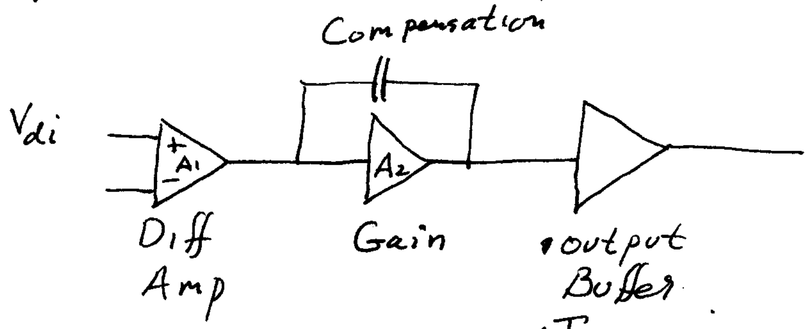
CH 25
Op Amps



- I-gain
- Overload protection (Shorting output to ground, Vss, V_{DD})

3

FIG. 25.2

0. Current Mirror I-Source M5 & M6.

I_{ss} bias current

1. Diff Amp with active load (Fig p 9.1)

(a) Source coupled pair M1 & M2

(b) Active load M3 & M4

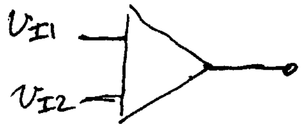
(c) Gain of diff amp

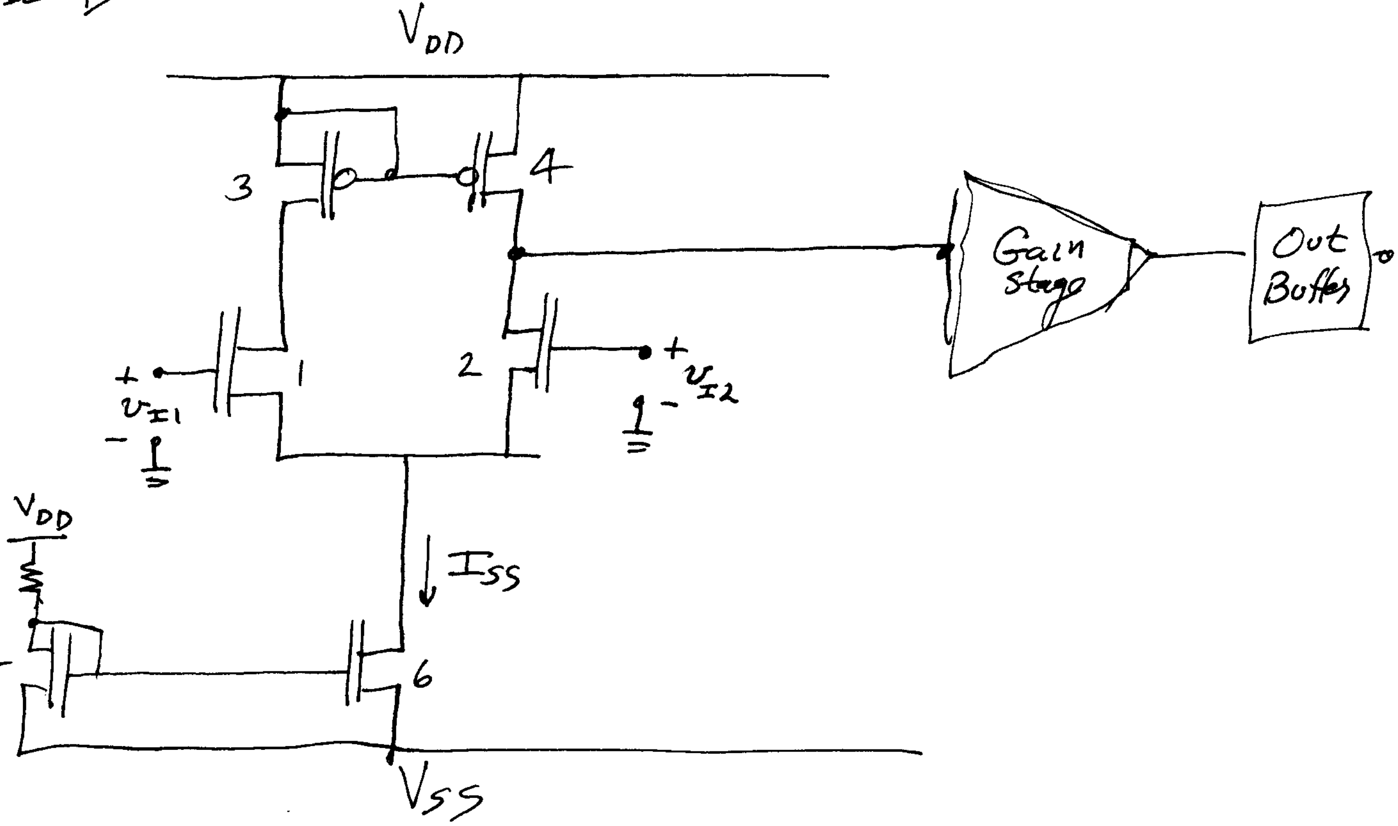
$$A_1 = g_{m1}(r_{o2} \| r_{o4})$$

$$= \frac{2\sqrt{\beta_1}}{(\lambda_2 + \lambda_4)\sqrt{I_{ss}}}$$

$$= \frac{2}{(\lambda_2 + \lambda_4)(V_{GS} - V_{THN})}$$

W6





(d) Design Considerations

$\uparrow \frac{W}{L} \Rightarrow \downarrow V_{GS} \Rightarrow \uparrow CMR \Rightarrow$ better matching

$\Rightarrow \uparrow$ gain

$\Rightarrow \uparrow$ parasitic $C_s \Rightarrow \downarrow f_{3dB}$.

