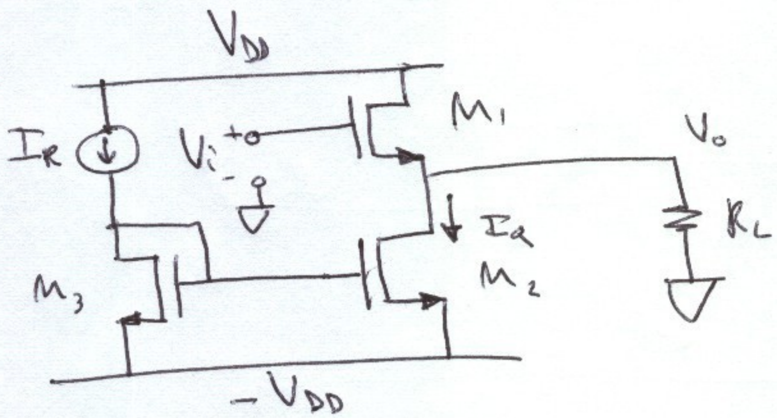
- COMPENSATION CAPACITOR NOT NECESSARY → CL ACTS AS COMP. CAP.

OUTPUT STAGES (CH 5)

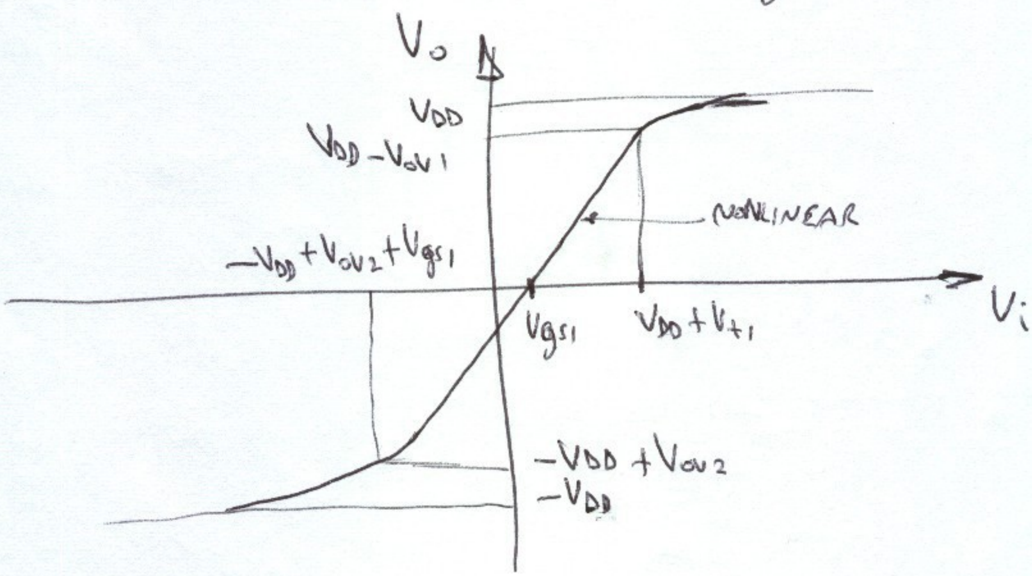
SOURCE FOLLOWER



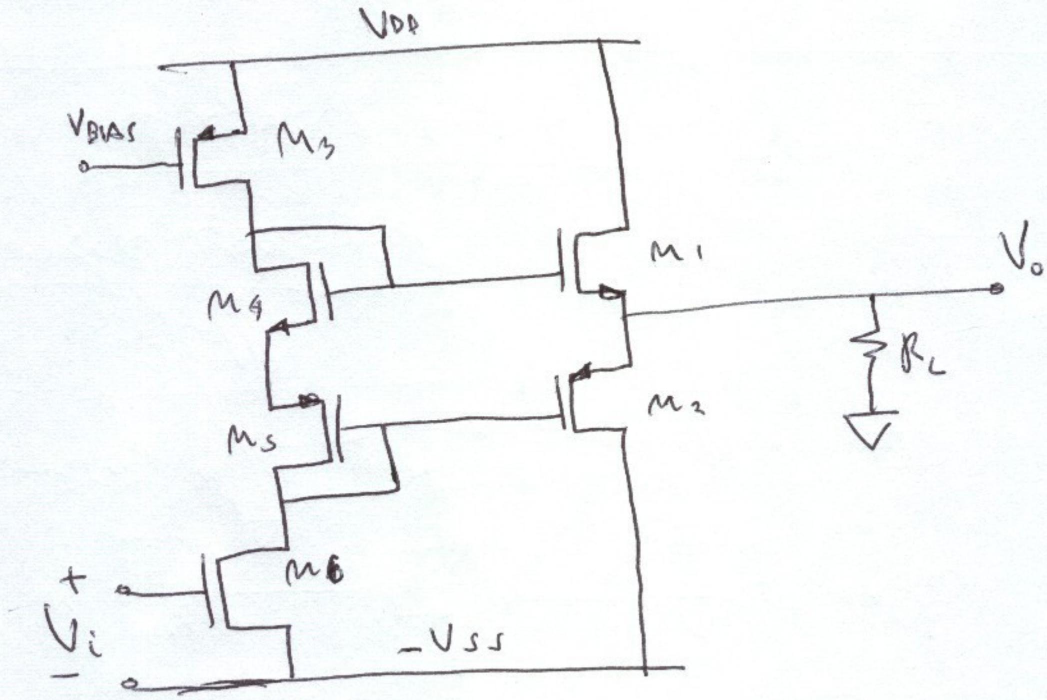
$$V_i = V_o + V_{t1} + V_{ov1}$$

$$V_i = V_o + V_{t0} + \gamma\left(\sqrt{2\phi_f + V_o + V_{DD}} - \sqrt{2\phi_f}\right) + \sqrt{\frac{2\left(I_Q + \frac{V_o}{R_L}\right)}{k'\left(\frac{W}{L}\right)_1}}$$

$$R_L \to \infty \Rightarrow \frac{v_o}{v_i} = \frac{1}{1+\chi} = \frac{g_m}{g_m + g_{mb}}$$



CLASS AB OUTPUT STAGE



$$\text{IF} \begin{cases} V_{ov4} = V_{ov1} \\ V_{ov5} = V_{ov2} \end{cases} \Rightarrow (*)$$

