106010006 黃詩瑜 電機 21

Working Item	Specification	Simulation	Calculation
Vdd	1.8-V		
Tail current(Imx)	Open for design(μA)#1	34.7230	
Differential-mode gain	9(V/V)	9.2782	9.2785422
Input common mode	Open for design (VBS, V)	VBS:0.7 VBS1:0.48	
Common-mode gain	Open for design (V/V)	-57.0533m	$-61.3153m$
Input size	Open for design(W/L)	Mx1:50u/1.5u Mx:50u/5u	
Differential gm	Open for design(mA/V)	352.7361m	
Load R	Open for design(Ohm)	29k	
Bandwidth	Open for design (MHz)#2	3.79705	3.662
Linear range	Single-ended input amplitude(mV)#3	21.4	4.015
FoM	(#2) x (#3) / (#1)	2.3401	0.4234

(a)

Mx1: W=50u L=1.5u

Mx: W=50u L=5u

VBS=0.7V

VBS1=0.48V

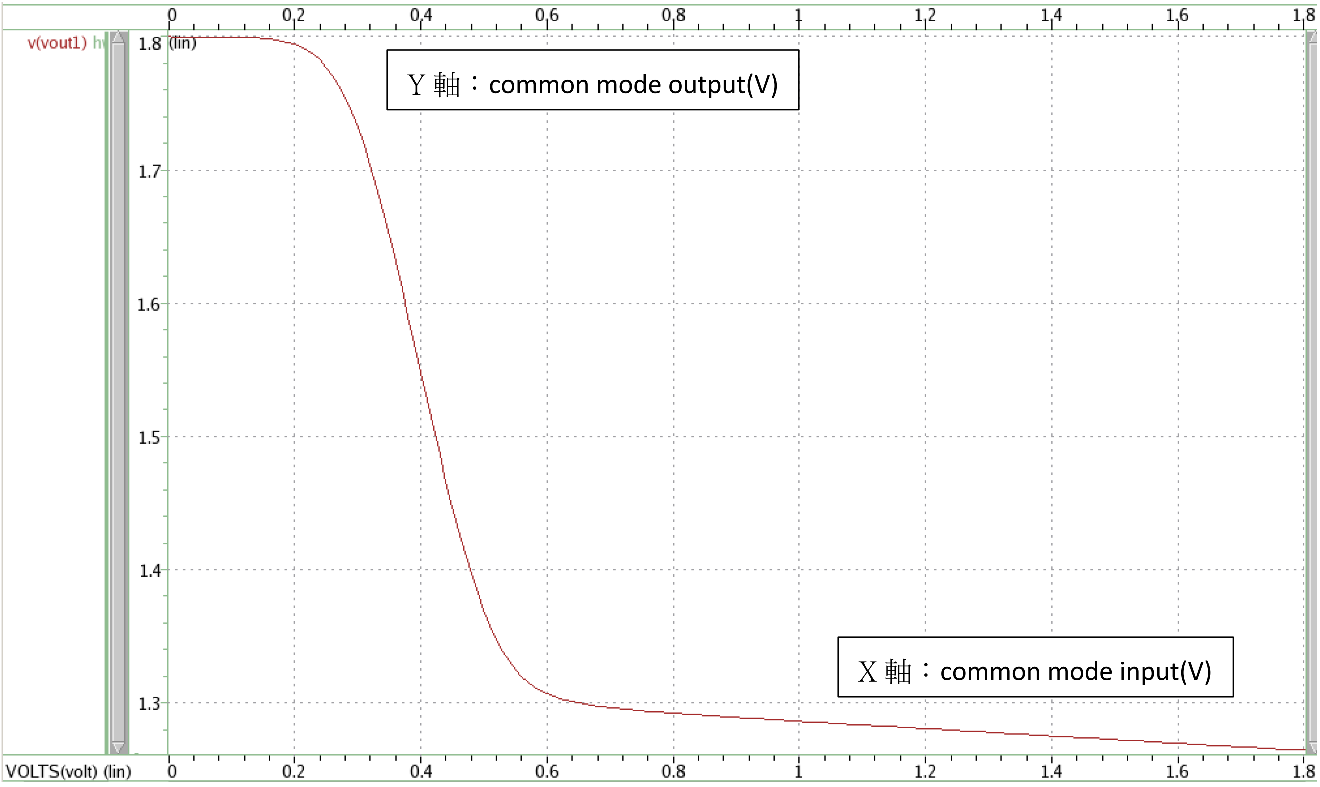
Rd=29k(ohm)

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

     v(vout1,vout2)/v+                         =     9.2782
     input resistance at              v+       =  1.000e+20
     output resistance at v(vout1,vout2)       =    52.6079k
```

(b)

