**Final Prjoect 108061151 陳均豪**

**Fully differential two-stage operation amplifier with Miller compensation and common-mode feedback**

(a) Please identify the constant gm, start-up, two-stage amplifier, Miller compensation, and common-mode feedback in Fig.1 1.

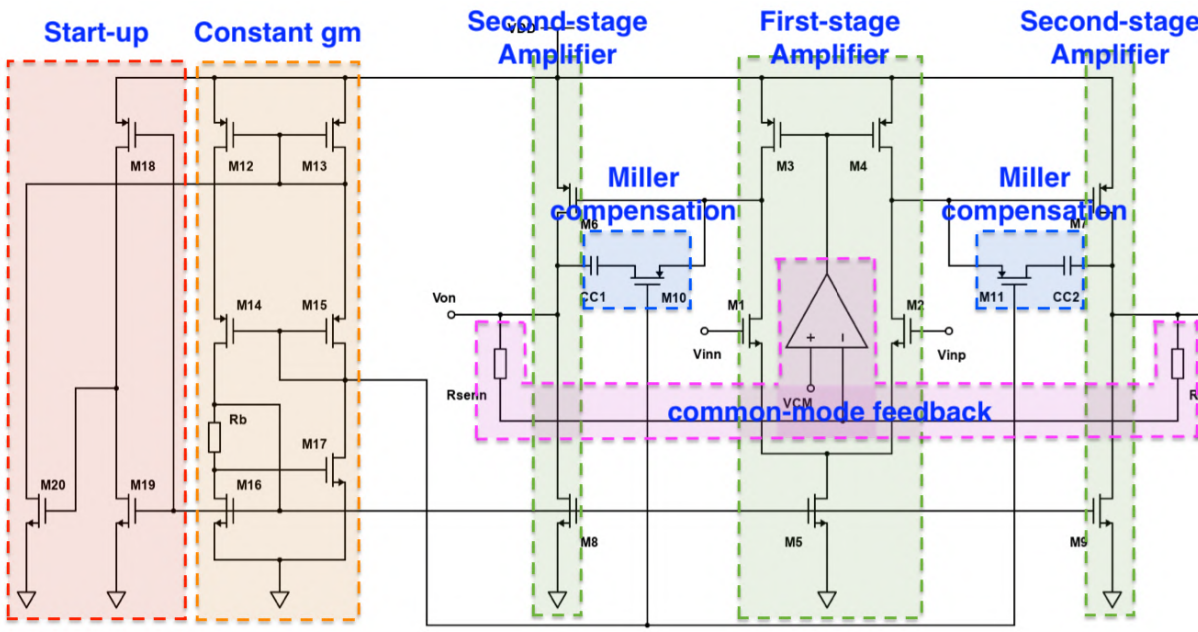


Figure 1: THD analysis for Von

(b) How the constant gm function if we choose $(W/L)_{17} = 4(W/L)_{16}$? If a target gm is given, how do you decide the bias current of the constant gm?

If we choose $(W/L)_{17} = 4(W/L)_{16}$, we can derive two equation,

$$\begin{cases} I_{16} = \dfrac{1}{2}\mu_n C_{ox}\left(\dfrac{W}{L}\right)(V_{GS,M_{16}} - V_{TH})^2 & \cdots(1) \\ I_{17} = \dfrac{1}{2}\mu_n C_{ox}\left(\dfrac{4W}{L}\right)(V_{GS,M_{17}} - V_{TH})^2 & \cdots(2) \end{cases}$$

Since $M_{14}$ and $M_{15}$ is current mirror,

$$I = I_{16} = I_{17} \quad \cdots(3)$$

And that,

$$V_{GS,M_{16}} - V_{GS,M_{17}} = I \cdot R_b \quad \cdots(4)$$

We can derive a equation from (1), (2), (3),

$$V_{GS,M_{16}} - V_{TH} = 2(V_{GS,M_{17}} - V_{TH}) \quad \cdots(5)$$

By (1), (2), (4), (5), we can get,

$$\sqrt{\frac{2I}{\mu_n C_{OX}\left(\frac{W}{L}\right)}} + V_{TH,M16} = \sqrt{\frac{2I}{\mu_n C_{OX}\left(\frac{4W}{L}\right)}} + V_{TH,M17} + I \cdot R_b$$

Since the source of $M_{16}$ and $M_{17}$ both connect to ground, the body effect doesn't exist, hence I assume their threshold voltage is same, then we can get,

$$\sqrt{\frac{2I}{\mu_n C_{OX}\left(\frac{W}{L}\right)}}\left(1-\frac{1}{\sqrt{4}}\right) = I \cdot R_b$$

From this, we can get the current $I$,

$$I = \frac{2}{\mu_n C_{OX}\left(\frac{W}{L}\right)}\frac{1}{R_b^2}\left(1-\frac{1}{\sqrt{4}}\right)^2$$

And we know that,

$$g_m = \sqrt{2\mu_n C_{OX}\left(\frac{W}{L}\right) I_D} \quad \cdots (6)$$

We can finally find the relationship between $(W/L)_{17} = 4(W/L)_{16}$ and $g_m$ by inserting $I$ into (6).

$$\begin{aligned} g_m &= \sqrt{2\mu_n C_{OX}\left(\frac{W}{L}\right)\frac{2}{\mu_n C_{OX}\left(\frac{W}{L}\right)}\frac{1}{R_b^2}\left(1-\frac{1}{\sqrt{4}}\right)^2} \\ &= \frac{2}{R_b}\left(1-\frac{1}{\sqrt{4}}\right) \\ &= \frac{1}{R_b} \end{aligned}$$

So if gm is given, we can derive the $I$ immediately with,

$$I = \frac{1}{\mu_n C_{ox}\left(\frac{W}{L}\right)}\frac{1}{R_b^2}$$

(c) Why do we need a start-up circuit? Please explain the functionality of the start-up circuit. How do you design the size of the transistor to improve the power efficiency after startup?

Apply initial condition (.IC) and run the trasient analysis with Hspice to verify the functionality of the start-up circuit.

Since the initial condition in circuit is unknown, if there doesn't exist start-up circuit, it is possible hat all of the transistors carry no current when the supply is turned on. Therefore we introduce start-up circuit.

To design a more power efficiency start-up circuit, the idea is making them carry no current after start-up. Therefore, I make the aspect ratio of $M_{19}$ larger and $M_{20}$ smaller. If design properly, I expect that $M_{20}$ will get into subth region to reduce the power consumption and $V_{DS,M19}$ is small which make itself get into triode region carrying as small current as possible.

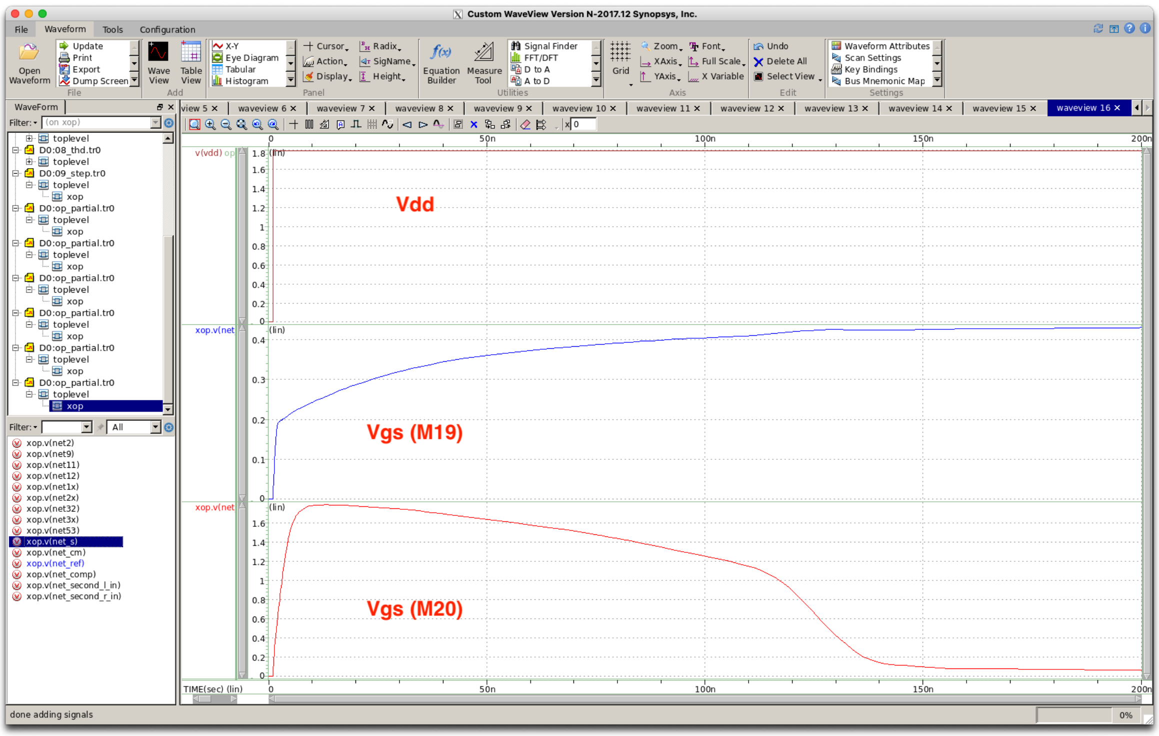


Figure 2: Transient analysis to verify the functionality of the start-up circuit
Upper part: Vertical axis: Vdd(V) Horizontal axis: time(s)
Middle part: Vertical axis: $V_{gs,M19}$(V) Horizontal axis: time(s)
Bottom part: Vertical axis: $V_{gs,M20} = V_{ds,M19}$(V) Horizontal axis: time(s)

From figure, we can find that at the time that supply turn on $M_{20}$ turn on immediately, force the current run through $M_{13}$. Then since $M_{12}$ and $M_{13}$ is current mirror, this step will make whole constant gm part active. As long as the constant gm part active, $V_{DS,M19}$ start to drop, gradually close $M_{20}$. At the time $125ns$, $M_{20}$ get into triode region and eventually shut down(get into subth region). Finally, $V_{GS,M19}$ stable at about $440.8622mV$ and $V_{GS,M19}$ stable at about $46.7429mV$. Start-up Complete!

(d) A simplified two-stage amplifier is shown in Fig. 3, the Miller effect can decrease -3dB bandwidth while moving the non-dominant pole up in frequency (pole splitting). However, the Miller compensation technique also introduces a right half-plane (RPH) zero, therefore a nulling resistor $R_z$ is added to remove the RPH zero. Apply KCL and KVL, find the DC gain, $\text{Pole}_1, \text{Pole}_2$ , unity-gain bandwidth $\omega_u$ and $\text{Zero}_1$ with the symbols are shown in Fig. 3.

Assume $R_z = 0$ first to make the analysis easier and compensate it latter. By KCL, we can derive two equation,

$$\begin{cases} g_{m1}V_{\text{in}} + \left(\dfrac{1}{R_1} + s(C_1 + C_c)\right) V_A - (sC_c)V_{\text{out}} = 0 \\ g_{m2}V_A + (sC_c)(V_{\text{out}} - V_A) + V_{\text{out}}\left(\dfrac{1}{R_2} + sC_2\right) = 0 \end{cases}$$

Solving using Cramer's rule and we can get the relationship between $V_{\text{out}}$ and $V_{\text{in}}$

$$\begin{aligned} \frac{V_{\text{out}}(s)}{V_{\text{in}}(s)} &= \frac{g_{m1}(g_{m2} - sC_c)}{\dfrac{1}{R_1R_2} + s\left(\dfrac{1}{R_2}(C_1 + C_2) + \dfrac{1}{R_1}(C_2 + C_c) + g_{m2}C_c\right) + s^2(C_1C_2 + C_cC_1 + C_cC_2)} \\ &= \frac{A_0(1 - s(C_c/g_{m2}))}{1 + s(R_1(C_1 + C_2) + R_2(C_2 + C_c) + g_{m2}R_1R_2C_c) + s^2(R_1R_2(C_1C_2 + C_cC_1 + C_cC_2))} \end{aligned} \quad \cdots (7)$$

where $A_0 = g_{m1}g_{m2}R_1R_2$ which also is DC gain.

