specs

① a) $I_{tail} = 200\mu A \Rightarrow 200\mu A = \frac{\mu_n C_{ox}}{2} \frac{W}{L} V_{dsat3}^2$

$\left(\frac{W}{L}\right)_3 V_{dsat3}^2 = \frac{200\mu A}{100\frac{\mu A}{V^2}} = 2V^2$

b) Sink $1mA \Rightarrow I_{d4} \geq 1mA$

c) output swing to w/in 200mV of rails $\Rightarrow$

$V_{dsat4} \leq 200mV$

$|V_{dsat5}| \leq 200mV$

d) input CM to w/in 200mV of $V_{dd} \Rightarrow$

$|V_{dsat2}| \leq 200mV$

Step 1: current source design

pick all $L = 1\mu m$ $(L_6, L_3, L_4)$

pick all $V_{dsats} \cong 140mV$ for M3, M4, M6

pick $I_{ref} = 100\mu A$

(convenient factor of $I_{tail}$, $I_{d4}$

low impact on total current)

Calculate $W_6$

$100\mu A = \frac{200\mu A}{2} \frac{V^2}{V^2} \left(\frac{W}{L}\right)_6 (140mV)^2$

$\frac{V^2}{0.02V^2} = \left(\frac{W}{L}\right)_6 = 50$

$\boxed{W_6 = 50L_6 = 50\mu m}$

calculate $W_3 = 2W_6 = 100\mu m$

calculate $W_4 \geq 10W_6 \geq 500\mu m$

pick $W_4 = 600\mu m$

why? 1mA sink min

play it safe. $I_{d4} = 1.2mA$

calculate $R = \frac{V_{DD} - (V_{on} + V_{dsat3})}{I_{ref}}$

pick $V_{dd} = 5V \Rightarrow R = \frac{4.36V}{100mA} \cong 44k\Omega$

Step 2 Diff pair

Mlab - pick $V_{dsat1} = 1V$, $L_1 = 0.5\mu m$

why? explore how small I can get them.

calculate $W_{1A} = W_{1B}$

$$\frac{I_{tail}}{2} = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)_{1A} V_{dsat1A}^2$$

$$100\mu A = 100\frac{\mu A}{V^2}\left(\frac{W_{1A}}{0.5\mu m}\right)(1V)^2$$

$W_{1A} = 0.5\mu m$ violates process limits ($W_{min} = 1\mu m$)

try again: pick $V_{dsat1} = 0.5V$, $L_1 = 0.5\mu m$

Calculate $W_{1A} = 2\mu m$

really low input capacitance

$$C_{gs1} = \left(5\frac{fF}{\mu m^2}\right)(1\mu m)\left(\frac{2}{3}\right) = 3.3\,fF$$
$$+\left(0.5\frac{fF}{\mu m}\right)(2\mu m) \quad +1\,fF$$
$$= 4.3\,fF$$

$C_{sd1} = 1\,fF$

Step 3 Active load

pick $|V_{dsat2}| = 200mV$

$L_2 = 2\mu m$

why? L bigger, a little more gain

$V_{dsat}$ as large as possible to minimize capacitive loading (& maximize speed)

calculate

$$100\mu A = \frac{100\mu A/V^2}{2}\left(\frac{W}{L}\right)_2 V_{dsat2}^2$$

$$2V^2 = \left(\frac{W_2}{2\mu m}\right)(0.04V^2)$$

$W_2 = 100\mu m$

pick $W_2 = 120\mu m$

why? a little wider means $|V_{dsat2}|$ will be a little less than 200mV, even w/ some process variation

top 4 ~~calculate~~ pick $V_{dsat5} = V_{dsat2}$

$L_5 = L_2$

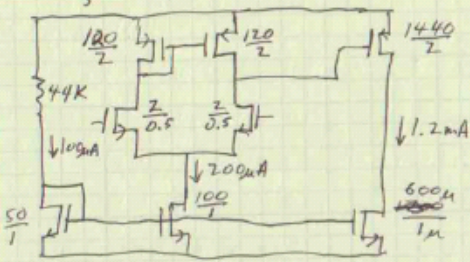
why? make it easy to calculate size of M5, and make bias point less sensitive to process variation

calculate $W_5$:

$$\frac{\left(\frac{W}{L}\right)_5}{\left(\frac{W}{L}\right)_2} = \frac{I_{dc}}{I_{dc/4}} = \frac{12}{1} \Rightarrow W_5 = 12 W_2$$

$$= 1440\mu m$$

5




layout only need 3 transistors:

NMOS $\frac{W}{L} = \frac{50\mu}{1\mu}$

M6 : 1 copy

M3 : 2 copies

M4 : 12 copies

NMOS $\frac{W}{L} = \frac{2\mu}{0.5\mu}$ $M_{1A}, M_{1B}$

PMOS $\frac{W}{L} = \frac{120\mu}{2\mu}$

$M_{2A}, M_{2B}$ 1 copy each

M5 12 copies

total gate area : $(WL)_5 = 2880\mu m^2$

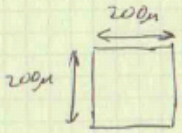
$(WL)_6 = 600\mu m^2$

$2(WL)_2 = 480\mu m^2$

$\sim 4,000\mu m^2$

total layout area $\approx 10\times$ gate area

$\approx 40,000\mu m^2$




total current 1.5mA

power 7.5mW

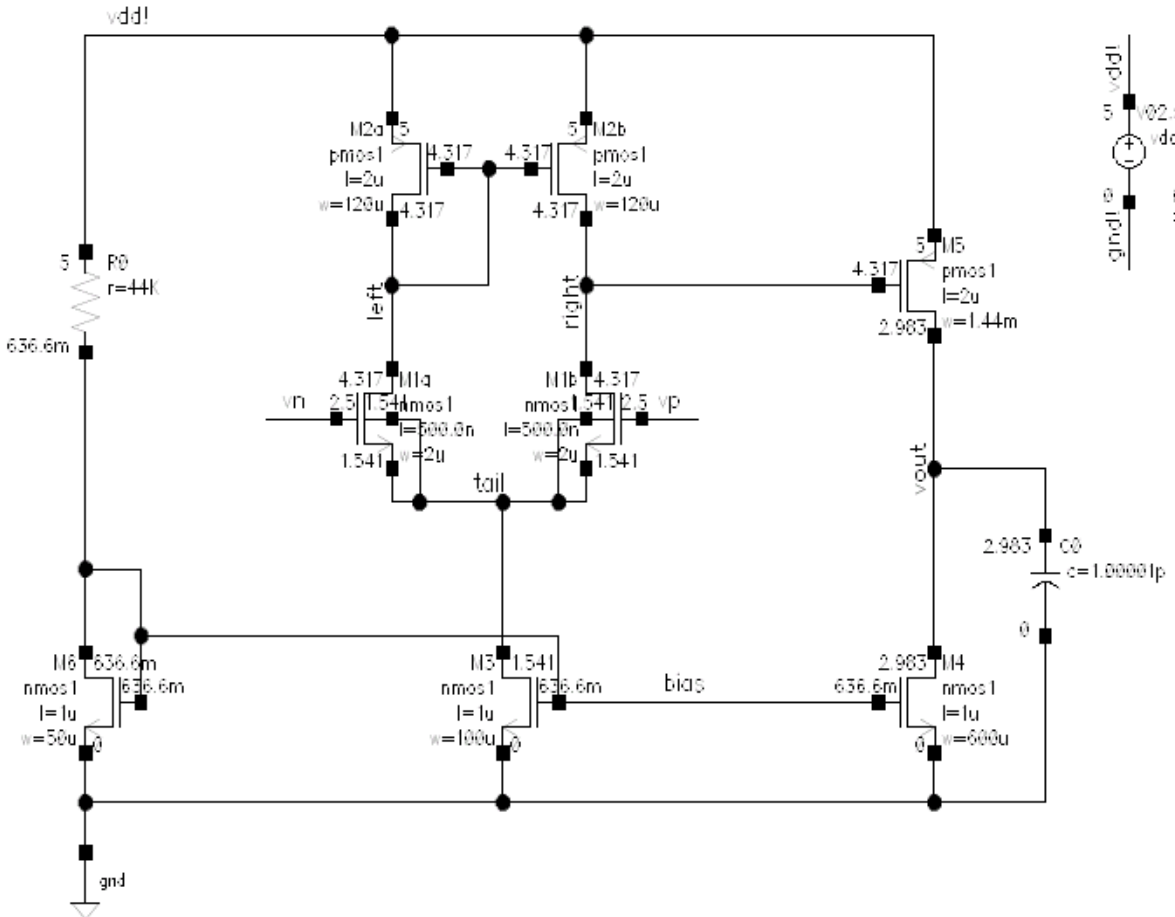



**Fig.1. Schematic**

[prob. 2]

(a) See Table 1

(b) $A_{v1} = -g_{m1} \times (r_{o,1b} \| r_{o,2b})$

$= -0.4mS \times (128K\Omega \| 107K\Omega)$

$= \underline{-23.31}$ vs. 25.25 (SPICE)

$A_{v2} = -g_{m5} \times (r_{o,4} \| r_{o,5})$

$= -12mS \times (10.4K\Omega/2)$

$= \underline{-62.4}$ vs. 68.21 (SPICE)

$A_{v,tot} = A_{v1} \times A_{v2} = \underline{1454.5}$ vs. 1720.1 (SPICE)

(c)

* $\omega_{p1} = [(r_{o,1b} \| r_{o2,b}) \times (C_{db1b} + C_{db2b} + (C_{gd,1b} + C_{gd,2b})(1 - \frac{1}{A_{v1}})^{0}]^{-1}$

$\cong [(128K\Omega \| 107K\Omega) \times (0.78fF + 78fF + 1fF + 60fF)]^{-1}$

$= (58.28K\Omega \times 139.78fF)^{-1}$

$= \underline{19.54MHz}$ vs. 14.43 MHz (SPICE)

* $\omega_{p2} = [(r_{o,4} \| r_{o,5})(C_{db4} + C_{db5} + (C_{gd4} + C_{gd5})(1 - \frac{1}{A_{v2}})^{0} + C_L)]^{-1}$

