AIC HW5

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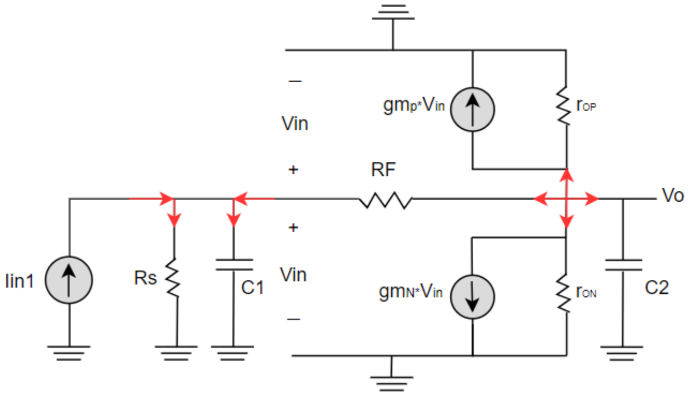
1. **With Feedback**

a. <u>**Design procedure**</u>(考慮低頻時，故 s=jω→0)

此電路小訊號模型:



$$\text{use KCL} \Rightarrow \begin{cases} I_{in1} + \dfrac{V_o - V_{in}}{R_F} = \dfrac{V_{in}}{R_S} + sC_1V_{in} \text{ ......(1)} \\ sC_2V_o + \left(\dfrac{V_o}{r_{op}} + gm_p \cdot V_{in}\right) + \left(\dfrac{V_o}{r_{on}} + gm_n \cdot V_{in}\right) + \dfrac{V_o - V_{in}}{R_F} = 0 \text{ ......(2)} \end{cases}$$

$$(1) \Rightarrow V_{in} = \left(I_{in} + \frac{V_o}{R_F}\right) \cdot (R_s \,||\, R_F)$$

$$(2) \Rightarrow V_{in} = V_o \cdot \frac{gds_p + gds_n + \frac{1}{R_F}}{\frac{1}{R_F} - (gm_p + gm_n)} = A \cdot V_o \left(\text{let } A = \frac{gds_p + gds_n + \frac{1}{R_F}}{\frac{1}{R_F} - (gm_p + gm_n)}\right)$$

$$\text{By(1)and(2)} \Rightarrow V_{in} = \left(I_{in} + \frac{V_o}{R_F}\right) \cdot (R_s \,||\, R_F) = A \cdot V_o$$

$$\Rightarrow V_o \cdot \left(A - \frac{1}{R_F} \cdot (R_s \,||\, R_F)\right) = I_{in} \cdot (R_s \,||\, R_F)$$

$$\Rightarrow \text{Closed loop gain} = \frac{V_o}{I_{in1}} = \frac{(R_S \,||\, R_F)}{A - \frac{1}{R_F} \cdot (R_S \,||\, R_F)} = \frac{1}{\frac{A}{(R_S \,||\, R_F)} - \frac{1}{R_F}}$$

I. 故可知，若要讓 Closed-loop gain > 0.85kΩ，$gm_p + gm_n$ 要很大，i.e. W / L 要很大。

II. 設 I_{in1} 的 DC=15uA，AC=1A (此處的 DC 電流值對於 Closed-loop gain 幾乎沒有影響)。

III. 在還沒考慮到 Vout 的情況下，先嘗試 $\frac{W_n}{L_n} = \frac{25um}{1um}$ (m=8)。

$\frac{W_p}{L_p} = \frac{25um}{1um}$ (m=8)。

I_{in1} = 15 uA。

第 1 次測試：

Design parameter:

Wn/Ln	Wp /Lp	I_{in1}
25um/1um(m = 8)	25 um/1um (m = 8)	15 uA

Result:

```
subckt
element  0:mn       0:mp
model    0:n_18.1   0:p_18.1
region   Saturation Saturation
 id         1.1126m   -1.1091m
 ibs      -1.699e-19  1.050e-19
 ibd        -8.3747f    8.4636f
 vgs      573.7692m -926.2308m
 vds      570.2446m -929.7554m
 vbs         0.         0.
 vth      384.4045m -494.5657m
 vdsat    180.9766m -378.7121m
 vod      189.3647m -431.6651m
 beta      62.4060m   13.2716m
 gam eff  507.4462m  557.0846m
 gm        10.1301m    4.5416m
 gds      134.5952u   46.3238u
 gmb        2.0069m    1.4486m
 cdtot    272.8803f  220.8009f
 cgtot      1.3760p    1.3057p
 cstot      1.5460p    1.5310p
 cbtot    746.5564f  714.3895f
 cgs        1.2024p    1.1575p
 cgd       71.5261f   72.3291f
```

```
v(vout1)/iivx                              = -919.0224
input resistance at                 iivx   =   79.3898
output resistance at v(vout1)              =   68.5729
```

```
dcgain_in_db=   59.2665
bw= 354.5972x
```

```
vout1     = 570.2446m
```

觀察與微調：

可以觀察到 Closed-loop gain 已經達到要求，然而 bw 和 Vout 沒有達到，根據下方(e)推導的 pole 公式可以知道，如果加大$(gm_p + gm_n)$的值就可以增加 pole 的大小，bw 因此變大，由於 bw 還與標準差很多所以我打算直接條小 L 值以達到更大的放大效果。

取 $\frac{W_n}{L_n} = \frac{25um}{0.2um}$ (m=8)，$\frac{W_p}{L_p} = \frac{25um}{0.2um}$ (m=8)。

第 2 次測試：

Design parameter:

