

Lecture 23: Practical Compensation

Announcements:

↳ None

Lecture Topics:

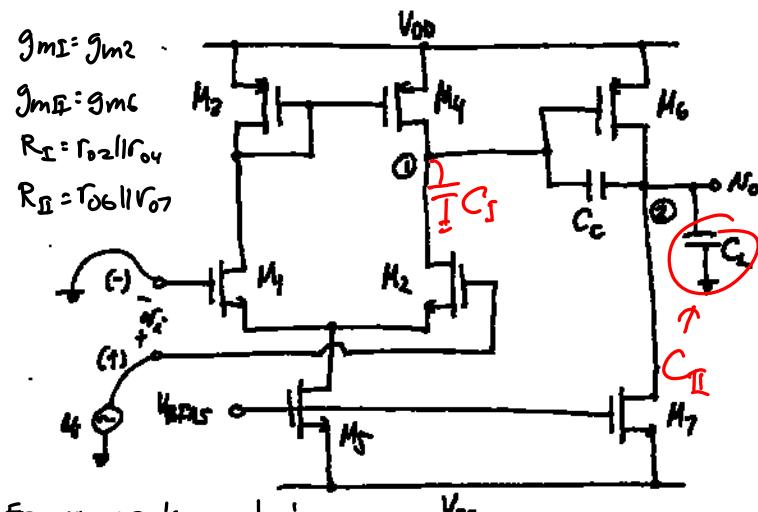
↳ RHP Zero

↳ Nulling the RHP Zero

↳ Slew Rate (revisited)

Last Time:

CMOS 2-Stage OpAmp Compensation (Summary)



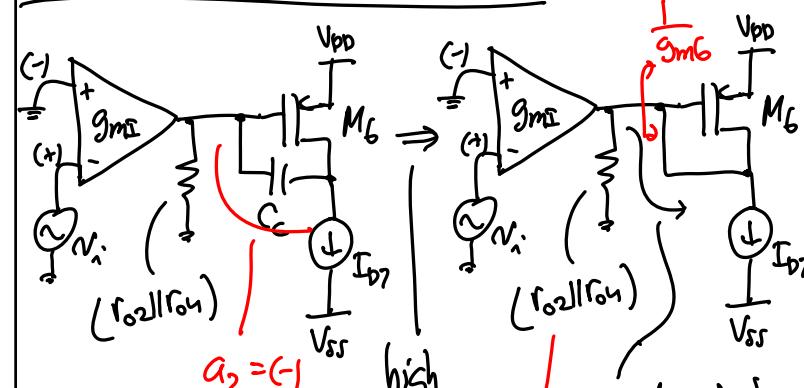
From our previous analysis:

$$P_1 = -\frac{1}{g_{mI} R_I R_{II} C_c} \quad [C_o \gg C_I \text{ and } C_{II}] \quad [C_L \gg C_I]$$

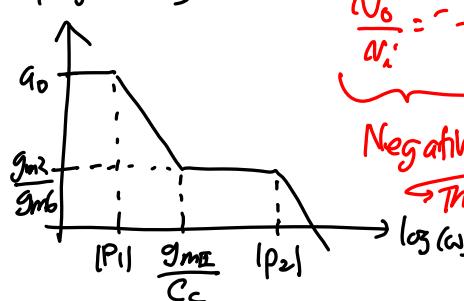
$$P_2 = -\frac{g_{mII} C_c}{C_I C_{II} + C_c (C_I + C_{II})} \approx -\frac{g_{mII}}{C_I + C_{II}} \approx -\frac{g_{m6}}{C_L}$$

$$Z = +\frac{g_{mII}}{C_c} \leftarrow \text{RHP zero} \quad (\text{this will cause problems})$$

Where does the RHP zero come from?



