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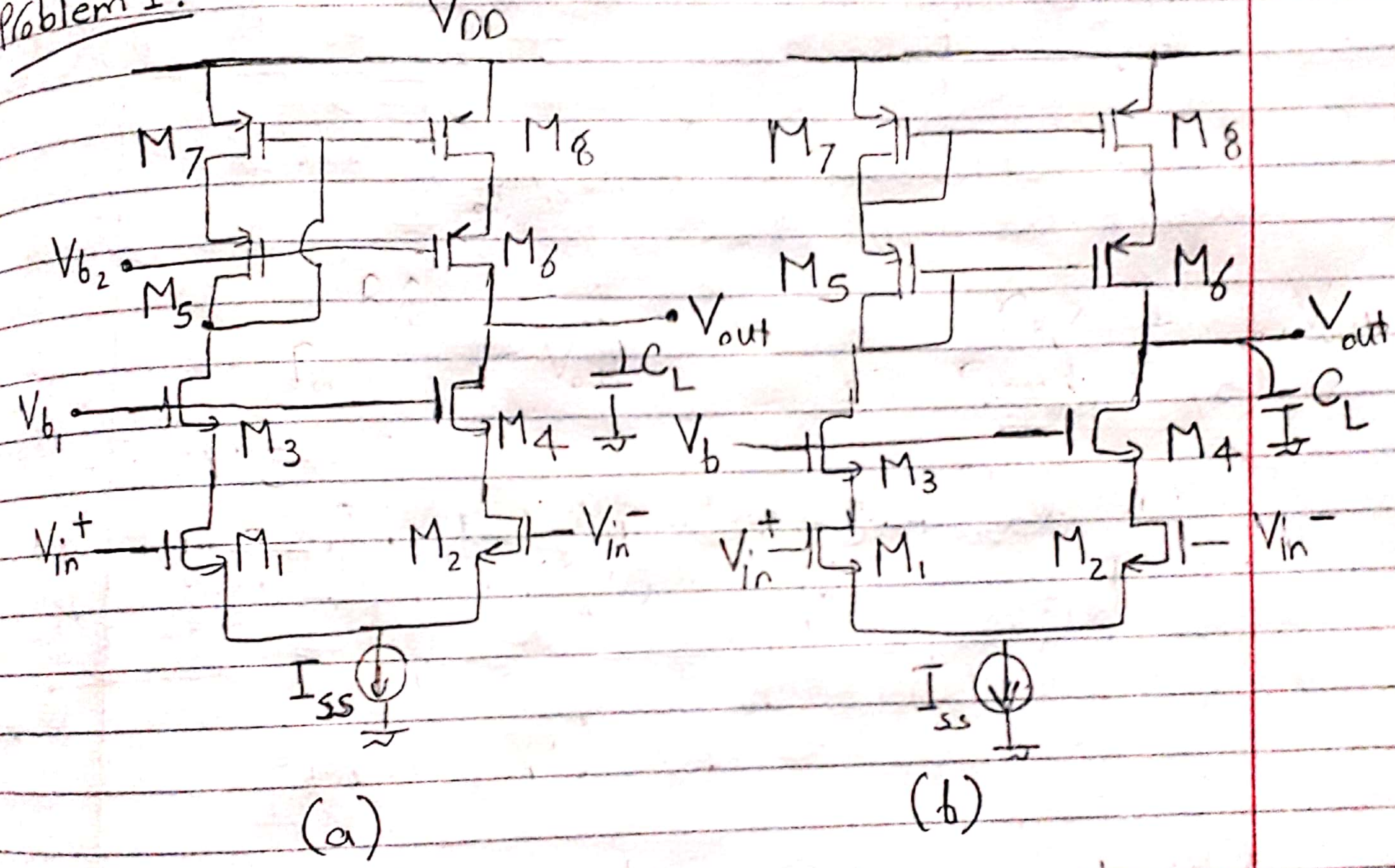
Operational Amplifiers

Problem 1:



Compare between the two operational amplifier circuits in terms of:

① DC gain:

Both have the same DC gain

$$G_m = g_{m1}$$

$$R_{out} \approx (g_{m6} r_{o6} r_{o8} \,//\, g_{m4} r_{o4} r_{o2})$$

$$\therefore A_v \approx -g_{m1} (g_{m6} r_{o6} r_{o8} \,//\, g_{m4} r_{o4} r_{o2})$$

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(2) GBW (assume a load Capacitance C_L):

dominant Pole ← $B.W. = \dfrac{1}{R_{out} C_L}$

$$\therefore GBW = A_v * B.W. = \frac{g_{m1}}{C_L} \quad \text{(for both)}$$

(3) Slew rate:

If $V_{in,differential}$ is large enough, current (I_{ss}) will be steered in one branch. Therefore, the whole biasing current (I_{ss}) will be pushed into or pulled from C_L

$$\therefore SR = \pm \frac{I_{ss}}{C_L} \quad \text{(for both)}$$

(4) Maximum available output swing:

Circuit (a)

