EE 435

Lecture 8:

High-Gain Single-Stage Op Amps
Operation of Op Amp – A different perspective

Small signal differential half-circuit

- If the input impedance to the counterpart circuit is infinite and the quiescent values of the left and right drain voltages are the same, connecting the bias port of the counterpart circuit to $V_0^-$ instead of to $V_{BB}$ will cause the signal current in the right counterpart circuit to be equal to that in the left counterpart circuit.

- This will approximately double the signal current steered to $V_o^+$ and thus double the voltage gain! (formal derivation on following slide)

- This will also eliminate the need for a CMFB circuit!
Doubling of Gain with “Current Mirror” connection

From KCL at two drain nodes

\[ V_{OUT} \left( sC_L + G_2 + G_4 \right) + G_{M2} \frac{V_d}{2} + G_{M4} V_Z = 0 \]

\[ V_Z (G_1 + G_3) + G_{M3} V_Z - G_{M1} \frac{V_d}{2} = 0 \]

Eliminating \( V_Z \) we obtain

\[ \frac{V_{OUT}}{V_d} = A_V = - \frac{G_{M4} G_{M1} + G_{M2} G_{M3} + G_{M2} (G_1 + G_3)}{2 \left( sC_L + G_2 + G_4 \right) \left( G_1 + G_3 + G_{M3} \right)} \]

Assuming \( G_M \)’s large compared to \( G \)’s and left-right symmetry, it follows that

\[ A_V = - \frac{G_{M1}}{sC_L + G_2 + G_4} \]
Where we are at:

Basic Op Amp Design

- Fundamental Amplifier Design Issues
- Single-Stage Low Gain Op Amps
- Single-Stage High Gain Op Amps
- Other Basic Gain Enhancement Approaches
- Two-Stage Op Amp
Inputs into Counterpart Circuit or Quarter Circuit

Gain, BW, and GB expressions identical

This is a general concept not related to what type of quarter circuit is used

Performance may be different because n-channel and p-channel performance different
Inputs into Counterpart Circuit or Quarter Circuit for single-transistor quarter circuit

Gain, BW, and GB expressions identical

Performance may be different because n-channel and p-channel performance different

Both are widely used
Single-stage op amps

Question – is the gain achievable with the single-stage low-gain op amps using a single MOS transistor as a quarter circuit adequate?

\[ A_{v0} = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left( \frac{1}{V_{EB1}} \right) \]

If \( \lambda_1 = \lambda_3 = 0.01 \text{V}^{-1} \) and \( V_{EB1} = 0.15 \text{V} \), then

\[ A_{v0} \approx \frac{1}{(.01 + .01)} \frac{1}{0.15} = 333 \]

or, in db, \( A_{v0\text{db}} = 20\log_{10}333 = 50\text{db} \)

This is inadequate for many applications!

What can be done about it?
Basic Op Amp Design

- Fundamental Amplifier Design Issues
- Single-Stage Low Gain Op Amps
- Single-Stage High Gain Op Amps
- Other Basic Gain Enhancement Approaches
- Two-Stage Op Amp
Recall from a previous lecture:

Determination of op amp characteristics from quarter circuit characteristics

Small signal differential half-circuit

\[ A_V = \frac{V_O^+}{V_d} = \frac{-G_{M1}}{2} \frac{2}{sC_L + G_1 + G_2} \]

\[ A_{VO} = \frac{-G_{M1}}{2(G_1 + G_2)} \]

\[ BW = \frac{G_1 + G_2}{C_L} \]

\[ GB = \frac{G_{M1}}{2C_L} \]
Single-Stage High Gain Op Amps

How can the gain of the op amp be increased?

