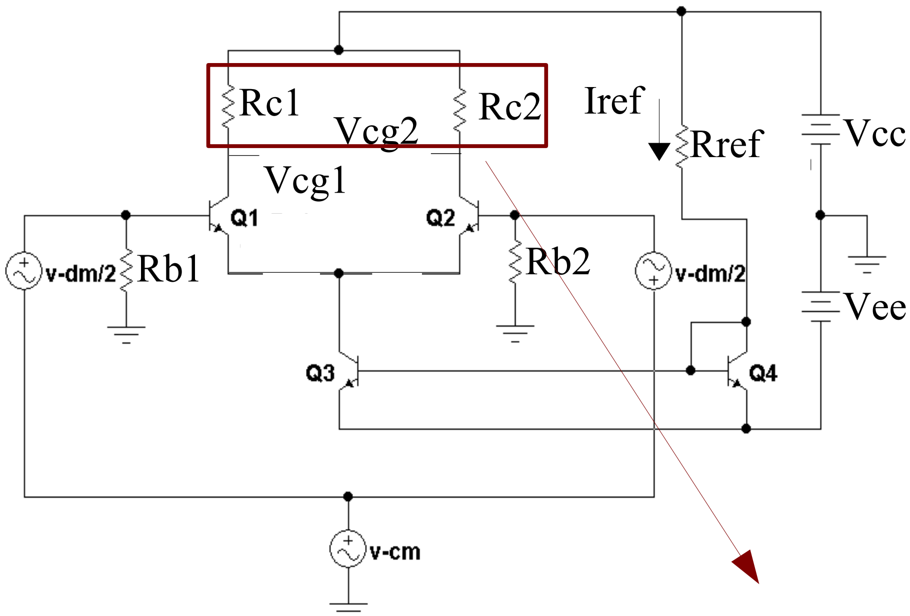
Differential Amplifier with Active Loads

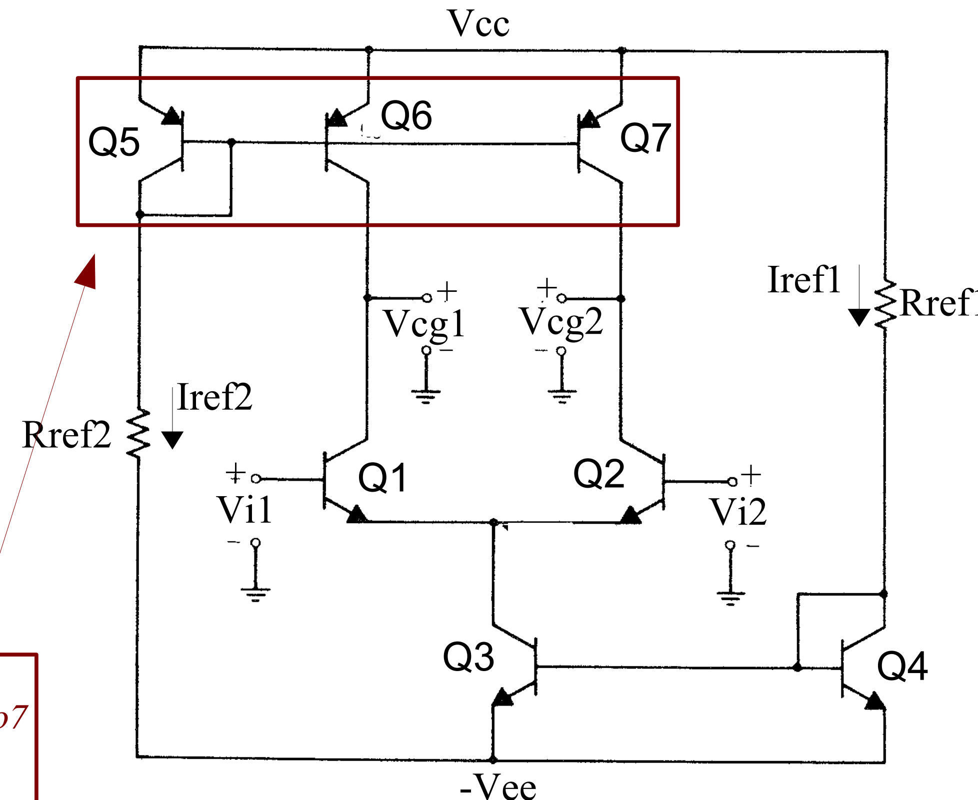
- Active load basics
- PNP BJT current mirror
- Small signal model
- Design example and simulation
- Comparison of CMRR with resistive load design

