Differential Amplifier Design

- Design with ideal current source bias.
- Differential and common mode gain results
- Add finite output resistance to current source.
- Replace ideal current source with current mirror.
Quick Amplifier Design

By inspection DC bias \( v_{i-dm} = v_{i-cm} = 0 \) for Q1 & Q2 is common mode:

\[
I_E = \frac{I}{2} = 5 \text{ mA}
\]

Neglecting \( I_B \):

\[
I_C = I_E = 5 \text{ mA}
\]

\[
V_{R_c} = 5 \text{ V} \Rightarrow V_{C1} = V_{CC} - V_{R_c} = 7 \text{ V}
\]

\[
V_E = -V_{BE} = -0.7 \text{ V}
\]

\[
V_{CE} = V_C - V_E = 7.7 \text{ V}
\]

Single-ended voltage gains w.r.t. \( v_{i-dm}/2 \) and \( v_{i-cm} \) (for Q1 side):

\[
A'_{v-dm1} = \frac{v_{c1-dm}}{v_i = v_{i-dm}/2} \approx -\frac{R_C}{R} = -10
\]

\[
A_{v-cm1} = \frac{v_{c1-cm}}{v_{cm}} \approx -\frac{R_C}{2r_o} = 0
\]

ideal current source, i.e. \( r_o = \infty \)
Differential-Mode AC Gain Results

“Scope” output B at collector of Q1, i.e. $v_B = v_{c1-dm}$. 

Input voltage $v_A = v_i = v_{i-dm}/2$

0.14 $V_{\text{peak}}$ $\arg (0^\circ)$ at $f = 1$ kHz.

Output voltage $v_B = v_{c1-dm}$

1.33 $V_{\text{peak}}$ $\arg (180^\circ)$. 

Measured gain:

$$A_{v-dm}' = \frac{v_B}{v_A} = \frac{v_{c1-dm}}{v_i} = \frac{-1.33}{0.14} V = -9.5$$
Common Mode AC Results

Since $I$ is an ideal current source, $i_{cm} = 0$ implies $i_{e-cm} = 0$.

No common mode signal current ($i_{cm} = 0$ implies $i_{e-cm} = 0$)

Thus, $v_{c1-cm} = 0$ V peak

$CMRR \approx 20 \log_{10} \left| \frac{-9.5}{0} \right| = \infty$
Comparing ac base and emitter voltages to ground for Q1, i.e. $v_{b1-cm}$, $v_{e1-cm}$.

$$v_{b1-cm} = v_{e1-cm} = 1.4 \, V_{peak}$$

$$\Rightarrow v_{be-cm} = 0 \, V_{peak}$$

Since $i_{e-cm} = 0$, we expect $v_{be-cm} = 0 \, V_{peak}$, i.e. all base voltage appears at emitter.
Common Mode Results - Add $r_o$ to Model

\[ A'_{v-dm1} = \frac{v_{c1-dm}}{v_i} \approx -\frac{R_C}{R_E} = -10 \]

\[ A_{v-cm1} = \frac{v_{c1-cm}}{v_{i-cm}} \approx -\frac{R_C}{2r_o} = -\frac{1}{200} = -0.005 \]

Insert finite $r_o$ to model non-ideal current source.
Common Mode Results - Add Finite $r_o$

$$r_o = 100 \, k\Omega$$

"Scope" output B at collector of Q1, i.e. $v_B = v_{c1-cm}$.

Input voltage $v_A = v_{i-cm}$

$$1.4 \, V_{\text{peak}} \arg (0^\circ) \text{ at } f = 1 \, kHz.$$  

Output voltage $v_B = v_{c1-cm}$

$$0.007 \, V_{\text{peak}} \arg (180^\circ).$$

$$A_{v-cm1} \approx \frac{-0.007}{1.4} = -0.005$$

$$A'_{v-dm1} = -9.5 \text{ (unchanged)}$$

$$CMRR \approx 20 \log_{10} \left( \frac{9.5}{0.005} \right) \approx 66 \, dB$$
Simulation with Current Mirror

Matched 2N2222 BJTs (Q1, Q2, Q3 and Q4).