(e) FOR off-chip use, W ~~≈~~ 200 μm range

2. Gain Stage (Fig. p 11)

(a) Single stage common source (~~CS~~) amp (M7) with active load (M8)

(b) M91 & M101 provide Voltage drop of $2\ V_{GS}$.

(c) BIASING

* SIZING M7

For $v_{I1} = v_{I2} = 0$

$I_{ss}/2$ flows thru M3 & M4, ~~Also~~ $V_{GS3} = V_{GS4}$ $\Rightarrow V_{SD3} = V_{SD4} = V_{SG3,4}$

$$\Rightarrow V_{SD4} = V_{SD3} = V_{SG3,4}$$

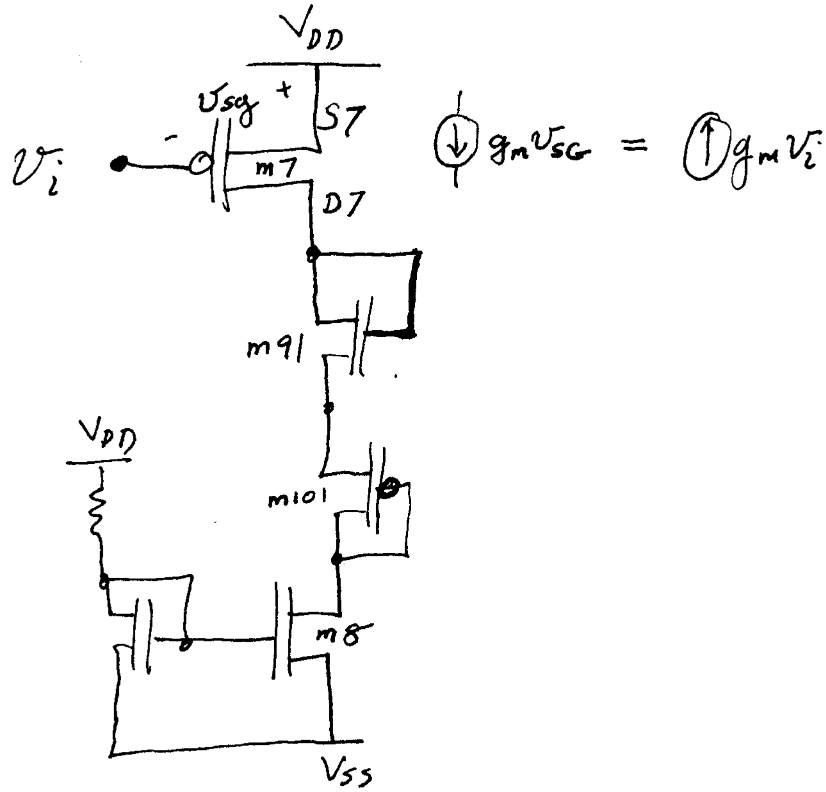
$$\Rightarrow V_{SG7} = V_{SG3,4}$$

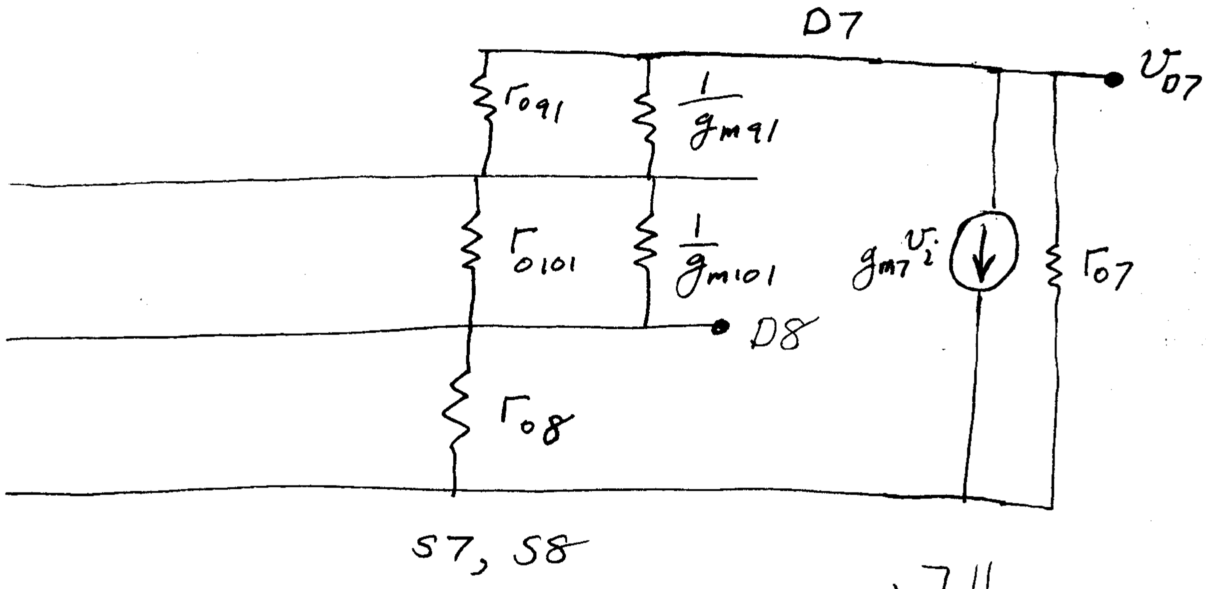
FOR $I_{D7} = I_{ss}/2$ choose $\left(\frac{W}{L}\right)_7 = \left(\frac{W}{L}\right)_{3,4}$

* SIZING M8

Choose $\left(\frac{W}{L}\right)_8$ s.t. $I_{D8} = I_{D7}$.