Wn/Ln	Wp /Lp	I_{in1}
25um/0.2um(m = 8)	25 um/0.2um (m = 8)	15 uA

Result:

```
subckt
element  0:mn       0:mp
model    0:n_18.1   0:p_18.1
region   Saturation Saturation
 id         5.7100m   -5.7082m
 ibs      -8.721e-19  5.404e-19
 ibd        -9.6632f    7.6640f
 vgs      659.8335m -840.1665m
 vds      658.0302m -841.9698m
 vbs         0.         0.
 vth      501.7690m -520.5216m
 vdsat    171.8318m -331.3581m
 vod      158.0645m -319.6449m
 beta     353.8547m   98.5872m
 gam eff  507.4476m  557.0842m
 gm        51.1851m   27.2428m
 gds        2.1461m    1.1936m
 gmb        7.7670m    8.5746m
 cdtot    266.7925f  222.6196f
 cgtot    388.2392f  390.1743f
 cstot    544.6052f  541.5520f
 cbtot    486.9150f  433.7577f
 cgs      283.2633f  296.7484f
 cgd       72.4185f   71.4828f
```

```
v(vout1)/iivx                              = -945.9153
input resistance at                 iivx   =   53.0242
output resistance at v(vout1)              =   12.4682
```

```
dcgain_in_db=   59.5170
bw= 903.0787x
```

```
vout1     = 658.0302m
```

觀察與微調:

觀察到確實因為$(gm_p + gm_n)$的上升，導致 bw 的上升，且已經達到標準，接這就是要調整 Vout 值，由於 Vout 值是由 Vx 值減去一個 $I_X R_F$，所以如果要使 Vout 值大一些，要減少 I_X 值，根據 KCL，$I_X + I_{d,p} = I_{d,n}$，因此需要盡量讓 $I_{d,p}$ 與 $I_{d,n}$ 接近。由於目前 $I_{d,n}$ 大於 $I_{d,p}$，因此我打算降低 $I_{d,n}$ 值，也就是降低 $\frac{W_n}{L_n}$。

取 $\frac{W_n}{L_n} = \frac{25um}{0.6um}$ (m=8)，$\frac{W_p}{L_p} = \frac{25um}{0.2um}$ (m=8)。

第 3 次測試:

Design parameter:

Wn/Ln	Wp /Lp	I_{in1}
25um/0.6um(m = 8)	25 um/0.2um (m = 8)	15 uA

Result:

```
subckt
element  0:mn        0:mp
model    0:n_18.1    0:p_18.1
region   Saturation  Saturation
 id         4.2282m    -4.2275m
 ibs     -6.458e-19   4.002e-19
 ibd      -10.4813f    7.1572f
 vgs      714.4320m  -785.5680m
 vds      713.7206m  -786.2794m
 vbs        0.          0.
 vth      422.8397m  -520.6358m
 vdsat    258.1640m  -288.3674m
 vod      291.5923m  -264.9322m
 beta     106.5621m    99.7415m
 gam eff  507.4471m   557.0843m
 gm        25.4048m    24.7224m
 gds      467.9648u   961.6245u
 gmb        4.8243m     7.6711m
 cdtot    265.0946f   224.6166f
 cgtot    859.1366f   390.1297f
 cstot      1.0219p   541.3678f
 cbtot    602.0831f   435.8875f
 cgs      726.3374f   296.5884f
 cgd       72.2230f    71.4735f
```

```
v(vout1)/iivx                          = -951.9717
input resistance at          iivx      =   47.0865
output resistance at v(vout1)          =   19.7721
```

```
dcgain_in_db=   59.5725
bw= 772.6968x
```

```
vout1    = 713.7206m
```

觀察與微調:

發現 Vout 確實升高了，於是繼續讓 $I_{d,n}$ 變小。

取 $\frac{W_n}{L_n} = \frac{25um}{0.6um}$ (m=5)，$\frac{W_p}{L_p} = \frac{25um}{0.2um}$ (m=8)。

第 4 次測試:

Design parameter:

Wn/Ln	Wp /Lp	I_{in1}
25um/0.6um(m = 5)	25 um/0.2um (m = 8)	15 uA

Result:

```
subckt
element  0:mn        0:mp
model    0:n_18.1    0:p_18.1
region   Saturation  Saturation
  id        3.2911m    -3.2912m
  ibs      -5.027e-19  3.116e-19
  ibd      -6.9076f    6.8034f
  vgs      752.5483m  -747.4517m
  vds      752.5992m  -747.4008m
  vbs        0.          0.
  vth      422.4102m  -520.7158m
  vdsat    284.4746m  -257.4331m
  vod      330.1381m  -226.7359m
  beta      66.5147m   100.5575m
  gam eff  507.4474m   557.0844m
  gm        17.5094m    22.5647m
  gds      333.8657u   796.8901u
  gmb        3.3083m     6.9288m
  cdtot    164.6323f   226.0683f
  cgtot    536.8273f   389.8980f
  cstot    638.6637f   540.9291f
  cbtot    374.5783f   437.4308f
  cgs      454.3960f   296.2187f
  cgd       45.1506f    71.4660f
```

```
v(vout1)/iivx                          = -947.3005
input resistance at             iivx   =   51.6661
output resistance at v(vout1)          =   24.7371
```

```
dcgain_in_db=   59.5298
bw= 813.8176x
```

```
+0:vdd      =    1.5000   0:vout1    = 752.5992m 0:vx       = 752.5483m
```

觀察與微調:

達題目要求 bw>650MHz，|Closed-loop gain|>0.85kΩ，

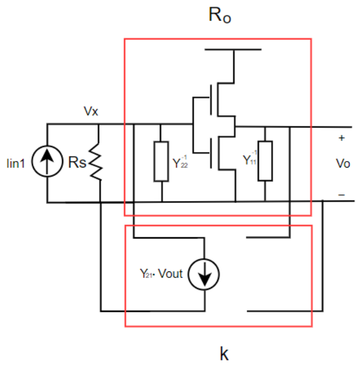
Output common voltage>0.75V。

b.

