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 (for Q1 & Q2):

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

Neglecting \( I_B \):

\[ I_C = I_E = 5 \, mA. \]

\[ V_{R_c} = 5 \, V \Rightarrow V_{CG} = V_{CC} - V_{R_c} = 7 \, V \]

\[ V_{EG} = -V_{BE} = -0.7 \, V \]

\[ V_{CE} = V_{CG} - V_{EG} = 7.7 \, V \]

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

\[ G_{dm1/2} = \frac{v_{clg-dm}}{v_i = v_{dm/2}} \approx \frac{-R_C}{R_E} = -10 \]

\[ G_{cm1} = \frac{v_{clg-cm}}{v_{cm}} \approx -\frac{R_C}{2r_o} = 0 \]
Differential-Mode Gain Results

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

Input voltage $v_{dm}/2$:
$0.14 \, V_{\text{peak}} \, \arg(0^\circ)$ at $f = 1 \, \text{kHz}$.

Output voltage $v_{clg-dm}$:
$1.33 \, V_{\text{peak}} \, \arg(180^\circ)$.

Measured gain:

$$G_{dm1/2} = \frac{v_{clg-dm}}{v_{i} = v_{dm}/2} = \frac{-1.33 \, V}{0.14 \, V} = -9.5$$
Common Mode Results

“Scope” output B at collector of Q1, i.e. $v_{cm}$. Input voltage $v_{cm}$:

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

Since $I$ is an ideal current source $r_o = \infty \Rightarrow G_{cm1} = 0$.

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

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

$$CMRR \approx 20 \log_{10} \left( \frac{9.5}{0} \right) = \infty$$
Comparing base and emitter voltages to ground for Q1, i.e. $v_{b_{1g}-cm}$, $v_{e_{1g}-cm}$.

$$v_{b_{1g}-cm} = v_{e_{1g}-cm} = 1.4 \text{ V}_{\text{peak}}$$

$$\Rightarrow v_{b_{e-cm}} = 0 \text{ V}_{\text{peak}}$$

Since $i_{e-cm} = 0$, we expect $v_{b_{e-cm}} = 0 \text{ V}_{\text{peak}}$, all base voltage appears at the emitter.
**Common Mode Results - Add $r_o$ to Model**

- **$G_{dm1/2}$**
  \[
  G_{dm1/2} = \frac{v_{clg-dm}}{v_i = v_{dm}/2} \approx -\frac{R_C}{R_E} = -10
  \]

- **$G_{cm1}$**
  \[
  G_{cm1} \approx -\frac{R_C}{2 \cdot r_o} = \frac{-1}{200} = -0.005
  \]

To model non-ideal current source, insert finite $r_o$. 

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Common Mode Results - Add Finite $r_o$

$r_o = 100 \, k \Omega$

“Scope” output B at collector of Q1, i.e. $v_{clg-cm}$.

Input voltage $v_{cm}$:

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

Output voltage $v_{clg-cm}$:

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

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

$G_{dm1/2} = -9.5 \text{ (unchanged)}$

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

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

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

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

\[ I_{REF} = \frac{V_{CC} - V_{BE4} - V_{EE}}{R_{ref}} = \frac{12 - 0.7 - (-12)}{23.3} \text{ mA} \approx 1 \text{ mA} \]

\[ V_{C1G} = 11.5 \text{ V} \]

\[ I_{C1} \approx \frac{I_{C3}}{2} \]

\[ I_{C2} \approx \frac{I_{C3}}{2} \]

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

\[ R_{c1} = 1 \text{ kOhm} \]

\[ R_{c2} = 1 \text{ kOhm} \]

\[ R_b1 = 100 \text{ Ohm} \]

\[ R_b2 = 10 \text{ kOhm} \]

\[ R_{ref} = 23.3 \text{ kOhm} \]

\[ V_{cc} = 12 \text{ V} \]

\[ V_{ee} = 12 \text{ V} \]

\[ V_{cm} \]

NOTE: - The zero-to-peak swing at the collector now only 0.5 V!
Simulation with Current Mirror - II

“Scope” output B at collector of Q1, i.e. $v_{c1g-cm}$.

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

Output voltage $v_{c1g-cm}$:
$7 \text{ mV}_{\text{peak}} \arg(180^\circ)$.

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

$1 \text{ kHz}$ 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).

\[ I_{C3} \approx 10 \text{ mA} \]

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

**NOTE:** - The zero-to-peak swing at the collector now increased to 5 V!
Simulation with Current Mirror - III

Input voltage $v_{cm}$:
$1.4 \, V_{peak} \, \arg (0^\circ)$ at $f = 1 \, kHz$.

Output voltage $v_{c1g-cm}$:
$60 \, mV_{peak} \, \arg (180^\circ)$.

$G_{cm} \approx -0.043$

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

Why? Early effect!