(d) Gain (low f) (Ignore C_c)





$$\frac{v_{D7}}{v_i} = -g_{m7}\left[r_{o8} + \underbrace{\left(r_{o101} \,\|\, \frac{1}{g_{m101}}\right)}_{1/g_m} + \underbrace{\left(r_{o91} \,\|\, \frac{1}{g_{m91}}\right)}_{1/g_m}\right] \Big\| \, r_{o7}$$

$$\approx -g_{m7}\, r_{o8} \,\|\, r_{o7}$$

$$v_{D8} = v_{D7}\frac{r_{o8}}{r_{o8} + 1/g_{m10} + \frac{1}{g_{m9}}} \approx v_{D7}\frac{r_{o8}}{r_{o8}} = v_{D7}$$

$$A_{v2} = -g_{m7}(r_{o7} \| r_{o8})$$

$$= \frac{-\sqrt{2\beta_7}}{(\lambda_7+\lambda_8)\sqrt{I_{D7}}} = \frac{-2\sqrt{\beta_7}}{(\lambda_7+\lambda_8)\sqrt{I_{SS}}}$$

$$= \frac{-2}{(\lambda_7+\lambda_8)(V_{SG7} - V_{THP})}$$

(e) Open Loop Gain A_{OL}

$$A_{OL} = A_{v1}A_{v2} =$$

$$= -g_{m1}g_{m7}(r_{o2}\|r_{o4})(r_{o7}\|r_{o8})$$

$$= \frac{-4\sqrt{\beta_1\beta_7}}{(\lambda_2+\lambda_4)(\lambda_7+\lambda_8)I_{SS}}$$

$$\left(\text{for } \left(\frac{W}{L}\right)_7 = \left(\frac{W}{L}\right)_4 \quad (I_{D7} = I_{SS}/2)\right)$$

FOR $I_{SS} = 10\mu A$

$$\beta_1 = \frac{1}{2}\,50\frac{\mu A}{V^2}\left(\frac{15}{5}\right)$$

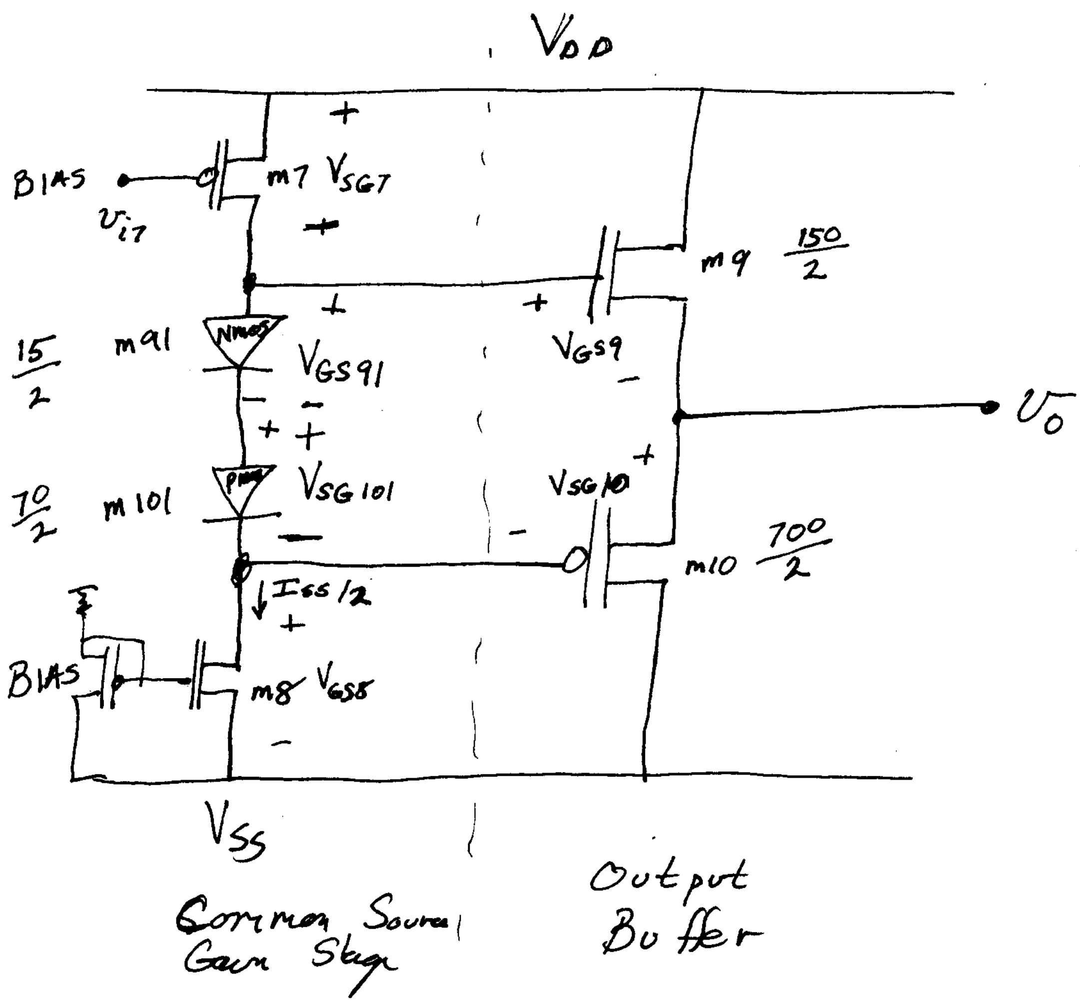
$$\beta_7 = \frac{1}{2}\,17\frac{\mu A}{V^2}\,\frac{70}{5}$$

