國立清華大學

Analog Circuit Design

Homework 2

Differential Pair

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目錄

Operation point 3

(a) Please design the device size of Mx, Ms, load resistance Rd, and the bias voltage VBS and VBS1, to make the small differential signal voltage gain (vout/vi) larger than 6.0 (V/V). (Please note, since Ms serves as a current source, Ms must stay in the saturation region). 3

(b) Please print out the small signal parameters of active devices from list file. 4

(c) Under the operation condition in (a), please run .DC then plot the differential input – differential output transfer curve (as in slide 6). Try to plot and measure its small signal differential mode gain. 5

(d) Compare the gain value with hand calculation using the small signal parameters from (b). 6

(e) Like (c) please also run .DC to plot the common-mode input – common-mode output transfer curve (as in slide 6). Try to plot and measure its small signal common mode gain. 7

(f) And compare the gain value with hand calculation using the small signal parameters from (b). 8

Frequency response 9

(g) The small signal -3dB bandwidth of differential mode signal has to be larger than 30MHz. Please simulate and plot the differential mode frequency response of this gain stage. 9

(h) Use .pz to simulate and mark the poles/zeros on this curve. 10

(i) Compare with hand calculations 10

Linearity 11

(j) Please input differential sinusoidal waveforms to estimate the harmonic distortion. Please use .four to simulate the THD performance. And also use .tran to plot the maximum output differential voltage waveforms that achieve -60dB THD at 1MHz. The single-ended input amplitude value is defined as the linear range in this homework. The linear range must be larger than 10mV. 11

(k) Please print out the .THD results. 12

(l) Compare the simulated input amplitude with the hand calculation. 12

(m) Under this amplitude please also simulate the THD performance under 100KHz and 10MHz respectively. 13

(n) We will use the “bandwidth (MHz) x linear range (mV) / current (μA)” as the figure of merit (FoM). Please try to make this FoM maximal. 14

(o) Please use your design equations to explain how to achieve max FOM. 15

Operation point

(a) Please design the device size of Mx, Ms, load resistance Rd, and the bias voltage VBS and VBS1, to make the small differential signal voltage gain (vout/vi) larger than 6.0 (V/V). (Please note, since Ms serves as a current source, Ms must stay in the saturation region).

Mx size	Ms size	RD	VBS	VBS1
W=0.31u L=0.18u m=10	W=0.51u L=0.18u m=10	14.3K	0.65V	0.61V