Then we can rewrite the denominator of (7) as,

$$D(s) = \left(1 - \frac{s}{\omega_{p_1}}\right)\left(1 - \frac{s}{\omega_{p_2}}\right) = 1 - s\left(\frac{1}{\omega_{p_1}} + \frac{1}{\omega_{p_2}}\right) + \frac{s^2}{\omega_{p_1}\omega_{p_2}} \quad \cdots (8)$$

Assume the "dominant pole" condition exists, then $|\omega_{p_1}| \ll |\omega_{p_2}|$, we can make some approximation on (8),

$$D(s) \approx 1 - \frac{s}{\omega_{p_1}} + \frac{s^2}{\omega_{p_1}\omega_{p_2}}$$

Then calculate the value of $\omega_{p_1}$, $\omega_{p_2}$ and $\omega_z$ by comparing (7)

$$\frac{V_{\text{out}}(s)}{V_{\text{in}}(s)} = \frac{A_0\left(1 - \dfrac{s}{w_z}\right)}{1 - \dfrac{s}{\omega_{p_1}} + \dfrac{s^2}{\omega_{p_1}\omega_{p_2}}} = (7)$$

Then we can get,

$$\begin{cases} \omega_{p_1} = \dfrac{-1}{R_1(C_1 + C_2) + R_2(C_2 + C_c) + g_{m2}R_1R_2C_c} \approx \dfrac{-1}{g_{m2}R_1R_2C_c} \\ \\ \omega_{p_2} = \dfrac{-(R_1(C_1 + C_2) + R_2(C_2 + C_c) + g_{m2}R_1R_2C_c)}{R_1R_2(C_1C_2 + C_cC_1 + C_cC_2)} \approx \underbrace{\dfrac{-g_{m2}C_c}{C_1C_2 + C_cC_1 + C_cC_2}}_{\text{Consider } C_2 > C_c > C_1} \approx \dfrac{-g_{m2}}{C_2} \\ \\ \omega_z = \dfrac{g_{m2}}{C_c} \end{cases}$$

With $R_z \neq 0$ lead compensation,

$$\omega_z' = \frac{-1}{C_c\left(\dfrac{1}{g_{m2}} - R_z\right)}$$

By **Reference 1.**, the unity gain bandwidth can be approximate as

$$\begin{aligned}\omega_u &\cong A_0\omega_{p_1} \quad \text{where } A_0 = g_{m1}g_{m2}R_1R_2 \\ &\cong \frac{-g_{m1}g_{m2}R_1R_2}{g_{m2}R_1R_2C_c} = \frac{-g_{m1}}{C_c}\end{aligned}$$

Summary above,

$$\begin{cases} \text{DC gain} = g_{m1}g_{m2}R_1R_2 \\ \omega_{p_1} = \dfrac{-1}{g_{m2}R_1R_2C_c} \quad (\text{Pole}_1) \\ \omega_{p_2} = \dfrac{-g_{m2}}{C_2} \quad (\text{Pole}_2) \\ \omega_z = \dfrac{-1}{C_c\left(\dfrac{1}{g_{m2}} - R_z\right)} \quad (\text{Zero}_1) \\ \omega_u = \dfrac{-g_{m1}}{C_c} \quad (\text{unity-gain bandwidth}) \end{cases}$$

(e) What is the function of $M_{10}$ and $M_{11}$? How do you design the aspect ratio of $M_{10}$ and $M_{11}$?

The presence of zero is able to increase the phase shift and the speed of reducing the gain and cause the circuit to be instability. To eliminate this phenomenon, we add $M_{10}$ and $M_{11}$ with miller capacitor. Then the zero should be moved to remove the effect of the first non-dominant pole. Note: We use $M_{10}$ and $M_{11}$ in triode region to act as resistor.

Since we know that,

$$\omega_z = \frac{-1}{C_c\left(\dfrac{1}{g_{m2}} - R_z\right)} \quad (\text{Zero}_1)$$

And,

$$R_z = \frac{1}{\mu_n C_{OX}\left(\dfrac{W}{L}\right)V_{ov}}$$

So, if we want to get larger $\omega_z$ just need to increase the aspect ratio of $M_{10}$ and $M_{11}$, but when I design, if we increase the aspect ratio too much, the phase margin will drop. After trading off, I design $\dfrac{W}{L} = \dfrac{22\mu}{0.4\mu}, m = 1$.

## II. Design

| Working Item | Specification | Your Work |
|---|---|---|
| Technology | CIC pseudo 0.18$\mu m$ technology | |
| Supply Voltage | 1.8V | |
| $V_{icm}, V_{ocm}$ | 0.9V, 0.9V | |
| Supply Current | $< 3mA$ | 1.8845mA |
| Loading | 5pF @ each output node | |
| Compensation $C_{c1}, C_{c2}$ | $< 5pF$ | 4.95pF |
| **Open-loop Simulation** | | |
| DC Gain | $> 65dB$, as large as possible | $67.1714dB$ |
| Unity Gain Bandwidth $\omega_u$ | $>$ 130MHz, as large as possible | 264.0032MHz |
| Phase Margin (P.M.) | $> 65°$ | 66.775° |
| CMRR @ 10KHz | $> 90dB$ | $98.1005dB$ |
| PSRR+ @ 10KHz | $> 100dB$ | $113.4948dB$ |
| PSRR- @ 10KHz | $> 100dB$ | $113.0792dB$ |
| **CLosed-loop Simulation** | | |
| Closed-loop Gain | $> -0.1dB$ | $-9.0409mdB$ |
| S.R.+(10% ∼ 90%) | $> 35V/\mu S$ | $40.1V/\mu S$ |
| S.R.-(10% ∼ 90%) | $> 35V/\mu S$ | $42.5V/\mu S$ |
| THD @ 100KHz | $< -55dB$ | $-55.65922213dB$ |
| Settling Time + (to 0.5%) | $0.1\mu s$ | $71.6378ns$ |
| Settling Time - (to 0.5%) | $0.1\mu s$ | $56.9055ns$ |

**Table. Summary table.**

(a) Redraw the schematic of your circuit, mark each active device dimension, passive component value, node voltage, and branch current on it.

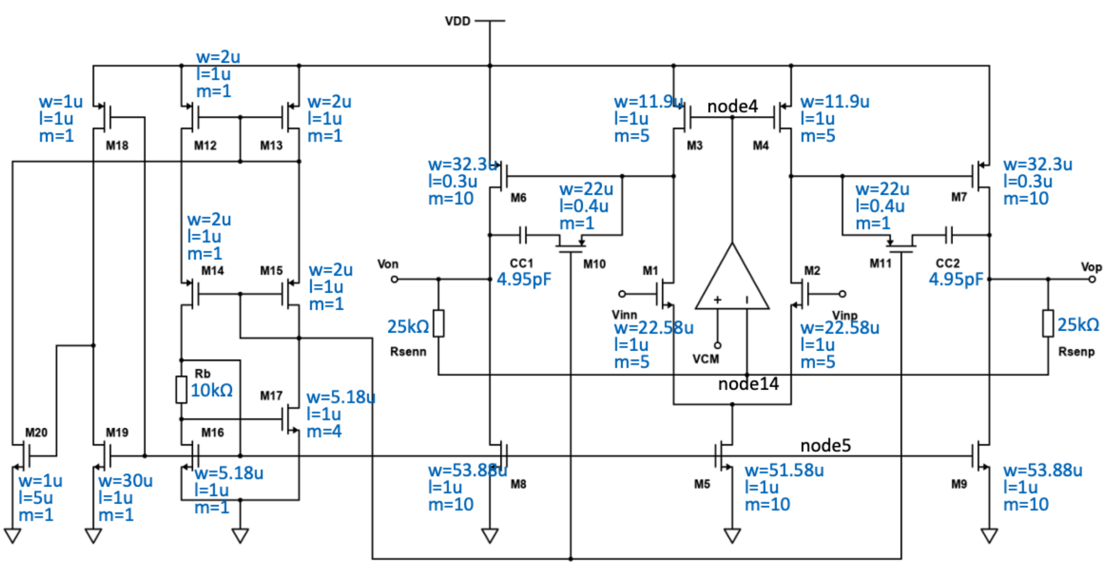


Figure 3: MOS parameters part.I

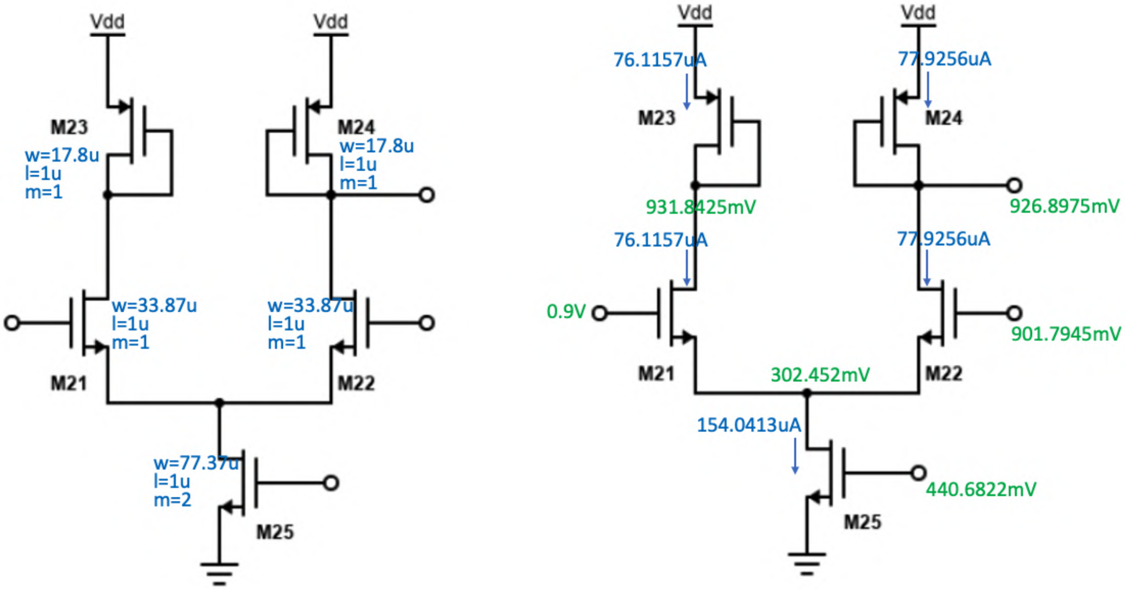


Figure 4: MOS parameters part.II

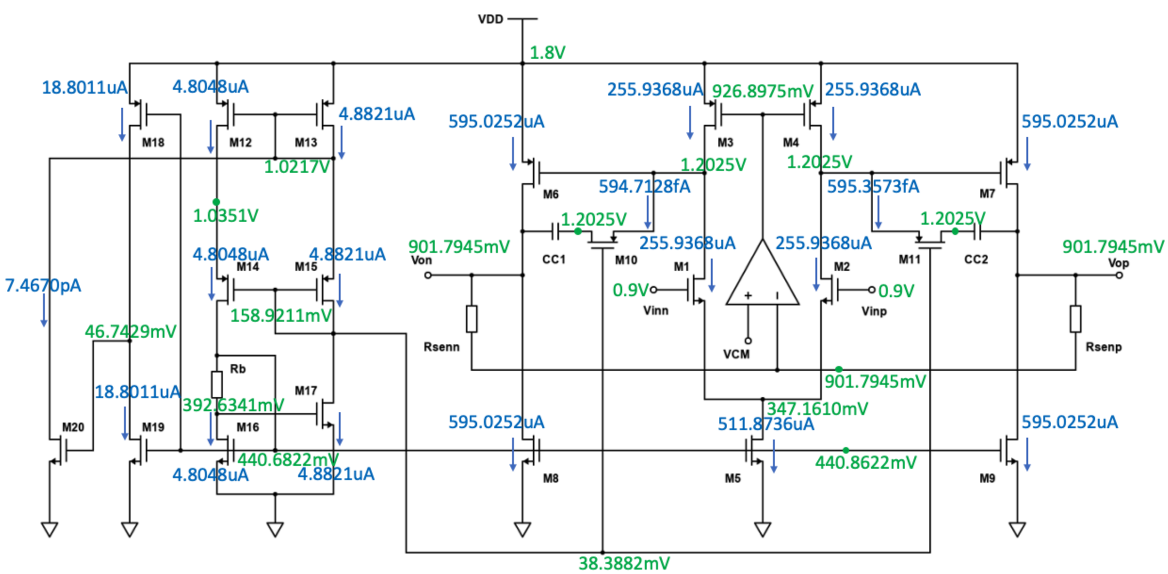


Figure 5: MOS parameters part.III

(b) Print all the small-signal parameters of each device from .op command in the report.

