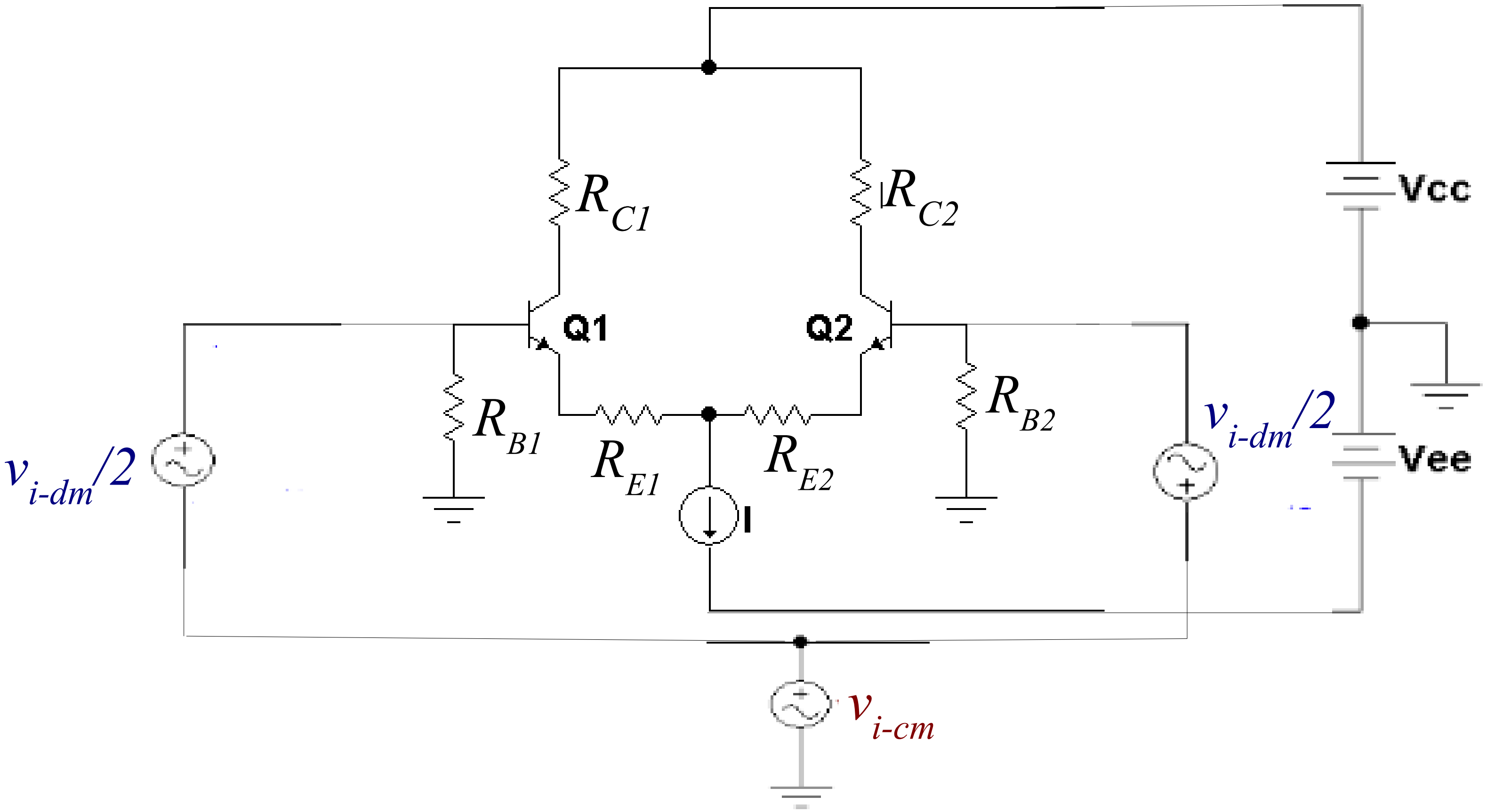
Quick Review



Balance op.

$$R_{C1} = R_{C2} = R_C$$

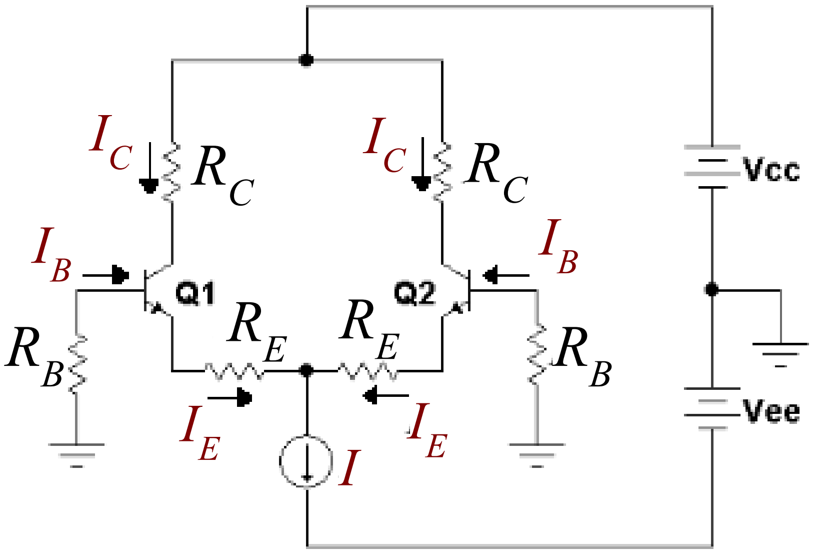
$$R_{B1} = R_{B2} = R_B$$

$$R_{E1} = R_{E2} = R_E$$

$$Q1 = Q2$$

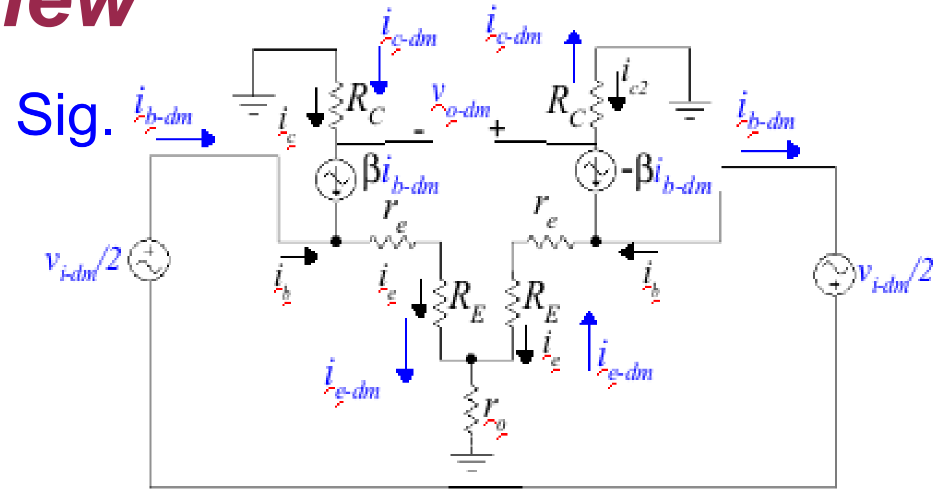
Quick Review

CM - DC



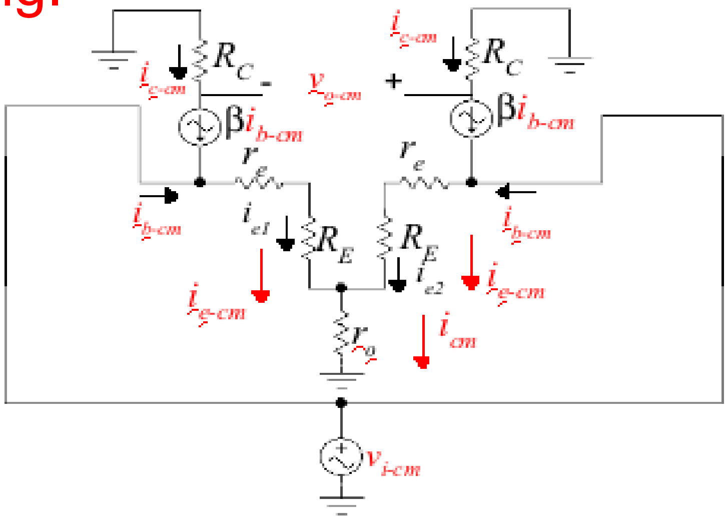
DM AC - Sm. Sig.

Balanced circuit



CM AC - Sm. Sig.

Balanced circuit



Quick Review

Differential mode (balanced)

$$r_{in-dm}=\frac{v_{i-dm}}{i_{b1-dm}}=(\beta+1)2(r_e+R_E)$$

$$A_{v-dm2}=\frac{v_{c2-dm}}{v_{i-dm}}=-A_{v-dm1}\approx\frac{R_C}{2(r_e+R_E)}$$

$$A_{v-dm}=\frac{v_{o-dm}}{v_{i-dm}}=\frac{R_C}{r_e+R_E}$$

Common mode (balanced)

$$r_{in-cm}=\frac{v_{i-cm}}{2i_{b-cm}}=(\beta+1)\left(\frac{r_e+R_E}{2}+r_0\right)$$

$$A_{v-cm1}=\frac{v_{c1-cm}}{v_{i-cm}}=A_{v-cm2}\approx-\frac{R_C}{2r_o}$$

$$A_{v-cm}=\frac{v_{o-cm}}{v_{i-cm}}=0$$ i.f.f. Balanced

$$A_{v-cm}=\frac{v_{o-cm}}{v_{i-cm}}\approx\frac{R_C}{2r_o}\frac{\Delta R_C}{R_C}$$

if Unbalanced due to $R_{C1}\neq R_{C2}$

Single-ended-output (balanced)

$$CMRR=\frac{A_{v-dm1,2}}{A_{v-cm1,2}}\approx 20\log_{10}\left(\frac{r_o}{r_e+R_E}\right)$$