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

     v(vout1)/iivx                          = -947.3005
     input resistance at             iivx   =   51.6661
     output resistance at v(vout1)          =   24.7371
```

c. **<u>Hand calculation</u>** (考慮低頻時，故 s=jω→0)



$Y_{11}= R_F^{-1}$

$Y_{22}= R_F^{-1}$

$Y_{21}=-R_F^{-1}$

$R_{in,open} = R_F \,||\, R_S \,||\, \frac{1}{sC1} = 50k||1k = 980.39216(\Omega)$

$R_{out,open} = R_F \,||\, r_{oN} \,||\, r_{oP} \,||\, \frac{1}{sC2} = 50k||3.127437k||1.2803964k = 476.018497(\Omega)$

$V_o = -V_x \cdot (g_{mN}+ g_{mP}) \cdot (R_F \,||\, r_{oN} \,||\, r_{oP} \,||\, \frac{1}{sC2})$

$= -I_{in1} \cdot (R_F \,||\, R_S \,||\, \frac{1}{sC1}) \cdot (g_{mN}+ g_{mP}) \cdot (R_F \,||\, r_{oN} \,||\, r_{oP} \,||\, \frac{1}{sC2})$

Open-loop gain $R_o = \frac{V_o}{I_{in1}} = -(R_F \,||\, R_S \,||\, \frac{1}{sC1}) \cdot (g_{mN}+ g_{mP}) \cdot (R_F \,||\, r_{oN} \,||\, r_{oP} \,||\, \frac{1}{sC2})$

$\cong -(R_F \,||\, R_S) \cdot (g_{mN}+ g_{mP}) \cdot (R_F \,||\, r_{oN} \,||\, r_{oP})$

$= -(980.39216) \cdot (0.01751+0.02256) \cdot 476.018497$

$= -18438.68(\Omega)$

將 $i_F = -i_{RF} = -\frac{V_{out}}{R_F}$ 代入 $K = \frac{i_F}{V_{out}} \Rightarrow K= Y_{21}= -\frac{1}{R_F} = -0.001(\frac{1}{\Omega})$

$(1+kR_o) = (1+(-0.001) \cdot (-18438.68)) = 19.43868$

$R_{in,Closed} = \frac{R_{in,open}}{1+kR_o} = \frac{980.39216}{19.43868} = 56.21939(\Omega)$

$R_{out,Closed} = \frac{R_{out,open}}{1+kR_o} = \frac{467.018497}{19.43868} = 26.91241(\Omega)$

Closed loop gain $\frac{V_{out}}{I_{in1}} = \frac{R_o}{1+kR_o} = \frac{-18438.68}{19.43868} = -1057.344(\Omega)$

	Calculate	Hspice	Error
$R_{in,Closed}(\Omega)$	56.21939	51.8785	7.72%
$R_{out,Closed}(\Omega)$	26.91241	25.1933	6.38%
Closed-loop gain(Ω)	-1057.344	-947.3084	10.4%

計算上有些許誤差，由於此三個數值都是由 Open-loop gain 推算得到，所以有可能在 Open-loop gain 上就有誤差存在，推測可能是沒有考慮到寄生電容和在推導的時候假設 s=jω→0，省略公式其中一部分導致。

d.

****** pole/zero analysis

input = 0:iivx output = v(vout1)

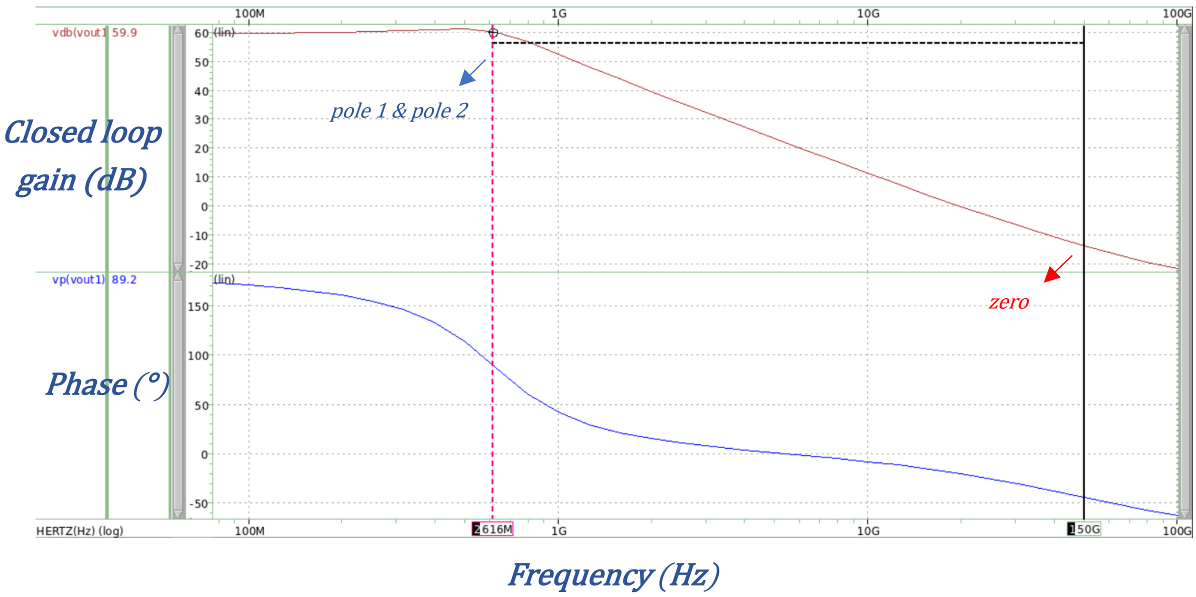
poles (rad/sec)		poles (hertz)	
real	imag	real	imag
-1.86792g	3.46165g	-297.289x	550.939x
-1.86792g	-3.46165g	-297.289x	-550.939x

zeros (rad/sec)		zeros (hertz)	
real	imag	real	imag
320.190g	0.	50.9599g	0.

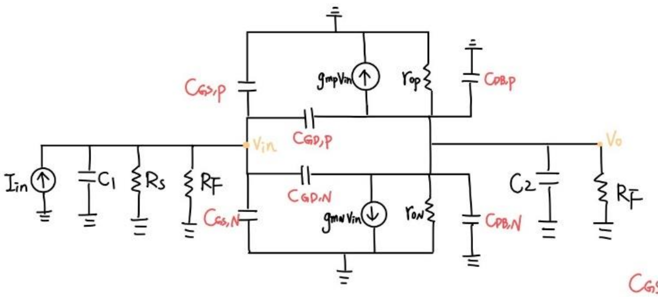
****** ac analysis tnom= 25.000 temp= 25.000 ******

dcgain_in_db= 59.5298

bw= 813.8176x



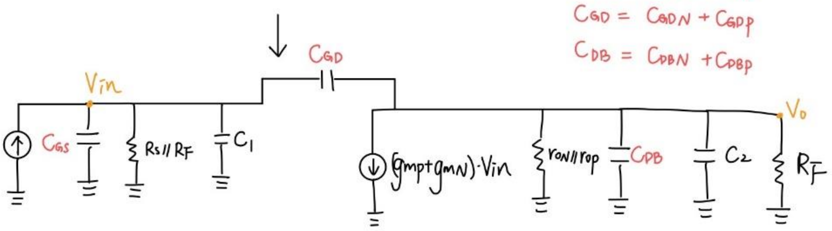
e.



$C_{GS} = C_{GS,N} + C_{GS,P}$

$C_{GD} = C_{GD,N} + C_{GD,P}$

$C_{DB} = C_{DB,N} + C_{DB,P}$