| subckt | xop | xop | xop | xop | xop | xop |
|---|---|---|---|---|---|---|
| element | 1:mm1 | 1:mm2 | 1:mm3 | 1:mm4 | 1:mm5 | 1:mm21 |
| model | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 | 0:n_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | 255.9368u | 255.9368u | -255.9368u | -255.9368u | 511.8736u | 76.1157u |
| ibs | -2.8904f | -2.8904f | 2.526e-20 | 2.526e-20 | -7.659e-20 | -849.5919a |
| ibd | -10.0120f | -10.0120f | 1.6867f | 1.6867f | -12.8804f | -2.2935f |
| vgs | 552.8390m | 552.8390m | -873.1025m | -873.1025m | 440.6822m | 554.8263m |
| vds | 855.3825m | 855.3825m | -597.4565m | -597.4565m | 347.1610m | 586.6688m |
| vbs | -347.1610m | -347.1610m | 0. | 0. | 0. | -345.1737m |
| vth | 448.6412m | 448.6412m | -494.6111m | -494.6111m | 385.6758m | 450.4259m |
| vdsat | 125.3580m | 125.3580m | -337.4606m | -337.4606m | 90.6945m | 125.7061m |
| vod | 104.1978m | 104.1978m | -378.4914m | -378.4914m | 55.0064m | 104.4003m |
| beta | 35.3819m | 35.3819m | 3.9755m | 3.9755m | 160.4409m | 10.6161m |
| gam eff | 516.3753m | 516.3753m | 557.0846m | 557.0846m | 507.4460m | 516.3280m |
| gm | 3.4877m | 3.4877m | 1.1932m | 1.1932m | 8.8971m | 1.0386m |
| gds | 42.9921u | 42.9921u | 17.9128u | 17.9128u | 112.6442u | 13.5374u |
| gmb | 579.4164u | 579.4164u | 377.8621u | 377.8621u | 1.8375m | 173.9770u |
| cdtot | 138.9303f | 138.9303f | 71.3296f | 71.3296f | 735.3143f | 43.2764f |
| cgtot | 758.3272f | 758.3272f | 388.9380f | 388.9380f | 3.2820p | 227.5243f |
| cstot | 822.7516f | 822.7516f | 455.6880f | 455.6880f | 3.6225p | 246.9647f |
| cbtot | 367.3700f | 367.3700f | 218.0692f | 218.0692f | 1.9711p | 111.7232f |
| cgs | 660.2272f | 660.2272f | 343.5523f | 343.5523f | 2.7593p | 198.2657f |
| cgd | 39.2098f | 39.2098f | 22.1263f | 22.1263f | 186.3213f | 11.8013f |

Figure 6: Operation part.I

| subckt | xop | xop | xop | xop | xop | xop |
|---|---|---|---|---|---|---|
| element | 1:mm22 | 1:mm23 | 1:mm24 | 1:mm25 | 1:mm6 | 1:mm7 |
| model | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Saturation |
| id | 77.9256u | -76.1157u | -77.9256u | 154.0413u | -595.0252u | -595.0252u |
| ibs | -849.5922a | 7.318e-21 | 7.492e-21 | -2.290e-20 | 5.584e-20 | 5.584e-20 |
| ibd | -2.2814f | 714.3265a | 718.3953a | -3.8169f | 13.0898f | 13.0898f |
| vgs | 556.6208m | -868.1575m | -873.1025m | 440.6822m | -597.4565m | -597.4565m |
| vds | 581.7237m | -868.1575m | -873.1025m | 345.1737m | -898.2055m | -898.2055m |
| vbs | -345.1737m | 0. | 0. | 0. | 0. | 0. |
| vth | 450.4705m | -494.5748m | -494.5748m | 385.5609m | -513.9539m | -513.9539m |
| vdsat | 126.9196m | -332.9571m | -336.8832m | 90.8745m | -127.6099m | -127.6099m |
| vod | 106.1503m | -373.5827m | -378.5277m | 55.1214m | -83.5026m | -83.5026m |
| beta | 10.6162m | 1.1959m | 1.1944m | 48.1350m | 88.7577m | 88.7577m |
| gam eff | 516.3280m | 557.0846m | 557.0846m | 507.4460m | 557.0846m | 557.0846m |
| gm | 1.0539m | 360.8018u | 364.5188u | 2.6761m | 8.4081m | 8.4081m |
| gds | 13.7868u | 3.3095u | 3.3773u | 33.9731u | 83.8989u | 83.8989u |
| gmb | 176.4910u | 114.0237u | 115.2993u | 552.7880u | 2.4990m | 2.4990m |
| cdtot | 43.3142f | 19.8724f | 19.8578f | 220.5964f | 355.6356f | 355.6356f |
| cgtot | 227.7113f | 116.2135f | 116.2106f | 984.6501f | 723.4272f | 723.4272f |
| cstot | 247.1996f | 136.2977f | 136.2983f | 1.0870p | 948.6906f | 948.6906f |
| cbtot | 111.7464f | 64.0940f | 64.0594f | 591.2404f | 731.3671f | 731.3671f |
| cgs | 198.4981f | 102.7859f | 102.8021f | 827.8736f | 555.4281f | 555.4281f |
| cgd | 11.8023f | 6.4360f | 6.4362f | 55.9077f | 115.8975f | 115.8975f |

Figure 7: Operation part.II

| subckt | xop | xop | xop | xop | xop | xop |
|---|---|---|---|---|---|---|
| element | 1:mm8 | 1:mm9 | 1:mm10 | 1:mm11 | 1:mm12 | 1:mm13 |
| model | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 | 0:p_18.1 |
| region | Saturation | Saturation | Linear | Linear | Saturation | Saturation |
| id | 595.0252u | 595.0252u | 594.7128f | 595.3573f | -4.8048u | -4.8821u |
| ibs | -8.895e-20 | -8.895e-20 | 601.4045a | 601.4045a | 6.566e-22 | 6.672e-22 |
| ibd | -34.9212f | -34.9212f | 601.4045a | 601.4045a | 65.0348a | 102.2677a |
| vgs | 440.6822m | 440.6822m | -1.1642 | -1.1642 | -778.2511m | -778.2511m |
| vds | 901.7945m | 901.7945m | 370.9786p | 371.3805p | -494.9126m | -778.2511m |
| vbs | 0. | 0. | 597.4565m | 597.4565m | 0. | 0. |
| vth | 381.4668m | 381.4668m | -663.1167m | -663.1167m | -502.1469m | -502.1469m |
| vdsat | 93.1365m | 93.1365m | -472.0165m | -472.0165m | -262.3673m | -262.3686m |
| vod | 59.2154m | 59.2154m | -501.0386m | -501.0386m | -276.1041m | -276.1041m |
| beta | 167.5594m | 167.5594m | 3.4709m | 3.4709m | 131.6082u | 131.6082u |
| gam eff | 507.4460m | 507.4460m | 553.2683m | 553.2683m | 557.0846m | 557.0846m |
| gm | 10.0907m | 10.0907m | 1.0084p | 1.0095p | 30.5959u | 31.1714u |
| gds | 106.9659u | 106.9659u | 1.6036m | 1.6036m | 358.3614n | 219.6953n |
| gmb | 2.0573m | 2.0573m | 321.6738f | 322.0224f | 9.3986u | 9.5790u |
| cdtot | 689.1711f | 689.1711f | 84.0788f | 84.0788f | 2.5747f | 2.3885f |
| cgtot | 3.4601p | 3.4601p | 74.4375f | 74.4375f | 13.0136f | 12.9872f |
| cstot | 3.8318p | 3.8318p | 92.6021f | 92.6021f | 15.3891f | 15.3976f |
| cbtot | 1.9847p | 1.9847p | 49.0398f | 49.0398f | 7.7158f | 7.5794f |
| cgs | 2.9169p | 2.9169p | 35.3755f | 35.3755f | 11.3562f | 11.3458f |
| cgd | 192.6136f | 192.6136f | 39.1573f | 39.1573f | 745.4775a | 722.5252a |

Figure 8: Operation part.III

| subckt | xop | xop | xop | xop | xop | xop | xop |
|---|---|---|---|---|---|---|---|
| element | 1:mm14 | 1:mm15 | 1:mm16 | 1:mm17 | 1:mm18 | 1:mm19 | 1:mm20 |
| model | 0:p_18.1 | 0:p_18.1 | 0:n_18.1 | 0:n_18.1 | 0:p_18.1 | 0:n_18.1 | 0:n_18.1 |
| region | Saturation | Saturation | Saturation | Saturation | Saturation | Linear | Subth |
| id | -4.8048u | -4.8821u | 4.8048u | 4.8821u | -18.8011u | 18.8011u | 7.4670p |
| ibs | 65.0361a | 102.2691a | -8.458e-22 | -8.594e-22 | 3.428e-21 | -2.853e-21 | -2.531e-27 |
| ibd | 178.6246a | 231.4892a | -171.4005a | -67.0314a | 153.6661a | -102.2892a | -146.4371a |
| vgs | -912.4532m | -983.3607m | 440.6822m | 392.6341m | -1.3593 | 440.6822m | 46.7429m |
| vds | -864.4051m | -983.3607m | 392.6341m | 38.3882m | -1.7533 | 46.7429m | 1.0217 |
| vbs | 494.9126m | 778.2511m | 0. | 0. | 0. | 0. | 0. |
| vth | -631.0408m | -694.8524m | 388.7396m | 391.4189m | -510.3566m | 388.2263m | 338.2859m |
| vdsat | -277.8949m | -288.2456m | 87.8748m | 63.7366m | -751.1921m | 89.0418m | 35.2955m |
| vod | -281.4124m | -288.5083m | 51.9427m | 1.2152m | -848.9611m | 52.4559m | -291.5430m |
| beta | 119.6995u | 114.0150u | 1.6019m | 6.3995m | 57.6098u | 9.3315m | 58.6832u |
| gam eff | 553.8606m | 552.2711m | 507.4460m | 507.4459m | 557.0844m | 507.4460m | 507.4459m |
| gm | 30.0566u | 29.8351u | 84.6632u | 91.9492u | 39.5594u | 268.4339u | 271.9087p |
| gds | 191.8508n | 172.5438n | 1.0201u | 74.9430u | 434.3584n | 258.9520u | 1.1234p |
| gmb | 7.6082u | 7.1116u | 17.4481u | 19.5392u | 13.3774u | 56.5775u | 62.5221p |
| cdtot | 2.1984f | 2.1035f | 7.3741f | 42.4301f | 1.1117f | 90.4944f | 1.3626f |
| cgtot | 12.8243f | 12.7627f | 32.6076f | 100.5480f | 6.4414f | 204.9955f | 10.1604f |
| cstot | 14.4712f | 14.1874f | 35.9684f | 97.2299f | 7.7736f | 208.3912f | 1.6980f |
| cbtot | 6.3329f | 5.8592f | 19.8492f | 82.5740f | 3.7017f | 120.5093f | 11.6663f |
| cgs | 11.3132f | 11.3485f | 27.3313f | 68.5174f | 5.7011f | 159.8389f | 389.1781a |
| cgd | 721.3162a | 720.0517a | 1.8582f | 11.7124f | 359.7971a | 28.7018f | 388.2985a |

