Differential Amplifier with Active Loads

- Active load basics
- PNP BJT current mirror
- Small signal model
- Design example and simulation
- Comparison of CMRR with resistive load design
**Differential Amp – Active Loads Basics 1**

-problem: op. pt. $V_{CG1}$, $V_{CG2}$ very sensitive to mismatch $I_{ref1} \neq I_{ref2}$. 

$$R_{C2} \Rightarrow r_{o7}$$

$$R_{C1} \Rightarrow r_{o6}$$
Differential Amp – Active Loads Basics 2

\[ \text{slope} = -\frac{1}{R_{C2}} \]

\[ \text{slope} = -\frac{1}{r_{o7}} \]
**PROBLEM**: Op. Pt. $V_{CG1}$, $V_{CG2}$ very sensitive to mismatch $I_{ref1} \neq I_{ref2}$.

**SOLUTION**: all currents referenced to $I_{ref1}$. Op. Pt. sensitivity eliminated.

**COST**: output single-ended only.

**GOOD NEWS**: CMRR is much improved over resistive-load differential amp single-ended CMRR.
Quick Review - PNP BJT

Voltage bias equations:

\[ I_E = \frac{V_{CC} - (V_{BG} + 0.7)}{R_E} \]
\[ I_E = \frac{(V_{CC} - V_{BG}) - 0.7}{R_E} \]
\[ I_E = \frac{V_{R1} - 0.7}{R_E} = \frac{I \times R_l - 0.7}{R_E} \]

Note reference current directions!

\[ I \approx \frac{I_C}{10} \]
Quick Review – PNP BJT

Usual Large signal equations:

\[ i_C = I_S e^{\frac{v_{EB}}{V_T}} \]

\[ i_B = \frac{i_C}{\beta} \]

\[ i_E = i_C + i_B = \frac{(\beta + 1)}{\beta} i_C \]

\[ i_C = \alpha i_E \]
Quick Review - PNP – Small Signal Model

NPN: dc and ac currents in same direction

Small signal model is identical for NPN and PNP transistors!

PNP: dc and ac currents in opposite direction due to vsig polarity
PNP Mirror

Current source model $Q_1 = Q_2$:

$$I = \frac{V_{CC} - 0.7}{R_{REF}}$$

$$V_{CC} = V_{EB1} + I R_{REF}$$

Small signal model:

$$i_x = \frac{V_{eb1}}{r_\pi} + g_m V_{eb1} = \left(\frac{1}{r_\pi} + g_m\right) V_{eb1}$$

$$i_x = \left(\frac{g_m}{\beta} + g_m\right) V_{eb1} = \left(\frac{\beta + 1}{\beta}\right) g_m V_{eb1} = \frac{V_{eb1}}{r_e}$$

Current through $r_\pi$ and $g_m V_{eb1}$:

$$r_\pi = \frac{\beta}{g_m}$$

$$r_e = \frac{r_\pi}{\beta + 1}$$
**Simplified Midband DM Small Signal Model**

1. Due to imbalance created by active load current mirror, only single-ended output is available from common collector of Q2 and Q4.
2. Symmetry creates virtual ground at amplifier emitter connection.

\[ v_{eg} = 0, \ i = 0 \]
Matched NPN: \( Q_3 = Q_4 \)

\[
\begin{align*}
g_{m3} &= g_{m4} = g_{mn} \\
r_{e3} &= r_{e4} = r_{en} \\
r_{\pi3} &= r_{\pi4} = r_{\pi n} \\
r_{o3} &= r_{o4} = r_{on}
\end{align*}
\]

combining parallel resistances to ground:
\( r_{el} || r_{o1} || r_{o3} || r_{pi2} \approx r_{el} \)

From previous slide

Matched PNP \( Q_1 = Q_2 \)

\[
\begin{align*}
g_{m1} &= g_{m2} = g_{mp} \\
r_{el} &= r_{e2} = r_{cp} \\
r_{\pi1} &= r_{\pi2} = r_{\pi p} \\
r_{o1} &= r_{o2} = r_{op}
\end{align*}
\]
Simplified DM Small Signal Model - cont.

From previous slide with \( re_1 \parallel ro_1 \parallel ro_3 \parallel rpi_2 \approx re_1 \)

Matched NPN: Q3 = Q4
Matched PNP: Q1 = Q4
Matched NPN: Q3 = Q4
Matched PNP: Q1 = Q4

Determine \( i_{c2} \) and \( i_{c4} \):

\[
V_{eb1} \approx g_{mn} \frac{V_{dm}}{2} r_{ep}
\]

\[
i_{c2} = g_{mp} V_{eb1} = g_{mp} \left( g_{mn} \frac{V_{dm}}{2} r_{ep} \right)
\]

where:

\[
r_{ep} = \frac{\beta + 1}{\beta} \frac{1}{g_{mp}} \approx 1
\]

hence:

\[
i_{c2} \approx g_{mn} \frac{V_{dm}}{2}
\]

by inspection:

\[
i_{c4} = g_{mn} \frac{V_{dm}}{2}
\]

\[\Rightarrow i_{c2} \approx i_{c4}\]
Simplified DM Small Signal Model - cont.

