# EE3235 Analog Integrated Circuit Analysis and Design I
# Homework 6
# 2-Stage Opamp with CMFB

In this homework, you are asked to build the circuit shown in Fig. 1, and the specifications you need to meet are listed in Table. 1. Please make sure your circuit meets all specs in TT, FF, and SS corners.

Please note that there's no restriction on how to design the CM SENSE and CMFB blocks, if only the common-mode feedback loops are stable; however, you are welcomed to refer to Fig. 5. for a basic implementation.

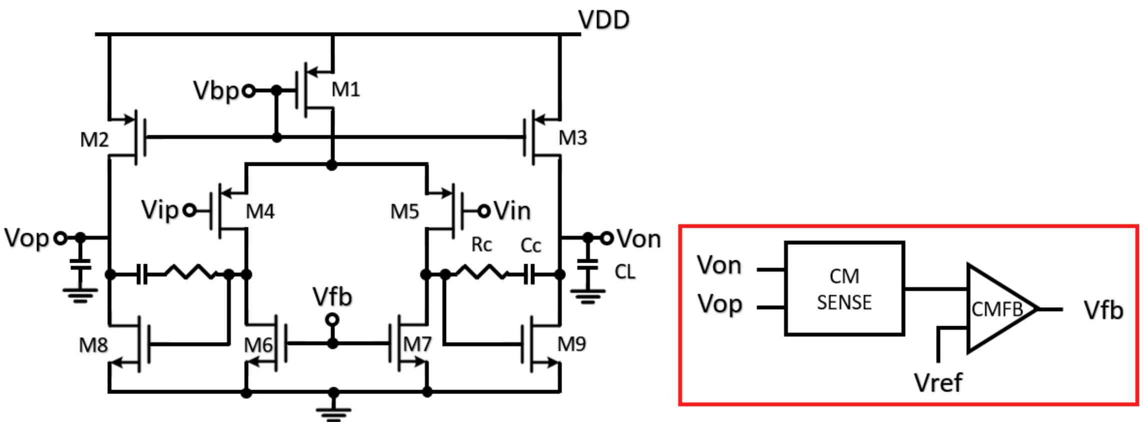



Fig. 1. 2-Stage Opamp with Common Mode Feedback.

| Parameters | Specification | This Work | | |
|---|---|---|---|---|
| | | TT | FF | SS |
| Supply Voltage(V) | 1.8 | | | |
| Temp. (°C) | 27 | | | |
| Loading Cap. (pF) | 1 | | | |
| Output CM Voltage (V) @ Vin, cm=0.8V | 0.9±20mV | 899.9916m | 899.9872m | 899.9943 |
| Open Loop Gain(dB) | >70 | 75.7115 | 74.6379 | 77.6288 |
| GBW (MHz) | >5 | 14.4632 | 26.7331 | 5.3342 |
| Phase Margin (degree) | > 60 | 80.2694 | 60.2790 | 104.2876 |
| Phase Margin Mode Range (V) | ≥ 1 | 1.26 | 1.33 | 1.06 |
| Power Consumption(uW) | < 50 | 17.2189 | 28.7019 | 9.9794 |

Table. 1. Specification and Performance

1. Elaborate on your design strategy, including how you intend to meet each specification and how you determine the size of the transistors. Please note that every design strategy must come from certain reasonable inferences or calculations, no SPICE monkeys are allowed in the class!
   Step1. Use ideal E element first and choose the size of NMOS and PMOS and CM SENSE

- r1 and r2 are used as CM SENSE, so r1 and r2 must be large enough to ensure that M8 or M9 is not starved when a large differential swing appears at the output. Therefore, I choose r1=r2=80MΩ which are large enough to maintain the output CM level.
- Choose the size of NMOS and PMOS
  - Assume the mobility of NMOS is three times of that of PMOS, so the $W_{PMOS} = 3W_{NMOS}$
  - M1 is the current source and is divided into two path (M4 and M5), so the Id of M1 should be two times the Id of M4 or M5 so I assume width of M1 is two times of M4 or M5.
  - Choose bias voltage Vbp=1.2V since threshold voltage of PMOS in this process is about 450mV to 550mV so I set bias voltage equal 1.2 so $V_{SG} = 1.8 - 1.2 = 600mV$. In this way, M1 will not go to subthreshold region.
  - All transistors should be in saturation region.
    - VGS > VTH. Otherwise, it will go to subth or cut off. So, VTH should be small enough which means the length of transistors should be large enough.
    - VDS > VGS – VTH. Otherwise, it will go to linear region. So, VTH should also no too small which means the length of transistors should be larger enough.
    - So I considers using l = 1.4u for all transistors which gives VTH = 375mV
  - Gain should be larger than 70dB (3162.3V/V), and by the gain equation I derive below:

$$
\begin{aligned}
-\text{gain} &= (\text{gain first stage}) \times (\text{gain second stage}) \\
&= (g_{m4or5} \times R_{out1}) \times (g_{m8.9} \times R_{out2}) \\
&= g_{m4or5} \times (r_{o4.5} \parallel r_{o6.7}) \times g_{m8.9} \times (r_{o8.9} \parallel r_{o2.3} \parallel r_{1or2}) \\
&= g_{m4or5} \times \left(\frac{1}{g_{ds4.5}} \parallel \frac{1}{g_{ds6.7}}\right) \times g_{m8.9} \times \left(\frac{1}{g_{ds8.9}} \parallel \frac{1}{g_{ds2.3}} \parallel 80\,M\Omega\right)
\end{aligned}
$$

    We can see the best way to boost the gain is to increase the gm, since there are two gm factors. And we know.

$$g_m = \frac{2I_D}{V_{GS}-V_{th}}$$

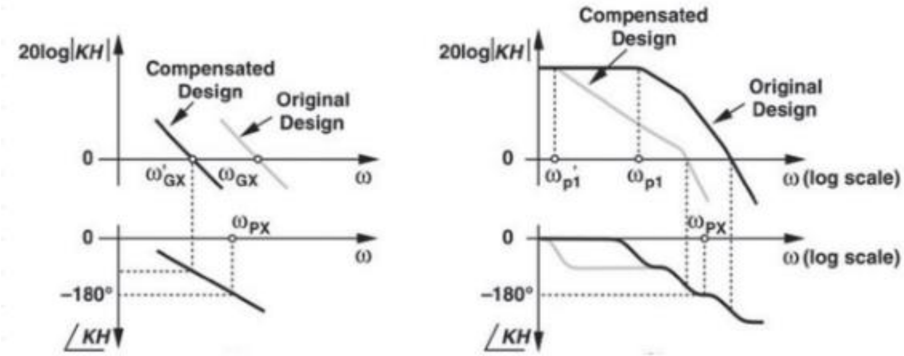
    Since I fixed the length(VTH) and bias voltage so VGS – VTH does not change a lot, so I decided to increase ID(do not increase too much, or the power consumption would be too large). By the ID equation:

$$M_1 = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{th})^2$$

    we can see that as I fixed the length and bias voltage, so I can only increase current by increase the width. And consider M1 which is the current source of the circuit, I decided to use w = 8.4u, which has enough but not too much power consumption. Since I have decided the ratio of all NMOS and PMOS, I can derive the width of all other transistors(M2~M9).

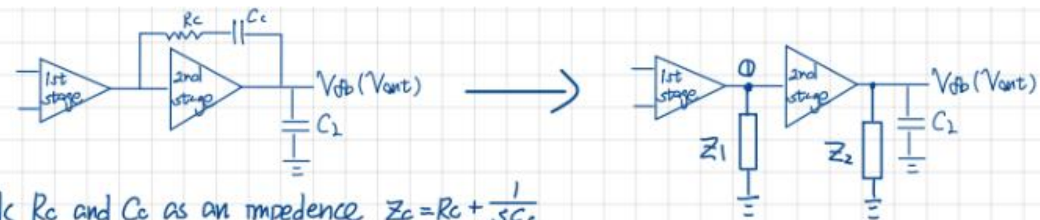
Step2. Adjust Rc and Cc

- in step1, I only check gain and power consumption meet the spec. or not. To satisfy GBW and phase margin, we use miller compensation with Rc and Cc. According to frequency compensation learned in class:




So, by adjust Rc and Cc, we can have enough phase margin.

- Look at the pole and zero in my design:




look Rc and Cc as an impedence $Z_c = R_c + \frac{1}{sC_c}$

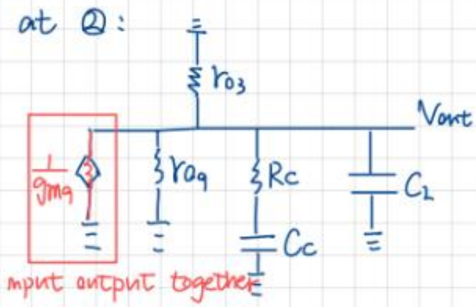
then do the Miller compensation

$$\begin{cases} Z_1 = Z_c \times \left(\frac{1}{1-A_{V2}}\right) = -\frac{1}{A_{V2}}\left(R_c + \frac{1}{sC_c}\right) \\ Z_2 = Z_c \times \left(\frac{1}{1-\frac{1}{A_{V2}}}\right) \approx R_c + \frac{1}{sC_c} \end{cases}$$

at ①:

$$W_{p1} = \frac{1}{R_{out,stage1} \cdot C_{out,stage1}} \approx \frac{1}{\left((r_{o5} \| r_{o7}) + \frac{-R_c}{A_{V2}}\right) \cdot (-A_{V2} \cdot C_c)}$$

at ②:



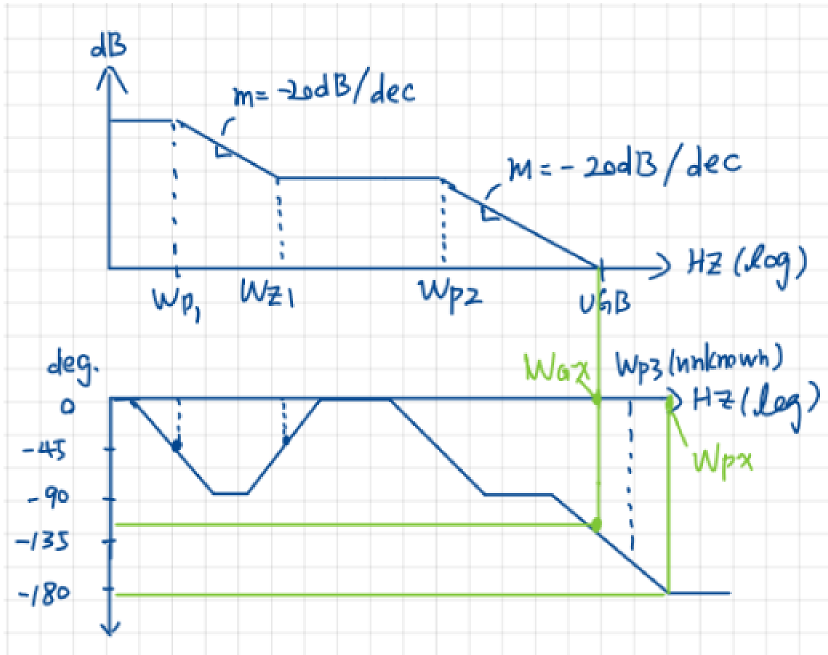

for $C_L$:

$$W_p = \frac{1}{\left(r_{o3} \| r_{o9} \| \frac{1}{g_{m9}}\right) C_L}$$

for $C_c$:

$$W_z = \frac{1}{\left(\frac{1}{g_{m9}} - R_c\right) C_c}$$

- Bode plot.