Differential Amp – Active Loads Basics 1



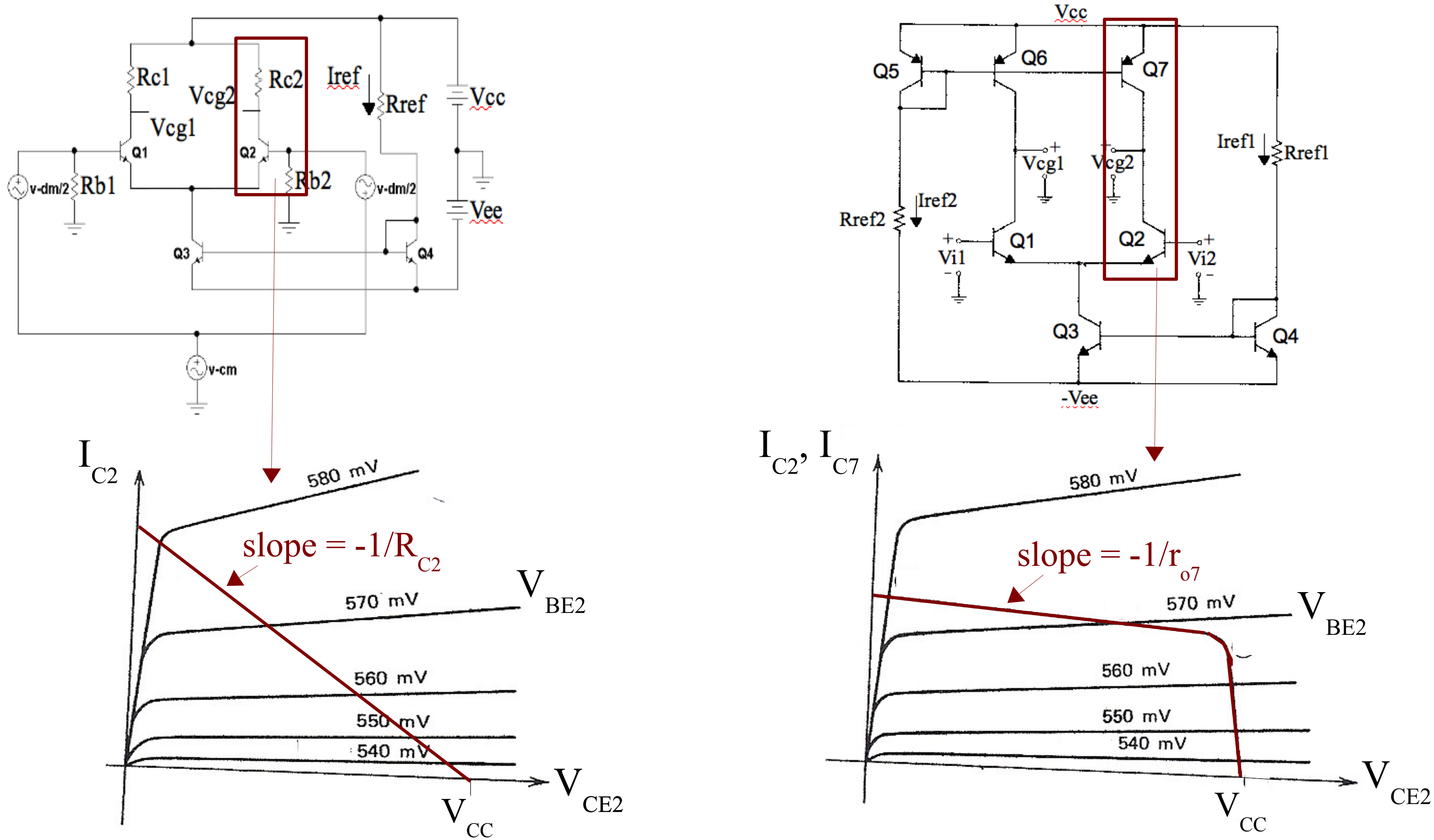
$R_{C2} \Rightarrow r_{o7}$

$R_{C1} \Rightarrow r_{o6}$

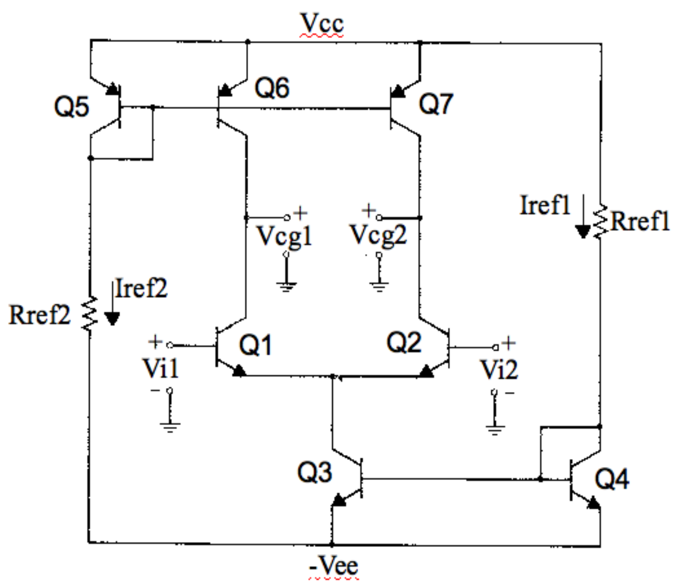


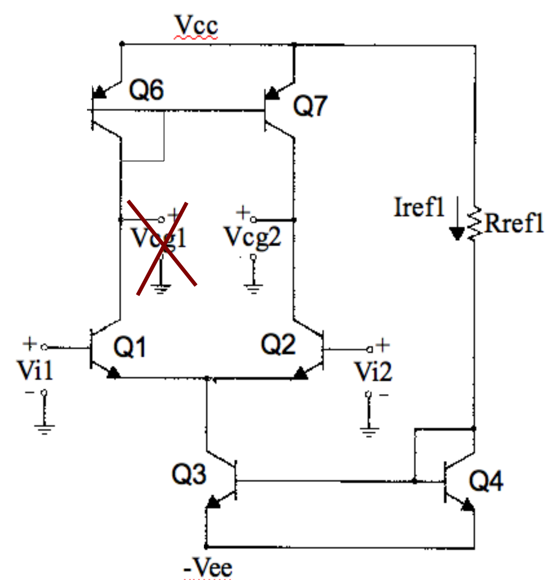
<u>PROBLEM</u>: Op. Pt. V_{CG1}, V_{CG2} very sensitive to mismatch $I_{ref1} \neq I_{ref2}$.

Differential Amp – Active Loads Basics 2



Differential Amp – Active Loads Basics 3





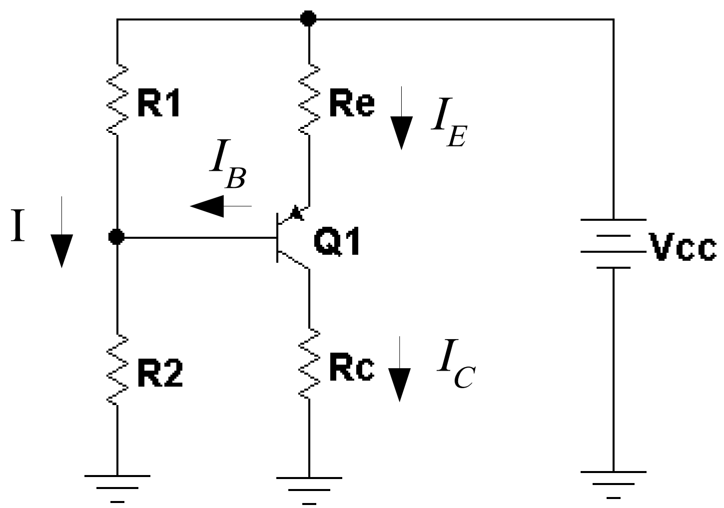
PROBLEM: Op. Pt. V_{CG1}, V_{CG2} very sensitive to mismatch $I_{ref1} \neq I_{ref2}$.

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:

$$I_E = \frac{V_{CC} - (V_{BG} + 0.7)}{R_E}$$

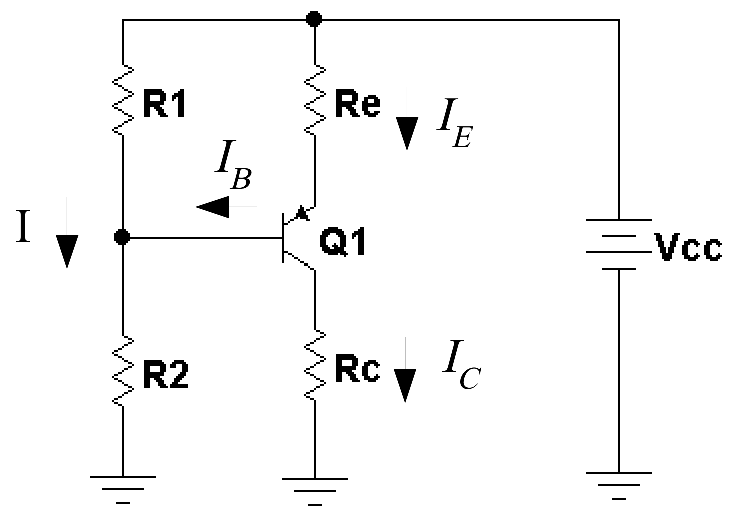
$$I_E = \frac{(V_{CC} - V_{BG}) - 0.7}{R_E}$$

$$I_E = \frac{V_{R1} - 0.7}{R_E} = \frac{I * R_1 - 0.7}{R_E}$$

Note reference current directions!

