Lecture 21: CMOS Op Amp Compensation

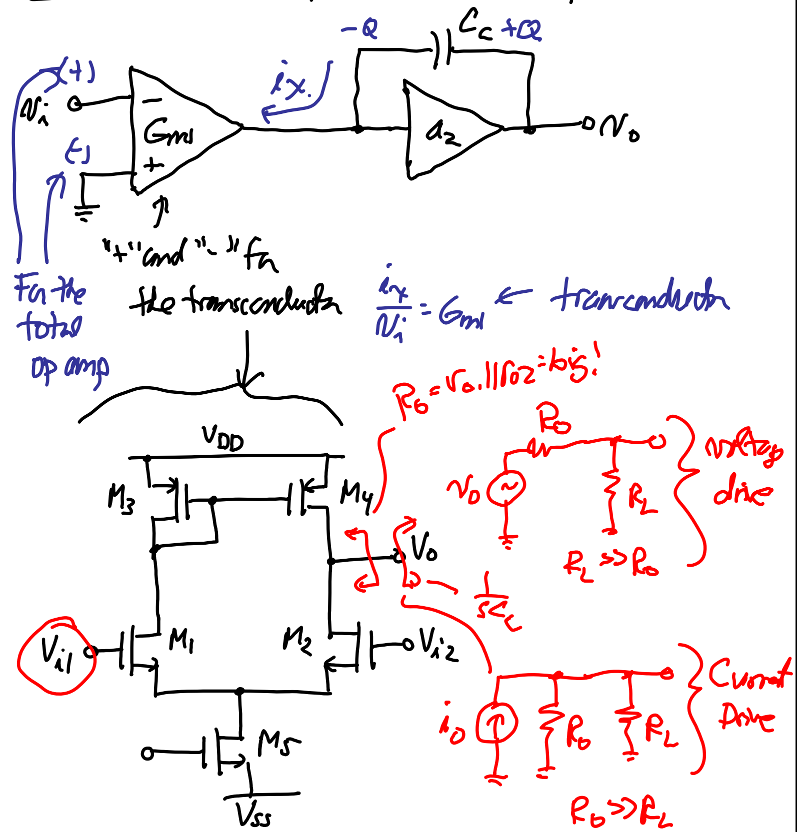
- Announcements:
- HW#8 due Wednesday at 8 a.m.
- HW#9 online soon
- Lab#3 (Design Project) in progress
- Design Project Checkpoint:
  - Due Tuesday, Nov. 17, 11:59 p.m.
  - Send to your TA a spice file for your op amp design that simulates correctly, i.e., that reaches a stable bias point where all transistors are saturated (or linear if an MOS resistor)
  - It doesn't need to meet the project specs, but it should simulate correctly
- Thursday (next week) I'll be traveling
  - Lecture by videotape
  - People seemed to like this last time
- Handout on pole/zero plots online
- Lecture Topics:
  - Choosing Cc
  - CMOS Op Amp Compensation
- ------------------------------------
- Last Time: Choosing Cc

over

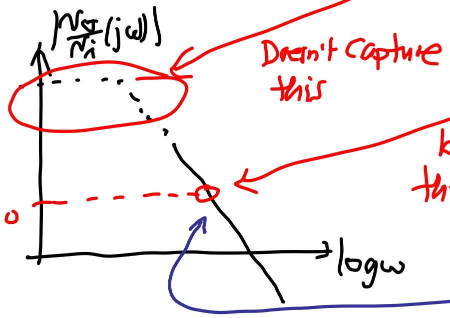
$\boxed{\text{Choosing } C_c}$ (assume no RHP zeros & $|p_3| \gg |p_2|$)

⇒ assume $\frac{1}{sC_c} \ll$ surrounding impedance @ high freq.

Case ①: Two-Stage Amplifier w/ Miller Compensation



$$\left.\begin{aligned} i_x &= G_{m1} v_i \\ v_0 &= \frac{i_x}{sC_c} \end{aligned}\right\} \; v_o = \frac{G_{m1}}{sC_c} v_1 \rightarrow \boxed{\frac{v_o}{v_i}(s) = \frac{G_{m1}}{sC_c}}$$



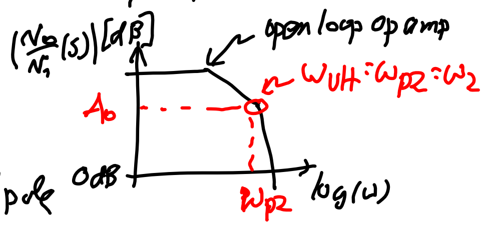
Really care most about freqs. around this point, since the PM determined here

$$\left|\frac{v_o}{v_i}(j\omega)\right| = \frac{G_{m1}}{\omega C_c} \Rightarrow$$ this should equal A_o @ the freq. corresponding to the target phase margin (PM)