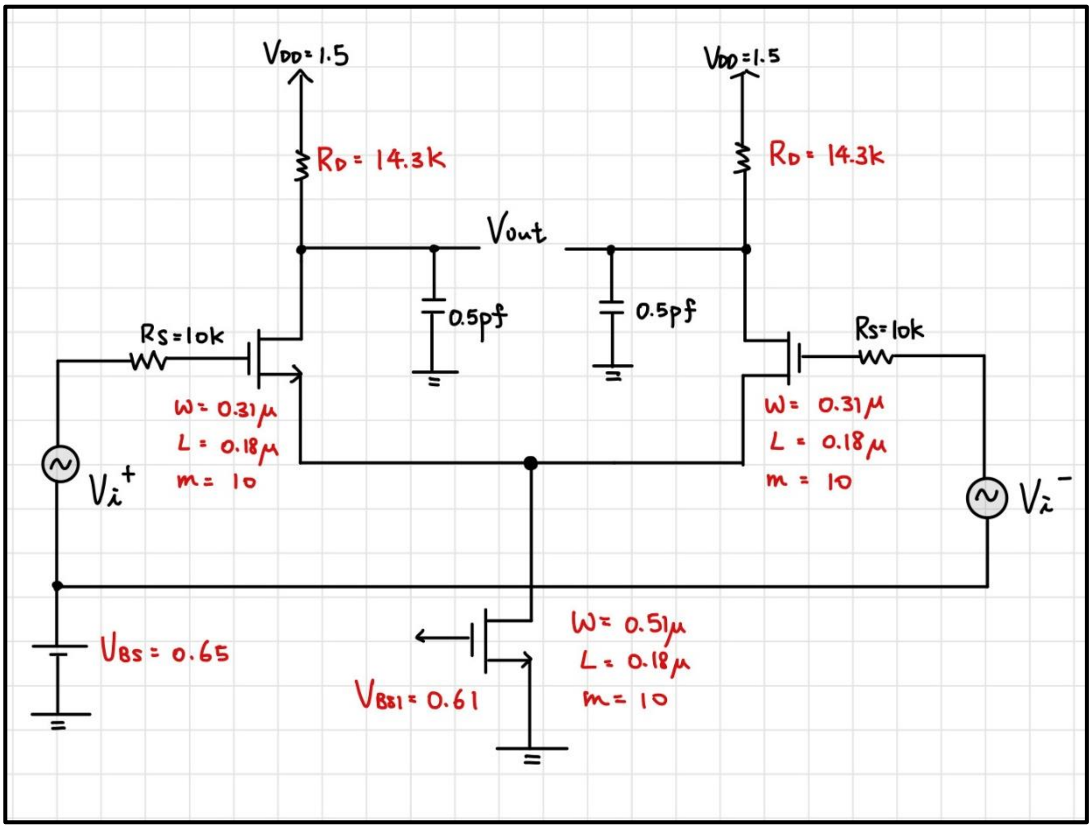

圖 1 電路設計圖

(b) Please print out the small signal parameters of active devices from list file.

```
subckt
element  0:m1       0:m2       0:ms
model    0:n_18.1   0:n_18.1   0:n_18.1
region   Saturation Saturation Saturation
 id        44.5820u   44.5820u   89.1640u
 ibs     -119.0185a -119.0185a -3.955e-20
 ibd     -816.4033a -816.4033a -136.6795a
 vgs      524.2989m  524.2989m  610.0000m
 vds      736.7764m  736.7764m  125.7011m
 vbs     -125.7011m -125.7011m    0.
 vth      455.3604m  455.3604m  491.3857m
 vdsat    135.9140m  135.9140m  157.6911m
 vod       68.9385m   68.9385m  118.6143m
 beta       6.2822m    6.2822m   10.2385m
 gam eff  510.8537m  510.8537m  507.4469m
 gm       583.0242u  583.0242u  816.0696u
 gds       27.1547u   27.1547u  343.6628u
 gmb       69.7562u   69.7562u  108.4005u
 cdtot      5.0940f    5.0940f    9.6347f
 cgtot      5.4177f    5.4177f    9.6315f
 cstot      8.9258f    8.9258f   14.6480f
 cbtot      9.5365f    9.5365f   15.8733f
 cgs        3.7246f    3.7246f    6.6305f
 cgd        1.1194f    1.1194f    2.1391f
```

