Solutions to Homework 4
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BJT Model:

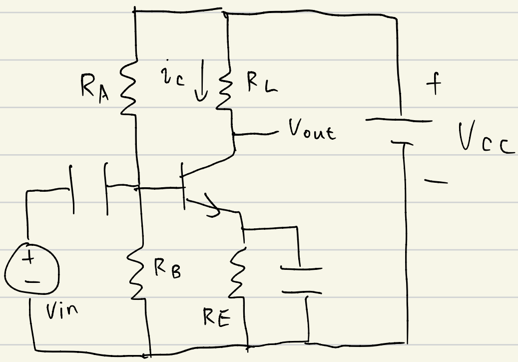
```
.model Q2N3904  NPN(Is=6.734f Xti=3 Eg=1.11 Vaf=74.03 Bf=416.4 Ne=1.259
+               Ise=6.734f Ikf=66.78m Xtb=1.5 Br=.7371 Nc=2 Isc=0 Ikr=0
Rc=1
+               Cjc=3.638p Mjc=.3085 Vjc=.75 Fc=.5 Cje=4.493p Mje=.2593
Vje=.75
+               Tr=239.5n Tf=301.2p Itf=.4 Vtf=4 Xtf=2 Rb=10)
*               National        pid=23          case=TO92
*               88-09-08 bam    creation
*$

.model Q2N3906  PNP(Is=1.41f Xti=3 Eg=1.11 Vaf=18.7 Bf=180.7 Ne=1.5
Ise=0
+               Ikf=80m Xtb=1.5 Br=4.977 Nc=2 Isc=0 Ikr=0 Rc=2.5
Cjc=9.728p
+               Mjc=.5776 Vjc=.75 Fc=.5 Cje=8.063p Mje=.3677 Vje=.75
Tr=33.42n
+               Tf=179.3p Itf=.4 Vtf=4 Xtf=6 Rb=10)
*               National        pid=66          case=TO92
*               88-09-09 bam    creation
*$
```

MOSFET Model:

```
.model nch nmos(Level=1 Tox=300n Uo=600 Kp=20.54u W=144u L=8u Vto= 1.3
+               Lambda=15m Cbd=4p Cbs=4p Cgdo=1.7n Cgso=1.7n Rs=1 Rd=1)
.model pch pmos(Level=1 Tox=300n Uo=300 Kp=10.32u W=328u L=8u Vto=-1.5
+               Lambda=15m Cbd=8p Cbs=8p Cgdo=1.7n Cgso=1.7n Rs=1 Rd=1)
```

Common - Emitter Amp. using npn 2N3904



$V_{cc} = 6V$ $R_E = 1k\Omega$

$V_A = 74.03V$, $\beta = 416.4$

Q Point ⇒ $I_c = 2.6mA$

small-signal :

$$g_m = \frac{I_c}{V_T} = \frac{2.6mA}{25mV} = 0.104\ S$$

$$r_o = \frac{V_A}{I_c} = \frac{74.03V}{2.6mA} = 28.5k\Omega$$

$A_v = -g_m(R_L // r_o)$, $R_L = -\dfrac{A_v r_o}{g_m r_o + A_v} = 193.6\Omega$

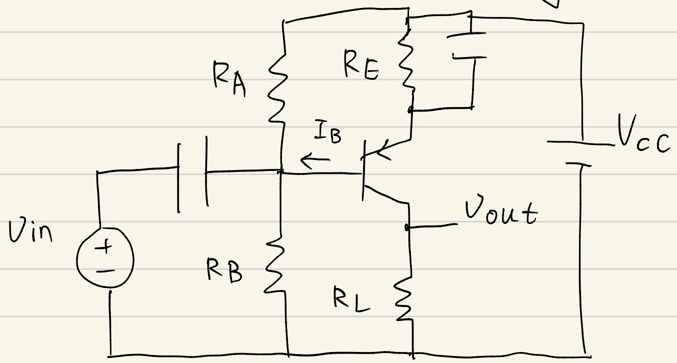
$$I_E = \frac{I_c}{\alpha} = \frac{I_c}{\beta/\beta+1} = \frac{2.6mA}{0.9976} = 2.606mA, \quad I_B = \frac{I_c}{\beta} = 6.244\mu A,$$

$V_{BE} \cong 0.7V$ $V_B = V_{BE} + I_E R_E = 3.306\ V$

choose $R_A = 1k\Omega$, I_{RA} should be larger than I_B,

$$R_B = \frac{V_B}{I_{RA} - I_B} = \frac{V_B}{\frac{V_{cc} - V_B}{R_A} - I_B} = 1.23\ k\Omega$$

Common – Emitter using pnp 2N3906



$\beta = 180.7$ $V_A = 18.7V$

$V_{CC} = 6V$, $V_E = 1k\Omega$

$I_C = 2.6mA$,

$g_m = \frac{I_C}{V_T} = 0.104\,S$

$r_o = \frac{V_A}{I_C} = \frac{18.7V}{2.6mA} = 7.19\,k\Omega$

$I_B = \frac{I_C}{\beta} = \frac{2.6mA}{180.7} = 14.39\,\mu A$

$I_S = 1.41\,fA$

$R_L = -\frac{A_v r_o}{g_m r_o + A_v} = 197.59\,\Omega$

$I_E = \frac{I_C}{\alpha} = \frac{I_C}{\beta/\beta+1} = \frac{2.6mA}{0.9945} = 2.614\,mA$