$$I \approx \frac{I_C}{10}$$

Quick Review - PNP BJT



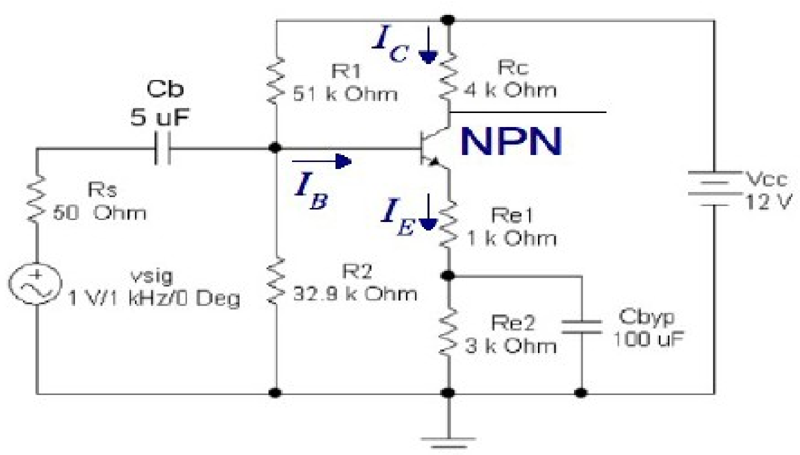
Usual Large signal equations:

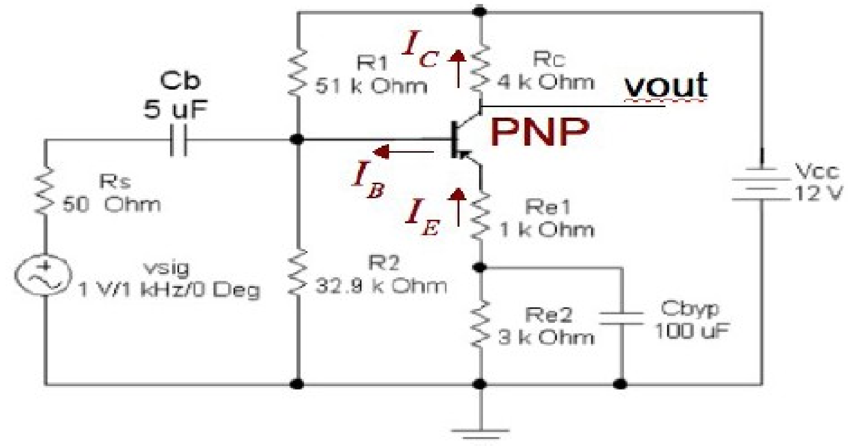
$$i_C = I_S e^{\frac{v_{EB}}{V_T}}$$

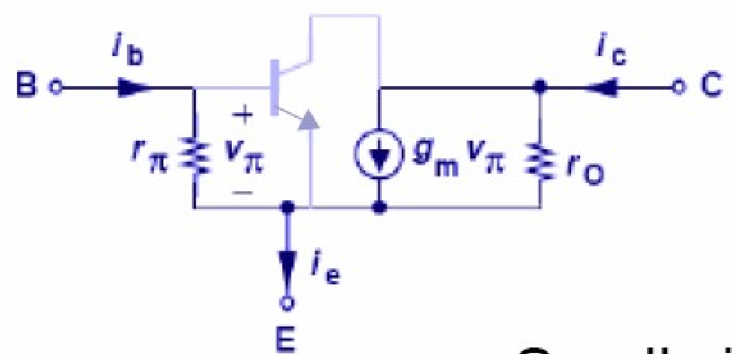
$$i_B = \frac{i_C}{\beta}$$

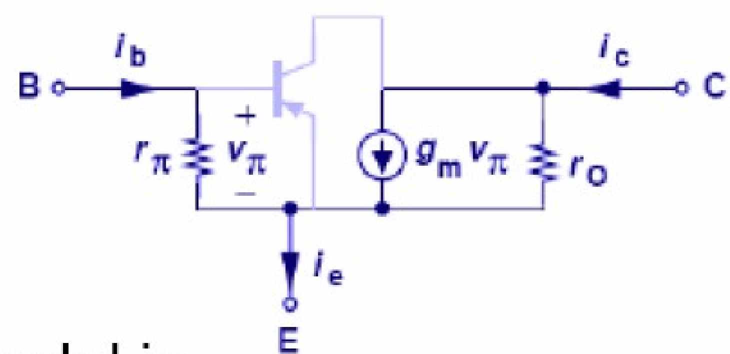
$$i_E = i_C + i_B = \frac{(\beta+1)}{\beta} i_C$$

$$i_C = \alpha i_E$$







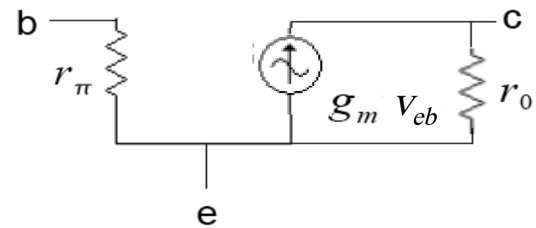


NPN: dc and ac currents in same direction

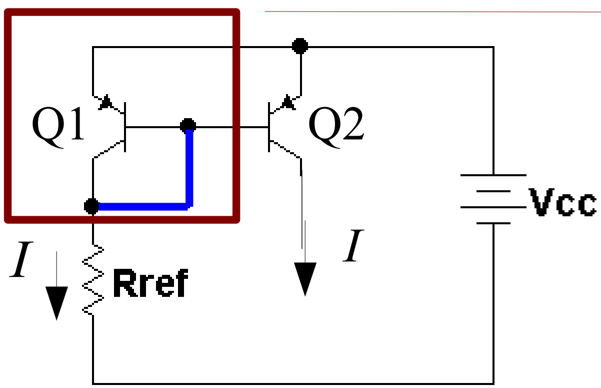
Small signal model is identical for NPN and PNP transistors!

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

PNP Mirror



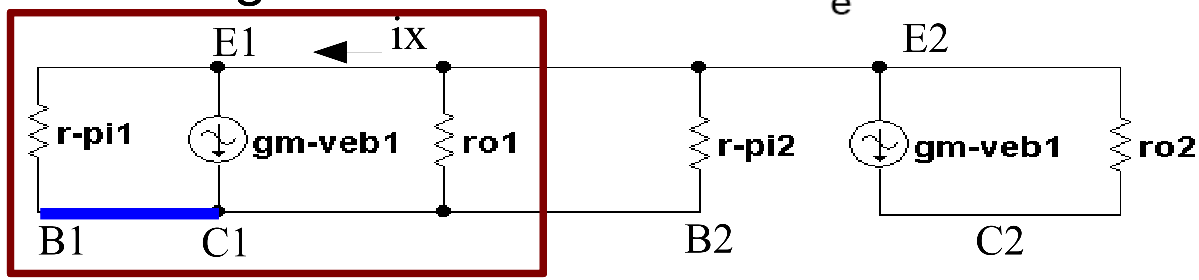
Current source model Q1 = Q2:



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

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

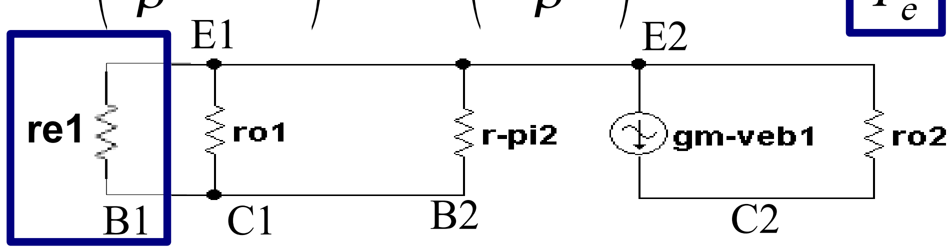
Small signal model:



Current through r_π and $g_m v_{eb1}$:

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

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

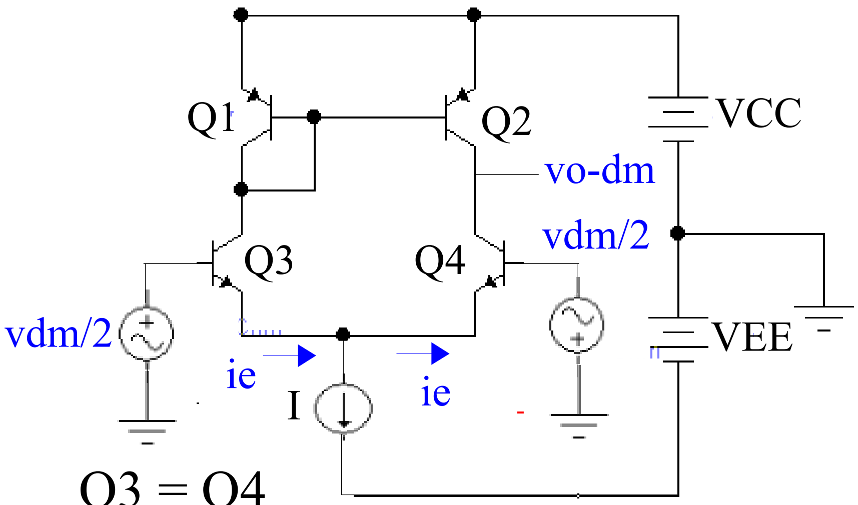


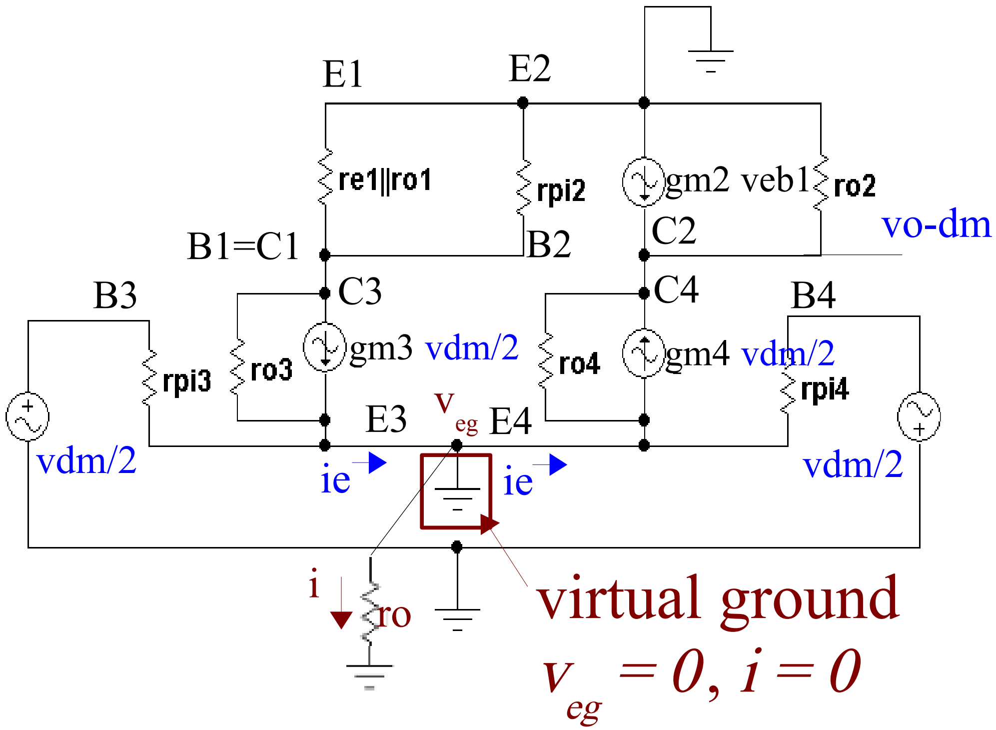
recall

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

$$r_e=\frac{r_\pi}{\beta+1}$$

Simplified Midband DM Small Signal Model





Q3 = Q4

Q1 = Q2

vo-dm is single-ended output.

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. Symmetry creates virtual ground at amplifier emitter connection.

Simplified DM Small Signal Model cont.