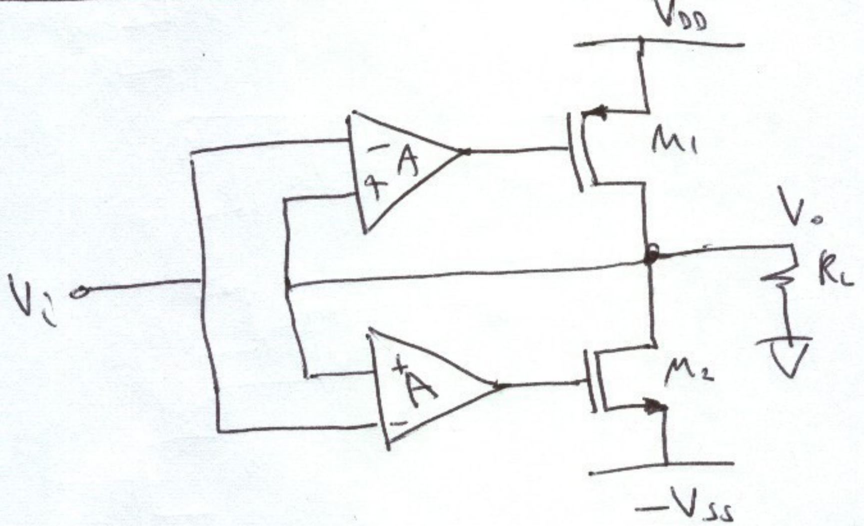
$$\sqrt{\frac{2 I_{D4}}{k_p' \left(\frac{W}{L}\right)_5}} + \sqrt{\frac{2 I_{D4}}{k' \left(\frac{W}{L}\right)_4}} = \sqrt{\frac{2 I_{D1}}{k_n' \left(\frac{W}{L}\right)_1}} + \sqrt{\frac{2 I_{D2}}{k_p' \left(\frac{W}{L}\right)_2}}$$

$$(*) \quad I_{D_1} = I_{D4} \frac{\left(\frac{1}{k_n' \left(\frac{W}{L}\right)_4} + \frac{1}{k_p' \left(\frac{W}{L}\right)_5}\right)}{\left(\frac{1}{k_n' \left(\frac{W}{L}\right)_1} + \frac{1}{k_p' \left(\frac{W}{L}\right)_2}\right)}$$

$$\begin{cases} V_{o_{MAX}} = V_{DD} - |V_{ds3}|_{min} - V_{gs1} = V_{DD} - |V_{ov3}| - V_{GS1} \\ V_{o_{MIN}} = -V_{SS} + V_{ov6} + V_{sg2} \end{cases}$$

- (DISCUSS EXAMPLE PAGE 384)

COMMON SOURCE CONFIGURATION WITH ERROR AMPLIFIERS



- GOOD SWING BUT BAD FREQUENCY RESPONSE.

PROBLEM 5.22 : SWING $\pm 1V$, $R_L = 1k\Omega$, $V_{DD} = V_{SS} = 2.5V$

$I_{BIAS} = 10\mu A$, $I_{D1_Q} = 100\mu A$

$\left(\frac{W}{L}\right)_3 = \frac{50}{1}$, $\left(\frac{W}{L}\right)_6 = \frac{25}{1}$

$\left(\frac{W}{L}\right)_{1-6}$? (MINIMIZE AREA)

TABLE 2.3 BUT $L_{eff} = L_{drawn}$, $L = 1\mu m$.

(THERE IS BODY EFFECT).

$$k' = \frac{\mu_n \epsilon_{ox}}{t_{ox}} = \frac{\overset{550\times10^{-4}}{\cancel{4\times10^{-15}}} \times 3.45\times10^{-11}}{150\times10^{-10}} = 126.5 \frac{\mu A}{V^2}$$

$$k'_p = \frac{\mu_p \epsilon_{ox}}{t_{ox}} = \frac{250\times10^{-4} \times 3.45\times10^{-11}}{150\times10^{-10}} = 57.5 \frac{\mu A}{V^2}$$

$V_{tn} = 0.7V$

$V_{tp} = -0.7V$

$V_{ov_1} = V_{ov_4} \Rightarrow$ SAME CURRENT DENSITY

$$I_{D_1} = \frac{k'}{2}\left(\frac{W}{L}\right)_1 V_{ov_1}^2 \Rightarrow V_{ov_1}^2 = \frac{2 I_{D1}}{k'\left(\frac{W}{L}\right)_1} = \frac{2 I_{D4}}{k'\left(\frac{W}{L}\right)_4}$$

$$\left(I_{D1} = 10\, I_{D4}\right) \qquad \frac{I_{D1}}{I_{D4}} = \frac{\left(\frac{W}{L}\right)_1}{\left(\frac{W}{L}\right)_4} = \frac{W_1}{W_4}$$

$$\therefore \begin{cases} W_4 = \dfrac{W_1}{10} \\ W_5 = \dfrac{W_2}{10} \end{cases}$$

ALSO:

$$I_{D_1} = I_{D4}\, \frac{\left(\frac{1}{k_n'\left(\frac{W}{L}\right)_4} + \frac{1}{k_p'\left(\frac{W}{L}\right)_5}\right)}{\left(\frac{1}{k_n'\left(\frac{W}{L}\right)_1} + \frac{1}{k_p'\left(\frac{W}{L}\right)_2}\right)} = I_{D4}\, \frac{\left(\frac{1}{k_n' W_4} + \frac{1}{k_p' W_5}\right)}{\left(\frac{1}{k_n' 10 W_4} + \frac{1}{k_p' 10 W_5}\right)}$$

$$= 10\, I_{D4} \quad \text{(NOTHING NEW)}$$

$$V_{OMAX} = V_{DD} - |V_{ov_3}| - V_{GS1} = 2.5V - V_{GS1} - 83mV$$

$$|V_{ov_3}| = \sqrt{\frac{2 \times 10\mu A}{k_p' \times 50}} = 83\, mV$$

~~≈ DEEP SUBTHRESHOLD ?~~
~~(ASSUME ZERO)~~

$$V_{OMIN} = -V_{SS} + V_{ov6} + V_{SG2}$$

$$V_{ov6} = \sqrt{\frac{2 \times 10\mu A}{k' \times 25}} = \underline{80\, mV}$$

$$\text{AVAILABLE SWING} = V_{OMAX} - V_{OMIN} = 5V - 2 \times 80mV = 4.84V$$

$$V_{GS1} + 83\,mV = 2.5V - 1V \Rightarrow V_{GS1} \leq 1.42\,V$$
$$|V_{GS_2}| \leq 1.42\,V$$