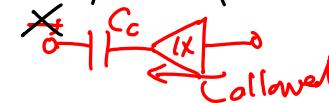
$|a(j\omega)| [\text{dB}]$

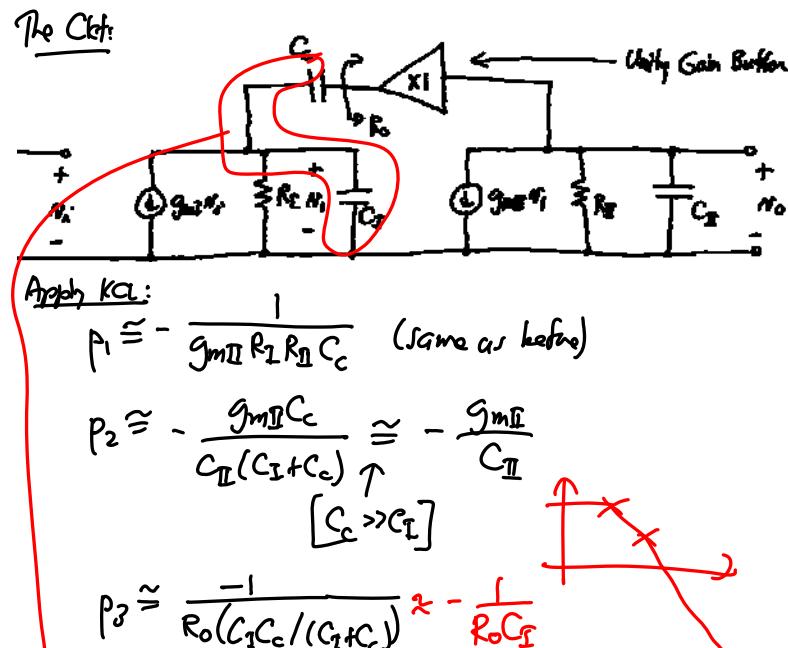


Observation:

The Miller effect (for compensation) requires FB path
↳ BUT! the feedforward path (that causes the zero) is not needed

Solution: ① kill the feedforward path } stick a unity gain buffer in series with C_c
② keep the FB path





$$z_2 \approx -\frac{1}{R_o C_c} \leftarrow \text{LHP zero!} \quad (\text{Good!})$$

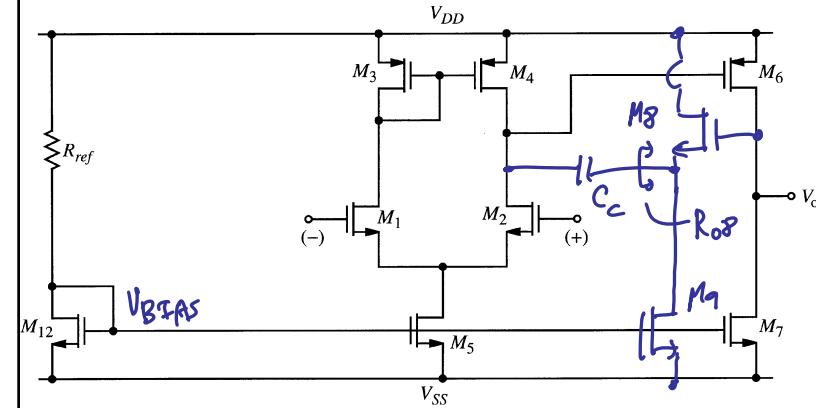
Remarks:

- An additional pole $P_3 = -\frac{1}{R_o C_I}$ has been created! But since R_o is small (for a buffer) and C_I is small, P_3 is at a very high freq. \rightarrow contributes very little phase at ω_{ulg} , where $|T(j\omega)|=1$.

- A LHP zero now emerges, $z_I = -\frac{1}{R_o C_c}$.

\nearrow
This helps stability as discussed before.
(by contributing (G) phase shift \rightarrow PM)

Actual Implementation of Butter-Band Zero Compensation



$$R_{OB} = \frac{1}{g_{mOB}} = \frac{1}{\sqrt{2} \mu_n C_{ox} (W/L) P I_{DD}} \rightarrow \text{want this sufficiently small to drive } |P_3| \uparrow$$

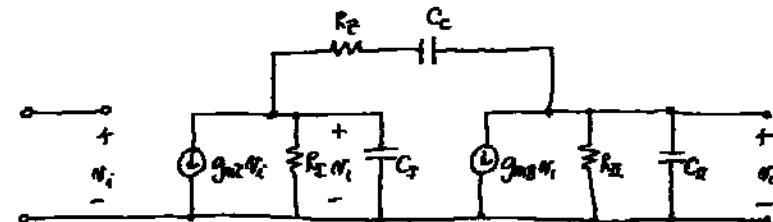
must have $(W/L)_P = \text{large}$

Solution: a better technique!