\[ I_{C3} \approx 1 \, mA \]
\[ \Rightarrow I_{C1} = I_{C2} \approx 0.5 \, mA \]
\[ R_{\text{ref}} = 23.3 \, k\Omega \]

\[ V_{C1} = 11.5 \, V \]
\[ I_{C1} \approx \frac{I_{C3}}{2} \]
\[ I_{C2} \approx \frac{I_{C3}}{2} \]
\[ V_{i-cm} \]
\[ I_{\text{REF}} = \frac{V_{cc} - V_{BE4} - V_{EE}}{R_{\text{ref}}} = \frac{12 - 0.7 - (-12V)}{23.3} \, mA \approx 1 \, mA \]

NOTE: - The zero-to-peak ac voltage swing across each \( R_C \) now only 0.5 \( V \)!
Simulation with Current Mirror - II

“Scope” output B at collector of Q1, i.e. \( V_B = V_{c1-cm} \).

Input voltage \( V_A = V_{i-cm} \)

\( 1.4 \text{ V}_{\text{peak}} \ \text{arg}(0^\circ) \) at \( f = 1 \text{ kHz} \).

Output voltage \( V_B = V_{c1-cm} \)

\( 7 \text{ mV}_{\text{peak}} \ \text{arg}(180^\circ) \).

\[
A_{v-cml} \approx \frac{-0.007}{1.4} = -0.005
\]

1 kHz common mode results almost exactly same as those for \( r_o = 100 \text{ k}\Omega \) model.
Simulation with Current Mirror - III

Matched 2N2222 BJTs (Q1, Q2, Q3 and Q4).

$I_{C3} \approx 10 \text{ mA}$

$\Rightarrow I_{C1} = I_{C2} \approx 5 \text{ mA}$

$R_{ref} = 2.33 \text{ k}\Omega$

NOTE: - The zero-to-peak ac voltage swing across each $R_C$ increased to 5 V!
Simulation with Current Mirror - III

Input voltage $v_A = v_{i-cm}$

$1.4 \text{ V}_{\text{peak}} \arg (0^\circ)$ at $f = 1 \text{ kHz}$.

Output voltage $v_B = v_{c1-cm}$

$60 \text{ mV}_{\text{peak}} \arg (180^\circ)$.

$A_{v-cml} \approx -0.043$

Common mode output now about $10X$ its previous value with $0.5 \text{ mA}$ collector current.

Why? Early effect!

$r_o = \frac{V_A}{I_c} \approx 10k \Omega$

$10$ times the current means $1/10$ the value of $r_o$!
Simulation with Current Mirror - Bode Plots

5 mA current: $A_{v-cm1(db)}$ + 3 dB frequency

$A_{v-cm1(db)}(f = 1 kHz) \approx 20 \log_{10} \left( \frac{0.06}{1.4} \right) = -27.3 \text{ dB}$

$A_{v-cm1(db)}(f = 9.7 MHz) = -24.2 \text{ dB} (+ 3 \text{ dB})$

$\approx 10 k \Omega \quad (I_{REF} = 10 mA)$

$\approx 100 k \Omega \quad (I_{REF} = 1 mA)$

$f_B \approx \frac{1}{2 \pi r_o C_o}$

theory

$\frac{f_B(1 mA)}{f_B(10 mA)} \approx \frac{r_o(10 mA)}{r_o(1 mA)} = \frac{10k}{100k} = 0.1$

simulation

$\frac{f_B(1 mA)}{f_B(10 mA)} = \frac{1.9 MHz}{9.7 MHz} = 0.2$

$0.5 mA current: A_{v-cm1(db)} + 3 dB frequency$

$A_{v-cm1(db)}(f = 1 kHz) \approx 20 \log_{10} \left( \frac{0.007}{1.4} \right) = -46 \text{ dB}$

$A_{v-cm1(db)}(f = 1.9 MHz) = -43.2 \text{ dB} (+ 3 \text{ dB})$
Summary & Comparison

\[ I_{\text{REF}} = 1 \text{ mA} \]

\[ V_{RC1} \approx \frac{I_{\text{REF}}}{2} R_{C1} = 0.5 \text{ V} \]

\[ r_o \approx \frac{V_A}{I_{\text{REF}} / 2} = 100 \text{ k} \Omega \]

\[ A_{v-cml} = \frac{-R_{C1}}{2 r_o} \approx \frac{-0.007}{1.4} = -0.005 \]

\[ f_B \approx 1.9 \text{ MHz} \]

\[ A'_{v-dm1} = -9.5 \]

\[ I_{\text{REF}} = 10 \text{ mA} \]

\[ V_{RC1} \approx \frac{I_{\text{REF}}}{2} R_{C1} = 5 \text{ V} \]

