110 Fall EE3235 Analog Integrated Circuit Analysis and Design I

Homework 7 Common Mode Feedback

Due date:2021.01.05 (Wed.) 13:20 pm (upload to eeclass System)

This homework is for you to design a fully-differential amplifier with/without common mode feedback. The problem sets include HSPICE simulations and hand calculations. The SPICE model is cic018.l. Please use the parameters from HSPICE simulation results for hand calculations.

In this homework, please use V_{DD}=1.5V, temperature=25^{o}C.

Also, please set **measdgt** higher than 15 and **numdgt** higher than 7.

Note that the minimum channel length and width step is 0.01μm in this homework.

Please note that:

1. **No delay allowed**.
2. Please hand in your report using eeclass system.
3. Please generate your report in **pdf** format, name your report as HWX_studentID_name.pdf.
4. Please hand in the spice code file (.sp) for each work. Do not include the output file.
5. Please print waveform with white background, and make sure the X, and Y labels are clear.
6. Please do not zip your report.

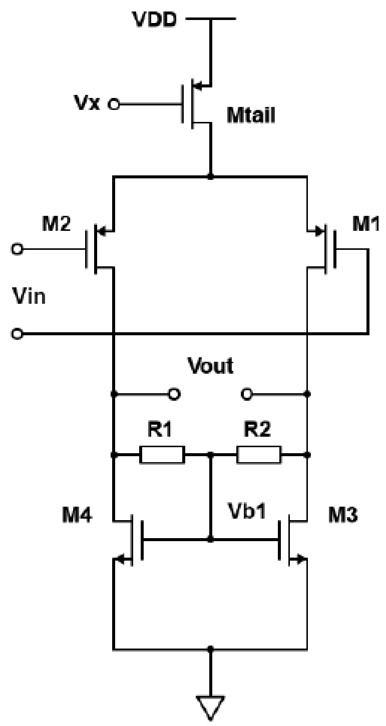


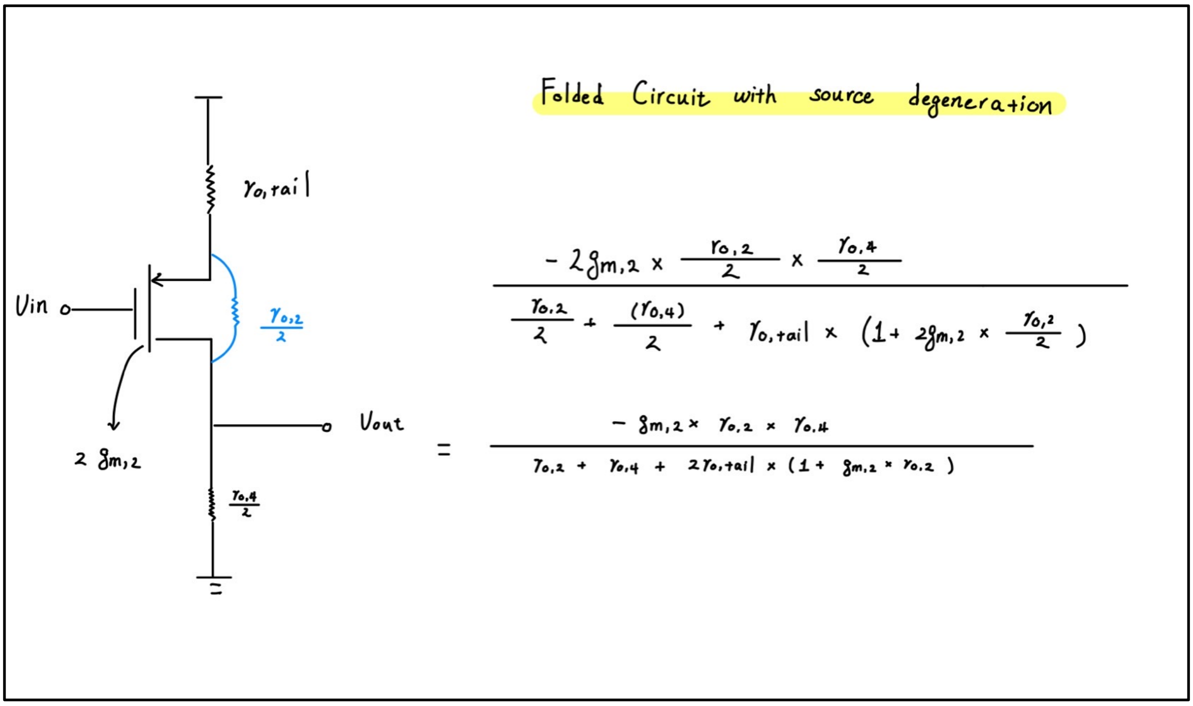
Fig. 1. Differential amplifier with CMFB.

In Fig. 1, please design your M_{tail} and its bias voltage V_x to generate the tail current 5μA.

(a) Please design your amplifier and input common mode level to achieve differential mode DC gain (V_{out}/V_{in}) of 20 and the output common mode level of 0.7V.

Design Flow:

The first trial is a mess without considering through the model so that my common mode gain is not strongly suppressed even with common mode feedback system. Thus, I remove the resistor pair and calculated the common mode gain without considering body effect to see what parameters should I set stage for.



From above formula, I observed that the if the r_o of $M_{1(2)}$ and the tail MOS is larger compared to the r_o of the r_o of the M_4 then the denominator of the above formula can be simplified to $2 \times r_{o,tail} \times (g_{m,2} \times r_{o,2})$ where since the multiplied value of two resistance is high. Then calculated with the numerator, the common mode gain without feedback can approximated as $V_{CM,no\ FB} \cong \frac{-r_{o,4}}{2 \times r_{o,tail}}$ so the main goal is to increase the r_o of M_2 and M_{tail} while maintaining a smaller r_o of M_4 for reaching output common level of 0.7 V.

There is another SPEC that I have to achieve, which is drain current of 5μA. The relatively predictable is $M_{3,4}$ since the gate and drain are in same voltage level and we want to set the level to 0.7V, thus through calculation $\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(0.7 - V_{TH})^2 = 2.5 \times 10^{-6}$ and from previous homework that $\mu_n C_{ox}$ can be approximated by $325\ \mu A/V^2$, so the equation can be rewritten as $\frac{W}{L} \cong \frac{0.015}{(0.7-V_{TH})^2}$ and the threshold voltage encountered for NMOS is typically 0.5~0.4V. so through the above approximation, I will expect to see that the size of the aspect ratio of NMOS is less than 1, use threshold voltage = 0.45V as approximation, I would have to start by using W/L = 1/5 as a starting design size.

Starting with size of 0.3/1.5 for the NMOS where 0.3μm is the minimum width for this manufacture. And then first set the input common level at 0.7 V where it is at the midpoint of the circuit. And then set the resistor of the feedback system to 100k where it is sufficiently large to serve a stable feedback. The NMOS part is partially deterministic, then I move the focus point to the Tail MOS.

From earlier analysis, I am looking for a large r_o for the tail MOS, so I will have to set a small aspect ratio and a large channel length to do that, thus I started to increase from 5μm all the way to 40μm for large tail resistance with aspect ratio slightly higher than 1. And the threshold voltage of the PMOS of is usually around 0.5 V so I set the bias level of the gate to 0.9 V where $V_{SG} = 1.5 - 0.9 = 0.6V$ so that when V_{DD} drops to 1.425 V, the tail is still in saturation. But with the size constrain, the g_m is not high enough to increase to the drain current, the current by that time is slightly below 1μA, so I set m=6 to the tail MOS for higher drain current.

Also from the other part from earlier analysis, $M_{1,2}$ has to have a large r_o also, so the channel length is also large with small aspect ratio where I set it to 2, about 2 times larger than the tail MOS, acknowledging that the bulk is connected to V_{DD} but the source isn't, so that the threshold voltage is larger than the tail MOS where it is around 0.55 V so that I decrease my input level from 0.7V to 0.6V. Same thing happens with $M_{1,2}$ where the transconductance is not strong enough thus I have to increase the m of $M_{1,2}$.

Then I want my desired output level to be at 0.7 V, the output level was at 0.57V at the moment, the way to raise up the level is increasing the length of the NMOS where simultaneously decrease the aspect ratio which makes the V_{GS} increases so that it can sustain same drain current. From the drain current formula I can calculated that the aspect ratio has to be dropped from 1/5 to about 1/6 for the output common level to raise up to 0.7V, so I switch from 0.3/1.5 to 0.3/1.75, but the output level is slightly lower, so then I increase the minimum step of 0.01 u to raise the point.

Then for the V_{DD} test, increasing to 1.575V has no hardship for 5 MOS to stay in the saturation region, but suppressing it to 1.425V, makes all V_S of NMOS to be suppressed, then $M_{2(1)}$ is prone to entering subthreshold, which means I have to decrease the input common level making sure V_{SG} of the $M_{2(1)}$ is large enough to stay in linear when V_{DD} is suppressed, so I have to drop m for the PMOS and then readjusted the W/L to match the drain current while making sure that the output common level is at the 0.7V.

Eventually, I reach the SPEC with slightly higher M_4 channel length and slightly smaller M_2 width for the MOS to be less prone to enter subthreshold when V_{DD} is altered. The final part is to design the differential gain with the support of the resistor of the common mode feedback system. The differential gain can be calculated by $g_{m,2} \times (r_{o,2} \parallel r_{o,4} \parallel R_1)$. Since the gain is adjusted after the stage is set, I then have the first 3 parameters.

利用excel 的目標搜尋，找到R_1 = 585110 Ω 時會讓 differential gain 變成近乎20 V/V

Differential gain	gm2 (S)	ro2 (Ω)	ro4 (Ω)	R1 (Ω)
19.99998382	3.79376E-05	35860349.43	6253402.497	585110.0658

I set the resistance to 585 k Ω to reach the SPEC.