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

     v(vop,von)/vac                                =   -6.0033
     input resistance at              vac          =  1.000e+20
     output resistance at v(vop,von)               =   20.6033k
```

(c) Under the operation condition in (a), please run .DC then plot the differential input – differential output transfer curve (as in slide 6). Try to plot and measure its small signal differential mode gain.

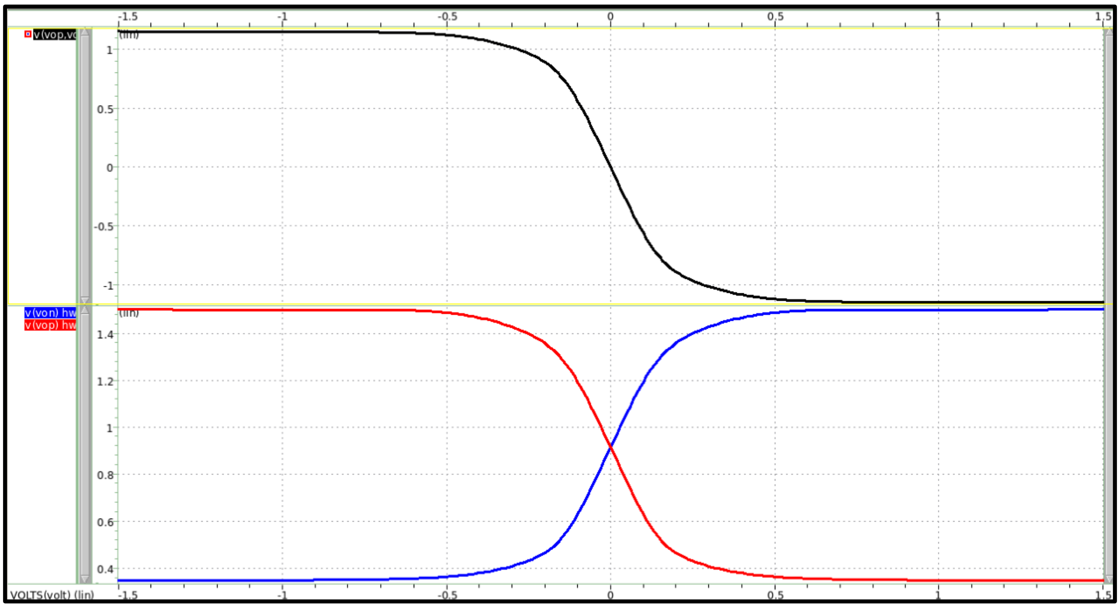

圖 2 differential output-input Transfer curve

上圖是雙端輸出，下圖是兩單端輸出

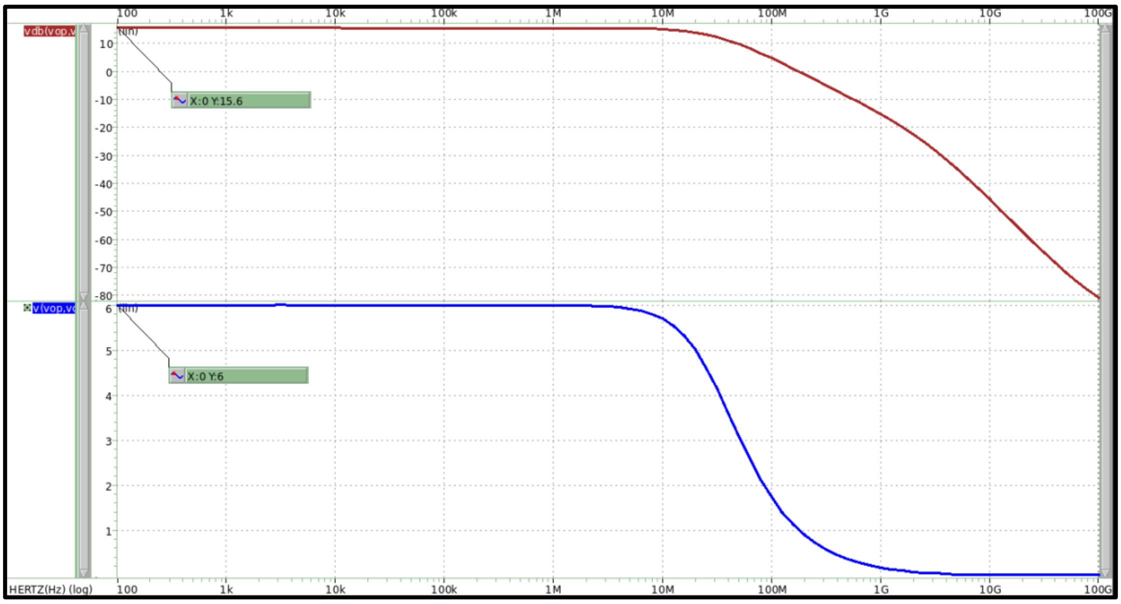

圖 3 measure differential mode gain

上圖為 db 為縱軸，下圖則為 gain 為縱軸(V/V)

(d) Compare the gain value with hand calculation using the small signal parameters from (b).

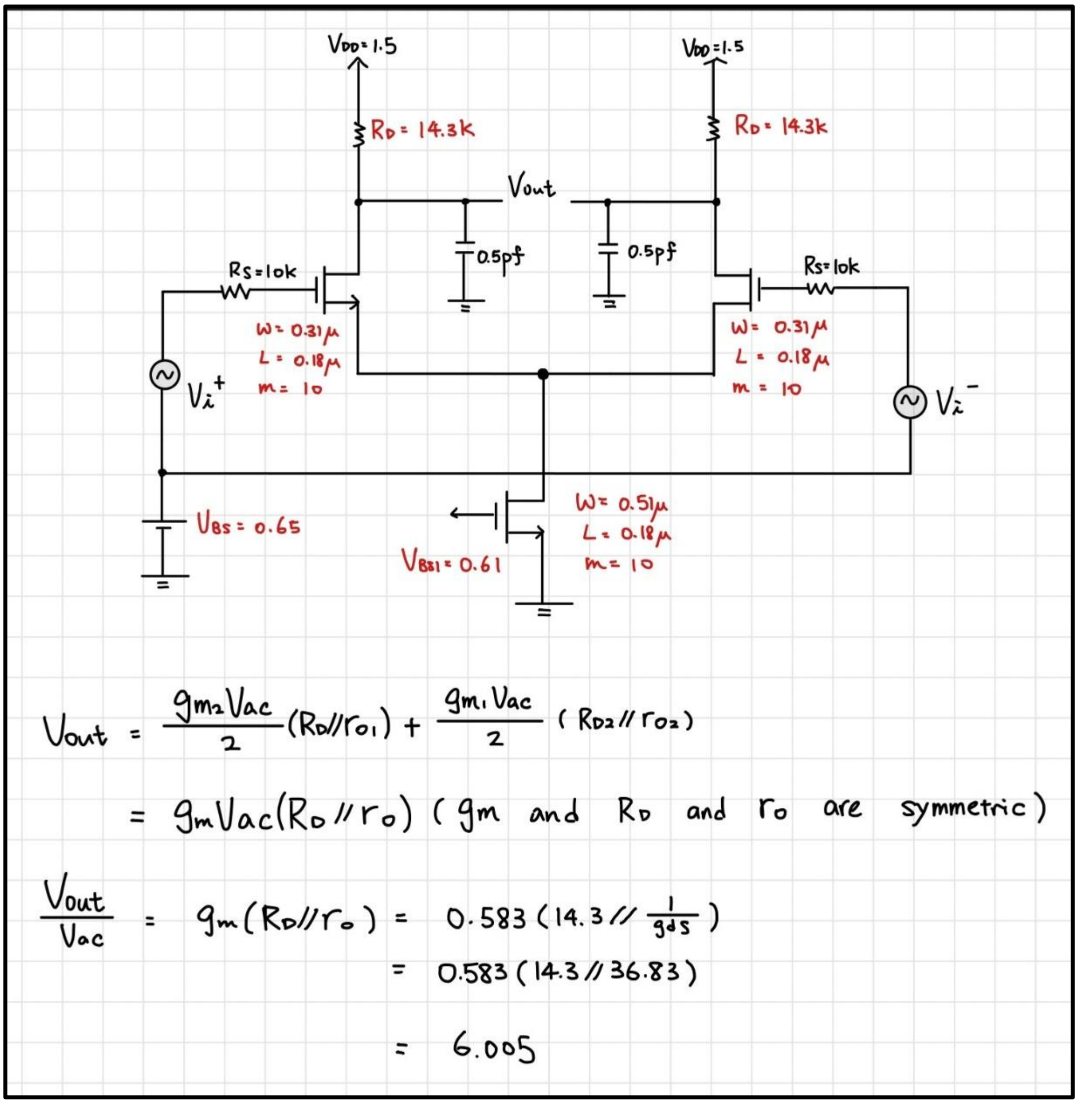

圖 4 hand calculate gain(differential mode)