$V_{EB} \cong 0.7V$

$V_B = V_{CC} - I_E R_E - V_{EB} = 6V - 2.614mA \cdot 1k\Omega - 0.7V = 2.686V$

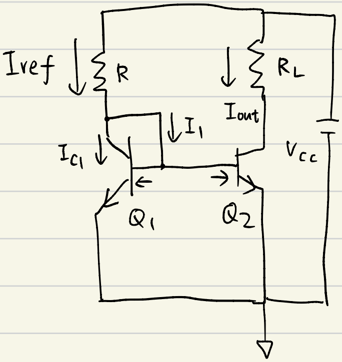
choose $R_A = 1k\Omega$, then,

$R_B = \frac{V_B}{I_{RA} + I_B} = \frac{V_B}{\frac{V_{CC} - V_B}{R_A} + I_B} = 807\,\Omega$

Current Mirror using BJT

1) Sinking, npn, 2N3904

↳ $\beta = 416.4$, $V_A = 74.03\,V$ $\quad I_s = 6.734\,fA$



$$I_{B1} = \frac{I_{C1}}{\beta}$$

Q_1 & Q_2 share V_{BE}

$\Rightarrow I_{B2} = I_{B1} = I_{C1}/\beta$

$\Rightarrow I_1 = I_{B1} + I_{B2} = 2I_{C1}/\beta$

$$I_{ref} = I_1 + I_{C1} = \left(1+\frac{2}{\beta}\right) I_{C1} = \left(1+\frac{2}{\beta}\right) I_s e^{\frac{V_{BE}}{V_T}}$$

Solve $V_{BE} \simeq 0.683\,V$ [which is close to $0.7\,V$]

$$R = \frac{V_{CC} - V_{CE}}{I_{ref}} = \frac{6V - 0.683V}{5mA} = 1063\,\Omega$$

mirror:

$$I_o = I_{ref} \frac{1}{1+\frac{2}{\beta}} \left[1 + \frac{V_o - V_{BE}}{V_A}\right]$$

as we want $I_o = I_{ref}$, then, $\dfrac{2}{\beta} = \dfrac{V_o - V_{BE}}{V_A}$

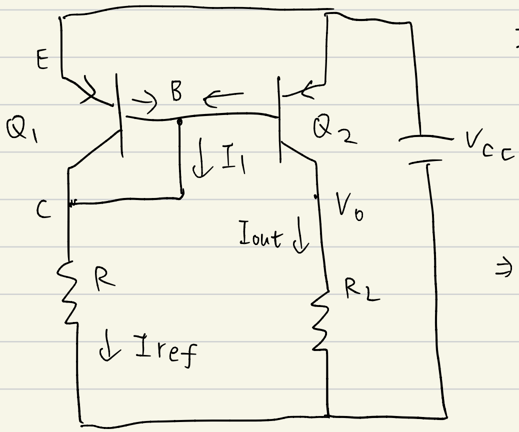
$$V_o = V_{BE} + V_A \frac{2}{\beta} = 0.683V + 74.03V \cdot \frac{2}{416.4} = 1.039V$$

$$R_L = \frac{V_{CC} - V_o}{I_o} = \frac{(6-1.039)V}{5mA} = 992\,\Omega$$

2) Sourcing, pnp 2N3906

$\beta = 180.7$, $I_s = 1.41 fA$

$V_A = 18.7V$



$$I_1 = 2I_B = \frac{2I_{C1}}{\beta}$$

$$I_{ref} = I_1 + I_{C1} = \left(\frac{2}{\beta}+1\right) I_{C1}$$

$$= \left(\frac{2}{\beta}+1\right) I_s\, e^{V_{EB}/V_T}$$

Solve $V_{EB} = 0.722V$

$$\Rightarrow R = \frac{V_{CC} - V_{EB}}{I_{ref}} = \frac{6V - 0.722V}{5mA} = 1056\Omega$$

Similarly, $I_o = I_{ref} \dfrac{1}{1+\frac{2}{\beta}} \cdot \left[1 + \dfrac{V_{CC} - V_{EB} - V_o}{V_A}\right]$

then, $\dfrac{2}{\beta} = \dfrac{V_{CC} - V_{EB} - V_o}{V_A}$

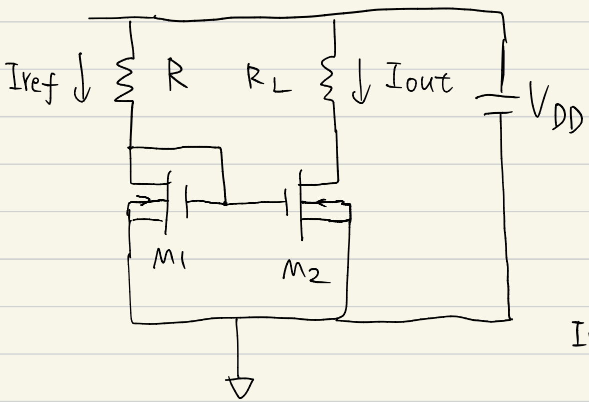
$$V_o = V_{CC} - V_{EB} - \frac{2}{\beta} V_A = 6V - 0.722V - \frac{2}{180.7} \cdot 18.7V$$

