Quick Review

Balance op.

\[ R_{C1} = R_{C2} = R_C \]
\[ R_{B1} = R_{B2} = R_B \]
\[ R_{E1} = R_{E2} = R_E \]
\[ Q_1 = Q_2 \]
Quick Review

CM - DC

DM AC - Sm. Sig.

CM AC - Sm. Sig.
Quick Review

Differential mode (balanced)

\[ Z_{in-dm} = \frac{v_{id}}{i_{bld}} = (\beta + 1) \frac{2(r_e + R_E)}{2(r_e + R_E)} \]

\[ A_{v-dm} = \frac{v_{c2-dm}}{v_{i-dm}} = \frac{RC}{2(r_e + R_E)} \]

Common mode (balanced)

\[ Z_{in-cm} = \frac{v_{ic}}{2i_{bc}} = (\beta + 1) \frac{r_e + R_E}{2} + r_0 \]

\[ A_{v-cm} = \frac{v_{c1-cm}}{v_{i-cm}} = \frac{RC}{2r_o} \]

\[ A_{v-cm} (unbal) = \frac{v_{ocm}}{v_{ic}} \approx \frac{RC}{2r_o} \frac{\Delta R_C}{R_C} \]

if Unbalanced due to \( R_{C1} \neq R_{C2} \)

Single-ended-output (balanced)

\[ CMRR = \frac{A_{vdm1,2}}{A_{vcm1,2}} \approx 20 \log_{10} \left( \frac{r_o}{r_e + R_E} \right) \]

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

Neglecting $I_B$: let $I_B = 0$

$$V_{E} = -V_{BE} = -0.7 \text{ V}$$
$$V_{C} = V_{CC} - V_{R_e} = 7 \text{ V}$$
$$I_C = I_E = 5 \text{ mA} \Rightarrow V_{R_e} = \frac{I_C}{R_C} = 5 \text{ V}$$
$$V_E = -V_{BE} = -0.7 \text{ V}$$
$$V_{CE} = V_C - V_E = 7.7 \text{ V}$$

Single-ended voltage gains w.r.t. $v_{id}/2$ and $v_{ic}$ (for Q2 side):

$$A'_{vdm1} = \frac{v_{o1d}}{v_i} \approx \frac{-R_C}{R_E + r_e} = -10$$

$$r_e = \frac{V_T}{I_E} \approx 5 \Omega$$

$$A_{vcm2} = \frac{v_{o1c}}{v_{ic}} \approx -\frac{R_C}{2r_o} = 0$$

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

$$V_{CC} = 12 \text{ V}$$
$$V_{EE} = 12 \text{ V}$$

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

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

Input voltage  \( v_A = v_t = \frac{v_{id}}{2} \)

\[ 0.14 \text{ V}_{\text{peak}} \arg(0^\circ) \text{ at } f = 1 \text{ kHz}. \]

Output voltage  \( v_B = v_{old} \)

\[ 1.33 \text{ V}_{\text{peak}} \arg(180^\circ). \]

Measured gain:

\[ A'_{vdm1} = \frac{v_B}{v_A} = \frac{v_{old}}{\frac{v_{id}}{2}} = \frac{-1.33 \text{ V}}{0.14 \text{ V}} = -9.5 \approx -\frac{R_C}{2R_E} \]
Common Mode AC Results

Since \( I \) is an ideal current source \( r_o = \infty \) \( \Rightarrow A_{vcm1} = 0 \).

\[
A_{vcm1} = \frac{v_B}{v_A} = \frac{v_{o1c}}{v_{ic}} = -\frac{0 V}{0.14 V} = 0
\]

\[
CMRR = 20 \log_{10} \left| \frac{A'_{vdm1}}{A_{vcm1}} \right| = 20 \log_{10} \left| \frac{9.5}{0} \right| = \infty
\]
Common Mode Results - Add $r_o$ to Model

\[ A'_{vdm1} = \frac{v_{old}}{v_{id}} \approx \frac{-R_C}{R_E} = -10 \]

\[ A'_{vcm1} = \frac{v_{o1c}}{v_{ic}} \approx -\frac{R_C}{2r_o} = -0.005 \]

\[ CMRR = 20 \log_{10} \left| \frac{A'_{vdm1}}{A'_{vcm1}} \right| = 66 \text{ dB} \]