```
**** mosfets


subckt
element  0:mx1a      0:mx1b      0:mx
model    0:n_18.1    0:n_18.1    0:n_18.1
region     Saturati    Saturati    Saturati
  id       17.3615u    17.3615u    34.7230u
  ibs    -968.9916a  -968.9916a  -5.198e-21
  ibd      -4.6659f    -4.6659f  -968.9838a
  vgs     430.7466m   430.7466m   480.0000m
  vds       1.0273      1.0273    269.2534m
  vbs    -269.2534m  -269.2534m     0.
  vth     410.6667m   410.6667m   324.8238m
  vdsat    72.1285m    72.1285m   147.4870m
  vod      20.0799m    20.0799m   155.1762m
  beta     10.2686m    10.2686m     3.0062m
  gam eff 514.4938m   514.4938m   507.4460m
  gm      352.7361u   352.7361u   377.8529u
  gds       3.5344u     3.5344u     4.5115u
  gmb      62.6927u    62.6927u    75.4141u
  cdtot    60.6532f    60.6532f    97.8384f
  cgtot   388.2851f   388.2851f     1.6549p
  cstot   387.9204f   387.9204f     1.7093p
  cbtot   203.6234f   203.6234f   541.7903f
  cgs     309.7622f   309.7622f     1.4923p
  cgd      17.7400f    17.7400f    26.5692f
```

(c)



測得 Waveform 斜率為 gain= -57.1m(V/V)

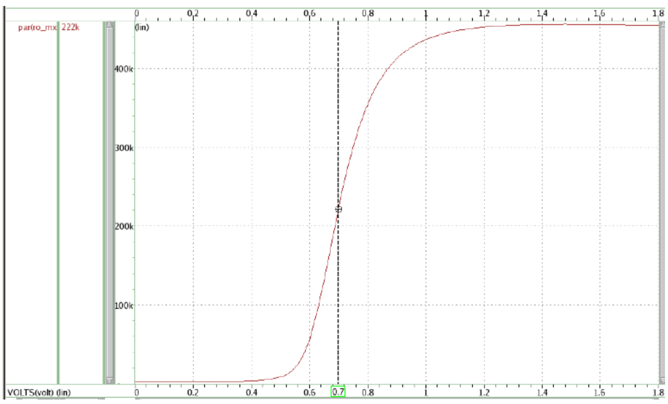
Equation					
File	Equation	Specification		Result	
		Min	Max	Value	Mean
