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(b)

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

     v(vout)/iin                                   = -951.8127
     input resistance at              iin          =   47.7102
     output resistance at v(vout)                  =   20.6553
```

Fig. 1 .tf command results

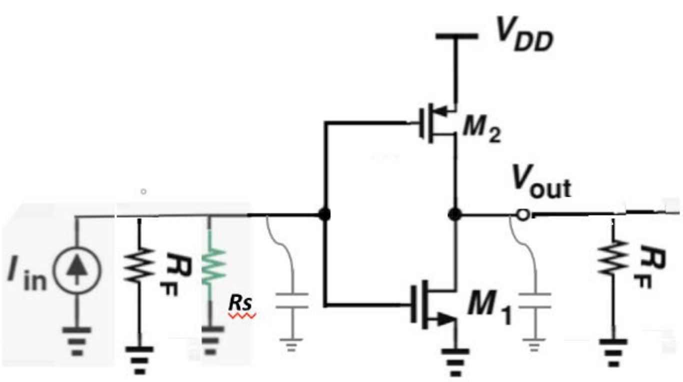
(c)

```
 **** mosfets


 subckt
 element   0:m2        0:m1
 model     0:p_18.1    0:n_18.1
 region      Saturati    Saturati
  id        -3.2650m    3.2597m
  ibs       3.002e-19 -4.831e-19
  ibd         7.5096f   -9.0565f
  vgs      -863.4154m  636.5846m
  vds      -858.0495m  641.9505m
  vbs         0.          0.
  vth      -513.9782m  484.1763m
  vdsat    -341.0126m  169.0697m
  vod      -349.4372m  152.4084m
  beta       51.3762m  223.5379m
  gam eff   557.0844m  507.4469m
  gm         15.3589m   32.1995m
  gds       429.7724u  903.6235u
  gmb         4.8331m    5.4728m
  cdtot     219.0978f  264.2759f
  cgtot     464.8845f  485.0370f
  cstot     613.2899f  638.5869f
  cbtot     447.1775f  506.9820f
  cgs       370.1272f  373.8095f
  cgd        71.1546f   71.9082f
```

Fig. 2 devices' parameters

First, I calculate open loop gain, input impedance, output impedance. So, I need to break the feedback (i.e. put R_F at both input and output)



Open loop:

Input impedance: $R_F//R_S$

Output impedance: $r_{o2}//r_{o1}//R_F$

Gain (A): $-(g_{m1}+g_{m2})(r_{o2}//r_{o1}//R_F)(R_S//R_F)$ = -2.02E+04

And, K = $\frac{-1}{R_F}$ = -0.001

Closed loop:

Input impedance: $\frac{R_F//R_S}{1+KA} = \frac{9.90E+02}{2.12E+01}$ = 46.7Ω

Output impedance: $\frac{r_{o2}//r_{o1}//R_F}{1+KA}$ = 20.2Ω

Gain: $\frac{A}{1+KA}$ = -953Ω

These calculations can be done by fig. 2 (small signal parameters) and Excel on the right hand side!

CL	Rs	RF	gds2	gds1
1.00E-12	1.00E+05	1000	4.30E-04	9.04E-04
			ro2	ro1
			2.33E+03	1.11E+03
	Rs//RF	RF//ro1//ro2	CGS'	CGD'
	9.90E+02	4.29E+02	2.06E-12	1.43E-13
gm2	gm1			
1.54E-02	3.22E-02			
open loop small signal gain (A)				
-2.02E+04				
1+KA				
2.12E+01				
closed loop				
input impedance				
4.67E+01				
output impedance				
2.02E+01				
small signal gain				
-9.53E+02				

	Simulation	Hand calculation
Input impedance	47.7102Ω	46.7Ω
Output impedance	20.6553Ω	20.2Ω
Gain	-951.8127Ω	-953Ω

Tabel1. Comparison table between simulation and hand calculation results

All of the result calculated by hand is pretty close to the simulation results done in part (b)!

(d)

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


  input =   0:iin           output = v(vout)

        poles  (rad/sec)                  poles  ( hertz)
real              imag              real              imag
-2.18683g         3.50005g          -348.045x         557.050x
-2.18683g         -3.50005g         -348.045x         -557.050x

        zeros  (rad/sec)                  zeros  ( hertz)
real              imag              real              imag
311.721g          0.                49.6119g          0.

 ***** constant factor = 52.0074g

         ***** job concluded
******
```