Differential-output

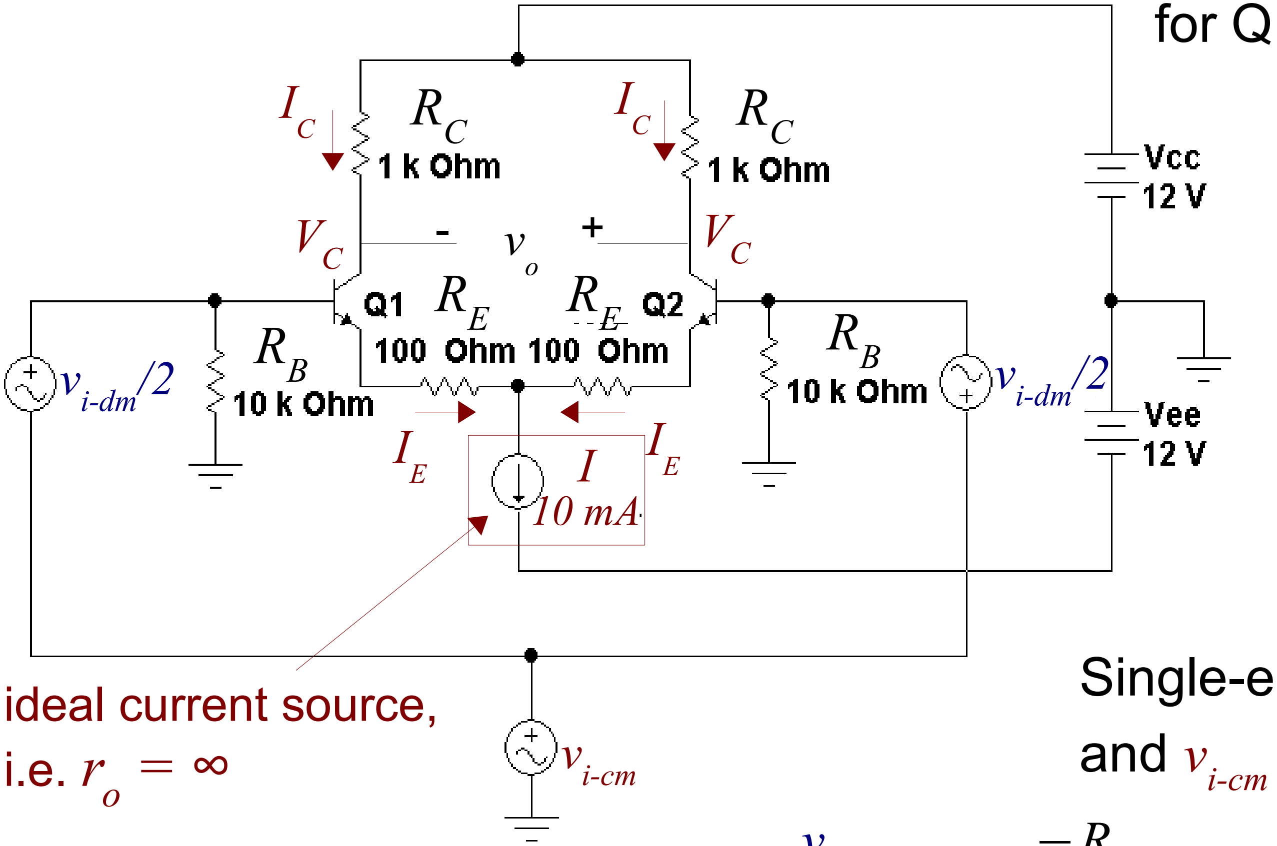
$CMRR=\infty$ i.f.f. Balanced

$$CMRR=20\log_{10}\left(2\frac{r_o}{r_E+R_E}\frac{1}{\Delta R_C/R_C}\right)$$

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



ideal current source, i.e. $r_o = \infty$

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

$$I_E = \frac{I}{2} = 5\,mA$$

Neglecting I_B:

$$I_C = I_E = 5\,mA \Rightarrow V_{Rc} = \frac{I_C}{R_C} = 5\,V$$

$$V_{R_c} = 5\,V \Rightarrow V_C = V_{CC} - V_{R_c} = 7\,V$$

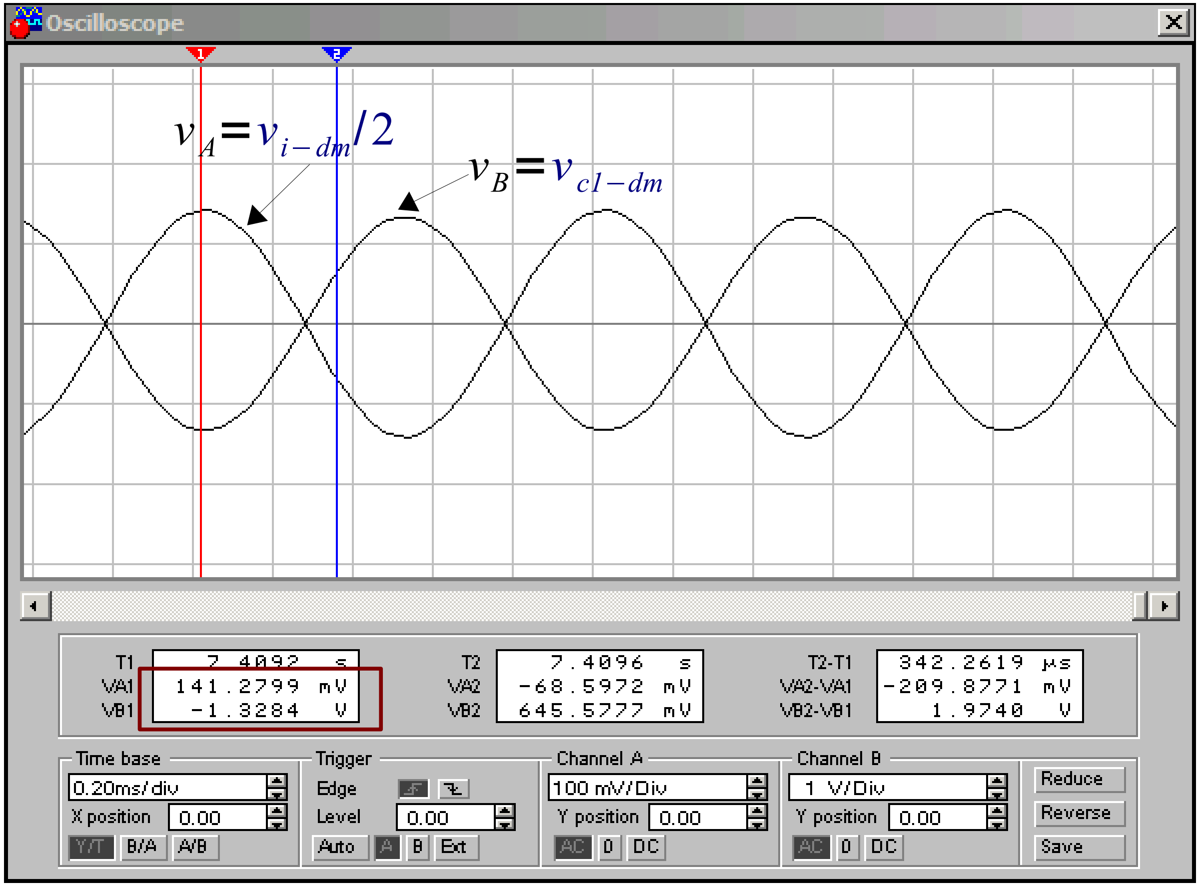
$$V_E = -V_{BE} = -0.7\,V$$

$$V_{CE} = V_C - V_E = 7.7\,V$$

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

$$A'_{v-dm1} = \frac{v_{c1-dm}}{v_i = v_{i-dm}/2} \approx \frac{-R_C}{R_E} = -10 \qquad A_{v-cm1} = \frac{v_{c1-cm}}{v_{cm}} \approx -\frac{R_C}{2\,r_o} = 0$$

Differential- Mode AC Gain Results



T1	7.4092 s	T2	7.4096 s	T2-T1	342.2619 µs
VA1	141.2799 mV	VA2	-68.5972 mV	VA2-VA1	-209.8771 mV
VB1	-1.3284 V	VB2	645.5777 mV	VB2-VB1	1.9740 V

Time base: 0.20ms/div, X position 0.00
Trigger: Edge, Level 0.00
Channel A: 100 mV/Div, Y position 0.00
Channel B: 1 V/Div, Y position 0.00

"Scope" output B at collector of Q1, i.e. $v_B = v_{c1-dm}$.

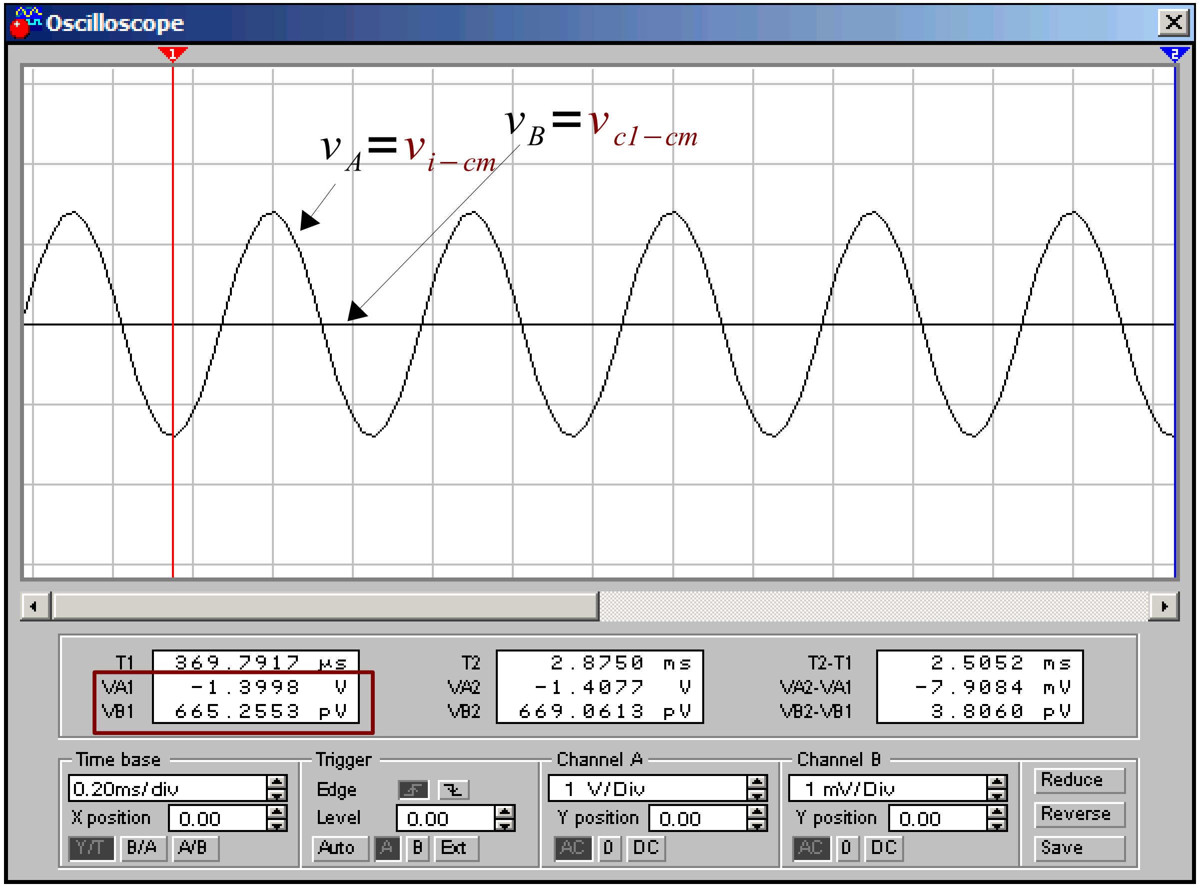
Input voltage $v_A = v_i = v_{i-dm}/2$ $0.14\ V_{peak}\ arg\ (0^o)$ at $f = 1\ kHz$.

Output voltage $v_B = v_{c1-dm}$ $1.33\ V_{peak}\ arg\ (180^o)$.