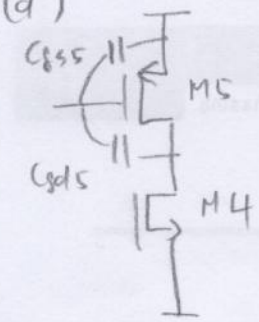
$\cong [5.2K\Omega \times (227.3fF + 642fF + 300fF + 720fF + 1000fF)]^{-1}$

$= (5.2K\Omega \times 2.89pF)^{-1}$

$= \underline{10.6MHz}$ vs. 5.36 MHz (SPICE)

(The simulated $\omega_p$'s are lower than the calculated values, because $C_{gd}$'s are millerized)

(d)



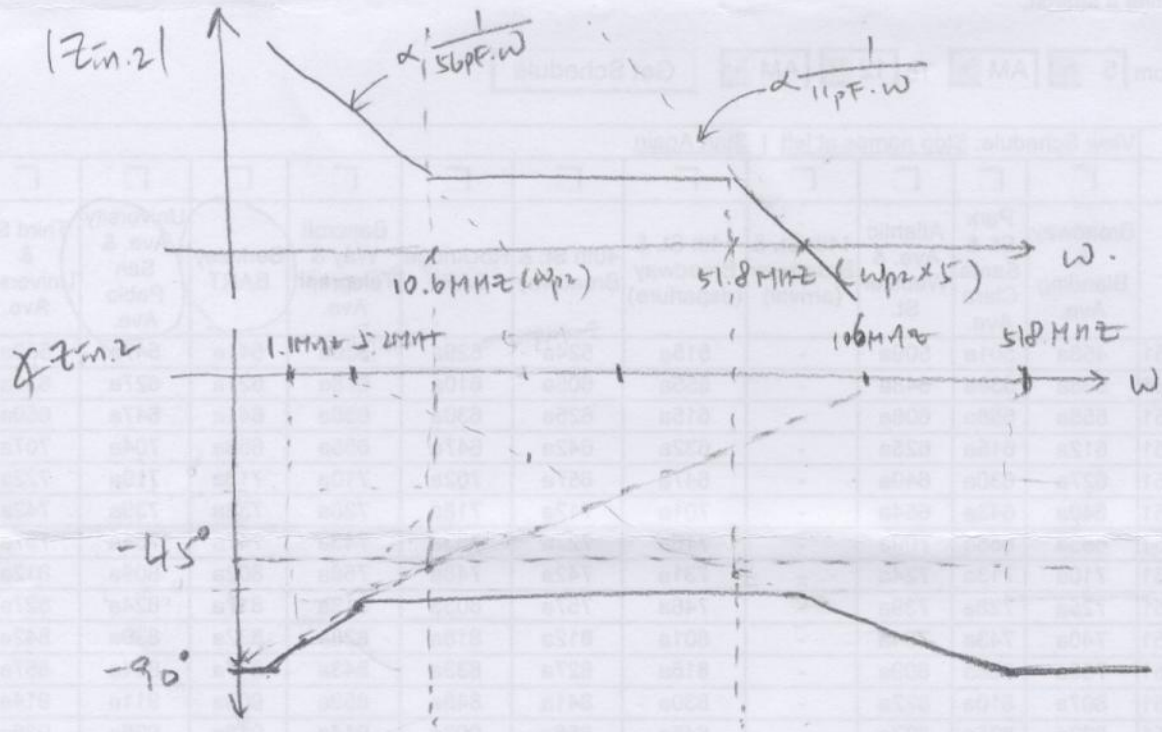

$C_{in,\,low\,freq} = C_{gs5} + (1 - A_{v2}) \cdot C_{gd,5}$

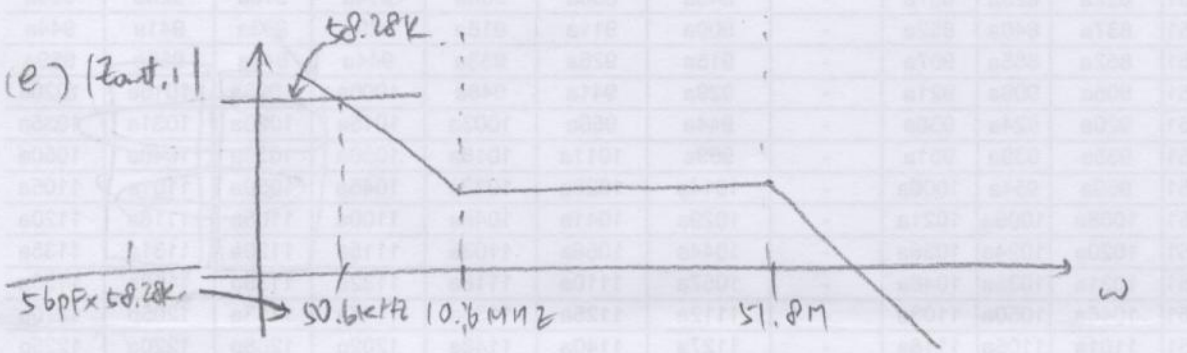