D0:hw5c.sw0	gain			-57.1m	

利用 hspice measure 測得 gain= -57.0533m(V/V)

```
****** dc transfer curves tnom=  25.000 temp=  25.000 ******
dcgain= -57.0533m
```

手算 gain 值：

$$\frac{\Delta Vout}{\Delta Vin} = \frac{-Rd}{2ro + \dfrac{1}{gm}}\text{，}ro\text{為}Mx\text{的，}gm\text{為}Mx1\text{ 的}$$



ro=222k(ohm)，gm=352.7361u(V/A)

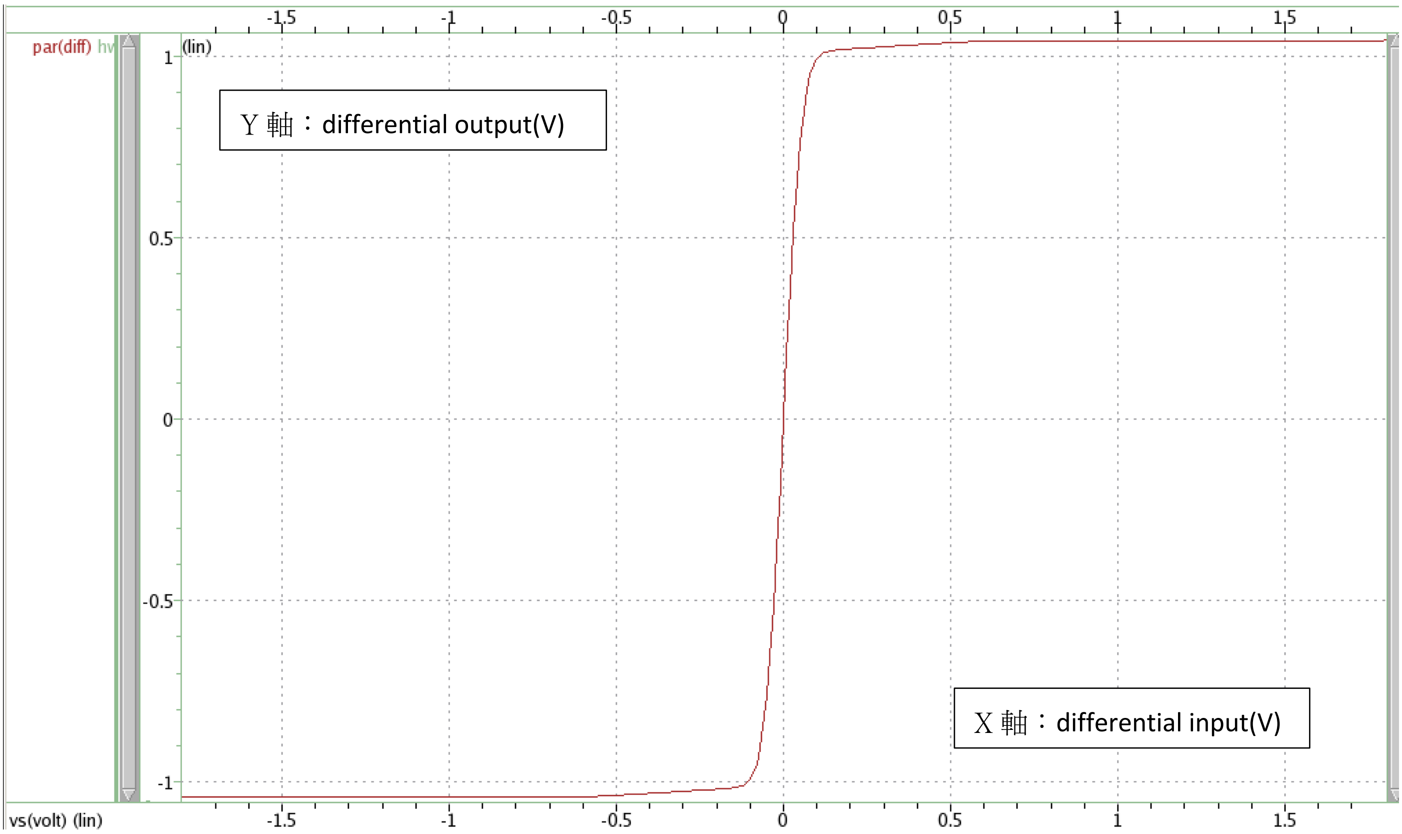
$$\frac{\Delta Vout}{\Delta Vin}=\frac{-Rd}{2ro+\frac{1}{gm}}=\frac{-29k}{2X222k+\frac{1}{352.73621u}}=-0.0613153(\frac{V}{V})$$

與 hspice measure 測得 gain 值誤差：

$$\frac{57.0533m-(61.3153m)}{57.0533m}X100\%=7.47\%$$

有一些誤差，原因是左右兩邊結構完全對稱，Vout1=Vout2 的理想情況下，才可以將 differential amplifer 視為兩個 half circuit，因為某些 variation 的問題，所以實際出來的模擬值會有誤差。

(d)



測得 Waveform 斜率為 gain= 10.5(V/V)

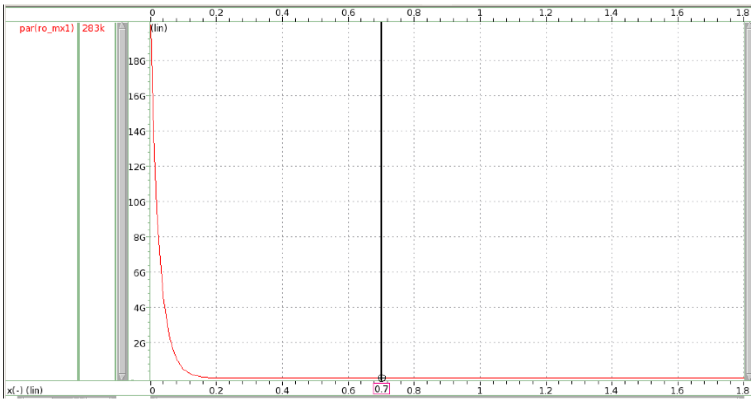
Equation					
File	Equation	Specification		Result	
		Min	Max	Value	Mean
D0:hw5d.sw0	slope('0|par(diff)',0)			10.5	

利用 hspice measure 測得 gain=9.2782 (V/V)

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

     v(vout1,vout2)/v+                        =    9.2782
     input resistance at          v+          =  1.000e+20
     output resistance at v(vout1,vout2)      =   52.6079k
```