$$\begin{cases} \dfrac{V_o - V_{in}}{\frac{1}{sC_{GD}}} = \dfrac{V_{in}}{\frac{1}{sC_{GS}}} + \dfrac{V_{in}}{\frac{1}{sC_1}} + \dfrac{V_{in}}{R_S /\!/ R_F} - I_{in} \quad \cdots\cdots (1) \\ \dfrac{V_o - V_{in}}{\frac{1}{sC_{GD}}} + (g_{mN} + g_{mp}) V_{in} + \dfrac{V_o}{(r_{oN} /\!/ r_{op})} + \dfrac{V_o}{\frac{1}{sC_{DB}}} + \dfrac{V_o}{\frac{1}{sC_2}} + \dfrac{V_o}{R_F} = 0 \quad \cdots\cdots (2) \end{cases}$$

$$(1) \Rightarrow sC_{GD} V_o - sC_{GD} V_{in} = V_{in}\left(sC_{GS} + sC_1 + \frac{1}{R_S /\!/ R_F} \right) - I_{in}$$

$$\Rightarrow sC_{GD} V_o + I_{in} = V_{in}\left(sC_{GD} + sC_{GS} + sC_1 + \frac{1}{R_S /\!/ R_F} \right)$$

$$(2) \Rightarrow sC_{GD} V_o - sC_{GD} V_{in} + (g_{mN} + g_{mp}) V_{in} + V_o\left(\frac{1}{r_{oN} /\!/ r_{op}} + sC_{DB} + sC_2 + \frac{1}{R_F} \right)$$

$$\Rightarrow V_o\left(sC_{GD} + \frac{1}{r_{oN} /\!/ r_{op}} + sC_{DB} + sC_2 + \frac{1}{R_F} \right) = V_{in}\left(sC_{GD} - (g_{mN} + g_{mp}) \right)$$

$$\Rightarrow V_{in} = \frac{V_o\left(sC_{GD} + \frac{1}{r_{oN} /\!/ r_{op}} + sC_{DB} + sC_2 + \frac{1}{R_F} \right)}{\left(sC_{GD} - (g_{mN} + g_{mp}) \right)}$$

(2) 代入 (1)

$$sC_{GD} V_o + I_{in} = \frac{V_o\left(sC_{GD} + \frac{1}{r_{oN} /\!/ r_{op}} + sC_{DB} + sC_2 + \frac{1}{R_F} \right)}{\left(sC_{GD} - (g_{mN} + g_{mp}) \right)} \left(sC_{GD} + sC_{GS} + sC_1 + \frac{1}{R_S /\!/ R_F} \right)$$

$$\Rightarrow I_{in} = \left[\frac{\left(sC_{GD} + \frac{1}{r_{oN} /\!/ r_{op}} + sC_{DB} + sC_2 + \frac{1}{R_F} \right)}{\left(sC_{GD} - (g_{mN} + g_{mp}) \right)} \left(sC_{GD} + sC_{GS} + sC_1 + \frac{1}{R_S /\!/ R_F} \right) - sC_{GD} \right] V_o$$

• open loop gain R_o

$$R_o = \frac{V_o}{I_{in}} = \left[\frac{\left(sC_{GD} + \underbrace{\frac{1}{r_{ON} /\!/ r_{OP}}}_{\frac{1}{R_1}} + \underbrace{sC_{DB} + sC_2 + \frac{1}{R_F}}_{sC_A} \right)}{sC_{GD} - (g_{mN} + g_{mp})} \cdot \left(\underbrace{sC_{GD} + sC_{GS} + sC_1}_{sC_B} + \underbrace{\frac{1}{R_S /\!/ R_F}}_{\frac{1}{R_2}} \right) - sC_{GD} \right]^{-1}$$

$$= \left[\frac{\left(\frac{1}{R_1} + sC_A\right)\left(\frac{1}{R_2} + sC_B\right)}{sC_{GD} - (g_{mN} + g_{mp})} - sC_{GD} \right]^{-1}$$

$$= \left[\frac{1}{\left(sC_{GD} - (g_{mN} + g_{mp})\right) \cdot \left(R_1 /\!/ \frac{1}{sC_A}\right)\left(R_2 /\!/ \frac{1}{sC_B}\right)} - sC_{GD} \right]^{-1}$$

$$= \frac{\left(sC_{GD} - (g_{mN} + g_{mp})\right) \cdot \left(R_1 /\!/ \frac{1}{sC_A}\right) \cdot \left(R_2 /\!/ \frac{1}{sC_B}\right)}{1 - s \cdot C_{GD} \left[\left(sC_{GD} - (g_{mN} + g_{mp})\right) \cdot \left(R_1 /\!/ \frac{1}{sC_A}\right) \cdot \left(R_2 /\!/ \frac{1}{sC_B}\right) \right.}$$