Figure 9: Operation part.IV

(d) Simulation and Calculations

**1. Open-loop differential mode AC response**

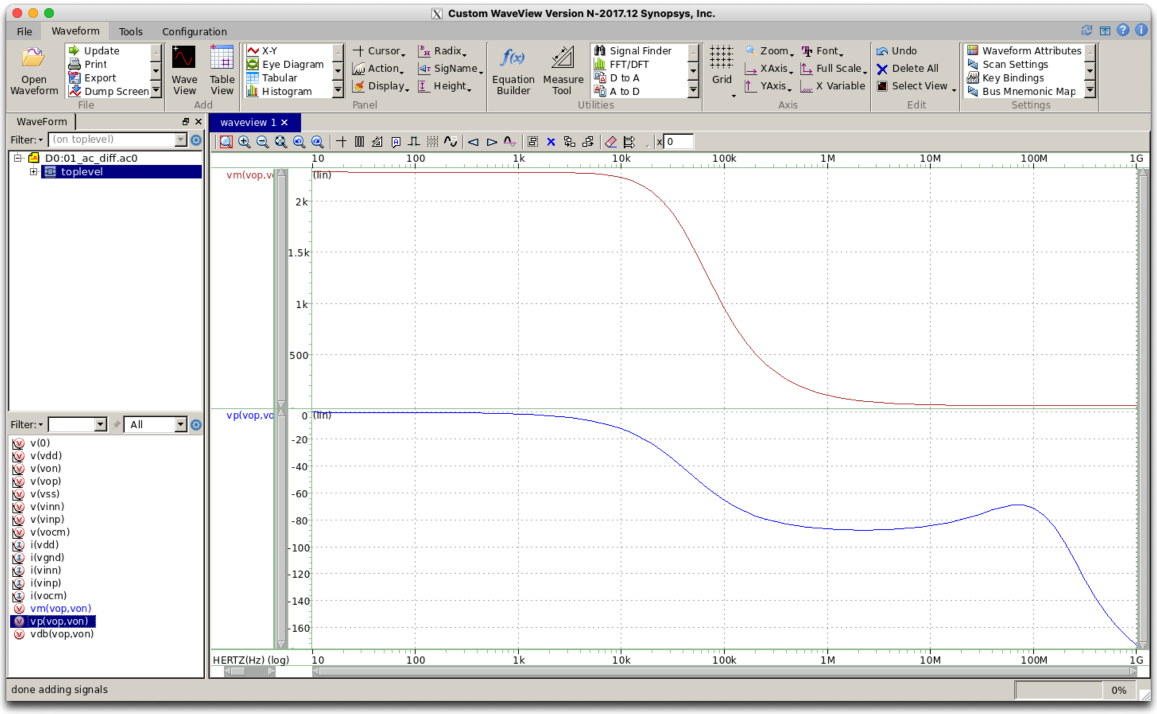


Figure 10: AC magnitude and phase responses of differential-mode gain
Upper part: Vertical axis: Vm(Vop, Von)(V) Horizontal axis: frequency(Hz)
Bottom part: Vertical axis: Phase(Vop, Von)(°) Horizontal axis: frequency(Hz)

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

      v(vop,von)/vinn                              =    -2.2833k
      input resistance at               vinn       =   1.000e+20
      output resistance at v(vop,von)              =     9.4852k
```

Figure 11: Gain and impedance

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


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

Output first 10 Poles, (total 17)
Use .option pz_num = NUM to control output number, (default:10)

      poles (rad/sec)                 poles ( hertz)
real            imag            real            imag
-288.208k       0.              -45.8698k       0.
-7.05096x       0.              -1.12220x       0.
-76.7465x       263.217x        -12.2146x       41.8922x
-76.7465x       -263.217x       -12.2146x       -41.8922x
-400.626x       0.              -63.7616x       0.
-447.507x       0.              -71.2230x       0.
-921.642x       0.              -146.684x       0.
-1.17093g       -944.924x       -186.359x       -150.389x
-1.17093g       944.924x        -186.359x       150.389x
-1.34801g       -863.513x       -214.543x       -137.432x

Output first 10 Zeros, (total 17)
Use .option pz_num = NUM to control output number, (default:10)

      zeros (rad/sec)                 zeros ( hertz)
real            imag            real            imag
-7.05099x       0.              -1.12220x       0.
-80.6943x       -267.930x       -12.8429x       -42.6425x
-80.6943x       267.930x        -12.8429x       42.6425x
-386.415x       0.              -61.4998x       0.
-402.587x       0.              -64.0737x       0.
-448.103x       0.              -71.3178x       0.
-921.649x       0.              -146.685x       0.
-1.31708g       -846.985x       -209.619x       -134.802x
-1.31708g       846.985x        -209.619x       134.802x
-1.64376g       0.              -261.613x       0.

 ***** constant factor = 730.546m
******
```

Figure 12: Poles and zeros

Dis. d-1

By (d) we derive above, we know that,

$$
\begin{cases}
R_1 = r_{o,M2}||r_{o,M4} = \dfrac{1}{42.9942\mu + 17.9128\mu} = 16418.47407 \\
R_2 = r_{o,M6}||r_{o,M8} = \dfrac{1}{83.8989\mu + 106.9659\mu} = 5239.310758 \\
C_2 = C_L = 5pF \\
\text{Gain} = g_{m1}g_{m6}(r_{o2} \parallel r_{o4})(r_{o6} \parallel r_{o8}) = 2522.574141 \\
R_z = \dfrac{1}{g_{m,M10}V_{ov,M10}} = \dfrac{1}{3.4709m \cdot (1.1642 - 663.1167m)} = 574.9736864 \\
\omega_{p_1} = \dfrac{-1}{g_{m2}R_1R_2C_c} = \dfrac{-1}{8.4081m \cdot 16418.47407 \cdot 5239.310758 \cdot 4.95p} = -44453.92523(Hz) \\
\omega_{p_2} = \dfrac{-g_{m2}}{C_2} = \dfrac{-8.4081m}{5p} = -267638135.4(Hz) \\
\omega_z = \dfrac{-1}{C_c\left(\dfrac{1}{g_{m2}} - R_z\right)} = \dfrac{-1}{4.95p \cdot (\dfrac{1}{8.4081m} - 574.9736864)} = -70503597.69(Hz)
\end{cases}
$$

**Comparison Table**

| Working Item | Simulation | Hand calculation | Error |
|---|---|---|---|
| $\omega_{p_1}$ | $-45.8698kHz$ | $-44.45392523kHz$ | $\approx -3.18\%$ |
| $\omega_{p_2}$ | $-254.7866823MHz$ | $-267.6381354MHz$ | $\approx -4.8\%$ |
| $\omega_z$ | $-71.3178MHz$ | $-70.50359769MHz$ | $\approx 1.15\%$ |

**Comment:**

The error is small enough to ignore.

By the formula we use, we can see that after compensation, the zero will be moved the right-half-plane zero into the left-half-plane zero to cancel the nondominant pole $\omega_{p2}$. But the poles seems not to move as zero does.

## 2. Open-loop differential mode DC sweep

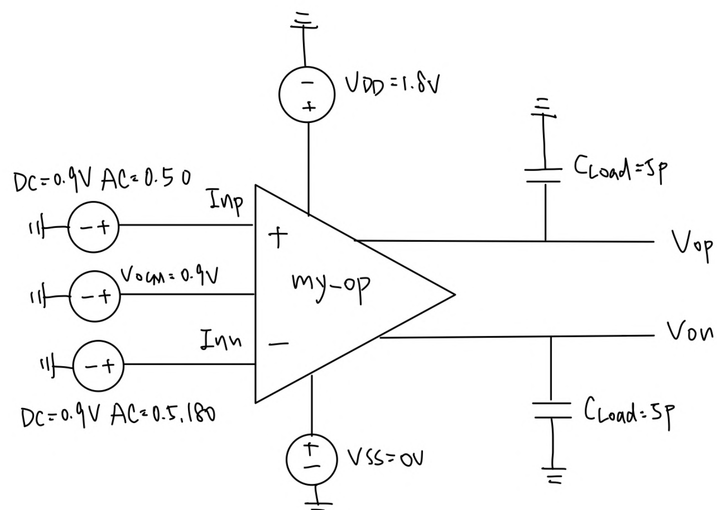


Figure 13: Test circuit schematic

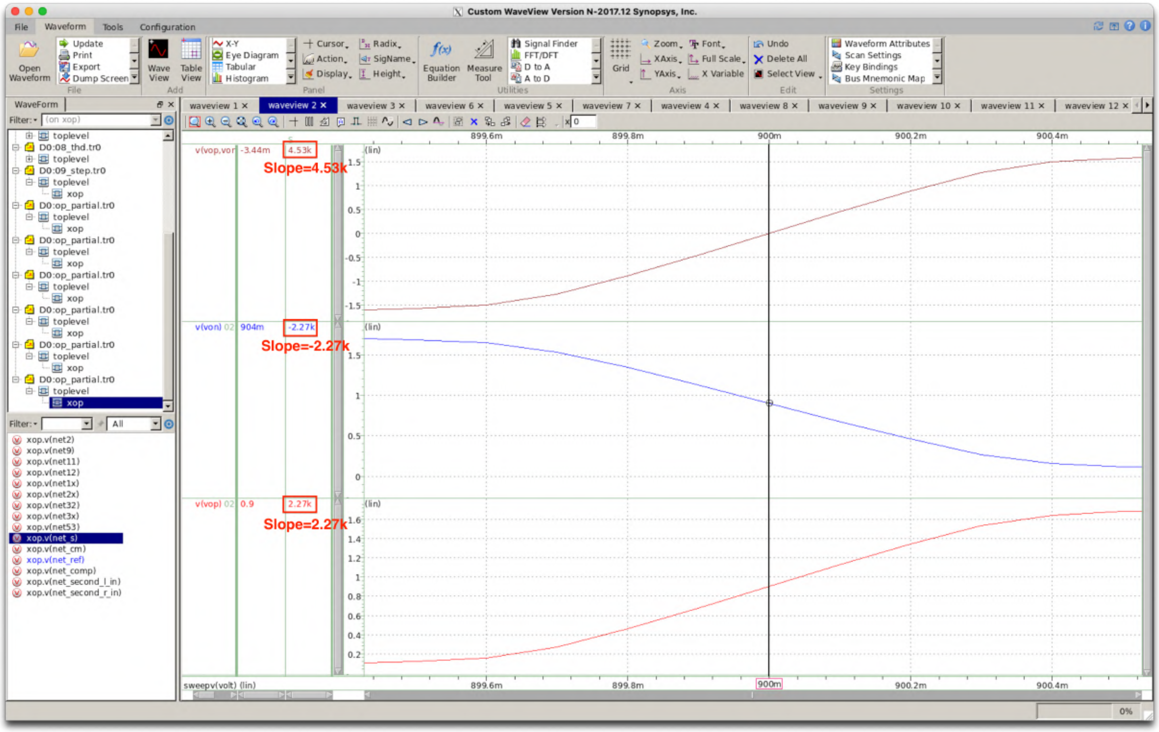


Figure 14: Differential and single-ended outputs
Upper part: Vertical axis: V(vop, von)(V) Horizontal axis: DC voltage(V)
Middle part: Vertical axis: V(von)(V) Horizontal axis: DC voltage(V)
Bottom part: Vertical axis: V(vop)(V) Horizontal axis: DC voltage(V)

Compare it with the AC response, see the below table, they are almost the same.

**Comparison Table**

| Working Item | AC | DC | Error |
|---|---|---|---|
| Gain | $2.2833k$ | $2.27k$ | $\approx -0.58\%$ |

**Comment:**

The error is small enough to ignore.

### 3. Open-loop common-mode AC response

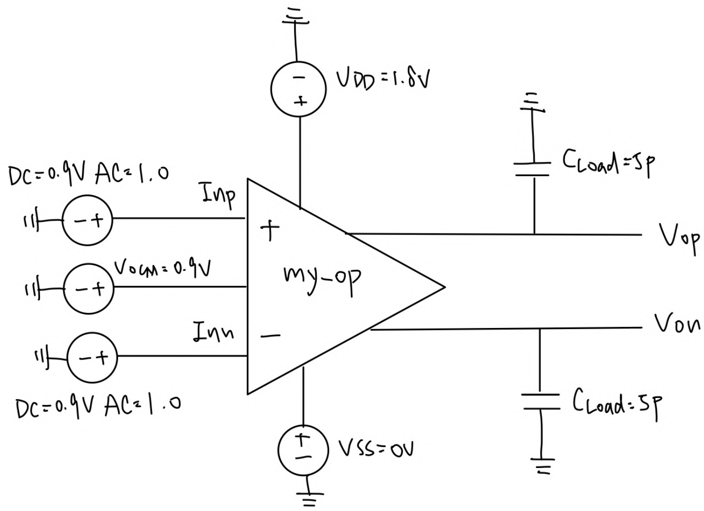


Figure 15: Test circuit schematic

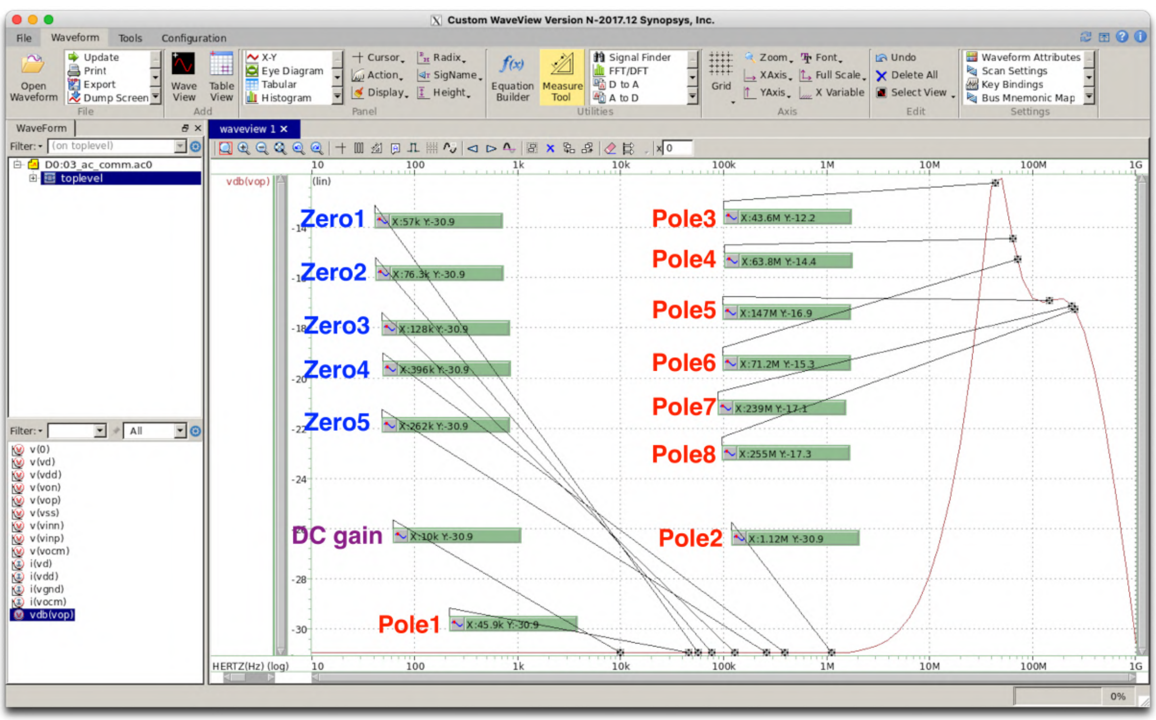


Figure 16: Magnitude response of common-mode gain
Vertical axis: V(vop)(dB) Horizontal axis: Frequency(Hz)