Hand calculate 值:6.005

Simulation gain value:6.003

誤差值:0.03%

Differential input signal 一正一負，套用在 spice 上打的架構，將這裡的正負輸入訊號指定成 Vac/2。

(e) Like (c) please also run .DC to plot the common-mode input – common-mode output transfer curve (as in slide 6). Try to plot and measure its small signal common mode gain.

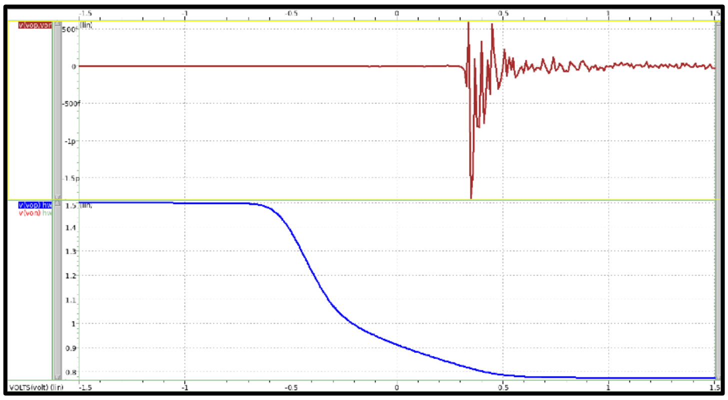

圖 5 common mode input-output transfer curve

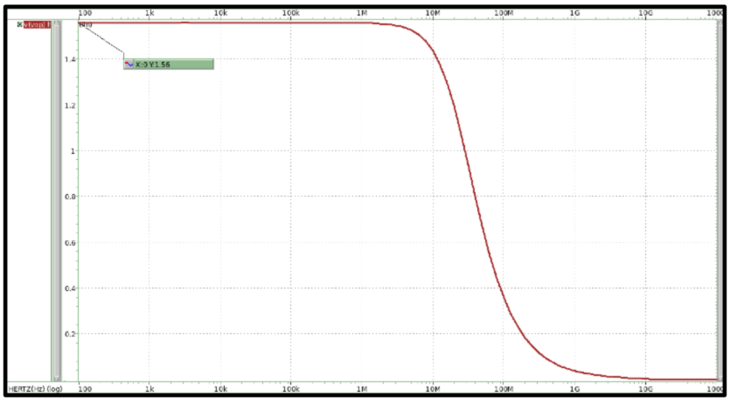

圖 6 measure common gain

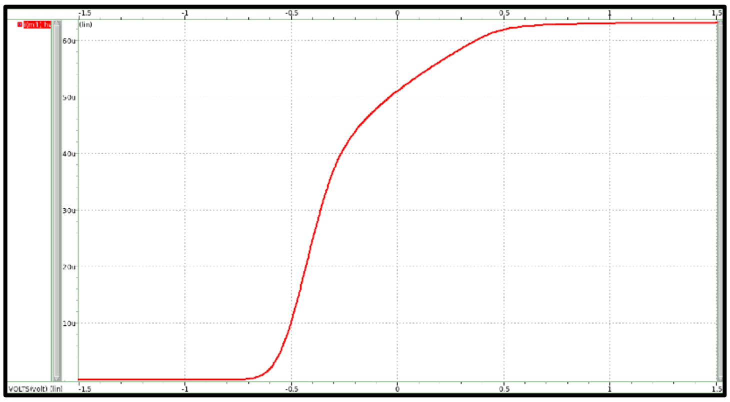

圖 7 output current transfer curve

(f) And compare the gain value with hand calculation using the small signal parameters from (b).

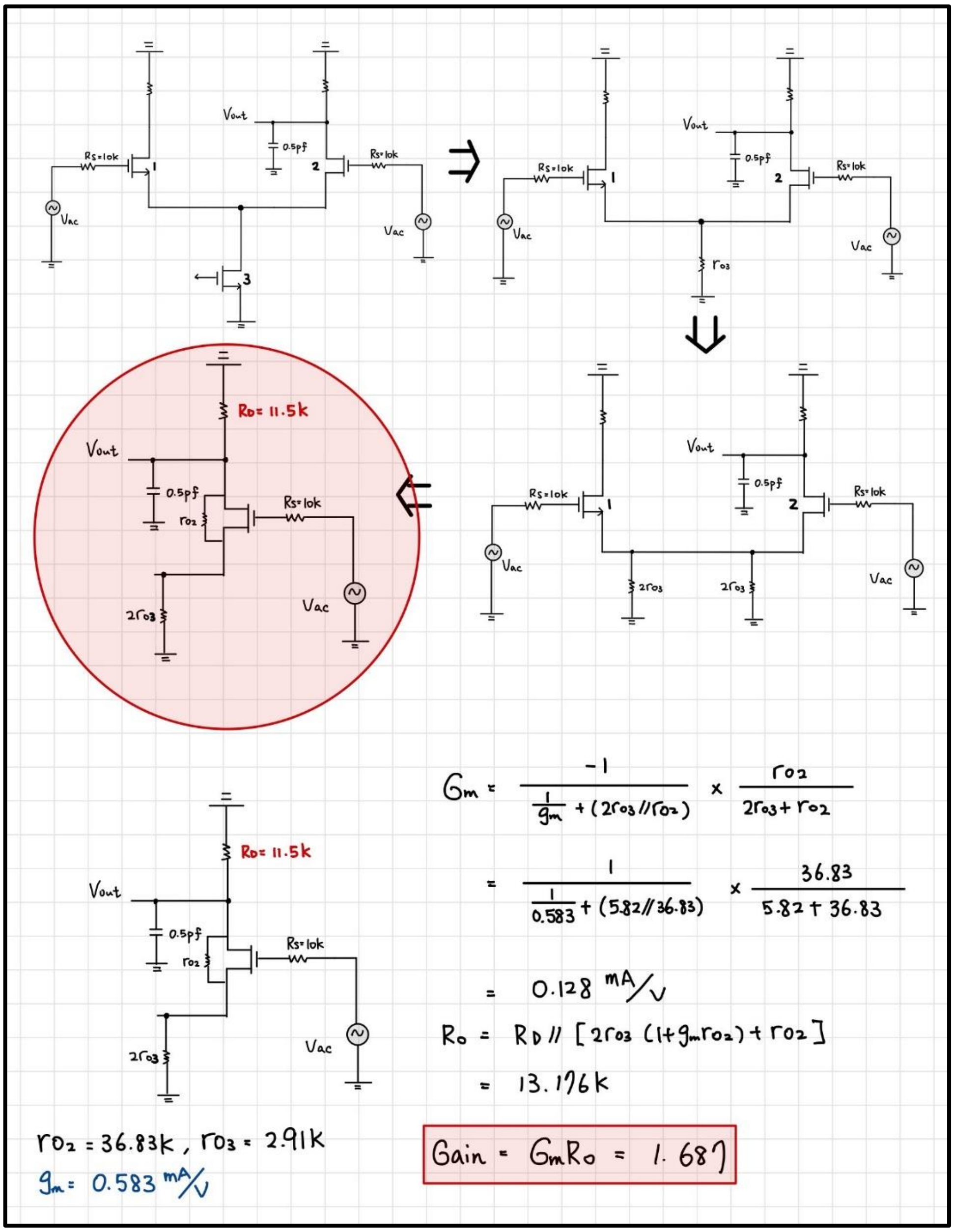

圖 8 hand calculate gain(differential mode)

Hand calculate 值:1.687,

Simulation gain value:1.56

誤差值:8.14%

Frequency response

