EE 508

Lecture 34

Transconductor Design
Transconductor Design

Transconductor-based filters depend directly on the $g_m$ of the transconductor.

Feedback is not used to make the filter performance insensitive to the transconductance gain.

Linearity and spectral performance of the filter strongly dependent upon the linearity of the transconductor.

Often can not justify elegant linearization strategies in the transconductors because of speed, area, and power penalties.
Seminal Work on the OTA

OTA Obsoletes Op Amp

by C.F. Wheatley
H.A. Wittlinger

From:
1969 N.E.C. PROCEEDINGS
December 1969
Current Mirror Op Amp W/O CMFB

\[ g_{mEQ} = M g_m \]

Often termed an OTA

Introduced by Wheatley and Whitlinger in 1969

\[ I_{OUT} = g_m V_{IN} \]
Basic OTA based upon differential pair

Assume $M_1$ and $M_2$ matched, $M_3$ and $M_4$ matched

$$g_m = g_{m1}$$
Differential output OTA based upon differential pair

\[ g_m = \frac{g_{m1}}{2} M \]

CMFB needed for the two output biasing current sources
Differential output OTA based upon differential pair

\[ g_m = \frac{g_{m1}}{2} M \]

CMFB needed for the two output biasing current sources
Telescopic Cascode OTA

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

Standard p-channel Cascode Mirror

Wide-Swing p-channel Cascode Mirror
Telescopic Cascode OTA

CMFB needed
Single-ended High-Frequency TA

\[ g_m = -g_{m1} \]

\[ g_m = Mg_{m1} \]
Signal Swing and Linearity

Ideal Scenario:

Completely Linear over Input and Output Range
Realistic Scenario:

- Modest Nonlinearity throughout Input Range
- But operation will be quite linear over subset of this range
Signal Swing and Linearity

V_{OUT} \quad V_{IN}

Output Range

Input Range

Linear Output Range

Linear Input Range
Linearity of Amplifiers

Strongly dependent upon linearity of transconductance of differential pair
Differential Input Pairs

MOS Differential Pair

Bipolar Differential Pair
MOS Differential Pair

\[ I_{D1} = \frac{\mu C_{ox} W}{2L} (V_1 - V_S - V_T)^2 \]
\[ I_{D2} = \frac{\mu C_{ox} W}{2L} (V_2 - V_S - V_T)^2 \]
\[ I_{D1} + I_{D2} = I_T \]

\[ \sqrt{I_{D1}} \sqrt{\frac{2L}{\mu C_{ox} W}} = V_1 - V_S - V_T \]
\[ \sqrt{I_{D2}} \sqrt{\frac{2L}{\mu C_{ox} W}} = V_2 - V_S - V_T \]

\[ V_d = \sqrt{2L \frac{\mu C_{ox} W}{\mu C_{ox} W}} \left( \sqrt{I_T - I_{D1}} - \sqrt{I_{D1}} \right) \]
\[ V_d = \sqrt{2L \frac{\mu C_{ox} W}{\mu C_{ox} W}} \left( \sqrt{I_{D2}} - \sqrt{I_T - I_{D2}} \right) \]
MOS Differential Pair

\[ V_d = \sqrt{\frac{2L}{\mu C_{ox} W}} \left( \sqrt{I_T - I_{D1}} - \sqrt{I_{D1}} \right) \]

\[ V_d = \sqrt{\frac{2L}{\mu C_{ox} W}} \left( \sqrt{I_{D2}} - \sqrt{I_T - I_{D2}} \right) \]

What values of \( V_d \) will cause all of the current to be steered to the left or the right?

\[ V_{dx} = \pm \sqrt{\frac{2L}{\mu C_{ox} W}} \left( \sqrt{I_T} \right) \]
\[ V_d = \sqrt{\frac{2L}{\mu C_{ox} W}} \left( \sqrt{I_{D2}} - \sqrt{I_T - I_{D2}} \right) \]
Q-point Calculations

\[ \frac{I_T}{2} = \frac{\mu C_{ox} W}{2L} (V_{EB})^2 \]

\[ V_{EB} = \sqrt{I_T} \sqrt{\frac{L}{\mu C_{ox} W}} \]

Observe !!

\[ V_{dx} = \pm \sqrt{2} V_{EB} \]
\[ V_d = \sqrt{\frac{2L}{\mu C_{ox} W}} \left( \sqrt{I_{D2}} - \sqrt{I_T - I_{D2}} \right) \]

Diagram:
- \( I_{D1} \)
- \( I_T \)
- \( I_{D2} \)

- \(-\sqrt{2V_{EB}}\)
- \(\sqrt{2V_{EB}}\)

\( V_{EB} \) affects linearity

How linear is the amplifier?
How linear is the amplifier?

$$V_d = \sqrt{\frac{2L}{\mu C_{ox} W}} (\sqrt{I_T - I_{D1}} - \sqrt{I_{D1}})$$

Consider the fit line:

$$I = m V_d + h$$

When $V_d = 0$, $I = I_T / 2$, thus

$$h = \frac{I_T}{2}$$

$$V_{dint} = -\frac{h}{m} = -\frac{I_T}{2m}$$

$$m = \left. \frac{\partial I_{D1}}{\partial V_d} \right|_{Q-pt}$$
How linear is the amplifier?

\[ I = mV_d + h \]

\[ V_{d_{int}} = \frac{-h}{m} = \frac{-I_T}{2m} \]

\[ V_d = \sqrt{\frac{2L}{\mu C_{ox} W \left( \sqrt{I_T - I_{D1}} - \sqrt{I_{D1}} \right)}} \]

\[ \frac{\partial V_d}{\partial I_{D1}} = -2 \sqrt{\frac{L}{\mu C_{ox} W}} \frac{1}{\sqrt{I_T}} \]

\[ \frac{\partial V_d}{\partial I_{D1}} = -2 \frac{V_{EB1}}{I_T} \]

\[ m = \frac{\partial I_{D1}}{\partial V_d} \bigg|_{Q\text{-pt}} = -\frac{I_T}{2V_{EB1}} \]
How linear is the amplifier?

\[ V_{\text{dint}} = -\frac{h}{m} = -\frac{I_T}{2m} = V_{EB1} \]

\[ I = -\left(\frac{I_T}{2V_{EB1}}\right)V_d + \frac{I_T}{2} \]
How linear is the amplifier?