手算 gain 值：

$$gain = gm(ro//Rd) = \frac{gm}{\frac{1}{ro}+\frac{1}{Rd}}$$ ，ro為Mx1a的，gm為Mx1a的



ro=283k(ohm)

$$gain = \frac{gm}{\frac{1}{ro}+\frac{1}{Rd}} = \frac{325.7361u}{\frac{1}{283k}+\frac{1}{29k}} = 9.2785422$$

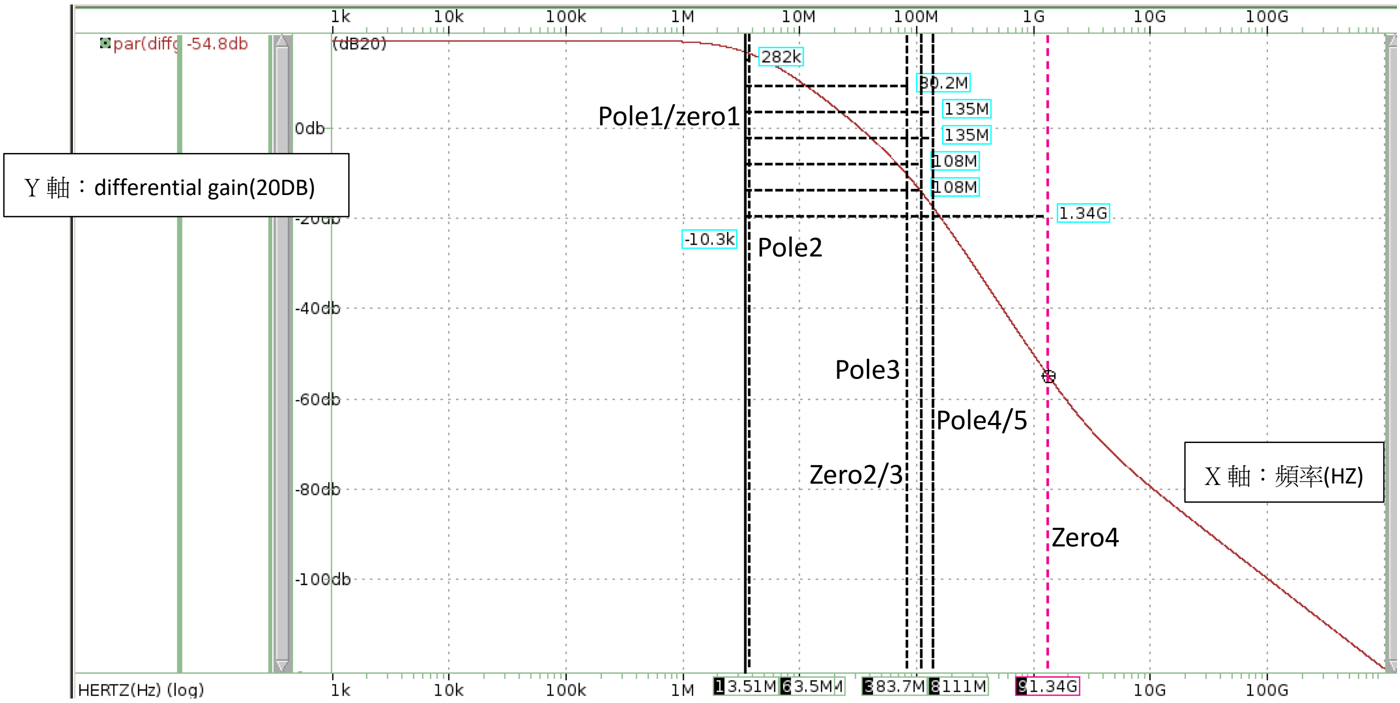
與 hspice measure 測得 gain 值誤差：

$$\frac{9.2782-9.2785422}{9.2782} X100\% = 0.000584\%$$

誤差極小，模擬值與手算值幾乎一樣

(e)

```
   input =   0:v+           output = v(vout1,vout2)

        poles (rad/sec)                   poles ( hertz)
real            imag              real            imag
-22.0801x       0.                -3.51416x       0.
-23.8576x       0.                -3.79705x       0.
-526.232x       0.                -83.7525x       0.
-872.817x       -523.986x         -138.913x       -83.3949x
-872.817x       523.986x          -138.913x       83.3949x

        zeros (rad/sec)                   zeros ( hertz)
real            imag              real            imag
-22.0825x       0.                -3.51454x       0.
-698.132x       485.545x          -111.111x       77.2768x
-698.132x       -485.545x         -111.111x       -77.2768x
8.46003g        0.                1.34645g        0.
```

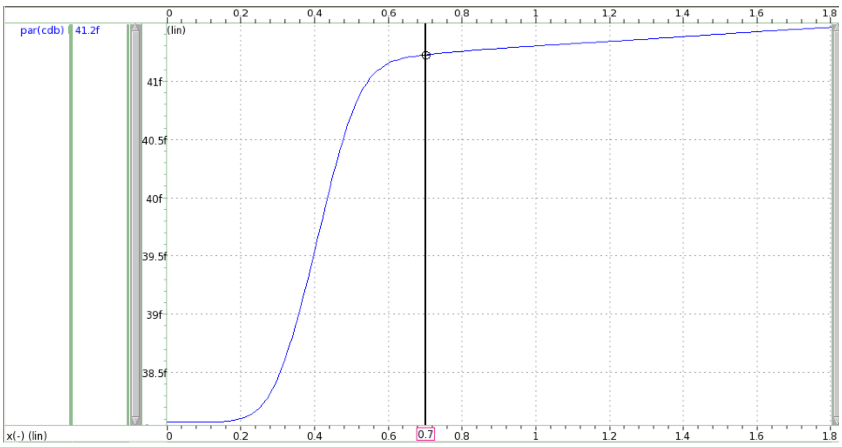


手算:

$$\text{gain} = \frac{(C_{GD} - g_m)R}{as^2 + bs + 1}$$

$$R = Rd//ro = \frac{1}{\frac{1}{29k} + \frac{1}{283k}} = 2.63X10^4$$

$$gm = 352.7361\text{u}(\text{V/A}), Rs = 5k(ohm), Cgs = 309.7622f(F), Cgd = 17.74f(F)$$



Cdb=41.2f(F)

$$\text{a} = R_S R(C_{GS}C_{GD} + C_{DB}C_{GD} + C_{GS}C_{DB} + C_{GD}C_L + C_{GS}C_L)$$
$$= 5kX2.63X10^4(309.7622fX17.74f + 41.2fX17.74f + 309.7622fX41.2f + 17.74fX1.5p$$
$$+ 309.7622fX1.5p = 6.7096X10^{-17}$$

$$b = (1 + g_m R)C_{GD}R_S + R_S C_{GS} + R(C_{DB} + C_{GD} + C_L)$$
$$= (1 + 352.7361uX2.63X10^4)17.74fX5k + 5kX309.7622f$$
$$+ 2.63X10^4(41.2f + 17.74f + 1.5p) = 4.346X10^{-8}$$

$$pole1 = \frac{1}{bX2X\pi} = \frac{1}{4.346X10^{-8}X2X\pi} = 3.662 \times 10^6(\text{Hz})$$