(b) Print out the small-signal parameters using .op command.

```
****** operating point information tnom=  25.000 temp=  25.000 ******
****** operating point status is all       simulation time is     0.
   node     =voltage          node     =voltage          node     =voltage

+0:vb1      = 700.20231486m 0:vcm_in   = 500.00000000m 0:vdd      =   1.50000000
+0:vin      =    0.         0:vin_left= 500.00000000m 0:vin_righ= 500.00000000m
+0:vout_lef= 700.20231527m 0:vout_rig= 700.20231445m 0:vp       =   1.14085707
+0:vss      =    0.         0:vx       = 900.00000000m
```

```
**** mosfets


subckt
element      0:mtail        0:m1           0:m2           0:m3
model        0:p_18.1       0:p_18.1       0:p_18.1       0:n_18.1
region    Saturation     Saturation     Saturation     Saturation
 id         -5.00375401u  -2.50187883u  -2.50187883u   2.50188240u
 ibs        4.6559651e-22   1.32033605f   1.32033605f -1.6297974e-21
 ibd          4.33791741f   2.94033758f   2.94033758f  -65.78657886a
 vgs      -600.00000000m -640.85707497m -640.85707497m 700.20231486m
 vds      -359.14292503m -440.65476052m -440.65475970m 700.20231445m
 vbs          0.          359.14292503m 359.14292503m    0.
 vth      -457.19064737m -562.82792429m -562.82792429m 356.68486015m
 vdsat    -141.95818482m -104.81385791m -104.81385791m 294.97371197m
 vod      -142.80935263m  -78.02915068m  -78.02915068m 343.51745472m
 beta      490.38179660u  547.84928067u  547.84928067u  48.42213491u
 gam eff   557.08465667m  554.67912047m  554.67912047m 507.44640053m
 gm         56.21882891u   37.93751514u   37.93751514u  13.68655442u
 gds        86.70041054n   27.90780250n   27.90780259n 159.88838139n
 gmb        17.30681156u   10.04865690u   10.04865690u   2.54868331u
 cdtot     710.35523701f   95.42951902f   95.42951906f 518.45197988a
 cgtot      68.25367796p    4.75370482p    4.75370482p   3.63188690f
 cstot      76.14530686p    5.10513622p    5.10513622p   4.05278893f
 cbtot      24.30919161p    1.61298214p    1.61298214p   1.75627593f
 cgs        62.09174329p    4.27952759p    4.27952759p   3.24809789f
 cgd       273.92067225f   31.41398601f   31.41398602f 106.51673223a
```

```
region    Saturation
 id           2.50188240u
 ibs        -1.6297974e-21
 ibd         -65.78657894a
 vgs         700.20231486m
 vds         700.20231527m
 vbs           0.
 vth         356.68486014m
 vdsat       294.97371197m
 vod         343.51745472m
 beta         48.42213491u
 gam eff     507.44640053m
 gm           13.68655442u
 gds         159.88838129n
 gmb           2.54868331u
 cdtot       518.45197977a
 cgtot         3.63188690f
 cstot         4.05278893f
 cbtot         1.75627593f
 cgs           3.24809789f
 cgd         106.51673221a
```

```
**** resistors

subckt
element       0:r1          0:r2
 r value   585.00000000k  585.00000000k
 v drop    409.60723702p -409.60779213p
 current   700.18331114a -700.18426005a
 power     2.8680015e-25  2.8680093e-25
```

(c) Please use .tf command to simulate the differential and common mode gain, and print out the results.

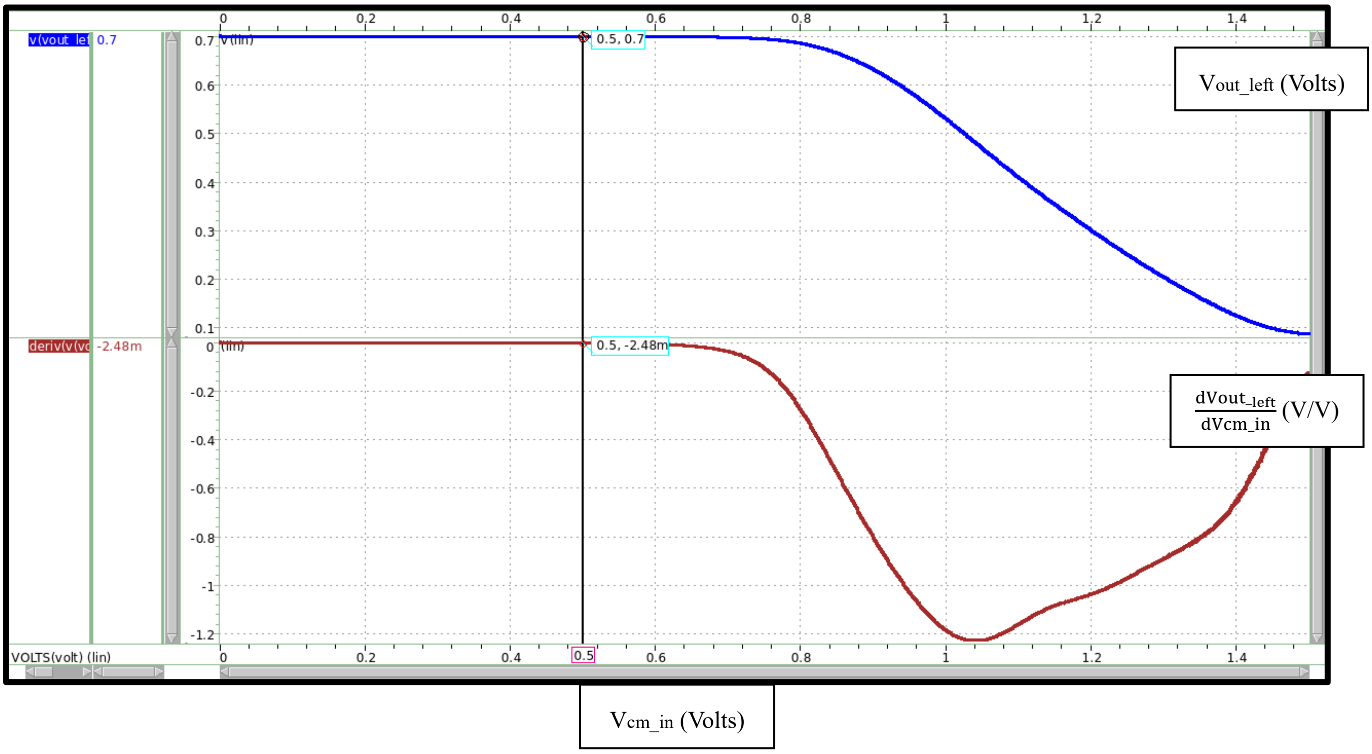
Differential mode gain

```
****     small-signal transfer characteristics

     v(vout_left,vout_right)/vin                 =  -19.9967
     input resistance at              vin        =  1.000e+20
     output resistance at v(vout_left,vout_ri =     1.0542x
```

Common mode gain

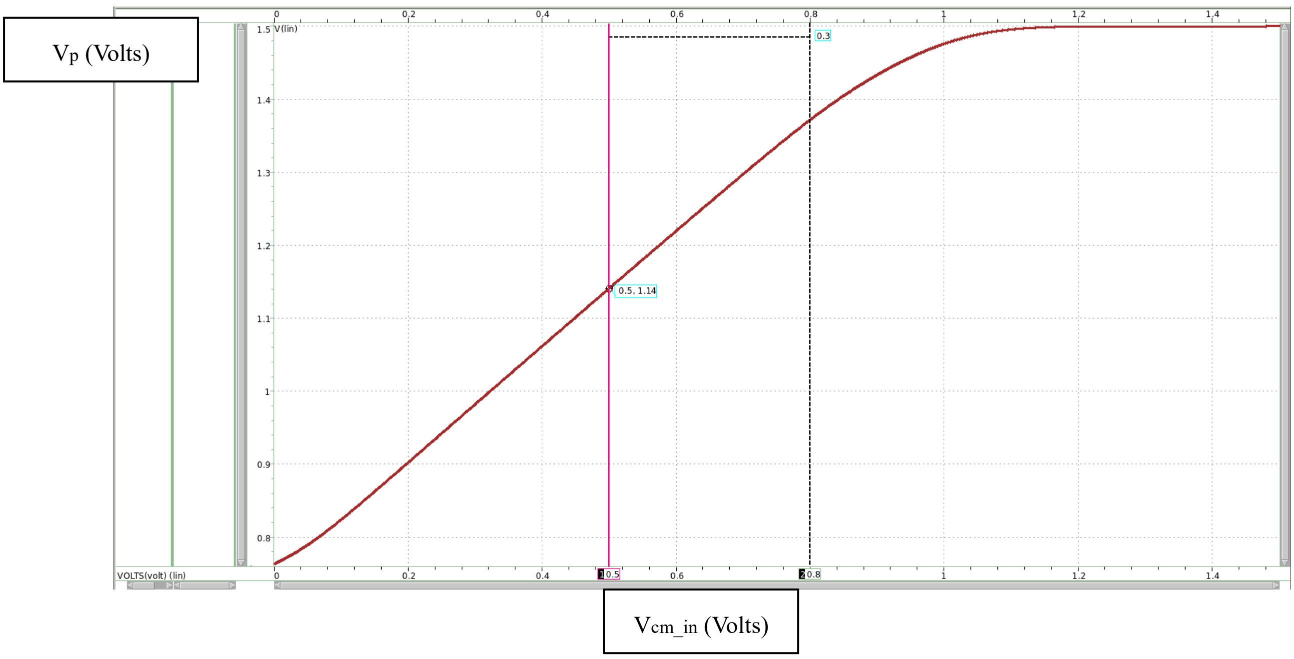
```
****     small-signal transfer characteristics

     v(vout_left)/vcm_in                          =   -2.4724m
     input resistance at                vcm_in    =  1.000e+20
     output resistance at v(vout_left)            =  299.6622k
```

(d) Please sweep the input common mode voltage from 0V to V_{DD}, probe the output common mode voltage and its slope. Mark the bias point on the figures and explain what happens when the input common mode voltage increases.