Fig. 2 pole/zero analysis results

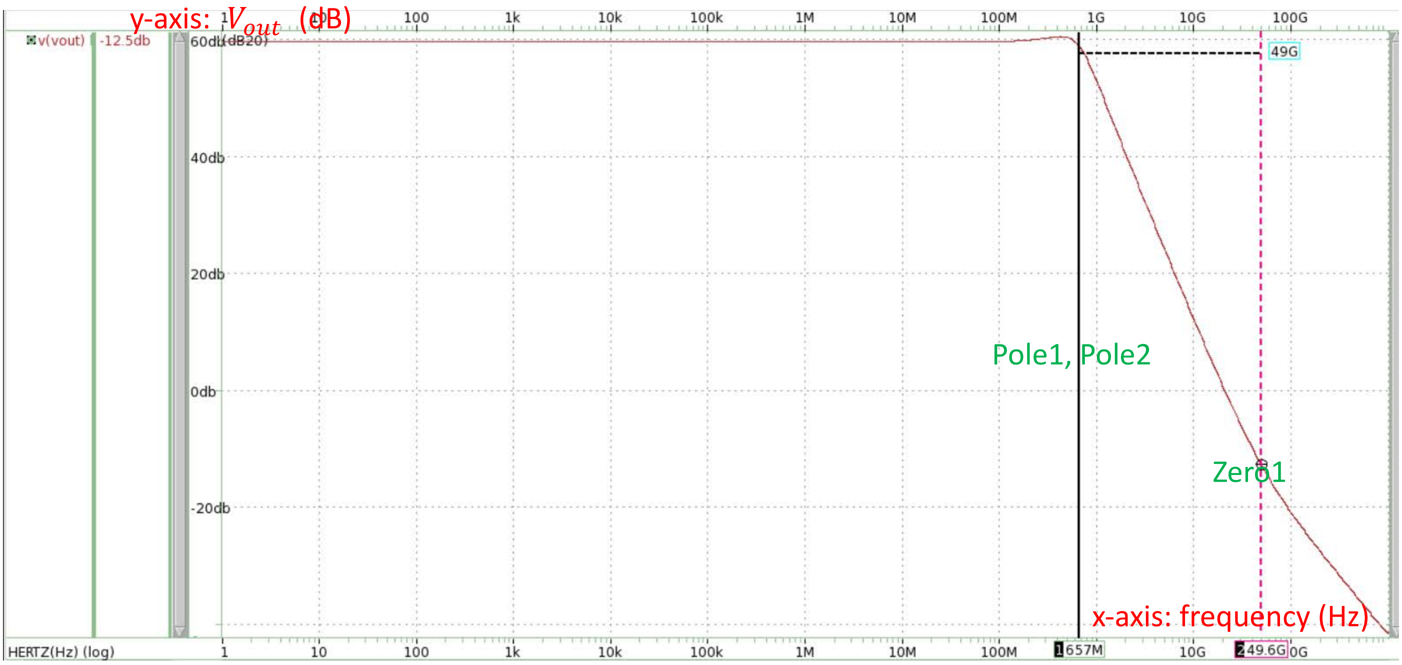


Fig. 3 frequency response

(e)

Consider an amplifier with open-loop transfer function with two real poles

$$A(s) = \frac{A_0}{(1+\frac{s}{\omega_{p1}})(1+\frac{s}{\omega_{p2}})}$$

Closed loop poles come from 1+A(s)K = 0

$$\Rightarrow s^2 + s(\omega_{p1} + \omega_{p2}) + (1 + KA_0)\omega_{p1}\omega_{p2} = 0$$

$$\Rightarrow s = \frac{-1}{2}(\omega_{p1} + \omega_{p2}) \pm \frac{1}{2}\sqrt{(\omega_{p1} + \omega_{p2})^2 - 4(1 + KA_0)\omega_{p1}\omega_{p2}}$$

Therefore, I need to calculate open loop poles first.