Recall from Quarter-Circuit Concept

\[ A_{VO} = \frac{1}{2} \frac{-G_{M1}}{G_1 + G_2} \]

A possible strategy:

- Increase \( G_{M1} \) or Decrease \( G_1 \) (and \( G_2 \)) in Quarter Circuit or Both
Single-Stage High-Gain Op Amps

• If the output conductance can be decreased without changing the transconductance, the gain can be enhanced

• Will concentrate on quarter-circuits and extend to op amps
Determination of 2-port parameters

Background

Determination of \{g_{o1}, g_{o2}, g_{M1}, g_{M2}\}

Method 1  Open-Short Termination Approach

Method 2  Load Termination Approach
Background

**Determination of 2-port parameters**

Determination of \{g_{o1}, g_{o2}, g_{M1}, g_{M2}\}

**Method 1  Open-Short Termination Approach**

By structural symmetry, repeat to obtain \(g_{m1}\) and \(g_{o1}\)
Background

Determination of 2-port parameters

Determination of \( \{g_{o1}, g_{o2}, g_{M1}, g_{M2} \} \)

Method 2  Load Termination Approach

Since first-order express the gain \( A(s) \) in form

\[
A(s) = \frac{a_0}{sC_L + b_0}
\]

observe

\[
V_2(g_{o2} + sC_L) + g_{M2}V_{TST} = 0
\]

\[
A(s) = \frac{V_2(s)}{V_{TST}(s)} = -\frac{g_{M2}}{sC_L + g_{o2}}
\]

(must express with coefficient of \( s \) in den equal to \( C_L \))
Background

Recall Cascode Amplifier (dc current source bias)
Background

Analysis of Cascode Amplifier (dc current source bias)

\[
\begin{align*}
V_{\text{OUT}} \left( g_{o2} + sC_L \right) + g_{m2} V_2 &= V_X g_{o2} \\
V_X \left( g_{o1} + g_{o2} \right) + g_{m1} V_1 - g_{m2} V_2 &= V_{\text{OUT}} g_{o2} \\
V_2 &= -V_X \\
V_1 &= V_{\text{IN}}
\end{align*}
\]

\( V_X, V_1 \) and \( V_2 \) can be eliminated from these 4 equations.
Analysis of Cascode Amplifier

Background

\[
\begin{align*}
V_{\text{OUT}}(g_{o2} + sC_L) + g_{m2} V_2 &= V_x g_{o2} \\
V_x(g_{o1} + g_{o2}) + g_{m1} V_1 - g_{m2} V_2 &= V_{\text{OUT}} g_{o2} \\
V_2 &= -V_x \\
V_1 &= V_{\text{IN}}
\end{align*}
\]

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{-g_{m1}(g_{o2} + g_{m2})}{sC_L(g_{o1} + g_{o2} + g_{m2}) + g_{o1}g_{o2}} \approx \frac{-g_{m1}g_{m2}}{sC_Lg_{m2} + g_{o1}g_{o2}}
\]

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} \approx \frac{-g_{m1}}{sC_L + g_{o1}\left(\frac{g_{o2}}{g_{m2}}\right)}
\]

\[g_{\text{MEQ}}\]
\[g_{\text{OEQ}}\]
Comparison of Basic Amplifier and Cascode Amplifier

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} \approx \frac{-g_{m1}}{sC_L + g_{o1} \left(\frac{g_{o2}}{g_{m2}}\right)}
\]

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{-g_{m1}}{sC_L + g_{o1}}
\]
High output impedance quarter-circuits

Output conductance appears to have been decreased!

$$g_{OEQ} \approx g_{O1} \left[ \frac{g_{O2}}{g_{m2}} \right]$$

$$g_{mEQ} \approx g_{m1}$$

$$A_v(s) \approx \frac{-g_{m1}}{sC_l + g_{o1} \left[ \frac{g_{o2}}{g_{m2}} \right]}$$

$$A_{V0} \approx \left( \frac{g_{m1}}{g_{o1}} \right) \left[ \frac{g_{m2}}{g_{o2}} \right]$$

$$GB \approx \frac{g_{m1}}{C_L}$$

But must verify in the practical parameter domain to be sure!
High output impedance quarter-circuits

How does this compare with previous amplifier using single transistor as quarter circuit?

