Announcements

• Project Report Due May 1
  • Email it to me by 5PM

• Exam 3 is on May 3
  • 3PM-5PM
  • 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
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)

OpAmp

- High "voltage" gain
  - As long as it’s driving a high impedance load (capacitor)
- High input impedance
- Current source output (high impedance)

OTA
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)

\[ A_{VDC} = (g_m R_1) A_2 A_3 \]

\[ A_2 \approx g_m r_0 \]

\[ A_3 \approx 1 - 0.5 \]

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

\[ R_{out} = r_0 \approx \frac{1}{g_m} \]

\[ GBW < \frac{1}{r_0 C_L} \]

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

- Maximum $V_o$ is set by M1 saturation condition
  - 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 $V_o$ depends on $R_L$
  - 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
\[ P_{ac} = \frac{\left( \frac{V_m}{\sqrt{2}} \right)^2}{R_L} = \frac{V_m^2}{2R_L} \]

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
\[ P_{eff} = \frac{P_{ac}}{P_{av}} = \frac{V_m^2}{4R_L I_Q V_{DD}} \]

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

- Employs a “gain-boosting” technique where the effective transconductance of M2 is boosted by $1-A_v$, where $A_v$ is the gain from the source-to-gate, which should be negative for stability.
- Results in an output resistance reduction by a $1/(1+A_v)$ factor.

$R_{out} \approx \frac{1}{g_{m2}(1+A_v)}$
Push-Pull Source Follower (Class B) Output Stage

- Class B output stages have only one transistor conducting current for each half cycle
  - M1 during positive half
  - M2 during negative half
- Results in improved 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

[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  

\[ P_{av} = \left( -\frac{V_m}{\pi R_L} \right) (-V_{DD}) + \left( \frac{V_m}{\pi R_L} \right) (V_{DD}) = \frac{2V_m V_{DD}}{\pi R_L} \]  

The output stage power efficiency is  

\[ P_{eff} \equiv \frac{P_{ac}}{P_{av}} = \frac{\pi V_m}{4V_{DD}} \]  

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 $V_{GS1}$ and $V_{SG2}$ 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