$$\gamma_n = \frac{1}{C_{ox}} \cdot \sqrt{2 q \epsilon N_A} = \frac{150 \times 10^{-10}}{3.45 \times 10^{-11}} \sqrt{2 \times 1.6 \times 10^{-19} \times 3.45 \times 10^{-11} \times 4 \times 10^{15} \times 10^{6}}$$

$$\simeq 0.09$$

$$\gamma_p \simeq 0.250 \qquad \phi_F \simeq 0.3$$

$$V_{t_n}\Big|_{V_o = 1V} = V_{t_n}\Big|_{V_{SB}=3.5V} = 0.7V + \gamma_n\left(\sqrt{2\phi_f + 3.5V} - \sqrt{2\phi_f}\right)$$

$$= 0.81V$$

$$V_{tp}\Big|_{V_o = -1V} = -0.7 - \gamma_p\left(\sqrt{2\phi_f + 3.5V} - \sqrt{2\phi_f}\right)$$

$$= 1.01V$$

$$V_{ov_1} = 1.42V - 0.81V = 0.61V$$

$$|V_{ov_2}| = 1.42V - 1.01V = 0.41V$$

WITH MAX CURRENT $I = \frac{1V}{1k\Omega} = 1mA$

$$1mA = \frac{k'}{2}\left(\frac{W}{L_1}\right)(0.6V)^2 \Rightarrow \left(\frac{W}{L}\right)_1 = 43.9$$

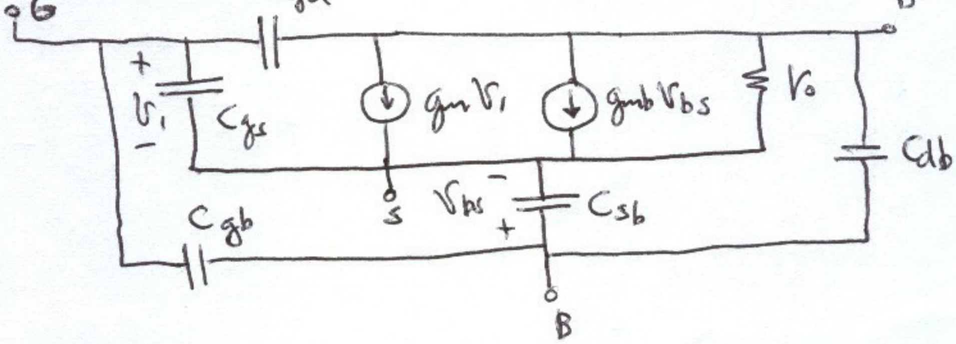
$$1mA = \frac{k_p'}{2}\left(\frac{W}{L}\right)_2 (0.4)^2 \Rightarrow \left(\frac{W}{L}\right)_2 = 217.4$$

TAKE : $W_1 = 45\,\mu m$, $W_4 = 4.5\,\mu m$

$W_2 = 220\,\mu m$, $W_5 = 22\,\mu m$

FREQUENCY RESPONSE

(DISCUSS MOS CAPACITANCE MODEL)



$$C_{gs} \approx \frac{2}{3} C_{ox} W L_{eff} + W L_d C_{ox}$$

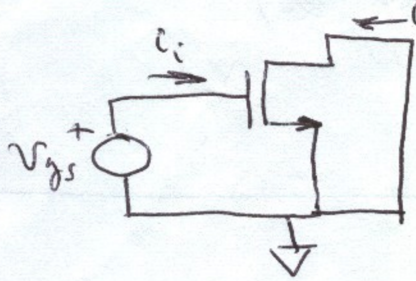
$$C_{gd} = W L_d C_{ox}$$

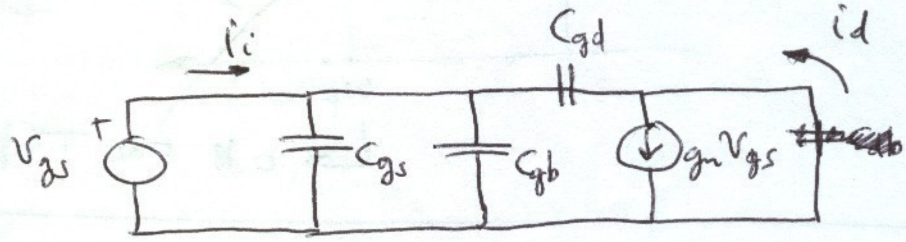
$$C_{sb} = \frac{C_{sbo}}{\left(1 + \frac{V_{SB}}{\psi_0}\right)^{\frac{1}{2}}} \quad , \quad C_{db} = \frac{C_{dbo}}{\left(1 + \frac{V_{DB}}{\psi_0}\right)^{\frac{1}{2}}}$$

(GO BACK TO PAGE 10 AND EXPLAIN SIDEWALL CAPACITANCES.)

C_{gb} : CAPACITANCE OF THE ROUTING THAT CONNECTS THE GATE.

TRANSITION FREQUENCY





$$i_i = \frac{V_{gs}}{[s(C_{gs} + C_{gb} + C_{gd})]^{-1}} = V_{gs}\, s\,(C_{gs} + C_{gb} + C_{gd})$$

$$i_d \approx g_m V_{gs}$$

$$\frac{i_d}{i_i} \approx \frac{g_m}{s\,(\Sigma C)}$$

$$\omega_T \rightarrow \left|\frac{i_d}{i_i}\right| = 1 \Rightarrow \omega_T = \frac{g_m}{(C_{gs} + C_{gb} + C_{gd})}$$

IF $C_{gs} \gg C_{gb}$ AND C_{gd} :

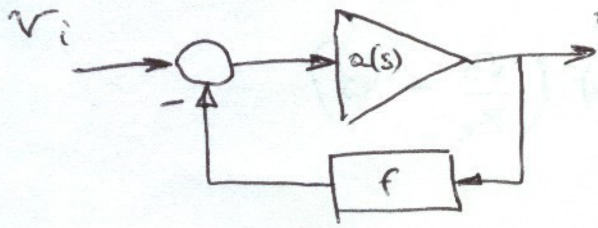
$$f_T \simeq \frac{g_m}{2\pi\, C_{gs}} = \frac{\frac{k'}{\cancel{2}} \frac{W}{L} V_{oV}}{2\pi \quad C_{gs}} = \frac{\mu_n \cancel{C_{ox}} V_{oV} \frac{W}{L}}{2\pi\, \frac{2}{3} \cancel{C_{ox}} \cancel{W} L}$$

$$\boxed{= \frac{3\mu_n}{4\pi L^2} \cdot V_{oV}}$$

$V_{ov} \uparrow \rightarrow f_T \uparrow$

$L \downarrow \rightarrow f_T \uparrow$ QUADRATICALLY

STABILITY OF FEEDBACK AMPLIFIERS (CH9)