Matched NPN: Q3 = Q4

$g_{m3} = g_{m4} = g_{mn}$

$r_{e3} = r_{e4} = r_{en}$

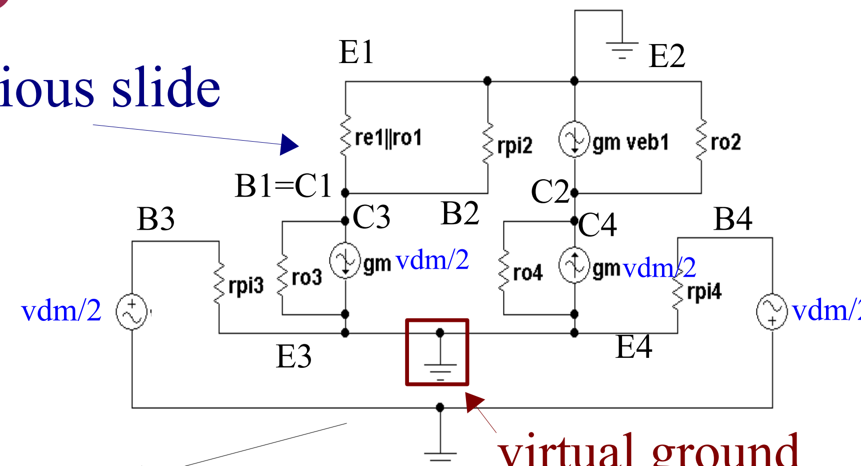
$r_{\pi 3} = r_{\pi 4} = r_{\pi n}$

$r_{o3} = r_{o4} = r_{on}$

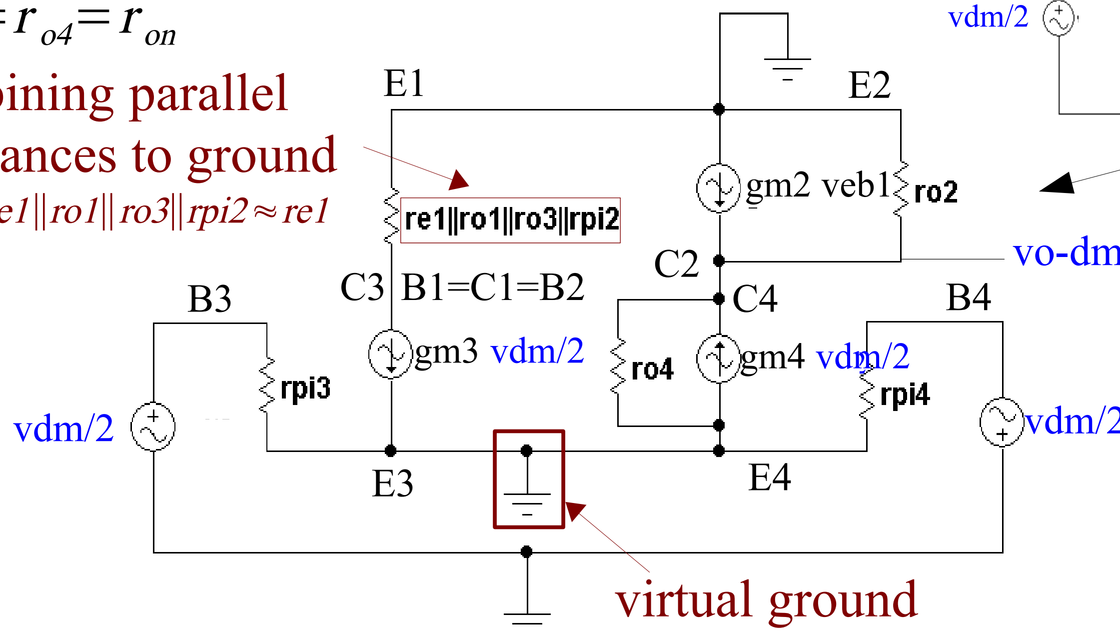
combining parallel resistances to ground

$re1 \| ro1 \| ro3 \| rpi2 \approx re1$

From previous slide



virtual ground



Matched PNP Q1 = Q2

$g_{m1} = g_{m2} = g_{mp}$

$r_{e1} = r_{e2} = r_{ep}$

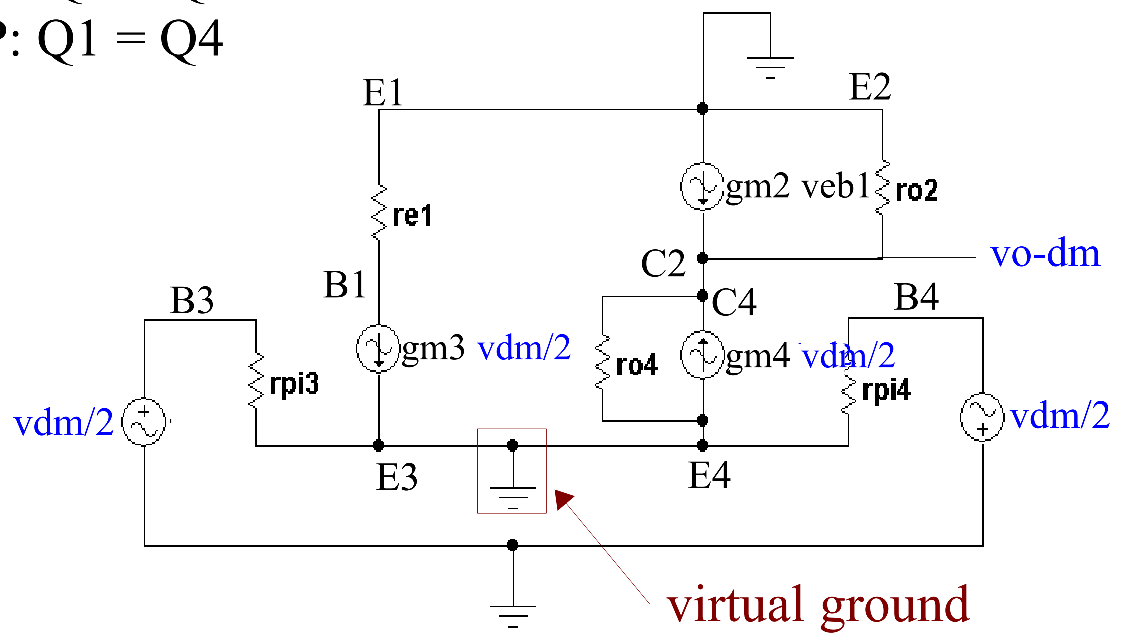
$r_{\pi 1} = r_{\pi 2} = r_{\pi p}$

$r_{o1} = r_{o2} = r_{op}$

Simplified DM Small Signal Model - cont.

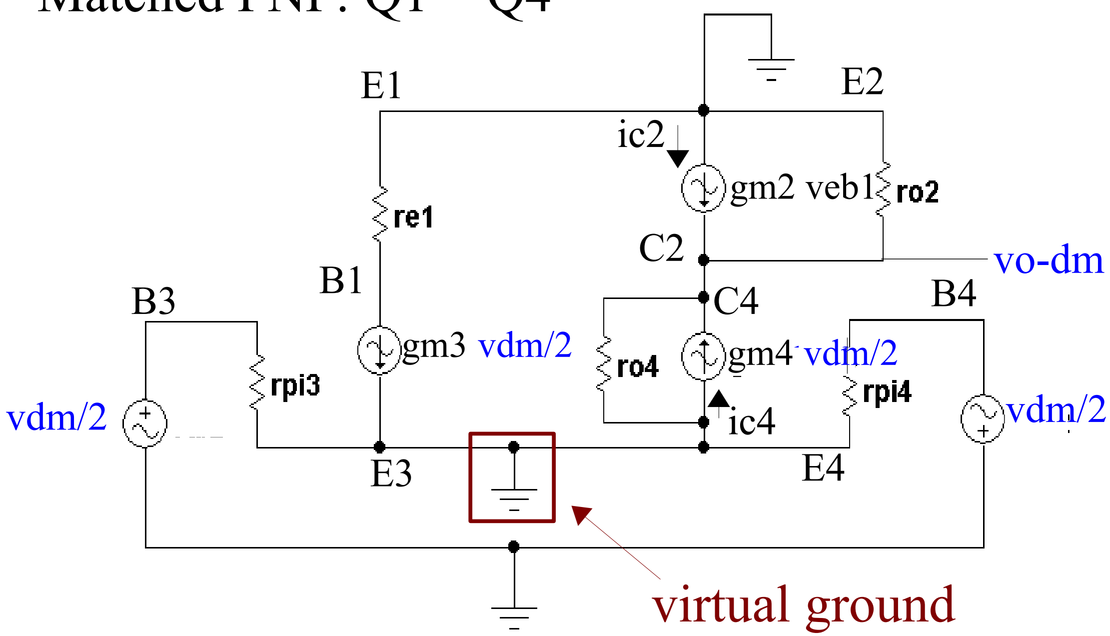
From previous slide with $re1 \| ro1 \| ro3 \| rpi2 \approx re1$

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



Simplified DM Small Signal Model - cont.

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



Matched transistors has been assumed throughout.