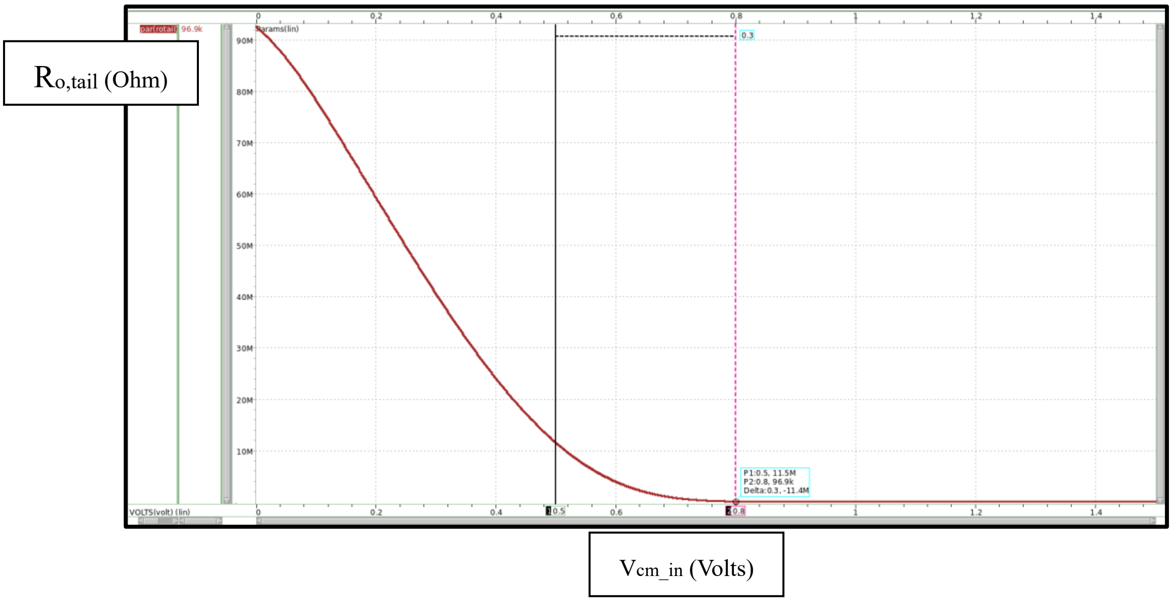


Comment:

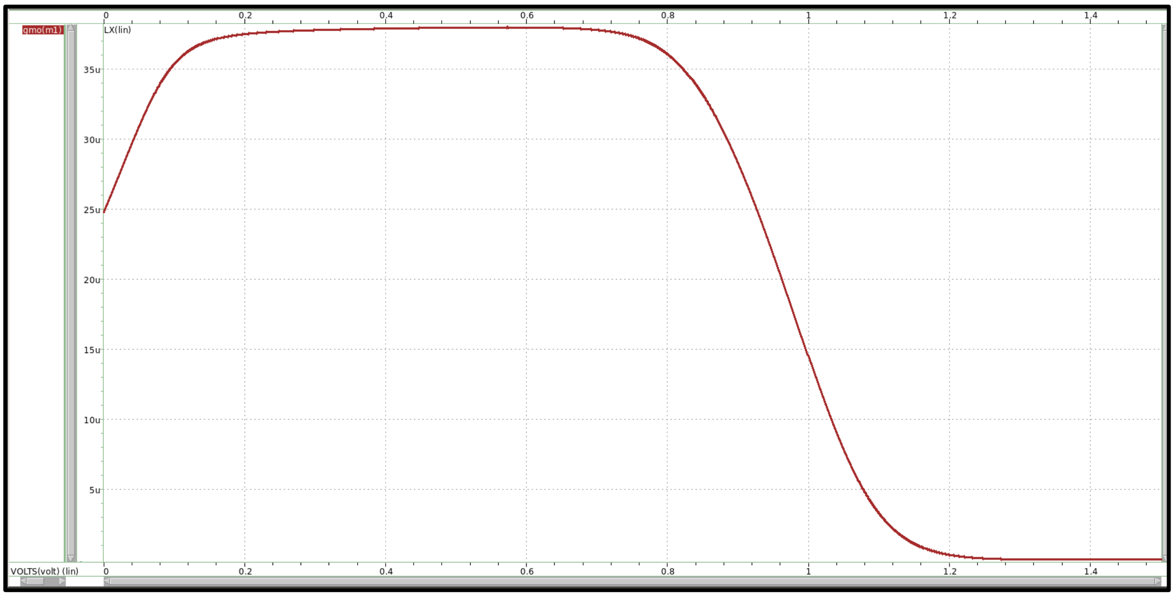
The common mode gain started to increase and the output common level starts to fall when V_{cm_in} is approaching 0.8V. From the graph below, we see that the PMOS wants to sustain the same drain current thus the voltage of its source and the tail MOS' drain (denoted as V_p) is then raised to a higher level since the gate of $M_{1,2}$ is increasing.



Then, while V_p is increasing, the V_{DD} remains the same. The V_{SD} of the tail MOS decreases which leads the tail MOS into linear region, then the drain current started to decrease and the output resistance of the tail MOS starts to decrease, thus the effect of degeneration is not strong enough to suppress the common mode gain, causing the common mode gain started to increase.



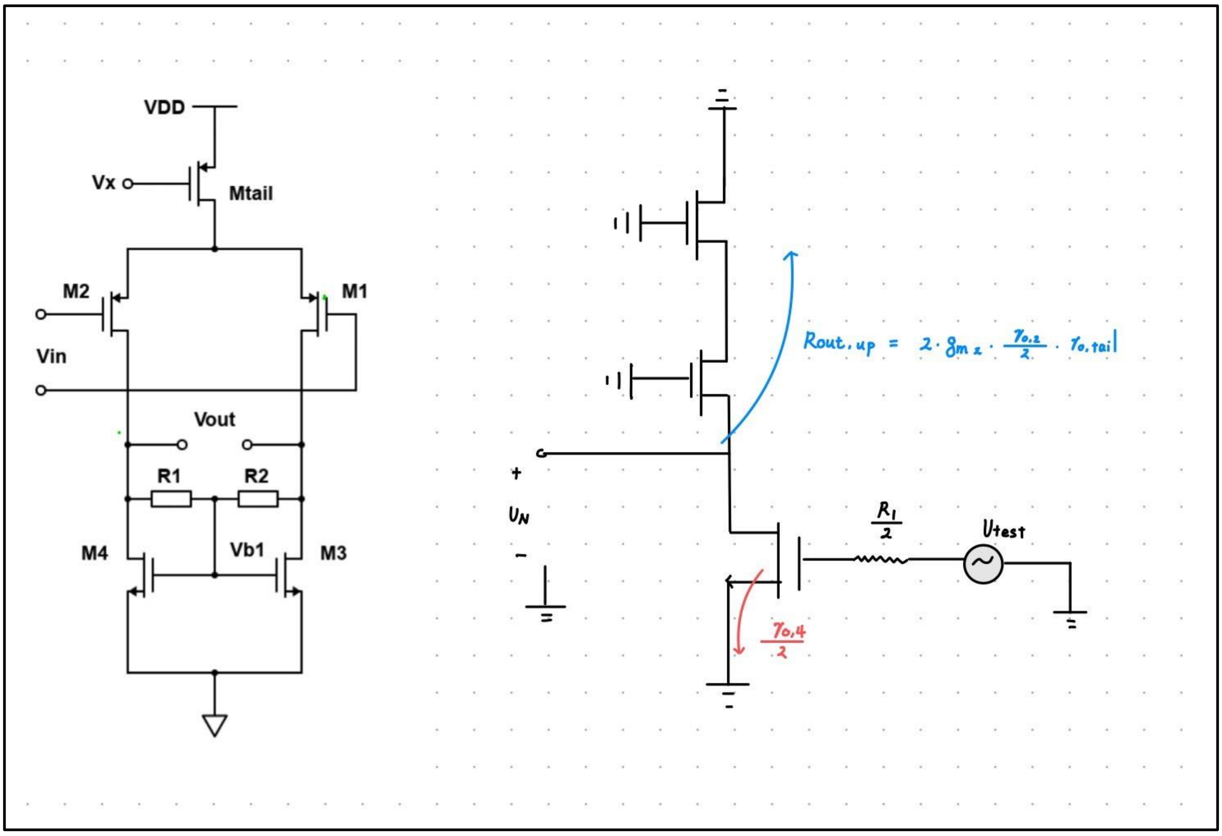
But when the V_{cm_in} keeps increasing, $M_{1,2}$ started to fall into subthreshold region then the transconductance started to fall, causing the common mode gain then again becomes smaller.



As a result, I observe that the common mode gain started to increase as V_{cm_in} increases because the tail MOS falls into linear region so it's r_o drops. Then V_{cm_in} increases to an extent that M_1 falls into subthreshold which the transconductance drops rapidly, which causes the common mode gain then again drops. This matches the slope graph.

(e) The common mode feedback system can be illustrated by the concept shown in Fig. 2. Please simplify Fig. 2 based on Fig. 1. Calculate the common mode gain with the small-signal parameters and the block diagram you draw.