- I found that adjust Cc doesn't affect the simulation result too much. I think it is because:

$$W_{p1} = \frac{1}{R_{out,stage1} \cdot C_{out,stage1}} \approx \frac{1}{\left((r_{o5} \| r_{o9}) + \frac{-R_c}{A_{V2}}\right) \cdot (-A_{V2} \cdot C_c)}$$

$$W_z = \frac{1}{\left(\frac{1}{g_{m9}} - R_c\right) C_c}$$

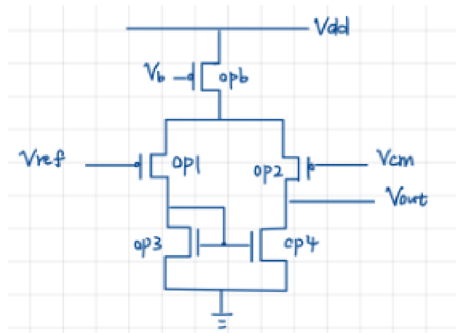
if we adjust $C_c$, both pole and zero will move,

if we adjust $R_c$, since $\frac{-R_1}{A_{V2}}$ is small, $W_{p1}$ will not change a lot, but $W_z$ will change so change $R_c$ will change phase Margin and UGB.

$$\boxed{\begin{array}{l} R_c \uparrow, W_{p1} \downarrow, W_z \uparrow \\ C_c \uparrow, W_{p1} \downarrow, W_z \downarrow \end{array}}$$

So, I decided to change Rc to 250kΩ and Cc I used my original value (50pF)

Step3. Design CMFB: replace the ideal CMFB with the following design:




- Using same strategy in step1, PMOS width is three times of NMOS and since MOPB is the current source and is divided into two path (MOP1 and MOP2), so the Id of MOPB should be two times the Id of MOP1 or MOP2 so I assume width of MOPB is two times of MOP1 or MOP2.
- When using ideal E element, I assume that gain equal 1000, so the gain of my design should be larger as possible, so using the same strategy in step1, I use (W/L)NMOS =1.4u/1.4u, (W/L)PMOS = 4.2u/1.4u and bias voltage VB = 1.2V to have larger gain and keep the power not too large.
- Input is connected to PMOS gate. Compare with input connected to NMOS:

  I found that it is easier to enter linear region when input connected to NMOS. I think it is because in my design under this process, VTH of PMOS is higher than that of NMOS so:

$V_{DS} > V_{GS} - V_{th}$

$V_{GS}$ is fixed ($V_G$ is $V_{ref}$ or $V_{cm}$)

so if $V_{th}$ is larger, $V_{GS} - V_{th}$ is smaller

, it's easier to enter sat.

Stap4. Return to check if I meet all the spec. or not.

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m1 | 0:m2 | 0:m3 | 0:m4 | 0:m5 | 0:m6 |
| model | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | -3.1824u | -1.6139u | -1.6139u | -1.5912u | -1.5912u | 1.5912u |
| ibs | 4.510e-22 | 2.531e-22 | 2.531e-22 | 98.9238a | 98.9238a | -5.641e-22 |
| ibd | 178.7780a | 285.0362a | 285.0362a | 424.2736a | 424.2736a | -109.8365a |
| vgs | -600.0000m | -600.0000m | -600.0000m | -687.6469m | -687.6469m | 463.6577m |
| vds | -312.3531m | -900.0084m | -900.0084m | -1.0273 | -1.0273 | 460.3467m |
| vbs | 0. | 0. | 0. | 312.3531m | 312.3531m | 0. |
| vth | -488.0098m | -488.6972m | -488.6972m | -575.8956m | -575.8956m | 375.2334m |
| vdsat | -128.6114m | -129.2682m | -129.2682m | -134.2345m | -134.2345m | 107.3303m |
| vod | -111.9902m | -111.3028m | -111.3028m | -111.7513m | -111.7513m | 88.4243m |
| beta | 424.7954u | 209.6698u | 209.6698u | 196.9040u | 196.9040u | 301.9646u |
| gam eff | 557.0847m | 557.0847m | 557.0847m | 554.9713m | 554.9713m | 507.4460m |
| gm | 40.7298u | 20.6658u | 20.6658u | 20.2658u | 20.2658u | 23.6267u |
| gds | 253.0841n | 49.7514n | 49.7514n | 44.7198n | 44.7198n | 242.7020n |
| gmb | 12.4045u | 6.2893u | 6.2893u | 5.4364u | 5.4364u | 4.8111u |
| cdtot | 10.8661f | 4.7513f | 4.7513f | 4.4763f | 4.4763f | 2.0681f |
| cgtot | 74.6345f | 37.1086f | 37.1086f | 36.8262f | 36.8262f | 12.9906f |
| cstot | 85.1467f | 42.6675f | 42.6675f | 41.2103f | 41.2103f | 14.2086f |
| cbtot | 39.2337f | 19.1978f | 19.1978f | 16.8783f | 16.8783f | 6.5216f |
| cgs | 65.5249f | 32.5313f | 32.5313f | 32.6696f | 32.6696f | 11.3650f |
| cgd | 3.1695f | 1.5092f | 1.5092f | 1.5084f | 1.5084f | 495.1688a |

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m7 | 0:m8 | 0:m9 | 0:mopb | 0:mop1 | 0:mop2 |
| model | 0:n_18.1 | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | 1.5912u | 1.6139u | 1.6139u | -3.1558u | -1.5778u | -1.5780u |
| ibs | -5.641e-22 | -5.721e-22 | -5.721e-22 | 4.473e-22 | 74.2319a | 74.2319a |
| ibd | -109.8365a | -214.7343a | -214.7342a | 134.1539a | 423.4140a | 423.2250a |
| vgs | 463.6577m | 460.3467m | 460.3467m | -600.0000m | -665.6120m | -665.6204m |
| vds | 460.3467m | 899.9916m | 899.9916m | -234.3880m | -1.1026 | -1.1020 |
| vbs | 0. | 0. | 0. | 0. | 234.3880m | 234.3880m |
| vth | 375.2334m | 372.5647m | 372.5647m | -488.0098m | -555.2350m | -555.2350m |
| vdsat | 107.3303m | 106.9271m | 106.9271m | -128.6111m | -132.2717m | -132.2777m |
| vod | 88.4243m | 87.7820m | 87.7820m | -111.9902m | -110.3769m | -110.3853m |
| beta | 301.9646u | 301.8915u | 301.8915u | 424.7954u | 199.9312u | 199.9308u |
| gam eff | 507.4460m | 507.4460m | 507.4460m | 557.0847m | 555.4707m | 555.4707m |
| gm | 23.6267u | 23.9341u | 23.9341u | 40.2420u | 20.2285u | 20.2295u |
| gds | 242.7020n | 225.4346n | 225.4346n | 491.2756n | 43.0826n | 43.0974n |
| gmb | 4.8111u | 4.8293u | 4.8293u | 12.2579u | 5.5820u | 5.5823u |
| cdtot | 2.0681f | 1.9014f | 1.9014f | 11.6711f | 4.4769f | 4.4772f |
| cgtot | 12.9906f | 12.9716f | 12.9716f | 74.9339f | 36.8524f | 36.8527f |
| cstot | 14.2086f | 14.1886f | 14.1886f | 85.0338f | 41.4709f | 41.4712f |
| cbtot | 6.5216f | 6.3666f | 6.3666f | 39.5072f | 17.3110f | 17.3113f |
| cgs | 11.3650f | 11.3264f | 11.3264f | 65.6642f | 32.5950f | 32.5953f |
| cgd | 495.1688a | 490.7838a | 490.7838a | 3.4157f | 1.5080f | 1.5080f |

| subckt | | |
|---|---|---|
| element | 0:mop3 | 0:mop4 |
| model | 0:n_18.1 | 0:n_18.1 |
| region | Saturation | Saturation |
| id | 1.5778u | 1.5780u |
| ibs | -5.593e-22 | -5.594e-22 |
| ibd | -110.4842a | -110.6265a |
| vgs | 463.0610m | 463.0610m |
| vds | 463.0610m | 463.6577m |
| vbs | 0. | 0. |
| vth | 375.2169m | 375.2133m |
| vdsat | 106.9656m | 106.9679m |
| vod | 87.8441m | 87.8477m |
| beta | 301.9574u | 301.9573u |
| gam eff | 507.4460m | 507.4460m |
| gm | 23.4946u | 23.4962u |
| gds | 240.8166n | 240.7610n |
| gmb | 4.7847u | 4.7850u |
| cdtot | 2.0666f | 2.0663f |
| cgtot | 12.9833f | 12.9834f |
| cstot | 14.1991f | 14.1992f |
| cbtot | 6.5206f | 6.5204f |
| cgs | 11.3558f | 11.3558f |
| cgd | 495.0775a | 495.0576a |

TT: All transistors are in saturation.

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m1 | 0:m2 | 0:m3 | 0:m4 | 0:m5 | 0:m6 |
| model | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | -5.2840u | -2.7165u | -2.7165u | -2.6420u | -2.6420u | 2.6420u |
| ibs | 7.487e-22 | 4.258e-22 | 4.258e-22 | 100.2219a | 100.2219a | -9.304e-22 |
| ibd | 180.8908a | 285.8592a | 285.8592a | 426.6419a | 426.6419a | -109.9615a |
| vgs | -600.0000m | -600.0000m | -600.0000m | -684.4584m | -684.4584m | 459.0090m |
| vds | -315.5416m | -900.0128m | -900.0128m | -1.0277 | -1.0277 | 456.7410m |
| vbs | 0. | 0. | 0. | 315.5416m | 315.5416m | 0. |
| vth | -452.5666m | -452.3564m | -452.3564m | -537.2371m | -537.2371m | 341.0607m |
| vdsat | -155.1721m | -156.5774m | -156.5774m | -161.6227m | -161.6227m | 127.3774m |
| vod | -147.4334m | -147.6436m | -147.6436m | -147.2212m | -147.2212m | 117.9483m |
| beta | 456.8398u | 226.1769u | 226.1769u | 212.3268u | 212.3268u | 331.8475u |
| gam eff | 557.0846m | 557.0846m | 557.0846m | 554.9512m | 554.9512m | 507.4460m |
| gm | 57.2119u | 29.3681u | 29.3681u | 28.4868u | 28.4868u | 33.9157u |
| gds | 484.4332n | 81.8204n | 81.8204n | 72.0396n | 72.0396n | 367.4424n |
| gmb | 16.9173u | 8.6828u | 8.6828u | 7.4213u | 7.4213u | 6.6335u |
| cdtot | 10.4892f | 4.5194f | 4.5194f | 4.2712f | 4.2712f | 1.9734f |
| cgtot | 78.4274f | 39.0444f | 39.0444f | 38.6868f | 38.6868f | 13.7090f |
| cstot | 87.9824f | 44.1928f | 44.1928f | 42.6385f | 42.6385f | 14.7493f |
| cbtot | 37.4021f | 18.3605f | 18.3605f | 16.1138f | 16.1138f | 6.2288f |
| cgs | 69.4098f | 34.5474f | 34.5474f | 34.5671f | 34.5671f | 12.0878f |
| cgd | 3.4883f | 1.6235f | 1.6235f | 1.6222f | 1.6222f | 534.8457a |

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m7 | 0:m8 | 0:m9 | 0:mopb | 0:mop1 | 0:mop2 |
| model | 0:n_18.1 | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | 2.6420u | 2.7165u | 2.7165u | -5.2285u | -2.6141u | -2.6144u |
| ibs | -9.304e-22 | -9.567e-22 | -9.567e-22 | 7.409e-22 | 75.3909a | 75.3909a |
| ibd | -109.9615a | -216.6750a | -216.6750a | 136.0728a | 426.1887a | 425.9215a |
| vgs | 459.0090m | 456.7410m | 456.7410m | -600.0000m | -662.6375m | -662.6503m |
| vds | 456.7410m | 899.9872m | 899.9872m | -237.3625m | -1.1045 | -1.1036 |
| vbs | 0. | 0. | 0. | 0. | 237.3625m | 237.3625m |
| vth | 341.0607m | 338.3576m | 338.3576m | -452.5666m | -517.2850m | -517.2850m |
| vdsat | 127.3774m | 127.6721m | 127.6721m | -155.1718m | -159.0710m | -159.0808m |
| vod | 117.9483m | 118.3834m | 118.3834m | -147.4334m | -145.3525m | -145.3653m |
| beta | 331.8475u | 331.7714u | 331.7714u | 456.8398u | 215.6337u | 215.6330u |
| gam eff | 507.4460m | 507.4460m | 507.4460m | 557.0846m | 555.4514m | 555.4514m |
| gm | 33.9157u | 34.6570u | 34.6570u | 56.1999u | 28.4450u | 28.4467u |
| gds | 367.4424n | 333.8863n | 333.8863n | 1.1093u | 68.7014n | 68.7387n |
| gmb | 6.6335u | 6.7110u | 6.7110u | 16.6274u | 7.6201u | 7.6205u |
| cdtot | 1.9734f | 1.8137f | 1.8137f | 11.7124f | 4.2706f | 4.2710f |
| cgtot | 13.7090f | 13.6961f | 13.6961f | 78.8863f | 38.7420f | 38.7422f |
| cstot | 14.7493f | 14.7422f | 14.7422f | 87.8622f | 42.9369f | 42.9371f |
| cbtot | 6.2288f | 6.0866f | 6.0866f | 37.6749f | 16.5341f | 16.5345f |
| cgs | 12.0878f | 12.0589f | 12.0589f | 69.5580f | 34.5340f | 34.5341f |
| cgd | 534.8457a | 527.6920a | 527.6920a | 3.9239f | 1.6216f | 1.6217f |

| subckt | | |
|---|---|---|
| element | 0:mop3 | 0:mop4 |
| model | 0:n_18.1 | 0:n_18.1 |
| region | Saturation | Saturation |
| id | 2.6141u | 2.6144u |
| ibs | -9.206e-22 | -9.207e-22 |
| ibd | -110.3050a | -110.5076a |
| vgs | 458.1677m | 458.1677m |
| vds | 458.1677m | 459.0090m |
| vbs | 0. | 0. |
| vth | 341.0520m | 341.0469m |
| vdsat | 126.8155m | 126.8189m |
| vod | 117.1157m | 117.1209m |
| beta | 331.8344u | 331.8343u |
| gam eff | 507.4460m | 507.4460m |
| gm | 33.6962u | 33.6991u |
| gds | 364.1506n | 363.9651n |
| gmb | 6.5920u | 6.5925u |
| cdtot | 1.9724f | 1.9720f |
| cgtot | 13.7051f | 13.7050f |
| cstot | 14.7444f | 14.7444f |
| cbtot | 6.2287f | 6.2283f |
| cgs | 12.0827f | 12.0827f |
| cgd | 534.7049a | 534.6584a |

FF: All transistors are in saturation.

