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**

\[ R_{C2} \Rightarrow r_{o7} \]
\[ R_{C1} \Rightarrow r_{o6} \]

**PROBLEM:** Op. Pt. \( V_{C1} \), \( V_{C2} \) very sensitive to mismatch \( I_{ref1} \neq I_{ref2} \).
Differential Amp – Active Loads Basics 2

slope = \(-1/R_{c2}\)

slope = \(-1/r_{o7}\)
**PROBLEM**: Op. Pt. $V_{c1}$, $V_{c2}$ 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:

\[
I_E = \frac{V_{CC} - (V_B + V_{EB})}{R_E}
\]

\[
I_E = \frac{(V_{CC} - V_B) - 0.7}{R_E}
\]

\[
I_E = \frac{V_{R1} - 0.7}{R_E} = \frac{I R_1 - 0.7}{R_E}
\]

Note reference current directions!

\[
I \approx \frac{I_E}{10}
\]
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**

\[ Q_1 = Q_2: \quad g_{m1} = g_{m2} = g_{mp}; \]

\[ r_{e1} = r_{e2} = r_{ep}; \quad r_{\pi 1} = r_{\pi 2} = r_{\pi p}; \]

\[ \beta_1 = \beta_2 = \beta_p \]

\[ I \]

**Small signal model:**

\[ V_{CC} = V_{EB1} \]

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

\[ V_{EB2} = V_{EB1} \]

**Current through** \( r_{\pi} \) **and** \( g_{mp} V_{eb1} \):

\[ i_x = \frac{V_{eb1}}{r_{\pi p}} + g_{mp} V_{eb1} = \left( \frac{1}{r_{\pi p}} + g_{mp} \right) V_{eb1} \]

\[ i_x = \left( \frac{g_{mp}}{\beta_p} + g_{mp} \right) V_{eb1} = \left( \frac{\beta_p + 1}{\beta_p} \right) g_{mp} V_{eb1} = \frac{V_{eb1}}{r_{ep}} \]

**recall**

\[ r_{\pi p} = \frac{\beta_p}{g_{mb}} \]

\[ r_{ep} = \frac{r_{\pi p}}{\beta_p + 1} \]
Simplified Mid-band DM Small Signal Model

NOTE:
1. Due to imbalance created by active load current mirror, only single-ended output is available from common collector of Q2 and Q4.
2. Q3, Q4 emitter symmetry creates virtual ground at amplifier emitter connection.
Simplified DM Small Signal Model cont.

Matched NPN: Q3 = Q4
\[ g_{m3} = g_{m4} = g_{mn} \]
\[ r_{e3} = r_{e4} = r_{en} \]
\[ r_{\pi 3} = r_{\pi 4} = r_{\pi n} \]
\[ r_{o3} = r_{o4} = r_{on} \]

combining parallel resistances to ground
\[ r_{el} || r_{ol} || r_{\pi 2} || r_{o3} \approx r_{el} \]

From previous slide
\[ v_{c4-dm} \]

Matched PNP Q1 = Q2
\[ g_{m1} = g_{m2} = g_{mp} \]
\[ r_{el} = r_{e2} = r_{ep} \]
\[ r_{\pi 1} = r_{\pi 2} = r_{\pi p} \]
\[ r_{ol} = r_{o2} = r_{op} \]
Matched NPN & PNP transistors have been assumed throughout.

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

1. \( v_{eb1} \approx g_{mn} \frac{v_{i-dm}}{2} r_{ep} \)  
2. \( i_{c2} = g_{mp} v_{eb1} = g_{mp} \left( g_{mn} \frac{v_{i-dm}}{2} r_{ep} \right) \)

where: \( r_{ep} = \frac{\beta_p + 1}{\beta_p} \frac{1}{g_{mp} g_{mp}} \approx 1 \)

hence: \( i_{c2} \approx g_{mn} \frac{v_{i-dm}}{2} \)

by inspection: \( i_{c4} = g_{mn} \frac{v_{i-dm}}{2} \)

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

Matched NPN: Q3 = Q4

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

\[
R_o = r_{op} \| r_{on} 
\]

\[
v_{c4-dm} = (i_{c2} + i_{c4}) R_o \approx 2 g_{mn} \frac{v_{i-dm}}{2} \frac{R_o}{2} \]

\[
v_{c4-dm} = g_{mn} R_o v_{i-dm} \]

\[
A_{v-dm4} = \frac{v_{c4-dm}}{v_{i-dm}} = g_{mn} r_{op} \| r_{on} \]

\[
A_{v-cm4} = \frac{v_{c4-cm}}{v_{i-cm}} = -\frac{r_{op}}{\beta p r_o} \]