$$= 5.071V$$

$$R_L = \frac{V_o}{I_o} = \frac{5.071V}{5mA} = 1014\Omega$$

Current Mirror using 4007 NMOS

① sinking, use NMOS



we want $I_{out} = I_{ref} = 5mA$

for M_1 : $V_{GS} = V_{DS}$,

$k_n' = 20.54u$, $W = 144u$

$V_{to} = 1.3V$ $L = 8u$

$\lambda = 15m$

$$I_{ref} = \frac{1}{2} k_n' \left(\frac{W}{L}\right)(V_{GS} - V_{to})^2 (1 + \lambda V_{DS})$$

↓

Solve V_{GS} in matlab, $V_{GS} = V_{DS} = 6.27V$

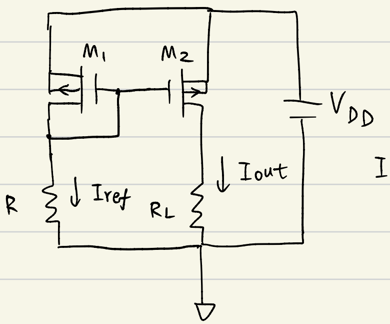
We notice that $V_{GS} > V_{DD}$, so $V_{DD} = 6V$ is not enough to drive this current mirror,

So we change V_{DD} to $9V$, then

$$R = \frac{V_{DD} - V_{GS}}{I_{ref}} = \frac{9V - 6.27V}{5mA} = 546\Omega$$

So we approximately set $R_L = R = 546\Omega$

② sourcing, using PMOS



$k_p' = 10.32\mu$, $W = 328u$,

$V_{to} = -1.5V$ $L = 8u$

$\lambda = 15m$

$$I_{ref} = \frac{1}{2} k_p' \left(\frac{W}{L}\right)\left(V_{SG} - |V_{to}|\right)^2 (1 + \lambda V_{SD})$$

$$= 5mA$$

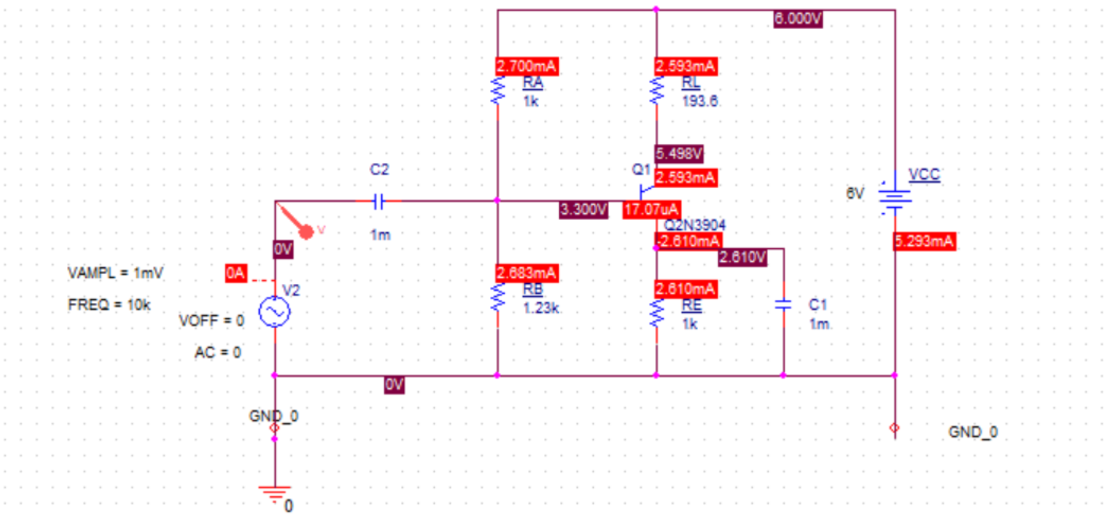
solve in matlab, $V_{SG} = V_{SD} = 6.15V$

Set $V_{DD} = 9V$, $\quad R = \dfrac{V_{DD} - V_{SD}}{I_{ref}} = \dfrac{9V - 6.15V}{5A} = 570\Omega$

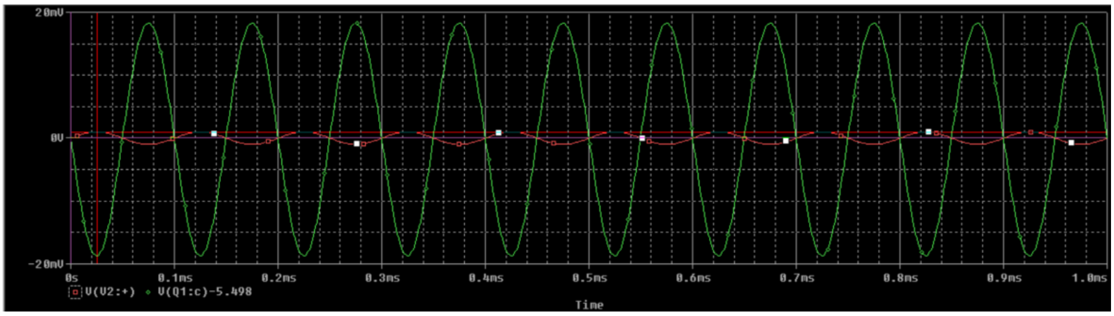
$R_L = R = 570\Omega$

Problem 1

b.