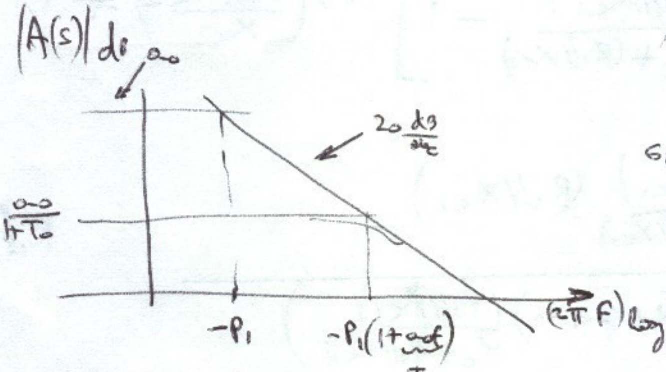


$T(j\omega) = a(s)f$ ← OPEN-LOOP TRANSFER FUNCTION

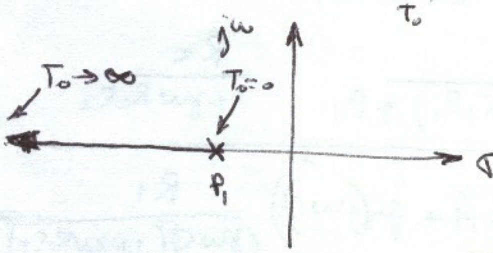
$T_o = a_o f$

$$A(s) = \frac{v_o}{v_i} = \frac{a(s)}{1 + a(s)f}, \qquad a(s) = \frac{a_o}{1 - \frac{s}{p_1}}$$

$$A(s) = \frac{a_o}{1 + a_o f}\left(\frac{1}{1 - \frac{s}{p_1}\frac{1}{1 + a_o f}}\right) \left(\simeq \frac{1}{f} \text{ IF } a_o \rightarrow \infty\right)$$



GAIN × PRODUCT = CONSTANT.

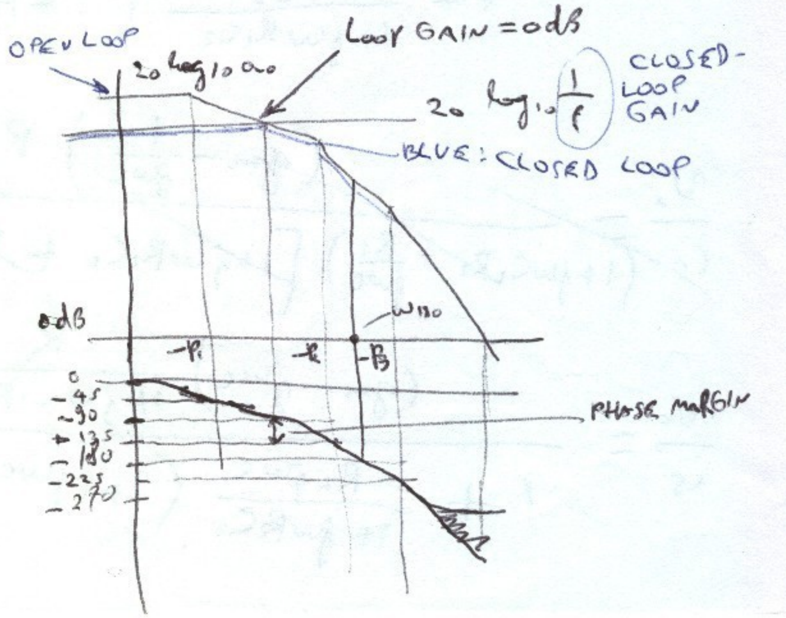


LOCUS OF POLE

$T_{dB} = a_{dB} + f_{dB} \Rightarrow T = a_{dB} - \left(\frac{1}{f}\right)_{dB}$

(MENTION NYQUIST CRITERION)

(MENTION GAIN PEAKING)