Theory

-insert finite $r_o$ to model non-ideal current source

Kenneth R. Laker updated KRL 01Oct14
Common Mode Results - Add Finite $r_o$

$r_o = 100 \, k\Omega$

“Scope” output B at collector of Q1, i.e. $v_B = v_{o1cm}$.

Input voltage $v_A = v_{ic}$

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

Output voltage $v_B = v_{o1cm}$

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

$A_{vcm1} \approx \frac{-0.007}{1.4} = -0.005$

$A_{vdm1}' = -9.5$ (unchanged)

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

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

\[ I_{C3} \approx 1 \text{ mA} \]
\[ \Rightarrow I_{C1} = I_{C2} \approx 0.5 \text{ mA} \]

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

NOTE: - The zero-to-peak ac voltage swing across each \( R_C \) now only 0.5 V!
Simulation with 1 mA Current Mirror cont.

“Scope” output B at collector of Q1, i.e. $v_B \approx v_{o1c}$.

Input voltage $v_A = v_{ic}$

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

Output voltage $v_B = v_{o1c}$

$7 \text{ mV peak arg(180°)}$.

$$A_{vcm1} \approx \frac{-0.007}{1.4} = -0.005$$

$1 \text{ kHz}$ common mode results almost exactly same as those for $r_o = 100 \text{ kΩ}$ model.
Simulation with 10 mA Current Mirror

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

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

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

\[ R_{ref} = 2.33 \text{ k}\Omega \]

\[ I_{REF} = \frac{V_{CC} - V_{BE4} - V_{EE}}{R_{ref}} \approx 10 \text{ mA} \]

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 $v_A = v_{ic}$

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

Output voltage $v_B = v_{o1c}$

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

$A_{vcm1} \approx -0.043$

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

Why? $r_o$ has decreased!

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

10 times the current means $1/10$ the value of $r_o$!
Simulation with 1 mA & 10 mA CMs - Bode Plots

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

$A_{vcm1}(dB)(f=1 \, kHz) \approx 20 \log_{10} \left( \frac{0.06}{1.4} \right) = -27.3 \, dB$

$A_{vcm1}(dB)(f=9.7 \, MHz) = -24.2 \, dB \ (+ 3dB)$

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

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

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

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

$A_{vcm1}(dB)(f=1 \, kHz) \approx 20 \log_{10} \left( \frac{0.007}{1.4} \right) = -46 \, dB$

$A_{vcm1}(dB)(f=1.9 \, MHz) = -43.2 \, dB \ (+ 3dB)$
Comparison of 1 mA & 10 mA CM Results

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

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

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

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

\[ f_B \approx 1.9 \ MHz \]

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

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

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

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

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

\[ f_B \approx 9.7 \ MHz \]

\[ A'_{v-dm1} = -9.5 \]
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\ mA amplifier" emitter return path.

This drops the amplifier $A_{vcm1(db)} + 3\ dB$ frequency from 1.9\ MHz to about 645\ kHz!

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 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 $A_{vcm(dB)}$ break frequency from 9.7 MHz to about 2.5 MHz!

<table>
<thead>
<tr>
<th>$I_{REF}$</th>
<th>$f_B$</th>
<th>$A_{vcm(dB)}(f=1\text{ kHz})$</th>
<th>$A_{vdm(dB)}(f=1\text{ kHz})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mA</td>
<td>2.5 MHz</td>
<td>$-27$ dB</td>
<td>$+20$ dB</td>
</tr>
<tr>
<td>1 mA</td>
<td>234 kHz</td>
<td>$-46$ dB</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.