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

      v(von)/vd                                  =   28.4149m
      input resistance at               vd       =  1.000e+20
      output resistance at v(von)                =    2.3720k
```

Figure 17: Gain and impedance

```
Output first 10 Poles, (total 17)
Use .option pz_num = NUM to control output number, (default:10)

      poles (rad/sec)                  poles ( hertz)
real            imag            real            imag
-288.208k       0.              -45.8698k       0.
-7.05096x       0.              -1.12220x       0.
-76.7465x       -263.217x       -12.2146x       -41.8922x
-76.7465x       263.217x        -12.2146x       41.8922x
-400.626x       0.              -63.7616x       0.
-447.507x       0.              -71.2230x       0.
-921.642x       0.              -146.684x       0.
-1.17093g       944.924x        -186.359x       150.389x
-1.17093g       -944.924x       -186.359x       -150.389x
-1.34801g       863.513x        -214.543x       137.432x

Output first 10 Zeros, (total 24)
Use .option pz_num = NUM to control output number, (default:10)

      zeros (rad/sec)                  zeros ( hertz)
real            imag            real            imag
-358.084k       -11.2068k       -56.9909k       -1.78362k
-358.084k       11.2068k        -56.9909k       1.78362k
-408.003k       -252.193k       -64.9357k       -40.1378k
-408.003k       252.193k        -64.9357k       40.1378k
-801.769k       -28.4416        -127.606k       -4.52661
-801.769k       28.4416         -127.606k       4.52661
1.19484x        2.17908x        190.165k        346.811k
1.19484x        -2.17908x       190.165k        -346.811k
-1.36706x       -915.517k       -217.575k       -145.709k
-1.36706x       915.517k        -217.575k       145.709k
```

Figure 18: Poles and zeros

Dis. d-3

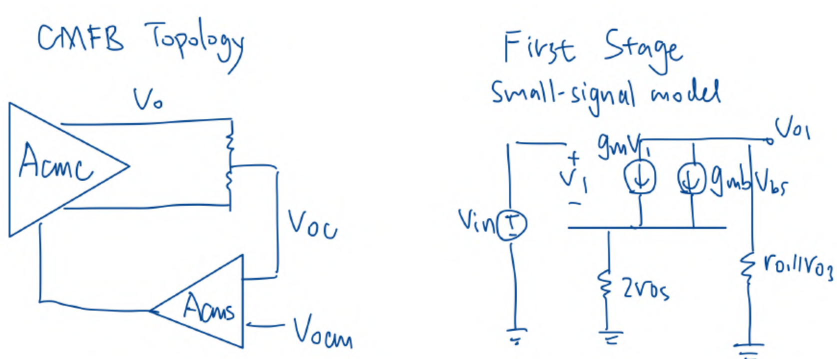


Figure 19: CMFB Topology and First-stage small-signal model

To calculate common mode gain, calculate the CM gain without CMFB first:

For the first stage CM gain, we can derive it from the small-signal model,

$$\begin{cases} V_i = V_1 + V_2 \\ V_2 = (g_{m1}V_1 + g_{mb1}(-V_2))2r_{o5} \\ V_o = -(g_{m1}V_1 - g_{mb1}V_2)(r_{o1} \mid\mid r_{o3}) \end{cases}$$

Solving using Cramer's rule and we can get the relationship between $V_o$ and $V_i$

$$\frac{V_o 1}{V_i} = \frac{-r_{o1} \mid\mid r_{o3}}{2r_{o5}} \cdot \frac{1}{1 + \dfrac{1 + g_{mb1} 2r_{o5}}{g_{m1}}}$$

For the second stage, we can easily get

$$\frac{V_o c}{V_o 1} = -g_{mb}(r_{o_6} \mid\mid r_{o_8})$$

Then the transfer function of second stage is,

$$\frac{V_o 1}{V_{\text{in}}} = \frac{-g_{m6}}{\dfrac{1}{r_{o6}} + \dfrac{1}{r_{o8}}}$$

Finally, the total open-loop gain of two amplifier is,

$$A_{cm} = \left( \frac{-r_{o1} \mid\mid r_{o3}}{2r_{o5}} \cdot \frac{1}{1 + \dfrac{1 + g_{mb1} 2r_{o5}}{g_{m1}}} \right) \left( \frac{-g_{m6}}{\dfrac{1}{r_{o6}} + \dfrac{1}{r_{o8}}} \right)$$

Then calculate the error amplifier gain,

$$A_{cms} = g_{m22}(2g_{m22} r_{o22} r_{o25} \mid\mid \frac{1}{g_{m24}} \mid\mid r_{o24})$$

And then calculate $A_{cmc}$,

$$A_{cmc} = g_{m3}(r_{o3} \mid\mid g_{m1} r_{o1} r_{o5}) g_{mb1}(r_{o6} \mid\mid r_{o8})$$

Finally get,

$$\frac{V_{oc}}{V_{ic}} = \frac{A_{cm}}{1 - A_{cmc} A_{cms}} = 23.7199m \quad \text{(By Excel)}$$

**Comparison Table**

| **Working Item** | **Simulation** | **Calculation** | **Error** |
|---|---|---|---|
| Common-mode gain | $28.4149m$ | $23.7199m$ | $\approx 19.79\%$ |

**Comment:**

There exists some error, I think the error is come from some approximation when derive the transfer function.

For low frequency zero,

$$\omega_{z,\text{low frequency}} = \frac{1}{(r_{o6} \mid\mid r_{o8})C_L} = 6.075MHz \quad \text{(By Excel)}$$

## 4. Open-loop power supply+ AC response

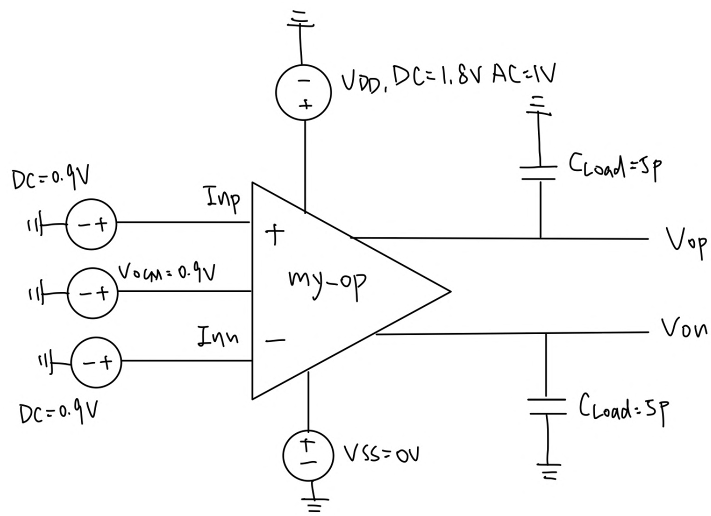


Figure 20: Test circuit schematic

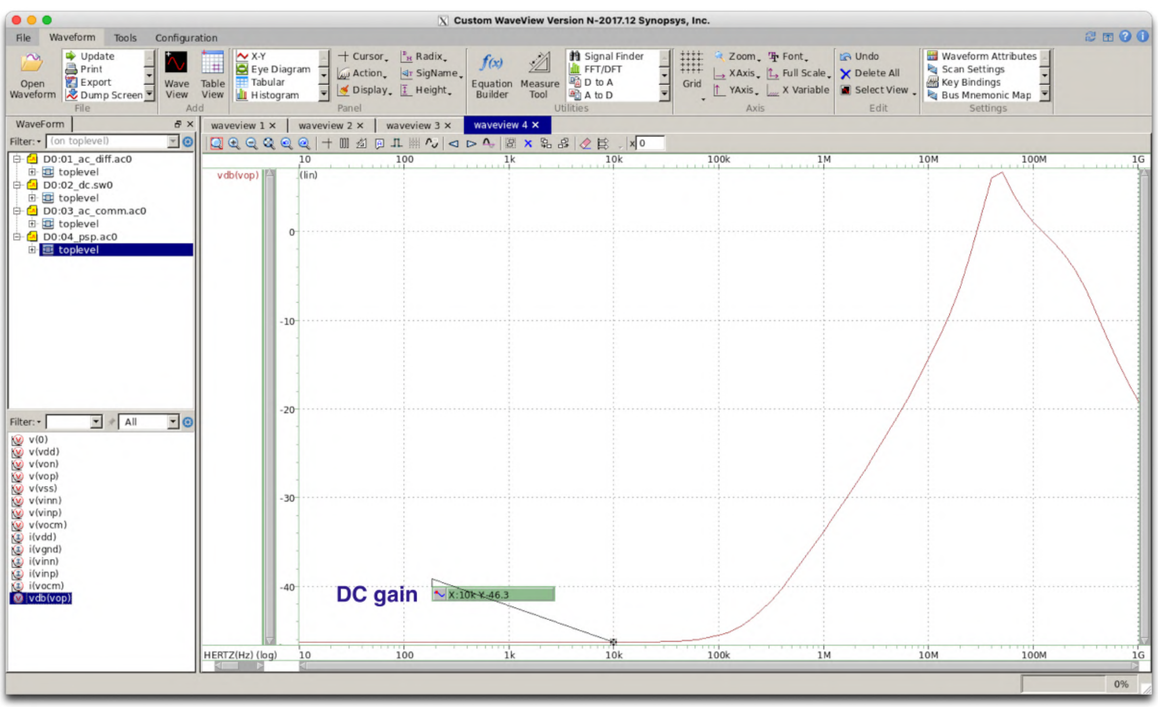


Figure 21: Magnitude response of power supply+ gain
Vertical axis: V(vop)(dB) Horizontal axis: Frequency(Hz)

## 5. Open-loop power supply- AC response

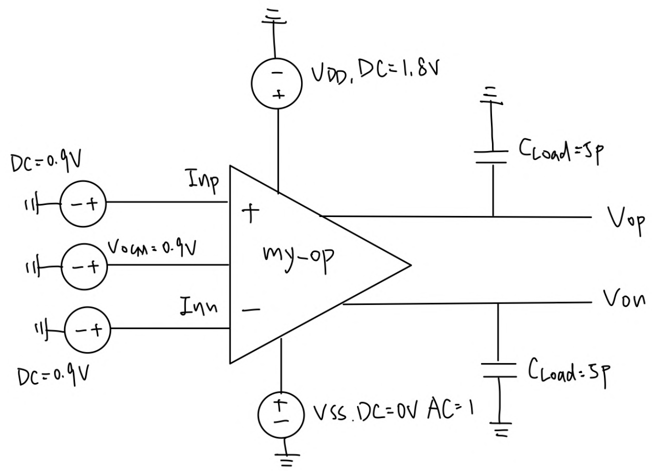


Figure 22: Test circuit schematic

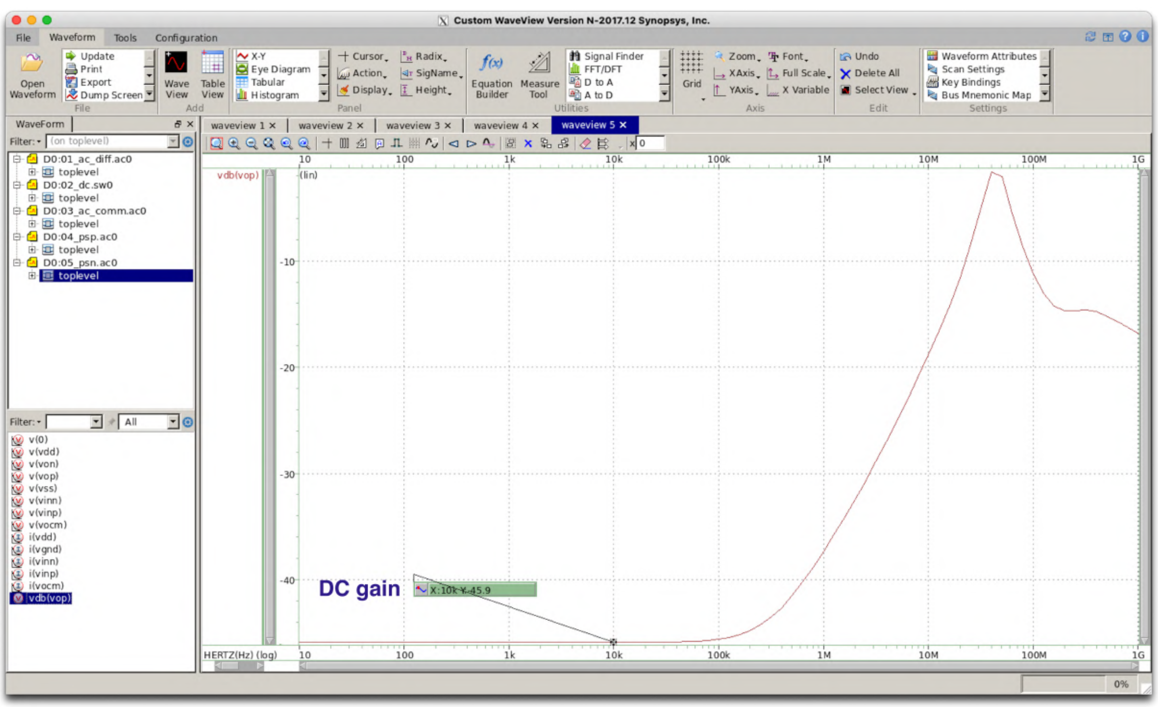


Figure 23: Magnitude response of power supply+ gain
Vertical axis: V(vop)(dB) Horizontal axis: Frequency(Hz)

## 6. Closed-loop differential mode AC response

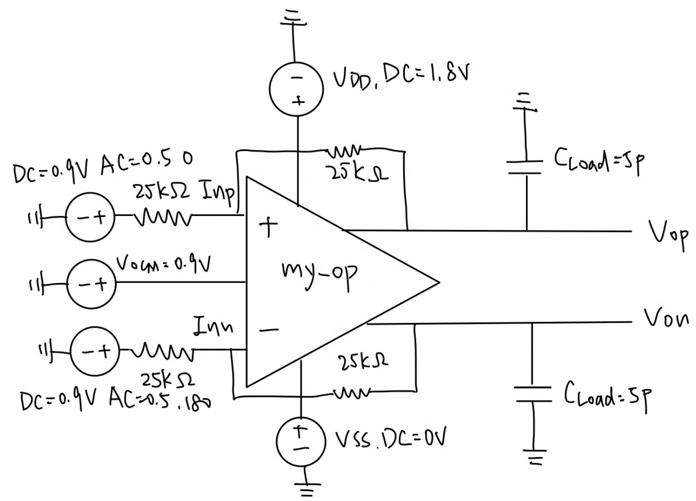


Figure 24: Test circuit schematic

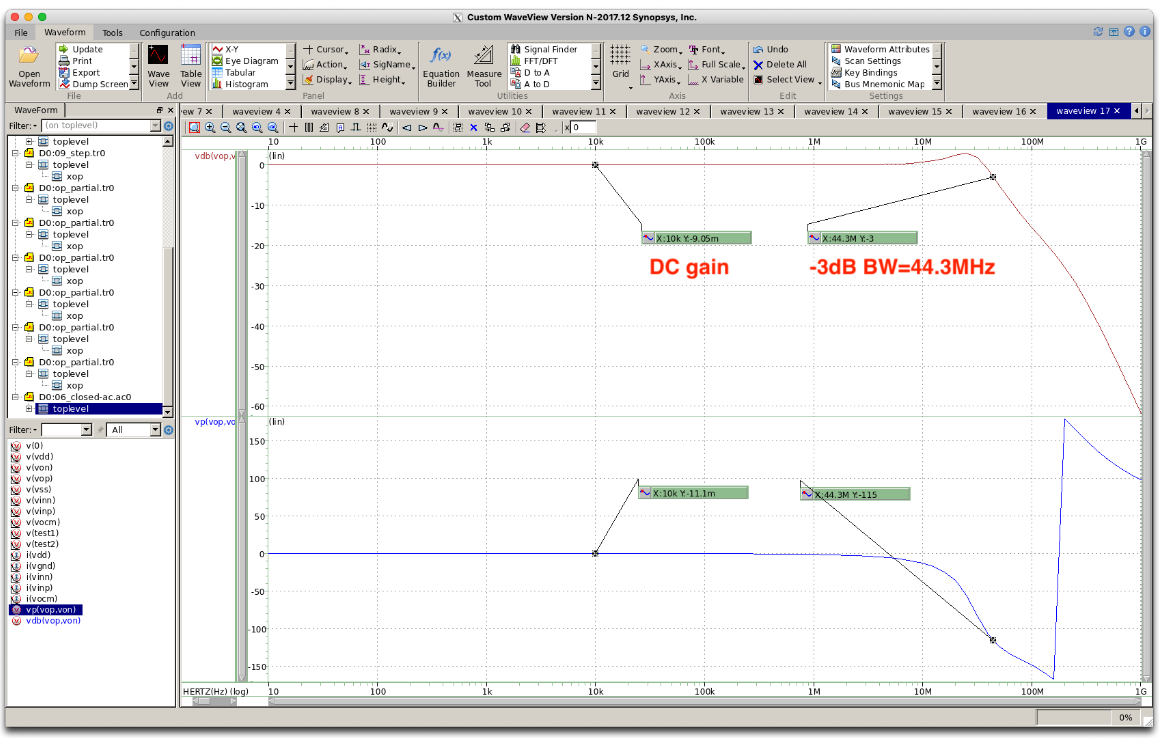


Figure 25: AC magnitude and phase response of differential-mode gain
Upper: Vertical axis: Vdb(vop, von)(dB) Horizontal axis: Frequency(Hz)
Bottom: Vertical axis: Vp(vop, von)(°) Horizontal axis: Frequency(Hz)