First, calculate the loop gain of this common mode feedback of the system. By breaking up the loop at the common output node, where I use a test voltage V_{Test} to go into the path of the feedback system. Then folds the circuit, where the output resistance looking up is $2 \times g_{m,2} \times \frac{r_{o,2}}{2} \times r_{o,tail}$ and output resistance looking down is $\frac{r_{o,4}}{2}$

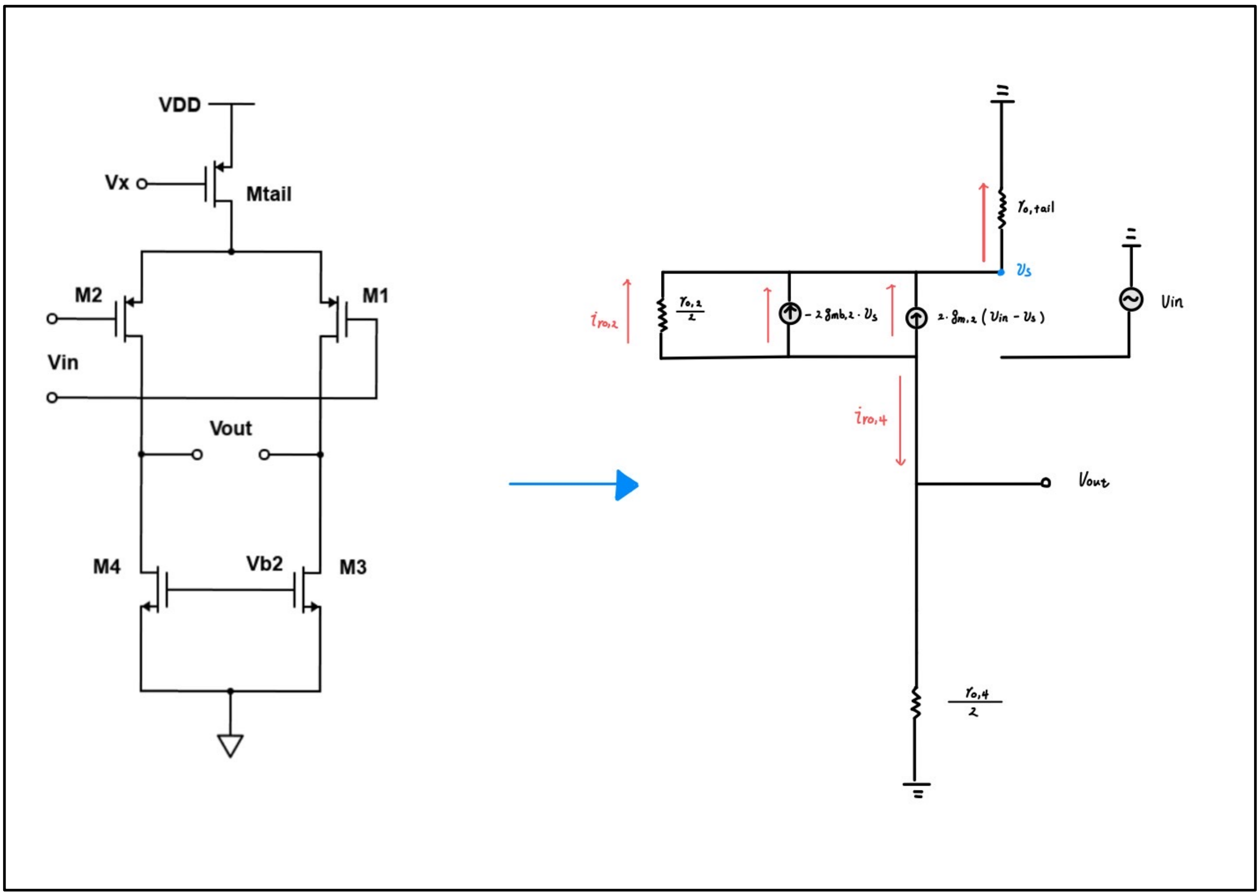


Thus, the loop gain is $\frac{V_N}{V_{Test}} = 2 \times g_{m,4} \times (\frac{r_{0,4}}{2} \parallel 2 \times g_{m,2} \times \frac{r_{0,2}}{2} \times r_{o,tail})$

gm2 (S)	ro2 (Ω)	ro4 (Ω)	gm4 (S)	ro,tail (Ω)
3.79375E-05	35832272.96	6254363.146	1.36866E-05	11533970.76

$$\text{loop gain} = -85.5836 \text{ (V/V)}$$

Then calculate the open-loop gain for the system without the common mode feedback using folded circuit method.



$$\begin{cases} \dfrac{2V_{out}}{r_{o,4}} + \dfrac{2(V_{out}-V_s)}{r_{o,2}} - 2 \cdot g_{mb,2} V_s + 2 \cdot g_{m,2}(V_{in}-V_s) = 0 \\ \left[2\dfrac{(V_{out}-V_s)}{r_{o,2}} - 2 \cdot g_{mb,2} V_s + 2 \cdot g_{m,2}(V_{in}-V_s)\right] \cdot r_{o,tail} = V_s \end{cases}$$

$$\frac{2V_{out}}{r_{o,2}} \times r_{o,tail} + 2 \cdot g_{m,2} V_{in} \cdot r_{o,tail} = \left(1 + 2 g_{mb,2} \cdot r_{o,tail} + 2\frac{r_{o,tail}}{r_{o,2}} + 2 g_{m,2} \cdot r_{o,tail}\right) V_s$$

$$V_s = \frac{\frac{2V_{out}}{r_{o,2}} \times r_{o,tail} + 2 \cdot g_{m,2} V_{in} , r_{o,tail}}{1 + 2 \cdot g_{mb,2} \cdot r_{o,tail} + 2 \cdot g_{m,2} \cdot r_{o,tail} + 2\frac{r_{o,tail}}{r_{o,2}}}$$

τ

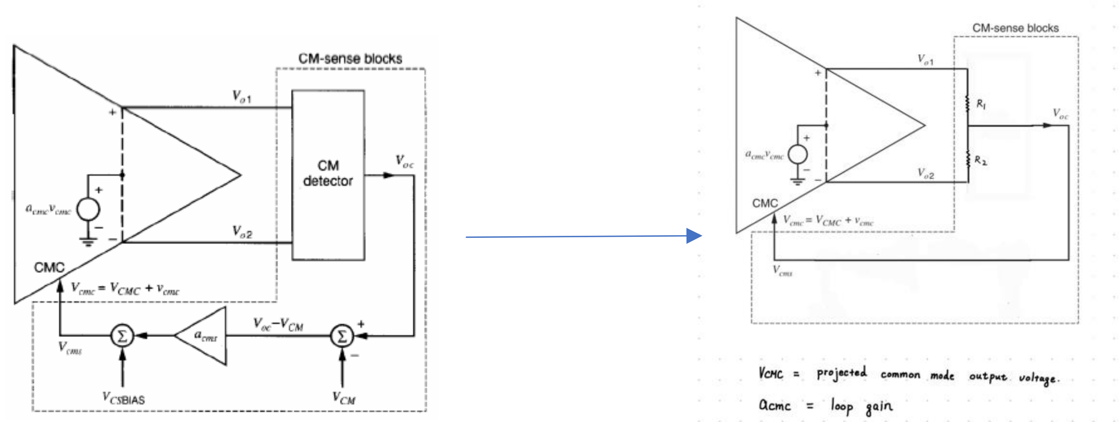
$$\frac{2V_{out}}{r_{o,4}} + \frac{2V_{out}}{r_{o,2}} + 2 \cdot g_{m,2} V_{in} = \left(\frac{2}{r_{o,2}} + 2 g_{mb,2} + 2 g_{m,2}\right) \frac{\frac{2 r_{o,tail}}{r_{o,2}} \times V_{out} + 2 g_{m,2} V_{in} \cdot r_{o,tail}}{1 + 2 g_{mb,2} \cdot r_{o,tail} + 2 g_{m,2} \cdot r_{o,tail} + 2\frac{r_{o,tail}}{r_{o,2}}}$$

$$A_{CM} = \frac{2 \cdot g_{m,2}\,(1-\tau \cdot r_{o,tail})}{\left(\frac{2\tau \cdot r_{o,tail}}{r_{o,2}} - \frac{2}{r_{o,4}} - \frac{2}{r_{o,2}}\right)}$$

gmb2 (S)	gm2 (S)	ro2 (Ω)	ro4 (Ω)	ro,tail (Ω)	τ
1.00487E-05	3.79375E-05	35832272.96	6254363.146	11533970.76	8.66222E-08

$$A_{CM,opened-loop} = -0.214000219\ (V/V)$$

The below left figure can be simplified to the below right figure



Where the $(a_{cmc} \times a_{cms})$ product is the calculated loop gain and a_{cms} is 1, V_{CMC} equals to the projected common mode output voltage.

Then, referenced from *"Analysis and Design of Analog Integrated Circuits 4th Edition", Paul R. Gray, Paul J. Hurst, Stephen H. Lewis, Robert G. Meyer.*

$a'_{cm} = \frac{a_{cm}}{1+a_{cms}(-a_{cmc})}$ where a'_{cm} is the common mode gain with CMFB, and a_{cm} is the common mode gain without CMFB and $a_{cms}(a_{cmc})$ is the loop gain calculated earlier.

$$a'_{cm} = \frac{a_{cm}}{1+a_{cms}(-a_{cmc})} = \frac{-0.214000219}{1+1\times(85.58361202)} = -0.002471602\ (V/V)$$

ACM with CMFB (calculated)	Acm with CMFB (simulation)	error	loop gain
-0.002471602	-0.0024724	-0.032%	-85.58361202

<u>Comment:</u>

The calculated value is identical to the simulation value, which tells that the loop simplified is correct.

