Quick Review

Balance op.:

\[ R_{C1} = R_{C2} = R_C \]
\[ R_{B1} = R_{B2} = R_B \]
\[ R_{E1} = R_{E2} = R_E \]

\[ Q1 = Q2 \]
Quick Review

CM - DC

CM AC - Sm. Sig.
Quick Review

Differential mode (balanced)

\[ r_{in\_dm} = \frac{v_{i\_dm}}{i_{b1\_dm}} = (\beta + 1) \frac{2(r_e + R_E)}{r_e + R_E} \]

\[ A_{v\_dm} = \frac{v_{o\_dm}}{v_{i\_dm}} = \frac{R_C}{r_e + R_E} \]

Common mode (balanced)

\[ r_{in\_cm} = \frac{v_{i\_cm}}{2i_{b\_cm}} = (\beta + 1) \left( \frac{r_e + R_E}{2} + r_0 \right) \]

\[ A_{v\_cm} = \frac{v_{o\_cm}}{v_{i\_cm}} = 0 \text{ i.f.f. Balanced} \]

Single-ended-output (balanced)

\[ CMRR = \frac{A_{v\_dm1,2}}{A_{v\_cm1,2}} \approx 20 \log_{10} \left( \frac{r_o}{r_e + R_E} \right) \]

Differential-output

\[ CMRR = \infty \text{ i.f.f. Balanced} \]

\[ CMRR = 20 \log_{10} \left( 2 \frac{r_o}{r_e + R_E} \frac{1}{\Delta R_C / R_C} \right) \]
**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:

$$I_E = \frac{I}{2} = 5 mA$$

Neglecting $I_B$:

$$I_C = I_E = 5 mA \Rightarrow V_{RC} = \frac{I_C}{R_C} = 5 V$$

$$V_{RC} = 5 V \Rightarrow V_C = V_{CC} - V_{RC} = 7 V$$

$$V_E = -V_{BE} = -0.7 V$$

$$V_{CE} = V_C - V_E = 7.7 V$$

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

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

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

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

"Scope" output B at collector of Q1, i.e. \( v_B = v_{cl - dm} \).

Input voltage \( v_A = v_i = v_{i - dm}/2 \)  
0.14 \( V_{\text{peak}} \) arg (0°) at \( f = 1 \) kHz.

Output voltage \( v_B = v_{cl - dm} \)  
1.33 \( V_{\text{peak}} \) arg (180°).

Measured gain:

\[
A'_{v - dm} = \frac{v_B}{v_A} = \frac{v_{cl - dm}}{v_{i - dm}/2} = \frac{-1.33 \text{ V}}{0.14 \text{ V}} = -9.5
\]
Common Mode AC Results

“Scope” output B at collector of Q1, i.e. \( V_B = V_{cl-cm} = 0 \) V.

Input voltage \( V_A = V_{i-cm} \)
\[
\begin{align*}
0.14 \text{ V}_{\text{peak}} \quad \text{arg} \,(0^\circ) \text{ at } f = 1 \text{ kHz}.
\end{align*}
\]

Since \( I \) is an ideal current source \( r_o = \infty \) \( \Rightarrow \ A_{v-cml} = 0 \).

\[
A_{v-cml} = \frac{V_B}{V_A} = \frac{V_{cl-dm}}{V_{i-cm}} = \frac{0 \text{ V}}{0.14 \text{ V}} = 0
\]

\[
CMRR = 20 \log_{10} \left| \frac{A'_{v-dml}}{A_{v-cml}} \right| = 20 \log_{10} \left| \frac{-9.5}{0} \right| = \infty
\]
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

Theory

$A'_{v-dm} = \frac{v_{cl-dm}}{v_i} \approx -\frac{R_C}{R_E} = -10$

$A'_{v-cm} = \frac{v_{cl-cm}}{v_{i-cm}} \approx -\frac{1}{2 \cdot r_o} = -0.005$

$CMRR = 20 \log_{10} \left| \frac{A'_{v-dm}}{A'_{v-cm}} \right| = 66 \text{ dB}$
**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 $v_A = v_{i-cm}$

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

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

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

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

$A'_{v-dm} = -9.5$ (unchanged)

$CMRR \approx 20 \log_{10}(\frac{9.5}{0.005}) \approx 66 \, dB$
Simulation with 1 mA Current Mirror

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

\[ I_{C3} \approx 1 \text{ mA} \]

\[ \Rightarrow I_{C1} = I_{C2} \approx 0.5 \text{ mA} \]

\[ R_{ref} = 23.3 \text{ k} \Omega \]

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

\[ I_{REF} = \frac{V_{CC} - V_{BE4} - V_{EE}}{R_{ref}} = \frac{12 - 0.7 - (-12)}{23.3} \text{ mA} \approx 1 \text{ mA} \]
"Scope" output B at collector of Q1, i.e. \( v_B = v_{c1-cm} \).

Input voltage \( v_A = v_{i-cm} \)

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

Output voltage \( v_B = v_{c1-cm} \)

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

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

1 kHz common mode results almost exactly same as those for \( r_o = 100 \, k\Omega \) model.
Simulation with 10 mA Current Mirror

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 10 mA Current Mirror cont.