$= 10.32pF + (1+62.4) \cdot 720fF$

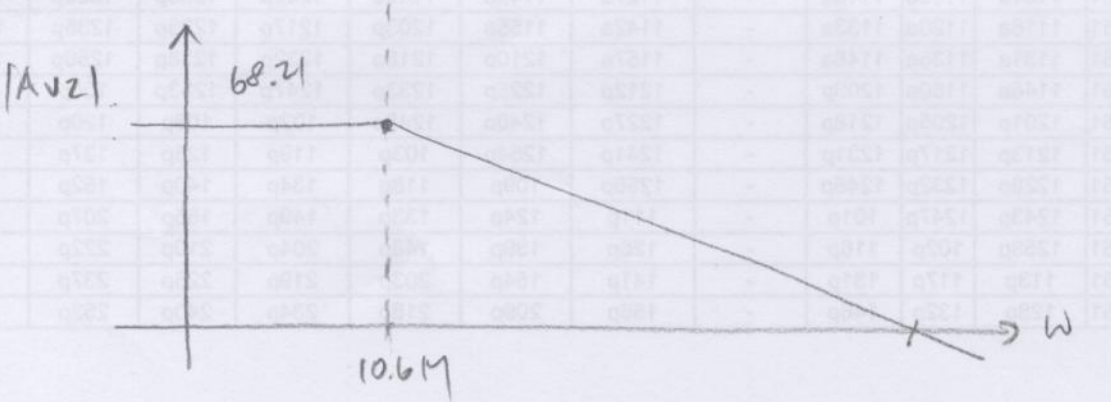
$\simeq 56pF.$

$C_{in,\,high\,freq} = C_{gs5} + C_{gd5}$

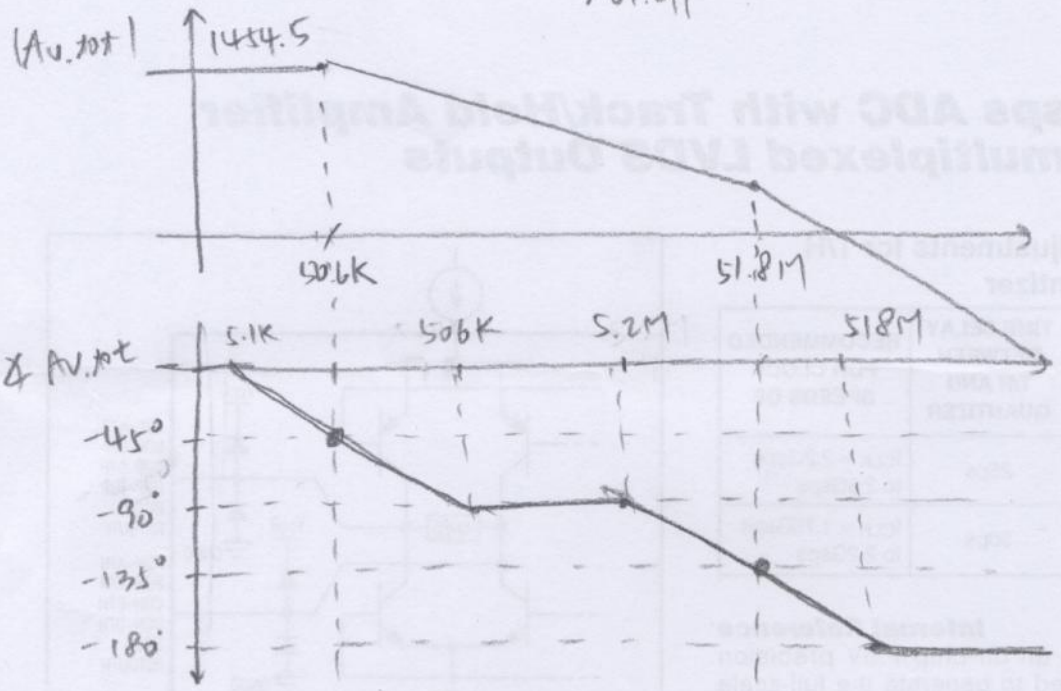
$\triangleq 11pF$ (×5 difference)



· The overall gain = $\frac{g_{m1} \times |Z_{out1}| \times A_{V2}}{A_{V1.eff}}$




[prob.3]

(a) The SPICE deck, DC analysis results, and comparisons are listed in list 1, 2, and table 1, respectively.