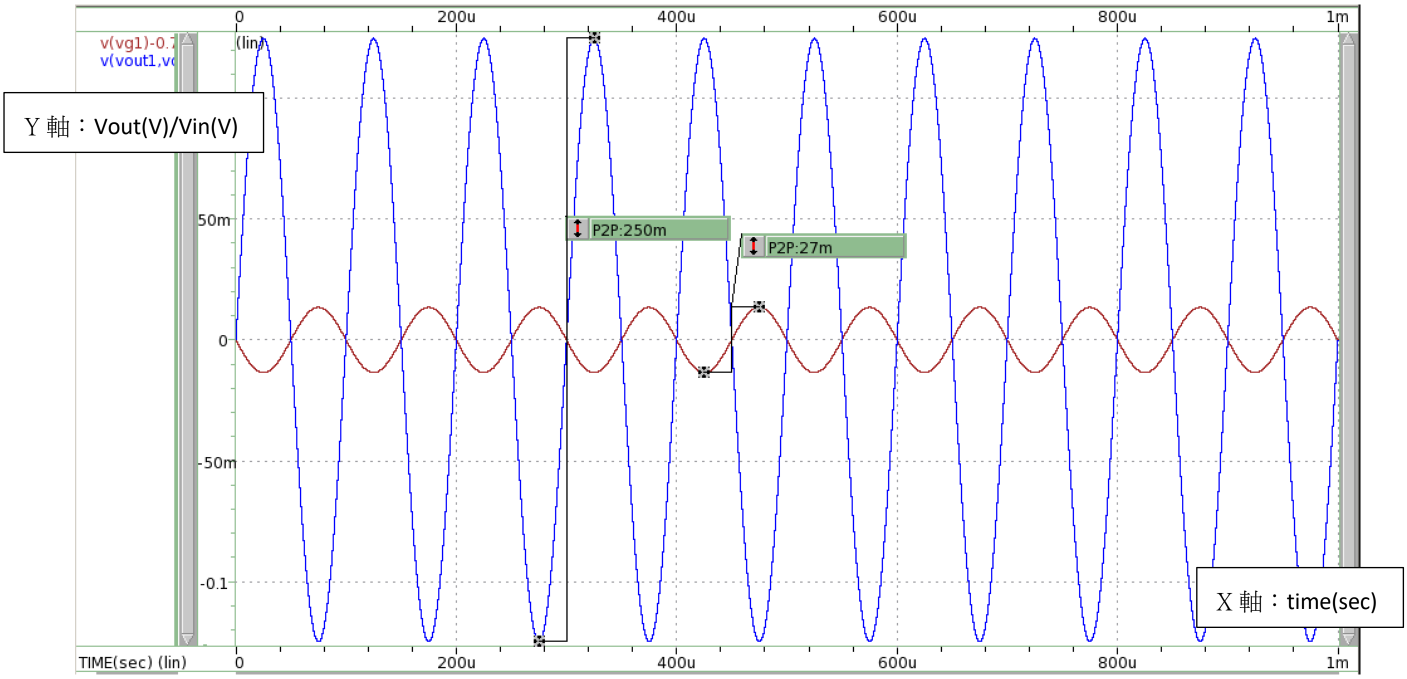
$$pole2=\frac{\mathrm{b}}{\mathrm{a}X2X\pi}=\frac{4.346X10^{-8}}{6.7096X10^{-17}X2X\pi}=1.03\times10^{8}(\mathrm{Hz})$$

$$zero=\frac{g_m}{C_{GD}X2X\pi}=\frac{352.7361u}{17.74fX2X\pi}=2.1646\times10^{9}(\mathrm{Hz})$$

因為這個 differential circuit 上有許多寄生電容，產生很多 pole 和 zero，從.pz 檔可看到有 5 個 pole 和 4 個 zero，其中 pole1 和 zero1 幾乎重疊，所以兩個抵銷，手算結果的 pole1 在 3.662M(HZ)與.pz 的 pole2 在 3.797M(HZ)還蠻接近的，而 pole3/4/5 與 zero2/3 都很相近，2 個 pole 和 2 個 zero 抵銷後，會剩一個 pole，手算結果的 pole2 在 103M(HZ)，在 pole3/4/5 與 zero2/35 之間，我認為很合理，.pz 的 zero4 和手算的 zero 有點差距，但是在能接受的範圍，整體來看只有 2 個 pole 和 1 個 zero 影響整個 bandwidth。

(f)

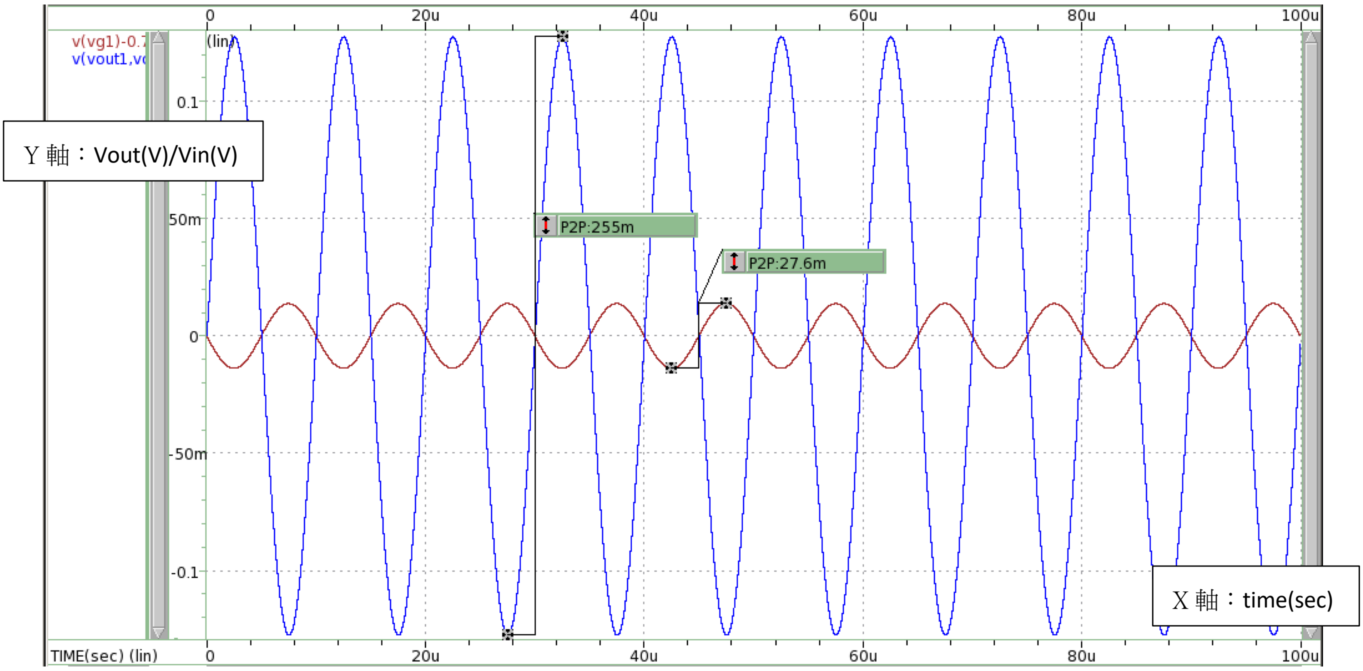
頻率:10K(HZ) Vin (p-p)=27mV 振幅=13.5mV，Vout (p-p)=250mV 振幅=125mV