(g) The small signal -3dB bandwidth of differential mode signal has to be larger than 30MHz. Please simulate and plot the differential mode frequency response of this gain stage.

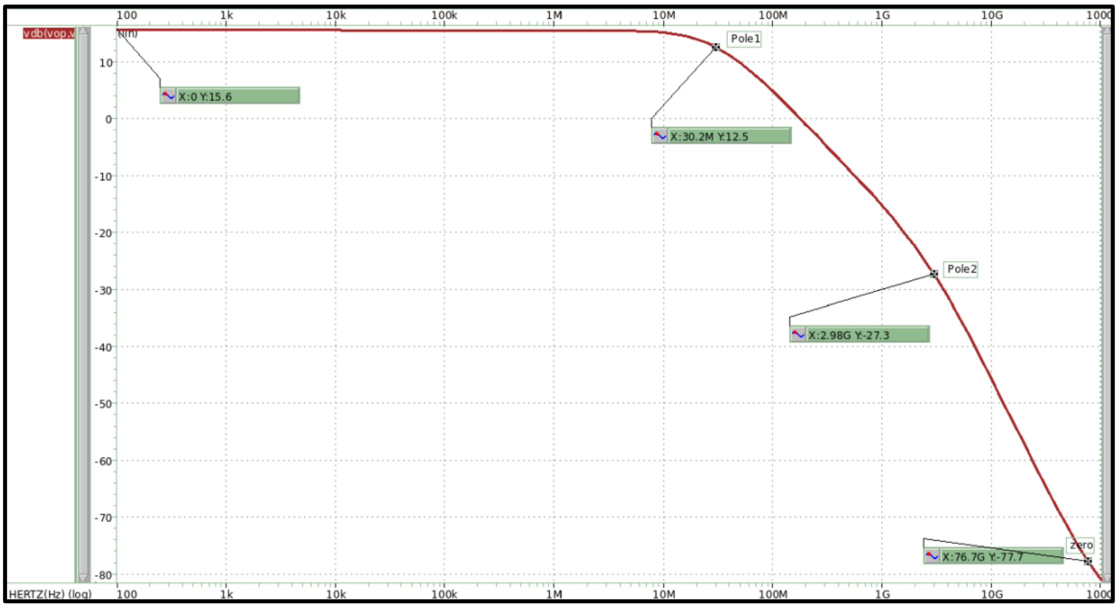

圖 9 frequency response

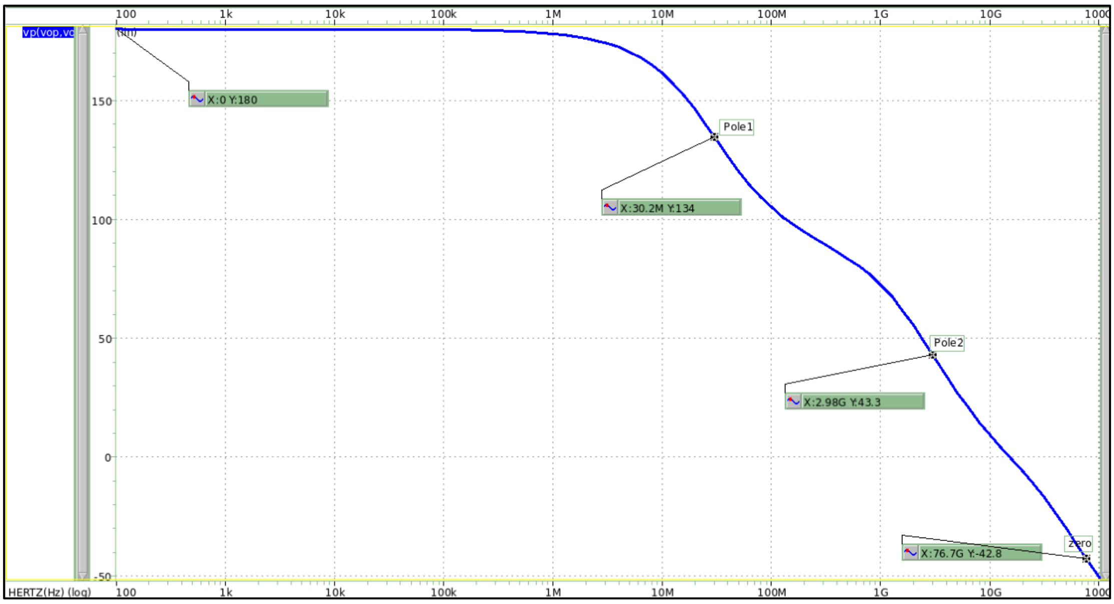

圖 10 phase response

(h) Use .pz to simulate and mark the poles/zeros on this curve.

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


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

     poles (rad/sec)                   poles ( hertz)
real              imag            real              imag
-189.709x         0.              -30.1932x         0.
-18.7112g         0.              -2.97799g         0.

     zeros (rad/sec)                   zeros ( hertz)
real              imag            real              imag
482.077g          0.              76.7250g          0.
```