I_C=2.593mA, which is close to the required 2.6mA



	Trace Color	Trace Name	Y1
		X Values	25.439u
	CURSOR 1,2	V(V2:+)	1.0000m
		V(Q1:c)-5.498	-18.714m

The amplitude of output voltage is approximately 18.7mV, and v_{in} and v_{out} are in opposite phase.

So the voltage gain

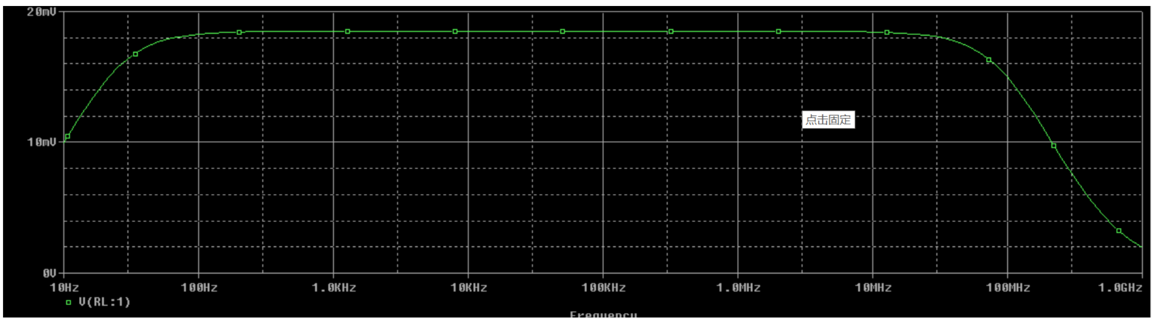
A_v = 18.7mV/1mV=-18.7, which is close to -20.

c.

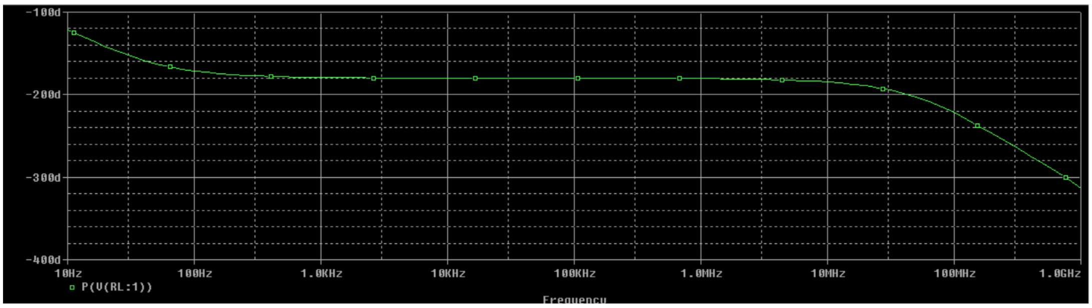
Use Pspice>>Markers>>Advanced>>phase of voltage

AC=1m，run in AC sweep

Voltage magnitude:



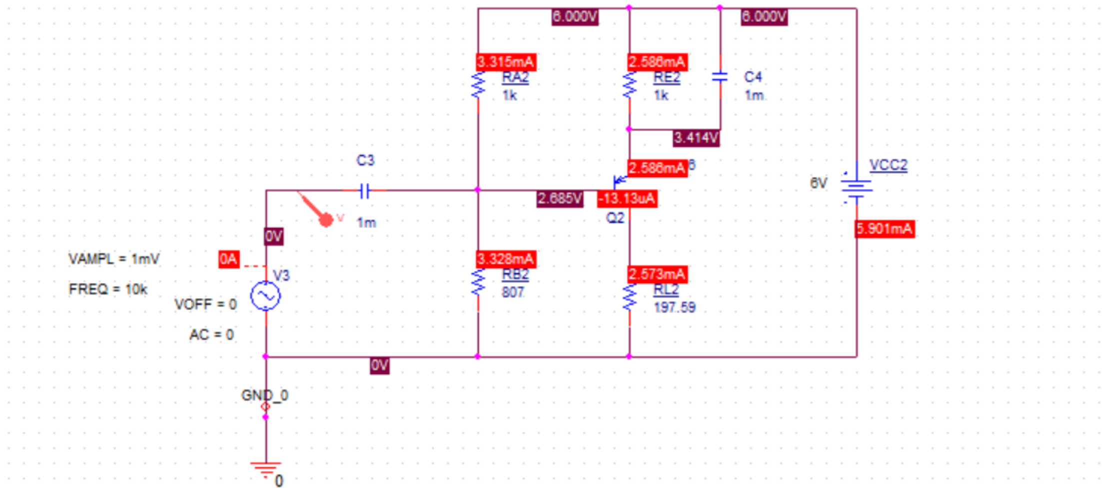
Voltage phase:



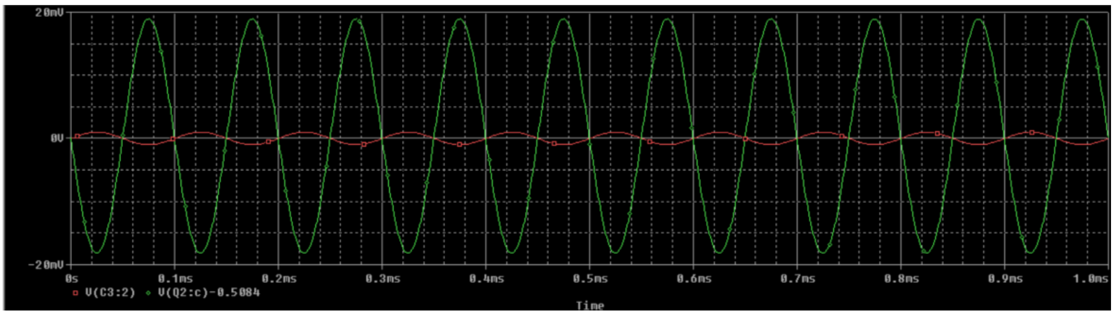
The amplitude of output voltage remains nearly 20mV and the phase stays at -180 degrees in a frequency band with the range of about 100Hz-10MHz. At low frequency, voltage gain is lower and the phase is higher than -180 degrees because of the bypass capacitors. As the frequency further increases, the amplitude starts to drop and the phase starts to drop. It is because of the existence of parasitic capacitors of the transistor.

d.

pnp



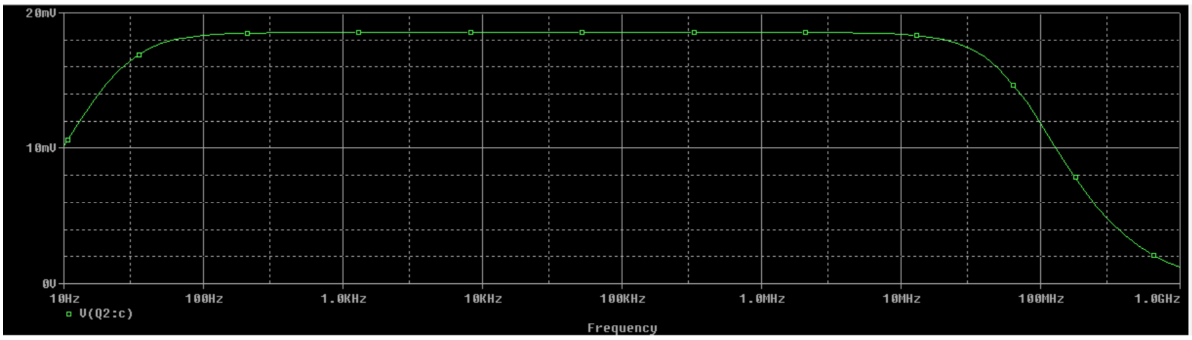
I_C=2.586mA.

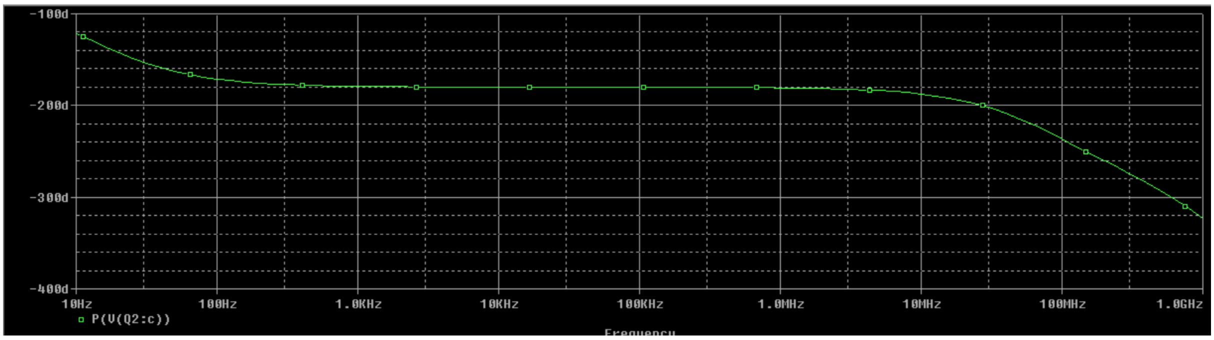


Trace Color	Trace Name	Y1
	X Values	74.561u
CURSOR 1,2	V(C3:2)	-1.0003m
	V(Q2:c)-0.5084	18.915m