(b) The SPICE AC analysis results are shown in Fig2. The second pole is slightly off. But overall, the hand calculation well predicts the simulation.

```
** design view name: schematic
.global vdd!

.ac dec 10 10.0 10e9
  .op all 0

.param vtn=0.5
.param vtp=-0.5
.model nmos1 nmos vto='vtn'
+ tox=6.9nm kp=200u lambda=0.1 gamma=0.5 phi=0.6
+ capop=0 cgso=0.5n cgdo=0.5n pb=0.5 cj=1e-3
.model pmos1 pmos vto='vtp' tox=6.9nm kp=100u lambda=0.1 gamma=0.5 phi=0.6
+ capop=0 cgso=0.5n cgdo=0.5n pb=0.5 cj=1e-3


c0 vout 0 1.00001e-12
m1a left vn tail tail nmos1 l=500e-9 w=2e-6 ad=2e-12 as=2e-12
m1b right vp tail tail nmos1 l=500e-9 w=2e-6 ad=2e-12 as=2e-12
v2 vn 0 dc=2.5 ac 0
v0 vdd! 0 dc=5
v1 vp 0 dc=2.5 ac 1
r0 vdd! bias 44e3
m5 vout right vdd! vdd! pmos1 l=2e-6 w=1.44e-3 ad=1.44e-9 as=1.44e-9
m2b right left vdd! vdd! pmos1 l=2e-6 w=120e-6 ad=120e-12 as=120e-12
m2a left left vdd! vdd! pmos1 l=2e-6 w=120e-6 ad=120e-12 as=120e-12
m4 vout bias 0 0 nmos1 l=1e-6 w=600e-6 ad=600e-12 as=600e-12
m6 bias bias 0 0 nmos1 l=1e-6 w=50e-6 ad=50e-12 as=50e-12
m3 tail bias 0 0 nmos1 l=1e-6 w=100e-6 ad=100e-12 as=100e-12
.end
```

**List. 1. Spice Deck**

| subckt | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| element | 0:m1a | 0:m1b | 0:m2a | 0:m2b | 0:m3 | 0:m4 | 0:m5 | 0:m6 |
| model | 0:nmos1 | 0:nmos1 | 0:pmos1 | 0:pmos1 | 0:nmos1 | 0:nmos1 | 0:pmos1 | 0:nmos1 |
| region | Saturati | Saturati | Saturati | Saturati | Saturati | Saturati | Saturati | Saturati |
| id | 1.076e-04 | 1.076e-04 | -1.076e-04 | -1.076e-04 | 2.152e-04 | 1.453e-03 | -1.453e-03 | 9.917e-05 |
| ibs | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| ibd | -2.776e-14 | -2.776e-14 | 6.832e-15 | 6.832e-15 | -1.541e-14 | -2.983e-14 | 2.017e-14 | -6.366e-15 |
| vgs | 9.589e-01 | 9.589e-01 | -6.832e-01 | -6.832e-01 | 6.366e-01 | 6.366e-01 | -6.832e-01 | 6.366e-01 |
| vds | 2.775e+00 | 2.775e+00 | -6.832e-01 | -6.832e-01 | 1.541e+00 | 2.982e+00 | -2.017e+00 | 6.366e-01 |
| vbs | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| vth | 5.000e-01 | 5.000e-01 | -5.000e-01 | -5.000e-01 | 5.000e-01 | 5.000e-01 | -5.000e-01 | 5.000e-01 |
| vdsat | 4.589e-01 | 4.589e-01 | -1.832e-01 | -1.832e-01 | 1.366e-01 | 1.366e-01 | -1.832e-01 | 1.366e-01 |
| beta | 1.022e-03 | 1.022e-03 | 6.410e-03 | 6.410e-03 | 2.308e-02 | 1.558e-01 | 8.653e-02 | 1.064e-02 |
| gam eff | 5.000e-01 | 5.000e-01 | 5.000e-01 | 5.000e-01 | 5.000e-01 | 5.000e-01 | 5.000e-01 | 5.000e-01 |
| gm | 4.690e-04 | 4.690e-04 | 1.175e-03 | 1.175e-03 | 3.152e-03 | 2.127e-02 | 1.585e-02 | 1.452e-03 |
| gds | 8.423e-06 | 8.423e-06 | 1.007e-05 | 1.007e-05 | 1.865e-05 | 1.119e-04 | 1.209e-04 | 9.323e-06 |
| gmb | 1.514e-04 | 1.514e-04 | 3.791e-04 | 3.791e-04 | 1.017e-03 | 6.866e-03 | 5.117e-03 | 4.688e-04 |
| cdtot | 1.781e-15 | 1.781e-15 | 1.380e-13 | 1.380e-13 | 9.949e-14 | 5.273e-13 | 1.362e-12 | 5.816e-14 |
| cgtot | 5.336e-15 | 5.336e-15 | 9.207e-13 | 9.207e-13 | 4.336e-13 | 2.602e-12 | 1.105e-11 | 2.168e-13 |
| cstot | 6.336e-15 | 6.336e-15 | 9.807e-13 | 9.807e-13 | 4.836e-13 | 2.902e-12 | 1.177e-11 | 2.418e-13 |
| cbtot | 2.781e-15 | 2.781e-15 | 1.980e-13 | 1.980e-13 | 1.495e-13 | 8.273e-13 | 2.082e-12 | 8.316e-14 |
| cgs | 4.336e-15 | 4.336e-15 | 8.607e-13 | 8.607e-13 | 3.836e-13 | 2.302e-12 | 1.033e-11 | 1.918e-13 |
| cgd | 1.000e-15 | 1.000e-15 | 6.000e-14 | 6.000e-14 | 5.000e-14 | 3.000e-13 | 7.200e-13 | 2.500e-14 |