圖 11 pole&zero (.pz)

(i) Compare with hand calculations

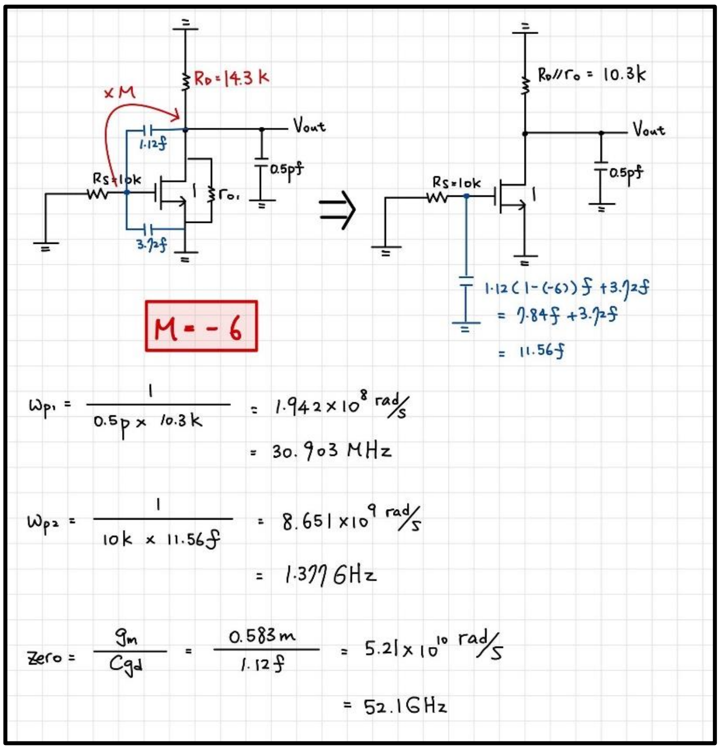

圖 12 pole&zero hand calculation

Pole1 誤差值:2.31%

Pole2 誤差值:53.7%

Zero 誤差值:32.1%

Linearity

(j) Please input differential sinusoidal waveforms to estimate the harmonic distortion. Please use .four to simulate the THD performance. And also use .tran to plot the maximum output differential voltage waveforms that achieve -60dB THD at 1MHz. The single-ended input amplitude value is defined as the linear range in this homework. The linear range must be larger than 10mV.

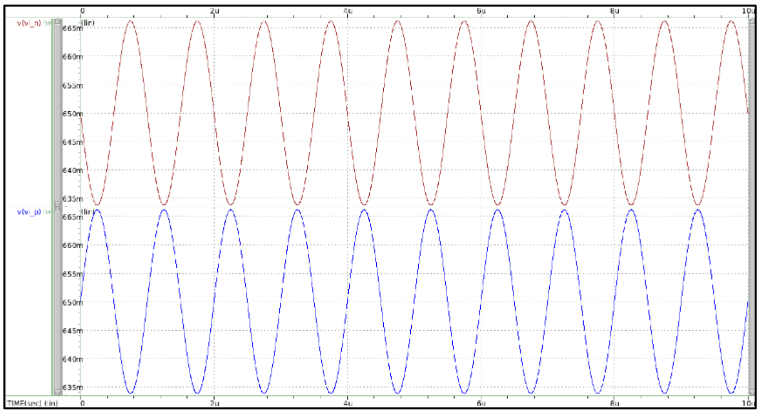

圖 13 differential sinusoidal input(linear range=16.25mv)