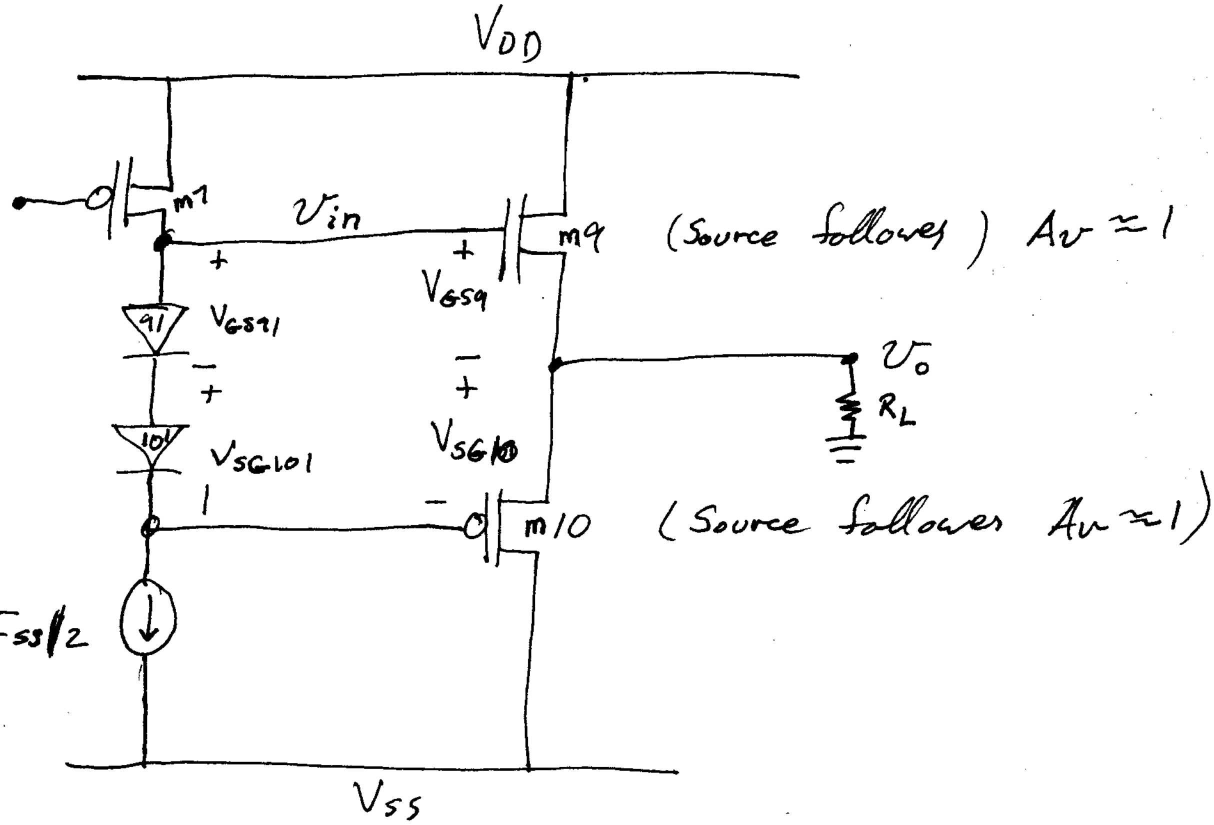
$$\lambda_2 = \lambda_4 = \lambda_7 = \lambda_8 = 0.06\,\frac{1}{V}$$

$A_{OL} = 2600$ (typical order of magnitude)

$A_{OL}(I_{SS} = 1\mu A) = 26{,}000$

3. Output Stage Class AB





With no ac signal, $v_{i7} = 0$

$$I_{D7} = I_{SS}/2 = I_{D91} = I_{D101}$$

$$V_{GS9} + V_{SG10} = V_{GS91} + V_{SG101} = \text{fixed}$$

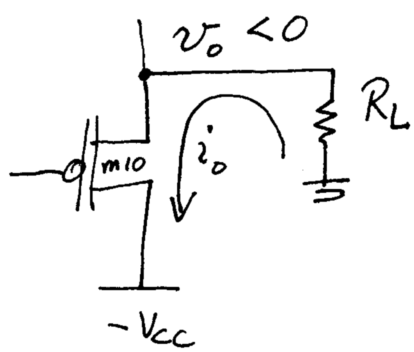
Choose $(W/L)_{9,10}$

$\Longrightarrow$ M9 & M10 are biased on w/ current dependent on $\frac{W}{L}$ ratios.