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: $$r_{ep} = \frac{\beta+1}{\beta} \frac{1}{g_{mp}} \approx \frac{1}{g_{mp}}$$

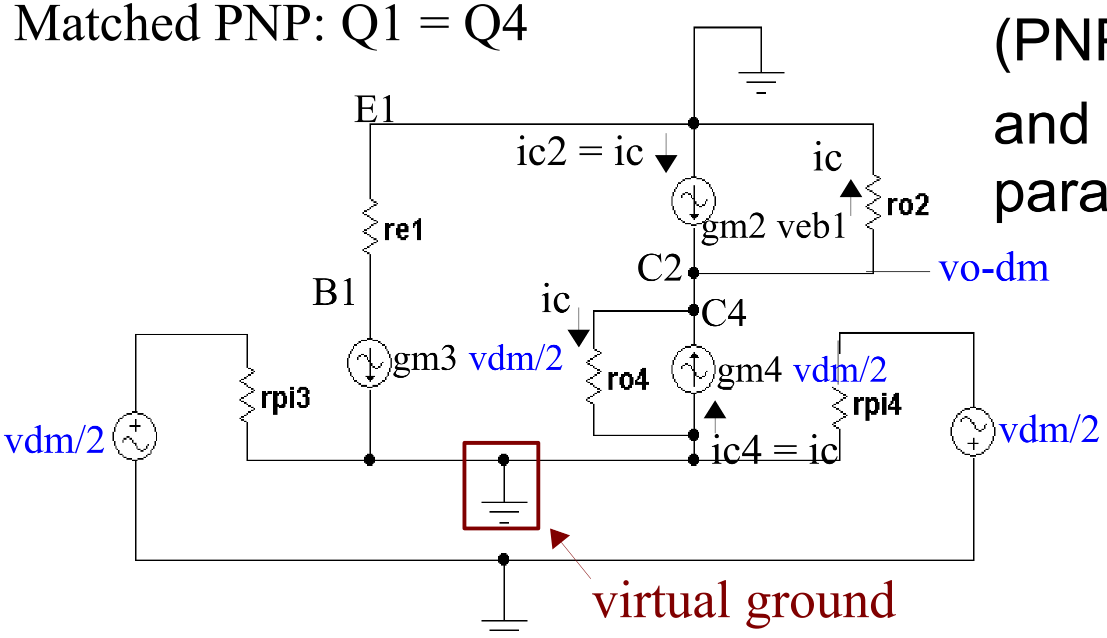
hence: $$i_{c2} \approx g_{mn} \frac{v_{dm}}{2}$$

by inspection: $$i_{c4} = g_{mn} \frac{v_{dm}}{2}$$

$$\Rightarrow i_{c2} \approx i_{c4}$$

Simplified DM Small Signal Model - cont.

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



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 parallelcurrent sources.

$$R_o = r_{op} \| r_{on} \neq r_o \| r_o = \frac{r_o}{2}$$

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

$$v_{o-dm} = 2 g_{mn} R_o \frac{v_{dm}}{2}$$

$$G_{dm} = \frac{v_{o-dm}}{v_{dm}} = g_{mn} r_{op} \| r_{on}$$

From previous slide:

$$i_{c2} \approx g_{mn} \frac{v_{dm}}{2} = i_{c4}$$

also $G_{cm} = \dfrac{v_{o-cm}}{v_{cm}} = -\dfrac{r_{op}}{\beta_p r_o}$

Simplified Midband CM Small Signal Model

Matched NPN: Q3 = Q4

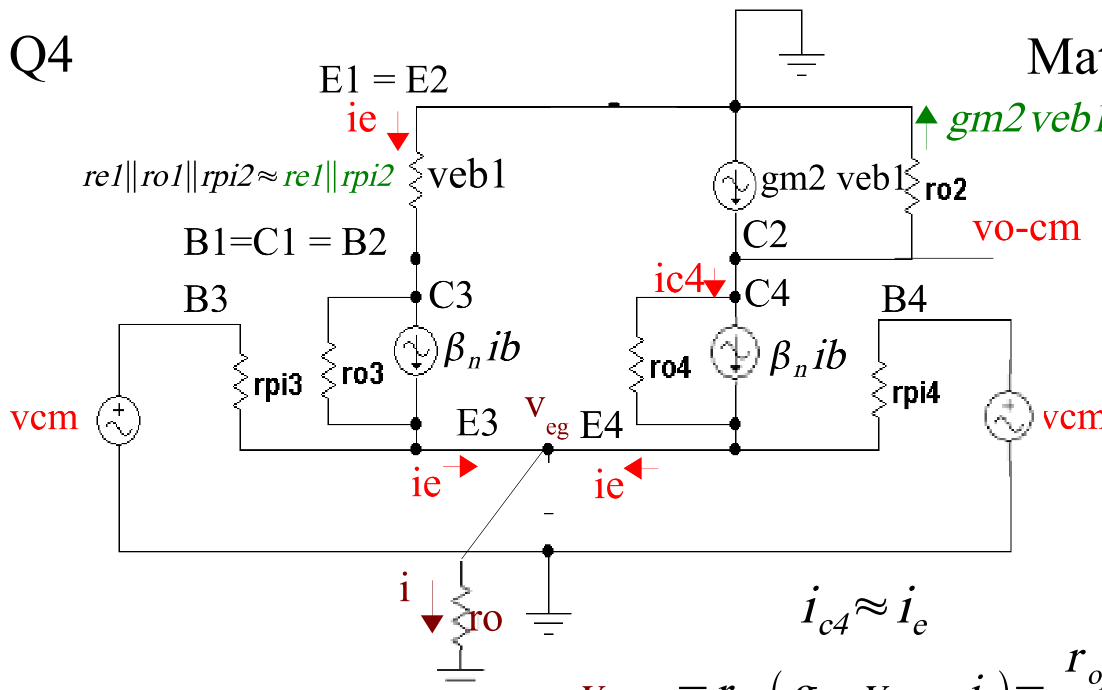
$r_{o3}=r_{o4}=r_{on}$

$r_{\pi 3}=r_{\pi 4}=r_{\pi n}$

$r_{e3}=r_{e4}=r_{en}$

$g_{m3}=g_{m4}=g_{mn}$

$\beta_3=\beta_4=\beta_n$



Matched PNP: Q1 = Q2

$r_{o1}=r_{o2}=r_{op}$

$r_{\pi 1}=r_{\pi 2}=r_{\pi p}$

$r_{e1}=r_{e2}=r_{ep}$

$g_{m1}=g_{m2}=g_{mp}$

$\beta_1=\beta_2=\beta_p$

$i_{c4}\approx i_e$

$$v_{cm}=\frac{r_{\pi n}}{\beta+1} i_e+2 r_o i_e \approx 2 r_o i_e \Rightarrow i_e \approx \frac{v_{cm}}{2 r_o}$$