Measured gain:

$$A'_{v-dm1} = \frac{v_B}{v_A} = \frac{v_{c1-dm}}{v_{i-dm}/2} = \frac{-1.33\ V}{0.14\ V} = -9.5$$

Common Mode AC Results



T1 369.7917 µs
VA1 -1.3998 V
VB1 665.2553 pV

T2 2.8750 ms
VA2 -1.4077 V
VB2 669.0613 pV

T2-T1 2.5052 ms
VA2-VA1 -7.9084 mV
VB2-VB1 3.8060 pV

Time base 0.20ms/div
X position 0.00

Trigger Edge
Level 0.00

Channel A 1 V/Div
Y position 0.00

Channel B 1 mV/Div
Y position 0.00

"Scope" output B at collector of Q1, i.e. $v_B = v_{c1-cm} = 0\,V$.

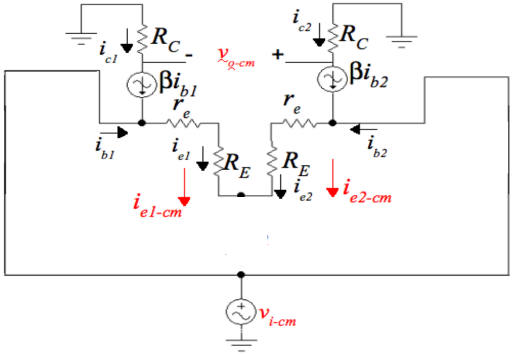
Input voltage $v_A = v_{i-cm}$ *0.14 V$_{peak}$ arg (0°)* at *f = 1 kHz*.

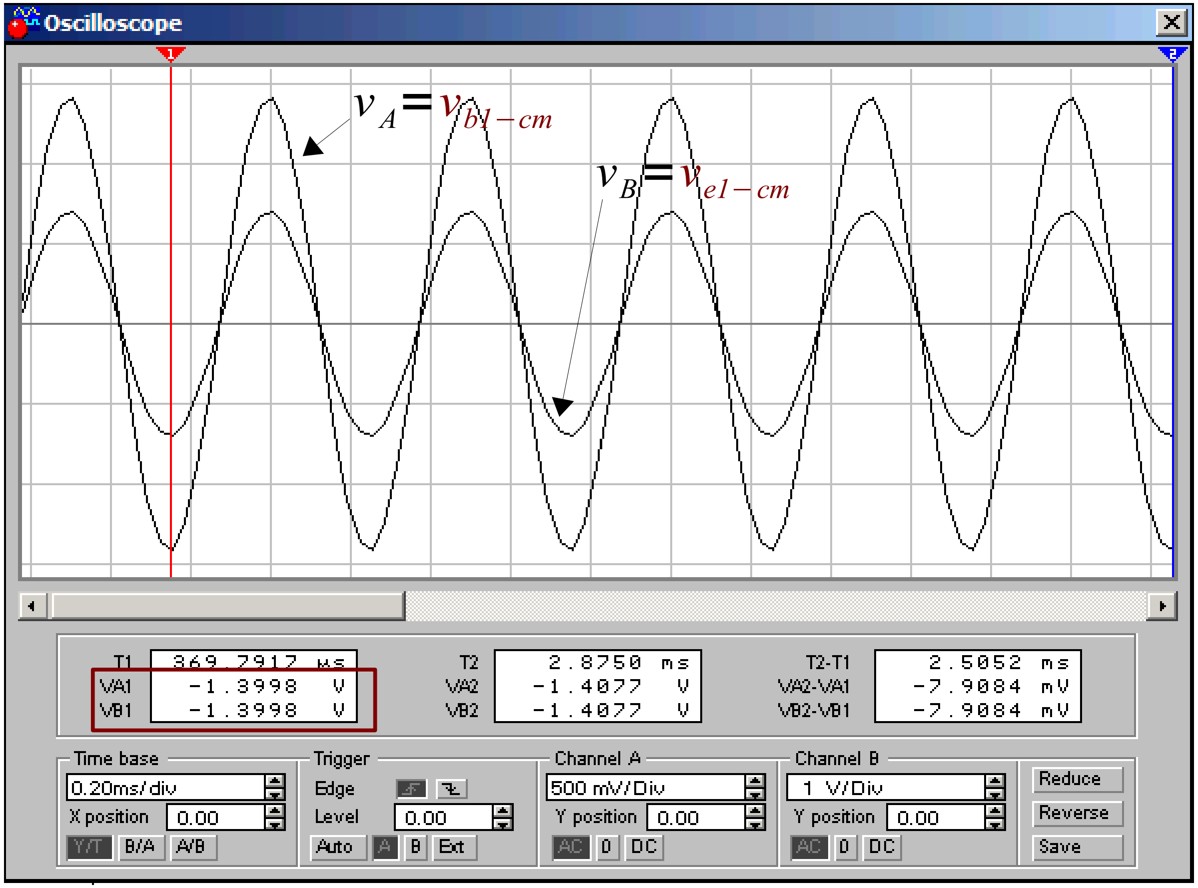
Since I is an ideal current source $r_o = \infty$ => $A_{v-cm1} = 0$.

$$A_{v-cm1} = \frac{v_B}{v_A} = \frac{v_{c1-dm}}{v_{i-cm}} = \frac{0\,V}{0.14\,V} = 0$$

$$CMRR = 20\log_{10}\frac{\left|A'_{v-dm1}\right|}{\left|A_{v-cm1}\right|} = 20\log_{10}\left|\frac{-9.5}{0}\right| = \infty$$

Common Mode AC Results - II





$v_A = v_{b1-cm}$

$v_B = v_{e1-cm}$

T1	369.7917 ms	T2	2.8750 ms	T2-T1	2.5052 ms
VA1	-1.3998 V	VA2	-1.4077 V	VA2-VA1	-7.9084 mV
VB1	-1.3998 V	VB2	-1.4077 V	VB2-VB1	-7.9084 mV

Time base 0.20ms/div, X position 0.00
Trigger Edge, Level 0.00
Channel A 500 mV/Div, Y position 0.00
Channel B 1 V/Div, Y position 0.00

Comparing ac base and emitter voltages to ground for Q1, i.e. v_{b1-cm} , v_{e1-cm} .

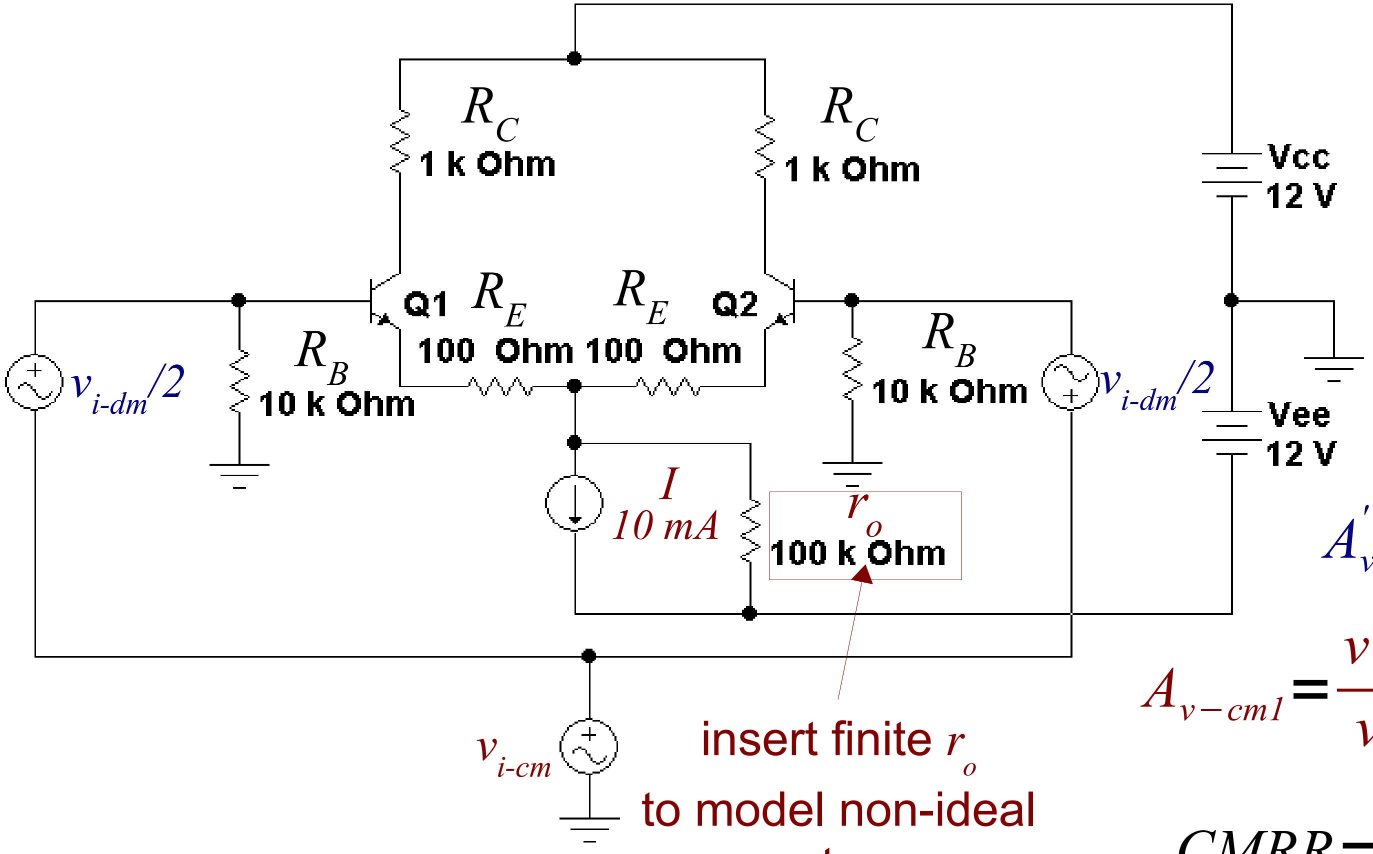
$$v_{b1-cm} = v_{e1-cm} = 1.4\,V_{peak}$$

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

Since $i_{e\text{-}cm} = 0$, we expect $v_{be-cm} = 0\,V_{peak}$, i.e. all base voltage appears at emitter.