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m1 | 0:m2 | 0:m3 | 0:m4 | 0:m5 | 0:m6 |
| model | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | -1.8610u | -917.5766n | -917.5766n | -930.4951n | -930.4951n | 930.4965n |
| ibs | 2.638e-22 | 1.440e-22 | 1.440e-22 | 97.5510a | 97.5510a | -3.319e-22 |
| ibd | 176.6012a | 283.9398a | 283.9398a | 417.2131a | 417.2131a | -113.0062a |
| vgs | -600.0000m | -600.0000m | -600.0000m | -690.7926m | -690.7926m | 482.1970m |
| vds | -309.2074m | -900.0057m | -900.0058m | -1.0132 | -1.0132 | 477.5573m |
| vbs | 0. | 0. | 0. | 309.2074m | 309.2074m | 0. |
| vth | -516.8058m | -519.0340m | -519.0340m | -607.6159m | -607.6159m | 411.3252m |
| vdsat | -108.5583m | -108.1892m | -108.1892m | -113.6215m | -113.6215m | 94.8166m |
| vod | -83.1942m | -80.9660m | -80.9660m | -83.1767m | -83.1767m | 70.8718m |
| beta | 374.0022u | 183.8773u | 183.8773u | 172.7108u | 172.7108u | 236.2273u |
| gam eff | 557.0847m | 557.0847m | 557.0847m | 554.9911m | 554.9911m | 507.4460m |
| gm | 27.2107u | 13.4973u | 13.4973u | 13.5372u | 13.5372u | 15.0470u |
| gds | 129.0664n | 27.2561n | 27.2561n | 25.4338n | 25.4338n | 139.8550n |
| gmb | 8.4659u | 4.1962u | 4.1962u | 3.7099u | 3.7099u | 3.2099u |
| cdtot | 11.4228f | 5.0136f | 5.0136f | 4.7199f | 4.7199f | 2.1540f |
| cgtot | 75.3562f | 37.2892f | 37.2892f | 37.1507f | 37.1507f | 13.8397f |
| cstot | 86.4467f | 43.0544f | 43.0544f | 41.8278f | 41.8278f | 15.2161f |
| cbtot | 42.6815f | 20.8276f | 20.8276f | 18.3530f | 18.3530f | 7.2835f |
| cgs | 65.2882f | 32.1936f | 32.1936f | 32.5974f | 32.5974f | 12.0265f |
| cgd | 2.9481f | 1.4178f | 1.4178f | 1.4173f | 1.4173f | 453.1779a |

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m7 | 0:m8 | 0:m9 | 0:mopb | 0:mop1 | 0:mop2 |
| model | 0:n_18.1 | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | 930.4965n | 917.5766n | 917.5766n | -1.8480u | -923.9469n | -924.0129n |
| ibs | -3.319e-22 | -3.273e-22 | -3.273e-22 | 2.620e-22 | 73.0177a | 73.0177a |
| ibd | -113.0062a | -212.9695a | -212.9694a | 132.1874a | 415.8992a | 415.7493a |
| vgs | 482.1970m | 477.5573m | 477.5573m | -600.0000m | -668.5558m | -668.5616m |
| vds | 477.5573m | 899.9943m | 899.9942m | -231.4442m | -1.0868 | -1.0864 |
| vbs | 0. | 0. | 0. | 0. | 231.4442m | 231.4442m |
| vth | 411.3252m | 408.9751m | 408.9751m | -516.8058m | -586.4603m | -586.4603m |
| vdsat | 94.8166m | 93.4848m | 93.4848m | -108.5581m | -112.0589m | -112.0627m |
| vod | 70.8718m | 68.5822m | 68.5822m | -83.1942m | -82.0955m | -82.1012m |
| beta | 236.2273u | 236.1722u | 236.1722u | 374.0022u | 175.3462u | 175.3459u |
| gam eff | 507.4460m | 507.4460m | 507.4460m | 557.0847m | 555.4899m | 555.4899m |
| gm | 15.0470u | 14.9391u | 14.9391u | 26.9637u | 13.5043u | 13.5049u |
| gds | 139.8550n | 130.8501n | 130.8501n | 230.0878n | 24.6791n | 24.6852n |
| gmb | 3.2099u | 3.1623u | 3.1623u | 8.3894u | 3.8084u | 3.8086u |
| cdtot | 2.1540f | 1.9840f | 1.9840f | 12.0541f | 4.7217f | 4.7220f |
| cgtot | 13.8397f | 13.7742f | 13.7742f | 75.5839f | 37.1443f | 37.1446f |
| cstot | 15.2161f | 15.1295f | 15.1295f | 86.3389f | 42.0401f | 42.0406f |
| cbtot | 7.2835f | 7.1224f | 7.1224f | 42.9680f | 18.8189f | 18.8192f |
| cgs | 12.0265f | 11.9283f | 11.9283f | 65.4213f | 32.4644f | 32.4648f |
| cgd | 453.1779a | 450.2457a | 450.2457a | 3.1107f | 1.4170f | 1.4170f |

| subckt | | |
|---|---|---|
| element | 0:mop3 | 0:mop4 |
| model | 0:n_18.1 | 0:n_18.1 |
| region | Saturation | Saturation |
| id | 923.9484n | 924.0143n |
| ibs | -3.295e-22 | -3.296e-22 |
| ibd | -113.9918a | -114.1042a |
| vgs | 481.7221m | 481.7221m |
| vds | 481.7221m | 482.1970m |
| vbs | 0. | 0. |
| vth | 411.3020m | 411.2994m |
| vdsat | 94.5528m | 94.5544m |
| vod | 70.4201m | 70.4227m |
| beta | 236.2236u | 236.2236u |
| gam eff | 507.4460m | 507.4460m |
| gm | 14.9728u | 14.9737u |
| gds | 138.9000n | 138.8857n |
| gmb | 3.1942u | 3.1944u |
| cdtot | 2.1517f | 2.1515f |
| cgtot | 13.8287f | 13.8287f |
| cstot | 15.2014f | 15.2015f |
| cbtot | 7.2816f | 7.2813f |
| cgs | 12.0126f | 12.0126f |
| cgd | 453.1116a | 453.1004a |

SS: All transistors are in saturation.

| phase_margin alter# | gain_db | gbw | temper |
|---|---|---|---|
| 80.2785 | 75.3294 | 1.446e+07 | 27.0000 |

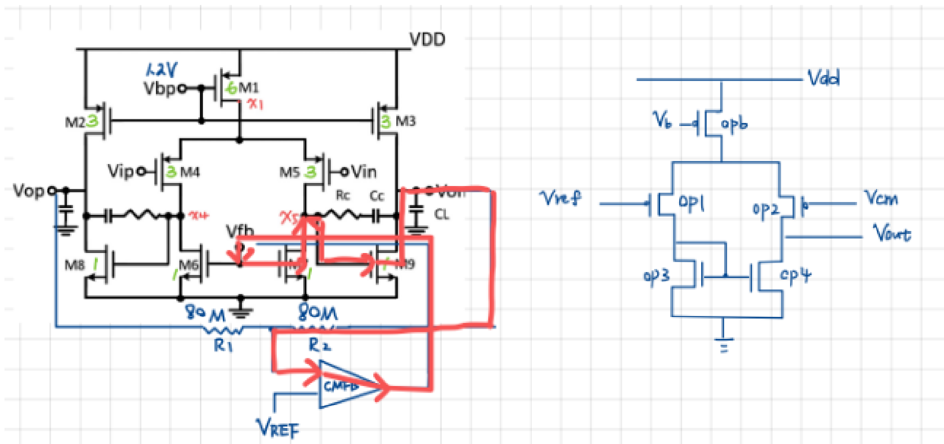
| phase_margin alter# | gain_db | gbw | temper |
|---|---|---|---|
| 60.2839 | 74.3817 | 2.673e+07 | 27.0000 |

| phase_margin alter# | gain_db | gbw | temper |
|---|---|---|---|
| 104.3118 | 76.9882 | 5.333e+06 | 27.0000 |

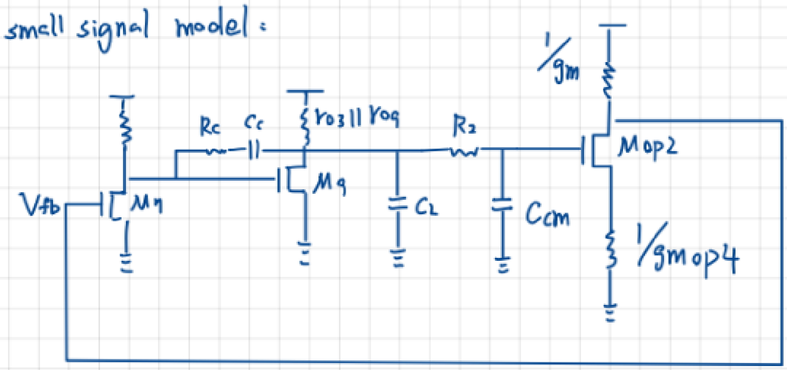
Meet spec. in TT FF and SS

2. From fig. 1, we can observe a common-mode feedback loop in this circuit. Please analyze the loop by hand, the content must include the breakdown of the entire loop gain and also the distribution of poles.

   Breakdown the loop:

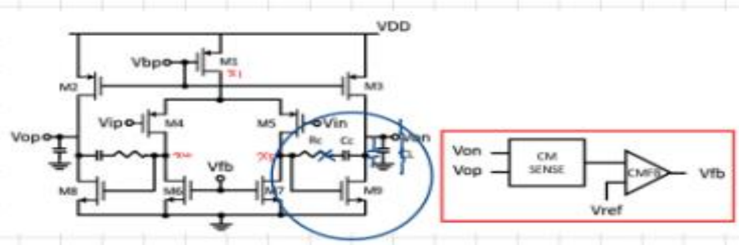



small signal model :




1st pole :

Gain:




gain :

first stage: gain = $g_{m4,5} ( r_{o6,7} \parallel r_{o4,5} )$

second stage: gain = $g_{m8,9} ( r_{o2,3} \parallel r_{o8,9} \parallel 80M\Omega )$

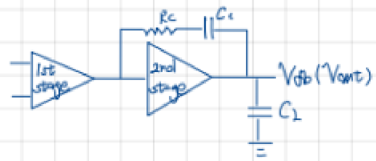
$20.2658u \times \left( \frac{1}{44.7168n} \parallel \frac{1}{242.7020n} \right) \cong 70.5089$

$23.9341u \times \left( \frac{1}{223.4346n} \parallel \frac{1}{49.7514n} \parallel 80M\Omega \right) \cong 82.5$

$\therefore$ total gain = 5816.984 (V/V) $\cong$ 75.293 dB

Poles:

pole and zero :

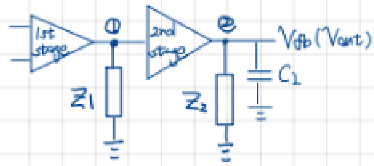



$$\begin{cases} Z_1 = Z_c \times \left(\frac{1}{1-A_{V_2}}\right) = -\frac{1}{A_{V_2}}\left(R_c + \frac{1}{sC_c}\right) \\ Z_2 = Z_c \times \left(\frac{1}{1-\frac{1}{A_{V_2}}}\right) \approx R_c + \frac{1}{sC_c} \end{cases}$$

look Rc and Cc as an impedence $Z_c = R_c + \frac{1}{sC_c}$

then do the Miller compensation

↓

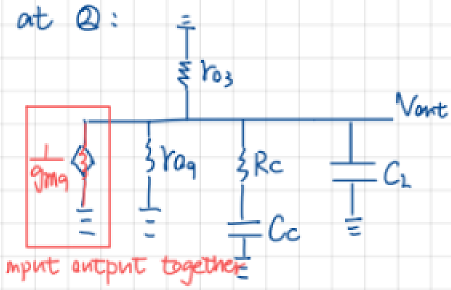



at ① :

$$W_{p1} = \frac{1}{R_{out,stage1} \cdot C_{out,stage1}} \approx \frac{1}{\left((r_{o5} \| r_{o7}) + \frac{-R_c}{A_{V_2}}\right) \cdot (-A_{V_2} \cdot C_c)}$$

$\cong 69.626$ rad/s $\approx 11.087$ Hz → 1st pole

at ② :




for $C_L$ :

$$W_p = \frac{1}{\left(r_{o3} \| r_{o9} \| \frac{1}{g_{m9}}\right) C_L} \approx 24.2 \text{ M rad/s}$$

$= 3.853$ MHz → 2nd pole

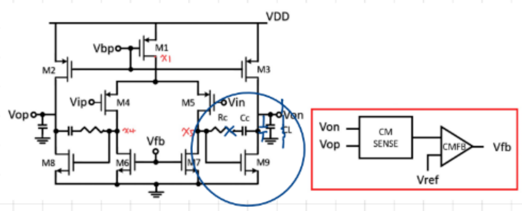
for $C_c$ :

$$W_z = \frac{1}{\left(\frac{1}{G_{m9}} - R_c\right) C_c} = -96.053\text{k rad/s}$$

$= -15.287$ kHz

3. Compare the SPICE simulation result with the hand analysis you do in question number 1, and explain what causes the error between the simulation and your calculation (at least include open loop gain, GBW, and Power Consumption).