Cascode amplifier quarter circuit:

$$A_{V0} \approx \frac{2}{\lambda V_{EB1}} \cdot \frac{2}{\lambda V_{EB2}}$$

$$GB = \frac{2P}{V_{DD}C_L} \cdot \frac{1}{V_{EB1}}$$

Single transistor quarter circuit:

$$A_{V0} = \frac{2}{\lambda V_{EB}}$$

$$GB = \left( \frac{2P}{V_{DD}C_L} \right) \cdot \left( \frac{1}{V_{EB}} \right)$$

Substantial increase in dc gain

No improvement in GB but also no deterioration in GB!
High output impedance quarter-circuits

Cascode Amplifier (small-signal equiv)
High output impedance quarter-circuits

Cascode Amplifier

Quarter Circuit

Counterpart Circuit
Telescopic Cascode Op Amp

Needs CMFB Circuit for $V_{B1}$ or $V_{B5}$
Either single-ended or differential outputs
Can connect counterpart as current mirror to eliminate CMFB
Recall:  
Determination of op amp characteristics from quarter circuit characteristics

Small signal Quarter Circuit

\[ A_{V0QC} = -\frac{G_M}{G} \]
\[ BW = \frac{G}{C_L} \]
\[ GB = \frac{G_M}{C_L} \]
\[ A(s) = \frac{-G_M}{sC_L + G} \]

Small signal differential amplifier

\[ A_V = \frac{-G_{M1}}{2(G_1 + G_3)} \]
\[ BW = \frac{G_1 + G_3}{C_L} \]
\[ GB = \frac{G_{M1}}{2C_L} \]
\[ A(s) = \frac{-G_{M1}}{sC_L + G_1 + G_3} \]

Note:  Factor of 4 reduction of single-ended gain
Telescopic Cascode Op Amp

Single-ended operation

\[ \text{\( g_{OQC} = \)} \]

\[ \text{\( g_{OCC} = \)} \]

\[ \text{\( g_{mQC} = \)} \]
Telescopic Cascode Op Amp

Single-ended operation

\[ A_d(s) = \frac{-g_{m1}}{2} \left( sC_L + g_{o1} \frac{g_{o3}}{g_{m3}} + g_{o5} \frac{g_{o7}}{g_{m7}} \right) \]

\[ A_0 = \frac{-g_{m1}}{2} \frac{g_{o1} \frac{g_{o3}}{g_{m3}} + g_{o5} \frac{g_{o7}}{g_{m7}}}{\frac{g_{m1}}{2C_L}} \]

\[ GB = \frac{g_{m1}}{2C_L} \]
Telescopic Cascode Op Amp

\[ A_d(s) = \frac{-\frac{g_{m1}}{2}}{sC_L + \frac{g_{o3}}{g_{m3}} + \frac{g_{o5}}{g_{m7}} + \frac{g_{o7}}{g_{m7}}} \]

\[ A_0 = \frac{-\frac{g_{m1}}{2}}{g_{o1} \frac{g_{o3}}{g_{m3}} + g_{o5} \frac{g_{o7}}{g_{m7}}} \]

\[ GB = \frac{g_{m1}}{2C_L} \]

- Large improvement in \( A_0 \)
- No change in GB

This circuit is widely used!!
Telescopic Cascode Op Amp

- One tail bias current generator shown
- $I_T$ often one of many outputs for current mirror
- $I_B$ and $M_{12}$ often common to many blocks
- $I_B$ often generated from a reference generator circuit
- Tail voltage bias can also be used

(CMFB circuit not shown)
Telescopic Cascode Op Amp

Standard p-channel Cascode Mirror

- Current-Mirror p-channel Bias to Eliminate CMFB
- Only single-ended output available
- Doubles dc gain

Wide-Swing p-channel Cascode Mirror
Telescopic Cascode Op Amp

- Differential Output
- CMFB to establish $V_{B1}$ or $V_{B5}$ needed
- Tail current generally generated with current mirror
Telescopic Cascode Op Amp

Signal Swing and Power Supply Limitations

There are a minimum of 2 $V_{DSAT}$ drops between $V_{OUT}$ and $V_{DD}$ and a minimum of 3 $V_{DSAT}$ drops between $V_{OUT}$ and $V_{SS}$

Thus, there are a minimum of 5 $V_{DSAT}$ drops between $V_{DD}$ and $V_{SS}$

This establishes a lower bound on $V_{DD}-V_{SS}$ and it will be reduced by the p-p signal swing on the output
Telescopic Cascode Op Amp

n-channel inputs

p-channel inputs
End of Lecture 8