2008 Kenneth R. Laker updated KRL 28Oct11

Common Mode Results - Add r_o to Model



insert finite r_o
to model non-ideal
current source

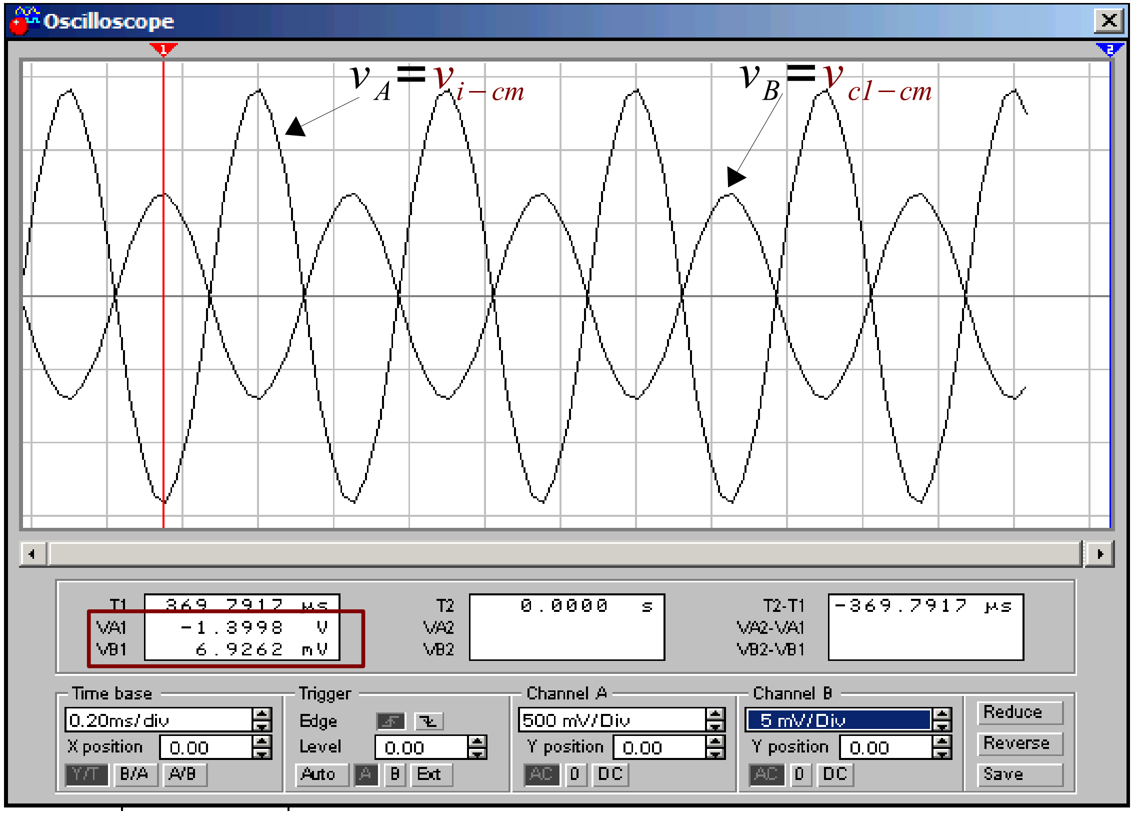
Theory

$$A'_{v-dm1} = \frac{v_{c1-dm}}{v_i} \approx \frac{-R_C}{R_E} = -10$$

$$A_{v-cm1} = \frac{v_{c1-cm}}{v_{i-cm}} \approx -\frac{R_C}{2\,r_o} = \frac{-1}{200} = -0.005$$

$$CMRR = 20\log_{10}\left|\frac{A'_{v-dm1}}{A_{v-cm1}}\right| = 66\,dB$$

Common Mode Results - Add Finite r_o



T1 369.7912 µs
VA1 -1.3998 V
VB1 6.9262 mV
T2 0.0000 s
VA2
VB2
T2-T1 -369.7917 µs
VA2-VA1
VB2-VB1

Time base: 0.20ms/div; X position 0.00; Y/T B/A A/B
Trigger: Edge; Level 0.00; Auto A B Ext
Channel A: 500 mV/Div; Y position 0.00; AC 0 DC
Channel B: 5 mV/Div; Y position 0.00; AC 0 DC

$$CMRR \approx 20 \log_{10}\left(\frac{9.5}{0.005}\right) \approx 66\, dB$$

$$r_o = 100\, k\,\Omega$$

"Scope" output B at collector of Q1, i.e. $v_B = v_{c1-cm}$.

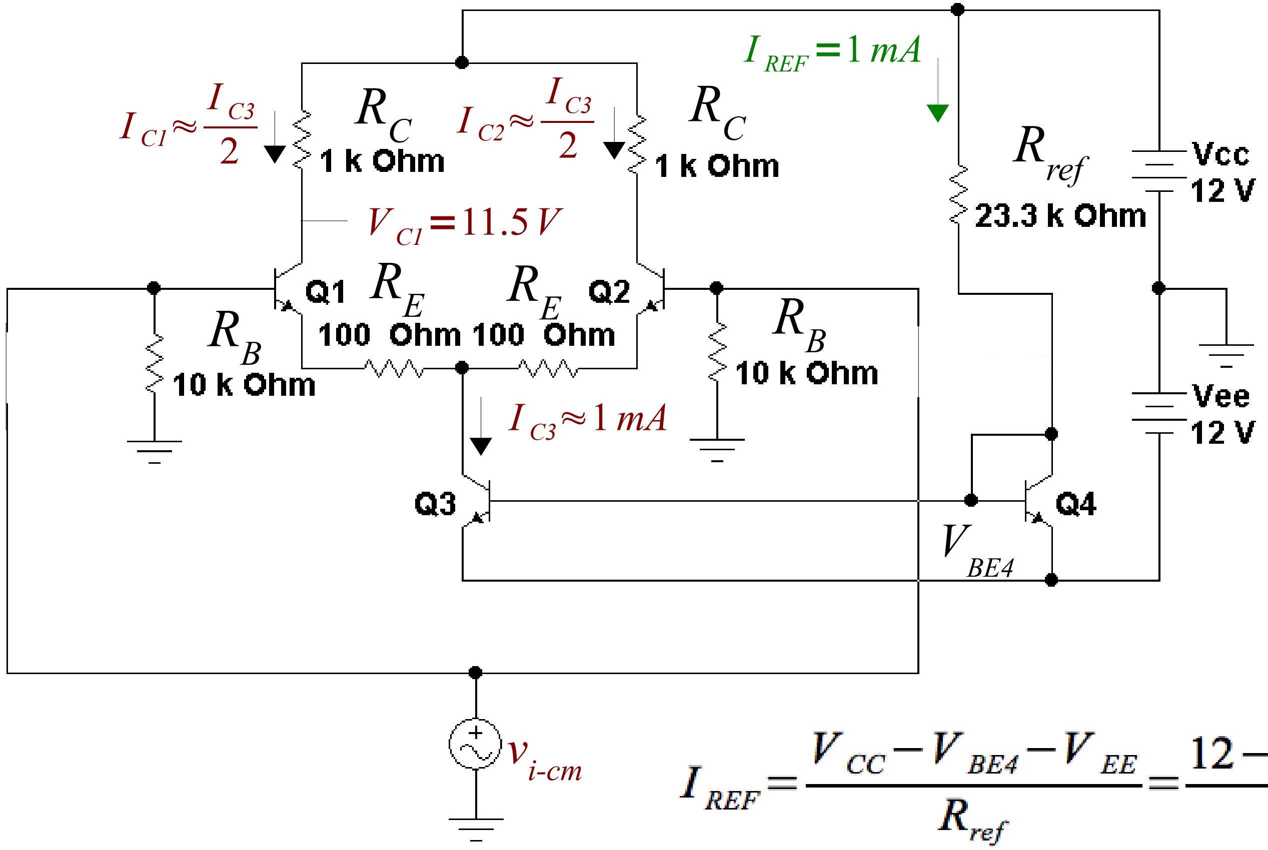
Input voltage $v_A = v_{i-cm}$
1.4 V_{peak} *arg* (0^o) at $f = 1\ kHz$.

Output voltage $v_B = v_{c1-cm}$
0.007 V_{peak} *arg* (180^o).

$$A_{v-cm1} \approx \frac{-0.007}{1.4} = -0.005$$

$A'_{v-dm1} = -9.5$ (unchanged)

Simulation with 1 mA Current Mirror



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

$$I_{C3}\approx 1\,mA$$

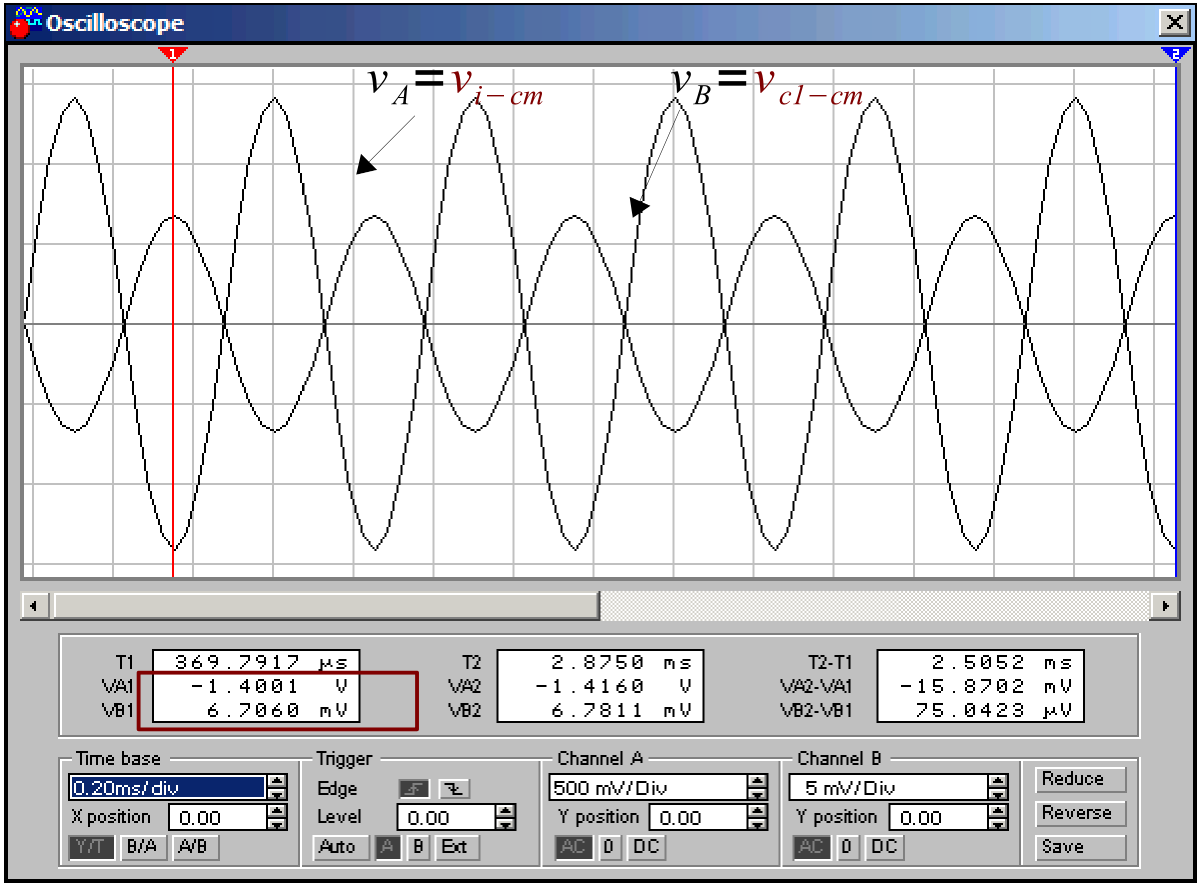
$$\Rightarrow I_{C1}=I_{C2}\approx 0.5\,mA$$

$$R_{ref}=23.3\,k\,\Omega$$

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

NOTE: - The zero-to-peak ac voltage swing across each R_C now only $0.5\;V$!