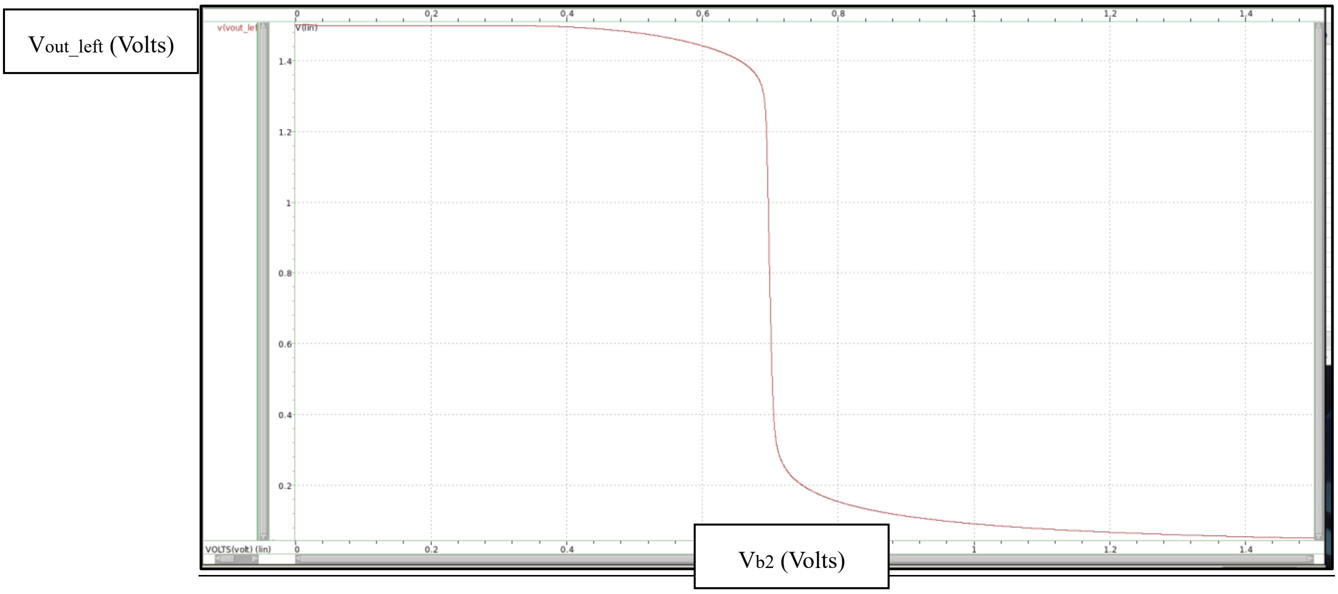
(f) In Fig. 3, based on your design in (a), please remove R_1 and R_2, design the bias voltage V_{b2} to achieve the output common mode level of 0.7V.

Design Flow:

Originally, I use the drain current formula to find the V_{b2} $V_{b2} = \sqrt{\frac{2\times2.50188240\times10^{-6}}{48.42213491\times10^{-6}}} + 0.356684860515 = 0.6781445173\ V$

This value is too inaccurate since square law isn't an accurate method. So instead of calculating for it, observe how the output common voltage changes with V_{b2}.

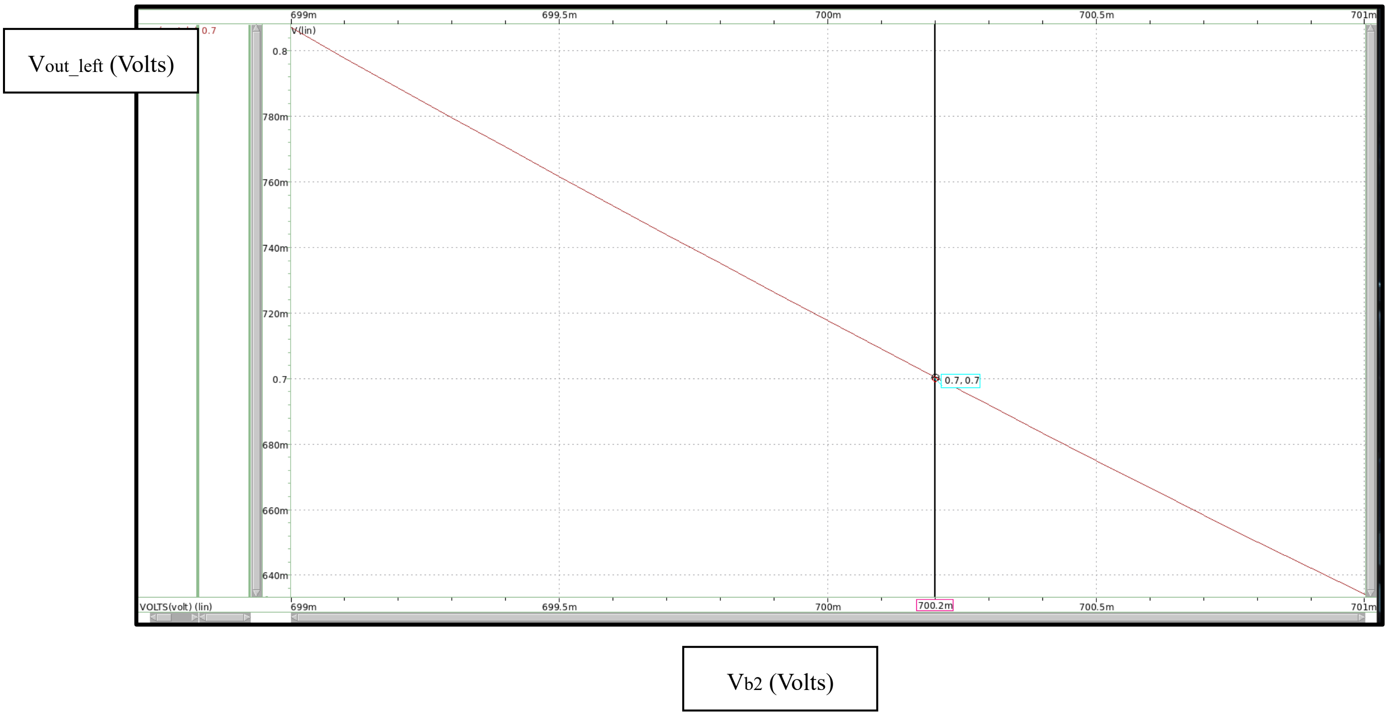
First use DC sweep to see how the output common level changes when V_{b2} changes.



I observe that there is a steep change when V_{b2} approaches to 0.7 V from both sides and the output level = 0.7 V is in the range in between the steep slope.

Then, use DC sweep around the region of 0.699 V to 0.701 V with 0.0001V/ step to find the point to estimate the input V_{b2} where the output common level is 0.7 V, I found out that when V_{b2} is 0.7002 mV the output level is about 0.7 V, but the figure rounding is rough in waveview, thus more significant digit needs to be added to 0.7002 mV to achieve more accurate output level.

```
.dc Vb2 0.699 0.701 0.0001
```



Then V_{b2} is set to 700.2046 mV for the output level to be 700.00680174 mV, the result is in the below figure.

```
****** operating point information tnom=  25.000 temp=  25.000 ******
****** operating point status is all       simulation time is     0.
   node     =voltage              node     =voltage              node     =voltage

+0:vb2      = 700.20460000m 0:vcm_in   = 500.00000000m 0:vdd      =    1.50000000
+0:vin      =    0.         0:vin_left= 500.00000000m 0:vin_righ= 500.00000000m
+0:vout_lef= 700.00680174m 0:vout_rig= 700.00680174m 0:vp       =    1.14085696
+0:vss      =    0.         0:vx       = 900.00000000m
```

(g) Please compare the feedback voltage V_{b1} in Fig. 1 with the bias voltage V_{b2} in Fig. 3.

Vb1 (mV)	Vb2 (mV)
700.2023149	700.2046

Comment:

The V_{b2} is the same V_{b2} until the 6th significant digit after the decimal point (in V). Meaning that almost the same value of bias voltage applied to the gate of the NMOS gives the same common output level.

(h) Please use .tf command to simulate the differential and common mode gain, and print out the results.

Differential mode gain

```
****     small-signal transfer characteristics

     v(vout_left,vout_right)/vin                   = -202.0202
     input resistance at               vin         =  1.000e+20
     output resistance at v(vout_left,vout_ri =      10.6502x
```

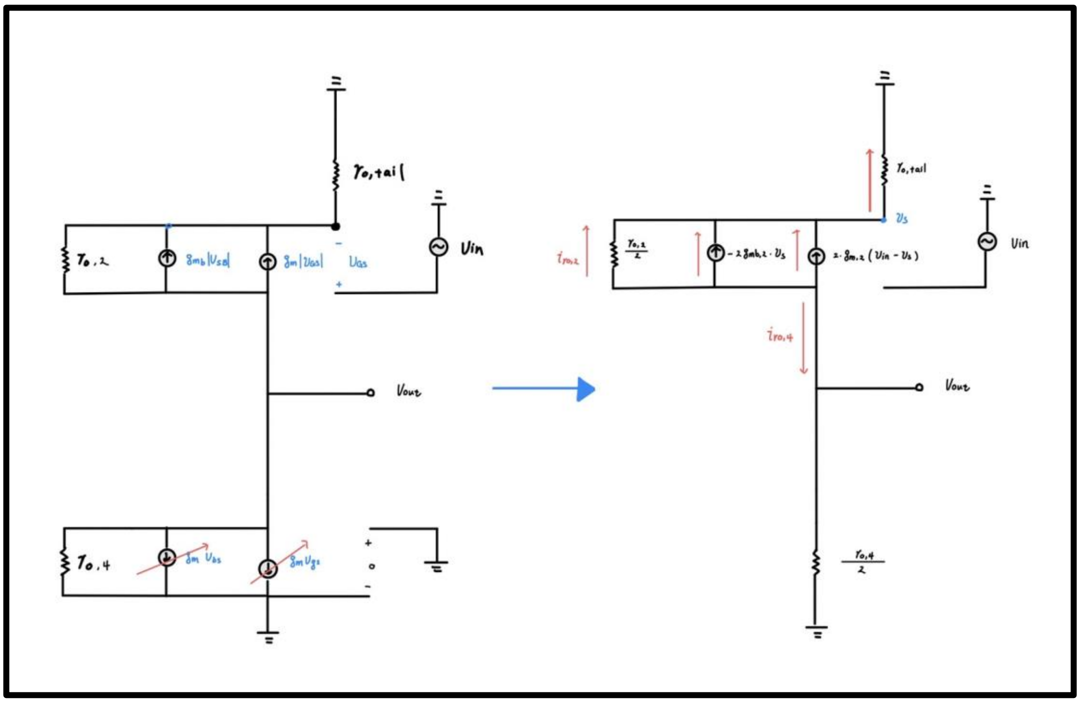
Common mode gain

```
****     small-signal transfer characteristics

     v(vout_left)/vcm_in                           = -214.0315m
     input resistance at               vcm_in      =  1.000e+20
     output resistance at v(vout_left)             =     5.7890x
```

(i) Please calculate the common mode gain with the small-signal parameters.