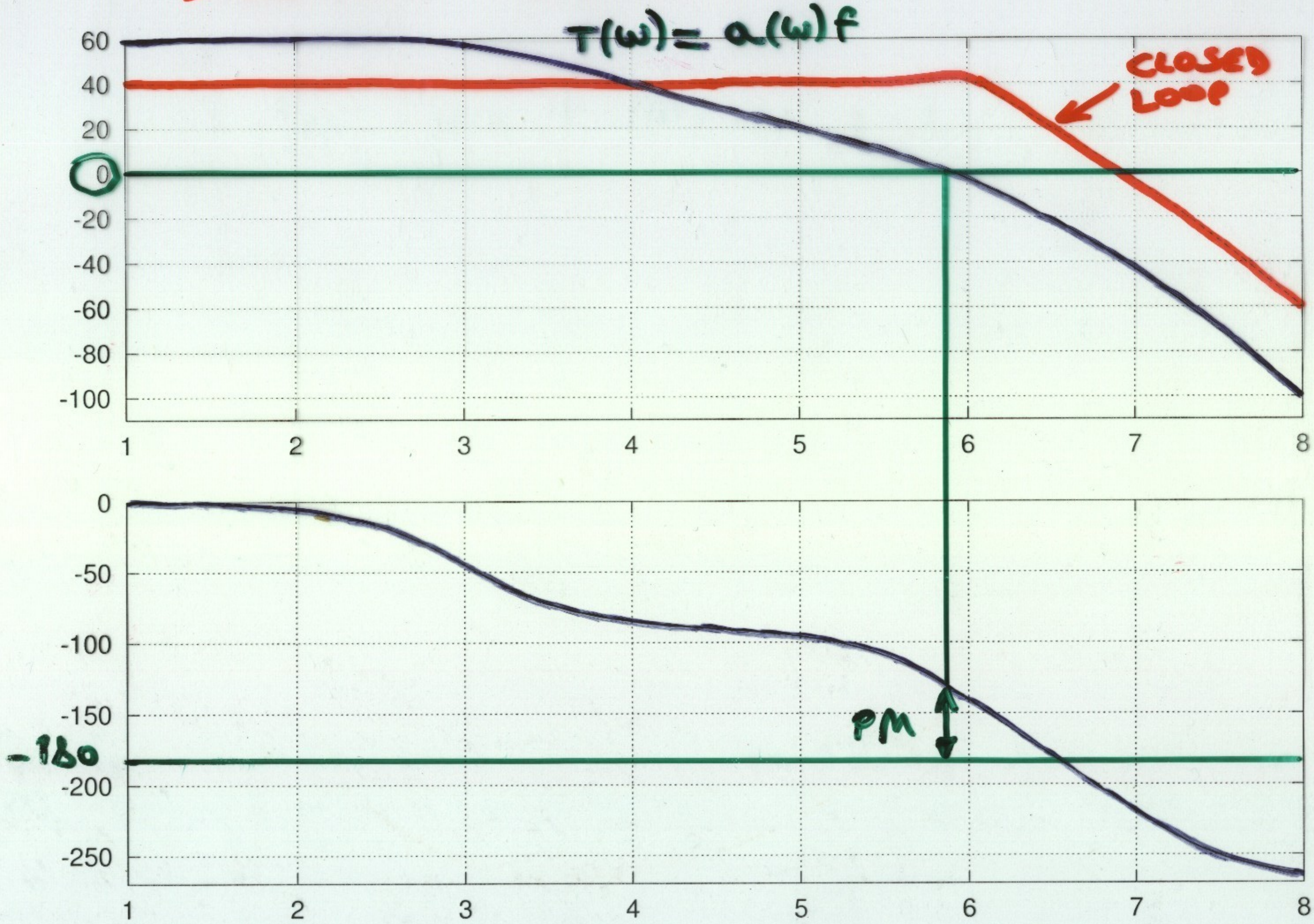


PHASE $T(j\omega_o) = -135°$

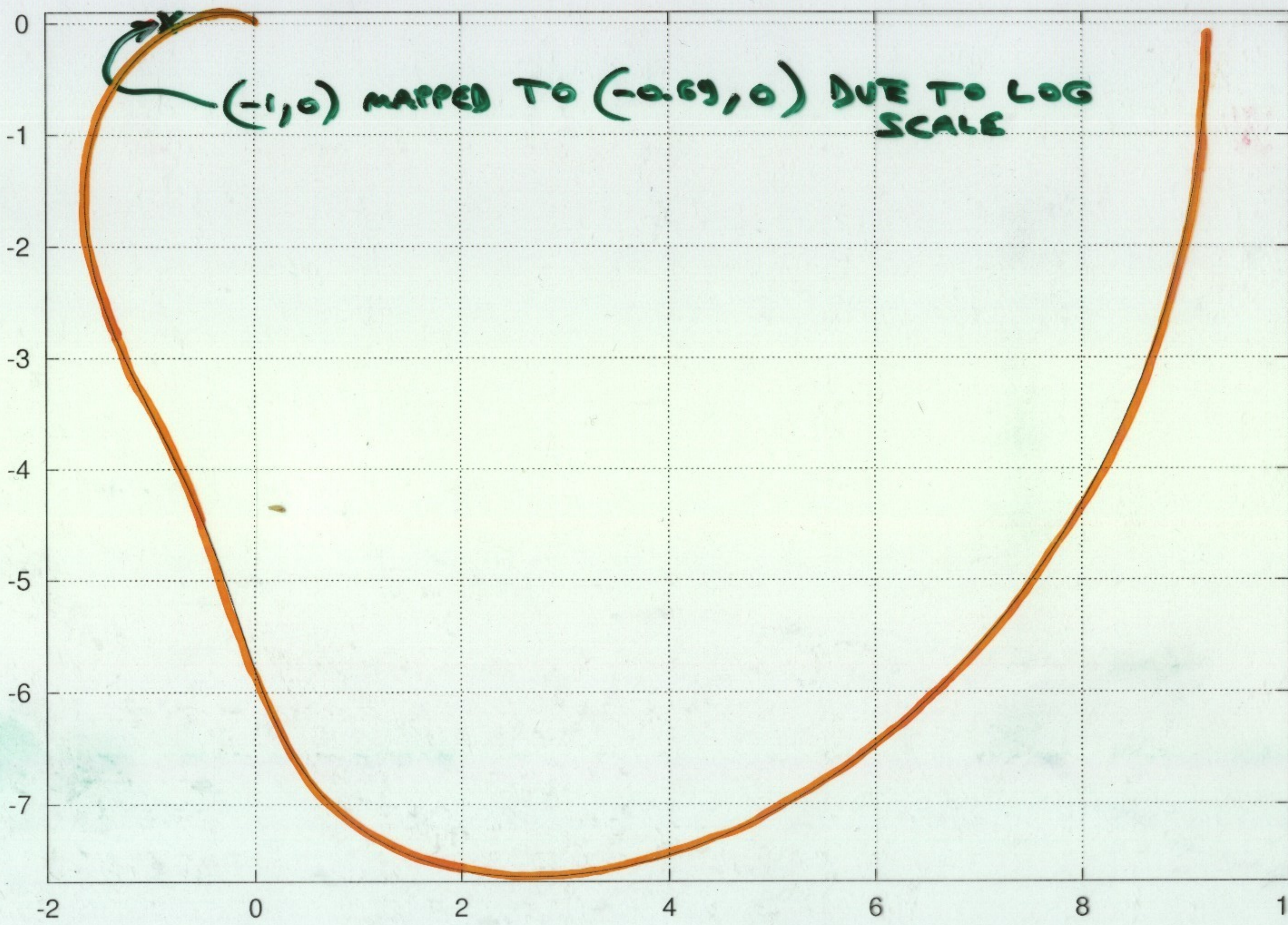
SAME $\begin{cases} |T(j\omega_o)| = 1 \\ |a(j\omega_o)f| = 1 \end{cases}$

$$|A(j\omega_o)| = \frac{|a(j\omega_o)|}{|1 - 0.7 - j0.7|} \doteq \frac{1.3}{f} > \frac{1}{f}$$