- As v_{g9} goes $(-)\downarrow$, ~~M9 forces v_o to follow~~

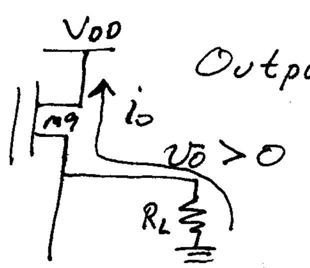
$$\left.\begin{array}{l} V_{GS9} \downarrow \\ V_{SG10} \uparrow \end{array}\right\} V_{GS9} + V_{SG10} = \text{const.}$$

FOR negative V_{g9}



Output current flows thru M10

- FOR + v_{g9}



Output flows thru M9.

W7

$$V_{G9\,MAX} = V_{DD} \iff V_{SD7} = 0 = V_{SG7} - V_{THP}$$

$$V_{G10\,MIN} = V_{SS} \iff V_{DS8} = 0 = V_{GS8} - V_{THN}$$

- Choose a max $|V_{gs}| = 1.2\,V$

$$\Longrightarrow V_{OUTMAX} = V_{DD} - 1.2$$

$$V_{OUTMIN} = V_{SS} + 1.2$$

$$I_{OUTMAX} = \frac{\beta_9}{2}\left(V_{GS9} - V_{THN}\right)^2 =$$

$$= 50\frac{\mu A}{V^2}\,\frac{150}{2}(1.2-0.83)^2 = 500\mu A$$

$$I_{o\,MIN} = \frac{\beta_{10}}{2}\left(V_{SG10} - V_{THP}\right)^2 = 17\frac{\mu A}{V^2}\,\frac{700}{2}\,(1.2-0.91)^2$$

$$= 500\mu A$$

OVERLOAD PROTECTION

What happens when $V_{G9} = V_{DD}$ &

V_o is shorted to V_{SS}?

For $V_{DD} = |V_{SS}| = 2.5V$,

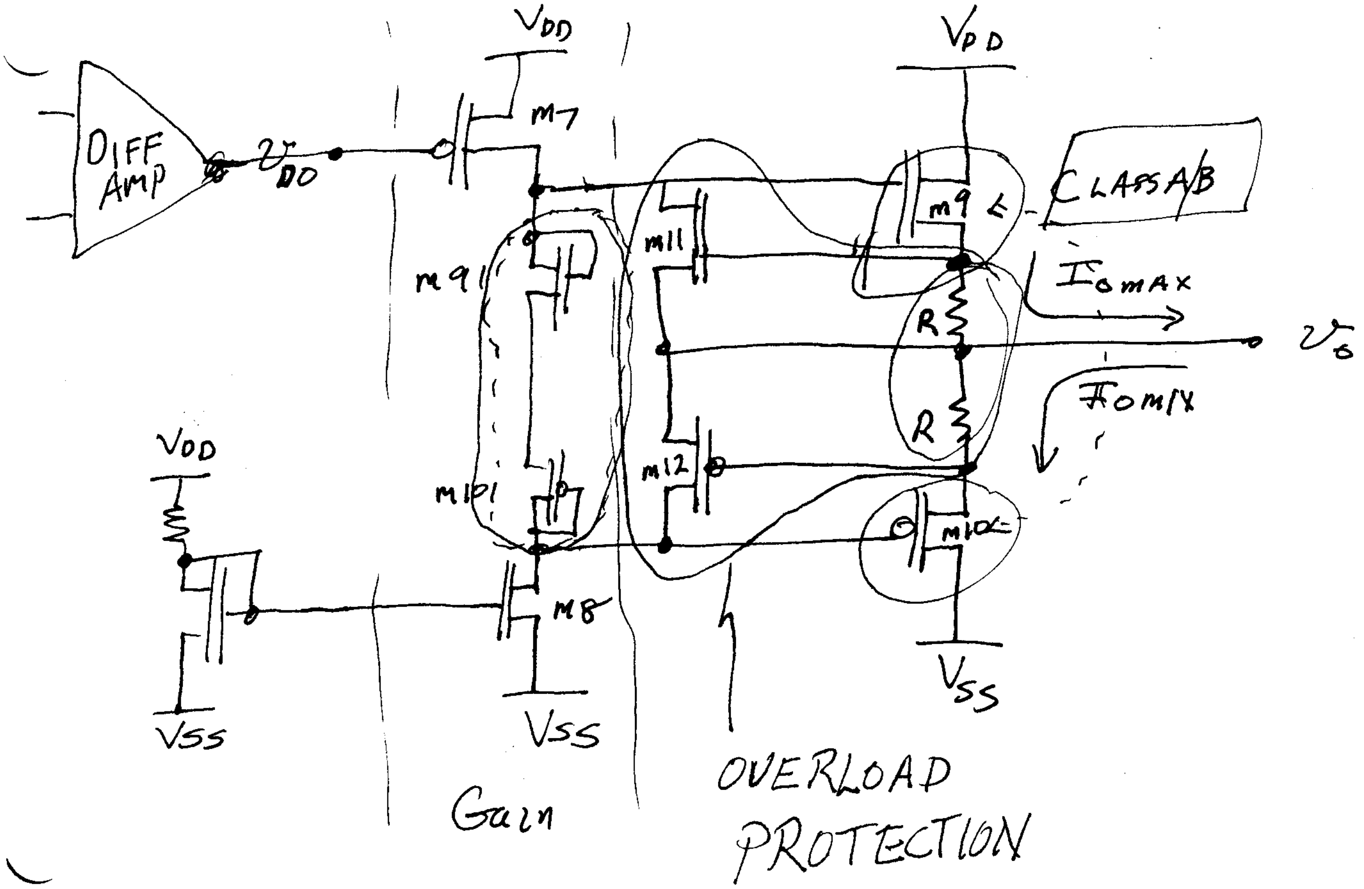
$$V_{GS9} = 5\,V$$

$$I_o = 65\ mA$$

$$P_9 = 0.065\ (5) = 0.33\ W$$

How to keep max V_{GS9} & max $V_{SG10} \lessapprox 1.2V$?