Open loop gain:




gain:

first stage: gain $= g_{m4,5}\,(r_{o6,7} \parallel r_{o4,5})$

second stage: gain $= g_{m8,9}\,(r_{o2,3} \parallel r_{o8,9} \parallel 80M\Omega)$

$$20.2658u \times \left(\frac{1}{44.7158n} \parallel \frac{1}{242.7020n}\right) \cong 70.5089$$

$$23.9341u \times \left(\frac{1}{225.4346n} \parallel \frac{1}{49.7514n} \parallel 80M\Omega\right) \cong 82.5$$

$\therefore$ total gain $= 5816.984$ (V/V) $\cong 75.293$ dB

error: $\dfrac{5816.984 - 5865.9}{5816.984} \approx -0.84\%$ .

output R:

$$\left(\frac{1}{225.4367n} \parallel \frac{1}{49.7314n} \parallel 80M\Omega\right) \times 2 \cong 6893.92\,k\Omega$$

error: $\dfrac{6893.92 - 6952.2}{6893.92} \cong -0.845\%$

Error discussion: CM sense resistance is not large enough, so in stage2, the resistance will affect output resistance which make some error.

Power consumption:

Power:

$V_{dd} \times i_{\text{total to } V_{dd}}$

$= V_{dd} \times (I_d\,M1 + I_d\,M2 + I_d\,M3 + I_d\,\text{opb})$

$= 1.8 \times (3.1824u + 1.6139u + 1.6139u + 3.1558$

$= 17.2188\,uW$

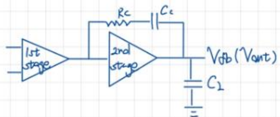
error: $\dfrac{17.2189 - 17.2188}{17.2189} \approx 5.8 \times 10^{-4}\,\%$

Error discussion: simulation result round to the fourth decimal place, so it will have a little difference with my calculations.

GBW:

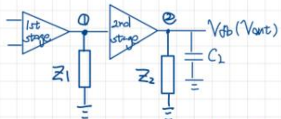
1. Find pole and zero.

pole and zero :




look Rc and Cc as an impedence $Z_c = R_c + \frac{1}{sC_c}$

then do the Miller compensation ↓




$$\begin{cases} Z_1 = Z_c \times \left(\frac{1}{1-A_{V2}}\right) = -\frac{1}{A_{V2}}\left(R_c + \frac{1}{sC_c}\right) \\ Z_2 = Z_c \times \left(\frac{1}{1-\frac{1}{A_{V2}}}\right) \approx R_c + \frac{1}{sC_c} \end{cases}$$

3418742
3030.30

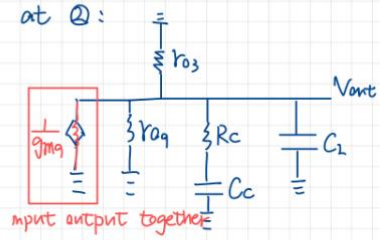
at ① :

$$W_{p1} = \frac{1}{R_{out,stage1} \cdot C_{out,stage1}} \approx \frac{1}{\left((r_{o5}\|r_{o7}) + \frac{-R_c}{A_{V2}}\right)\cdot(-A_{V2}\cdot C_c)}$$

$\cong 69.626$ rad/s $\approx 11.087$ Hz → 1st pole

error : $\frac{11.087 - 10.7268}{11.087} = 3.249\,\%$

at ② :




for CL :

$$W_p = \frac{1}{\left(r_{o3}\|r_{o9}\|\frac{1}{g_{m9}}\right)C_L} \approx 24.2 \text{ M rad/s}$$

$= 3.853$ MHz → 2nd pole

∴ error : $\frac{3.853 - 3.9881}{3.853} \cong -3.5\,\%$

for Cc :

$$W_z = \frac{1}{\left(\frac{1}{g_{m9}} - R_c\right)C_c} = -96.053\text{k rad/s}$$

$= -15.287$ kHz

∴ error : $\frac{15.2873 - 15.2874}{15.2874} = 1.242 \times 10^{-2}\,\%$

```
**************************************************
  ******    pole/zero analysis


   input =  0:vdiff          output = v(vop,von)

        poles (rad/sec)                 poles ( hertz)
real            imag             real             imag
-67.3987        0.               -10.7268         0.
-25.0581x       0.               -3.98813x        0.
-199.360x       0.               -31.7292x        0.

        zeros (rad/sec)                 zeros ( hertz)
real            imag             real             imag
-96.0537k       0.               -15.2874k        0.
13.2705g        0.               2.11207g         0.
36.0740g        0.               5.74136g         0.
```

Pole and zero in simulation

Error discussion: I think it is because we neglect parasitic capacitance.

2. Use bode plot to estimate unit gain bandwidth.

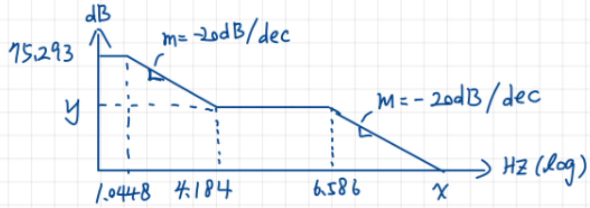
∴ by hand cal.:

gain = 74.2035 dB

pole1 = 11.087 Hz $\xrightarrow{\log}$ 1.0448

pole2 = 3.853 MHz $\xrightarrow{\log}$ 6.586

zero1 = 15.287 KHz $\xrightarrow{\log}$ 4.184




$$\frac{75.293 - y}{4.184 - 1.0488} = 20 \rightarrow y = 12.589$$

$$\frac{12.589 - 0}{x - 6.586} = 20 \rightarrow x \cong 7.21$$

$$\therefore \text{UGB} = 10^{7.2052} \cong 16.04\ \text{MHz}$$

$$\rightarrow \text{error} = \frac{16.04 - 14.46}{16.04} \cong 9.85\%$$

Error discussion: first, we neglect parasitic capacitance. Second, bode plot is just an estimation, if two pole or zero are too close, there will be some error.

4. Run the ac simulation to make sure your common-mode feedback loop is stable. Please note that the content must include the graph of gain and phase margin. Hints are provided in Fig. 4.

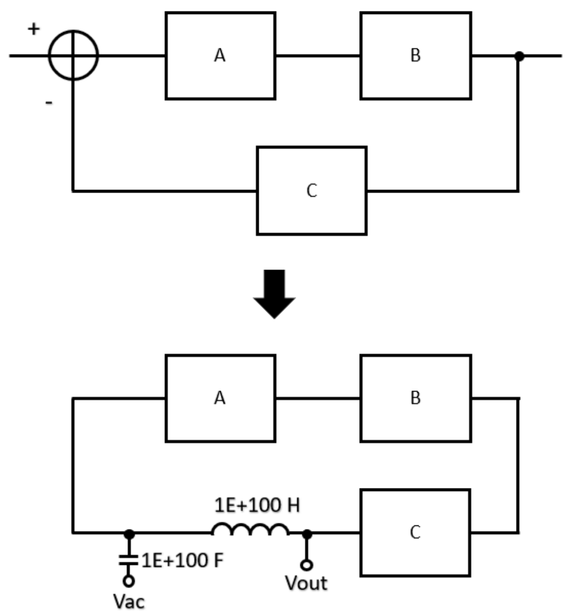
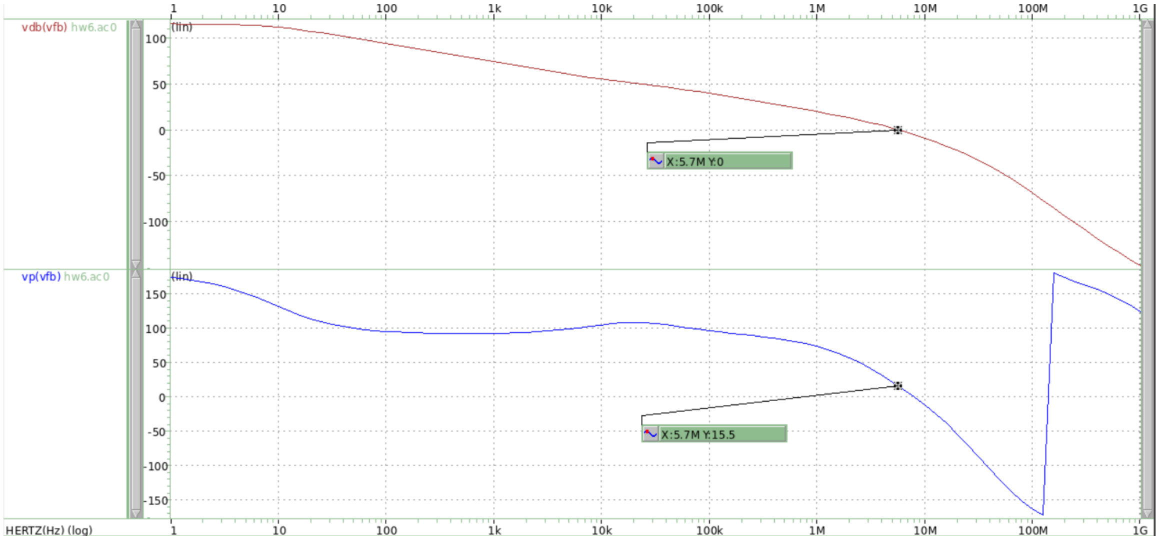


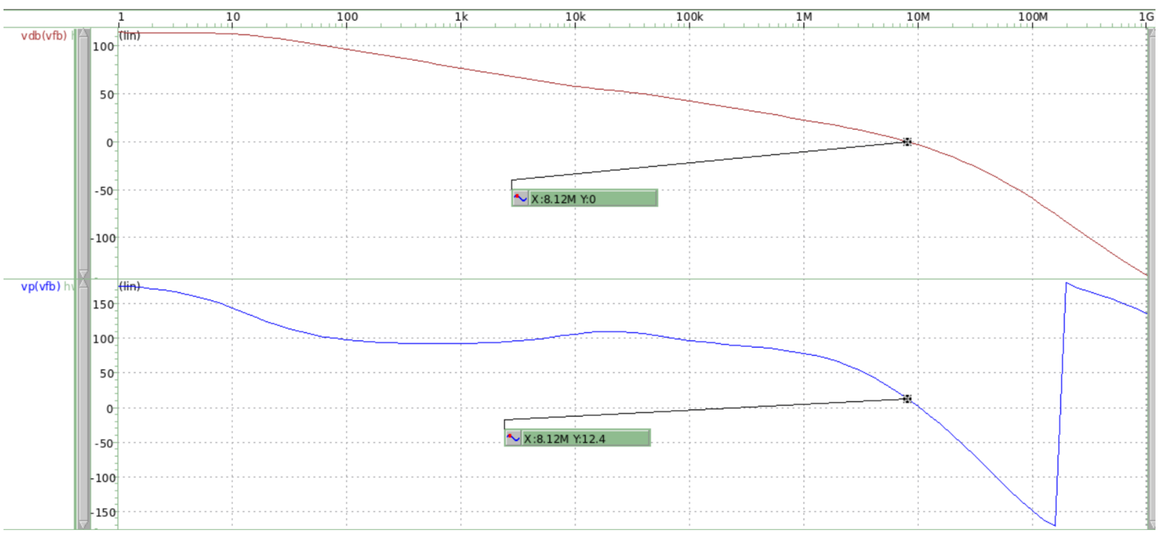

Fig. 4. Frequency Analysis of a Feedback Loop

TT:



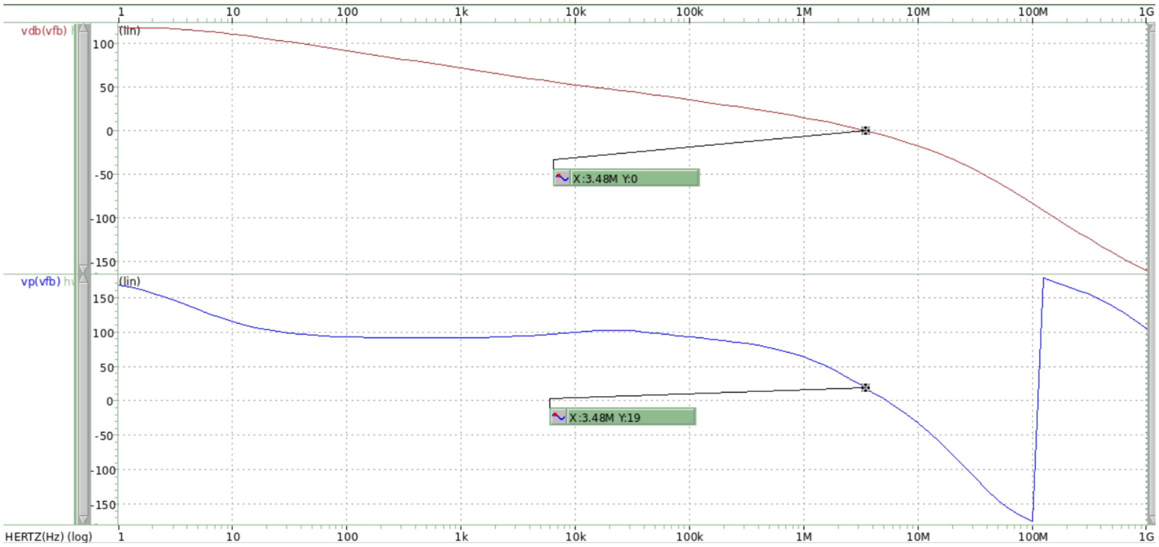

x-axis: frequency in log(Hz) – y-axis: gain in dB(red line) and phase in degree(blue line)

FF:




x-axis: frequency in log(Hz) – y-axis: gain in dB(red line) and phase in degree(blue line)

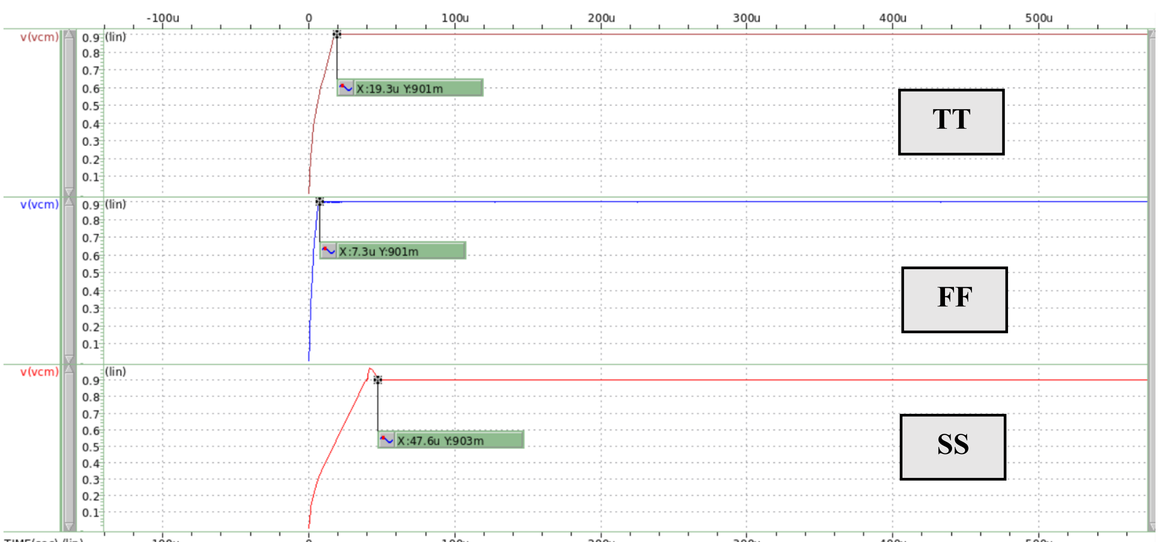
SS:




x-axis: frequency in log(Hz) – y-axis: gain in dB(red line) and phase in degree(blue line)

From the above 3 figures, we can see that under the 3 different corners, before gain reaches 0dB, the phase of Vfb is always positive, which make that the design remains negative feedback and provide stability in the output node.

5. Run the transient simulation. Insert an input signal with an amplitude of 0.1mVpp and set the initial value of both output nodes to 0V. Observe whether, after a period of time, the output common mode stabilizes back to 0.9V±20mV.



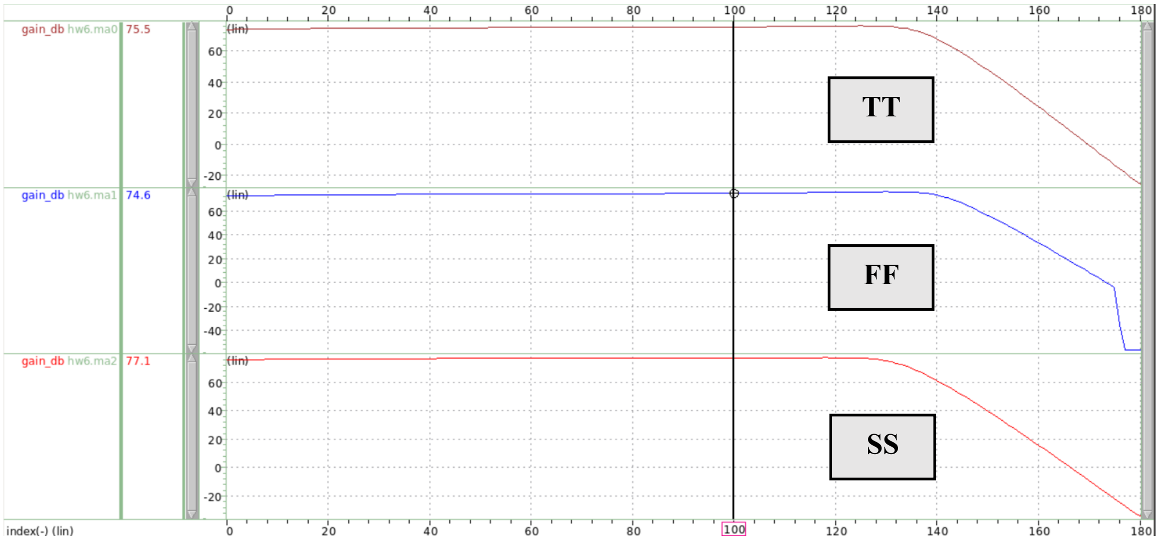

x-axis: time(second) – y-axis: common mode voltage(V)

By measuring the voltage output common mode at time when vocm is stable in each corner, we can see that the voltage matches the requirement of 0.9±20mV. and FF corner become stable fastest and SS corner become stable slower.

6. Sweep input common-mode voltage to make sure your input CM range meets the spec.

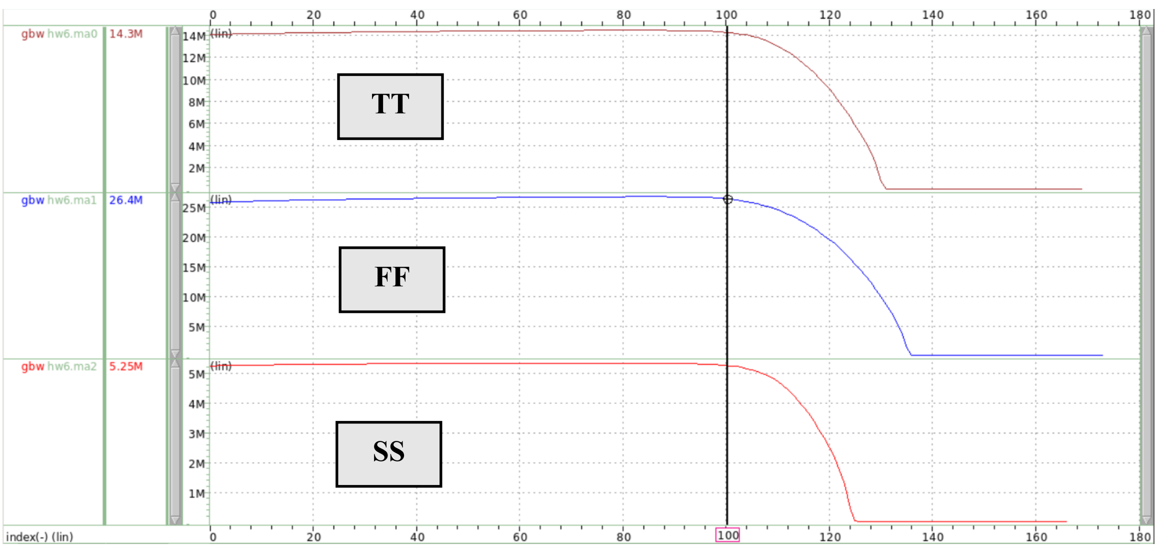
Check when vincm=0V, vincm=0.5V and vincm=1V all transistors are in saturation

Gain:



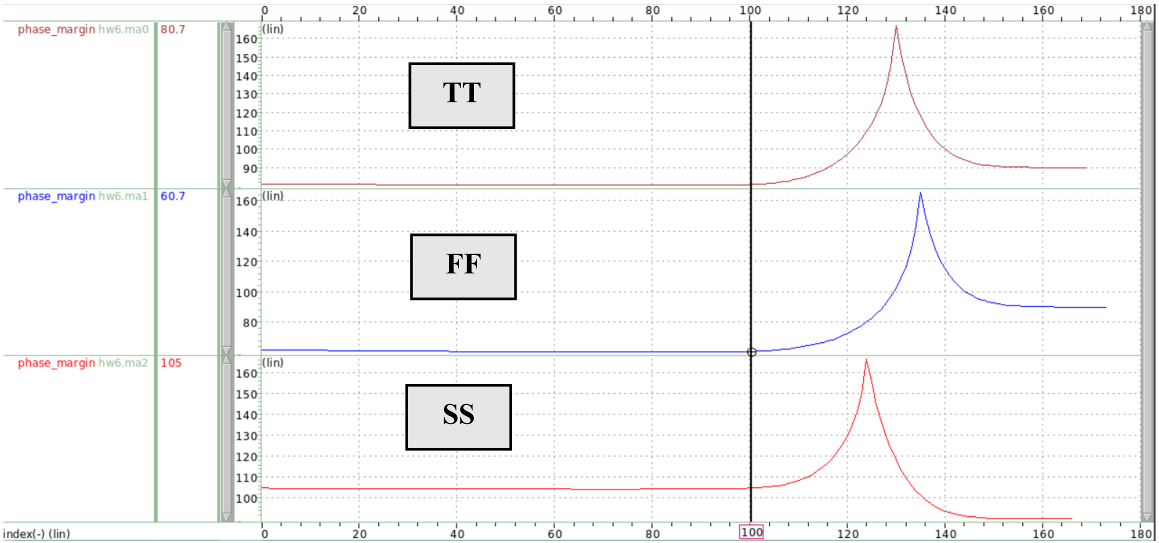

x-axis: input common mode(V) – y-axis: gain in dB

UGB:




x-axis: input common mode (V) – y-axis: gain bandwidth (MHz)

phase margin:




x-axis: input common mode (V) – y-axis: phase margin in degree

saturation of all transistors when input common mode is 0V:

TT

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m1 | 0:m2 | 0:m3 | 0:m4 | 0:m5 | 0:m6 |
| model | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | -3.2705u | -1.6139u | -1.6139u | -1.6352u | -1.6352u | 1.6352u |
| ibs | 4.635e-22 | 2.531e-22 | 2.531e-22 | 301.5763a | 301.5763a | -5.797e-22 |
| ibd | 545.0192a | 285.0445a | 285.0445a | 424.2735a | 424.2735a | -109.8366a |
| vgs | -600.0000m | -600.0000m | -600.0000m | -847.7677m | -847.7677m | 465.5046m |
| vds | -952.2323m | -900.0344m | -900.0344m | -387.4207m | -387.4207m | 460.3470m |
| vbs | 0. | 0. | 0. | 952.2323m | 952.2323m | 0. |
| vth | -488.0099m | -488.6972m | -488.6972m | -726.4934m | -726.4934m | 375.2334m |
| vdsat | -128.6143m | -129.2682m | -129.2682m | -147.0177m | -147.0177m | 108.4950m |
| vod | -111.9901m | -111.3028m | -111.3028m | -121.2742m | -121.2742m | 90.2712m |
| beta | 424.7949u | 209.6698u | 209.6698u | 175.9542u | 175.9542u | 301.9861u |
| gam eff | 557.0847m | 557.0847m | 557.0847m | 551.3608m | 551.3608m | 507.4460m |
| gm | 41.8856u | 20.6658u | 20.6658u | 19.9068u | 19.9068u | 24.0596u |
| gds | 98.3664n | 49.7506n | 49.7506n | 90.3835n | 90.3835n | 247.7770n |
| gmb | 12.7625u | 6.2893u | 6.2893u | 4.4595u | 4.4595u | 4.8965u |
| cdtot | 9.2900f | 4.7513f | 4.7513f | 4.5806f | 4.5806f | 2.0684f |
| cgtot | 74.3806f | 37.1086f | 37.1086f | 36.7498f | 36.7498f | 13.0122f |
| cstot | 85.2907f | 42.6675f | 42.6675f | 39.6707f | 39.6707f | 14.2375f |
| cbtot | 37.9720f | 19.1978f | 19.1978f | 14.4328f | 14.4328f | 6.5209f |
| cgs | 65.3500f | 32.5313f | 32.5313f | 33.1536f | 33.1536f | 11.3922f |
| cgd | 3.0176f | 1.5092f | 1.5092f | 1.5559f | 1.5559f | 495.1746a |

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m7 | 0:m8 | 0:m9 | 0:mopb | 0:mop1 | 0:mop2 |
| model | 0:n_18.1 | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | 1.6352u | 1.6139u | 1.6139u | -3.1558u | -1.5776u | -1.5782u |
| ibs | -5.797e-22 | -5.721e-22 | -5.721e-22 | 4.473e-22 | 74.2346a | 74.2346a |
| ibd | -109.8366a | -214.7280a | -214.7280a | 134.1588a | 423.4170a | 422.6401a |
| vgs | 465.5046m | 460.3470m | 460.3470m | -600.0000m | -665.6034m | -665.6378m |
| vds | 460.3470m | 899.9656m | 899.9656m | -234.3966m | -1.1026 | -1.1001 |
| vbs | 0. | 0. | 0. | 0. | 234.3966m | 234.3966m |
| vth | 375.2334m | 372.5648m | 372.5648m | -488.0098m | -555.2374m | -555.2374m |
| vdsat | 108.4950m | 106.9272m | 106.9272m | -128.6111m | -132.2641m | -132.2886m |
| vod | 90.2712m | 87.7822m | 87.7822m | -111.9902m | -110.3661m | -110.4005m |
| beta | 301.9861u | 301.8915u | 301.8915u | 424.7954u | 199.9314u | 199.9297u |
| gam eff | 507.4460m | 507.4460m | 507.4460m | 557.0847m | 555.4707m | 555.4707m |
| gm | 24.0596u | 23.9342u | 23.9342u | 40.2421u | 20.2267u | 20.2311u |
| gds | 247.7770n | 225.4351n | 225.4351n | 491.2208n | 43.0772n | 43.1383n |
| gmb | 4.8965u | 4.8293u | 4.8293u | 12.2579u | 5.5815u | 5.5827u |
| cdtot | 2.0684f | 1.9014f | 1.9014f | 11.6709f | 4.4768f | 4.4782f |
| cgtot | 13.0122f | 12.9716f | 12.9716f | 74.9339f | 36.8522f | 36.8531f |
| cstot | 14.2375f | 14.1886f | 14.1886f | 85.0338f | 41.4704f | 41.4717f |
| cbtot | 6.5209f | 6.3666f | 6.3666f | 39.5071f | 17.3110f | 17.3123f |
| cgs | 11.3922f | 11.3264f | 11.3264f | 65.6641f | 32.5947f | 32.5958f |
| cgd | 495.1746a | 490.7838a | 490.7838a | 3.4156f | 1.5080f | 1.5080f |

| subckt | | |
|---|---|---|
| element | 0:mop3 | 0:mop4 |
| model | 0:n_18.1 | 0:n_18.1 |
| region | Saturation | Saturation |
| id | 1.5776u | 1.5782u |
| ibs | -5.592e-22 | -5.594e-22 |
| ibd | -110.4819a | -111.0672a |
| vgs | 463.0517m | 463.0517m |
| vds | 463.0517m | 465.5046m |
| vbs | 0. | 0. |
| vth | 375.2170m | 375.2021m |
| vdsat | 106.9597m | 106.9691m |
| vod | 87.8347m | 87.8496m |
| beta | 301.9573u | 301.9571u |
| gam eff | 507.4460m | 507.4460m |
| gm | 23.4924u | 23.4990u |
| gds | 240.7921n | 240.5657n |
| gmb | 4.7843u | 4.7854u |
| cdtot | 2.0666f | 2.0653f |
| cgtot | 12.9832f | 12.9832f |
| cstot | 14.1990f | 14.1992f |
| cbtot | 6.5207f | 6.5196f |
| cgs | 11.3557f | 11.3557f |
| cgd | 495.0778a | 494.9968a |

FF

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m1 | 0:m2 | 0:m3 | 0:m4 | 0:m5 | 0:m6 |
| model | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | -5.4354u | -2.7165u | -2.7165u | -2.7177u | -2.7177u | 2.7177u |
| ibs | 7.702e-22 | 4.258e-22 | 4.258e-22 | 304.3371a | 304.3371a | -9.571e-22 |
| ibd | 549.3018a | 285.8700a | 285.8699a | 426.6417a | 426.6417a | -109.9616a |
| vgs | -600.0000m | -600.0000m | -600.0000m | -841.8134m | -841.8134m | 461.2226m |
| vds | -958.1866m | -900.0466m | -900.0466m | -385.0720m | -385.0720m | 456.7414m |
| vbs | 0. | 0. | 0. | 958.1866m | 958.1866m | 0. |
| vth | -452.5666m | -452.3564m | -452.3564m | -682.8906m | -682.8906m | 341.0607m |
| vdsat | -155.1748m | -156.5774m | -156.5774m | -177.4649m | -177.4649m | 128.8751m |
| vod | -147.4334m | -147.6436m | -147.6436m | -158.9228m | -158.9228m | 120.1619m |
| beta | 456.8393u | 226.1769u | 226.1769u | 189.5170u | 189.5170u | 331.8815u |
| gam eff | 557.0846m | 557.0846m | 557.0846m | 551.3304m | 551.3304m | 507.4460m |
| gm | 58.9826u | 29.3682u | 29.3682u | 27.6804u | 27.6804u | 34.5070u |
| gds | 158.0994n | 81.8184n | 81.8184n | 171.3437n | 171.3437n | 375.3257n |
| gmb | 17.4476u | 8.6828u | 8.6828u | 6.0343u | 6.0343u | 6.7445u |
| cdtot | 8.8221f | 4.5194f | 4.5194f | 4.4501f | 4.4501f | 1.9739f |
| cgtot | 78.0770f | 39.0444f | 39.0444f | 38.4685f | 38.4685f | 13.7184f |
| cstot | 88.1423f | 44.1928f | 44.1928f | 40.8753f | 40.8753f | 14.7618f |
| cbtot | 36.2608f | 18.3605f | 18.3605f | 13.7364f | 13.7364f | 6.2276f |
| cgs | 69.2125f | 34.5474f | 34.5474f | 34.8173f | 34.8173f | 12.1003f |
| cgd | 3.2397f | 1.6235f | 1.6235f | 1.7042f | 1.7042f | 535.0119a |

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m7 | 0:m8 | 0:m9 | 0:mopb | 0:mop1 | 0:mop2 |
| model | 0:n_18.1 | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | 2.7177u | 2.7165u | 2.7165u | -5.2285u | -2.6137u | -2.6148u |
| ibs | -9.571e-22 | -9.567e-22 | -9.567e-22 | 7.409e-22 | 75.3944a | 75.3944a |
| ibd | -109.9616a | -216.6669a | -216.6669a | 136.0791a | 426.1924a | 425.2184a |
| vgs | 461.2226m | 456.7414m | 456.7414m | -600.0000m | -662.6264m | -662.6730m |
| vds | 456.7414m | 899.9534m | 899.9534m | -237.3736m | -1.1045 | -1.1014 |
| vbs | 0. | 0. | 0. | 0. | 237.3736m | 237.3736m |
| vth | 341.0607m | 338.3578m | 338.3578m | -452.5666m | -517.2879m | -517.2879m |
| vdsat | 128.8751m | 127.6722m | 127.6722m | -155.1718m | -159.0606m | -159.0961m |
| vod | 120.1619m | 118.3836m | 118.3836m | -147.4334m | -145.3385m | -145.3852m |
| beta | 331.8815u | 331.7714u | 331.7714u | 456.8398u | 215.6341u | 215.6314u |
| gam eff | 507.4460m | 507.4460m | 507.4460m | 557.0846m | 555.4513m | 555.4513m |
| gm | 34.5070u | 34.6570u | 34.6570u | 56.2002u | 28.4425u | 28.4487u |
| gds | 375.3257n | 333.8875n | 333.8875n | 1.1092u | 68.6920n | 68.8280n |
| gmb | 6.7445u | 6.7110u | 6.7110u | 16.6275u | 7.6193u | 7.6211u |
| cdtot | 1.9739f | 1.8137f | 1.8137f | 11.7121f | 4.2706f | 4.2721f |
| cgtot | 13.7184f | 13.6961f | 13.6961f | 78.8862f | 38.7419f | 38.7424f |
| cstot | 14.7618f | 14.7422f | 14.7422f | 87.8622f | 42.9367f | 42.9373f |
| cbtot | 6.2276f | 6.0866f | 6.0866f | 37.6749f | 16.5340f | 16.5354f |
| cgs | 12.1003f | 12.0589f | 12.0589f | 69.5580f | 34.5338f | 34.5344f |
| cgd | 535.0119a | 527.6921a | 527.6921a | 3.9238f | 1.6216f | 1.6217f |

| subckt | | |
|---|---|---|
| element | 0:mop3 | 0:mop4 |
| model | 0:n_18.1 | 0:n_18.1 |
| region | Saturation | Saturation |
| id | 2.6137u | 2.6148u |
| ibs | -9.204e-22 | -9.208e-22 |
| ibd | -110.3022a | -111.0405a |
| vgs | 458.1560m | 458.1560m |
| vds | 458.1560m | 461.2226m |
| vbs | 0. | 0. |
| vth | 341.0521m | 341.0334m |
| vdsat | 126.8075m | 126.8202m |
| vod | 117.1040m | 117.1227m |
| beta | 331.8342u | 331.8340u |
| gam eff | 507.4460m | 507.4460m |
| gm | 33.6930u | 33.7038u |
| gds | 364.1120n | 363.4426n |
| gmb | 6.5914u | 6.5930u |
| cdtot | 1.9724f | 1.9708f |
| cgtot | 13.7051f | 13.7048f |
| cstot | 14.7443f | 14.7445f |
| cbtot | 6.2287f | 6.2275f |
| cgs | 12.0827f | 12.0824f |
| cgd | 534.7048a | 534.5367a |

SS

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m1 | 0:m2 | 0:m3 | 0:m4 | 0:m5 | 0:m6 |
| model | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | -1.9086u | -917.5771n | -917.5771n | -954.3222n | -954.3222n | 954.3229n |
| ibs | 2.706e-22 | 1.440e-22 | 1.440e-22 | 298.8210a | 298.8210a | -3.404e-22 |
| ibd | 540.9710a | 283.9459a | 283.9458a | 417.2130a | 417.2130a | -113.0063a |
| vgs | -600.0000m | -600.0000m | -600.0000m | -852.8262m | -852.8262m | 483.7665m |
| vds | -947.1738m | -900.0249m | -900.0248m | -375.2687m | -375.2687m | 477.5575m |
| vbs | 0. | 0. | 0. | 947.1738m | 947.1738m | 0. |
| vth | -516.8058m | -519.0340m | -519.0340m | -761.6547m | -761.6547m | 411.3252m |
| vdsat | -108.5606m | -108.1892m | -108.1892m | -124.0187m | -124.0187m | 95.7365m |
| vod | -83.1942m | -80.9660m | -80.9660m | -91.1715m | -91.1715m | 72.4413m |
| beta | 374.0019u | 183.8773u | 183.8773u | 154.4515u | 154.4515u | 236.2389u |
| gam eff | 557.0847m | 557.0847m | 557.0847m | 551.3866m | 551.3866m | 507.4460m |
| gm | 27.9055u | 13.4973u | 13.4973u | 13.4185u | 13.4185u | 15.3168u |
| gds | 55.6787n | 27.2558n | 27.2558n | 47.9695n | 47.9695n | 142.6057n |
| gmb | 8.6861u | 4.1962u | 4.1962u | 3.0619u | 3.0619u | 3.2659u |
| cdtot | 9.8193f | 5.0136f | 5.0136f | 4.7987f | 4.7987f | 2.1542f |
| cgtot | 75.1469f | 37.2892f | 37.2892f | 37.3089f | 37.3089f | 13.8759f |
| cstot | 86.5844f | 43.0544f | 43.0544f | 40.6094f | 40.6094f | 15.2653f |
| cbtot | 41.2912f | 20.8276f | 20.8276f | 15.7215f | 15.7215f | 7.2832f |
| cgs | 65.1226f | 32.1936f | 32.1936f | 33.4699f | 33.4699f | 12.0717f |
| cgd | 2.8418f | 1.4178f | 1.4178f | 1.4531f | 1.4531f | 453.0729a |