```
****** 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:test1   = 900.0000m 0:test2   = 900.0000m 0:vdd     =   1.8000
+0:vinn    = 900.9102m 0:vinp    = 900.9102m 0:vocm    = 900.0000m
+0:von     = 901.8203m 0:vop     = 901.8203m 0:vss     =   0.
+1:net11   = 901.8203m 1:net12   = 345.1846m 1:net1x   =   1.3051
+1:net2    =    1.2025  1:net2x   =    1.0217  1:net32   = 347.9228m
+1:net3x   = 392.6341m 1:net53   =    1.2025  1:net9    = 931.8778m
+1:net_cm  = 926.8616m 1:net_comp=  38.3882m 1:net_ref = 440.6822m
+1:net_s   =  46.7428m 1:net_seco=    1.2025  1:net_seco=   1.2025
```

Figure 26: Input and output node voltages

-3dB bandwidth of closed-loop is,

$$\omega_{-3dB,\text{closed}} = (1 + KA)\omega_{-3dB,\text{open}}$$

And we know K = 1,

$$A = g_{m1}g_{m6}(r_{o2} \mid\mid r_{o4})(r_{o6} \mid\mid r_{o8}) = 2522.574141$$

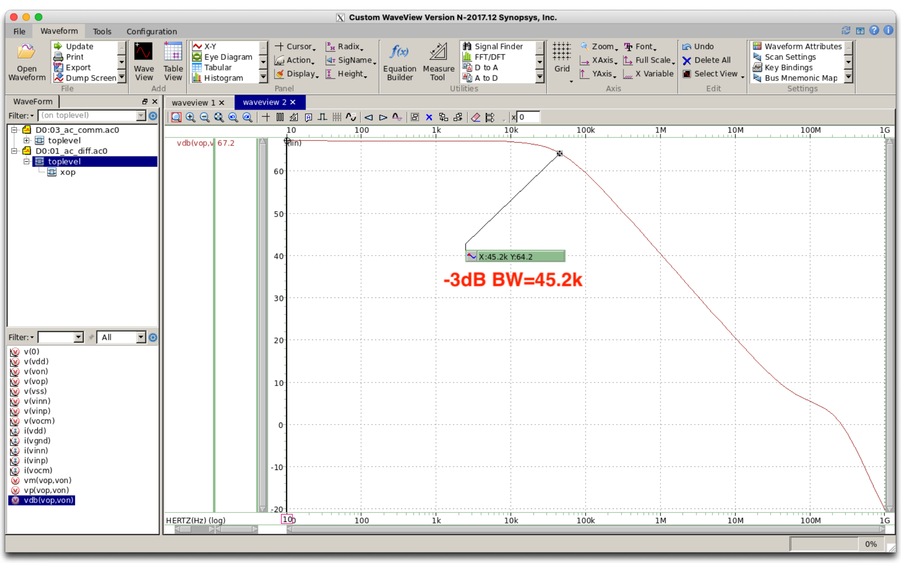


Figure 27: Open-loop -3dB bandwidth

Then we can calculate -3dB closed-loop bandwidth,

$$(1 + 2522.574141) \cdot 45.2k = 114.065551MHz$$

**Comparison Table**

| **Working Item** | **Simulation** | **Calculation** | **Error** |
|---|---|---|---|
| -3dB Bandwidth(closed-loop) | $44.3MHz$ | $114.065551MHz$ | $\approx -61\%$ |

**Comment:**

The error is very big, I think that was caused by lots of poles and zeros in it which makes the formula fault.

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

     v(vop,von)/vinp                                  =  998.9586m
     input resistance at             vinp             =   33.5061k
     output resistance at v(vop,von)                  =    8.3022
```

Figure 28: Small-signal transfer characteristics

Dis. d-6(v)

The Closed-loop gain is,

$$A_{v,\text{closed}} = \frac{A_{v,\text{open}}}{1 + A_{v,\text{open}}} = 0.9996$$

**Comparison Table**

| Working Item | Simulation | Calculation | Error |
|---|---|---|---|
| Closed-loop gain | 0.9989586 | 0.9996 | $\approx -6.42 \times 10^{-4}$ |

**Comment:**

The error is small enough to ignore.