OVERLOAD PROTECTION



- When $I_{omax} = \dfrac{V_{THN}}{R}$, m11 turns on

  $\Rightarrow$ Pulls $V_{G9} \downarrow$ & shuts off m9

- When $I_{omin} = \dfrac{V_{THP}}{R}$, m12 turns on

  $\Rightarrow$ Pulls $V_{G10} \uparrow$ & shuts off m10.

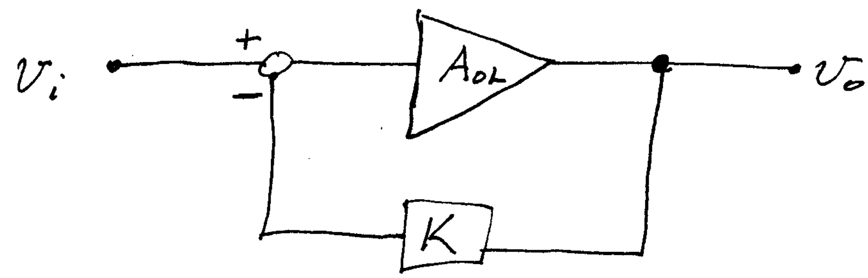
Choose $R = 1\ k\Omega$

$1\,mA \cdot 1\,k\Omega = 1V \Rightarrow$ m11 on

pulling V_{G9} down to v_o.

- Op - Amps Always used in feedback configuration.

STABILITY of FEEDBACK AMP

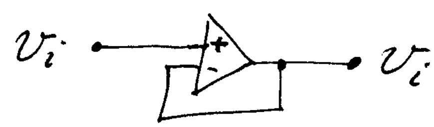


$$A_{CL} = \frac{A_{OL}}{1 + K A_{OL}}$$

Unstable when $K A_{OL} = -1. \Rightarrow A_{CL} = \infty$

$K A_{OL} = -1 \iff |K A_{OL}| = 1$ & $\angle K A_{OL} = \pm 180°$

MAX $K = 1.$



Voltage follower

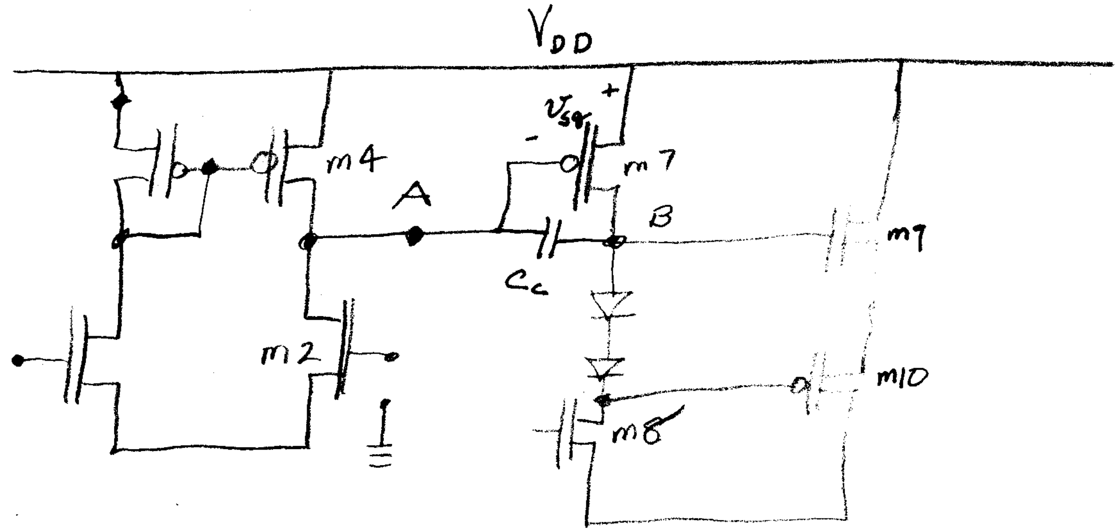
$\Downarrow$

Unstable if $|A_{OL}| \geq 1$ when $\angle A_{OL} = \pm 180°$

COMPENSATION

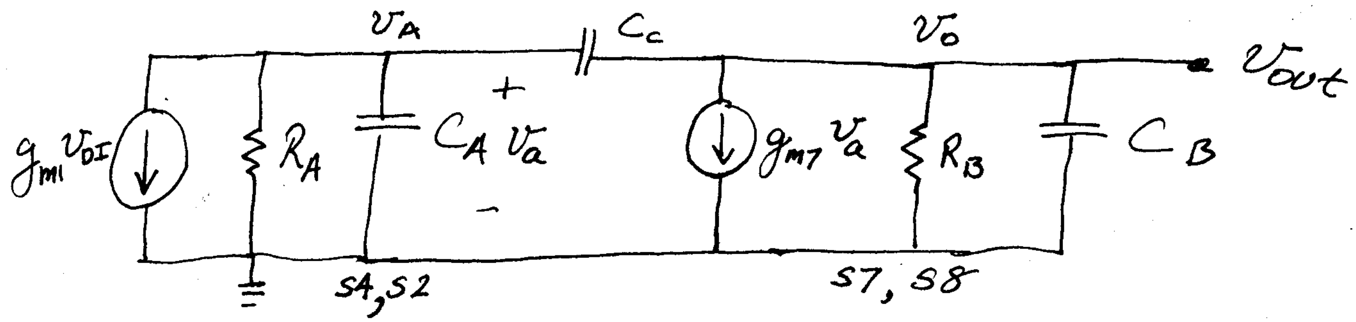
To adjust $|A_{OL}|$ & $\angle A_{OL}$ for stable unity feedback (Worst case scenario)