**** mosfets

subckt				
element	0:mtail	0:m1	0:m2	0:m3
model	0:p_18.1	0:p_18.1	0:p_18.1	0:n_18.1
region	Saturation	Saturation	Saturation	Saturation
id	-5.00375402u	-2.50187884u	-2.50187884u	2.50188242u
ibs	4.6559651e-22	1.32033647f	1.32033647f	-1.6297974e-21
ibd	4.33791878f	2.94105636f	2.94105636f	-65.76820927a
vgs	-600.00000000m	-640.85696155m	-640.85696155m	700.20460000m
vds	-359.14303845m	-440.85015981m	-440.85015981m	700.00680174m
vbs	0.	359.14303845m	359.14303845m	0.
vth	-457.19064737m	-562.82795375m	-562.82795375m	356.68588325m
vdsat	-141.95818482m	-104.81376930m	-104.81376930m	294.97467160m
vod	-142.80935263m	-78.02900780m	-78.02900780m	343.51871675m
beta	490.38179660u	547.84928754u	547.84928754u	48.42213593u
gam eff	557.08465667m	554.67911977m	554.67911977m	507.44640053m
gm	56.21882909u	37.93755188u	37.93755188u	13.68650233u
gds	86.70030129n	27.88497944n	27.88497944n	159.91406317n
gmb	17.30681161u	10.04866619u	10.04866619u	2.54868515u
cdtot	710.35480689f	95.41860549f	95.41860549f	518.47879693a
cgtot	68.25367770p	4.75369525p	4.75369525p	3.63189093f
cstot	76.14530696p	5.10513915p	5.10513915p	4.05279021f
cbtot	24.30919157p	1.61297823p	1.61297823p	1.75629417f
cgs	62.09174315p	4.27951939p	4.27951939p	3.24810150f
cgd	273.92047671f	31.41019830f	31.41019830f	106.52038570a



$$\begin{cases} \dfrac{2v_{out}}{r_{o,4}} + \dfrac{2(v_{out}-v_s)}{r_{o,2}} - 2\cdot g_{mb,2}\, v_s + 2\cdot g_{m,2}\,(v_{in}-v_s) = 0 \\[2ex] \left[2\dfrac{(v_{out}-v_s)}{r_{o,2}} - 2\cdot g_{mb,2}\, v_s + 2\cdot g_{m,2}\,(v_{in}-v_s)\right]\cdot r_{o,tail} = v_s \end{cases}$$

$$\frac{2v_{out}}{r_{o,2}} \times r_{o,tail} + 2\cdot g_{m,2}\, v_{in}\cdot r_{o,tail} = \left(1 + 2 g_{mb,2}\cdot r_{o,tail} + 2\frac{r_{o,tail}}{r_{o,2}} + 2 g_{m,2}\cdot r_{o,tail}\right) v_s$$

$$v_s = \frac{\dfrac{2v_{out}}{r_{o,2}} \times r_{o,tail} + 2\cdot g_{m,2}\, v_{in}\, , r_{o,tail}}{1 + 2\cdot g_{mb,2}\cdot r_{o,tail} + 2 g_{m,2}\cdot r_{o,tail} + 2\dfrac{r_{o,tail}}{r_{o,2}}}$$

$$\tau$$

$$\frac{2v_{out}}{r_{o,4}} + \frac{2v_{out}}{r_{o,2}} + 2\cdot g_{m,2}\, v_{in} = \left(\frac{2}{r_{o,2}} + 2 g_{mb,2} + 2 g_{m,2}\right) \frac{\dfrac{2 r_{o,tail}}{r_{o,2}} v_{out} + 2\cdot g_{m,2}\, v_{in}\cdot r_{o,tail}}{1 + 2\cdot g_{mb,2}\cdot r_{o,tail} + 2 g_{m,2}\cdot r_{o,tail} + 2\dfrac{r_{o,tail}}{r_{o,2}}}$$

$$A_{CM} = \frac{2\cdot g_{m,2}\,(1 - \tau\cdot r_{o,tail})}{\left(\dfrac{2\tau\cdot r_{o,tail}}{r_{o,2}} - \dfrac{2}{r_{o,4}} - \dfrac{2}{r_{o,2}}\right)}$$

gmb2 (S)	gm2 (S)	ro2 (Ω)	ro4 (Ω)	ro,tail (Ω)	τ
1.00487E-05	3.79376E-05	35861600.76	6253358.711	11533985.29	8.66221E-08

Acm calculated (V/V)	Acm simulation (V/V)	error
-0.213965719	-0.2140315	-0.03%

Comment:

The common mode gain calculated identical to the simulation result. This also proves that from previous two homework of neglecting body effect is the reason that causes large error when calculating the gain.

Discussions:

(j) Please discuss the precision requirement for the bias voltage V_{b2}.

Comment:

From part (f) and (g), I observe that output voltage changes drastically when Vb2 is altered through 0.7V, so that more precision value have to be considered to make the output common level to be 0.7V, this can be viewed as the 3 PMOS serves as a deterministic current source, and we are now altering the gate voltage of the NMOS below, if small changes deviates from the original feedback gate voltage will breakdown the configuration I built in part A. So V_{b2} given has to be at least 6th digit same as the original gate voltage (V_{b1}) with feedback system. And the reason that it breakdown so drastically is that, since there is no support of CMFB, thus changes of V_{b2} has no pathway to balance and feedback the whole circuit stage to hold stability, so that's why we have to use extremely precise value of V_{b2}.

(k) For both Fig. 1 and Fig. 3, please compare and discuss the common mode voltage with ±5% V_{DD} variation.

With Common Mode Feedback

V_{DD} = 1.5V

```
****** operating point information tnom=  25.000 temp=  25.000 ******
****** operating point status is all       simulation time is     0.
   node      =voltage            node      =voltage            node      =voltage

+0:vb1      = 700.20231486m 0:vcm_in   = 500.00000000m 0:vdd      =   1.50000000
+0:vin      =   0.          0:vin_left= 500.00000000m 0:vin_righ= 500.00000000m
+0:vout_lef= 700.20231527m 0:vout_rig= 700.20231445m 0:vp       =   1.14085707
+0:vss      =   0.          0:vx       = 900.00000000m
```

```
**** mosfets

subckt
element      0:mtail          0:m1             0:m2             0:m3
model        0:p_18.1         0:p_18.1         0:p_18.1         0:n_18.1
region       Saturation       Saturation       Saturation       Saturation
  id          -5.00375401u     -2.50187883u     -2.50187883u      2.50188240u
  ibs          4.6559651e-22    1.32033605f      1.32033605f    -1.6297974e-21
  ibd          4.33791741f      2.94033758f      2.94033758f    -65.78657886a
  vgs       -600.00000000m   -640.85707497m   -640.85707497m    700.20231486m
  vds       -359.14292503m   -440.65476052m   -440.65475970m    700.20231445m
  vbs          0.             359.14292503m    359.14292503m      0.
  vth       -457.19064737m   -562.82792429m   -562.82792429m    356.68486015m
  vdsat     -141.95818482m   -104.81385791m   -104.81385791m    294.97371197m
  vod       -142.80935263m    -78.02915068m    -78.02915068m    343.51745472m
  beta       490.38179660u    547.84928067u    547.84928067u     48.42213491u
  gam eff    557.08465667m    554.67912047m    554.67912047m    507.44640053m
  gm          56.21882891u     37.93751514u     37.93751514u     13.68655442u
  gds         86.70041054n     27.90780250n     27.90780259n    159.88838139n
  gmb         17.30681156u     10.04865690u     10.04865690u      2.54868331u
  cdtot      710.35523701f     95.42951902f     95.42951906f    518.45197988a
  cgtot       68.25367796p      4.75370482p      4.75370482p      3.63188690f
  cstot       76.14530686p      5.10513622p      5.10513622p      4.05278893f
  cbtot       24.30919161p      1.61298214p      1.61298214p      1.75627593f
  cgs         62.09174329p      4.27952759p      4.27952759p      3.24809789f
  cgd        273.92067225f     31.41398601f     31.41398602f    106.51673223a

element      0:m4
model        0:n_18.1
region       Saturation
  id           2.50188240u
  ibs        -1.6297974e-21
  ibd         -65.78657894a
  vgs        700.20231486m
  vds        700.20231527m
  vbs          0.
  vth        356.68486014m
  vdsat      294.97371197m
  vod        343.51745472m
  beta        48.42213491u
  gam eff    507.44640053m
  gm          13.68655442u
  gds        159.88838129n
  gmb          2.54868331u
  cdtot      518.45197977a
  cgtot        3.63188690f
  cstot        4.05278893f
  cbtot        1.75627593f
  cgs          3.24809789f
  cgd        106.51673221a
```

```
**** resistors

subckt
element        0:r1            0:r2
  r value    585.00000000k   585.00000000k
  v drop     409.60723702p  -409.60779213p
  current    700.18331114a  -700.18426005a
  power      2.8680015e-25   2.8680093e-25
```