harmonic no	frequency (hz)	fourier component	normalized component	phase (deg)	normalized phase (deg)
1	10.0000k	124.9096m	1.0000	-90.1580	0.
2	20.0000k	31.0538u	248.6100u	-50.8016m	90.1071
3	30.0000k	115.0463u	921.0368u	-90.4578	-299.8293m
4	40.0000k	2.5307n	20.2604n	171.9430	262.1010
5	50.0000k	61.0016n	488.3661n	-90.6948	-536.8852m
6	60.0000k	183.5598p	1.4695n	-175.6228	-85.4648
7	70.0000k	72.9156p	583.7466p	74.9815	165.1394
8	80.0000k	100.6337p	805.6523p	23.9129	114.0708
9	90.0000k	46.5886p	372.9786p	-104.0390	-13.8811

total harmonic distortion = 0.0954 percent

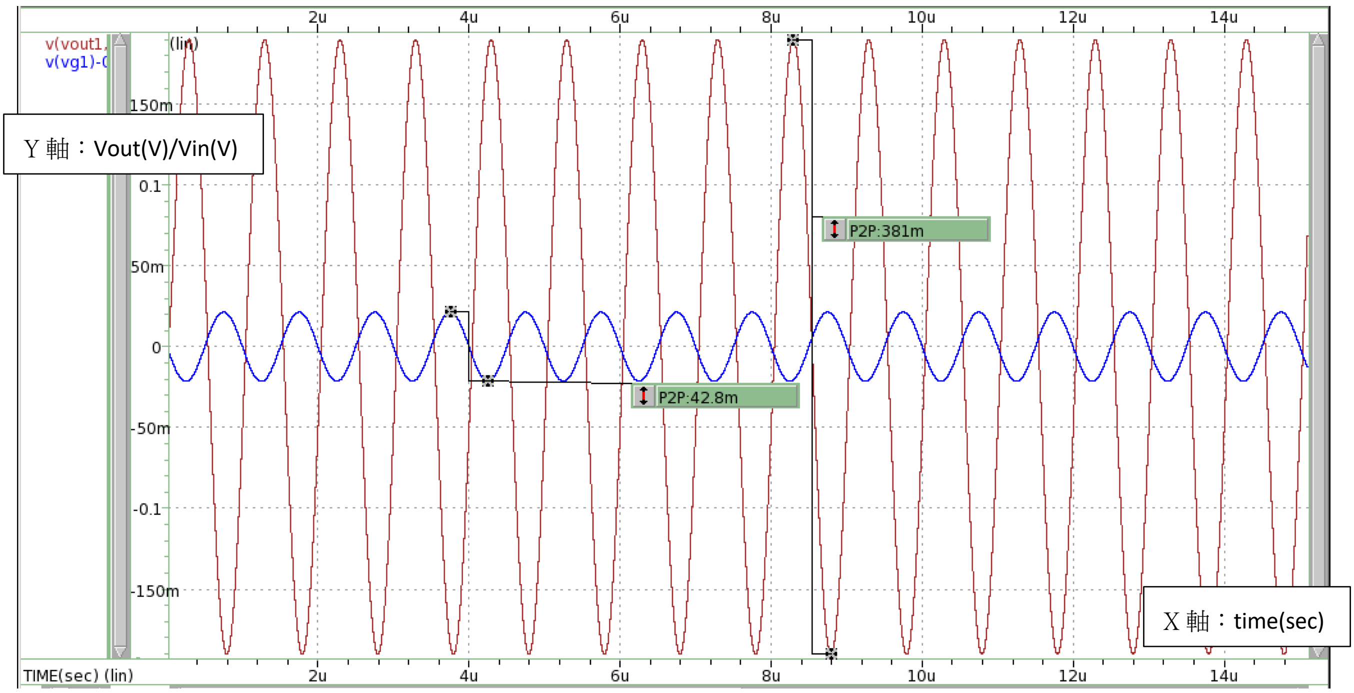
頻率:100K(HZ)　Vin (p-p)=27.6mV 振幅=13.8mV，Vout (p-p)=255mV　振幅=127.5mV