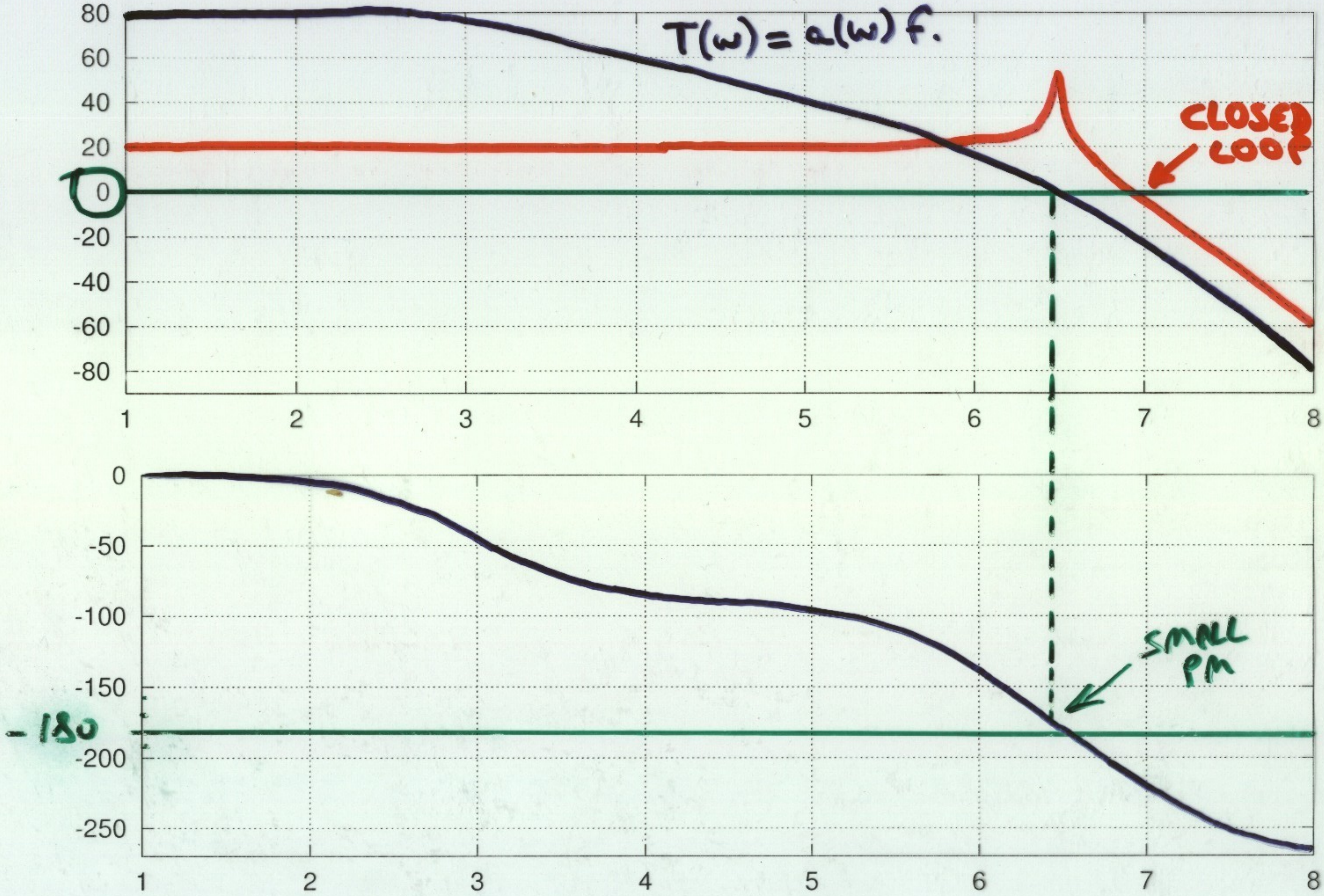
BODE PLOT : $f = 0.01$



NYQUIST : $f = 0.1$

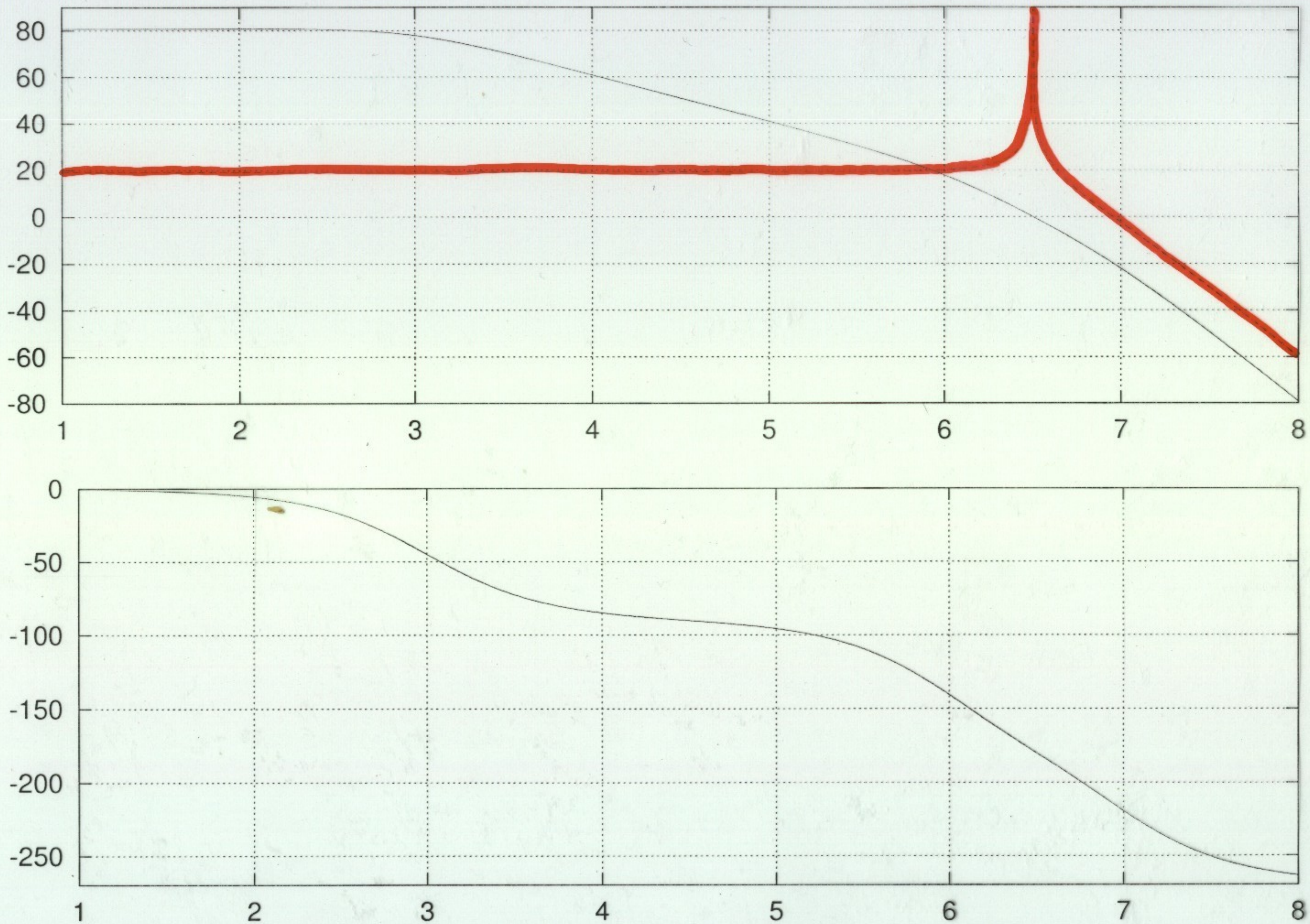


BODE PLOT : $f =$ [illegible]!