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m7 | 0:m8 | 0:m9 | 0:mopb | 0:mop1 | 0:mop2 |
| model | 0:n_18.1 | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | 954.3229n | 917.5771n | 917.5771n | -1.8480u | -923.8382n | -924.1231n |
| ibs | -3.404e-22 | -3.273e-22 | -3.273e-22 | 2.620e-22 | 73.0197a | 73.0197a |
| ibd | -113.0063a | -212.9649a | -212.9649a | 132.1910a | 415.9014a | 415.2542a |
| vgs | 483.7665m | 477.5575m | 477.5575m | -600.0000m | -668.5495m | -668.5744m |
| vds | 477.5575m | 899.9751m | 899.9752m | -231.4505m | -1.0868 | -1.0848 |
| vbs | 0. | 0. | 0. | 0. | 231.4505m | 231.4505m |
| vth | 411.3252m | 408.9752m | 408.9752m | -516.8058m | -586.4621m | -586.4621m |
| vdsat | 95.7365m | 93.4848m | 93.4848m | -108.5581m | -112.0538m | -112.0700m |
| vod | 72.4413m | 68.5823m | 68.5823m | -83.1942m | -82.0875m | -82.1123m |
| beta | 236.2389u | 236.1722u | 236.1722u | 374.0022u | 175.3463u | 175.3453u |
| gam eff | 507.4460m | 507.4460m | 507.4460m | 557.0847m | 555.4899m | 555.4899m |
| gm | 15.3168u | 14.9391u | 14.9391u | 26.9637u | 13.5032u | 13.5059u |
| gds | 142.6057n | 130.8503n | 130.8503n | 230.0714n | 24.6765n | 24.7029n |
| gmb | 3.2659u | 3.1623u | 3.1623u | 8.3894u | 3.8081u | 3.8089u |
| cdtot | 2.1542f | 1.9840f | 1.9840f | 12.0540f | 4.7217f | 4.7229f |
| cgtot | 13.8759f | 13.7742f | 13.7742f | 75.5839f | 37.1438f | 37.1453f |
| cstot | 15.2653f | 15.1295f | 15.1295f | 86.3390f | 42.0394f | 42.0415f |
| cbtot | 7.2832f | 7.1224f | 7.1224f | 42.9679f | 18.8188f | 18.8201f |
| cgs | 12.0717f | 11.9283f | 11.9283f | 65.4213f | 32.4638f | 32.4657f |
| cgd | 453.0729a | 450.2457a | 450.2457a | 3.1107f | 1.4170f | 1.4170f |

| subckt | | |
|---|---|---|
| element | 0:mop3 | 0:mop4 |
| model | 0:n_18.1 | 0:n_18.1 |
| region | Saturation | Saturation |
| id | 923.8396n | 924.1245n |
| ibs | -3.295e-22 | -3.296e-22 |
| ibd | -113.9901a | -114.4756a |
| vgs | 481.7149m | 481.7149m |
| vds | 481.7149m | 483.7665m |
| vbs | 0. | 0. |
| vth | 411.3021m | 411.2907m |
| vdsat | 94.5486m | 94.5553m |
| vod | 70.4128m | 70.4243m |
| beta | 236.2235u | 236.2234u |
| gam eff | 507.4460m | 507.4460m |
| gm | 14.9716u | 14.9751u |
| gds | 138.8877n | 138.8268n |
| gmb | 3.1940u | 3.1946u |
| cdtot | 2.1517f | 2.1507f |
| cgtot | 13.8285f | 13.8287f |
| cstot | 15.2012f | 15.2016f |
| cbtot | 7.2816f | 7.2806f |
| cgs | 12.0124f | 12.0125f |
| cgd | 453.1123a | 453.0641a |

saturation of all transistors when input common mode is 1V:

TT

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m1 | 0:m2 | 0:m3 | 0:m4 | 0:m5 | 0:m6 |
| model | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | -3.0740u | -1.6139u | -1.6139u | -1.5370u | -1.5370u | 1.5370u |
| ibs | 4.357e-22 | 2.531e-22 | 2.531e-22 | 50.0330a | 50.0330a | -5.448e-22 |
| ibd | 90.4206a | 205.0258a | 205.0258a | 424.2738a | 424.2738a | -109.8365a |
| vgs | -600.0000m | -600.0000m | -600.0000m | -642.0206m | -642.0206m | 461.3359m |
| vds | -157.9794m | -899.9756m | -899.9756m | -1.1817 | -1.1817 | 460.3463m |
| vbs | 0. | 0. | 0. | 157.9794m | 157.9794m | 0. |
| vth | -488.0098m | -488.6972m | -488.6972m | -534.3279m | -534.3279m | 375.2334m |
| vdsat | -128.6107m | -129.2682m | -129.2682m | -129.3241m | -129.3241m | 105.8748m |
| vod | -111.9902m | -111.3028m | -111.3028m | -107.6927m | -107.6927m | 86.1025m |
| beta | 424.7955u | 209.6698u | 209.6698u | 203.0990u | 203.0990u | 301.9374u |
| gam eff | 557.0847m | 557.0847m | 557.0847m | 555.9770m | 555.9770m | 507.4460m |
| gm | 38.1668u | 20.6658u | 20.6658u | 19.9603u | 19.9603u | 23.0848u |
| gds | 2.3036u | 49.7524n | 49.7524n | 40.9664n | 40.9664n | 236.3952n |
| gmb | 11.6537u | 6.2893u | 6.2893u | 5.6724u | 5.6724u | 4.7040u |
| cdtot | 14.4011f | 4.7514f | 4.7514f | 4.4747f | 4.4747f | 2.0677f |
| cgtot | 75.9578f | 37.1086f | 37.1086f | 36.8465f | 36.8465f | 12.9615f |
| cstot | 84.8113f | 42.6675f | 42.6675f | 41.7011f | 41.7011f | 14.1695f |
| cbtot | 39.9320f | 19.1978f | 19.1978f | 17.7771f | 17.7771f | 6.5225f |
| cgs | 65.9361f | 32.5313f | 32.5313f | 32.4699f | 32.4699f | 11.3283f |
| cgd | 4.4619f | 1.5092f | 1.5092f | 1.5077f | 1.5077f | 495.1766a |

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m7 | 0:m8 | 0:m9 | 0:mopb | 0:mop1 | 0:mop2 |
| model | 0:n_18.1 | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | 1.5370u | 1.6139u | 1.6139u | -3.1558u | -1.5781u | -1.5777u |
| ibs | -5.448e-22 | -5.721e-22 | -5.721e-22 | 4.473e-22 | 74.2285a | 74.2285a |
| ibd | -109.8365a | -214.7421a | -214.7421a | 134.1477a | 423.4103a | 423.9604a |
| vgs | 461.3359m | 460.3463m | 460.3463m | -600.0000m | -665.6228m | -665.5984m |
| vds | 460.3463m | 900.0244m | 900.0244m | -234.3772m | -1.1026 | -1.1043 |
| vbs | 0. | 0. | 0. | 0. | 234.3772m | 234.3772m |
| vth | 375.2334m | 372.5645m | 372.5645m | -488.0098m | -555.2321m | -555.2321m |
| vdsat | 105.8748m | 106.9270m | 106.9270m | -128.6111m | -132.2813m | -132.2640m |
| vod | 86.1025m | 87.7818m | 87.7818m | -111.9902m | -110.3906m | -110.3663m |
| beta | 301.9374u | 301.8915u | 301.8915u | 424.7954u | 199.9309u | 199.9321u |
| gam eff | 507.4460m | 507.4460m | 507.4460m | 557.0847m | 555.4708m | 555.4708m |
| gm | 23.0848u | 23.9341u | 23.9341u | 40.2419u | 20.2307u | 20.2276u |
| gds | 236.3952n | 225.4340n | 225.4340n | 401.3445n | 43.0893n | 43.0462n |
| gmb | 4.7040u | 4.8293u | 4.8293u | 12.2578u | 5.5827u | 5.5818u |
| cdtot | 2.0677f | 1.9014f | 1.9014f | 11.6713f | 4.4769f | 4.4759f |
| cgtot | 12.9615f | 12.9716f | 12.9716f | 74.9340f | 36.8528f | 36.8522f |
| cstot | 14.1695f | 14.1886f | 14.1886f | 85.0337f | 41.4714f | 41.4705f |
| cbtot | 6.5225f | 6.3666f | 6.3666f | 39.5072f | 17.3111f | 17.3102f |
| cgs | 11.3283f | 11.3264f | 11.3264f | 65.6642f | 32.5955f | 32.5946f |
| cgd | 495.1766a | 490.7837a | 490.7837a | 3.4158f | 1.5080f | 1.5080f |

| subckt | | |
|---|---|---|
| element | 0:mop3 | 0:mop4 |
| model | 0:n_18.1 | 0:n_18.1 |
| region | Saturation | Saturation |
| id | 1.5781u | 1.5777u |
| ibs | -5.594e-22 | -5.593e-22 |
| ibd | -110.4870a | -110.0726a |
| vgs | 463.0727m | 463.0727m |
| vds | 463.0727m | 461.3359m |
| vbs | 0. | 0. |
| vth | 375.2169m | 375.2274m |
| vdsat | 106.9730m | 106.9664m |
| vod | 87.8559m | 87.8453m |
| beta | 301.9575u | 301.9577u |
| gam eff | 507.4460m | 507.4460m |
| gm | 23.4973u | 23.4926u |
| gds | 240.8474n | 241.0110n |
| gmb | 4.7853u | 4.7845u |
| cdtot | 2.0666f | 2.0675f |
| cgtot | 12.9835f | 12.9835f |
| cstot | 14.1993f | 14.1991f |
| cbtot | 6.5206f | 6.5214f |
| cgs | 11.3560f | 11.3560f |
| cgd | 495.0770a | 495.1355a |

FF

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m1 | 0:m2 | 0:m3 | 0:m4 | 0:m5 | 0:m6 |
| model | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | -5.0252u | -2.7165u | -2.7165u | -2.5126u | -2.5126u | 2.5126u |
| ibs | 7.121e-22 | 4.258e-22 | 4.258e-22 | 51.3591a | 51.3591a | -8.848e-22 |
| ibd | 92.6975a | 285.8404a | 285.8404a | 426.6421a | 426.6421a | -109.9614a |
| vgs | -600.0000m | -600.0000m | -600.0000m | -638.3001m | -638.3001m | 455.1350m |
| vds | -161.6999m | -899.9535m | -899.9535m | -1.1816 | -1.1816 | 456.7403m |
| vbs | 0. | 0. | 0. | 161.6999m | 161.6999m | 0. |
| vth | -452.5665m | -452.3564m | -452.3564m | -497.3512m | -497.3512m | 341.0607m |
| vdsat | -155.1715m | -156.5774m | -156.5774m | -154.5559m | -154.5559m | 124.7695m |
| vod | -147.4335m | -147.6436m | -147.6436m | -140.9489m | -140.9489m | 114.0743m |
| beta | 456.8399u | 226.1769u | 226.1769u | 219.1337u | 219.1337u | 331.7875u |
| gam eff | 557.0846m | 557.0846m | 557.0846m | 555.9519m | 555.9519m | 507.4460m |
| gm | 51.2653u | 29.3681u | 29.3681u | 27.9250u | 27.9250u | 32.8820u |
| gds | 5.8561u | 81.8238n | 81.8238n | 64.1695n | 64.1695n | 353.8471n |
| gmb | 15.2551u | 8.6828u | 8.6828u | 7.6961u | 7.6961u | 6.4390u |
| cdtot | 16.3487f | 4.5195f | 4.5195f | 4.2689f | 4.2689f | 1.9724f |
| cgtot | 80.5044f | 39.0444f | 39.0444f | 38.7748f | 38.7748f | 13.6906f |
| cstot | 87.7065f | 44.1928f | 44.1928f | 43.2171f | 43.2171f | 14.7249f |
| cbtot | 38.1590f | 18.3605f | 18.3605f | 16.9843f | 16.9843f | 6.2309f |
| cgs | 69.7423f | 34.5474f | 34.5474f | 34.4638f | 34.4638f | 12.0636f |
| cgd | 5.7983f | 1.6235f | 1.6235f | 1.6212f | 1.6212f | 534.5755a |