Simulation with 1 mA Current Mirror cont.



T1	369.7917 µs	T2	2.8750 ms	T2-T1	2.5052 ms
VA1	-1.4001 V	VA2	-1.4160 V	VA2-VA1	-15.8702 mV
VB1	6.7060 mV	VB2	6.7811 mV	VB2-VB1	75.0423 µV

Time base 0.20ms/div, X position 0.00
Trigger Edge, Level 0.00
Channel A 500 mV/Div, Y position 0.00
Channel B 5 mV/Div, Y position 0.00

“Scope” output B at collector of Q1, i.e. $v_B = v_{c1-cm}$.

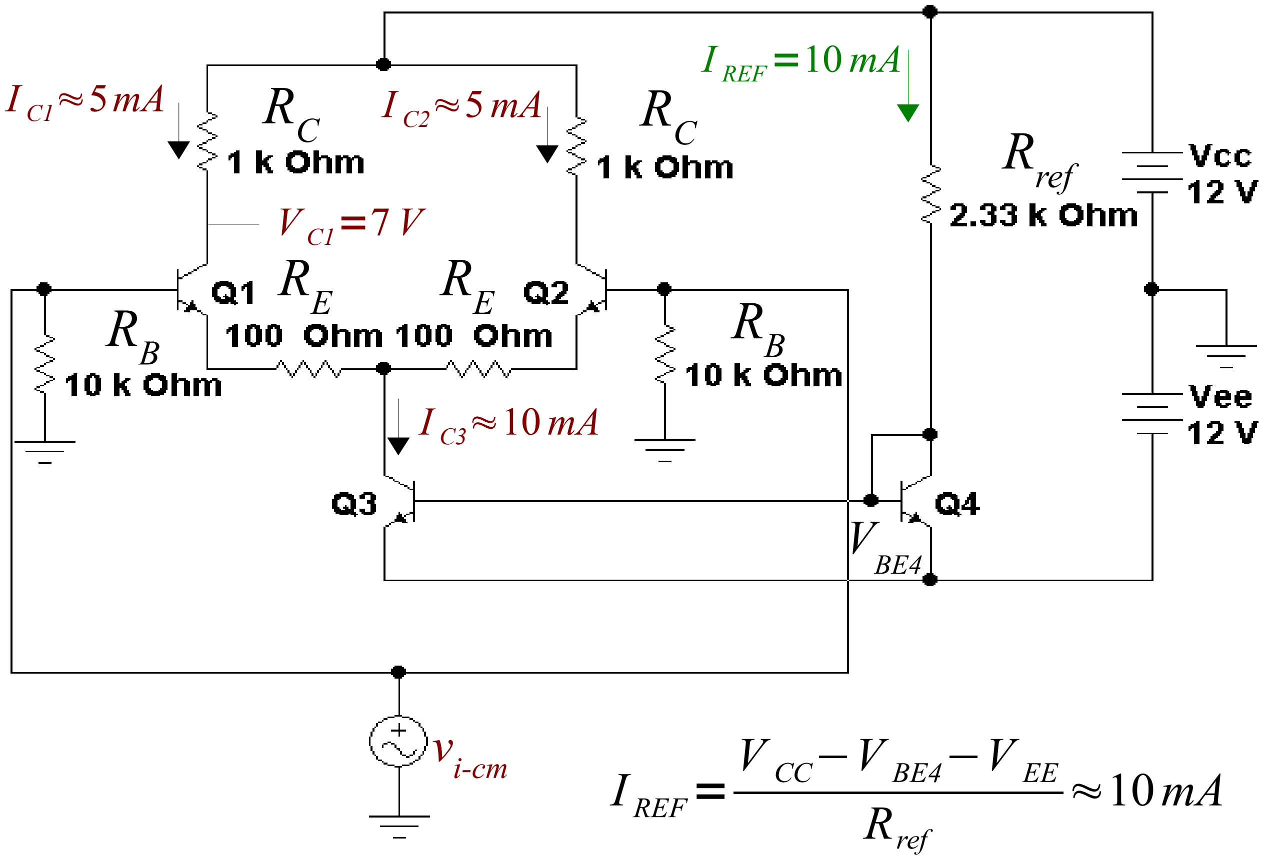
Input voltage $v_A = v_{i-cm}$ $1.4\ V_{peak}\ arg\ (0^o)$ at $f = 1\ kHz$.

Output voltage $v_B = v_{c1-cm}$ $7\ mV_{peak}\ arg(180^o)$.

$$A_{v-cm1} \approx \frac{-0.007}{1.4} = -0.005$$

1 kHz common mode results almost exactly same as those for $r_o = 100\,k\,\Omega$ model.

Simulation with 10 mA Current Mirror



$$I_{REF} = \frac{V_{CC} - V_{BE4} - V_{EE}}{R_{ref}} \approx 10\,mA$$

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

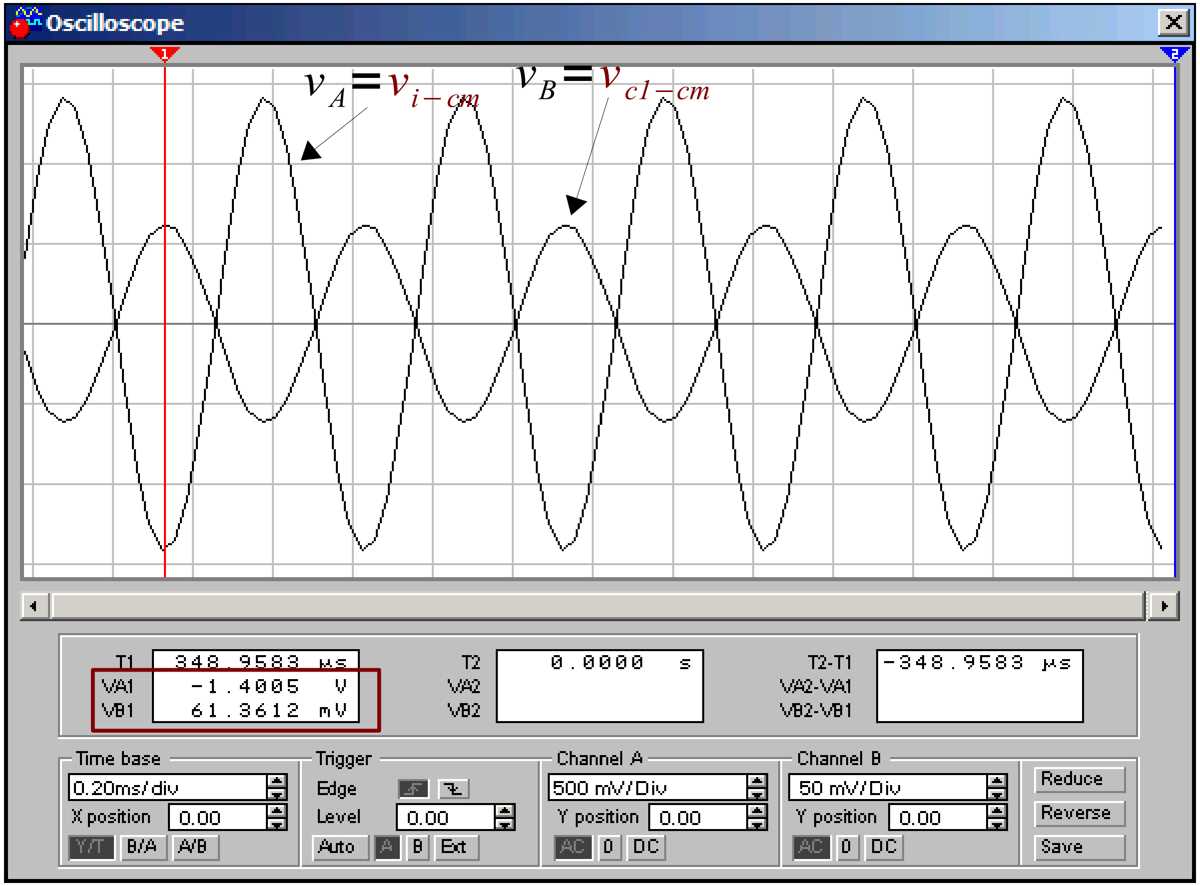
$$I_{C3} \approx 10\,mA$$

$$\Rightarrow I_{C1} = I_{C2} \approx 5\,mA$$

$$R_{ref} = 2.33\,k\,\Omega$$

NOTE: - The zero-to-peak ac voltage swing across each R_C increased to $5\ V$!

Simulation with 10 mA Current Mirror cont.



T1 348.9583 µs
VA1 -1.4005 V
VB1 61.3612 mV
T2 0.0000 s
T2-T1 -348.9583 µs

Time base 0.20ms/div, X position 0.00, Y/T
Trigger Edge, Level 0.00, Auto
Channel A 500 mV/Div, Y position 0.00, AC
Channel B 50 mV/Div, Y position 0.00, AC

$$A_{v-cm1} \approx \frac{-0.06}{1.4} = -0.043$$

Input voltage $v_A = v_{i-cm}$

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

Output voltage $v_B = v_{c1-cm}$

$60\ mV_{peak}\ arg\ (180^o)$.

$$A_{v-cm1} \approx -0.043$$

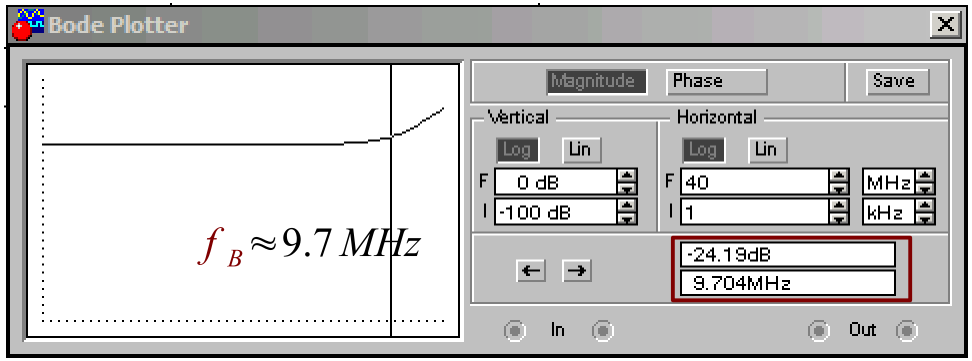
Common mode output now about $10X$ its previous value with $0.5\ mA$. collector current.

Why? r_0 has decreased!

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

10 times the current means $1/10$ the value of r_o!