harmonic no	frequency (hz)	fourier component	normalized component	phase (deg)	normalized phase (deg)
1	100.0000k	127.6256m	1.0000	-91.5792	0.
2	200.0000k	32.4515u	254.2709u	-508.5701m	91.0706
3	300.0000k	122.5135u	959.9449u	-94.5687	-2.9896
4	400.0000k	4.3028n	33.7142n	122.8711	214.4503
5	500.0000k	68.0304n	533.0470n	-97.0162	-5.4371
6	600.0000k	162.0975p	1.2701n	-116.0721	-24.4929
7	700.0000k	389.7459p	3.0538n	29.0518	120.6309
8	800.0000k	159.7193p	1.2515n	80.7979	172.3771
9	900.0000k	375.4179p	2.9416n	-162.4250	-70.8458

total harmonic distortion =　0.099305　percent

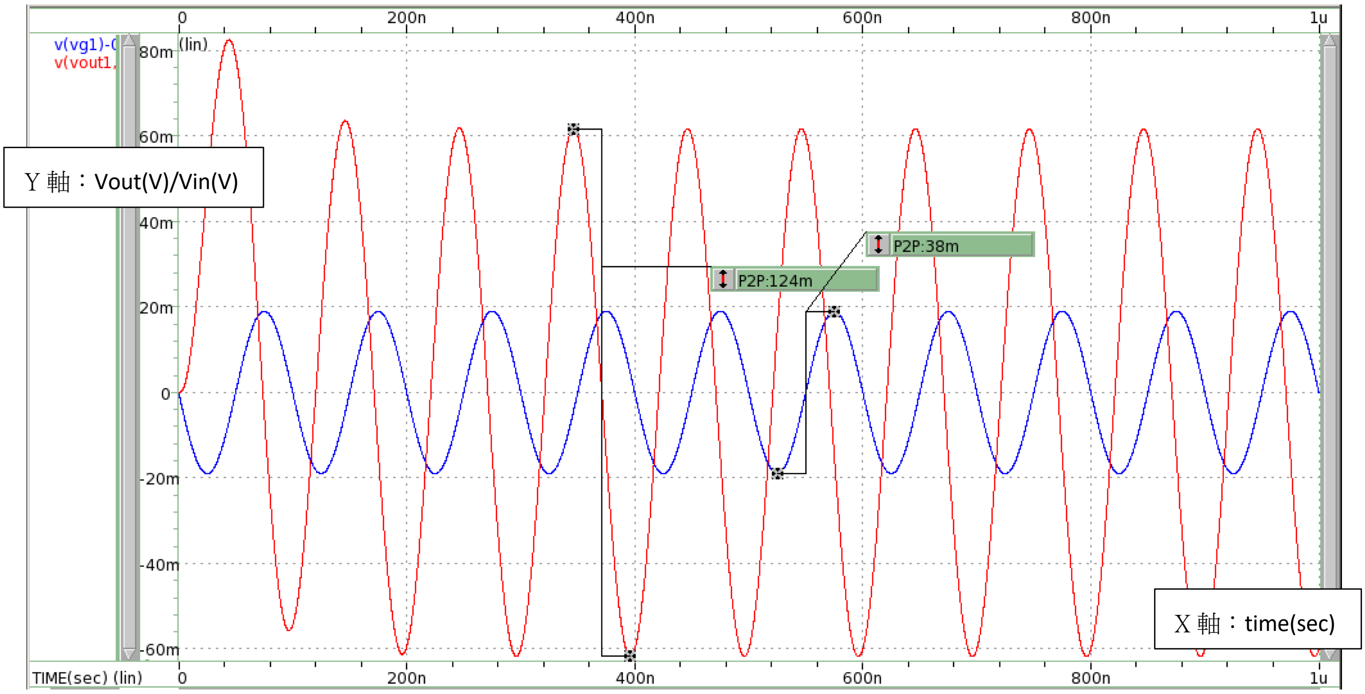
頻率:1M(HZ)　Vin (p-p)=42.8mV　振幅=21.4m，Vout (p-p)=381mV　振幅=190.5mV



harmonic no	frequency (hz)	fourier component	normalized component	phase (deg)	normalized phase (deg)
1	1.0000x	190.6444m	1.0000	-105.4617	0.
2	2.0000x	77.8965u	408.5960u	-5.5683	99.8934
3	3.0000x	362.8724u	1.9034m	-129.0558	-23.5941
4	4.0000x	115.4543n	605.6003n	41.2401	146.7018
5	5.0000x	500.6749n	2.6262u	-141.9146	-36.4529
6	6.0000x	6.8067n	35.7037n	-98.3980	7.0637
7	7.0000x	35.0908n	184.0644n	38.6944	144.1560
8	8.0000x	3.5709n	18.7306n	50.0157	155.4773
9	9.0000x	22.4682n	117.8542n	-158.0375	-52.5758