From previous slide:

\[
i_{c2} \approx g_{mn} \frac{v_{i-dm}}{2} = i_{c4} \]

also

\[
A_{v-cm4} = \frac{v_{c4-cm}}{v_{i-cm}} = -\frac{r_{op}}{\beta p r_o} \]
Matched NPN: Q3 = Q4

\[ r_{o3} = r_{o4} = r_{on} \]
\[ r_{\pi3} = r_{\pi4} = r_{\pi n} \]
\[ r_{e3} = r_{e4} = r_{en} \]
\[ g_{m3} = g_{m4} = g_{mn} \]
\[ \beta_3 = \beta_4 = \beta_n \]
\[ r_{el} \parallel r_{ol} \parallel r_{\pi 2} \approx r_{ep} \parallel r_{\pi p} \]

\[ v_{i-cm} = \frac{r_{\pi n}}{\beta + 1} i_e + 2 r_o i_e \approx 2 r_o i_e \]
\[ i_e \approx \frac{v_{i-cm}}{2 r_o} \]
\[ v_{eb1} \approx \frac{(r_{ep} \parallel r_{\pi p})}{2 r_o} i_e = \frac{(r_{ep} \parallel r_{\pi p})}{2 r_o} v_{i-cm} \]

Matched PNP: Q1 = Q2

\[ v_{o-cm} = r_{op} (g_{mp} v_{eb1} - i_e) = \frac{r_{op}}{2 r_o} \left( g_{mp} (r_{ep} \parallel r_{\pi p}) - 1 \right) v_{i-cm} \]
\[ r_{ep} \parallel r_{\pi b} = \frac{\beta_p}{g_{mp}} \frac{\beta_{p}}{g_{mp} (1 + \beta_p)} = \frac{\beta_p}{g_{mp} (1 + \beta_p)} \times \frac{1 + \beta_p}{2 + \beta_p} \]
Simplified CM Small Signal Model - cont.

Matched NPN: Q3 = Q4
Matched PNP: Q1 = Q2

From previous slide

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

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

\[ A_{v-cm4} = \frac{v_{c4-cm}}{v_{i-cm}} = \frac{r_{op}}{2r_o} \left( \frac{1}{g_{mp}} \frac{\beta_p}{2 + \beta_p} - 1 \right) \]

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

\[ \Rightarrow \]

\[ A_{v-cm4} = -\frac{r_{op}}{(2 + \beta_p)r_o} \approx -\frac{r_{op}}{\beta_p r_o} \]
DM Diff Amp 2N3906 PNP Active Loads

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

\[ A_{v_{\text{dm2}}} = \frac{V_{o_{\text{dm}}}}{V_{i_{\text{dm}}}} = g_m r_{o2} \parallel r_{o8} \]

\[ A_{v_{\text{dm2}}(dB)} = 55.5 \text{ dB @ 1 kHz} = 52.5 \text{ dB @ 1.43 MHz} \]

Matched NPN: Q1 = Q2 = Q3 = Q4
Matched PNP: Q7 = Q8
CM Diff Amp 2N3906 PNP Active Loads

\[ A_{v-cm2} = \frac{v_{c2-cm}}{v_{i-cm}} \]

\[ A_{v-cm2(dB)} = -79.9 \text{ dB @ 1 kHz} \]
\[ = -76.9 \text{ dB @ 0.54 MHz} \]

\[ A_{v-dm2(dB)} = 55.5 \text{ dB @ 1 kHz} \]

\[ \text{CMRR} = 20 \log_{10} \left( \frac{|A_{v-dm2}|}{|A_{v-cm2}|} \right) \]
\[ = A_{v-dm2(dB)} - A_{v-cm2(dB)} \]
\[ = 135.4 \text{ dB @ 1 kHz} \]

Matched NPN: Q1 = Q2
\[ = Q3 = Q4 \]

Matched PNP: Q7 = Q8
CMRR Comparison

\[ A_{v-cm2}(dB) = 20\log_{10} 0.043 = -27.3 \text{ dB @ 1 kHz} \]

\[ A_{v-dm2}(dB) = 55.5 \text{ dB @ 1 kHz} \]

CMRR = 82.8 dB @ 1 kHz

\[ A_{v-cm2}(dB) = -79.9 \text{ dB @ 1 kHz} \]

\[ A_{v-dm2}(dB) = 55.5 \text{ dB @ 1 kHz} \]

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 disadvantages:
1. No differential output available.