## 7. Closed-loop differential mode DC sweep

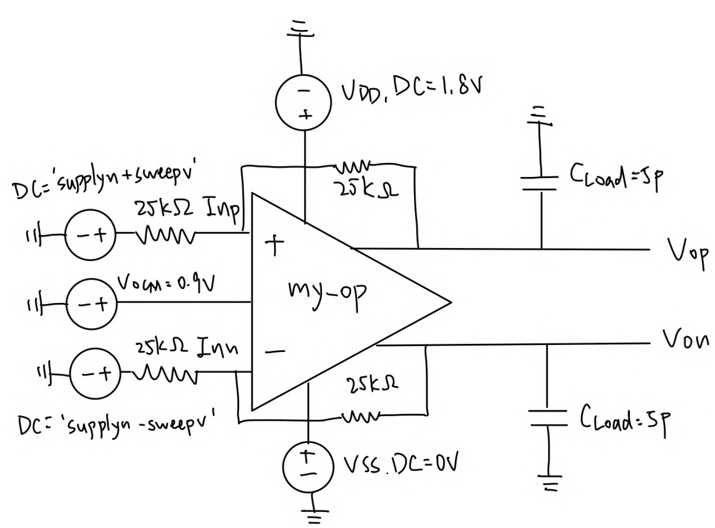


Figure 29: Test circuit schematic

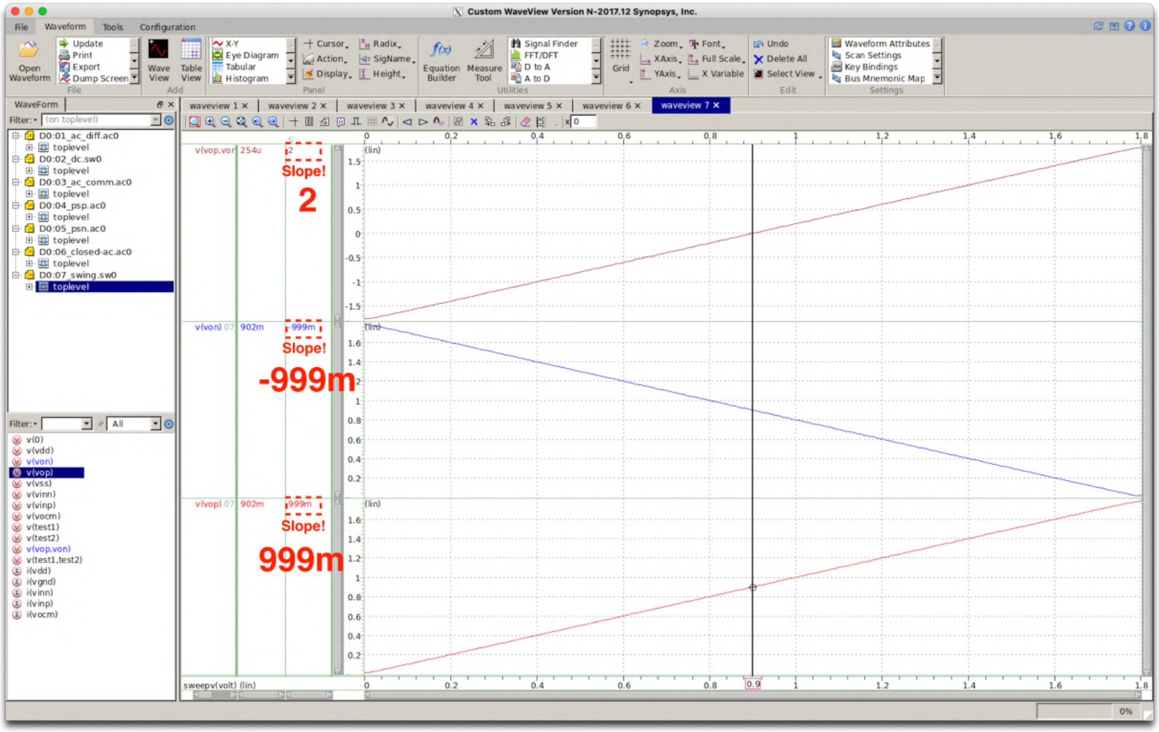


Figure 30: Single-ended and differential outputs for inputs with differential signals.
Upper: Vertical axis: Vdb(vop, von)(dB) Horizontal axis: Frequency(Hz)
Middle: Vertical axis: Vdb(von)(dB) Horizontal axis: Frequency(Hz)
Bottom: Vertical axis: Vdb(vop)(dB) Horizontal axis: Frequency(Hz)

Compare it with the AC response, see the below table, they are almost the same.

**Comparison Table**

| Working Item | AC | DC | Error |
|---|---|---|---|
| Gain | $998.9586m$ | $999m$ | $\approx 0\%$ |

**Comment:**

The error is small enough to ignore.

## 8. Closed-loop distortion simulation

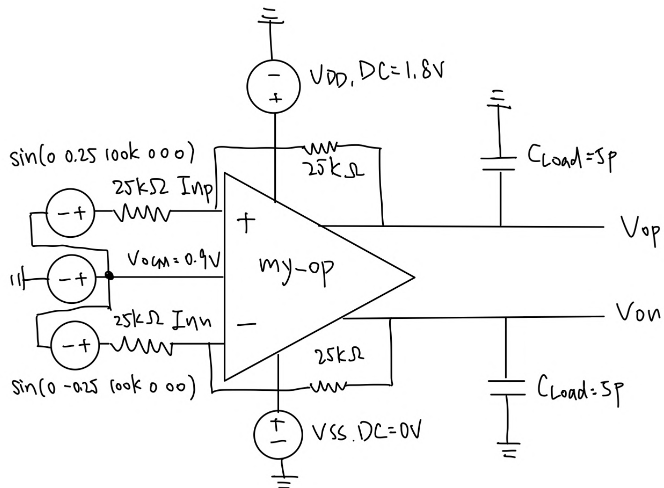


Figure 31: Test circuit schematic

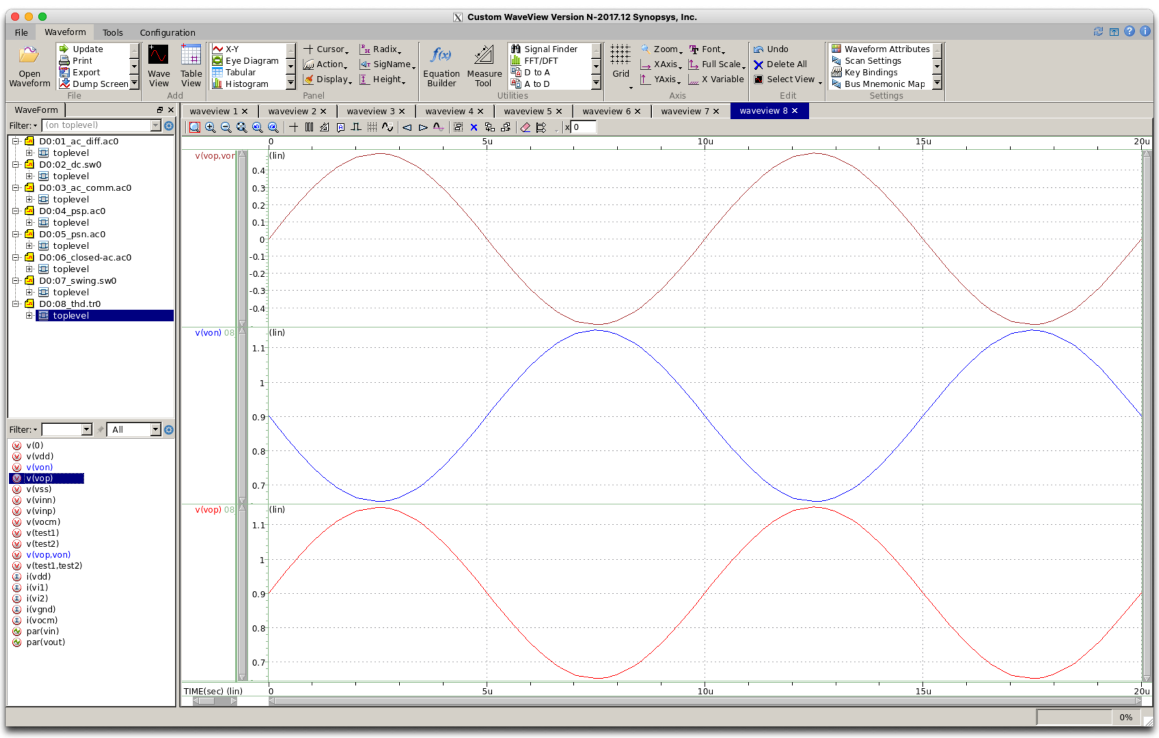


Figure 32: Single-ended and differential outputs for 100KHz sinusoidal inputs
Upper: Vertical axis: V(vop, von)(V) Horizontal axis: Frequency(Hz)
Middle: Vertical axis: V(von)(V) Horizontal axis: Frequency(Hz)
Bottom: Vertical axis: V(vop)(V) Horizontal axis: Frequency(Hz)

```
fourier components of transient response v(vop,von)
dc component = -143.5401n

harmonic frequency  fourier    normalized phase      normalized
no       (hz)       component  component  (deg)      phase (deg)
1         100.0000k  498.0022m    1.0000   -90.1273     0.
2         200.0000k  733.3971n    1.4727u -121.0818   -30.9544
3         300.0000k   90.4375u  181.6007u  -32.4198    57.7076
4         400.0000k  352.9208n  708.6732n  168.7104   258.8377
5         500.0000k  500.2514u    1.0045m  100.6176   190.7450
6         600.0000k  799.3956n    1.6052u  -49.1175    41.0099
7         700.0000k  313.2334u  628.9800u  -12.2261    77.9012
8         800.0000k    1.4949u    3.0018u   67.2315   157.3589
9         900.0000k  563.2578u    1.1310m -163.8669   -73.7396

total harmonic distortion =   0.16483  percent
```

Figure 33: THD analysis for differential

```
fourier components of transient response v(vop)
dc component =  901.8198m

harmonic frequency  fourier    normalized phase      normalized
no       (hz)       component  component  (deg)      phase (deg)
1         100.0000k  249.0011m    1.0000   -90.1273     0.
2         200.0000k  312.4916n    1.2550u   -1.0012    89.1261
3         300.0000k   45.2188u  181.6008u  -32.4197    57.7076
4         400.0000k  179.0609n  719.1170n  172.0671   262.1945
5         500.0000k  250.1257u    1.0045m  100.6176   190.7450
6         600.0000k  400.1813n    1.6071u  -48.7876    41.3398
7         700.0000k  156.6167u  628.9800u  -12.2261    77.9012
8         800.0000k  751.4805n    3.0180u   66.6682   156.7955
9         900.0000k  281.6289u    1.1310m -163.8669   -73.7396

total harmonic distortion =   0.16483  percent
```

Figure 34: THD analysis for Vop

```
fourier components of transient response v(von)
dc component =  901.8199m

harmonic frequency  fourier    normalized phase      normalized
no       (hz)       component  component  (deg)      phase (deg)
1         100.0000k  249.0011m    1.0000    89.8727     0.
2         200.0000k  930.1937n    3.7357u   42.0185   -47.8542
3         300.0000k   45.2187u  181.6005u  147.5802    57.7076
4         400.0000k  174.4824n  700.7294n  -14.7346  -104.6072
5         500.0000k  250.1256u    1.0045m  -79.3824  -169.2550
6         600.0000k  399.2277n    1.6033u  130.5519    40.6792
7         700.0000k  156.6167u  628.9800u  167.7739    77.9013
8         800.0000k  743.5167n    2.9860u -112.1991  -202.0718
9         900.0000k  281.6289u    1.1310m   16.1331   -73.7396

total harmonic distortion =   0.164831  percent
```