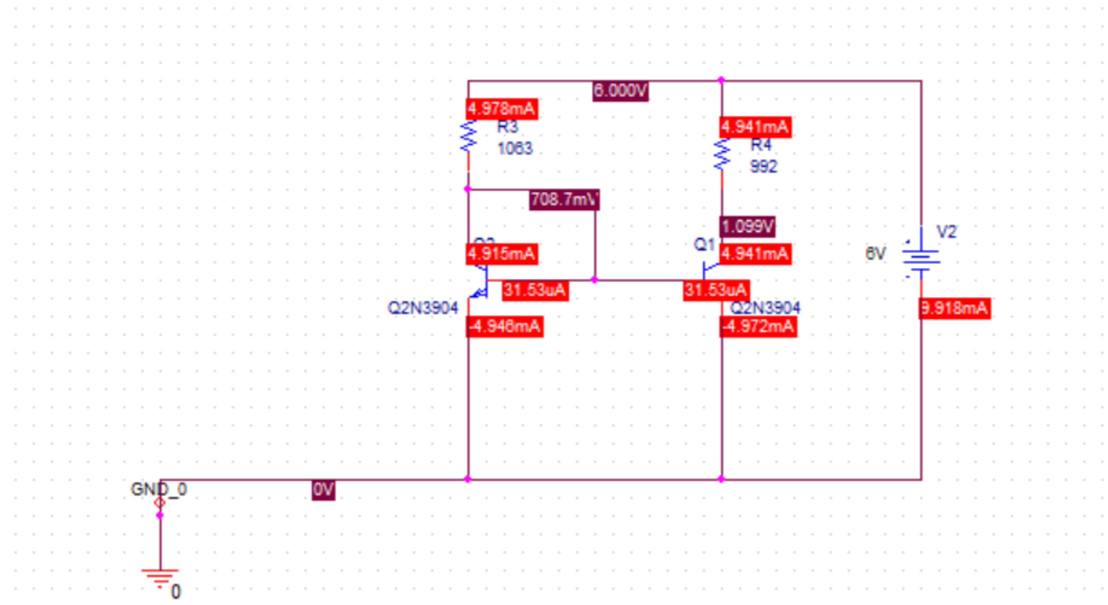
The amplitude of output voltage is approximately 18.9mV, and v_{in} and v_{out} are in opposite phase.
So the voltage gain
A_v = 18.9mV/1mV=-18.9, which is close to -20.

Frequency response:



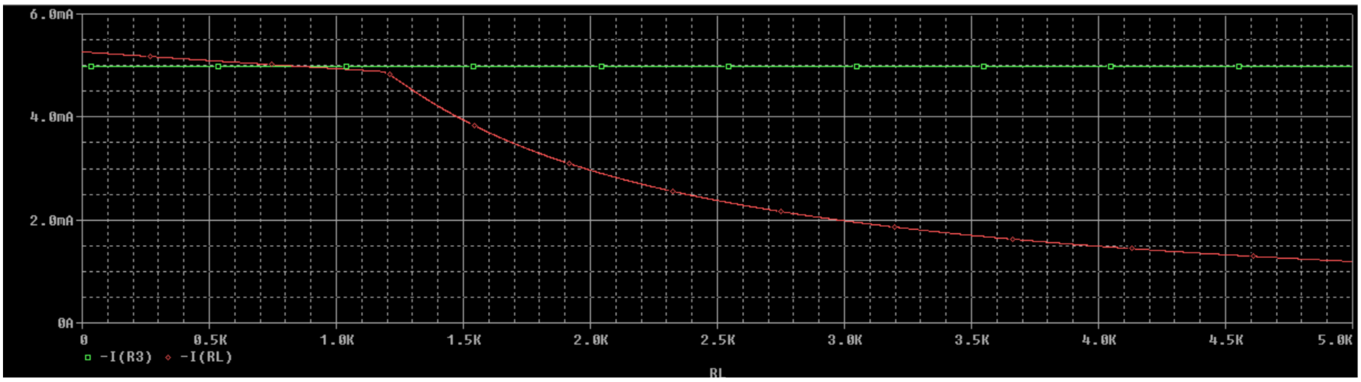


Problem 2
a/d.
Sinking current mirror:



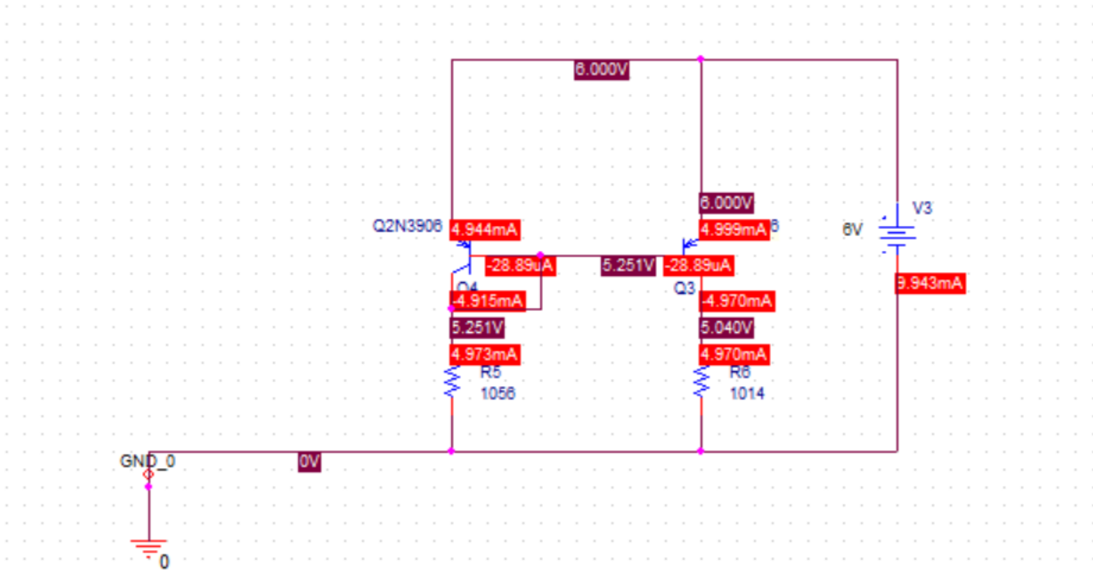
When R_L=992Ohm,
I_{ref}=4.978mA, I_{out}=4.941mA, which is very close.