**List. 2. Spice DC Analysis Result**

| | | Id (A) | Vdsat (V) | L (um) | lambda | Vds (V) | (1+lamba *Vds)(V) | gm (S) | W (um) | gds = 1/ro (S) | ro (ohms) | Vdb (V) | Cov (fF) | Cgd (fF) | Cdb (fF) | Cgs (fF) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M1a | Calc. | 1.00E-04 | 0.5 | 0.5 | 0.1 | 2.8 | 1.28 | 4.00E-04 | 2 | 7.81E-06 | 1.28E+05 | 2.8 | 1.00 | 1.00 | 0.78 | 4.33 |
| | SPICE | 1.08E-04 | 0.46 | | | | | 4.69E-04 | | 8.42E-06 | | | | 1.00 | 0.78 | 4.34 |
| | % error | -7.41 | 8.70 | | | | | -14.71 | | -7.21 | | | | 0.00 | -0.15 | -0.15 |
| M1b | Calc. | 1.00E-04 | 0.5 | 0.5 | 0.1 | 2.8 | 1.28 | 4.00E-04 | 2 | 7.81E-06 | 1.28E+05 | 2.8 | 1.00 | 1.00 | 0.78 | 4.33 |
| | SPICE | 1.08E-04 | 0.46 | | | | | 4.69E-04 | | 8.42E-06 | | | | 1.00 | 0.78 | 4.34 |
| | % error | -7.41 | 8.70 | | | | | -14.71 | | -7.21 | | | | 0.00 | -0.19 | -0.15 |
| M2a | Calc. | 1.00E-04 | 0.2 | 2 | 0.1 | 0.7 | 1.07 | 1.00E-03 | 120 | 9.35E-06 | 1.07E+05 | 0.7 | 60.00 | 60.00 | 77.46 | 860.00 |
| | SPICE | 1.08E-04 | 0.18 | | | | | 1.18E-03 | | 1.01E-05 | | | | 60.00 | 78.00 | 861.00 |
| | % error | -7.41 | 11.11 | | | | | -15.25 | | -7.47 | | | | 0.00 | -0.69 | -0.12 |
| M2b | Calc. | 1.00E-04 | 0.2 | 2 | 0.1 | 0.7 | 1.07 | 1.00E-03 | 120 | 9.35E-06 | 1.07E+05 | 0.7 | 60.00 | 60.00 | 77.46 | 860.00 |
| | SPICE | 1.08E-04 | 0.18 | | | | | 1.18E-03 | | 1.01E-05 | | | | 60.00 | 78.00 | 861.00 |
| | % error | -7.41 | 11.11 | | | | | -15.25 | | -7.47 | | | | 0.00 | -0.69 | -0.12 |
| M3 | Calc. | 2.00E-04 | 0.14 | 1 | 0.1 | 1.5 | 1.15 | 2.86E-03 | 100 | 1.74E-05 | 5.75E+04 | 1.5 | 50.00 | 50.00 | 50.00 | 383.33 |
| | SPICE | 2.15E-04 | 0.14 | | | | | 3.15E-03 | | 1.87E-05 | | | | 50.00 | 49.50 | 383.60 |
| | % error | -6.98 | 0.00 | | | | | -9.30 | | -7.00 | | | | 0.00 | 1.01 | -0.07 |
| M4 | Calc. | 1.20E-03 | 0.14 | 1 | 0.1 | 2.5 | 1.25 | 1.71E-02 | 600 | 9.60E-05 | 1.04E+04 | 2.5 | 300.00 | 300.00 | 244.95 | 2300.00 |
| | SPICE | 1.45E-03 | 0.14 | | | | | 2.13E-02 | | 1.12E-04 | | | | 300.00 | 227.30 | 2302.00 |
| | % error | -17.24 | 0.00 | | | | | -19.52 | | -14.29 | | | | 0.00 | 7.76 | -0.09 |
| M5 | Calc. | 1.20E-03 | 0.2 | 2 | 0.1 | 2.5 | 1.25 | 1.20E-02 | 1440 | 9.60E-05 | 1.04E+04 | 2.5 | 720.00 | 720.00 | 587.88 | 10320.00 |
| | SPICE | 1.45E-03 | 0.183 | | | | | 1.59E-02 | | 1.21E-04 | | | | 720.00 | 642.00 | 10330.00 |
| | % error | -17.24 | 9.29 | | | | | -24.53 | | -20.66 | | | | 0.00 | -8.43 | -0.10 |
| M6 | Calc. | 1.00E-04 | 0.14 | 1 | 0.1 | 0.6 | 1.064 | 1.43E-03 | 50 | 9.40E-06 | 1.06E+05 | 0.64 | 25.00 | 25.00 | 33.11 | 191.67 |
| | SPICE | 9.92E-05 | 0.137 | | | | | 1.45E-03 | | 9.32E-06 | | | | 25.00 | 33.14 | 191.80 |
| | % error | 0.81 | 2.19 | | | | | -1.48 | | 0.84 | | | | 0.00 | -0.08 | -0.07 |