80
60
40
20
0
-20
-40
-60
-80
T
$T(\omega) = a(\omega) f.$
CLOSED LOOP
1
2
3
4
5
6
7
8
0
-50
-100
-150
-200
-250
-180
SMALL PM

BODE PLOT: f = 0.1



EXAMPLE

$$a(\omega) = \frac{10^5}{\left(1+j\frac{\omega}{2\pi\times 1kHz}\right)\left(1+j\frac{\omega}{2\pi\times 1MHz}\right)\left(1+j\frac{\omega}{2\pi\times 10MHz}\right)}$$

$f = 0.01$

$f = 0.1$

$T(\omega) = a(\omega)\,f$ LOOP TRANSFER FUNCTION

IN dB: $20\log_{10}(|T(\omega)|) = 20\log_{10}|a(\omega)| - \underbrace{20\log_{10}\left(\frac{1}{f}\right)}_{\approx \text{ CLOSED-LOOP DC GAIN}}$

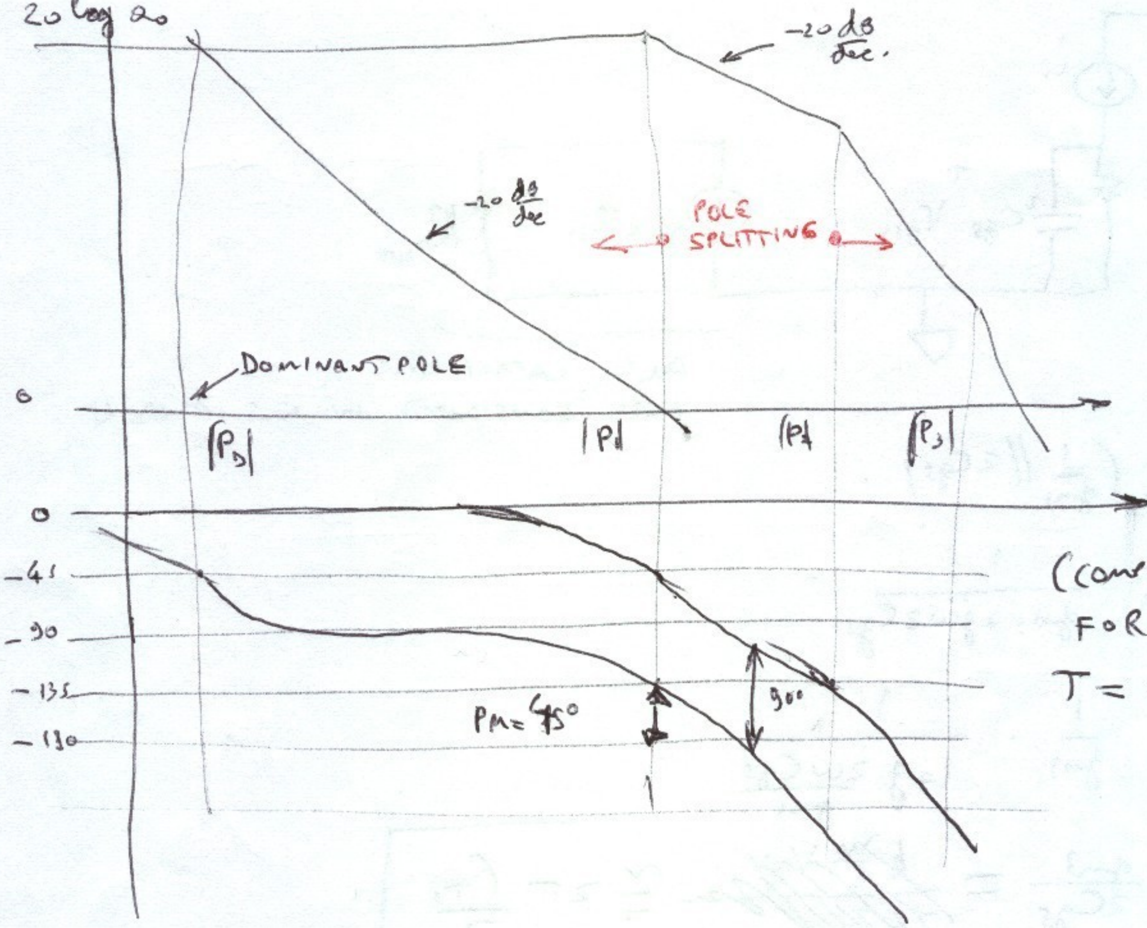
$f = 0.01 \Rightarrow$ SUBSTRACT 40 dB

$f = 0.1 \Rightarrow$ SUBSTRACT 20 dB.

$a_o \simeq 100$ dB.

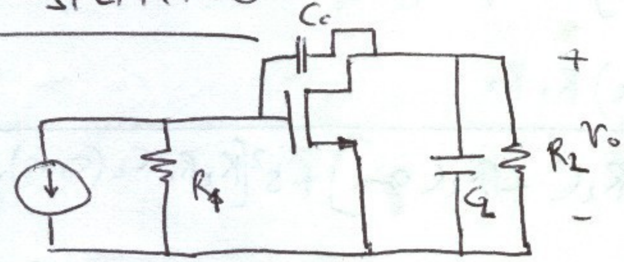
(FIG. 9.10) (GAIN PEAKING.)

