I_{C4} \approx 195 \, \mu\text{A}$
195 µA of base current in Q₁ can only support 19.5 mA of collector current, insufficient for high current operation (500 mA for 4 V on 8 Ω).
Modification of the PNP Emitter Follower

Instead of having a single PNP as the emitter-follower, it is now combined with an NPN (Q₂), providing a lower output resistance.

\[ R_{out} \approx \frac{1}{(\beta_2 + 1) g_{m3}} \]
Example 14.11: Input Resistance

Comparing with the standard EF,

\[
\frac{v_{out}}{v_{in}} = \frac{R_L}{R_L + \frac{1}{(\beta_2 + 1)g_{m3} + \frac{1}{r_{\pi3}}}}
\]

\[
1 
\frac{1}{(\beta_2 + 1)g_{m3} + \frac{1}{r_{\pi3}}}
\approx \frac{1}{(\beta_2 + 1)g_{m3}}
\]

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Example 14.11: Input Resistance

\[ i_{in} = \frac{1}{r_{\pi 3}} \left( v_{in} - v_{in} \right) \frac{R_L}{R_L + \left( \beta_2 + 1 \right)g_{m3}} \]

\[ r_{in} = \beta_3 (\beta_2 + 1)R_L + r_{\pi 3} \]
Additional Bias Current

- $I_1$ is added to the base of $Q_2$ to provide an additional bias current to $Q_3$ so the capacitance at the base of $Q_2$ can be charged/discharged quickly. Additional pole at the base of $Q_2$. 
Example 14.12: Minimum $V_{in}$

\[ \text{Min } V_{in} \approx 0 \]
\[ V_{out} \approx |V_{EB2}| \]

\[ \text{Min } V_{in} \approx V_{BE2} \]
\[ V_{out} \approx |V_{EB3}| + V_{BE2} \]
Power Amplifier Classes

Class A: High linearity, low efficiency

Class B: High efficiency, low linearity

Class AB: Compromise between Class A and B
As $V_{out}$ becomes more positive, $g_m$ rises and $A_v$ comes closer to unity, resulting in nonlinearity.

Using negative feedback, linearity is improved, providing higher fidelity.
Q_s and r are used to “steal” some base current away from Q_1 when the output is accidentally shorted to ground, preventing short-circuit damage.
Power transistors

- Package and heat sink

Power Transistor in Heat Sink

Power Transistor Inside

Small-signal Transistor
Emitter Follower Power Rating (Class A)

Pull down is done by a current source with huge current!

\[ P_{av} = \frac{1}{T} \int_0^T I_C \cdot V_{CE} \, dt \]
\[ = \frac{1}{T} \int_0^T \left( I_1 + \frac{V_P \sin \omega t}{R_L} \right) \cdot (V_{CC} - V_P \sin \omega t) \, dt \]
\[ = I_1 \cdot V_{CC} - \frac{V_P^2}{R_L} = I_1 \left( V_{CC} - \frac{V_P}{2} \right) \text{ if } I_1 = \frac{V_P}{R_L} \]

- Maximum power dissipated across Q₁ occurs in the absence of a signal.

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Example 14.13: Power Dissipation

Avg Power Dissipated in the Current Source \( I_1 \)

\[
P_{I1} = \frac{1}{T} \int_0^T I_1 \left( V_p \sin \omega t - V_{EE} \right) dt
\]

\[
= -I_1 \cdot V_{EE}
\]
Push-Pull Stage Power Rating

\[ P_{av,NPN} = \frac{1}{T} \int_{0}^{T/2} I_C \cdot V_{CE} \, dt \]

\[ = \frac{1}{T} \int_{0}^{T/2} (V_{CC} - V_P \sin \omega t) \cdot \frac{V_P \sin \omega t}{R_L} \, dt \]

\[ = \frac{V_{CC} \cdot V_P}{\pi R_L} - \frac{V_P^2}{4R_L} = \frac{V_P}{R_L} \left( \frac{V_{CC}}{\pi} - \frac{V_P}{4} \right) \]

➢ No power for half of the period.
No power for half of the period.

Maximum power occurs between $V_p=0$ and $4V_{cc}/\pi$.