**Table.1. Device Parameters**

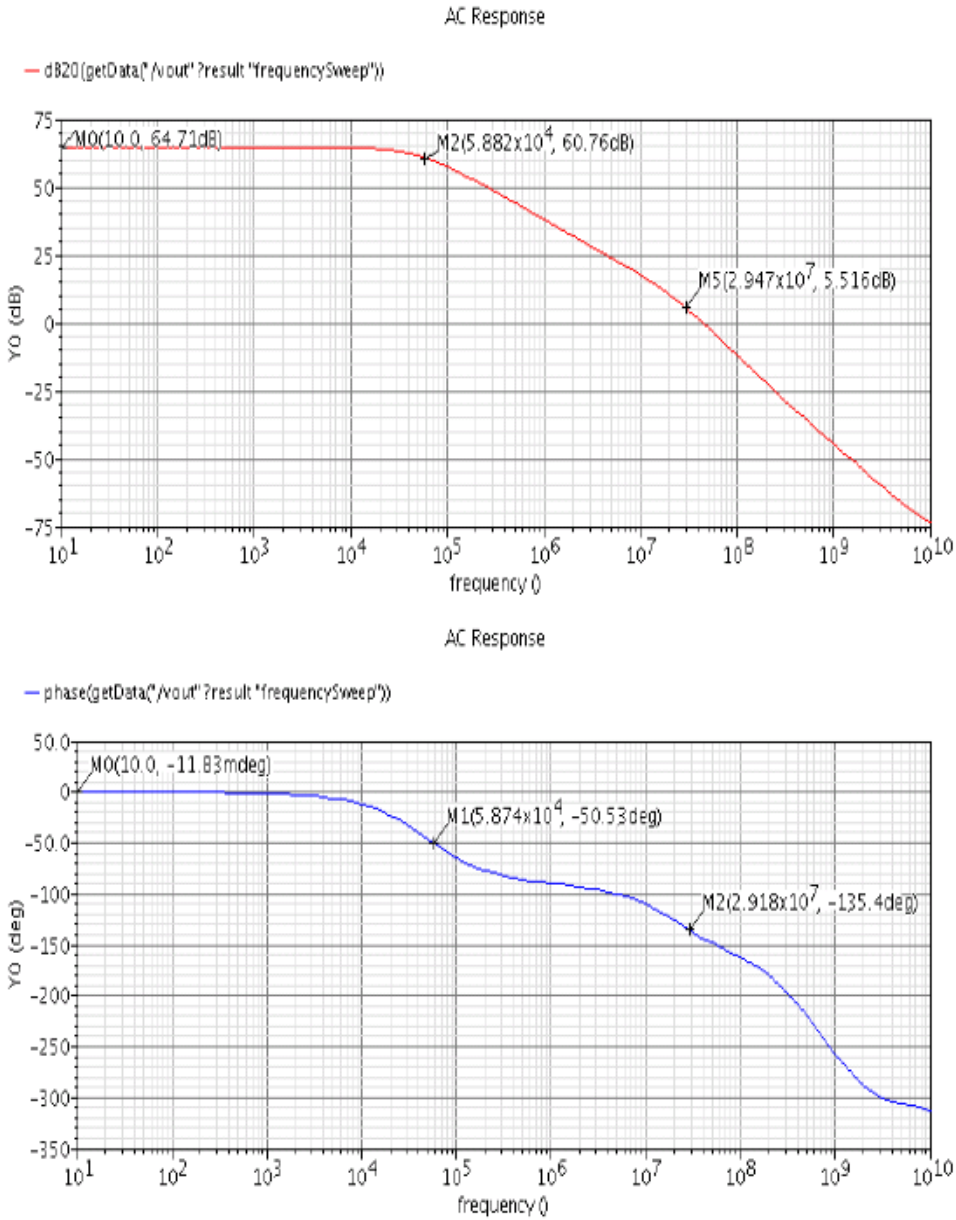
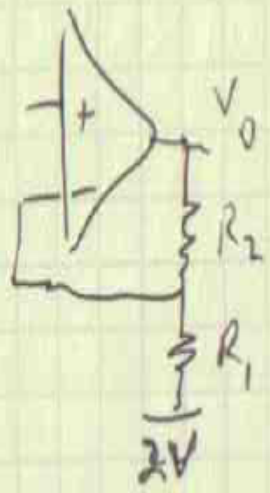
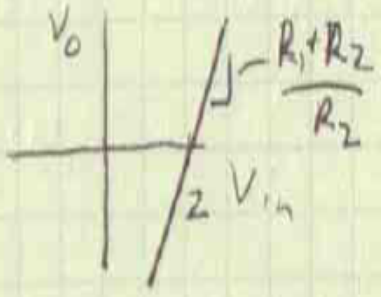