Parametric sweep on RL:



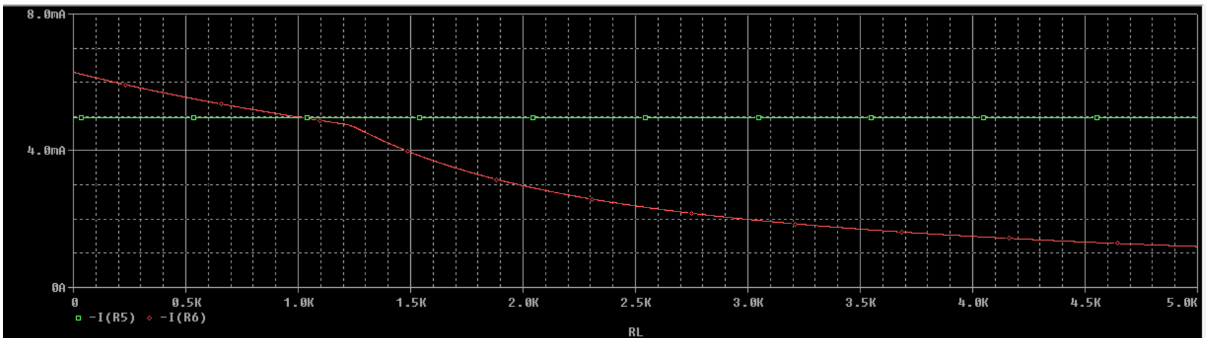
Current mirror is valid when RL is smaller than around 1.2k ohm.

Source current mirror:



When R_L=1014Ohm,

I_{ref}=4.973mA, I_{out}=4.970mA, which is very close.

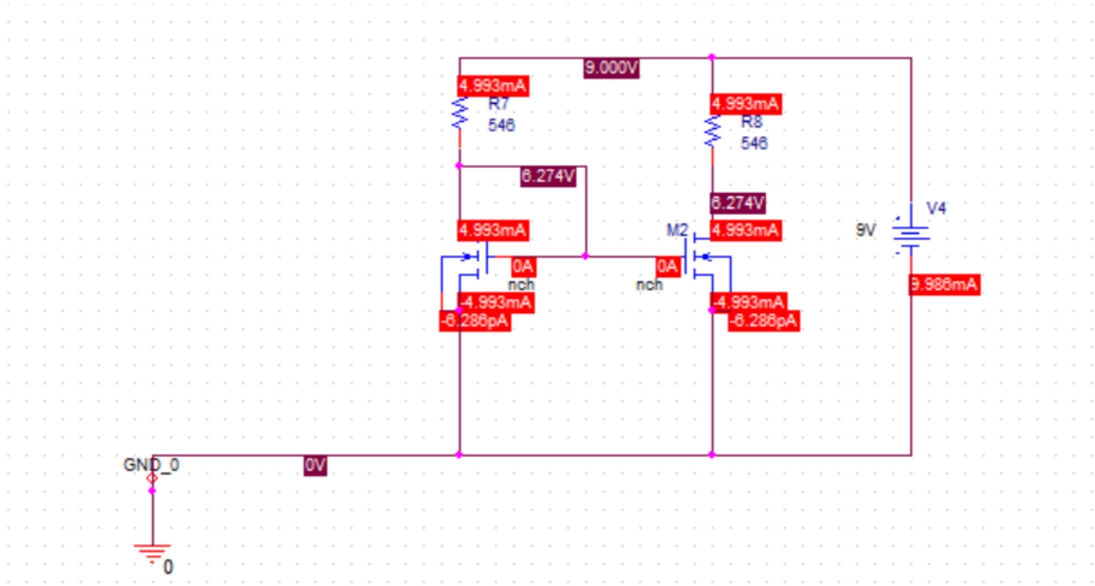


Parametric sweep on RL:

Current mirror is valid when RL is smaller than around 1.2k ohm.