Simulation with 1 mA & 10 mA CMs - Bode Plots



Vertical: Log, F 0 dB, I -100 dB

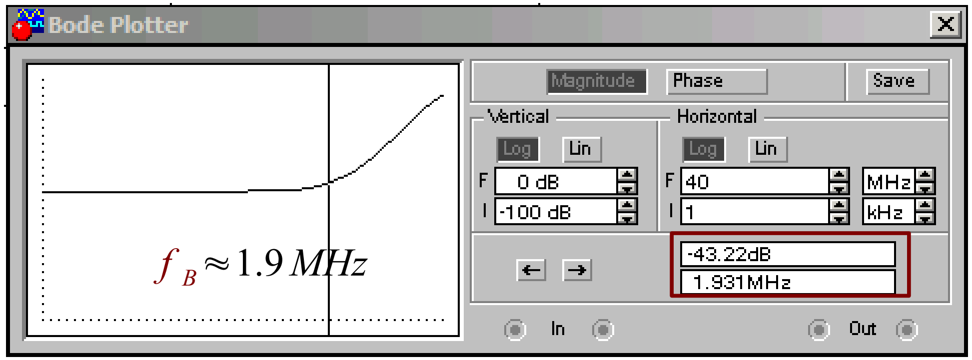
Horizontal: Log, F 40 MHz, I 1 kHz

-24.19dB

9.704MHz

$f_B \approx 9.7\ MHz$

5 mA current: $A_{v\text{-}cm1(dB)}$ + *3 dB* frequency



Vertical: Log, F 0 dB, I -100 dB

Horizontal: Log, F 40 MHz, I 1 kHz

-43.22dB

1.931MHz

$f_B \approx 1.9\ MHz$

0.5 mA current: $A_{v\text{-}cm1(dB)}$ + *3 dB* frequency

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

$A_{v-cm1(dB)}(f=1\,kHz) \approx 20\log_{10}(\frac{0.06}{1.4}) = -27.3\,dB$

$A_{v-cm1(dB)}(f=9.7\,MHz) = -24.2\,dB \quad (+\ 3dB)$

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

theory $\quad \frac{f_{B(1mA)}}{f_{B(10\,mA)}} \approx \frac{r_{o(10mA)}}{r_{o(1\,mA)}} = \frac{10\text{k}}{100\text{k}} = 0.1$

simulation $\quad \frac{f_{B(1mA)}}{f_{B(10\,mA)}} = \frac{1.9\ MHz}{9.7\ MHz} = 0.2$

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

$A_{v-cm1(dB)}(f=1\,kHz) \approx 20\log_{10}(\frac{0.007}{1.4}) = -46\,dB$

$A_{v-cm1(dB)}(f=1.9\,MHz) = -43.2\,dB \quad (+\ 3dB)$

Comparison of 1 mA & 10 mA CM Results

$I_{REF}=1\,mA \quad V_A=50\,V$

$$V_{RC1}\approx\frac{I_{REF}}{2}R_{C1}=0.5\,V$$

$$r_o\approx\frac{V_A}{I_{REF}/2}=100\,k\,\Omega$$

$$A_{v-cm1}=\frac{-R_{C1}}{2r_o}\approx\frac{-0.007}{1.4}=-0.005$$

$$f_B\approx 1.9\,MHz$$

$$A'_{v-dm1}=-9.5$$

$I_{REF}=10\,mA \quad V_A=50\,V$

$$V_{RC1}\approx\frac{I_{REF}}{2}R_{C1}=5\,V$$

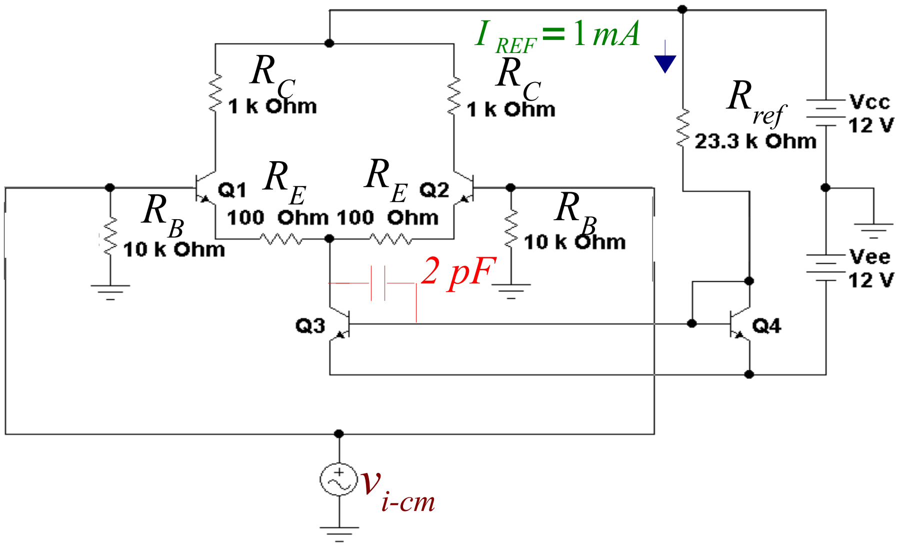
$$r_o\approx\frac{V_A}{I_{REF}/2}=10\,k\,\Omega$$

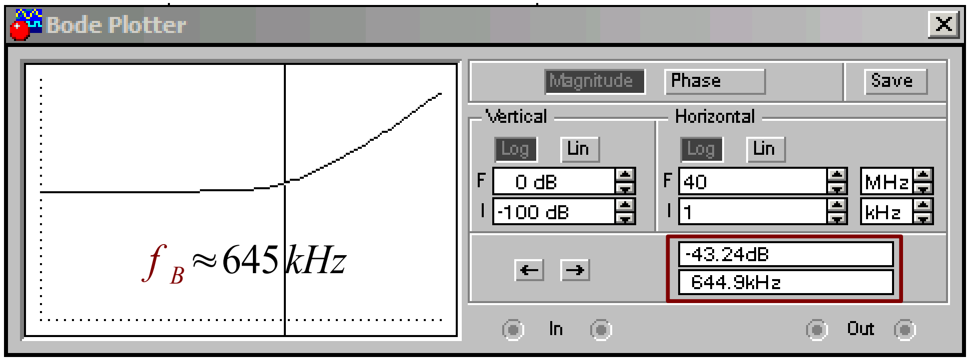
$$A_{v-cm1}=\frac{-R_{C1}}{2r_o}\approx\frac{-0.06}{1.4}=-0.043$$

$$f_B\approx 9.7\,MHz$$

$$A'_{v-dm1}=-9.5$$

Simulations with Parasitic Caps





$f_B \approx 645\,kHz$

Vertical: Log, F 0 dB, I -100 dB

Horizontal: Log, F 40 MHz, I 1 kHz

-43.24dB

644.9kHz

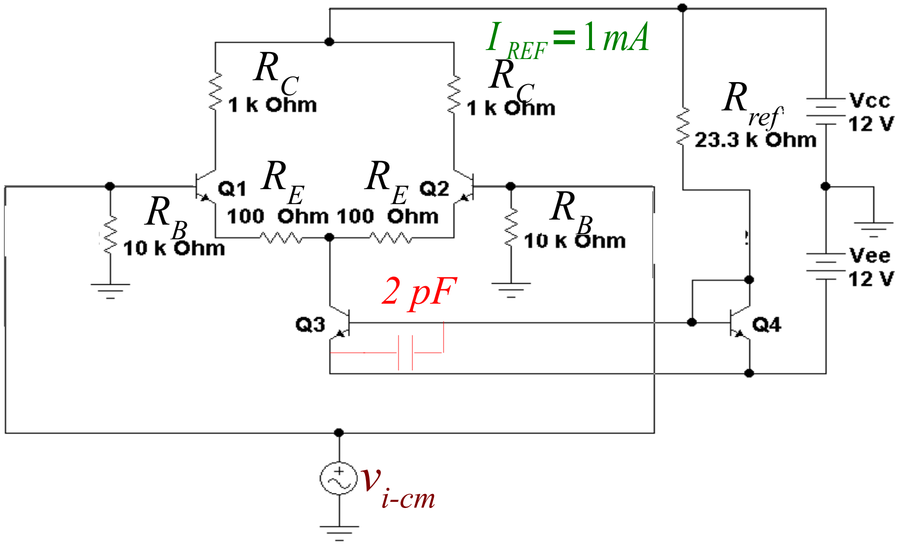
$$A_{v-cm1(dB)}(f=1\,kHz)\approx 20\log_{10}\left(\frac{0.007}{1.4}\right)=-46\,dB$$

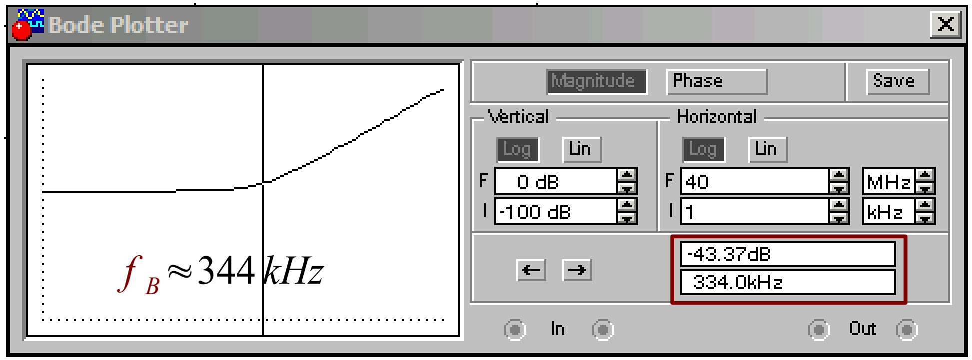
$$A_{v-cm1(dB)}(f=645\,kHz)=-43.2\,dB$$

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 $A_{v\text{-}cm1(dB)}$ $+\ 3\ dB$ frequency from $1.9\ MHz$ to about $645\ kHz$!

Simulations with Parasitic Caps - cont.





Vertical: Log Lin; F 0 dB; I -100 dB

Horizontal: Log Lin; F 40 MHz; I 1 kHz

-43.37dB

334.0kHz

$$A_{v-cm1(dB)}(f=1\,kHz)\approx 20\log_{10}\left(\frac{0.007}{1.4}\right)=-46\,dB$$

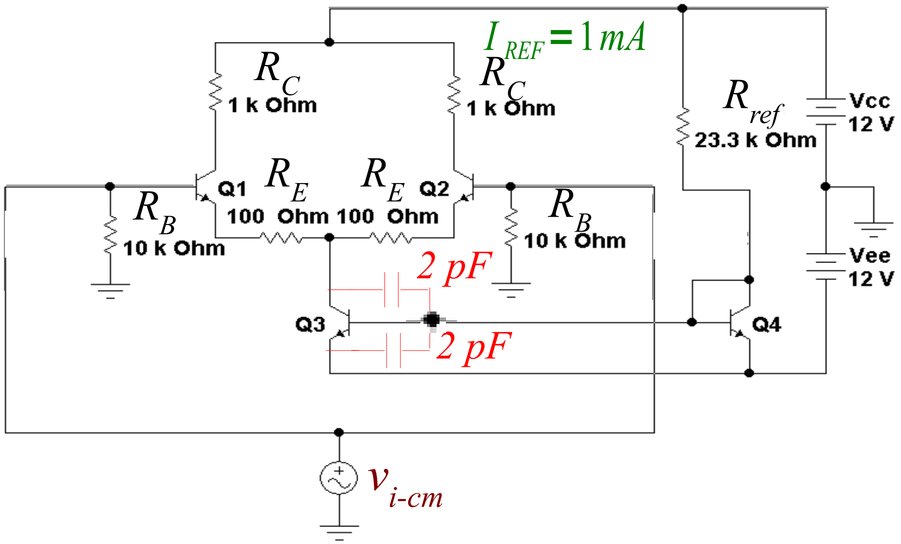
$$A_{v-cm1(dB)}(f=334\,kHz)=-43.2\,dB$$

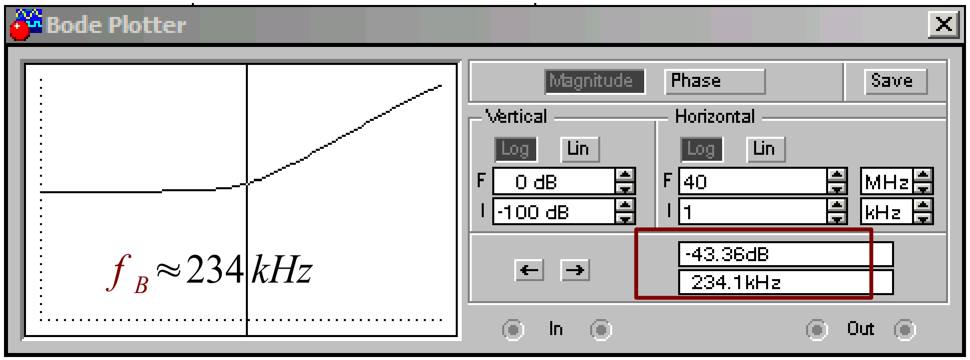
Results with *2 pF* capacitance added from base-to-emitter of mirror transistor.