**Fig.2. Spice AC Analysis Result**

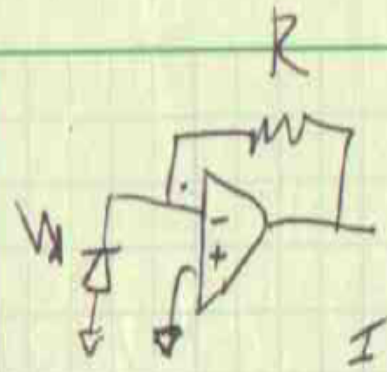



positive gain amplifier w/ input offset of 2V

$$V_o = \left(1 + \frac{R_1}{R_2}\right)(V_{in} - 2V)$$

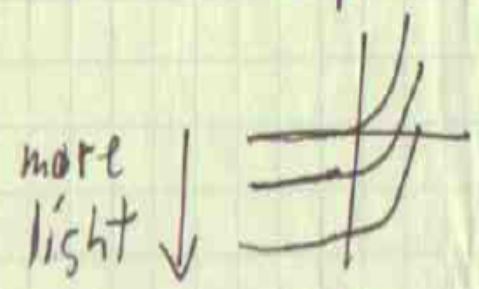



- input range ~~xxx~~ smaller than output swing
- need gain large compared to $\frac{R_2}{R_1+R_2}$
- need output resistance less than $R_1+R_2$



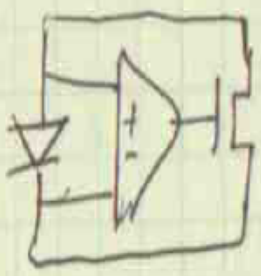

op-amp keeps $V_{diode} = 0$

IV curve for photodiode

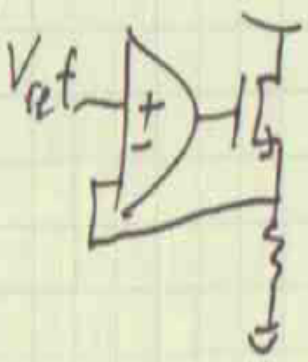



op-amp forces $V_{diode}$ here

- input range only at 0
- output only positive
- need output resistance less than R



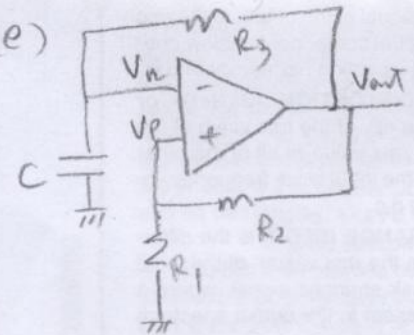

- super diode
- output can be very high impedance.
- output must be able to swing well above input CM, and probably a little below.




Voltage regulator

- input and output near top rail
- capacitive load - high Z OK

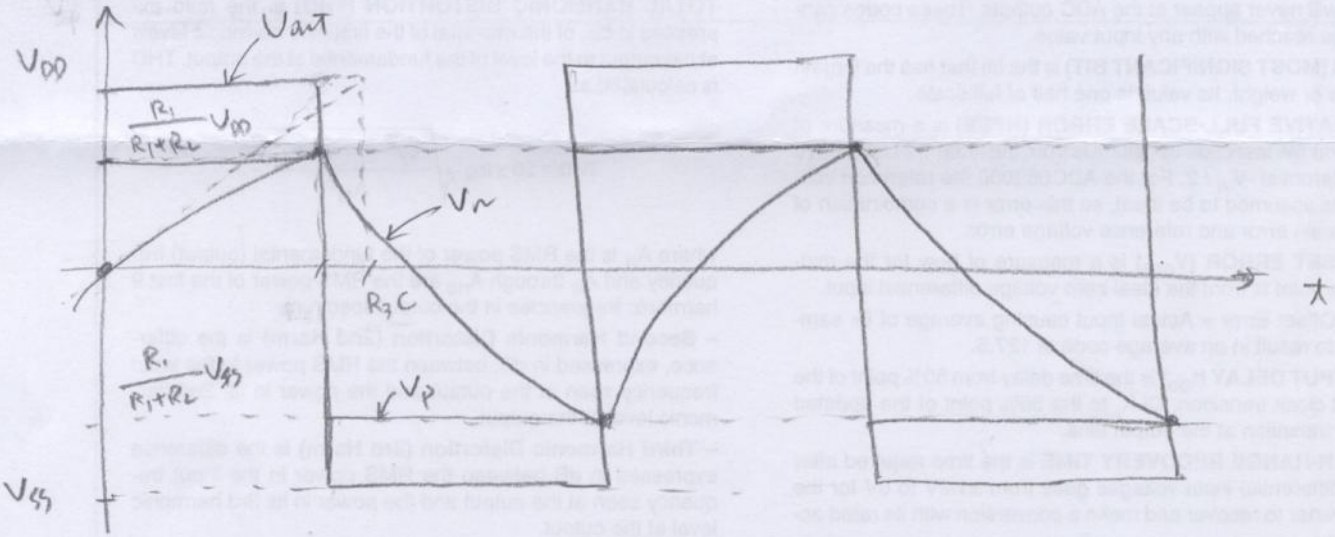
(e)




Assume that $V_{SS} \le V_{out} \le V_{DD}$,

$V_n = 0\ (t=0)$, $V_{out} = V_{DD}\ (t=0)$

$$V_p = \frac{R_1}{R_1+R_2} V_{out}$$




(Multi-Vibrator)