Figure 35: THD analysis for Von

We can see that all THD are less than $-55dB \approx 0.001778$

## 9. Closed-loop step response

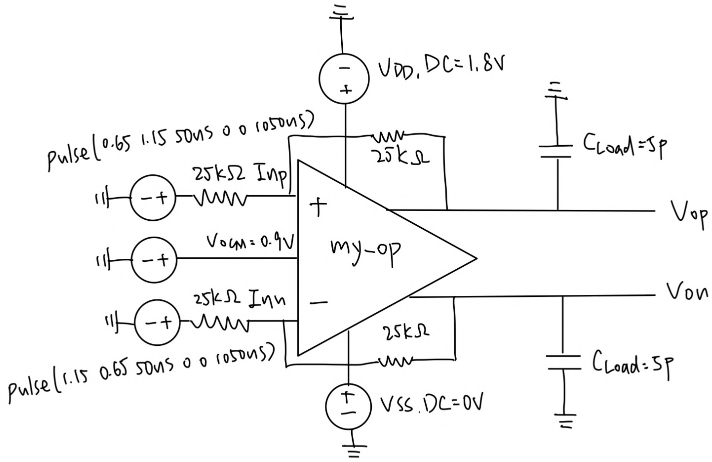


Figure 36: Test circuit schematic

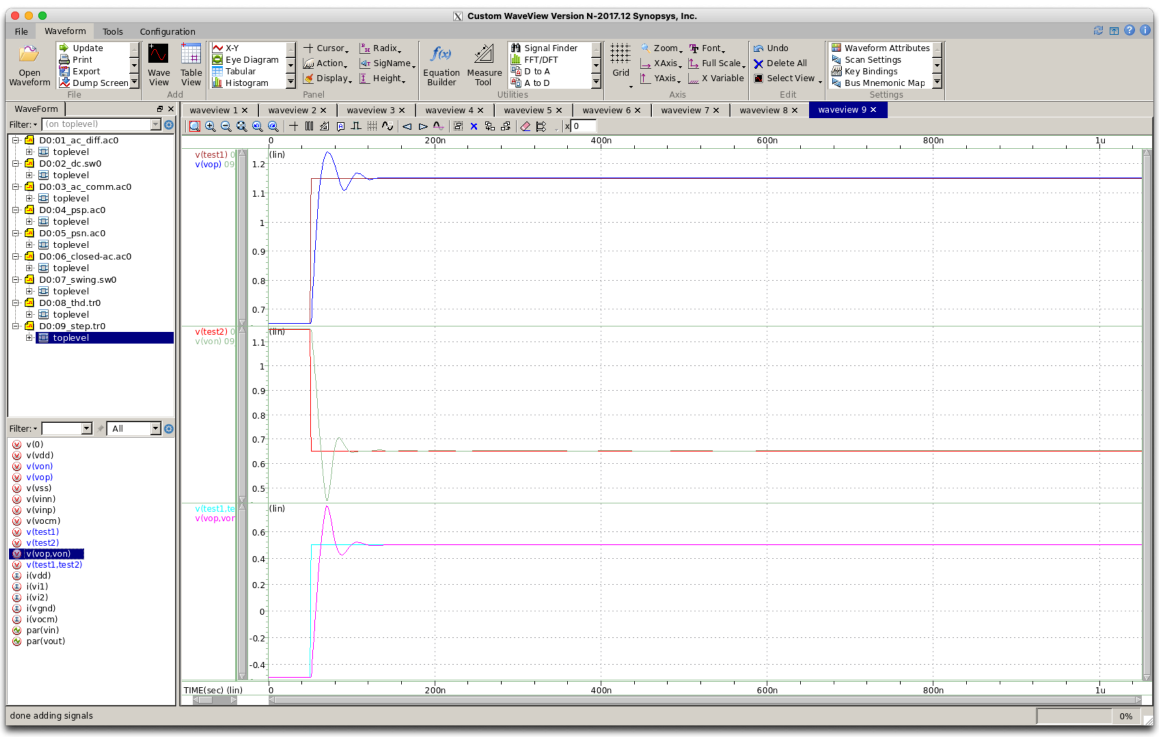

Figure 37: Single-ended and differential outputs for 1.0V differnetial step inputs.
Upper: Vertical axis: V(vop)(V) Horizontal axis: time(s)
Middle: Vertical axis: V(von)(V) Horizontal axis: time(s)
Bottom: Vertical axis: V(vop, von)(V) Horizontal axis: time(s)

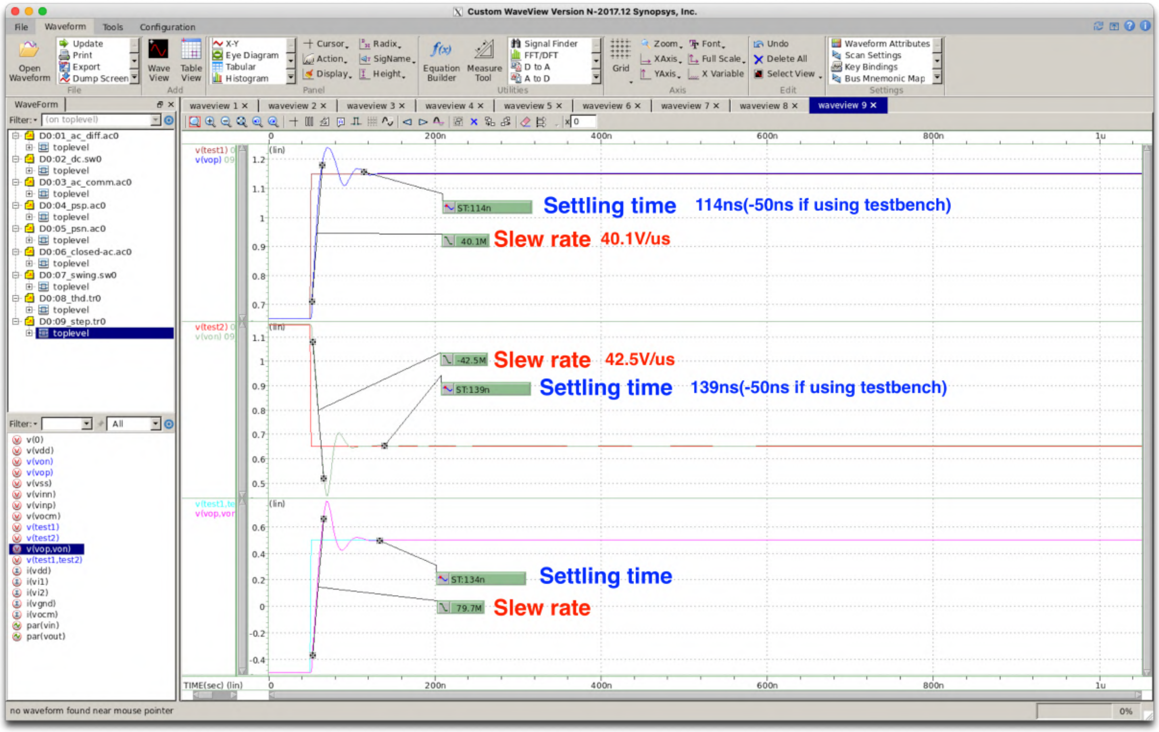


Figure 38: SLew rate and settling time
Upper: Vertical axis: V(vop)(V) Horizontal axis: time(s)
Middle: Vertical axis: V(von)(V) Horizontal axis: time(s)
Bottom: Vertical axis: V(vop, von)(V) Horizontal axis: time(s)

Slew rate $= \frac{dV_{\text{out}}}{dt}\Big|_{\text{max}}$.

For Vop,

$$\text{Slew rate} = \frac{I_{D5}}{C(vop)} = \frac{511.8736\mu}{10.9948} \approx 46.56$$

For Von,

$$\text{Slew rate} = \frac{I_{D5}}{C(von)} = \frac{511.8736\mu}{10.9948} \approx 46.56$$

**Comparison Table**

| Working Item | Simulation | Hand | Error |
|---|---|---|---|
| Slew rate vop | 40.1 | 46.56 | $\approx -13.87\%$ |
| Slew rate von | 42.5 | 46.56 | $\approx -8.72\%$ |

**Comment:**

This is very approximate estimation, but I think the error is still acceptable.

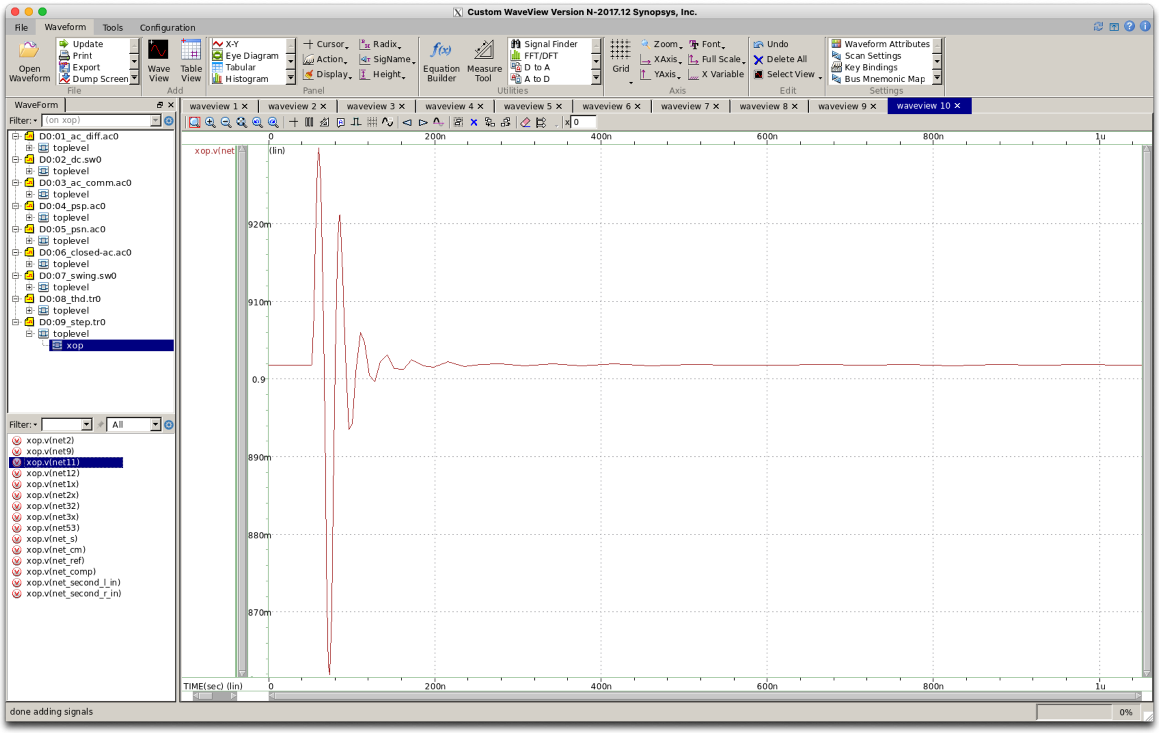


Figure 39: Common-mode sensing node
Vertical axis: V(sense node)(V) Horizontal axis: time(s)

Dis. d-9(v)

The common-mode feedback is very important for settling time. As we can see, if the gain of error amplifier is too large, the waveform will start to oscillate. But if the gain of error amplifier is too small, the settling time will be very long. How to balance the size of error amplifier is very import. Here I have some trick, if the error amplifier size is proportional to the size of first stage amplifier, it works not so back. And if the current density of error amplifier adjust will, the settling time can be very small. Here I get I think is not so bad!

(f)

(1)I think $\omega_u$ is a very important SPEC. From Internet, I get a formula from Internet $\omega_u = \frac{g_{m,M1,2}}{2\pi C_c}$, then I decide the $g_{m,M1}$ first.

(2)Select a good ratio for $\frac{g_{m,M1,2}}{I_{D,M1,2}}$, I choose 14. Then I get $I_{D,M1,2} = 224.62\mu A$ and run the simulation to get a proper aspect ratio $(\frac{W}{L})_{1,2} = \frac{22.58\mu}{1\mu}, m = 5$

(3)Select ratio for $\frac{g_{m,M3,4}}{I_{D,M3,4}} = 5$, then get $(\frac{W}{L})_{3,4} = \frac{11.9\mu}{1\mu}, m = 5$

(4)Select ratio for $\frac{g_{m,M5}}{I_{D,M5}} = 18$, then get $(\frac{W}{L})_5 = \frac{51.58\mu}{1\mu}, m = 10$

(5)Another formula $\frac{g_{m,M6,7}}{2\pi C_L} = 2\cdot\omega_u$. Then I get get $I_{D,M6,7} = 583.4\mu A$ and run the simulation to get a proper aspect ratio $(\frac{W}{L})_{6,7} = \frac{32.3\mu}{0.3\mu}, m = 10$

(6)Select ratio for $\frac{g_{m,M8,9}}{I_{D,M8,9}} = 17$, then get $(\frac{W}{L})_{8,9} = \frac{53.88\mu}{1\mu}, m = 10$

(7)Set Error amplifier size to 1/5 as first stage of amplifier.

(8)Set constant gm circuit to make stage one has correct current which I calculated.

Repeat (1)∼(8), adjust $gm/ID$ ratio, and find the trend, then I get a differential amplifier achieve all the SPEC and make some optimization.

(9)Setup start-up circuit last since it is not so important to SPEC or anything.

(g)

This design is harder than any homework before. After analysis the circuit, it seems not so hard as I image before. In this project, I try a new gm-ID method, it is very surprising and work very well. With that method, I get all MOSs into saturation region very fast(only try two or three times). But after that, the SPEC has a little bit high, I slow down to examine how the whole circuit work and finally find the direction to adjust it. I think that Phase Margin is the hardest part since the move of pole and zero is very hard to image. In fact, I didn't find the write way to adjust it very well, just feeling. The interesting part is this work is error amplifier, which control the feedback, careful adjust the size of it will make the waveform very beautiful. Yeah, so tired.

(h)

In this course, I learn lots of thing about analogy circuit design. Basically Amplifier, no wonder someone say "No gain no life". We are no gain no score. The suggestion is that The circuit design is not so easy, but we learn from the course is just theory. Maybe, can we have opportunity to have a circuit design hour to teach us how to better design a circuit not just "Monkey?" At the end of the class, have a happy winter vaction.

Reference:

1. Sadeqi, Abolfazl and Rahmam, Javad and Habibifar, Saeed and Ammar Khan, Muhammad and Mudassir Munir, Hafiz, "Design method for two-Stage CMOS operational amplifier applying load/miller capacitor compensation", Munich Personal RePEc Archiv, MPRA Paper NO. 102931, 12 June 2020