Define. $\omega_{ult} = \omega$ @ $|a(j\omega)f| = 1$
"ult" = "unity loop transmission"

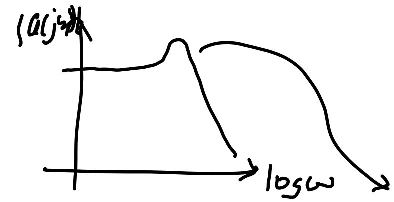
For PM = 45°:

$\omega_{ult} = \omega_2$ ← freq of the 2nd pole of the open loop $a(j\omega)$ transfer function

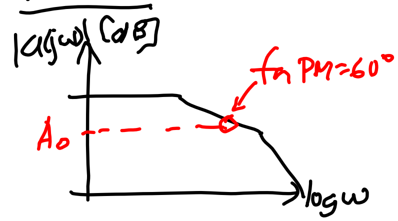


$$\left|\frac{v_o}{v_i}(j\omega_2)\right| = A_o = \frac{G_{m1}}{\omega_2 C_c} \rightarrow \boxed{C_c = \frac{G_{m1}}{\omega_2 A_o}}$$

↑ PM = 45° (provided $|p_3| \gg |p_2|$)



For PM = 60°:



$$a(j\omega) = \frac{a_o}{\left(1 - \frac{s}{p_1}\right)\left(1 - \frac{s}{p_2}\right)}$$

$$\measuredangle a(j\omega) = -\tan^{-1}\left(-\frac{\omega}{p_1}\right) - \tan^{-1}\left(-\frac{\omega}{p_2}\right) = -120° \text{ (for PM = 60°)}$$

$$\omega_{ult} = \frac{|p_2|}{\sqrt{3}} = \frac{\omega_2}{1.73}$$ ← for PM = 60°

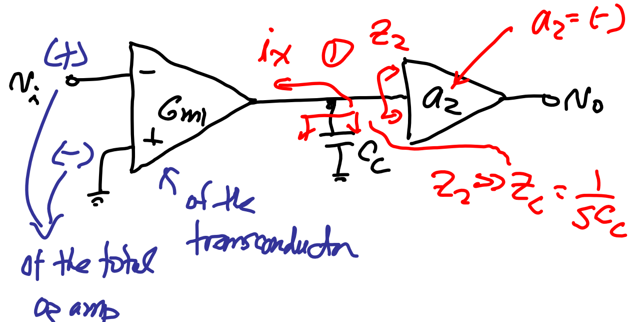
$$\left|\frac{v_o}{v_i}\left(j\frac{\omega_2}{1.73}\right)\right| = A_o = \frac{G_{m1}}{\left(\frac{\omega_2}{1.73}\right)C_c} \rightarrow \boxed{C_c = \frac{1.73 G_{m1}}{\omega_2 A_o}}$$

Remarks.

① Smaller A_o requires larger C_c.

② Dependence on G_{m1}.

② Case: Two-Stage Amplifier w/ Shunt C_c



$Z_2 \gg Z_c = \frac{1}{sC_c}$

$$\left.\begin{aligned} v_{①} &= -\frac{G_{m1} v_i}{sC_c} \\ v_o &= a_2 v_{①} \end{aligned}\right\} \quad v_o = -\frac{G_{m1} a_2}{sC_c} v_i$$

$$\therefore \frac{v_o}{v_i}(s) = -\underbrace{\frac{G_{m1} \overset{(-)}{a_2}}{sC_c}}_{(+)}$$

Closed-loop gain A_o must again intersect this curve @ the right ω_{u} for the desired PM

For PM = 45°:

$$\left|\frac{v_o}{v_i}(j\omega)\right| = A_o = \frac{G_{m1} a_2}{\omega_2 C_c} \rightarrow C_c = \frac{G_{m1} a_2}{\omega_2 A_o}$$

[For PM = 45°, $\omega_u = \omega_2$]

For PM: 45°

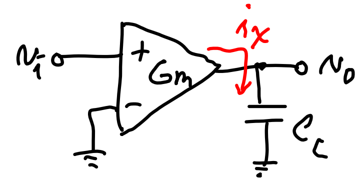
For PM = 60°:

$$C_c = \frac{1.73 G_{m1} a_2}{\omega_2 A_o}$$

For PM = 60°

Case ③: Single-Stage Amplifier w/ Shunt C_c

e.g., telescopic cascode op amp w/ C_c at the output node



$$\left.\begin{aligned} v_o &= \frac{i_x}{sC_c} \\ i_x &= G_m v_i \end{aligned}\right\} \quad \frac{v_o}{v_i}(s) = \frac{G_{m1}}{sC_c} \rightarrow \text{same as Case ① (Miller cap.)}$$