$$= \frac{\left(sC_{GD} - (g_{mN} + g_{mp})\right) \cdot \frac{R_1 R_2}{(R_1 s C_A + 1)(R_2 s C_B + 1)}}{1 - s \cdot C_{GD} \left[\left(sC_{GD} - (g_{mN} + g_{mp})\right) \cdot \left(R_1 /\!/ \frac{1}{sC_A}\right) \cdot \left(R_2 /\!/ \frac{1}{sC_B}\right) \right.}$$

$$= \frac{\left(sC_{GD} - (g_{mN} + g_{mp})\right) \cdot R_1 R_2}{(R_1 s C_A + 1)(R_2 s C_B + 1) - sC_{GD}\left(sC_{GD} - (g_{mN} + g_{mp})\right) \cdot R_1 R_2}$$

$$= \frac{sC_{GD} \cdot R_1 R_2 - (g_{mN} + g_{mp}) \cdot R_1 R_2}{R_1 R_2 \cdot C_A C_B s^2 + 1 + s(R_1 C_A + R_2 C_B) - s^2 C_{GD}^2 R_1 R_2 + s C_{GD} (g_{mN} + g_{mp}) \cdot R_1 R_2}$$

$$= \frac{\overset{d}{sC_{GD} R_1 R_2} \overset{e}{- (g_{mN} + g_{mp}) \cdot R_1 R_2}}{s^2 \underbrace{(R_1 R_2 C_A C_B - C_{GD}^2 \cdot R_1 R_2)}_{a} + s \underbrace{(R_1 C_A + R_2 C_B + C_{GD} (g_{mN} + g_{mp}) \cdot R_1 R_2)}_{b} + 1}$$

$$= \frac{ds + e}{as^2 + bs + 1}$$

• close loop gain $\left.\frac{V_{out}}{I_{in}}\right|_{closed}$

$$\left.\frac{V_{out}}{I_{in}}\right|_{closed} = \frac{R_o}{1 + kR_o} = \frac{\frac{ds+e}{as^2+bs+1}}{1 + k \cdot \frac{ds+e}{as^2+bs+1}} = \frac{ds + e}{(as^2 + bs + 1) + kds + ke} = \frac{ds + e}{as^2 + (b + kd)s + (1 + ke)}$$

$C_{GS,N}$	$C_{GS,P}$	$C_{GD,N}$	$C_{GD,P}$	$C_{DB,N}$	$C_{DB,P}$
4.54E-13(F)	2.96E-13(F)	4.52E-14(F)	7.14E-14(F)	1.2E-13(F)	1.54E-13(F)

C_{GS}	C_{GD}	C_{DB}	r_{ON}	r_{OP}	r_{ON} || r_{OP}
7.5E-13(F)	1.17E-13(F)	2.74E-13(F)	2995.216Ω	1254.878Ω	884.364Ω

RS	RF	RS||RF	R1	R2
50 kΩ	1 kΩ	980.39216Ω	469.3170Ω	980.3921Ω

C_A	C_B	gm_N	gm_P
1.39E-12(F)	1.87E-12(F)	0.017509(Ω^{-1})	0.022564(Ω^{-1})

a	b	d	e	k
1.19E-18	4.63E-9	5.37E-8	-18438.68421	-0.001

Zero: ds+e =0 $\Rightarrow W_Z = \frac{-e}{d} = 3.4364 \cdot 10^{11}$(rad/sec) = 54.691965852 (GHz)

$| W_{Zero,calculate} |$ = 54.691965852 (GHz)

$| W_{Zero,hspice} |$ = 50.9599 (GHz)

$W_{Zero,error} = |\frac{W_{Zero,hspice} - W_{Zero,calculate}}{W_{Zero,calculate}}| * 100\%$= 6.82%

Poles: $as^2+(b+kd)s+(1+ke) = 0 \Rightarrow W_{Pole} = \frac{-(b+kd)\pm\sqrt{(b+kd)^2-4a(1+ke)}}{2a}$

$= -1.93 \cdot 10^9 \pm 3.56 \cdot 10^9 j$ (rad/sec)

$= -3.066397 \cdot 10^8 \pm 5.659045 \cdot 10^8 j$ (Hz)

$W_{Pole1} = -306.6397 + 565.9045\, j$ (MHz)

$W_{Pole2} = -306.6397 - 565.9045\, j$ (MHz)

$| W_{Pole,calculate} | = \sqrt{(3.066397 \cdot 10^8)^2 + (5.659045 \cdot 10^8)^2}$

= 643.642650 (MHz)

$| W_{Pole,hspice} | = \sqrt{(2.97289 \cdot 10^8)^2 + (5.50939 \cdot 10^8)^2}$

= 626.030775 (MHz)

$W_{Pole,error} = |\frac{W_{Pole,hspice} - W_{Pole,calculate}}{W_{Pole,calculate}}| * 100\%$= 2.77%

Comparison	|Pole|	Zero
Hspice	626.030775 (MHz)	50.9599 (GHz)
Calculate	643.642650 (MHz)	54.691965852 (GHz)
Error	2.74%	6.82%

誤差不大，推測造成誤差原因為電路中的寄生電容，且因為此式子較為複雜，故在計算時，各值的四捨五入也會導致最終計算上的結果有些許誤差。