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

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

5 mA current: $G_{cm-dB} + 3$ dB frequency

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

theory $\frac{f_B(0.5 mA)}{f_B(5 mA)} \approx \frac{r_o(5 mA)}{r_o(0.5 mA)} = \frac{10k}{100k} = 0.1$

simulation $\frac{f_B(0.5 mA)}{f_B(5 mA)} = \frac{1.9 MHz}{9.7 MHz} = 0.2$

$G_{cm-dB}(f=1 kHz) \approx 20 \log_{10} \left( \frac{0.06}{1.4} \right) = -27.3$ dB

$G_{cm-dB}(f=9.7 MHz) = -24.2$ dB (+ 3dB)

$G_{cm-dB}(f=1 kHz) \approx 20 \log_{10} \left( \frac{0.007}{1.4} \right) = -46$ dB

$G_{cm-dB}(f=1.9 MHz) = -43.2$ dB (+ 3dB)

0.5 mA current: $G_{cm-dB} + 3$ dB frequency

$r_o \approx 100k \Omega \ (I_C = 5 mA)$

$r_o \approx 100k \Omega \ (I_C = 0.5 mA)$
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 $G_{cm-db} + 3 \, dB$ frequency from 1.9 MHz to about 645 kHz!

$$G_{cm-db}(f = 1 \, kHz) \approx 20 \log_{10}\left(\frac{0.007}{1.4}\right) = -46 \, dB$$

$$G_{cm-db}(f = 645 \, kHz) = -43.2 \, dB$$
Simulations with Parasitic Caps - cont.

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

This drops the amplifier $G_{cm-dB}$ frequency from $1.9 \text{ MHz}$ to about $334 \text{ kHz}$!

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

Drops amplifier $G_{cm-db}$ break frequency from 1.9 MHz to about 234 kHz!

$$G_{cm-dB}(f = 1 \text{ kHz}) \approx 20 \log_{10}(\frac{0.007}{1.4}) = -46 \text{ dB}$$

$$G_{cm-dB}(f = 234 \text{ kHz}) = -43.2 \text{ dB}$$
Simulate the 5 mA Design with 2 pF Parasitics

$3\text{dB}$ common mode bandwidth with 2 pF base-emitter and base collector capacitances.

About $10X$ the bandwidth as the 0.5 mA design with same low frequency CM gain as the 5 mA design for DM gain of -10.

$G_{cm-db}(f=1\text{kHz}) \approx -27 \text{ dB}$

$G_{cm-db}(f=2.5\text{MHz}) = -24.2 \text{ dB}$

Drops amplifier $G_{cm-db}$ break frequency from 9.5 MHz to about 2.5 MHz!

<table>
<thead>
<tr>
<th>$I_{C1}$</th>
<th>$f_B$</th>
<th>$G_{cm-db}(f=1\text{kHz})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mA</td>
<td>2.5 MHz</td>
<td>-27 dB</td>
</tr>
<tr>
<td>0.5 mA</td>
<td>234 kHz</td>
<td>-46 dB</td>
</tr>
</tbody>
</table>
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.
Try Redesign for Reasonable Differential Mode Voltage Swing & large $r_o$

$I_{C3} = 1 \, mA \Rightarrow r_o \approx 100 \, k\Omega$

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 $R_{C1}$ to increase $V_{RC1}$.

   $$R_{C1} = \frac{V_{RC1}}{I_{REF}/2}$$

3. Increase $R_{E1}$ to desired $G_{dm1/2}$.

   $$R_{E1} = -\frac{R_C}{G_{dm1/2}}$$

   $$G_{cm1} \approx \frac{R_C}{2 \, r_o} = \frac{V_{RC1} \cdot I_{REF}/2}{V_A} = \frac{V_{RC1}}{V_A}$$

**RESULT:** No help!
Redesign \( (I_{REF} = 1 \, mA) \) Bode Plot

1. Increasing \( r_o \) by \( 10X \), \( r_o = 10 \, k\Omega \to 100 \, k\Omega \) decreases the CM gain by \( 10X \).

2. Increasing \( R_C \) by \( R_C = 1 \, k\Omega \to 10 \, k\Omega \) increased the CM gain by \( 10X \).

3. Nothing gained!
\[
G_{cm-dB} (f = 1 \, kHz) \approx -26 \, dB
\]

About same as \( I_{REF} = 10 \, mA \) design!

\[
G_{cm-db} \text{ break frequency } f_b \approx 288 \, kHz
\]

About same as \( I_{REF} = 1 \, mA \) design!

where \( f_b \approx 234 \, kHz \)

Simulation with \( 2 - 2 \, pF \) caps.

1. \( f_B = 288 \, kHz \).

2. Low frequency CM gain -26 dB.

\[
f_B \approx \frac{1}{2\pi r_o C_o}
\]
v_{cm} = 0

\[2v_i = v_i/2\]
\[ v_{1} = \frac{v_{i}}{2} + \frac{v_{i}}{2} \]

\[ v_{2} = \frac{v_{i}}{2} - \frac{v_{i}}{2} \]

\[ v_{cm} = 0 \]