M_6 Sat

* $V_{out,max} = V_{b_2} + V_{th,6}$

M_4 Sat

* $V_{out,min} = V_{b_1} - V_{th4}$
* o/p swing $= V_{out,max} - V_{out,min}$
* To maximize o/p swing:

Choose: $V_{b_1} = V_{GS_3} + V_{eff_1} + V_{Comp,I_{ss}}$

$V_{b_2} = V_{DD} - V_{eff_7} - V_{SG_5}$

$V_{in,CM} = V_{GS_1} + V_{Comp,I_{ss}}$

Hence, $\text{o/p swing})_{max} = V_{DD} - \left(\sum_{\text{all } M} V_{eff} + V_{Comp,I_{ss}}\right)$

Circuit (b)

M_6 Sat

* $V_{out,max} = V_{DD} - V_{SG_7} - V_{eff,6}$

M_4 Sat

* $V_{out,min} = V_b - V_{th4}$
* o/p swing $= V_{out,max} - V_{out,min}$
* To maximize o/p swing:

Choose: $V_b = V_{GS_3} + V_{eff_1} + V_{Comp,I_{ss}}$

$V_{in,CM} = V_{GS_1} + V_{Comp,I_{ss}}$

Hence, $\text{o/p swing})_{max} = V_{DD} - (V_{SG_7} + 3V_{eff} + V_{Comp,I_{ss}})$

$V_{eff_1} + V_{eff_3} + V_{eff_6}$

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(5) Input Common mode range (assume $V_b = V_{b_1} = V_{th} + 4V_{eff}$)

Assuming equal V_{eff} for all transistors

$$V_{in,CM,min} = V_{eff} + V_{th_1} + V_{Comp,I_{SS}}$$

$$V_{in,CM,max} = 3V_{eff} + V_{th_1}$$

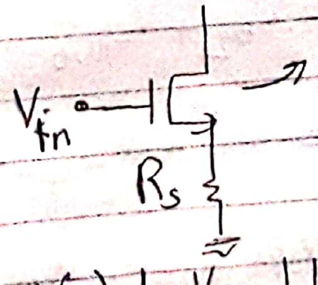
for both

(6) Noise & offet:

$$\overline{V_{n,in}^2} = 2 * \left[\underbrace{\frac{4KT\gamma}{g_{m1}}}_{M_{1-2}} + \underbrace{\frac{4KT\gamma g_{m7}}{g_{m1}^2}}_{M_{7-8}} \right] = \frac{8KT\gamma}{g_{m1}} \left[1 + \frac{g_{m7}}{g_{m1}} \right)$$

$$V_{os,in}^2 = \underbrace{V_{os_{1-2}}^2}_{M_{1-2}} + \underbrace{V_{os_{7-8}}^2 * \frac{g_{m7}^2}{g_{m1}^2}}_{M_{7-8}}$$

* The noise and offset of Cascode devices can be neglected because their overall transconductance is very small as they are degenerated



$$G_m = \frac{g_m}{1 + g_m R_s}$$

(7) Why will the transfer fn. A(s) have LHP Zeros?

* Because there are two Pathes form the input to output with different frequency dependence

Analysis can be found in Lec slides

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Problem(2):

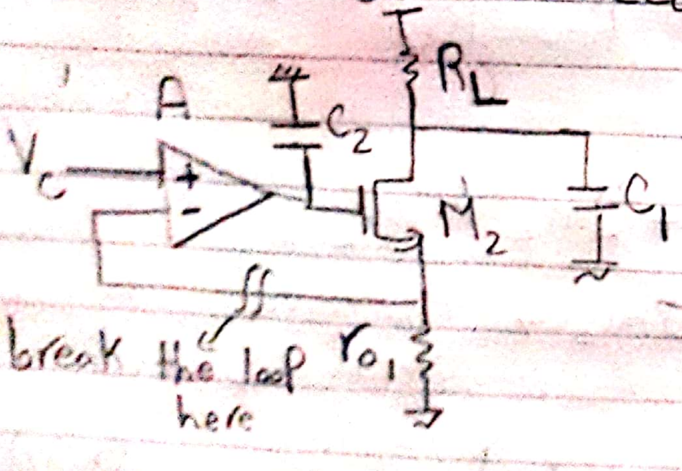
Study the stability of the self regulated current source.

Solution

* In order to judge the stability, we'll calculate the loop gain transfer function by breaking the loop, injecting a signal, and calculating the gain it experiences through the loop

* Stability can then be determined from the poles and zeros locations

* For reasonable stability, phase margin of about 60° is needed at the unity-gain freq.