Use high frequency model of Common source,

$$\frac{V_{out}}{V_{in}}\frac{(C_{GD}-g_m)R}{as^2+bs+1}, where \begin{cases} a = (R_s//R_F)R(C_{GS}'C_{GD}' + C_{DB}'C_{GD}' + C_{GS}'C_{DB}') \\ b = (1 + (g_{m1}g +_{m2})R)C_{GD}'(R_S//R_F) + (R_S//R_F)C_{GS}' + R(C_{DB}' + C_{GD}') \end{cases}$$

There is a zero (not affected by feedback)

$$w_z = \frac{g_{m1}+g_{m2}}{C_{GD1}+C_{GD2}}, f_z = 52.9GHz$$ (calculation was done by excel)

gm2	gm1	Cgd1	Cgd2
1.54E-02	3.22E-02	7.19E-14	7.12E-14
zero			
5.29E+10			

There are two poles , supposed $w_{p2} \gg w_{p1}$ (dominant pole approximation)

$$w_{p1} = \frac{1}{b} = \frac{1}{(1+(g_{m1}g+_{m2})R)C_{GD}'(R_S//R_F)+(R_S//R_F)C_{GS}'+R(C_{DB}'+C_{GD}')}$$

$$w_{p2} = \frac{b}{a} = \frac{(1+g_mR)C_{GD}R_S+R_SC_{GS}+R(C_{DB}+C_{GD}+C_L)}{(R_S//R_F)R(C_{GS}'C_{GD}'+C_{DB}'C_{GD}'+C_{GS}'C_{DB}')}$$

Notation: R = $R_F//r_{o1}//r_{o2}$

$$C'_{GD} = C_{GD1}+C_{GD2} + C_L$$

$$C'_{GS} = C'_{GS1}+C'_{GS2} + C_L$$

$$C'_{DB} = C_{DB1} + C_{DB2} + C_L$$

Using the value from 圖 5 , I can get two poles : (Note: $C_L = 1.5pF$ 、$R_s = 5kohm$)

$$f_{p1} = \frac{w_{p1}}{2\pi} = 31.3MHz$$

$$f_{p2} = \frac{w_{p2}}{2\pi} = 821\text{MHz}$$ (calculation was done by Excel)

Therefore the **real** part of poles of closed loop = $\frac{(f_{p1}+f_{p2})}{2}$ = 426MHz

	Simulation	Hand calculation
zero	49.6119G	52.9G
Pole	348M	426MHz

Poles:

It's quite different from simulation results. I think it's just because the simulation results are mirror poles. But I didn't use the right formula to calculate it, which leads to the big error.

Zero:

Error rate = $\frac{52.9-49.6119}{52.9} = 6.215\%$, which is small. The result of hand calculation is very close to the that of simulation as zero is not affected by feedback circuit.