Nulling Resistor in series w/ C_c

\downarrow or $I_{DD} = \text{large!}$

Problem: power dissipation!



Doing KCL:

$$P_1 \approx -\frac{1}{g_{mII} R_I R_{II} C_c}$$

$$P_2 \approx \frac{-g_{mII} C_c}{C_I C_{II} + C_c (C_I + C_{II})} \approx -\frac{g_{mII}}{C_{II}}$$

Same as before

$$P_3 = -\frac{1}{R_2 C_I} \leftarrow \text{pole due to } R_2$$

$$Z_1 = \frac{1}{C_c \left(\frac{1}{g_{mII}} - R_2 \right)} \leftarrow \text{relocated zero}$$

(function of R_2)

Note: The position of the zero depends upon the value of the "nulling resistor" R_2 .

If $R_2 < \frac{1}{g_{mII}}$ then Z_1 is in the RHP

If $R_2 > \frac{1}{g_{mII}}$ then Z_1 " " " LHP!

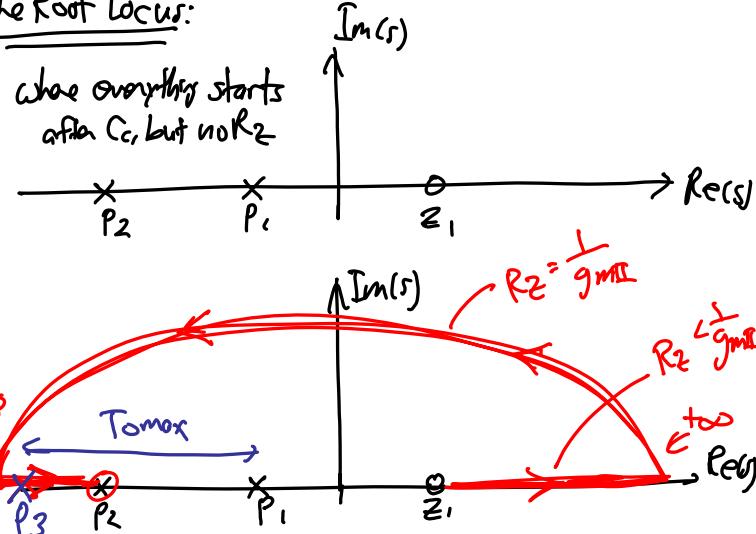
This is great! → can convert the zero to a LHP zero!

$$H(s) = \dots \frac{(s - Z_1)}{(s - P_1)}$$

If $Z_1 = P_1$

Can even stick right on top of a pole!

The Root Locus:



Zero Placement Strategies

- ① Eliminate $Z_1 \rightarrow$ move it to ∞ :

$$Z_1 = \frac{1}{C_c \left(\frac{1}{g_{mII}} - R_2 \right)} \rightarrow \infty \text{ when } R_2 = \frac{1}{g_{mII}}$$

load cap.

After doing this: $p_3 \approx -\frac{g_{mII}}{C_I}$

Usually $C_{II} \gg C_I$
∴ these poles are far apart...
but be careful...