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m7 | 0:m8 | 0:m9 | 0:mopb | 0:mop1 | 0:mop2 |
| model | 0:n_18.1 | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | 2.5126u | 2.7165u | 2.7165u | -5.2284u | -2.6148u | -2.6137u |
| ibs | -8.848e-22 | -9.566e-22 | -9.566e-22 | 7.409e-22 | 75.3847a | 75.3847a |
| ibd | -109.9614a | -216.6893a | -216.6893a | 136.0617a | 426.1822a | 427.1520a |
| vgs | 455.1350m | 456.7403m | 456.7403m | -600.0000m | -662.6568m | -662.6103m |
| vds | 456.7403m | 900.0465m | 900.0465m | -237.3432m | -1.1045 | -1.1075 |
| vbs | 0. | 0. | 0. | 0. | 237.3432m | 237.3432m |
| vth | 341.0607m | 338.3572m | 338.3572m | -452.5666m | -517.2800m | -517.2800m |
| vdsat | 124.7695m | 127.6718m | 127.6718m | -155.1718m | -159.0893m | -159.0539m |
| vod | 114.0743m | 118.3831m | 118.3831m | -147.4334m | -145.3769m | -145.3304m |
| beta | 331.7875u | 331.7714u | 331.7714u | 456.8398u | 215.6331u | 215.6359u |
| gam eff | 507.4460m | 507.4460m | 507.4460m | 557.0846m | 555.4515m | 555.4515m |
| gm | 32.8820u | 34.6570u | 34.6570u | 56.1995u | 28.4494u | 28.4432u |
| gds | 353.8471n | 333.8842n | 333.8842n | 1.1097u | 68.7179n | 68.5832n |
| gmb | 6.4390u | 6.7110u | 6.7110u | 16.6273u | 7.6213u | 7.6196u |
| cdtot | 1.9724f | 1.8137f | 1.8137f | 11.7129f | 4.2706f | 4.2691f |
| cgtot | 13.6906f | 13.6961f | 13.6961f | 78.8865f | 38.7423f | 38.7418f |
| cstot | 14.7249f | 14.7422f | 14.7422f | 87.8622f | 42.9373f | 42.9368f |
| cbtot | 6.2309f | 6.0866f | 6.0866f | 37.6750f | 16.5342f | 16.5328f |
| cgs | 12.0636f | 12.0589f | 12.0589f | 69.5581f | 34.5343f | 34.5336f |
| cgd | 534.5755a | 527.6918a | 527.6918a | 3.9241f | 1.6216f | 1.6216f |

| subckt | | |
|---|---|---|
| element | 0:mop3 | 0:mop4 |
| model | 0:n_18.1 | 0:n_18.1 |
| region | Saturation | Saturation |
| id | 2.6148u | 2.6137u |
| ibs | -9.208e-22 | -9.204e-22 |
| ibd | -110.3100a | -109.5749a |
| vgs | 458.1882m | 458.1882m |
| vds | 458.1882m | 455.1350m |
| vbs | 0. | 0. |
| vth | 341.0519m | 341.0705m |
| vdsat | 126.8294m | 126.8168m |
| vod | 117.1364m | 117.1178m |
| beta | 331.8347u | 331.8350u |
| gam eff | 507.4460m | 507.4460m |
| gm | 33.7017u | 33.6909u |
| gds | 364.2183n | 364.9038n |
| gmb | 6.5931u | 6.5914u |
| cdtot | 1.9724f | 1.9740f |
| cgtot | 13.7052f | 13.7054f |
| cstot | 14.7445f | 14.7444f |
| cbtot | 6.2287f | 6.2299f |
| cgs | 12.0828f | 12.0831f |
| cgd | 534.7052a | 534.8774a |

SS

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m1 | 0:m2 | 0:m3 | 0:m4 | 0:m5 | 0:m6 |
| model | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | -1.8128u | -917.5760n | -917.5760n | -906.4057n | -906.4057n | 906.4072n |
| ibs | 2.570e-22 | 1.440e-22 | 1.440e-22 | 48.8460a | 48.8460a | -3.233e-22 |
| ibd | 88.4280a | 283.9336a | 283.9336a | 417.2132a | 417.2132a | -113.0062a |
| vgs | -600.0000m | -600.0000m | -600.0000m | -645.1730m | -645.1730m | 480.5812m |
| vds | -154.8270m | -899.9861m | -899.9861m | -1.1676 | -1.1676 | 477.5571m |
| vbs | 0. | 0. | 0. | 154.8270m | 154.8270m | 0. |
| vth | -516.8058m | -519.0340m | -519.0340m | -564.9338m | -564.9338m | 411.3252m |
| vdsat | -108.5578m | -108.1892m | -108.1892m | -109.9337m | -109.9337m | 93.8753m |
| vod | -83.1942m | -80.9660m | -80.9660m | -80.2393m | -80.2393m | 69.2560m |
| beta | 374.0022u | 183.8773u | 183.8773u | 178.0915u | 178.0915u | 236.2154u |
| gam eff | 557.0847m | 557.0847m | 557.0847m | 555.9983m | 555.9983m | 507.4460m |
| gm | 26.0677u | 13.4973u | 13.4973u | 13.3568u | 13.3568u | 14.7707u |
| gds | 944.9822n | 27.2563n | 27.2563n | 23.7162n | 23.7162n | 137.0513n |
| gmb | 8.1196u | 4.1962u | 4.1962u | 3.8816u | 3.8816u | 3.1525u |
| cdtot | 13.9233f | 5.0136f | 5.0136f | 4.7187f | 4.7187f | 2.1537f |
| cgtot | 76.3273f | 37.2892f | 37.2892f | 37.0959f | 37.0959f | 13.8005f |
| cstot | 86.1004f | 43.0544f | 43.0544f | 42.2063f | 42.2063f | 15.1627f |
| cbtot | 43.3755f | 20.8276f | 20.8276f | 19.3204f | 19.3204f | 7.2837f |
| cgs | 65.7153f | 32.1936f | 32.1936f | 32.2655f | 32.2655f | 11.9775f |
| cgd | 3.7821f | 1.4178f | 1.4178f | 1.4167f | 1.4167f | 453.2983a |

| subckt | | | | | | |
|---|---|---|---|---|---|---|
| element | 0:m7 | 0:m8 | 0:m9 | 0:mopb | 0:mop1 | 0:mop2 |
| model | 0:n_18.1 | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | 906.4072n | 917.5760n | 917.5760n | -1.8480u | -924.0589n | -923.8994n |
| ibs | -3.233e-22 | -3.273e-22 | -3.273e-22 | 2.620e-22 | 73.0157a | 73.0157a |
| ibd | -113.0062a | -212.9741a | -212.9741a | 132.1837a | 415.8968a | 416.2591a |
| vgs | 480.5812m | 477.5571m | 477.5571m | -600.0000m | -668.5623m | -668.5484m |
| vds | 477.5571m | 900.0139m | 900.0139m | -231.4377m | -1.0868 | -1.0880 |
| vbs | 0. | 0. | 0. | 0. | 231.4377m | 231.4377m |
| vth | 411.3252m | 408.9750m | 408.9750m | -516.8058m | -586.4585m | -586.4585m |
| vdsat | 93.8753m | 93.4847m | 93.4847m | -108.5581m | -112.0642m | -112.0552m |
| vod | 69.2560m | 68.5821m | 68.5821m | -83.1942m | -82.1038m | -82.0898m |
| beta | 236.2154u | 236.1722u | 236.1722u | 374.0022u | 175.3461u | 175.3466u |
| gam eff | 507.4460m | 507.4460m | 507.4460m | 557.0847m | 555.4900m | 555.4900m |
| gm | 14.7707u | 14.9391u | 14.9391u | 26.9637u | 13.5054u | 13.5039u |
| gds | 137.0513n | 130.8499n | 130.8499n | 230.1047n | 24.6817n | 24.6669n |
| gmb | 3.1525u | 3.1623u | 3.1623u | 8.3894u | 3.8087u | 3.8083u |
| cdtot | 2.1537f | 1.9840f | 1.9840f | 12.0542f | 4.7217f | 4.7210f |
| cgtot | 13.8005f | 13.7742f | 13.7742f | 75.5839f | 37.1448f | 37.1440f |
| cstot | 15.1627f | 15.1295f | 15.1295f | 86.3389f | 42.0408f | 42.0397f |
| cbtot | 7.2837f | 7.1223f | 7.1223f | 42.9680f | 18.8190f | 18.8183f |
| cgs | 11.9775f | 11.9283f | 11.9283f | 65.4213f | 32.4650f | 32.4640f |
| cgd | 453.2983a | 450.2457a | 450.2457a | 3.1107f | 1.4170f | 1.4170f |

| subckt | | |
|---|---|---|
| element | 0:mop3 | 0:mop4 |
| model | 0:n_18.1 | 0:n_18.1 |
| region | Saturation | Saturation |
| id | 924.0604n | 923.9008n |
| ibs | -3.296e-22 | -3.295e-22 |
| ibd | -113.9935a | -113.7218a |
| vgs | 481.7295m | 481.7295m |
| vds | 481.7295m | 480.5812m |
| vbs | 0. | 0. |
| vth | 411.3020m | 411.3084m |
| vdsat | 94.5572m | 94.5535m |
| vod | 70.4275m | 70.4211m |
| beta | 236.2236u | 236.2237u |
| gam eff | 507.4460m | 507.4460m |
| gm | 14.9741u | 14.9721u |
| gds | 138.9126n | 138.9473n |
| gmb | 3.1945u | 3.1942u |
| cdtot | 2.1517f | 2.1523f |
| cgtot | 13.8289f | 13.8288f |
| cstot | 15.2017f | 15.2015f |
| cbtot | 7.2816f | 7.2821f |
| cgs | 12.0128f | 12.0127f |
| cgd | 453.1109a | 453.1382a |

7. Neatly list the sizes of all transistors, capacitance of the compensation capacitors and resistance of the compensation resistors.

| Size of NMOS and PMOS in the circuit | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Width | Length | | Width | Length | | Width | Length |
| M1 | 8.4um | 1.4um | M4 | 4.2um | 1.4um | M7 | 1.4um | 1.4um |
| M2 | 4.2um | 1.4um | M5 | 4.2um | 1.4um | M8 | 1.4um | 1.4um |
| M3 | 4.2um | 1.4um | M6 | 1.4um | 1.4um | M9 | 1.4um | 1.4um |
| Size of NMOS and PMOS in the CMFB | | | | | | | | |
| | Width | Length | | Width | Length | | Width | Length |
| Mopb | 8.4um | 1.4um | Mop2 | 4.2um | 1.4um | Mop4 | 1.4um | 1.4um |
| Mop1 | 4.2um | 1.4um | Mop3 | 1.4um | 1.4um | - | | |
| Compensation capacitor | | | | | | | | |
| Cc1 | 50pF | | Cc2 | 50pF | | - | | |
| Compensation resistors | | | | | | | | |
| Rc1 | 250kΩ | | Rc2 | 250kΩ | | - | | |

**R-Sense CMFB loop**

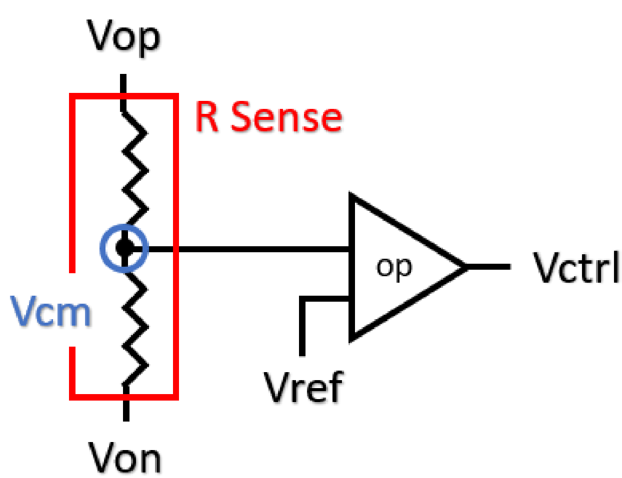



Fig. 5. R-Sense Common-Mode Feedback Loop