Announcements

- Exam 3 is on Apr 27
  - 9:10-10:35PM (10 extra minutes)
  - Closed book w/ one standard note sheet
  - 8.5”x11” front & back
  - **BRING YOUR CALCULATOR**
  - Covers material through Output Stages Lecture
  - Previous years’ exam 3s are posted on the website for reference

- Project
  - Final report due May 3
  - Presentations on May 6 8-10AM
Agenda

• Output Stages
  • Source Follower (Class A)
  • Push-Pull (Class B)
  • Push-Pull w/ Small Quiescent Current (Class AB)
OpAmps and OTAs

- High voltage gain
- High input impedance
- Voltage source output (low impedance)

- High “voltage” gain
- High input impedance
- Current source output (high impedance)
Three-Stage OpAmp

- **Differential input stage**
  - Amplifies differential input
  - Sets specs such as $G_m$, CMRR, and slew rate
- **Second gain stage**
  - Provides additional gain
  - Often used to provide Miller compensation
- **Output stage**
  - “Power Amplifier”
  - Large current gain and near unity voltage gain
  - Small output impedance
Buffered OTA = Operational Voltage Amplifier (OPAMP)

**SIMPLE MACROMODEL:**

\[ A_{VDC} = \left( g_{m1} R_1 \right) A_2 A_3 \]

\[ A_2 \approx g_{m3} r_0 \]

\[ A_3 \approx 1 - 0.5 \]

\[ GBW \approx \frac{g_{m1}}{C_M} \]

\[ R_{out} = r_0 \approx 1 / g_{m4} \]

Notice that load capacitors must satisfy the following condition, otherwise phase margin is not good enough.

\[ GBW < \frac{1}{r_0 C_L} \]
Source Follower (Class A) Output Stage

- Voltage gain close to 1
- Low output resistance
- DC level shift of $V_{GS1}$
- Class A output stage transistors conduct current over an entire input cycle

\[
A_{dc} = \frac{g_{m1}}{g_{m1} + g_{o1} + g_{mb1} + g_{o2} + g_L} \approx \frac{g_{m1}R_L}{1 + g_{m1}R_L} \approx 1 \quad \text{(Optimistic)}
\]

\[
R_{out} = \frac{1}{g_{m1} + g_{o1} + g_{mb1} + g_{o2}} \approx \frac{1}{g_{m1}}
\]
Source Follower (Class A) Transfer Characteristic

\[ V_o = V_i - V_{T1} - \sqrt{\frac{2\left(I_Q + \frac{V_o}{R_L}\right)}{\mu n C_{ox} (W/L)_1}} \]

- **Maximum** \( V_o \)
  - If \( V_{in} \leq V_{DD} \), then Maximum \( V_o = V_{DD} - V_{GS1} \)
  - Output transistors remain in saturation up to \( V_o = V_{DD} - V_{DSAT1} \) if \( V_{in} \) swings up to \( V_{DD} + V_{T1} \)

- **Minimum** \( V_o \)
  - For small \( R_L \) (heavy load), \( M1 \) gets cutoff and \( V_o \geq -I_Q R_L \)
  - For large \( R_L \) (light load), \( M2 \) will go into triode region at \( -V_{DD} + V_{DSAT2} \)
Source Follower (Class A)
Power Efficiency

Assuming a sinusoidal output voltage
\[ V_o = V_m \sin(\omega t) \]
The power delivered to the load at the signal frequency \( \omega \) is
\[ P_{ac} = \left( \frac{V_m}{\sqrt{2}} \right)^2 \frac{R_L}{2} = \frac{V_m^2}{2R_L} \]

The average power consumed by the source follower is
\[ P_{av} = (-I_Q)(-V_{DD}) + (I_Q)(V_{DD}) = 2I_QV_{DD} \]
The output stage power efficiency is
\[ P_{eff} \equiv \frac{P_{ac}}{P_{av}} = \frac{V_m^2}{4R_LI_QV_{DD}} \]

Maximum power efficiency is achieved when the output amplitude approaches \( V_{DD} \) and \( I_Q \) is designed to be \( \frac{V_{DD}}{R_L} \)

\[ \text{Max } P_{eff} = \frac{1}{4} \text{ or } 25\% \text{ (not that good!)} \]
Super Buffer Output Stage

\[ R_{out} \approx \frac{1}{g_{m2}(1 + A_v)} \]

[Silva]
Push-Pull Source Follower (Class B) Output Stage

• Class B output stages improve power efficiency by operating at zero quiescent current

• However, if 
  
  \[-|V_{TP}| \leq V_{in} \leq V_{TN},\]

  then no output signal
Push-Pull Source Follower (Class B)
Crossover Distortion

[Diagram showing waveforms and annotations]

[Sedra]
Push-Pull Source Follower (Class B) 
Power Efficiency

Assuming a sinusoidal output voltage
\[ V_o = V_m \sin(\omega t) \]
The power delivered to the load at the signal frequency \( \omega \) is
\[ P_{ac} = \frac{\left( \frac{V_m}{\sqrt{2}} \right)^2}{R_L} = \frac{V_m^2}{2R_L} \]
The current consumed by the push-pull stage from the two supplies consists of half-sine wave of peak amplitude \( \frac{V_m}{R_L} \)
The average current will be
\[ P_{av} = \left( -\frac{V_m}{\pi R_L} \right)(-V_{DD}) + \left( \frac{V_m}{\pi R_L} \right)(V_{DD}) = \frac{2V_mV_{DD}}{\pi R_L} \]
The output stage power efficiency is
\[ P_{eff} = \frac{P_{ac}}{P_{av}} = \frac{\pi V_m}{4V_{DD}} \]
Maximum power efficiency is achieved when the output amplitude approaches \( V_{DD} \)
\[ \text{Max } P_{eff} = \frac{\pi}{4} \text{ or } 78.5\% \text{ (much better!)} \]
Push-Pull w/ Small Quiescent Current (Class AB) Output Stage

- Power efficiency of the Class-B output stage is great, but the crossover distortion is a major issue.
- Solution to the crossover distortion is to bias the transistors into conduction at a low quiescent current.
- Level-shift transistors M4 and M5 are sized such that VGS1 and VGS2 are slightly larger than their threshold voltages.
Push-Pull w/ Small Quiescent Current (Class AB) Output Swing Range

- A drawback of the CMOS Class AB output stage is the limited output swing range

- Maximum $V_o$ set by M1 source follower
  - $V_o \leq V_{DD} - |V_{DSAT3}| - V_{GS1}$

- Minimum $V_o$ set by M2 source follower
  - $V_o \geq -V_{SS} + V_{DSAT6} + V_{SG2}$
Next Time

- Bandgap Reference Circuits