total harmonic distortion = 0.099467 percent

頻率:10M(HZ) Vin (p-p)=38mV 振幅=19mV，Vout (p-p)=124mV 振幅=62mV



harmonic no	frequency (hz)	fourier component	normalized component	phase (deg)	normalized phase (deg)
1	10.0000x	61.7309m	1.0000	-166.1785	0.
2	20.0000x	42.2247u	684.0122u	-30.9186	135.2599
3	30.0000x	44.4948u	720.7866u	152.7018	318.8803
4	40.0000x	784.7430n	12.7123u	-123.2529	42.9256
5	50.0000x	22.0115n	356.5712n	142.6648	308.8433
6	60.0000x	224.0632n	3.6297u	-85.0626	81.1159
7	70.0000x	352.8835n	5.7165u	-65.8757	100.3028
8	80.0000x	78.0921n	1.2650u	-42.6355	123.5430
9	90.0000x	375.4828n	6.0826u	-31.3161	134.8624

total harmonic distortion = 0.0993807 percent

模擬出的 single-ended input amplitude value at 1MHz 為 21.4mV，手算的 linear range 值為 0.2Vov=0.2X20.0799m=4.015mV，兩者誤差非常多，推測是因為我為了符合下一題的 FoM，盡量將電流減少，而 nmos 的狀態與 cutoff 太接近了，所以不能完全符合 current 在 saturation 的公式，且在推導公式的過程中利用了大量的近似，所以誤差才這麼多。

(g)

$$gain = gm(ro//Rd)\text{，}ro\text{為}Mx1a\text{的，}gm\text{為}Mx1a\text{的}$$

$$\mathrm{gm} = \mu\mathrm{Cox}\frac{w}{L}Vov$$

$$\mathrm{ro} = \frac{1}{\frac{1}{2}\mu Cox\frac{W}{L}Vov^2\lambda} = \frac{1}{\lambda XId}$$

$$\mathrm{FoM} = \frac{bandwidth \times linear\ range}{power} \propto \frac{\frac{1}{R_D C} \times V_{ov}}{I_D}$$

我先將 gain 調成大於 9，gain 正比於 Rd，所以將 Rd 設大，為了讓 gm 也增大，我將 Mx1/Mx 的 W/L 設大，再觀察 Vth 將 Vbs1 先設定在讓 Mx 保持在 saturation 的狀態，觀察.lis 檔 sweep 出的 Vbs 值再哪個地方會讓 gain 大於 9。

FoM 正比於 bandwidth 與 linear range，反比於 power，而 bandwidth 反比於 Rd*C，所以 Rd 不能太大，所以我將 Rd 減小一些，而 FoM 正比於 Vov，反比於 Id，微分後，FoM 反比於 2Vov，所以我將 Vbs 慢慢減小，FoM 就會上升，但因為 tail current 已經固定，所以 Mx1 的 source 端電壓會下降，造成 Mx 的 Vbs 下降，讓 Mx 跑到 linear region，所以 Vbs 不能調太小。降低 Mx1 的 W/L 也能增加 FoM，但是下降太多會讓 gain 變小，要隨時注意 gain 要保持在 9 以上。

Sp 檔:

```
***hw5
.prot
.lib 'cic018.l' TT
.unprot
.option
+ post=1
+ACCURATE=1
+runlvl=6
.option delmax = 1e-10
.temp 25


.param vs =0

Mx1a Vout1 VR1 Vx GND N_18 w=50u l=1.5u m=1
Mx1b Vout2 VR2 Vx GND N_18 w=50u l=1.5u m=1
Mx Vx VBS1 GND GND N_18 w=50u l=5u m=1


VBS VG GND dc = 0.7V
VBS1 VBS1 GND dc = 0.48V
V+ VG VG1 dc =  vs ac =0.5 0
V- VG VG2 dc = -vs ac =0.5 180
VD VDD GND 1.8V

CL1 Vout1 GND 1.5pF
CL2 Vout2 GND 1.5pF
Rd1 VDD Vout1 29k
Rd2 VDD Vout2 29k
Rs1 VG1 VR1 5k
Rs2 VG2 VR2 5k

*a
.tf V(Vout1,Vout2) V+

*b
.op


*c
.meas DC dcGain DERIV V(Vout1) at=0.7V
.dc VBS 0 1.8 0.01
.probe DC
+ gm = par('1/LX7(Mx1a)')
+ ro_mx1 = par('1/LX8(Mx1a)')
+ ro_mx  = par('1/LX8(Mx)')
+ cdb = par('LX29(Mx1a)')
```

```
*d
*.alter
*.dc vs -1.8 1.8 0.01
*.probe DC Diff= par('(V(vout1)-V(vout2))')

*e
*.ac dec 1k 1k 1000G
*.pz V(Vout1,Vout2) V+
*.probe ac Diffgain =par('(V(Vout1)-V(Vout2))/(V(VG1)-V(VG2))')

*f
*.alter
*V+ VG VG1 sin(0V 0.0135V 10k 0ns)
*V- VG VG2 dc =-vs ac =0
*.tran 0.1ns 1000us
*.four 10k v(vout1,vout2)

*.alter
*V+ VG VG1 sin(0V 0.0138V 100k 0ns)
*V- VG VG2 dc =-vs ac =0
*.tran 0.1ns 100us
*.four 100k v(vout1,vout2)

*.alter
*V+ VG VG1 sin(0V 0.0213V 1x 0ns)
*V- VG VG2 dc =-vs ac =0
*.tran 0.1ns 30us
*.four 1x v(vout1,vout2)

*.alter
*V+ VG VG1 sin(0V 0.019V 10x 0ns)
*V- VG VG2 dc =-vs ac =0
*.tran 0.1ns 1us
*.four 10x v(vout1,vout2)


.end
```