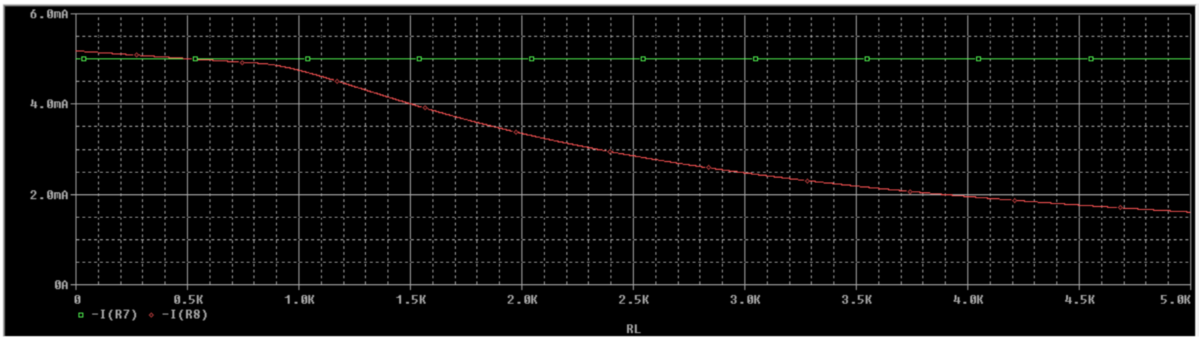
b/d

Sinking current mirror using NMOS:



When R_L=546Ohm,

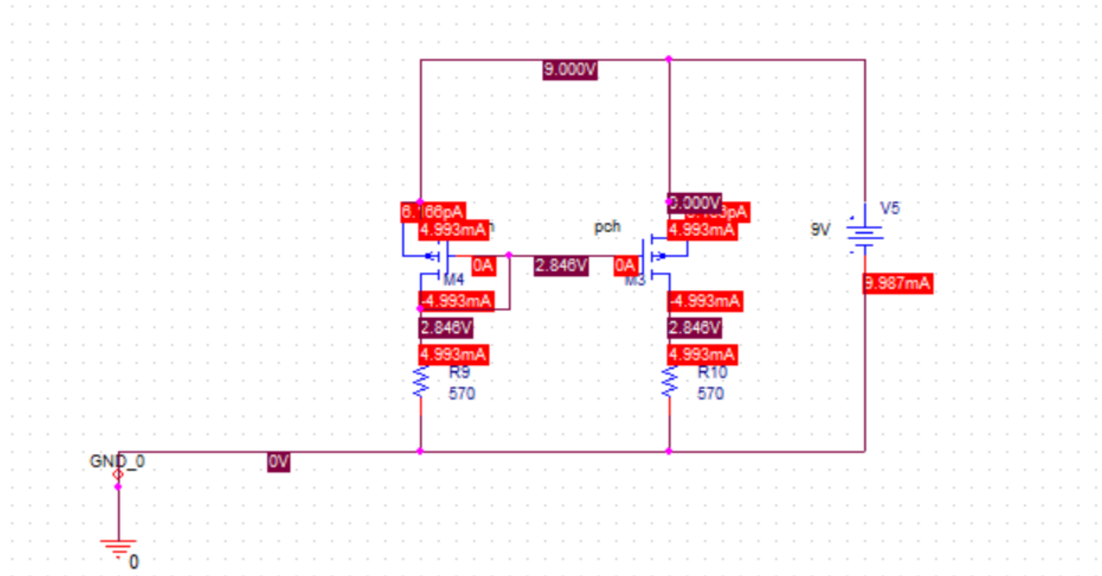
I_{ref}=4.993mA, I_{out}=4.993mA, which is very close.



Parametric sweep on RL:

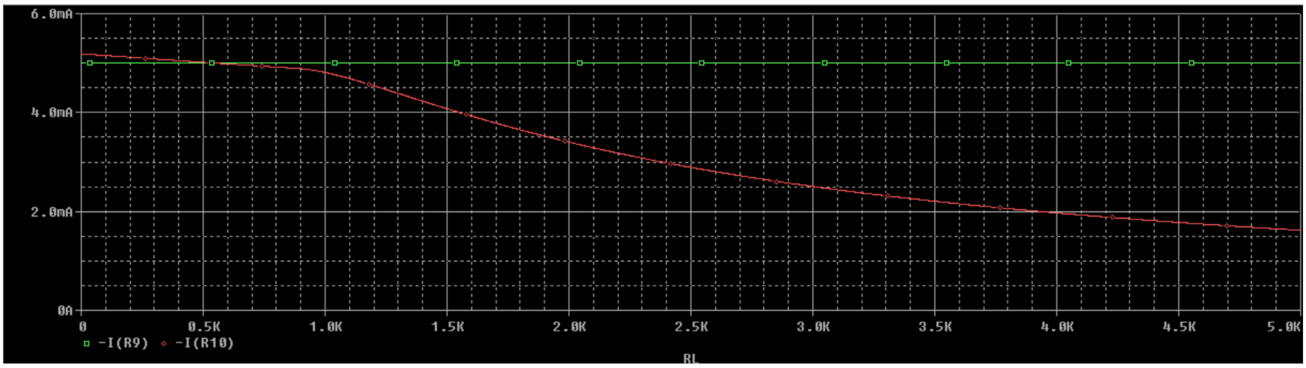
Current mirror is valid when RL is smaller than around 1k ohm.

Sourcing current mirror using PMOS:



When R_L=570Ohm,

I_{ref}=4.993mA, I_{out}=4.993mA, which is very close.



Parametric sweep on RL:

Current mirror is valid when RL is smaller than around 1k ohm.