VDD = 1.425V

```
'v = 1.425v'

****** operating point information tnom=  25.000 temp=  25.000 ******
****** operating point status is all       simulation time is     0.
   node    =voltage              node    =voltage              node    =voltage

+0:vb1     = 556.15243924m 0:vcm_in  = 500.00000000m 0:vdd     =   1.42500000
+0:vin     =   0.          0:vin_left= 500.00000000m 0:vin_righ= 500.00000000m
+0:vout_lef= 556.15243884m 0:vout_rig= 556.15243963m 0:vp      =   1.07888627
+0:vss     =   0.          0:vx      = 900.00000000m
```

```
**** mosfets


subckt
element       0:mtail        0:m1           0:m2           0:m3
model         0:p_18.1       0:p_18.1       0:p_18.1       0:n_18.1
region     Saturation     Saturation     Saturation     Saturation
  id        -1.82262924u -911.31599532n -911.31599533n  911.32045411n
  ibs       1.6959475e-22   1.27243600f    1.27243600f -5.9366027e-22
  ibd        4.18054426f    3.19418938f    3.19418938f  -52.25326496a
  vgs     -525.00000000m -578.88626616m -578.88626616m  556.15243924m
  vds     -346.11373384m -522.73382653m -522.73382731m  556.15243963m
  vbs        0.           346.11373384m  346.11373384m    0.
  vth     -457.19063988m -559.43557405m -559.43557405m  357.43623459m
  vdsat    -93.44714137m  -72.66000244m  -72.66000244m  186.06314819m
  vod      -67.80936012m  -19.45069211m  -19.45069211m  198.71620464m
  beta     499.72742007u  555.71312851u  555.71312851u   48.14578314u
  gam eff  557.08465685m  554.75992096m  554.75992096m  507.44609138m
  gm        29.02083637u   17.64822903u   17.64822903u    8.12749575u
  gds       22.59827590n    7.50806895n    7.50806893n   82.34888259n
  gmb        8.88051223u    4.68461672u    4.68461672u    1.56686967u
  cdtot    471.98958077f   89.83988047f   89.83988045f  531.19784848a
  cgtot     63.21850808p    3.76011166p    3.76011166p    3.63496386f
  cstot     68.27356066p    3.63432283p    3.63432283p    4.05148114f
  cbtot     24.24208971p    1.58406993p    1.58406993p    1.79338553f
  cgs       55.41457797p    3.01842198p    3.01842198p    3.23038171f
  cgd      162.77551800f   29.24346059f   29.24346059f  105.91268575a
```

```
element       0:m4
model         0:n_18.1
region     Saturation
  id        911.32045404n
  ibs     -5.9366027e-22
  ibd       -52.25326488a
  vgs       556.15243924m
  vds       556.15243884m
  vbs         0.
  vth       357.43623460m
  vdsat     186.06314819m
  vod       198.71620464m
  beta       48.14578314u
  gam eff   507.44609138m
  gm          8.12749575u
  gds        82.34888263n
  gmb         1.56686967u
  cdtot     531.19784859a
  cgtot       3.63496386f
  cstot       4.05148114f
  cbtot       1.79338553f
  cgs         3.23038171f
  cgd       105.91268576a
```

```
**** resistors

subckt
element       0:r1            0:r2
  r value   585.00000000k   585.00000000k
  v drop   -392.48293504p   392.48626571p
  current  -670.91100007a   670.91669352a
  power     2.6332112e-25   2.6332559e-25
```

V_{DD} = 1.575V

```
'v = 1.575v'

****** operating point information tnom=  25.000 temp=  25.000 ******
****** operating point status is all       simulation time is     0.
   node     =voltage            node     =voltage            node     =voltage

+0:vb1      = 855.77693919m 0:vcm_in   = 500.00000000m 0:vdd      =   1.57500000
+0:vin      =    0.         0:vin_left= 500.00000000m 0:vin_righ= 500.00000000m
+0:vout_lef= 855.77693814m 0:vout_rig= 855.77694023m 0:vp       =   1.19894155
+0:vss      =    0.         0:vx       = 900.00000000m
```

```
**** mosfets


subckt
element       0:mtail        0:m1           0:m2           0:m3
model         0:p_18.1       0:p_18.1       0:p_18.1       0:n_18.1
region      Saturation     Saturation     Saturation     Saturation
  id         -10.23896330u  -5.11948404u   -5.11948404u    5.11948659u
  ibs        9.5272961e-22   1.38252372f    1.38252372f -3.3349788e-21
  ibd          4.54223155f   2.64411664f    2.64411665f  -80.40204322a
  vgs     -675.00000000m -698.94155110m -698.94155110m  855.77693919m
  vds     -376.05844890m -343.16461087m -343.16461296m  855.77694023m
  vbs        0.            376.05844890m  376.05844890m    0.
  vth     -457.19065969m -567.20697116m -567.20697116m  355.87472252m
  vdsat   -196.73441167m -141.48112456m -141.48112456m  414.84606798m
  vod     -217.80934031m -131.73457995m -131.73457995m  499.90221667m
  beta       480.34684560u  538.99087997u  538.99087997u   48.43646733u
  gam eff    557.08465637m  554.57483429m  554.57483429m  507.44690930m
  gm          82.90025796u   60.10512148u   60.10512148u   19.52541640u
  gds        268.05164429n  134.18550945n  134.18550671n  255.80202674n
  gmb         25.80744769u   15.93117147u   15.93117147u    3.56956253u
  cdtot        1.11127506p  119.49646649f  119.49646585f  505.38438047a
  cgtot       68.98794552p    5.00047122p    5.00047121p    3.62780713f
  cstot       77.08841134p    5.43990241p    5.43990241p    4.05156287f
  cbtot       24.10511524p    1.60807746p    1.60807746p    1.71906216f
  cgs         63.11534491p    4.58874302p    4.58874302p    3.26561907f
  cgd        460.66554261f   42.19734603f   42.19734574f  106.67711891a
```

```
element       0:m4
model         0:n_18.1
region      Saturation
  id            5.11948659u
  ibs        -3.3349788e-21
  ibd         -80.40204302a
  vgs         855.77693919m
  vds         855.77693814m
  vbs           0.
  vth         355.87472253m
  vdsat       414.84606797m
  vod         499.90221666m
  beta         48.43646733u
  gam eff     507.44690930m
  gm           19.52541640u
  gds         255.80202720n
  gmb           3.56956253u
  cdtot       505.38438073a
  cgtot         3.62780713f
  cstot         4.05156287f
  cbtot         1.71906216f
  cgs           3.26561907f
  cgd         106.67711895a
```

```
**** resistors

subckt
element       0:r1            0:r2
  r value   585.00000000k  585.00000000k
  v drop     -1.04503151n    1.04503184n
  current    -1.78637864f    1.78637921f
  power     1.8668220e-24  1.8668232e-24
```

Without Common Mode Feedback

V_{DD} = 1.5V

```
****** operating point information tnom=  25.000 temp=  25.000 ******
****** operating point status is all       simulation time is     0.
   node      =voltage            node      =voltage            node      =voltage

+0:vb2      = 700.20460000m 0:vcm_in   = 500.00000000m 0:vdd      =   1.50000000
+0:vin      =   0.          0:vin_left= 500.00000000m 0:vin_righ= 500.00000000m
+0:vout_lef= 700.00680174m 0:vout_rig= 700.00680174m 0:vp       =   1.14085696
+0:vss      =   0.          0:vx       = 900.00000000m
```

**** mosfets

subckt					
element	0:mtail	0:m1	0:m2	0:m3	0:m4
model	0:p_18.1	0:p_18.1	0:p_18.1	0:n_18.1	0:n_18.1
region	Saturation	Saturation	Saturation	Saturation	Saturation
id	-5.00375402u	-2.50187884u	-2.50187884u	2.50188242u	2.50188242u
ibs	4.6559651e-22	1.32033647f	1.32033647f	-1.6297974e-21	-1.6297974e-21
ibd	4.33791878f	2.94105636f	2.94105636f	-65.76820927a	-65.76820927a
vgs	-600.00000000m	-640.85696155m	-640.85696155m	700.20460000m	700.20460000m
vds	-359.14303845m	-440.85015981m	-440.85015981m	700.00680174m	700.00680174m
vbs	0.	359.14303845m	359.14303845m	0.	0.
vth	-457.19064737m	-562.82795375m	-562.82795375m	356.68588325m	356.68588325m
vdsat	-141.95818482m	-104.81376930m	-104.81376930m	294.97467160m	294.97467160m
vod	-142.80935263m	-78.02900780m	-78.02900780m	343.51871675m	343.51871675m
beta	490.38179660u	547.84928754u	547.84928754u	48.42213593u	48.42213593u
gam eff	557.08465667m	554.67911977m	554.67911977m	507.44640053m	507.44640053m
gm	56.21882909u	37.93755188u	37.93755188u	13.68650233u	13.68650233u
gds	86.70030129n	27.88497944n	27.88497944n	159.91406317n	159.91406317n
gmb	17.30681161u	10.04866619u	10.04866619u	2.54868515u	2.54868515u
cdtot	710.35480689f	95.41860549f	95.41860549f	518.47879693a	518.47879693a
cgtot	68.25367770p	4.75369525p	4.75369525p	3.63189093f	3.63189093f
cstot	76.14530696p	5.10513915p	5.10513915p	4.05279021f	4.05279021f
cbtot	24.30919157p	1.61297823p	1.61297823p	1.75629417f	1.75629417f
cgs	62.09174315p	4.27951939p	4.27951939p	3.24810150f	3.24810150f
cgd	273.92047671f	31.41019830f	31.41019830f	106.52038570a	106.52038570a

VDD = 1.425V

```
'v = 1.425v'

****** operating point information tnom=  25.000 temp=  25.000 ******
****** operating point status is all       simulation time is     0.
   node      =voltage            node      =voltage            node      =voltage

+0:vb2      = 700.20460000m 0:vcm_in   = 500.00000000m 0:vdd      =   1.42500000
+0:vin      =   0.          0:vin_left= 500.00000000m 0:vin_righ= 500.00000000m
+0:vout_lef=  64.80083982m 0:vout_rig=  64.80083982m 0:vp       =   1.07876159
+0:vss      =   0.          0:vx       = 900.00000000m
```