$P_{av,NPN} = \frac{1}{T} \int_0^{T/2} I_C \cdot V_{CE} dt$

$= \frac{1}{T} \int_0^{T/2} (V_{CC} - V_p \sin \omega t) \cdot \frac{V_p \sin \omega t}{R_L} dt$

$= \frac{V_{CC} \cdot V_p}{\pi R_L} - \frac{V_p^2}{4R_L} = \frac{V_p}{R_L} \left( \frac{V_{CC}}{\pi} - \frac{V_p}{4} \right)$

$P_{av,max} = \frac{V_{CC}^2 \cdot V_p}{\pi^2 R_L}$ when $V_p = 2 \cdot \frac{V_{CC}}{\pi}$
Push-Pull Stage Power Rating

\[ P_{av,PNP} = \frac{1}{T} \int_{T/2}^{T} |I_C| \cdot |V_{CE}| \, dt \]

\[ = \frac{1}{T} \int_{T/2}^{T} (V_P \sin \omega t - V_{EE}) \cdot \left( -\frac{V_P \sin \omega t}{R_L} \right) \, dt \]

\[ = \frac{-V_{EE} \cdot V_P}{\pi R_L} - \frac{V_P^2}{4R_L} = \frac{V_P}{R_L} \left( \frac{-V_{EE}}{\pi} - \frac{V_P}{4} \right) \]

- Maximum power occurs between \( V_P = 0 \) and \( 4V_{CC}/\pi \).

\[ P_{av,\text{max}} = \frac{V_{CC}^2 \cdot V_P}{\pi^2 R_L} \quad \text{when} \quad V_P = 2 \cdot \frac{V_{CC}}{\pi} \]
Heat sink, provides large surface area to dissipate heat from the chip.
Using diode biasing prevents thermal runaway since the currents in Q₁ and Q₂ will track those of D₁ and D₂ as long as their $I_s$’s track with temperature.

\[ V_{D1} + V_{D2} = V_T \ln \frac{I_{D1}}{I_{S,D1}} + V_T \ln \frac{I_{D2}}{I_{S,D2}} \]

\[ = V_T \ln \frac{I_{D1}I_{D2}}{I_{S,D1}I_{S,D2}} \]

\[ V_{BE1} + V_{BE2} = V_T \ln \frac{I_{C1}}{I_{S,Q1}} + V_T \ln \frac{I_{C2}}{I_{S,Q2}} \]

\[ = V_T \ln \frac{I_{C1}I_{C2}}{I_{S,Q1}I_{S,Q2}} \]

With the same $V_T$,

\[ \frac{I_{D1}I_{D2}}{I_{S,D1}I_{S,D2}} = \frac{I_{C1}I_{C2}}{I_{S,Q1}I_{S,Q2}} \]
Efficiency

Efficiency is defined as the average power delivered to the load divided by the power drawn from the supply.

\[
\eta = \frac{\text{Power Delivered to Load}}{\text{Power Drawn From Supply Voltage}} = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{ckt}}}
\]

Emitter Follower (Class A)

\[
\eta_{EF} = \frac{V_P^2 / 2R_L}{V_P^2 / 2R_L + I_1(V_{CC} - V_P / 2) - I_1 \cdot V_{EE}}
\]

\[
= \frac{V_P}{4V_{CC}} \quad \text{if} \quad I_1 = \frac{V_P}{R_L} \quad \text{and} \quad -V_{EE} = V_{CC}
\]

Maximum efficiency for EF is 25%.

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Example 14.15: Efficiency of EF

EF designed for full swing operates with half swing.

With $I_1 = \frac{V_P}{R_L} = \frac{V_{CC}}{R_L}$ and $-V_{EE} = V_{CC}$

$$\eta_{EF} = \frac{V_P^2 / 2R_L}{V_P^2 / 2R_L + I_1(V_{CC} - V_P / 2) - I_1 \cdot V_{EE}}$$

$$= \frac{V_P^2 / 2R_L}{V_P^2 / 2R_L + \frac{V_{CC}}{R_L}(V_{CC} - V_P / 2) + \frac{V_{CC}}{R_L} \cdot V_{CC}}$$

Thus,

$$\eta_{EF} \bigg|_{V_P = V_{CC} / 2} = \frac{1}{15} = 6.7\%$$
Efficiency

Push-Pull Stage (Class A or AB)

\[ \eta_{PP} = \frac{V_P^2}{2R_L} - \frac{2V_P}{R_L} \left( \frac{V_{CC}}{\pi} - \frac{V_P}{4} \right) \]

\[ = \frac{\pi}{4} \frac{V_P}{V_{CC}} \]

- Maximum efficiency for PP is 78.5%.
Example 14.16: Efficiency incl. Predriver

\[ I_1 = \frac{V_P}{R_L} / \beta \]

\[ \eta = \frac{2V_P^2}{2R_L} \left( \frac{2V_P V_{CC}}{\pi R_L} + (V_{CC} - V_{EE}) \frac{V_P}{\beta R_L} \right) \]

\[ = \frac{1}{4} \frac{V_P}{V_{CC}/\pi + V_{CC}/\beta} \]

\[ = \frac{1}{4} \left( \frac{1}{\pi} + \frac{1}{\beta} \right) \frac{V_P}{V_{CC}} \]