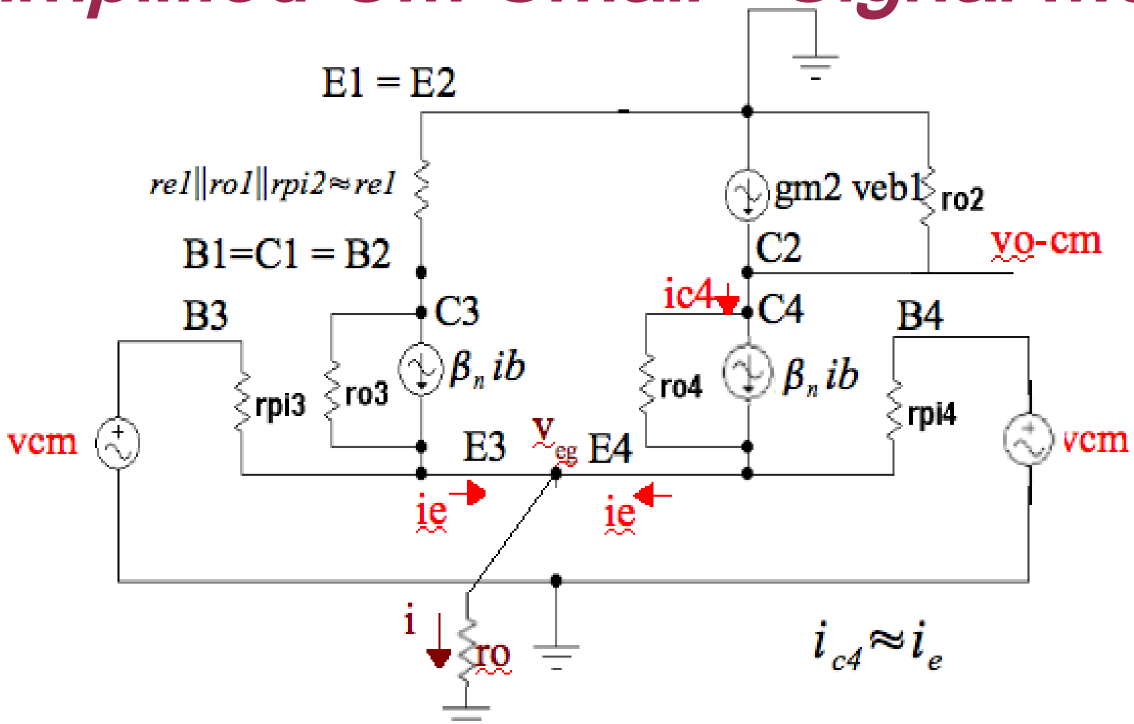
$$v_{eb1}\approx (r_{ep}\|r_{\pi p}) i_e=\frac{(r_{ep}\|r_{\pi b}) v_{cm}}{2 r_o}$$

re1||rpi2

$$v_{o-cm}=r_{op}(g_{mp} v_{eb1}-i_e)=\frac{r_{op}}{2 r_o}(g_{mp}(r_{ep}\|r_{\pi b})-1) v_{cm}$$

$$r_{\pi b}\|r_{ep}=\frac{\left(\frac{\beta_p}{g_{mp}}\right)\left(\frac{\beta_p}{g_{mp}(1+\beta_p)}\right)}{\frac{\beta_p}{g_{mp}}+\frac{\beta_p}{g_{mp}(1+\beta_p)}}=\frac{\beta_p}{g_{mp}(1+\beta_p)}*\frac{1+\beta_p}{2+\beta_p}$$

Simplified CM Small Signal Model - cont.



$$i_{c4} \approx i_e$$

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

From previous slide

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

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

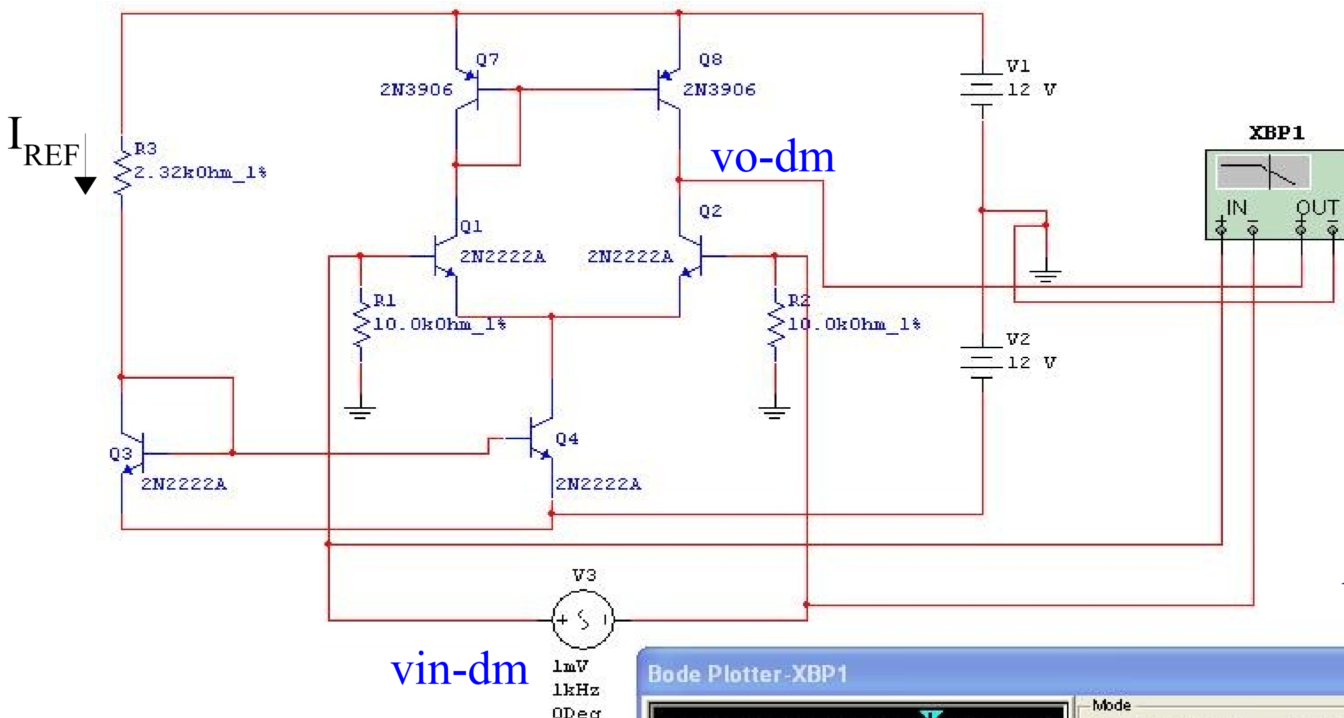
$$G_{cm} = \frac{v_{o-cm}}{v_{cm}} = \frac{r_{op}}{2\, r_o}\left(g_{mp} \frac{1}{g_{mp}} \frac{\beta_p}{2+\beta_p} - 1\right)$$

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

=>

$$G_{cm} = -\frac{r_{op}}{(2+\beta_p)\, r_o} \approx -\frac{r_{op}}{\beta_p r_o}$$