Input voltage \( v_A = v_{i-cm} \)
\[ 1.4 \text{ V}_{\text{peak}} \text{ arg (0°)} \text{ at } f = 1 \text{ kHz}. \]

Output voltage \( v_B = v_{c1-cm} \)
\[ 60 \text{ mV}_{\text{peak}} \text{ arg (180°)}. \]
\[ A_{v-cm1} \approx -0.043 \]

Common mode output now about 10X its previous value with 0.5 mA. collector current.

Why? \( r_o \) has decreased!
\[ r_o = \frac{V_A}{I_c} \approx 10 \text{ kΩ} \]
\[ 10 \text{ times the current means } 1/10 \text{ the value of } r_o! \]
Simulation with 1 mA & 10 mA CMs - Bode Plots

For 5 mA current:

- \[ f_B \approx 9.7 \text{ MHz} \]
- \[ A_{v-cm1}(dB) + 3 \text{ dB} \text{ frequency} \]

For 0.5 mA current:

- \[ f_B \approx 1.9 \text{ MHz} \]
- \[ A_{v-cm1}(dB) + 3 \text{ dB} \text{ frequency} \]

Calculation:

\[ r_o \approx 10 \text{ k}\Omega \quad (I_{REF} = 10 \text{ mA}) \]

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

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

\[ f_B \approx \frac{1}{2\pi r_o C_o} \Rightarrow \]

\[ \text{theory} \quad \frac{f_B(1mA)}{f_B(10mA)} \approx \frac{r_o(10mA)}{r_o(1mA)} = \frac{10k}{100k} = 0.1 \]

\[ \text{simulation} \quad \frac{f_B(1mA)}{f_B(10mA)} = \frac{1.9 \text{ MHz}}{9.7 \text{ MHz}} = 0.2 \]

\[ r_o \approx 100 \text{ k}\Omega \quad (I_{REF} = 1 \text{ mA}) \]

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

\[ A_{v-cm1}(dB)(f = 1.9 \text{ MHz}) = -43.2 \text{ dB} \ (+ 3\text{ dB}) \]
Comparison of 1 mA & 10 mA CM Results

\[ I_{REF} = 1 \text{ mA} \quad V_A = 50 \text{ V} \]

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

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

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

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

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

\[ I_{REF} = 10 \text{ mA} \quad V_A = 50 \text{ V} \]

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

\[ r_o \approx \frac{V_A}{I_{REF}/2} = 10 \text{ k } \Omega \]

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

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

\[ A'_{v-dml} = -9.5 \]
Simulations with Parasitic Caps

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

This drops the amplifier $A_{v-cm1(\text{dB})} + 3 \text{ dB}$ frequency from 1.9 MHz to about 645 kHz!
Simulations with Parasitic Caps - cont.

Results with $2 \, \text{pF}$ capacitance added from base-to-emitter of mirror transistor.

This drops the amplifier $A_{v_{cm1}(dB)}$ +3 dB frequency from 1.9 MHz to about 334 kHz!

RECALL: $2 \, \text{pF}$ 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 MHz to about 234 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.

Parasitic caps drop amplifier $A_{v-cm(dB)}$ break frequency from 9.7 MHz to about 2.5 MHz!

$$A_{v-cm1(dB)}(f = 1 kHz) \approx -27 dB$$
$$A_{v-cm1(dB)}(f = 2.5 MHz) = -24.2 dB$$

<table>
<thead>
<tr>
<th>$I_{REF} = 10 mA$</th>
<th>$I_{REF} = 1 mA$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_B \approx 2.5 MHz$</td>
<td>$234 kHz$</td>
</tr>
<tr>
<td>$A_{v-cm1(dB)}(f = 1 kHz)$</td>
<td>$-27 dB$</td>
</tr>
<tr>
<td>$A'_{v-dm1(dB)}(f = 1 kHz)$</td>
<td>$+20 dB$</td>
</tr>
</tbody>
</table>
Observations

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

2). For best $A_{v-cm}$ 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.
Try Redesign for Reasonable Differential Mode Voltage Swing & large $r_o$

Can we beat the $r_o$ trade-off?

**IDEA:**
1. Reduce $I_{REF}$ to increase $r_o$.
   \[
   r_o \approx \frac{V_A}{I_{REF}}
   \]
2. Increase $R_C$ to increase $V_{RC1}$.
   \[
   V_{RC1} = R_C \frac{I_{REF}}{2}
   \]
3. Increase $R_E$ to retain desired $A'_{v-dm1}$.
   \[
   A'_{v-dm1} = \frac{R_C}{R_E}
   \]

RESULT: No help!

\[
A_{v-cm1} \approx \frac{R_C}{2r_o} = -\frac{V_{RC1}}{I_{REF}/2} \frac{2V_A}{2V_A} = -\frac{V_{RC1}}{V_A}
\]
\[ v_1 = v_i \]
\[ v_{i-cm} = 0 \]
\[ v_2 = -v_i \]

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

\[ v_1 = v_i / 2 + v_i / 2 = v_i \]
\[ v_2 = v_i / 2 - v_i / 2 = 0 \]