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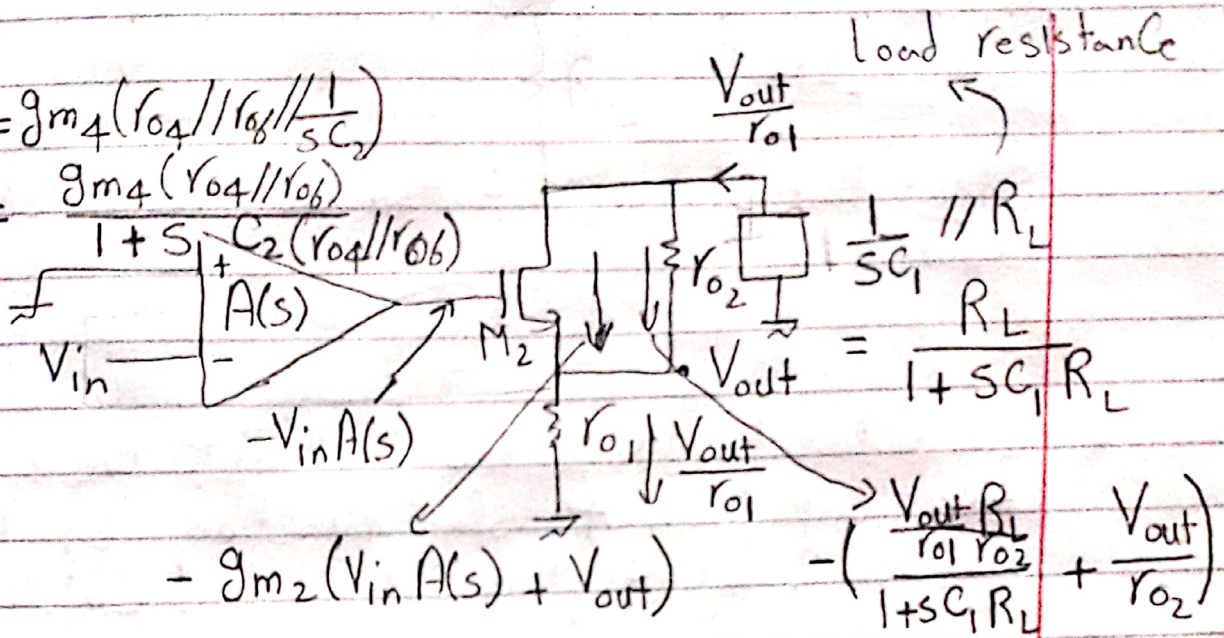
$$A(s) = g_{m4}\left(r_{o4} // r_{o6} // \frac{1}{sC_2}\right) = \frac{g_{m4}(r_{o4}//r_{o6})}{1 + sC_2(r_{o4}//r_{o6})}$$



KCL @ V_{out}:

$$-g_{m2}(V_{in}A(s) + V_{out}) - \frac{V_{out}}{r_{o2}}\left(\frac{R_L/r_{o1}}{1+sC_1R_L} + 1\right) = \frac{V_{out}}{r_{o1}}$$

$$V_{out}\left(\underbrace{\frac{1}{r_{o1}} + \frac{1}{r_{o2}}}_{\text{Can be neglected}} + g_{m2} + \frac{R_L/r_{o1}r_{o2}}{1+sC_1R_L}\right) = -g_{m2}A(s)V_{in}$$

$$\therefore \text{Loop gain}(s) = \frac{V_{out}}{V_{in}}(s) = \frac{-g_{m2}A(s)}{g_{m2} + \frac{R_L/r_{o1}r_{o2}}{1+sC_1R_L}}$$

$$= \frac{-g_{m2}g_{m4}(r_{o4}//r_{o6})/(1+sC_2(r_{o4}//r_{o6}))}{g_{m2} + \frac{R_L/r_{o1}r_{o2}}{1+sC_1R_L}}$$

$$= \frac{-g_{m2}g_{m4}(r_{o4}//r_{o6})(1+sC_1R_L)}{\left(g_{m2} + \frac{R_L}{r_{o1}r_{o2}} + sC_1g_{m2}R_L\right)\left(1+sC_2(r_{o4}//r_{o6})\right)}$$

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$$= \frac{\dfrac{-g_{m_2} g_{m_4} (r_{o4} // r_{o6})}{g_{m_2} + \dfrac{R_L}{r_{o1} r_{o2}}} (1 + SC_1 R_L)}{\left(1 + \dfrac{SC_1 g_{m_2} R_L}{g_{m_2} + \dfrac{R_L}{r_{o1} r_{o2}}}\right) \left(1 + SC_2 (r_{o4} // r_{o6})\right)}$$

In general, there are 2 Poles + LHP Zero

if $g_{m_2} \gg \dfrac{R_L}{r_{o1} r_{o2}} \rightarrow g_{m_2} r_{o1} r_{o2} \gg R_L$

$$\therefore \text{Loop gain}(s) \approx \frac{-g_{m_4} (r_{o4} // r_{o6})}{1 + SC_2 (r_{o4} // r_{o6})}$$

5T OTA DC gain * Source follower DC gain
(= 1 because we assumed $\frac{1}{r_{o1}} + \frac{1}{r_{o2}} \ll g_{m_2}$)

just 1 Pole
at the 5T OTA output

→ The loop will be UnCoditionally stable
(Note that we haven't considered
the Parasitic Cap. at the source of M_2)