DM Diff Amp 2N3906 PNP Active Loads



Design: set R3 for

$I_{REF} = 10\ mA$

$$R3 = \frac{23.3\ V}{10\ mA} = 2.33\ k\Omega$$

$$A_{dm} = \frac{V_{o-dm}}{V_{in-dm}} = g_m r_{o2} \| r_{o8}$$

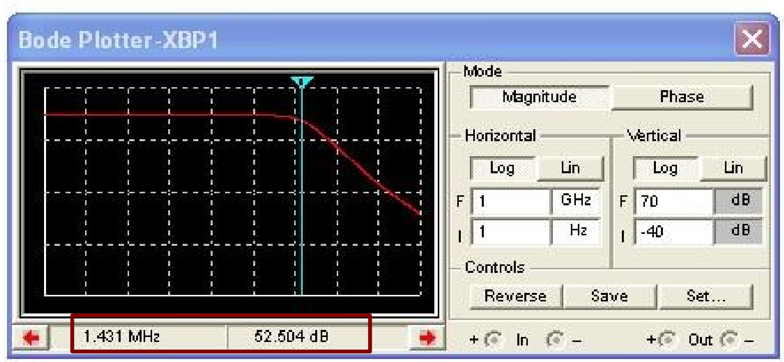
A_{dm} = 55.5 dB @ 1 kHz

= 52.5 dB @ 1.43 MHz

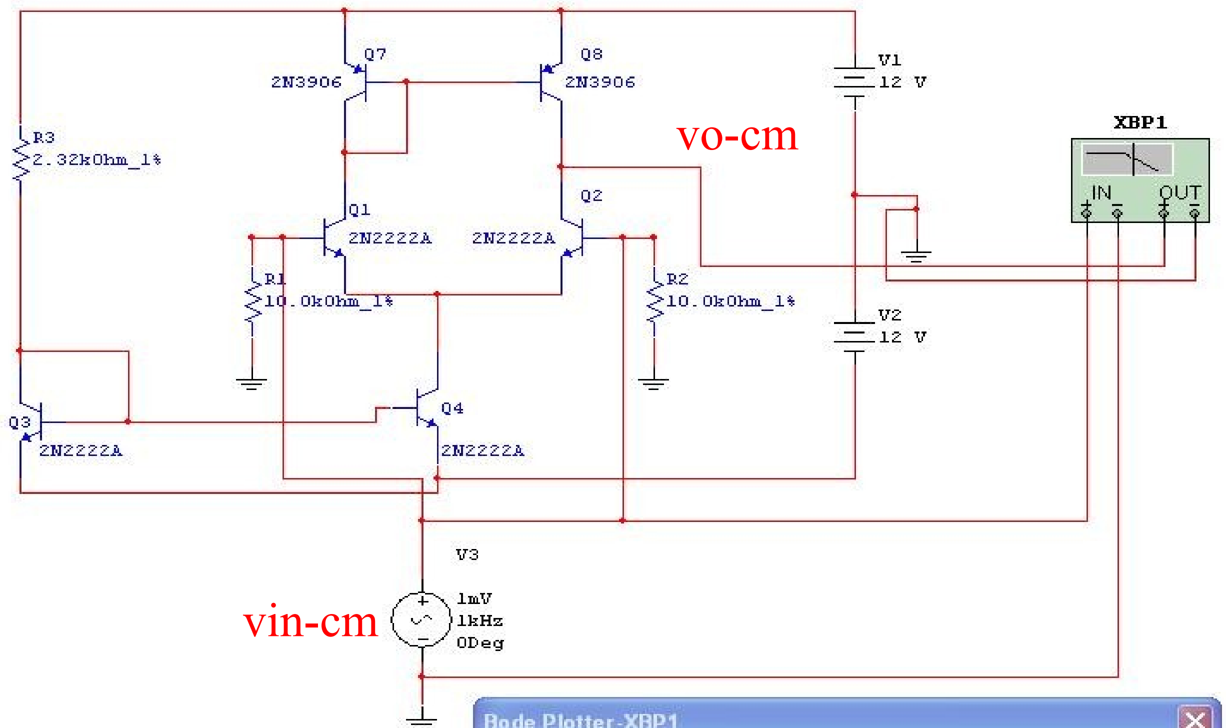
Matched NPN: Q1 = Q2

= 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 dB @ 1 kHz

= -76.9 dB @ 0.54 MHz

A_{dm} = 55.5 dB @ 1 kHz

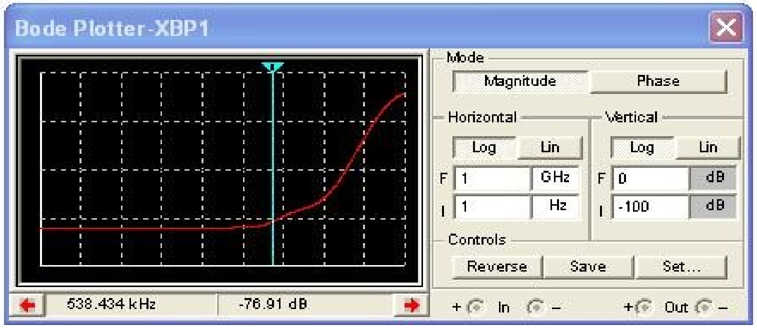
$$CMRR = 20\log_{10}\left(\frac{|A_{dm}|}{|A_{cm}|}\right)$$

$$= A_{dm-dB} - A_{cm-dB}$$

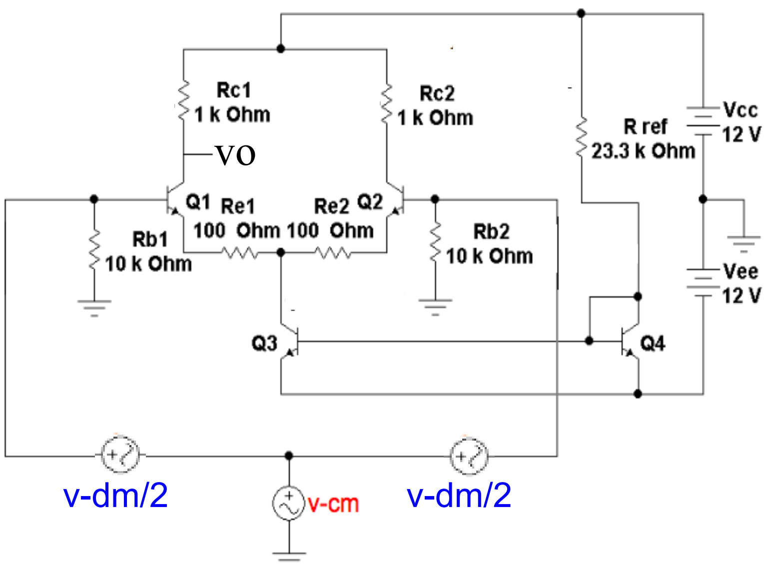
= 135.4 dB @ 1 k Hz

Matched NPN: Q1 = Q2 = Q3 = Q4

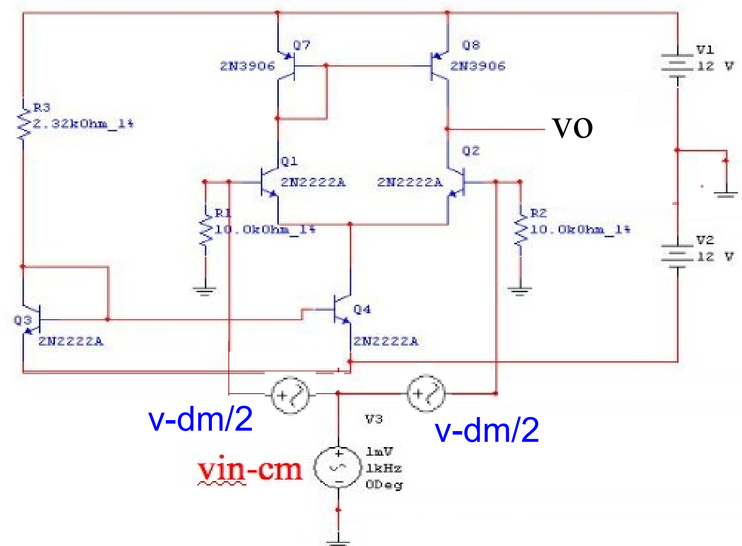
Matched PNP: Q7 = Q8



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.
3. Much larger single-ended CMRR then single-ended CMRR for resistive load differential amplifier.
3. Inherent differential-to-single-ended conversion.

Active load advantages:

1. No differential output available.