FREQUENCY RESPONSE & COMPENSATION



DOMINANT POLES AT High impedance nodes.

NODE A: OUTPUT OF DIFF AMP



Calc $\tau_1 = R_A C_A$

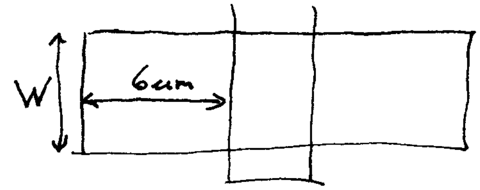
$$R_A = r_{o2} \parallel r_{o4} = \frac{1}{(\lambda_2 + \lambda_4)\frac{I_{SS}}{2}} = \frac{1}{(0.06+0.06)(10e-6)} = 833.33k\Omega$$

$$C_A = \underbrace{\left(C_{db4} + C_{gd4} + C_{db2} + C_{gd2}\right)}_{\text{DIFF AMP } C_{out}} + \underbrace{C_L}_{\text{due to M7}}$$

$$C_L = C_{gs7} + C_{gd7}(1 + |A_{v2}|)$$

$$C_{db2} = C_{jo} \cdot 6\mu m \cdot 15\mu m = 9.4\,fF$$

C_{jo}: $1e\text{-}4 \frac{pF}{\mu m^2}$



$$C_{db4} = C_{jo} \cdot 6\mu m \cdot 70\mu m = 137\,fF$$

$$C_{gd2} = CGDO_{Nmos} \cdot W_2 = 3.8e\text{-}10 \cdot 15\mu m = 5.7\,fF$$

$$C_{gd4} = CGDO_{pmos} \cdot W_4 = 5e\text{-}10 \cdot 70\mu m = 35\,fF$$

187 fF

$$C_{gs7} = \frac{2}{3} \cdot C'_{ox} \cdot W_7 L_7 =$$

$$= \frac{2}{3} \cdot \underset{\left(\frac{F}{\mu m^2}\right)}{7.94e\text{-}16} \cdot 70 \cdot 5 = 1.85e\text{-}13\,F = 185\,fF$$

$(t_{ox} = 4.35e\text{-}8\,m)$

$$C_{gd7} = CGDO_{pmos}\, W = 5e\text{-}10 \tfrac{F}{m}\ 70\mu m = 35\,fF$$

Multiply by miller effect

$$|A_{v2}| = \frac{2\sqrt{\beta_7}}{(\lambda_7 + \lambda_8)\sqrt{I_{SS}}} = \frac{2\sqrt{\frac{1}{2}\, 17 \frac{\mu A}{V^2} \cdot \frac{70}{5}}}{(0.06 + 0.06)\sqrt{10\mu A}}$$

$$= 57.5$$

$$C_{gd7}(1 + 57.5) = \underline{2.05\,pF = 2047\,fF} \quad \text{Miller Cap.}$$

$$= C_{M7}$$

$$C_{gs7} + C_{gd7}(1 + 57.5) = 2232\,fF$$

$$+\ 187$$

$$C_A = 2.42\,pF$$

$$\tau_1 = R_A C_A = 2.017\,\mu s$$

$$\boxed{f_1 = \frac{1}{2\pi \tau_1} = 78.9\,kHz}$$

CALC $\tau_2 = R_B C_B$

$R_B = r_{o7} \| r_{o8} = R_A = 833\,k\Omega$

$C_2 = C_{gd7} + C_{db7} + C_{db8} + C_{gd8} + \underbrace{(C_{gd9} + C_{gd10})}_{\text{Output Buffes}}$

$C_{gd7}\left(1 + \frac{1}{A_{v7}}\right) = C_{gd7}$

C_{gd7} appears in C_1 & C_2.

$C_2 = \underbrace{35\,fF + 137\,fF + 9.4\,fF + 5.7\,fF}_{\text{Gain Stage } M7 + M8} = 187.1\,fF$

$+ 3.8e{-10}\,\frac{F}{m} \cdot 150\,\mu m = 57\,fF$ (C_{gd9})

$+ 5e{-10}\,\frac{F}{m} \cdot 700\,\mu m = 350\,fF$ (C_{gd10})

$C_2 = 594\,fF$

$$\frac{1}{1+j\omega RC} = \frac{1}{1+j2\pi f RC} = \frac{1}{1+j\frac{f}{1/2\pi RC}}$$