```
**** voltage sources

subckt
element  0:vdd
 volts       1.5000
 current    -3.2912m
 power       4.9368m
```

$$\text{FoM}=\frac{total\ current\ (uA)}{transimpedence\ gain(k\Omega)\times -3dB\ bandwidth(MHz)}=\frac{3291.2}{0.9473005\times 813.8176}=4.26913$$

可以發現我的電流值太大了造成 FoM 值很大，於是我打算先將電流壓下來，且從上述計算可知，current 主要來自於 VDD 的電流，i.e. current source 影響很小。而若要讓 current↓，需要將 W/L 或 m 值往下調。可以注意到雖然(g_{mN}+ g_{mP})值會因為電流下降而降低，然而根據 HW1 得知 $r_O=\frac{1}{\lambda\times I_d}\propto\frac{L}{I_d}$，$r_{ON}$ 和 r_{OP} 值都會上升，所以 Closed-loop gain 不一定會下降，至於觀察 Pole 公式可以發現(g_{mN}+ g_{mP})和 r_{ON} 和 r_{OP} 值的上升都會導致 bw 的下降，所以電流不能取得太小，由於 r_O 值不能太大所以我打算取小的 L 調整 W 和 m 的值控制電流。

以下經過幾次測試之後得到的 FoM 值:

Iin1 (uA)	Wn/Ln (m)	Wp/Lp (m)	current(uA)	bw(MHz)	gain(kΩ)	Fom
10	45u/0.6u (1)	14u/0.2u (5)	1152.9	691.029	0.90186	1.849943177
10	15u/0.2u (1)	10u/0.2u (5)	812.2059	660.682	0.86809	1.416154268
10	32.7u/0.5u (1)	11u/0.2u (5)	911.2784	650.637	0.88416	1.584096631
10	13u/0.18u (1)	8u/0.18u (5)	833.3595	664.201	0.85915	1.460372526
10	3.3u/0.18u (1)	7.2u/0.18u (5)	797.0091	650.991	0.85455	1.432681212

可以觀察到降低電流對於 FoM 的降低有很大的幫助，但同時 bw 也會降低不少，而 Closed-loop gain 雖然也會降低，但如上述推測變化幅度不會像 bw 一樣那麼大，因此可以總結 Current 和 bw、Closed-loop gain 之間存在 Trade-off。

註:上傳的 sp 檔為還未優化過後之參數，有註解優化過的參數。

2.Without Feedback

a.

```
+0:vdd      =    1.5000   0:vout2    = 840.1937m 0:vy        = 750.0000m
```

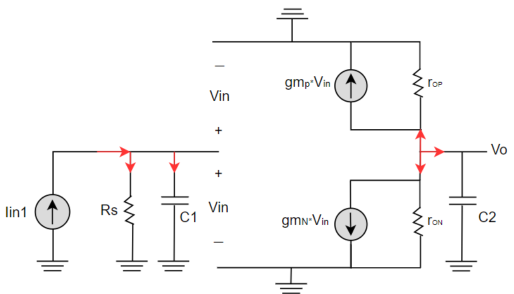
```
subckt
element  0:mn       0:mp
model    0:n_18.1   0:p_18.1
region   Saturation Saturation
  id        3.2743m   -3.2743m
  ibs      -5.001e-19  3.100e-19
  ibd      -7.7116f    6.0060f
  vgs     750.0000m -750.0000m
  vds     840.1937m -659.8063m
  vbs        0.         0.
  vth     421.4369m -520.9026m
  vdsat   283.4052m -259.3596m
  vod     328.5631m -229.0974m
  beta     66.5238m  100.4986m
  gam eff 507.4474m  557.0844m
  gm       17.5232m   22.2178m
  gds     303.6420u  895.4672u
  gmb       3.3039m    6.8303m
  cdtot   162.0940f  229.7144f
  cgtot   536.7187f  390.0009f
  cstot   638.5642f  540.9655f
  cbtot   372.3196f  440.9588f
  cgs     454.1642f  296.3367f
  cgd      45.0566f   71.5206f
```

```
dcgain_in_db= 124.3855
bw= 547.1992k
```

b.