This drops the amplifier $A_{v-cm1(dB)}$ *+3 dB* frequency from *1.9 MHz* to about *334 kHz*!

RECALL: *2 pF* is about the capacitance between 2 rows of Protoboard pins!

Simulations with Parasitic Caps - cont.





Vertical: F 0 dB, I -100 dB

Horizontal: F 40 MHz, I 1 kHz

-43.36dB

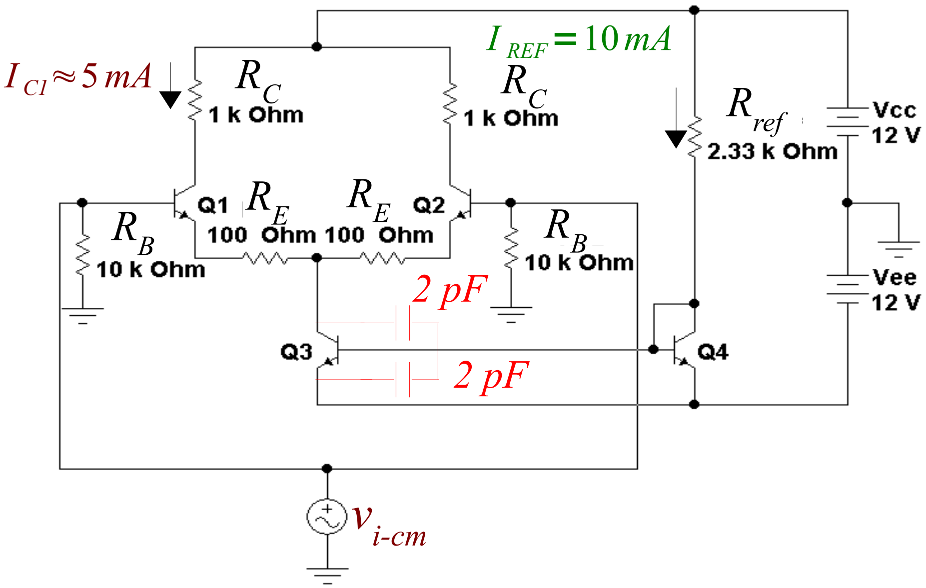
234.1kHz

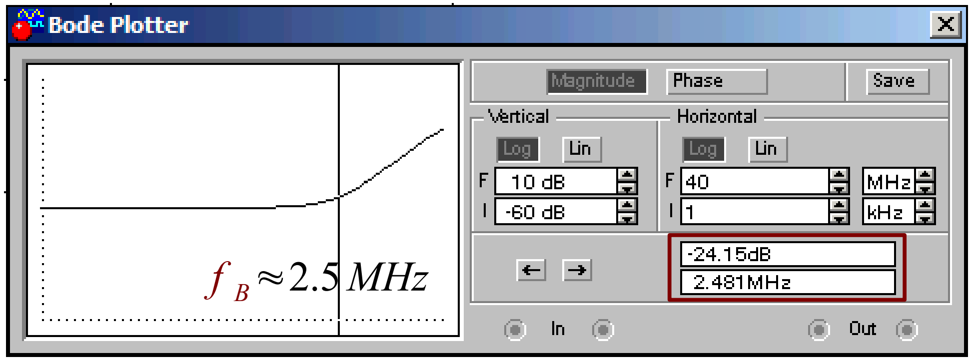
$$A_{v-cm1(dB)}(f=1\,kHz)\approx 20\log_{10}\left(\frac{0.007}{1.4}\right)=-46\,dB$$

$$A_{v-cm1(dB)}(f=234\,kHz)=-43.2\,dB$$

Drops amplifier $A_{v\text{-}cm1(dB)}$ break frequency from $1.9\ MHz$ to about $234\ kHz$!

Simulate the $5\ mA$ Design with $2\ pF$ Parasitics





Vertical: Log; F 10 dB; I -60 dB

Horizontal: Log; F 40 MHz; I 1 kHz

-24.15dB

2.481MHz

$$A_{v-cm1(dB)}(f = 1\ kHz) \approx -27\ dB$$

$$A_{v-cm1(dB)}(f = 2.5\ MHz) = -24.2\ dB$$

Parasitic caps drop amplifier $A_{v\text{-}cm(dB)}$ break frequency from $9.7\ MHz$ to about $2.5\ MHz$!

	$I_{REF} = 10\ mA$	$I_{REF} = 1\ mA$
f_B	$2.5\ MHz$	$234\ kHz$
$A_{v-cm1(dB)}(f = 1\ kHz)$	$-27\ dB$	$-46\ dB$
$A'_{v-dm1(dB)}(f = 1\ kHz)$	$+20\ dB$	$+20\ dB$

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

About $10X$ the bandwidth as the $I_{REF} = 1\ mA$ design.

Observations

1). For best common mode rejection use small collector currents i.e. increase r_o.

2). For best $A_{v\text{-}cm}$ bandwidth use large collector currents, i.e. decrease r_o.

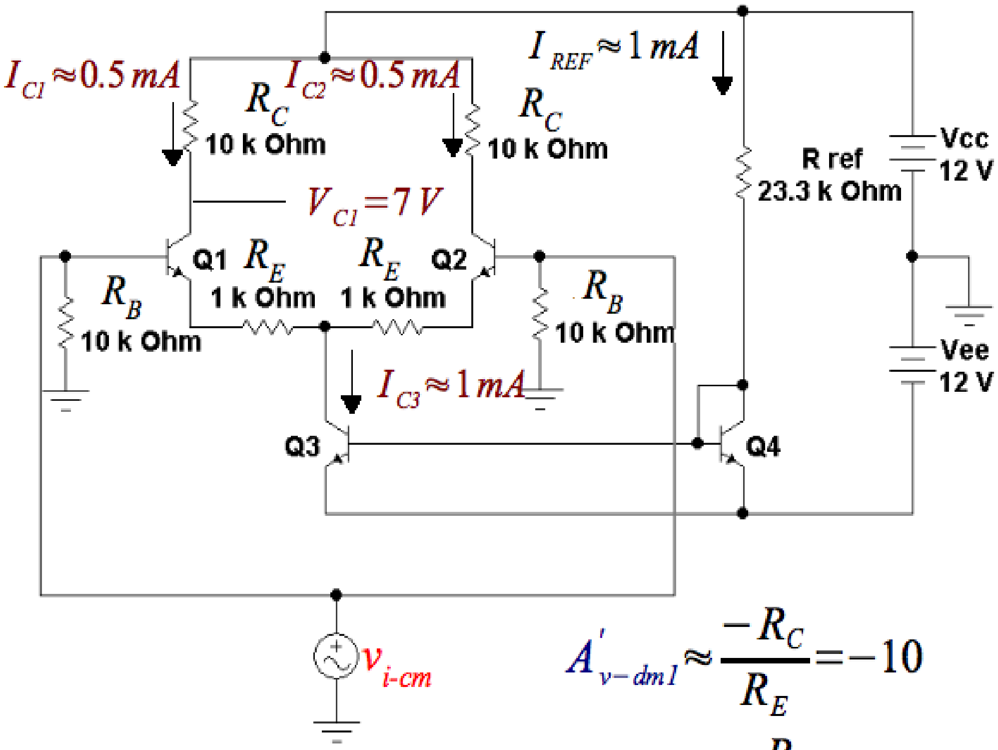
3). Minimize parasitic capacitance around mirror transistor to increase common mode rejection bandwidth.

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.

Try Redesign for Reasonable Differential Mode Voltage Swing & large r_o

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



$$A'_{v-dm1}\approx\frac{-R_C}{R_E}=-10$$

$$A_{v-cm1}\approx-\frac{R_C}{2r_o}$$

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_C to increase V_{RC1}.

$$V_{RC1}=R_C\frac{I_{REF}}{2}$$

3. Increase R_E to retain desired A'_{v-dm1}.

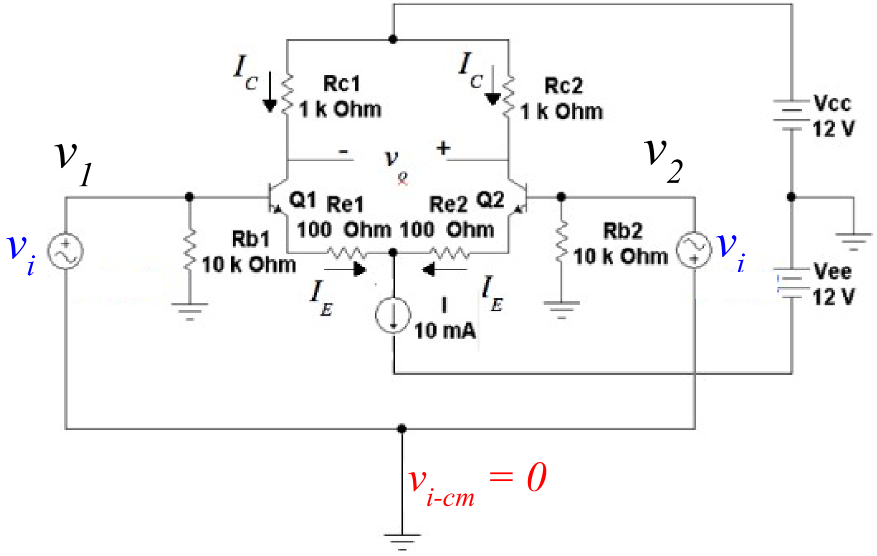
$$A'_{v-dm1}=\frac{R_C}{R_E}$$

op.pt

$$A_{v-cm1}\approx-\frac{R_C}{2r_o}=-\frac{V_{RC1}}{I_{REF}/2}\frac{I_{REF}}{2V_A}=-\frac{V_{RC1}}{V_A}$$

RESULT: No help!