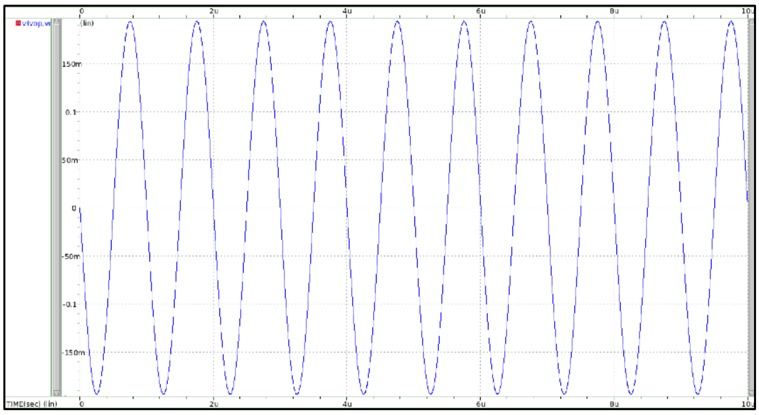

圖 14 maximum output differential voltage waveforms

(k) Please print out the .THD results.

```
harmonic frequency   fourier    normalized phase      normalized
no       (hz)        component  component  (deg)      phase (deg)
1           1.0000x   97.1821m     1.0000   -91.9170     0.
2           2.0000x  332.9918u     3.4265m   -1.9328    89.9842
3           3.0000x  105.1555u     1.0820m  -95.6365    -3.7194
4           4.0000x  335.3952n     3.4512u  -12.0272    79.8898
5           5.0000x   58.4523n  601.4715n   81.2525   173.1696
6           6.0000x    1.4839n   15.2693n  171.0534   262.9704
7           7.0000x   14.1428n  145.5287n -152.5265   -60.6095
8           8.0000x  114.6665p     1.1799n  -56.9775    34.9395
9           9.0000x    8.3586n   86.0092n  -46.0895    45.8275

total harmonic distortion =   0.359326  percent
fourier components of transient response v(vop,von)
dc component =    2.5275p

harmonic frequency   fourier    normalized phase      normalized
no       (hz)        component  component  (deg)      phase (deg)
1           1.0000x  194.3642m     1.0000    88.0830     0.
2           2.0000x    5.0561p   26.0133p  107.2401    19.1572
3           3.0000x  210.3109u     1.0820m   84.3635    -3.7194
4           4.0000x    5.0584p   26.0253p -145.5176  -233.6006
5           5.0000x  116.9045n  601.4713n  -98.7475  -186.8304
6           6.0000x    5.0614p   26.0410p  -38.2718  -126.3548
7           7.0000x   28.2855n  145.5286n   27.4735   -60.6095
8           8.0000x    5.0670p   26.0697p   68.9724   -19.1105
9           9.0000x   16.7171n   86.0091n  133.9105    45.8275

total harmonic distortion =   0.108205  percent
```

圖 15 THD result

(l) Compare the simulated input amplitude with the hand calculation.

$$HD_3 = \frac{A^2}{32\,(V_{GS} - V_t)^2}$$

Let $HD_3 = 0.1\%$ $\Rightarrow A^2 = 0.1\% \times 32 \times (68.94m)^2 = 1.992m$

$\Rightarrow A = 12.33\ m$

$-60dB$ distortion $\Rightarrow A < 0.2\ V_{ov}$

$\Rightarrow A < 13.79\ mV$

(m) Under this amplitude please also simulate the THD performance under 100KHz and 10MHz respectively.

```
harmonic frequency  fourier    normalized phase      normalized
no       (hz)       component  component  (deg)     phase (deg)
1         100.0000k   97.2352m    1.0000    89.8090     0.
2         200.0000k  331.8869u    3.4132m -194.0620m  -90.0031
3         300.0000k  105.7703u    1.0878m   90.1506   341.6216m
4         400.0000k  993.7889n   10.2205u -179.6698  -269.4788
5         500.0000k    1.3353u   13.7327u -178.7219  -268.5310
6         600.0000k    1.3346u   13.7255u  179.8992    90.0902
7         700.0000k    1.3333u   13.7121u  179.8911    90.0821
8         800.0000k    1.3333u   13.7117u  179.8676    90.0586
9         900.0000k    1.3332u   13.7112u  179.8511    90.0421

total harmonic distortion =   0.358253  percent
fourier components of transient response v(vop,von)
dc component =   -1.3335u

harmonic frequency  fourier    normalized phase      normalized
no       (hz)       component  component  (deg)     phase (deg)
1         100.0000k  194.4705m    1.0000    89.8090     0.
2         200.0000k    2.6669u   13.7137u  179.9669    90.1579
3         300.0000k  211.5405u    1.0878m   90.1507   341.6494m
4         400.0000k    2.6669u   13.7134u  179.9337    90.1247
5         500.0000k    2.6707u   13.7332u -178.7220  -268.5310
6         600.0000k    2.6668u   13.7129u  179.9006    90.0916
7         700.0000k    2.6667u   13.7126u  179.8911    90.0821
8         800.0000k    2.6666u   13.7122u  179.8675    90.0585
9         900.0000k    2.6665u   13.7118u  179.8510    90.0420

total harmonic distortion =   0.108838  percent
```