**** mosfets

subckt					
element	0:mtail	0:m1	0:m2	0:m3	0:m4
model	0:p_18.1	0:p_18.1	0:p_18.1	0:n_18.1	0:n_18.1
region	Saturation	Saturation	Saturation	Linear	Linear
id	-1.82263206u	-911.31543792n	-911.31543792n	911.32481068n	911.32481068n
ibs	1.6959501e-22	1.27289437f	1.27289437f	-5.9366278e-22	-5.9366278e-22
ibd	4.18205021f	5.00057082f	5.00057082f	-6.08783404a	-6.08783404a
vgs	-525.00000000m	-578.76158578m	-578.76158578m	700.20460000m	700.20460000m
vds	-346.23841422m	-1.01396075	-1.01396075	64.80083982m	64.80083982m
vbs	0.	346.23841422m	346.23841422m	0.	0.
vth	-457.19063988m	-559.46811730m	-559.46811730m	360.00741409m	360.00741409m
vdsat	-93.44714137m	-72.58939681m	-72.58939681m	292.45774937m	292.45774937m
vod	-67.80936012m	-19.29346848m	-19.29346848m	340.19718591m	340.19718591m
beta	499.72742007u	555.71543179u	555.71543179u	48.41765219u	48.41765219u
gam eff	557.08465685m	554.75914578m	554.75914578m	507.44609138m	507.44609138m
gm	29.02089556u	17.65484019u	17.65484019u	3.08348449u	3.08348449u
gds	22.57146488n	4.77377778n	4.77377778n	12.24280206u	12.24280206u
gmb	8.88053001u	4.68638527u	4.68638527u	629.04519486n	629.04519486n
cdtot	471.82075632f	83.19006383f	83.19006383f	4.43953835f	4.43953835f
cgtot	63.21836613p	3.75375288p	3.75375288p	4.44571096f	4.44571096f
cstot	68.27364068p	3.62989195p	3.62989195p	4.56175294f	4.56175294f
cbtot	24.24205967p	1.57793452p	1.57793452p	1.96196400f	1.96196400f
cgs	55.41446772p	3.01088259p	3.01088259p	2.60050881f	2.60050881f
cgd	162.70177602f	28.77244539f	28.77244539f	1.70646495f	1.70646495f

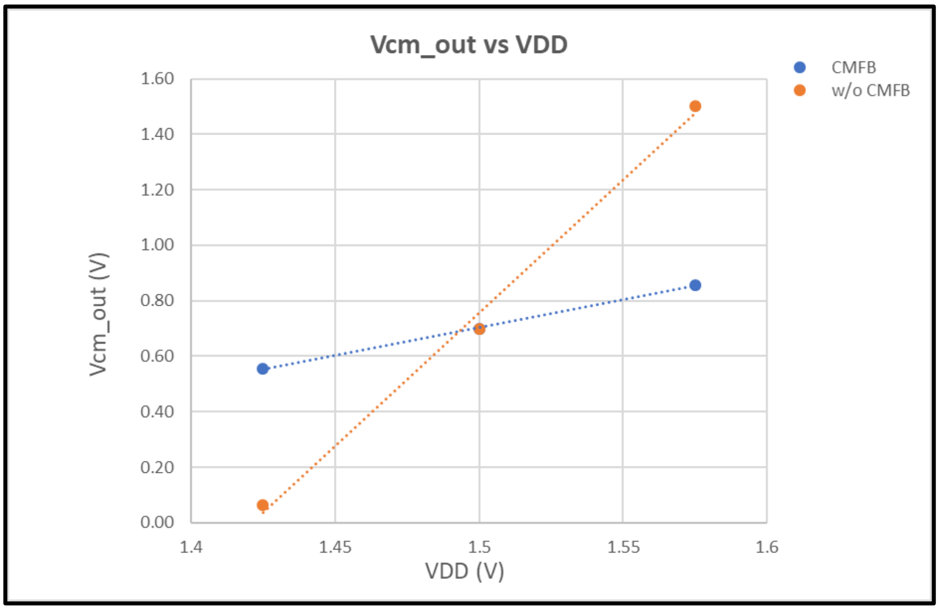
VDD = 1.575V

```
'v = 1.575v'

****** operating point information tnom=  25.000 temp=  25.000 ******
****** operating point status is all       simulation time is     0.
   node    =voltage          node    =voltage          node    =voltage

+0:vb2      = 700.20460000m 0:vcm_in  = 500.00000000m 0:vdd      =   1.57500000
+0:vin      =   0.          0:vin_left= 500.00000000m 0:vin_righ= 500.00000000m
+0:vout_lef=   1.50174499   0:vout_rig=    1.50174499   0:vp       =   1.51170288
+0:vss      =   0.          0:vx      = 900.00000000m
```

```
**** mosfets

subckt
element      0:mtail        0:m1           0:m2           0:m3
model        0:p_18.1       0:p_18.1       0:p_18.1       0:n_18.1
region       Linear         Linear         Linear         Saturation
  id          -5.23145945u   -2.61573031u   -2.61573031u    2.61572765u
  ibs         4.8678420e-22  232.70273007a  232.70273007a -1.7039599e-21
  ibd        764.53550457a  269.31095093a  269.31095096a -141.09624836a
  vgs       -675.00000000m   -1.01170288    -1.01170288   700.20460000m
  vds        -63.29711628m   -9.95789329m   -9.95789330m    1.50174499
  vbs          0.            63.29711628m   63.29711628m    0.
  vth       -457.19064790m -481.04130492m -481.04130492m  352.49062602m
  vdsat     -196.73444835m -446.92435213m -446.92435213m  298.16449454m
  vod       -217.80935210m -530.66157880m -530.66157880m  347.71397398m
  beta       480.34684261u  513.33494436u  513.33494436u   48.42761160u
  gam eff    557.08465665m  556.63015335m  556.63015335m  507.44642266m
  gm          27.56478229u    4.40079708u    4.40079708u   14.09495510u
  gds         66.15000982u  259.66010962u  259.66010961u  135.89046180n
  gmb          9.23090504u    1.79293138u    1.79293138u    2.57333193u
  cdtot       61.87890982p    6.75928666p    6.75928666p  455.70146151a
  cgtot       85.99248186p    6.56195221p    6.56195221p    3.62782060f
  cstot       81.54616610p    6.53118344p    6.53118344p    4.04502710f
  cbtot       26.63839300p    2.04888273p    2.04888273p    1.70042839f
  cgs         56.57680209p    3.51138917p    3.51138917p    3.23735181f
  cgd         28.65885438p    3.06670869p    3.06670869p  103.41521844a
```

```
element      0:m4
model        0:n_18.1
region       Saturation
  id           2.61572765u
  ibs        -1.7039599e-21
  ibd        -141.09624836a
  vgs        700.20460000m
  vds          1.50174499
  vbs          0.
  vth        352.49062602m
  vdsat      298.16449454m
  vod        347.71397398m
  beta        48.42761160u
  gam eff    507.44642266m
  gm          14.09495510u
  gds        135.89046180n
  gmb          2.57333193u
  cdtot      455.70146151a
  cgtot        3.62782060f
  cstot        4.04502710f
  cbtot        1.70042839f
  cgs          3.23735181f
  cgd        103.41521844a
```

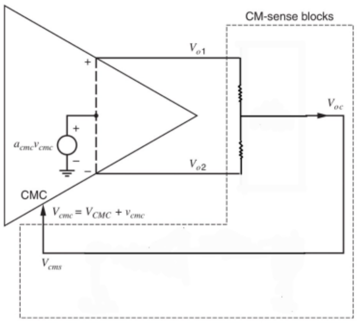
Discussion:



	VDD (V)	1.425	1.5	1.575
CMFB	**Vcm_out (V)**	**0.55615243884**	**0.70020231445**	**0.85577694023**
w/o CMFB	**Vcm_out (V)**	**0.06480083982**	**0.70000680174**	**1.50174499000**

Comment:

For my design with CMFB, the bias voltage and size are set that it is less prone to leave saturation region with V_{DD} variation. By observing the output level when CMFB is in the system and without. I see that the output common level has relatively small variation. where we see that without the CMFB, either the output common level either falls to V_{SS} or raises to V_{DD}.



VCMC = projected common mode output voltage.

acmc = loop gain

With the support of the left figure CMFB loop, the system senses the variation and can compare with a projected V_{CMC} value, where if compare value exceeds 0, then with the negative loop gain, it then has negative feedback so that it suppresses the difference. In contrast, if the sensed value is below 0, then the feedback will raise the level up. Thus, the feedback system maintains a stable system and is less prone to change with changes of other voltage source.

But with no support of the feedback system, once we deviate from the original balanced state, then there is no detection and negative feedback to maintain the output level, the output voltage then will lean to either the highest voltage or the lowest voltage, with NMOS pair remains working and tail and PMOS pair off or vice versa.

(l) Fill up Tab. I.

Working Item	Specification	Simulation Result			Calculation
Supply VDD	**1.5V±5%**	**1.575V**	**1.5V**	**1.425V**	
Tail Current	5μA		5.00375401 μA		
With Common Mode Feedback					
Output Common mode	0.7V	0.85577693814 V	0.70020231527 V	0.55615243884V	
Differential voltage gain	20		-19.9967 V/V		
Common mode gain	<1		-2.4724mV		-2.471602 mV
Without Common Mode Feedback					
Output Common mode	0.7V	1.50174499 V	0.70000680174 V	0.06480083982 V	
Differential voltage gain	-		-202.0203 V		
Common mode gain	<1		-214.0330 mV		-214.000219 mV
Vb2	V		0.7002045V		
Device Size					
Mtail (W/L ×m)	-		(45μm/40μm × 6)		
M1, M2 (W/L ×m)	-		(20μm/10μm × 4)		
M3, M4 (W/L ×m)	-		(0.3μm/1.81μm × 1)		
R1, R2	KΩ		585 KΩ		
Vx	V		0.9 V		