Note that the Early resistors \( r_{o2} = r_{op} \) (PNP) & \( r_{o4} = r_{on} \) (NPN) are in parallel, and are driven by two nearly equal parallel current sources.

\[
R_o = r_{op} \parallel r_{on} \neq r_o \Rightarrow r_o = \frac{r_o}{2}
\]

\[
v_{o-\text{dm}} = (i_{c2} + i_{c4}) R_o = 2 \left( g_{mn} \frac{V_{dm}}{2} \right) R_o
\]

\[
v_{o-\text{dm}} = 2 g_{mn} R_o \frac{V_{dm}}{2}
\]

\[
G_{dm} = \frac{v_{o-\text{dm}}}{V_{dm}} = g_{mn} r_{op} \parallel r_{on}
\]

\[
G_{cm} = \frac{v_{o-\text{cm}}}{V_{cm}} = - \frac{r_{op}}{\beta_p r_o}
\]

From previous slide:

\[
i_{c2} \approx g_{mn} \frac{V_{dm}}{2} = i_{c4}
\]
**Simplified Midband CM Small Signal Model**

Matched NPN: $Q_3 = Q_4$

- $r_{o3} = r_{o4} = r_{on}$
- $r_{\pi 3} = r_{\pi 4} = r_{\pi n}$
- $r_{e3} = r_{e4} = r_{en}$
- $g_{m3} = g_{m4} = g_{mn}$
- $\beta_3 = \beta_4 = \beta_n$

\[
V_{cm} = \frac{r_{\pi n}}{\beta + 1} i_e + 2 r_o i_e \approx 2 r_o i_e \Rightarrow i_e \approx \frac{V_{cm}}{2 r_o}
\]

\[
V_{eb1} \approx \left( r_{ep} \parallel r_{\pi b} \right) i_e = \frac{r_{ep} \parallel r_{\pi b}}{2 r_o} V_{cm}
\]

\[
r_{\pi b} \parallel r_{ep} = \frac{\beta_p}{g_{mp}} \left( \frac{\beta_p}{g_{mp}(1 + \beta_p)} \right) = \frac{\beta_p}{g_{mp}(1 + \beta_p)} \star \frac{1 + \beta_p}{2 + \beta_p}
\]

\[
V_{o-cm} = r_{op} (g_{mp} V_{eb1} - i_e) = \frac{r_{op}}{2 r_o} \left( g_{mp} (r_{ep} \parallel r_{\pi b}) - 1 \right) V_{cm}
\]

Matched PNP: $Q_1 = Q_2$

- $r_{o1} = r_{o2} = r_{op}$
- $r_{\pi 1} = r_{\pi 2} = r_{\pi p}$
- $r_{e1} = r_{e2} = r_{ep}$
- $g_{m1} = g_{m2} = g_{mp}$
- $\beta_1 = \beta_2 = \beta_p$

\[
\frac{\beta_p}{g_{mp}} \left( \frac{\beta_p}{g_{mp}(1 + \beta_p)} \right) \approx \frac{1 + \beta_p}{2 + \beta_p}
\]
Simplified CM Small Signal Model - cont.

Matched NPN: Q3 = Q4
Matched PNP: Q1 = Q4

From previous slide

\[ V_{o\text{-}cm} = \frac{r_{op}}{2 r_o} \left( g_{mp} (r_{\pi b} || r_{ep}) - 1 \right) v_{cm} \]

\[ r_{\pi b} || r_{ep} = \frac{1}{g_{mp}} \frac{\beta_p}{2 + \beta_p} \]

\[ G_{cm} = \frac{V_{o\text{-}cm}}{V_{cm}} = \frac{r_{op}}{2 r_o} \left( g_{mp} \frac{1}{2 + \beta_p} - 1 \right) \]

\[ = \frac{r_{op}}{2 r_o} \left( \frac{\beta_p}{2 + \beta_p} - 1 \right) = \frac{r_{op}}{2} \frac{-2}{r_o} \frac{2}{2 + \beta_p} \]

\[ \Rightarrow \]

\[ G_{cm} = -\frac{r_{op}}{(2 + \beta_p) r_o} \approx -\frac{r_{op}}{\beta_p r_o} \]
DM Diff Amp 2N3906 PNP Active Loads

Design: set R3 for
\[ I_{REF} = 10 \text{ mA} \]
\[ R3 = \frac{23.3 \text{ V}}{10 \text{ mA}} = 2.33 \text{ k}\Omega \]

\[ A_{dm} = \frac{V_{o-dm}}{V_{in-dm}} = g_m r_{o2} \parallel r_{o8} \]

\[ A_{dm} = 55.5 \text{ dB @ 1 kHz} \]
\[ = 52.5 \text{ dB @ 1.43 MHz} \]

Matched NPN: Q1 = Q2 = Q3 = Q4

Matched PNP: Q7 = Q8
**CM Diff Amp 2N3906 PNP Active Loads**

\[ A_{cm} = \frac{V_{o-cm}}{V_{in-cm}} \]

- \( A_{cm} = -79.9 \text{ dB} @ 1 \text{ kHz} \)
- \( A_{cm} = -76.9 \text{ dB} @ 0.54 \text{ MHz} \)
- \( A_{dm} = 55.5 \text{ dB} @ 1 \text{ kHz} \)

\[ CMRR = 20 \log_{10} \left( \frac{|A_{dm}|}{|A_{cm}|} \right) \]

- \( CMRR = 135.4 \text{ dB} @ 1 \text{ kHz} \)

Matched NPN: Q1 = Q2 = Q3 = Q4

Matched PNP: Q7 = Q8
CMRR Comparison

CMRR = 66 dB @ 1 kHz

CMRR = 135 dB @ 1 kHz
Summary

Active load advantages:
1. Minimizes number of passive elements needed.
2. Can produce very high gain in one stage.

Active load advantages:
1. No differential output available.