圖 16 100KHZ THD

```
harmonic frequency  fourier    normalized phase      normalized
no       (hz)       component  component  (deg)     phase (deg)
1          10.0000x   92.2596m    1.0000    71.4668     0.
2          20.0000x  313.8802u    3.4021m  -18.3665   -89.8333
3          30.0000x   70.8101u  767.5091u   47.6613   -23.8055
4          40.0000x  173.6961n    1.8827u  -86.1901  -157.6569
5          50.0000x   92.8698n    1.0066u   40.2875   -31.1792
6          60.0000x   57.2876n  620.9398n  706.0508m  -70.7607
7          70.0000x   69.8690n  757.3085n   10.8259   -60.6409
8          80.0000x   60.2239n  652.7658n    6.7675   -64.6993
9          90.0000x   67.5033n  731.6673n   11.3301   -60.1367

total harmonic distortion =   0.348764  percent
fourier components of transient response v(vop,von)
dc component = -172.1194n

harmonic frequency  fourier    normalized phase      normalized
no       (hz)       component  component  (deg)     phase (deg)
1          10.0000x  184.5191m    1.0000    71.4668     0.
2          20.0000x  639.5062n    3.4658u -102.7705  -174.2372
3          30.0000x  141.6209u  767.5134u   47.6589   -23.8079
4          40.0000x   95.1497n  515.6633n  -27.5210   -98.9877
5          50.0000x  182.2946n  987.9442n   40.8758   -30.5909
6          60.0000x  108.2365n  586.5871n  181.4353m  -71.2853
7          70.0000x  135.1008n  732.1777n   10.8621   -60.6047
8          80.0000x  114.9911n  623.1934n    6.7199   -64.7469
9          90.0000x  130.1566n  705.3829n   11.3390   -60.1278

total harmonic distortion =   0.0767523  percent
```

圖 17 10MHZ THD

(n) We will use the "bandwidth (MHz) x linear range (mV) / current (μA)" as the figure of merit (FoM). Please try to make this FoM maximal.

Working Item	Specification	Simulation	calculation
Vdd	1.5-V		
Tail current	As smaill as possible(uA)(#3)	89.16u	
Differential gain	>6(V/V)	6.003	6.005
Input common mode	Open for design(VBS,V)	0.65	
Tail current bias	Open for design(VBS1,V)	0.61	
Common-mode gain	Open for design(V/V)	1.56	1.69
Input size Mx	Open for design(W,L),m	0.31u/0.18u,m=10	
Differential gm	Open for design(mA,V)	0.583(mA/V)	
Load R	Open for design(Kohm)	14.3K	
Bandwidth	>30MHz(#1)	30.2M	30.9M
Linear range OUTPUT 60dB THD@1MHZ	Single-ended input amplitude>10mV(#2)	16.25 mV	12.3mV
FoM	#1*#2/#3	5.5	4.26

(o) Please use your design equations to explain how to achieve max FOM.

FoM 要上升的話，Tail current 要下降，BW 要提高，Linear range 要提高。同時達到 gmRd=(2KVov)Rd=6 及$\frac{1}{2\pi(Rd//ro)*0.5p} > 30MHZ$，先掌握較單一變數可操作的結果，故以(Rd//ro)<10.6K 為出發點開始設計。

在設計過程，我以 tail current 不超過 100u 為原則去設計各項數值，得到的參數範圍如下:

1. ro 大約落在 30~40(K)，所以 Rd 大約需設計在 14.39K 以內，以免 BW<30MHz。
2. 因 Rd 最大值約為 14.4K，為使 gain>6，gm 必須至少 0.42m，因有些製成參數無法設計(cox、electron mobility…)，optimizing gm 值還需經幾組實際嘗試比較，但原則上最小值不能低於 0.42m。
3. 所小 W/L ratio 可使 THD percentage 變低，也可使電流變小，而此次作業 Ms 的 size 設計大幅影響此電路的汲極電流，Is 的值因此變得由甚為重要，這也是為何我在一開始就將 tail current 不超過 100u 為原則去做電路設計。
4. 閘極電壓 VBS、VBS1 是決定 Vov 大小的參數，Vov 越大也可使 linear range 更大，但也相應的增加功耗。在 linear range 與 tail current 二選一中，我決定盡可能使 linear range 提高但不使 tail current 大於 100u 為前提下去做設計。(因 linear range 的變化值比 tail current 變化值，對 FoM 更有影響力)

接下來開始實際設計並觀察，我發現 Mx 的 size 很低程度的影響 gain(因主要都是由 tail current 提供並決定電流)，但又同時可改善 THD，多方嘗試後我認為**使所有 mos size 接近可得到最適當的 THD 與 gain 的平衡**(W 小有助於 THD 但卻使增益減少)，**也搭配最大可接受的 Vov 值去設計直流偏壓**(VBS、VBS1)，選擇更大 Vov 的好處還有可使 Rd 不用那麼大，以利增加頻寬。