(g)

Gain:

Open loop gain:

A = $-(g_{m1} + g_{m2})(r_{o1} // r_{o2} // R_F)(R_F // R_s)$

= $-(\frac{I}{V_{GS1}}+\frac{I}{V_{GS2}})(\frac{1}{\frac{1}{\lambda I}+\frac{1}{\lambda I}+\frac{1}{R_F}})(R_F // R_s)$, assume R_F is large, so current of M2 is equal to current of M1

= $-(\frac{I}{V_{GS1}}+\frac{I}{V_{GS2}})(\frac{R_F}{1+2\lambda I R_F})(R_F // R_s)$, assume λ of M1, M2 are the same for the convenience of analysis

= $-(\frac{1}{V_{GS1}}+\frac{1}{V_{GS2}})(\frac{1}{2\lambda})(R_F // R_s)$, as I have assumed R_F is large

$(R_F // R_s)$ is fixed, $\frac{1}{\lambda} \propto (\text{length of MOS})$, $V_{S1} = 0, V_{S2} = 1.5\ are\ fixed\ as\ well.\ V_G = I_{in} \times (R_F // R_s)$.

Closed loop gain:

$\frac{A}{1+KA}$ > -950, K = $\frac{-1}{R_F}$, thus, A needs to be large enough that closed loop gain $\approx \frac{1}{K}$, which is -1000Ω.

Bandwidth:

bandwidth = $(1+KA_0)\frac{1}{r_o C_L}$, $r_o = r_{on} // r_{op} // R_F$ (open loop, -3dB bandwidth = $\frac{1}{r_o C_L}$), $r_{on}\ \&\ r_{op} \propto \frac{1}{\text{current of MOS}}$, thus $r_o \propto (\text{current of MOS})$

Current:

$$\text{I} = 0.5 \times \mu_n \times C_{ox} \times (V_{GS} - V_{th})^2 \times (\frac{W}{L}) \times [1 + \lambda(V_{DS})]$$

Design flow and result:

As gain needs to be large, V_G is supposed to as low as possible according to my analysis on gain above. Therefore, I set I_{in} to a low value as $V_G = I_{in} \times (R_F // R_s)$, which is 1uA. And I didn't want to let current on MOS get smaller, so what I did was increase aspect ration $(\frac{W}{L})$. Also, I could increase length to reach higher gain as

$$\frac{1}{\lambda} \propto (\text{length of MOS})$$

However, by doing so, bandwidth wouldn't meet the requirement of problem sets, which states bandwidth has to be wider than 150MHz. I think it's because bandwidth $\propto$ (current of MOS). Therefor, I only increase length a little bit from 0.18u (minimum in ‘cic018.l’) to 0.3u

According to by my analysis on bandwidth above, it is proportional to current of MOS. And I have increase $(\frac{W}{L})$ to very large $\frac{99u}{0.3u}$. Bandwidth has met the requirement of problem sets, but gain hasn’t. So I change multiple device from m = 1 to m = 2. So both of bandwidth and gain have all reached the requirement of problem sets.

Although there are two mosfets to design, for the simplicity of design and analysis, I set the same parameters for both of M1 and M2 (same width, length and multiple device ratio).

Since FOM = $(\frac{Bandwidth}{current})$, so I made gain as close to -950 as possible or the current would be large. Also, bandwidth has been much higher than 150MHz, I didn’t keep increasing $(\frac{W}{L})$ to have better FOM.

Hspice code

```
.prot
.lib 'cic018.l' TT
.unprot
.option
+post
+accuracy = 1
+captab
.param VDD = 1.5

*MOS
M2 Vout Vg VDD VDD p_18 w = 99u l = 0.3u m = 2
M1 Vout Vg VSS VSS n_18 w = 99u l = 0.3u m = 2
*resistor
Rs Vg VSS 100K
RF Vg Vout 1K
*capacitor
CL_in Vg VSS 1p
CL_out Vout VSS 1p
*current source
```

```
Iin VSS Vg DC 1u AC 1 $DC = 1u

v1 VDD gnd VDD
v2 VSS gnd 0

.DC Iin 1u 20u 0.1u

.AC DEC 1k 1 1T
.probe AC
+ c_db_2 = LX29(M2)
+ c_db_1 = LX29(M1)
+gain = par('V(Vout)/I(Iin)')

.pz V(vout) Iin

.tf V(Vout) Iin


.op
.END
```