ESE319 Introduction to Microelectronics



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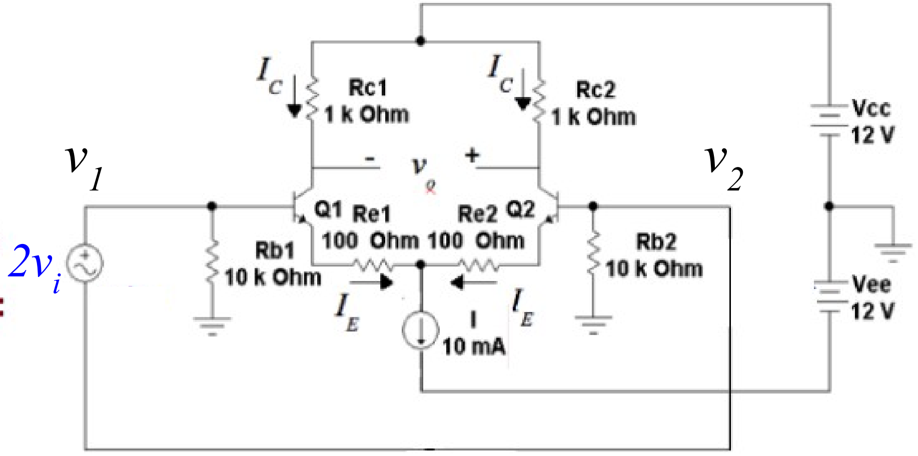

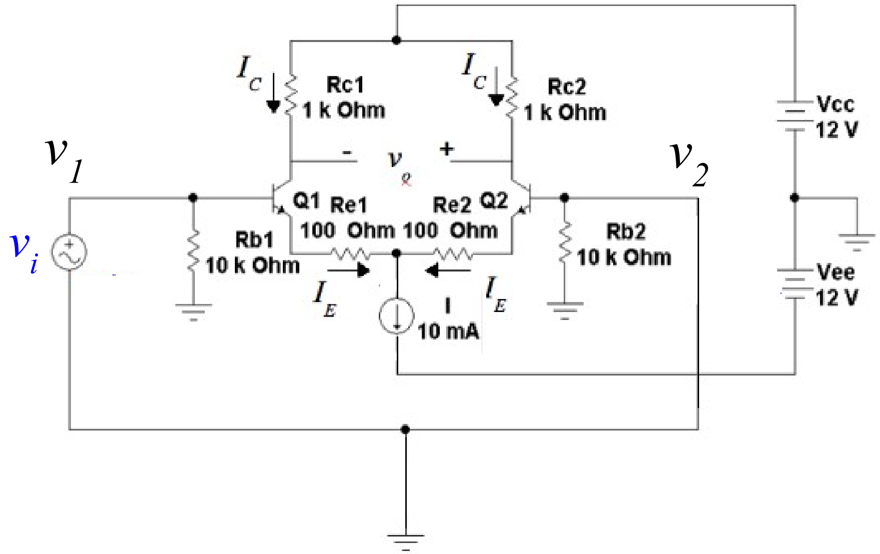

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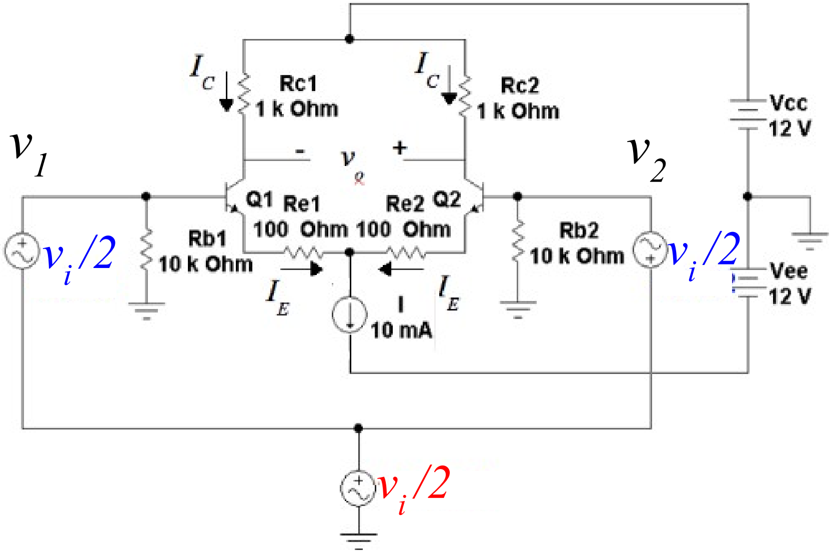
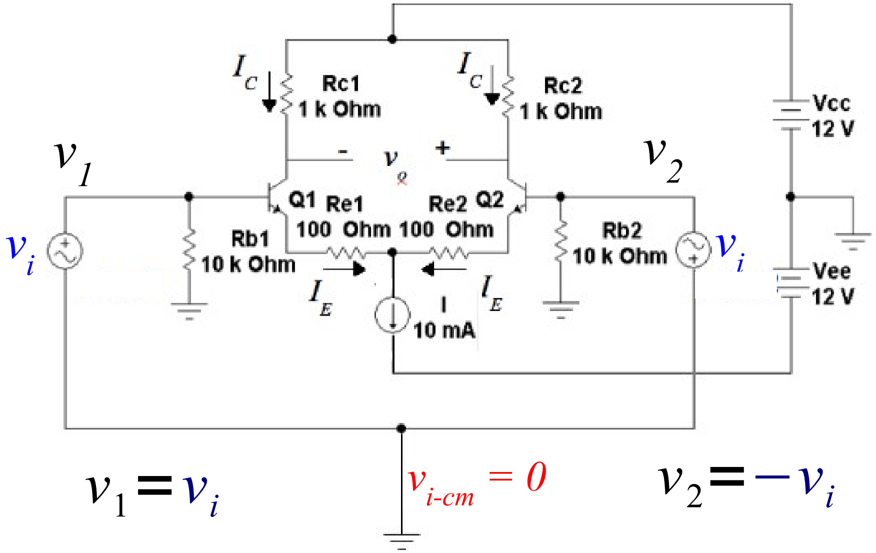
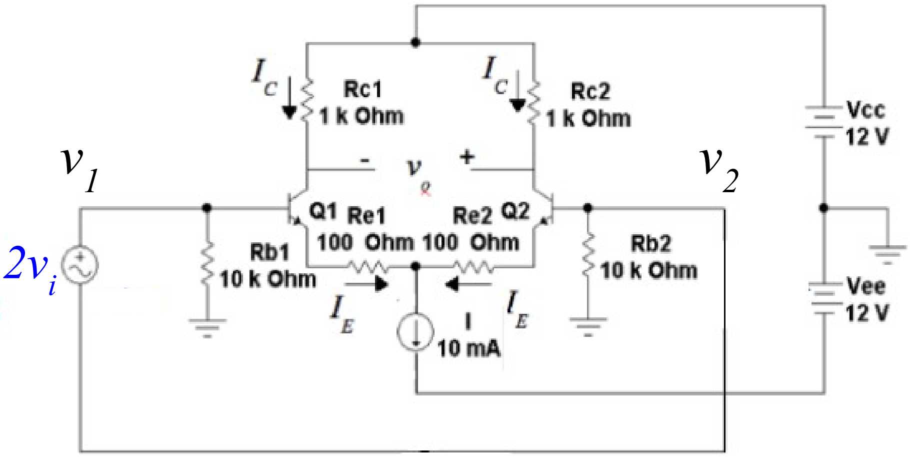


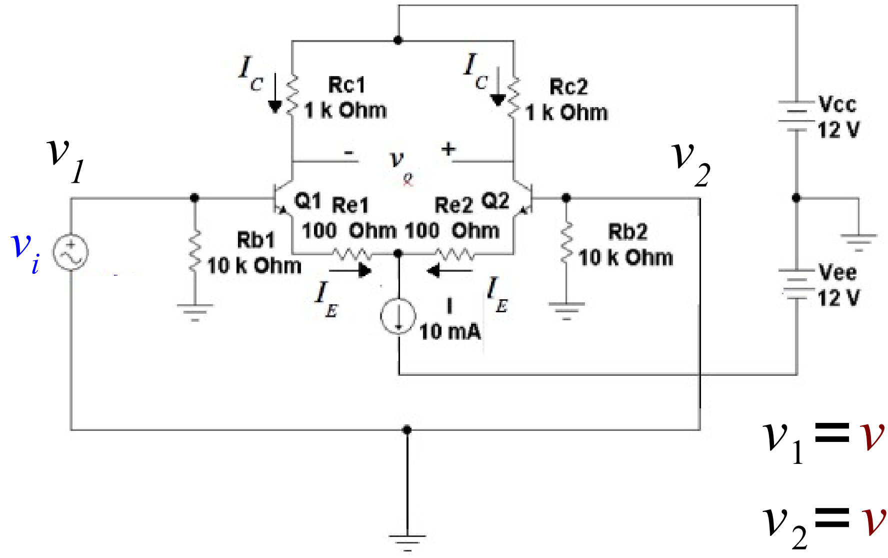


$v_1 = v_i$ $v_2 = -v_i$

$\neq$



$v_1 - v_2 = 2v_i$ $v_1 \neq v_i$ $v_2 \neq -v_i$



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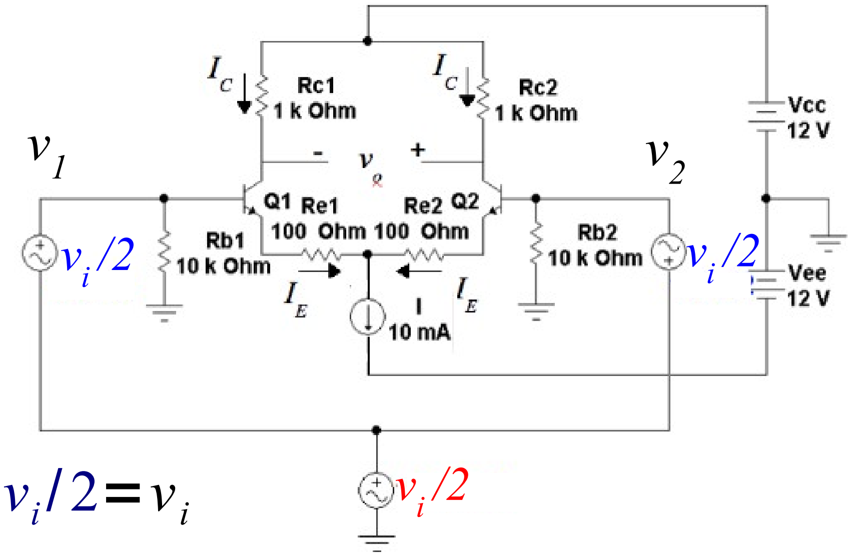

$v_1 = v_i/2 + v_i/2 = v_i$

$v_2 = v_i/2 - v_i/2 = 0$