Thus:

$$C_c = \frac{G_{m1}}{\omega_2 A_o}$$

For PM = 45°

$$C_c = \frac{1.73 G_{m1}}{\omega_2 A_o}$$

For PM = 60°

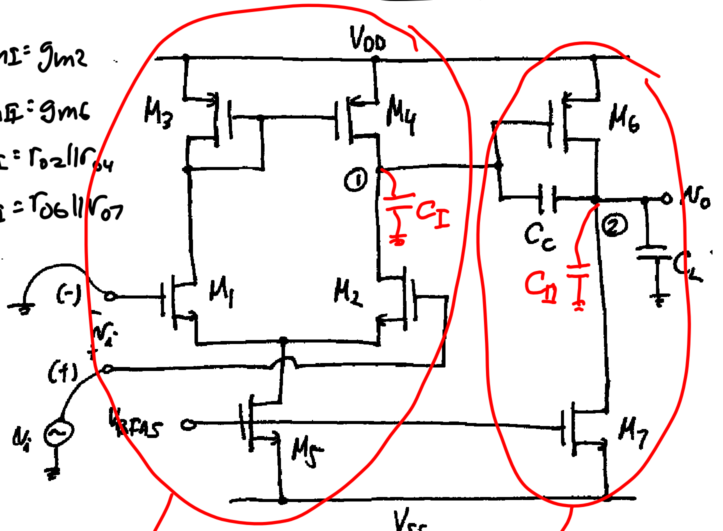
CMOS 2-Stage Op Amp Compensation

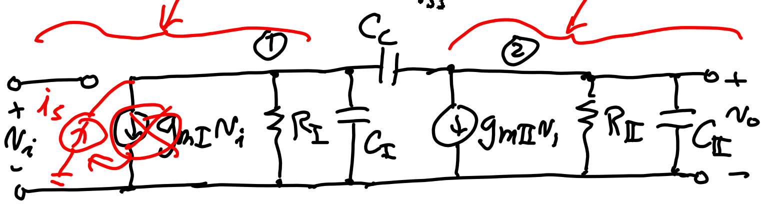
$g_{mI} = g_{m2}$

$g_{mII} = g_{m6}$

$R_I = r_{o2} \| r_{o4}$

$R_{II} = r_{o6} \| r_{o7}$





KCL①: $i_s = \frac{v_1}{R_I} + sC_I v_1 + (v_1 - v_o)sC_c$

KCL②: $g_{mII}v_1 + \frac{v_o}{R_{II}} + sC_{II}v_o + (v_o - v_1)sC_c = 0$

$$\frac{v_o}{i_s} = \frac{(g_{mII} - sC_c)R_I R_{II}}{1 + s\left[(C_{II}+C_c)R_{II} + (C_I + C_c)R_I + g_{mII}R_I R_{II} C_c\right] + s^2 R_I R_{II}(C_I C_{II} + C_c C_I + C_c C_{II})}$$

← $N(s)$

$D(s)$

$\frac{v_o}{i_s}(s) = \frac{N(s)}{D(s)}$ → This xfer fcn has 2 poles & one zero.

The Zero: $N(s) = 0 \xrightarrow{z=s} \boxed{z = \frac{g_{mII}}{C_c}}$ ← (+) & real

↑ RHP in the complex plane

The Poles:

$D(s) = \left(1 - \frac{s}{p_1}\right)\left(1 - \frac{s}{p_2}\right) = 1 - s\left(\frac{1}{p_1} + \cancel{\frac{1}{p_2}}\right) + \frac{s^2}{p_1 p_2}$ Negl.

$[|p_2| \gg |p_1|] \rightarrow \approx 1 - \frac{s}{p_1} + \frac{s^2}{p_1 p_2}$

↑ i.e., there is a dominant pole

$$p_1 = -\frac{1}{(C_{II}+C_c)R_{II} + (C_I + C_c)R_I + g_{mII}R_I R_{II} C_c}$$

as $C_c \uparrow \rightarrow |p_1| \downarrow \rightarrow$ pole-splitting

Miller multiplied term >> others

$$p_1 \approx -\frac{1}{g_{mII}R_I R_{II} C_c}$$

For the 2nd Pole:

$$p_1 p_2 = \frac{1}{R_I R_{II}(C_I C_{II} + C_c C_I + C_c C_{II})}$$

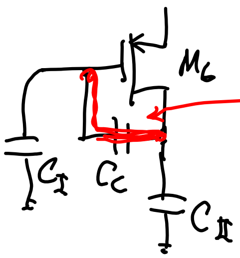
*

$$p_2 = -\frac{g_{mII} C_c}{C_I C_{II} + C_c C_I + C_c C_{II}} \rightarrow \boxed{p_2 \cong -\frac{g_{mII}}{C_I + C_{II}}}$$

as $C_c \uparrow \rightarrow |p_2| \uparrow$

$\boxed{\omega_2 \text{ by Inspection}}$

When C_c = big @ high freq. (around ω_2), $C_c \rightarrow$ short



M_6 becomes "diode-connected"

$$\omega_2 = \frac{1}{\tau} = \frac{1}{\left(\frac{1}{g_{mII}}\right)(C_I + C_{II})} = \frac{g_{mII}}{C_I + C_{II}}$$