```
v(vout2)/iivy                                =   -1.6571x
input resistance at              iivy        =   50.0000k
output resistance at v(vout2)                =  834.2275
```

c. <u>**Hand calculation**</u> (考慮低頻時，故 s=jω→0)



$$\text{use KCL} \Rightarrow \begin{cases} I_{in1} = \dfrac{V_{in}}{R_S} + sC_1V_{in} \text{ ......(1)} \\[2ex] sC_2V_o + \left(\dfrac{V_o}{r_{op}} + gm_p \cdot V_{in}\right) + \left(\dfrac{V_o}{r_{on}} + gm_n \cdot V_{in}\right) = 0 \text{ ......(2)} \end{cases}$$

$(1) \Rightarrow V_{in} = I_{in} \cdot R_s$

$(2) \Rightarrow V_{in} = V_o \cdot -\left(\dfrac{gds_p + gds_n}{(gm_p + gm_n)}\right)$

By(1)and(2) $\Rightarrow R_o = \dfrac{V_o}{I_{in1}} = -R_S \cdot (gm_N + gm_P) \cdot (r_{oN} \,||\, r_{oP})$

$Z_{out} = r_{oN} \,||\, r_{oP} \,||\, \dfrac{1}{sC2} = 3.293352k||1.1167355k = 833.9524(\Omega)$

$R_o = \dfrac{V_o}{I_{in1}} = -R_S \cdot (gm_N + gm_P) \cdot (r_{oN} \,||\, r_{oP})$

$= -(50000)\cdot(0.0175232+0.0222178)\cdot 833.9524$

$= -1657105.12\ (\Omega)$

	Calculate	Hspice	Error
$Z_{out}(\Omega)$	833.9524	834.2275	0.03%
Trans Impe. gain(Ω)	– 1657105.12	-1657100	0.0003%

誤差很小，可能來自計算時四捨五入造成計算上誤差，公式基本上正確。

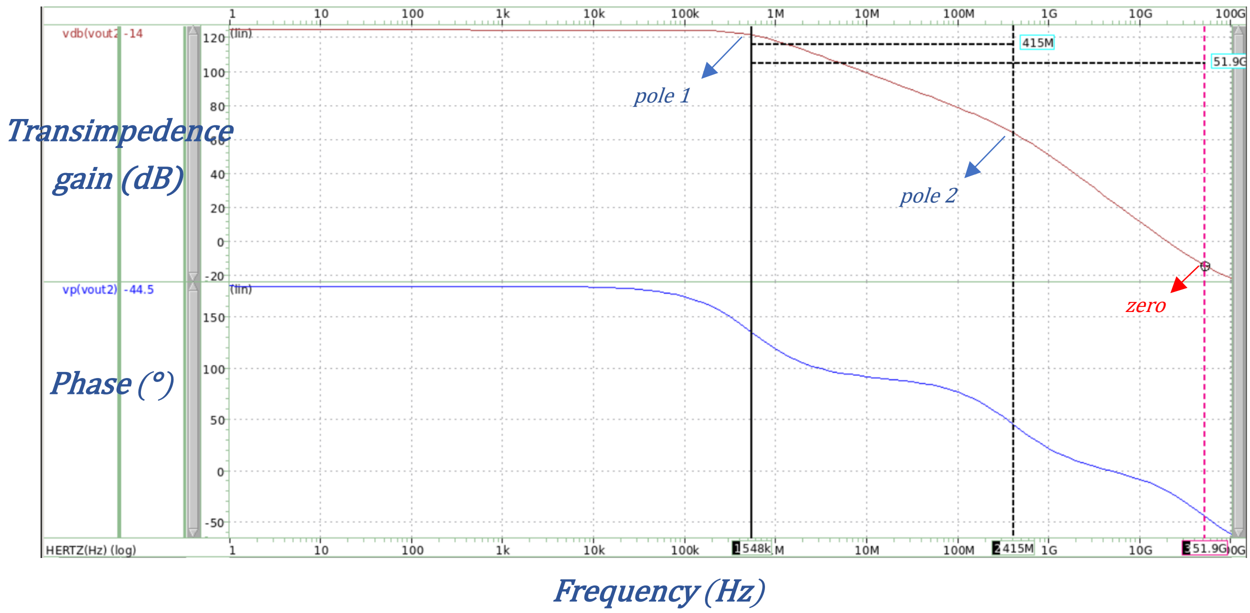
d.

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


 input =  0:iivy          output = v(vout2)

       poles (rad/sec)              poles ( hertz)
 real            imag            real            imag
 -3.44481x        0.             -548.258k        0.
 -2.60935g        0.             -415.291x        0.

       zeros (rad/sec)              zeros ( hertz)
 real            imag            real            imag
 325.944g         0.             51.8756g         0.
```



e.

Transfer Function 與第一題推導的公式很像，唯將 R_F 刪除，其餘都相同，就不再推導一次。

$$R_O = \frac{V_o}{I_{in1}} = \frac{sC_{GD}R_1R_2-(g_{mn}+g_{mp})R_1R_2}{s^2\left(R_1R_2C_AC_B - C_{GD}^2R_1R_2\right)+s\left(R_1C_A + R_2C_B + C_{GD}(g_{mn}+g_{mp})R_1R_2\right)+1} = \frac{sd-e}{s^2a+sb+1}$$

其中 $C_A = C_{GD} + C_{DB} + C_2$, $C_B = C_{GD} + C_{GS} + C_1$, $R_1 = r_{ON} \parallel r_{OP}$, $R_2 = R_S$

$C_{GS,N}$	$C_{GS,P}$	$C_{GD,N}$	$C_{GD,P}$	$C_{DB,N}$	$C_{DB,P}$
4.54E-13(F)	2.96E-13(F)	4.51E-14(F)	7.15E-14(F)	1.1E-13(F)	1.6E-13(F)

C_{GS}	C_{GD}	C_{DB}	r_{ON}	r_{OP}	$r_{ON} \parallel r_{OP}$
7.51E-13(F)	1.16E-13(F)	2.75E-13(F)	3293.3520Ω	1116.735Ω	833.9524Ω

C_A	C_B	R1	R2	g_{mN}	g_{mP}
1.39E-12(F)	1.87E-12(F)	833.9524Ω	50 kΩ	0.0175232(Ω^{-1})	0.0222178(Ω^{-1})

a	b	d	e
1.08E-16	2.88E-7	4.86099E-6	-1657105.124

Zero: ds–e =0 ⇒ $W_Z = \frac{e}{d} = 3.4089856 \cdot 10^{11}$(rad/sec) = 54.2557 (GHz)

$W_{Zero,calculate}$ = 54.2557 (GHz)

$W_{Zero,hspice}$ = 54.8258 (GHz)

$$W_{Zero,error} = \left|\frac{W_{Zero,hspice} - W_{Zero,calculate}}{W_{Zero,calculate}}\right| * 100\% = 1.05\%$$

Poles: $as^2+bs+1 = 0 \Rightarrow W_{Pole} = \frac{-b\pm\sqrt{b^2-4a}}{2a}$

$= -1.334525 \cdot 10^9 \pm 1.3310447 \cdot 10^9$ (rad/sec)

