Outline of Lecture

- Gain boosting technique
- Nested Miller technique
- Replica bias technique
- Improved slew rate opamp example
Recall the Folded Cascode Opamp

- Modified version of telescopic opamp
  - Significantly improved input/output swing
  - High BW (better than two stage, worse than telescopic)
  - Single stage of gain (lower than telescopic)

Can we further boost the DC gain?
Gain Boosting of Current Sources

- We can achieve increased output impedance of a current source with an amplifier
  - The amplifier essentially increases $g_{m1}$ by factor $K$

$$R_{out} = (K g_{m1} r_{o1}) R_{ref}$$

- Key issue: what is a convenient implementation of the above circuit?
A Simple Gain Boosting Amplifier

- Common source amplifier utilized

\[ K = g_{m4}r_{o4}, \quad R_{ref} = r_{o2} \]

\[ \Rightarrow R_{out} = \left(g_{m4}r_{o4}\right)\left(g_{m1}r_{o1}\right)r_{o2} \approx \left(g_m r_o\right)^2 r_{o2} \]

- Issue: current source requires significant headroom due to the fact that \( V_{ds2} = V_{gs4} \)
Folded cascode yields

\[ K = g_{m4} \left( \left( g_{m6} r_{o6} \right) r_{o5} \right) \left| \left( g_{m7} r_{o7} \right) r_{o8} \right) \]

\[ \Rightarrow R_{out} \approx \left( g_m r_o \right)^3 r_{o2} \]

- Improved headroom and higher gain!

Is there a convenient way to set \( V_{bias5} \)?
Differential Version of Gain Boosting Amplifier

- Leverage fully differential nature of current sources within the opamp
  - PMOS gain devices are now part of a differential pair
  - Need CMFB to set common-mode gate voltages of $M_1$ and $M_2$
Symbolic View of Folded Cascode Gain Boosting Amp

- We can apply this to the overall folded cascode opamp
Folded Cascode with Gain Boosting

- Gain boosting provides substantial increase of DC gain while maintaining good input and output swing
  - Gain is on the order of \((g_m r_o)^4\)
- Issue – very complex!

M.H. Perrott
Recall Pole Splitting for Two Stage Compensation

- Moves the dominant pole of the second stage to higher frequencies such that it becomes a parasitic pole
- Places the first stage pole as the dominant pole
  - Leverages the gain of the second stage to achieve capacitor multiplication using the Miller effect

Can we extend the pole splitting technique to more than 2 gain stages?
Nested Miller Compensation

- Advantage: increased DC gain with high input and output swing
- Issue: more parasitic poles to deal with
  - Leads to lower unity gain bandwidth for reasonable phase margin

Proving to be a useful technique in advanced CMOS processes which offer fast speed (high $g_m/C$) but low intrinsic gain (low $g_m r_o$)

Eschauzier, JSSC Dec 1992
Intermediate gain stages must be non-inverting in order to achieve stable feedback

Compensation resistors should also be included to eliminate the impact of RHP zeros
- Not shown for simplicity
Recall the Telescopic Opamp

- Key issue is input swing
- Can we improve this?
Replica Bias Technique

- Allows current source to maintain its output current even for low $V_{ds}$ using dynamic bias of $V_{gs}$
  - Allows extended input common-mode range

Gulati, JSSC
Dec, 1998

M.H. Perrott
Recall: Slew Rate Issues for Opamps

- Output currents of practical opamps have max limits
  - Impacts maximum rate of charging or discharging load capacitance, $C_L$
  - For large step response, this leads to the output lagging behind the ideal response based on linear modeling
    - We refer to this condition as being slew-rate limited

- Where slew-rate is of concern, the output stage of the opamp can be designed to help mitigate this issue
  - Will lead to extra complexity and perhaps other issues
Key Observations for Slew Rate Calculations

- **First stage**
  - Max $I_1 = I_{\text{bias}1}$
  - Min $I_1 = -I_{\text{bias}1}$

- **Second stage**
  - Max $I_2 = I_{\text{bias}2}$
  - Min $I_2 = \text{Large}$

Current Limits

How can we improve opamp slew rate?
Class A and AB Amplifiers/Buffers

- **Class A**
  - Maximum slew rate in one direction is set by the nominal bias current

- **Class AB**
  - Maximum slew rate is not set by the nominal bias current
    - Goal: low nominal bias current
Class AB Opamp

- Low bias current can be achieved for $V_{in+} = V_{in-}$
  - Must properly set $V_{bias}$
- Much higher current when $V_{in+} \neq V_{in-}$
- DC gain can be increased through cascoding of output stage

Costello, JSSC Dec 1985
Biasing Network for Class AB Opamp

- Bias current set by
  - Ratio of device sizes of $M_1$-$M_4$ versus $M_{13}$-$M_{16}$
  - $I_{\text{ref}}$ current
Summary

- Opamps invite a wide variety of techniques to address different application requirements
  - Cleverness can substantially improve performance and robustness
  - Changing of CMOS processes over time leads to new techniques which were previously unnecessary or unpractical
- Four techniques discussed today
  - Gain boosting
  - Nested Miller
  - Replica bias
  - Class AB stages