This is good...
but we can do better

- ② Eliminate p_3 by placing Z_1 on top of it:

$$Z_1 = P_3 \Rightarrow \frac{1}{C_c \left(\frac{1}{g_{mII}} - R_2 \right)} = -\frac{1}{R_2 C_I}$$

$$R_2 = \frac{1}{g_{mII} \left(1 - \frac{C_I}{C_c} \right)}$$

After this:

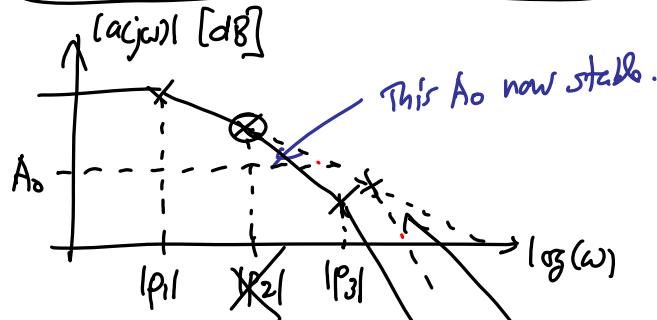
① P_3 gone, P_1 & P_2 left

② Now, can place ω_{ult} @ P_2 & really get $PM = 45^\circ$
but can still do better... over no worry about the influence of P_3

③ Eliminate p_2 by placing Z_2 on top of it:

$$Z_2 = p_2 \Rightarrow \frac{1}{C_c \left(\frac{1}{g_{mII}} - R_2 \right)} = - \frac{g_{mI}}{C_{II}}$$

$$R_2 = \frac{(C_c + C_{II})}{C_c} \left(\frac{1}{g_{mII}} \right) = \frac{1}{g_{mII}} \left(1 + \frac{C_{II}}{C_c} \right)$$



With this choice of R_2 :

$$p_3 = -\frac{1}{R_2 C_I} = -\frac{1}{\left(\frac{C_c + C_{II}}{C_c} \right) \left(\frac{1}{g_{mII}} \right) C_I}$$

$$p_3 = -\frac{g_{mII} C_c}{C_I (C_c + C_{II})}$$

This is the new p_2

For $PM = 45^\circ$:

$$\frac{C_c}{|p_3| A_o} = \frac{g_{mI}}{g_{mII}} \frac{C_{II}(C_c + C_{II})}{C_c A_o}$$

Get the "new" $|p_2|$

solve for C_c

$$C_c = \sqrt{\frac{g_{mI}}{g_{mII}} \frac{C_I C_{II}}{A_o}}$$

For $PM = 45^\circ$

For $PM = 60^\circ$:

$$C_c = \frac{1.73 g_{mI}}{|p_3| A_o}$$

$[C_I \ll C_{II}]$

$$C_c \approx \sqrt{\frac{1.73 g_{mI}}{g_{mII}} \frac{C_I C_{II}}{A_o}}$$

For $PM = 60^\circ$

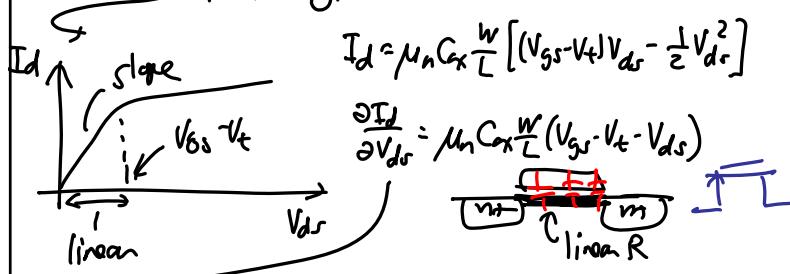
Remark: If settling time is important, then approach ③ may not be the best approach. The reason is that if the zero is not exactly equal to the pole, the a "doublet" ensues, which actually can hurt the settling time.

Discussed in a handout to be posted on the course website. → also, discussed in Razavi, problem 10.19.

Actual Implementation

→ resistor are too big! → .. implement using a much smaller MOS resistor!