$= -2.1239628 \cdot 10^8 \pm 2.1184235 \cdot 10^8$ (Hz)

$W_{Pole1,calculate} = -553.928$ (KHz)　　$W_{Pole1,hspice} = -548.258$ (kHz)

$W_{Pole2,calculate} = -424.238$ (MHz)　　$W_{Pole2,hspice} = -415.291$ (MHz)

$$W_{Pole,error} = \left|\frac{W_{Pole,hspice} - W_{Pole,calculate}}{W_{Pole,calculate}}\right| * 100\% = 1.10\%(\text{Pole1})$$

$$=2.06\%\ (\text{Pole2})$$

Comparison	Pole1	Pole2	Zero
Hspice	–548.258 (kHz)	–415.291 (MHz)	54.8258 (GHz)
Calculate	–553.928 (kHz)	–424.238 (MHz)	54.2557 (GHz)
Error	1.02%	2.1%	1.05%

誤差不大，推測造成誤差原因為電路中的寄生電容，且因為此式子較為複雜，故在計算時，各值的四捨五入也會導致最終計算上的結果有些許誤差。

3. Discussion

a.

I. 可以發現有 Feedback 的電路 Band-width 大很多，假設不考慮 Loading R_F，如果有一個 Feedforward 放大器的 Transfer function 為 $A(s)=\frac{A_0}{1+s/\omega_0}$，可以推導出 Closed-loop $\frac{Y}{X}(s)=\frac{\frac{A_0}{1+s/\omega_0}}{1+\beta\frac{A_0}{1+s/\omega_0}}=\frac{A_0}{1+\beta A_0+s/\omega_0}=\frac{\frac{A_0}{1+\beta A_0}}{1+\frac{s}{\omega_0(1+\beta A_0)}}$，也就是加了 feedback 的系統可以使得−3dB band-width 增加$1+\beta A_0$倍。

II. 然而觀察上述公式可以發現 Closed-loop gain 會下降許多，如果 A_0 很大的話，Closed-loop gain 會只剩下$\frac{1}{\beta}$。

III. 如果從 Output Impedence 的觀點來看，因此題型形式為 V-I 的 Feedback 的系統，所以 Output Impedence 大幅下降了，此題可以推出 $Z_{out,with\ fb.}=\frac{(Z_{out,without\ fb.})\,||\,R_F}{1+kA}$，其中$k=-R_F^{-1}$, A = Open-loop gain。

IV. 如果從 input impedence 的觀點來看，因此題型形式為 V-I 的 feedback 的系統，所以 input impedence 大幅下降了，此題可以推出 $Z_{in,with\ fb.}=\frac{(Z_{in,without\ fb.})\,||\,R_F}{1+kA}$，其中$k=-R_F^{-1}$, A = Open-loop gain。

In summary, Negative Feedback system offers the following benefits:

a. **Desensitize the gain:**
   According to the formula, if the Open-loop gain is very large, the Closed-loop gain will approach $\frac{1}{\beta}$.

b. **Reduce effect of noise:**
   The feedback network itself may contain resistors or transistors,degrading the overall noise performance.

c. **Control the input and output impedence:**
   As the derivation of the formula, the input and output impedances are related to $1+\beta A$. Depending on the type of feedback system, we can determine whether it amplifies or attenuates. If it's a voltage-current (V-I) feedback system like in this case, we can get smaller input and output impedances.

d. **Extend bandwidth of the amplifier:**
   As stated in I.

   However, if a Negative Feedback system is used, the advantages mentioned above are traded off with gain, as described in statement II.

b.

table. 1(還未優化過後的數據)

Fig. 1			
Working item	Specification	Simulation	Calculation
Vdd (V)	1.5		
C1, C2 (F)	1p		
transimpedance DC gain (kΩ)	> 0.85	0.947	1.057
bandwidth (MHz)	> 650	813.8176	
Closed-loop poles/zeros (rad/s)		$W_{Pole} =$ $-1.86 \cdot 10^9 \pm 3.46 \cdot 10^9 j$ $W_{zero} =$ $3.20190 \cdot 10^{11}$	$W_{Pole} =$ $-1.93 \cdot 10^9 \pm 3.56 \cdot 10^9 j$ $W_{zero} =$ $3.4364 \cdot 10^{11}$
Closed-loop input impedance (Ω)		51.8785	56.2194
Closed-loop output impedance (Ω)		25.1933	26.9124
Input common mode current (uA)		15	
Output common mode voltage (V)	0.75 (± 1%)	0.752599	
M1 (W/L), m		25um/0.6um (m = 5)	
M2 (W/L), m		25 um/0.2um (m = 8)	
FoM (uA/($\boldsymbol{k\Omega} \times \boldsymbol{MHz}$))		4.26913	

table. 2(還未優化過後的數據)

Fig. 2			
Working item	Specification	Simulation	Calculation
Vdd (V)	1.5		
C3, C4 (F)	1p		
transimpedance DC gain (kΩ)	-	1657.1	1657.105
bandwidth (MHz)	-	0.5471992	
Closed-loop poles/zeros (rad/s)		W_{Pole1} =-344.481M W_{Pole2} =-2.60935G W_{zero} =325.944G	W_{Pole1} =-348.043M W_{Pole2} =-2.66557G W_{zero} =340.898G
Closed-loop input impedance (Ω)		50k	
Closed-loop output impedance (Ω)		834.2275	833.9524
Input common mode current (uA)	same as Iin1	15	
Output common mode voltage (V)	-	0.8401937	
M3 (W/L), m	same as M1	25um/0.6um (m = 5)	
M4 (W/L), m	same as M2	25 um/0.2um (m = 8)	

註:上傳的 sp 檔為還未優化過後的參數。