$\tau_2 = 0.495\,\mu S$

$$\boxed{f_2 = \frac{1}{2\pi \tau_2} = 321\,kHz}$$

UNITY GAIN f

$$A_v = \frac{A_{vo}}{\left(1+j\frac{f}{f_1}\right)\left(1+j\frac{f}{f_2}\right)} \qquad (A_{vo} = 2600)$$

$$|A_v| = \frac{A_{vo}}{\left(1+\left(\frac{f}{f_1}\right)^2\right)^{1/2}\left(1+\left(\frac{f}{f_2}\right)^2\right)^{1/2}} = 1$$

$$A_{vo}^2 = \left(1+\left(\frac{f}{f_1}\right)^2\right)\left(1+\left(\frac{f}{f_2}\right)^2\right)$$

$$A_{vo}^2 \cong \frac{f^4}{f_1^2 f_2^2} \qquad f = \sqrt{f_1 f_2 A_{vo}}$$

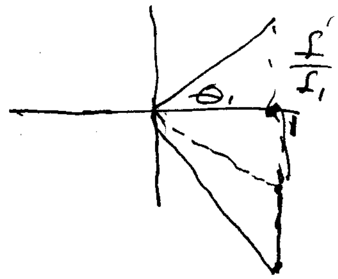
$$= 8.1\,MHz$$

SPICE $\Rightarrow$ 20 MHz

PHASE

$$A_v = A_{vo} \frac{\left(1-j\frac{f}{f_1}\right)\left(1-j\,{}^{f}/_{f_2}\right)}{\left[1+\left(\frac{f}{f_1}\right)^2\right]\left[1+\left({}^{f}/_{f_2}\right)^2\right]}$$

$$A_{vo}\, R_1 e^{i\theta_1} R_2 e^{i\theta_2} = R_1 R_2 e^{i(\theta_1+\theta_2)}$$



$$\theta_1 = -\operatorname{atan}\frac{f}{f_1}$$

$$\theta_2 = -\operatorname{atan}\frac{f}{f_2}$$

$$\theta_1 + \theta_2 =$$

@ $f = 8.1\,\mathrm{MHz}$ $\quad \theta_1 = -\operatorname{atan}\frac{8100}{78.9} = -89^\circ$

$\theta_2 = -\operatorname{atan}\frac{8100}{321} = -87^\circ$

$$\left.\begin{aligned}\theta_1 &= -89^\circ\\ \theta_2 &= -87^\circ\end{aligned}\right\} \quad \theta_1+\theta_2 = -176^\circ$$

$\Longrightarrow$ NO PHASE MARGIN!

FOR STABILITY, WANT

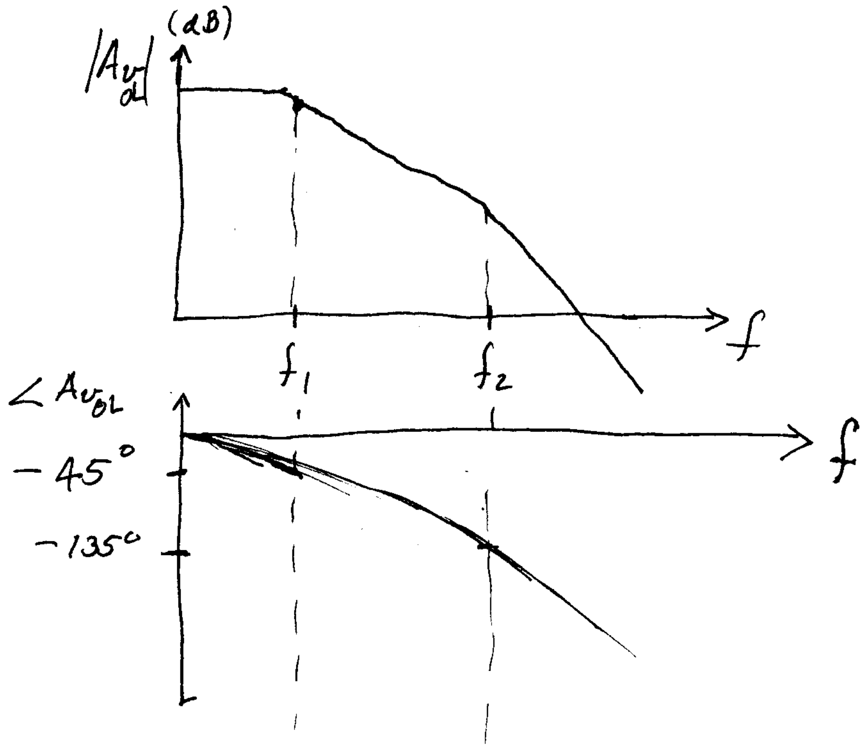
$|\theta| \le$

$$|\angle A_v| \le 135^\circ \quad @ \quad |A_v(f)| = 1$$

$\equiv$ 45° Phase Margin

WHY?

$$A_v(f) = \frac{A_{vo}\left(1 - j\frac{f}{f_1}\right)\left(1 - j\frac{f}{f_2}\right)}{\left(1+\left(\frac{f}{f_1}\right)^2\right)\left(1+\left(\frac{f}{f_2}\right)^2\right)}$$



If $|A_v| > 1$ when $|\angle A_v|$ reaches $180°$,

$\Rightarrow$ poles in RHP (s-plane)

$$\frac{A_{vOL}(s=0)}{\left(1 - \frac{s}{p_1}\right)\left(1 - \frac{s}{p_2}\right)}$$

FOR $p_{1,2} = \sigma \pm j\omega$ with $\sigma > 0$

$A_v(t) \cancel{\propto} = e^{\sigma t} \sin\omega t \Rightarrow$ unstable or oscillatory.