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\[ A_{v-cml} = \frac{-R_{C1}}{2 r_o} \approx \frac{-0.06}{1.4} = -0.043 \]

\[ f_B \approx 9.7 \text{ MHz} \]

\[ A'_{v-dm1} = -9.5 \]
Try Redesign for Reasonable Differential Mode Voltage Swing & large \( r_o \)

Can we beat the \( r_o \) trade-off?

**IDEA:**

1. Reduce \( I_{\text{REF}} \) to increase \( r_o \).

\[
r_o \approx \frac{V_A}{I_{\text{REF}}}
\]

2. Increase \( R_C \) to increase \( V_{RC1} \).

\[
V_{RC1} = R_C \frac{I_{\text{REF}}}{2}
\]

3. Increase \( R_E \) to retain desired \( A'_{v-dm1} \).

\[
A'_{v-dm1} = \frac{R_C}{R_E}
\]

\[
A_{v-cm1} \approx - \frac{R_C}{2r_o} = - \frac{V_{RC1}}{I_{\text{REF}}/2} \frac{I_{\text{REF}}}{2V_A} = - \frac{V_{RC1}}{V_A}
\]

RESULT: No help!
Simulations with Parasitic Caps

Results with 2 pF capacitance added from collector-to-base of mirror transistor in the "\( I_{C1} = I_{C2} = 0.5 \ mA \) amplifier" emitter return path.

This drops the amplifier \( A_{v-cm1(db)} + 3 \ dB \) frequency from 1.9 MHz to about 645 kHz!

\[
A_{v-cm1(db)}(f = 1 \ kHz) \approx 20 \log_{10}\left(\frac{0.007}{1.4}\right) = -46 \ dB
\]

\[
A_{v-cm1(db)}(f = 645 \ kHz) = -43.2 \ dB
\]
Simulations with Parasitic Caps - cont.

Results with 2 pF capacitance added from base-to-emitter of mirror transistor.

This drops the amplifier $A_{v-cm1}(f = 1 \text{ kHz}) \approx 20 \log_{10} \left( \frac{0.007}{1.4} \right) = -46 \text{ dB}$

$A_{v-cm1}(f = 334 \text{ kHz}) = -43.2 \text{ dB}$

RECALL: 2 pF is about the capacitance between 2 rows of Protoboard pins!
Simulations with Parasitic Caps - cont.

Drops amplifier $A_v-cm1(dB)$ break frequency from $1.9 \text{ MHz}$ to about $234 \text{ kHz}$!
Simulate the 5 mA Design with 2 pF Parasitics

3dB common mode bandwidth with 2 pF base-emitter and base collector capacitances.

About 10X the bandwidth as the $I_{REF} = 1$ mA design.
Observations

1). For best common mode rejection use small collector currents i.e. increase $r_o$.

2). For best bandwidth use large collector currents, i.e. decrease $r_o$.

3). Minimize parasitic capacitance around mirror transistor to increase common mode rejection bandwidth.

4). Since no differential mode current flows through the mirror transistor (Q3, i.e. $r_o$), it should have no effect on differential mode performance.

5). Observations 1) and 2) force a trade-off in selecting the bias current.
\[ v_{i-cm} = 0 \]

\[ 2v_i = \frac{v_i}{2} \]

\[ \frac{v_i}{2} \]

\[ \frac{v_i}{2} \]
\[ v_1 = v_i \]
\[ v_{i-cm} = 0 \]
\[ v_2 = -v_i \]

\[ v_1 - v_2 = 2v_i \]
\[ v_1 \neq v_i \]
\[ v_2 \neq -v_i \]

\[ v_1 = \frac{v_i}{2} + \frac{v_i}{2} = v_i \]
\[ v_2 = \frac{v_i}{2} - \frac{v_i}{2} = 0 \]