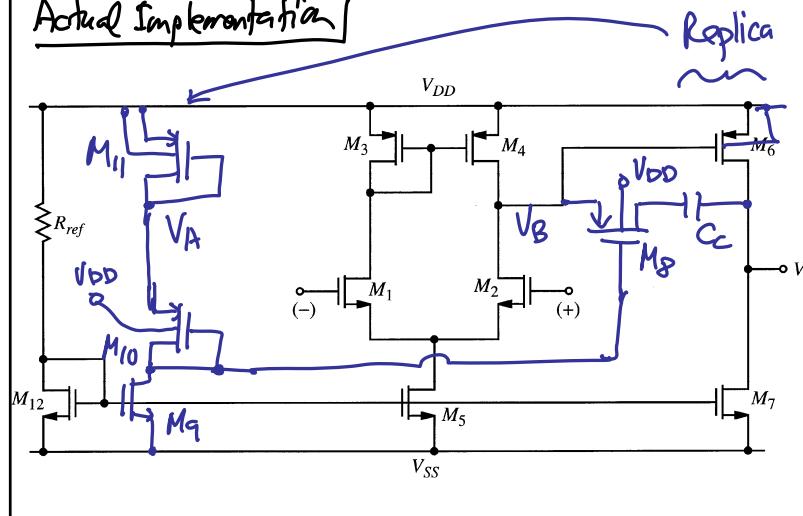
MOS Resistor: just an MOS Xistor operated in the linear region



$$R_{S.S.} = \left[\frac{dI_D}{dV_{DS}} \right]^{-1} = \frac{1}{\mu_n C_{ox} \left(\frac{W}{L} \right) (V_{GS} - V_t - V_{DS})} = \frac{1}{\mu_n C_{ox} \left(\frac{W}{L} \right) g_{ds}}$$

$\boxed{\text{a Variable resistor controlled by } V_{GS}!}$

Actual Implementation



$$I_{DP} = 0 \rightarrow V_{DSR} = 0 \text{ V} \Rightarrow R_S = \frac{1}{\mu_p C_{ox} (W/L)_P \underbrace{(|V_{GSR}| - |V_{TP}|)}_{|V_{OVPL}|}}$$

Design:

Need $V_A = V_B \rightarrow |V_{GSI}| = |V_{GS6}|$, know that $|V_{F11}| = |V_{F6}|$

$$\sqrt{\frac{2I_{D11}}{\mu_p C_{ox} \left(\frac{W}{L} \right)_{11}}} = \sqrt{\frac{2I_{D6}}{\mu_p C_{ox} \left(\frac{W}{L} \right)_6}}$$

$$\left(\frac{W}{L} \right)_{11} = \left(\frac{W}{L} \right)_6 \frac{I_{D11}}{I_{D6}} = \left(\frac{W}{L} \right)_6 \frac{I_{D10}}{I_{D6}}$$

Also, need $|V_{ov10}| = |V_{ov6}|$

Because $V_A : V_B \rightarrow V_{SD} \rightarrow V_{SP} \rightarrow |V_{F10}| = |V_{FP}|$

$$\therefore |V_{ov10}| / |V_{ov6}| = \sqrt{\frac{2I_{D10}}{\mu_p C_{ox} \left(\frac{W}{L} \right)_{10}}}$$

Thus:

$$R_S = \frac{1}{\mu_p C_{ox} \left(\frac{W}{L} \right)_P \sqrt{\frac{2I_{D10}}{\mu_p C_{ox} \left(\frac{W}{L} \right)_{10}}}} = \frac{\mu_p C_{ox} (W/L)_{10}}{\mu_p C_{ox} \left(\frac{W}{L} \right)_P \sqrt{2I_{D10}}}$$

Case: Eliminate p_2 by placing Z_1 on top of it.

$$R_Z = \frac{C_c + C_L}{g_m G_C} = \frac{\sqrt{\mu_p C_{ox} (W/L)_{10}}}{\mu_p C_{ox} \left(\frac{W}{L}\right)_P \sqrt{2 I_{D10}}}$$

$$\left(\frac{W}{L}\right)_P = \sqrt{\left(\frac{W}{L}\right)_G \left(\frac{W}{L}\right)_{10}} \cdot \frac{I_{D6}}{I_{D10}} \cdot \left(\frac{C_L}{C_c + C_L}\right)$$

Case: Make $Z_1 \rightarrow \infty$.

$$R_Z = \frac{1}{g_m G_C} \Rightarrow \left(\frac{W}{L}\right)_P = \sqrt{\left(\frac{W}{L}\right)_G \left(\frac{W}{L}\right)_{10}} \cdot \frac{I_{D6}}{I_{D10}}$$