$[g_{m6} = g_{mII}]$

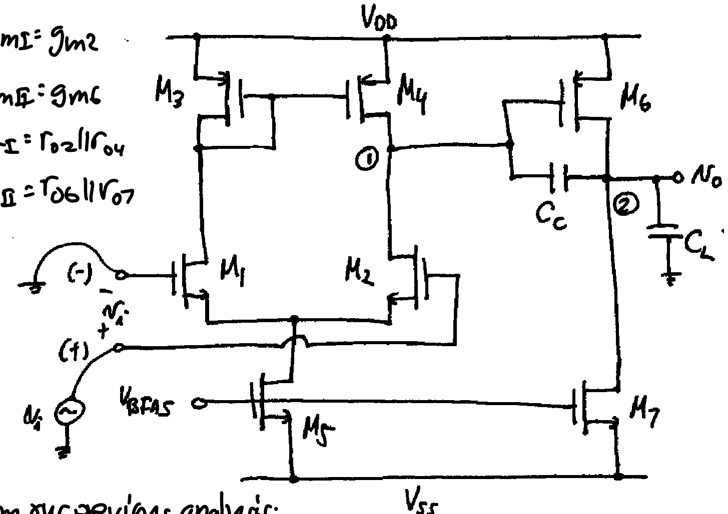
$\boxed{\text{CMOS 2-Stage Op Amp Compensation}}$ (Summary)

$g_{mI} = g_{m2}$

$g_{mII} = g_{m6}$

$R_I = r_{o2} \| r_{o4}$

$R_{II} = r_{o6} \| r_{o7}$



From our previous analysis:

$$p_1 = -\frac{1}{g_{mII} R_I R_{II} C_c} \qquad [C_c \gg C_I \text{ or } C_{II}] \qquad [C_L \gg C_I]$$

$$p_2 = -\frac{g_{mII} C_c}{C_I C_{II} + C_c (C_I + C_{II})} \approx -\frac{g_{mII}}{C_I + C_{II}} \approx -\frac{g_{m6}}{C_L}$$

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

Remarks:

① Note that as $C_c \uparrow \rightarrow |p_1| \downarrow$

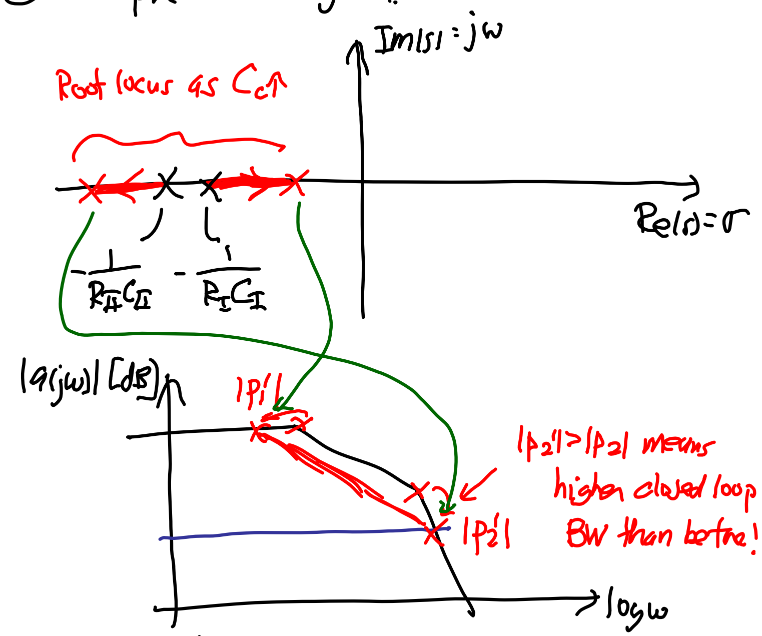
② As $C_c \uparrow \rightarrow |p_2| \uparrow \rightarrow |p_2| = \frac{g_{mII}}{C_I + C_{II}}$

} pole-splitting

③ With $C_c = 0$ (i.e., before compensation)

$$p_1 = -\frac{1}{R_I C_I}, \quad p_2 = -\frac{1}{R_{II} C_{II}}$$

(4) On a pole-zero diagram:



Great! → But what about the RHP zero?