It can be shown that the deviation from the line in % is given by

\[ \theta = 100\% \left( 1 - \sqrt{1 - \frac{(V_d/V_{EB})^2}{4}} \right) \]

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How linear is the amplifier?

A 1% deviation from the straight line occurs at

$$V_d \approx 0.3V_{EB}$$

and a 0.1% variation occurs at

$$V_d \approx \frac{V_{EB}}{10}$$
What swings on drain currents are typical when using the differential pair in an amplifier?

Assume the differential amplifier is the input stage to an op amp with gain $A_V$ and signal swing $V_{OUT_{pp}}$

The differential swing at the input is thus

$$V_{IN_{pp}} = \frac{V_{OUT_{pp}}}{A_V}$$
What swings on drain currents are typical when using the differential pair in an amplifier?

\[ V_{INpp} = \frac{V_{OUTpp}}{A_V} \]

If the amplifier is the simple differential amplifier with current source loads

\[ A_V = -\frac{g_{m1}}{2g_0} = \frac{2I_{DQ}}{\lambda V_{EB1}} \]

\[ A_V = -\frac{1}{\lambda V_{EB1}} \]

\[ V_{INpp} = (\lambda V_{OUTpp})V_{EB1} \]

If \( \lambda = 0.01V^{-1} \)

and \( V_{OUTpp} = 5V \),

\[ V_{INpp} = 0.05V_{EB1} \]

This results in a very small nonlinearity and a very small change in current When used in two-stage structure, even much smaller!
Bipolar Differential Pair

\[ V_d = V_2 - V_1 \]

\[ I_{C1} = J_S A_{E1} e^{\frac{V_1 - V_E}{V_t}} \]

\[ I_{C2} = J_S A_{E2} e^{\frac{V_2 - V_E}{V_t}} \]

\[ I_{C1} + I_{C2} = I_T \]

\[ V_1 = V_E + V_t \ln \left( \frac{I_{C1}}{J_S A_{E1}} \right) \]

\[ V_2 = V_E + V_t \ln \left( \frac{I_{C2}}{J_S A_{E2}} \right) \]

\[ V_d = V_t \left( \ln \left( \frac{I_{C2}}{J_S A_{E2}} \right) - \ln \left( \frac{I_{C1}}{J_S A_{E1}} \right) \right)^{A_{E1}=A_{E2}} = V_t \ln \left( \frac{I_{C2}}{I_{C1}} \right) \]
Bipolar Differential Pair

\[ V_d = V_t \left( \ln \left( \frac{I_{C2}}{J_{S_{A_{E2}}}} \right) - \ln \left( \frac{I_{C1}}{J_{S_{A_{E1}}}} \right) \right) \]

\[ V_d = V_t \ln \left( \frac{I_T - I_{C1}}{I_{C1}} \right) \]

\[ V_d = V_t \ln \left( \frac{I_{C2}}{I_T - I_{C2}} \right) \]

As \( I_{C1} = I_{C2} = I_T / 2 \), \( V_d = 0 \)

As \( I_{C1} \) approaches 0, \( V_d \) approaches infinity

As \( I_{C1} \) approaches \( I_T \), \( V_d \) approaches minus infinity

Transition much steeper than for MOS case
Transfer Characteristics of Bipolar Differential Pair

Transition much steeper than for MOS case
Asymptotic Convergence to 0 and $I_T$
Signal Swing and Linearity of Bipolar Differential Pair

\[ I_{FIT} = mV_d + h \]

\[ m = \frac{\partial I_{C1}}{\partial V_d} \mid_{Q-point} \]

\[ \frac{\partial V_d}{\partial I_{C1}} \mid_{Q-point} = -V_t \frac{I_T}{I_{C1}(I_T - I_{C1})} \]

\[ \frac{\partial V_d}{\partial I_{C1}} \mid_{Q-point} = -\frac{4V_t}{I_T} \]

\[ I_{FIT} = -\frac{I_T}{4V_t} V_d + \frac{I_T}{2} \]

\[ V_{dint} = -\frac{h}{m} = ? \]

\[ V_{dint} = -\frac{h}{m} = 2V_t \]
Signal Swing and Linearity of Bipolar Differential Pair

For 1% deviation, \( V_d = 0.56V_t \)

For 0.1% deviation, \( V_d = 0.27V_t \)
Signal Swing and Linearity of Bipolar Differential Pair

1% linear = 0.56Vt
Signal Swing and Linearity Summary

- Signal swing of MOSFET can be rather large if $V_{EB}$ is large but this limits gain.
- Signal swing of MOSFET degrades significantly if $V_{EB}$ is changed for fixed W/L.
- Bipolar swing is very small but independent of $g_m$.
- Multiple-decade adjustment of bipolar $g_m$ is practical.
- Even though bipolar input swing is small, since gain is often very large, this small swing does usually not limit performance in feedback applications.