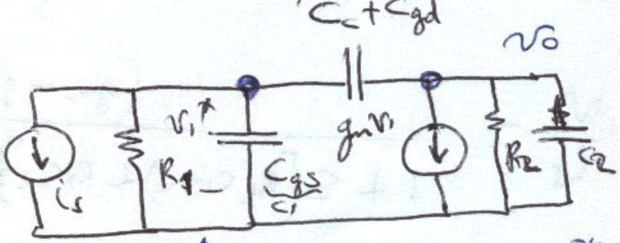
COMPENSATION (FIG. 9.12)



- SIMPLE
- BANDWIDTH GREATLY REDUCED
- CAP. CAN NOT BE INTEGRATED (COMMENT EXAMPLE P. 635)
- SOMETIMES COMPENSATION IS MADE FOR $f < 1$
- IDEA: ~~MOVE P2 LOWER~~ LOWER P1 INSTEAD → BANDWIDTH DEPENDS ON (P_2) (FIG. 9.15 P 638)

POLE SPLITTING





$$\frac{V_o}{i_s} = \frac{(g_m - C s) R_2 R_1}{1 + s\left[(C_2 + C) R_2 + (C_1 + C) R_1 + g_m R_2 R_1 C\right] + s^2 R_2 R_1 (C_2 C_1 + C C_2 + C C_1)}$$

ZERO → $\boxed{z = \frac{g_m}{C}}$ (HIGH IN BIPOLAR, LOW IN MOS)

DENOMINATOR

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

$$\text{IF } |p_2| \gg |p_1| \Rightarrow D(s) \simeq 1 - \frac{s}{p_1} - \frac{s^2}{p_1 p_2}$$

$$\therefore p_1 \simeq -\frac{1}{(C_2+C)R_2 + (C_1+C)R_1 + g_m R_2 R_1 C} \simeq -\frac{1}{\underbrace{(g_m R_2 C)}_{\text{MILLER CAP.}} R_1}$$

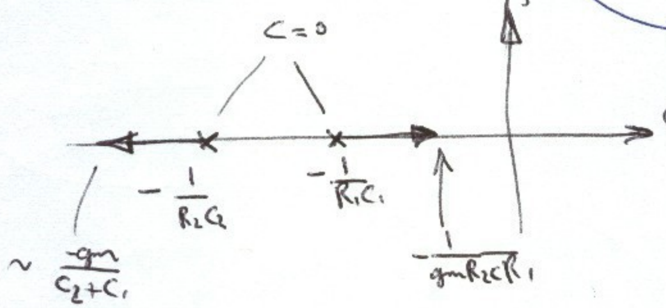
↓ WITH C

$$p_2 \simeq -\frac{g_m C}{C_2 C_1 + C(C_2 + C_1)}$$

↑ WITH C (AT LEAST INITIALLY FOR SMALL C)

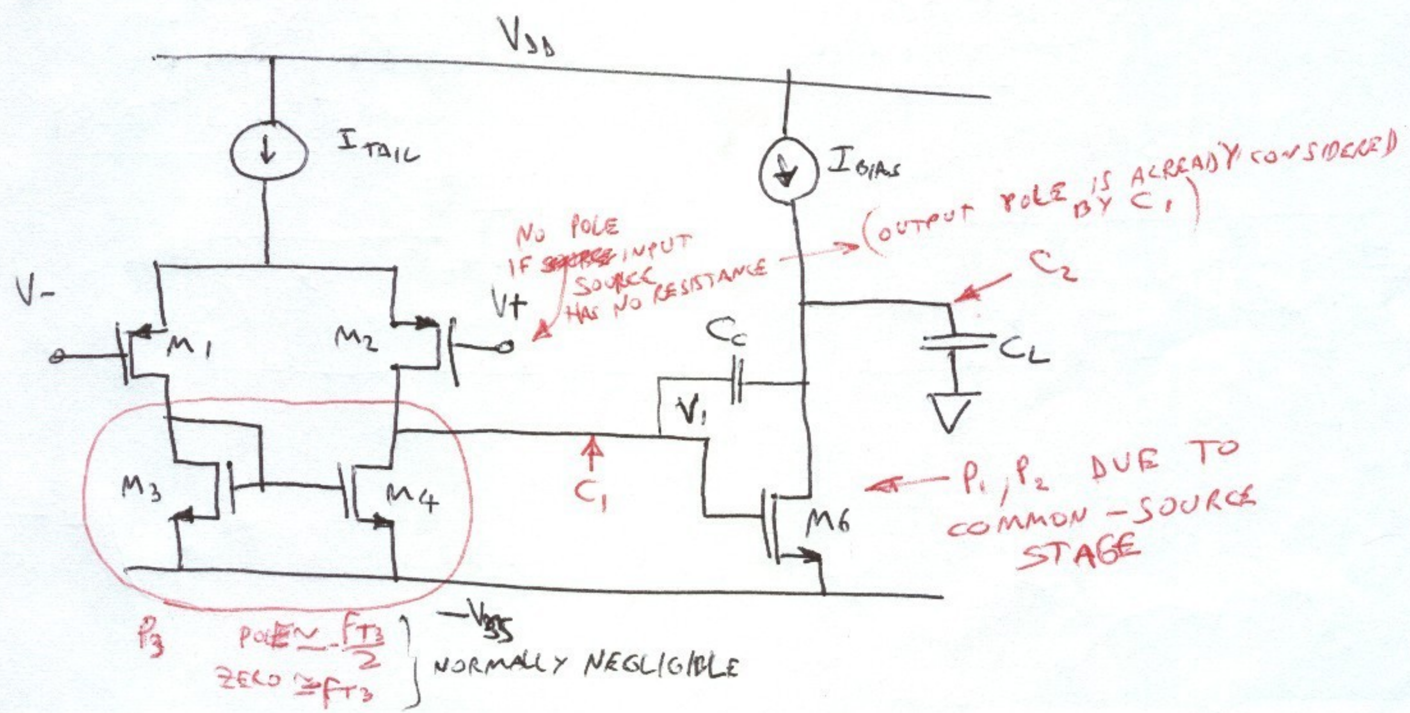
SINCE $C_1 C_2 \gg C_1$

$$p_2 \simeq -\frac{g_m}{C_2 + C_1}$$



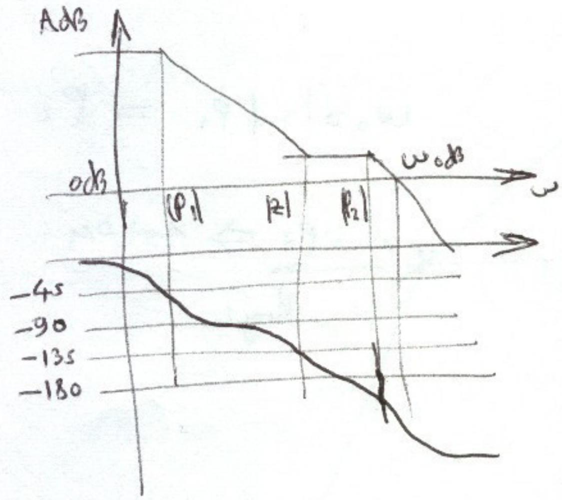
- COMMON-SOURCE STAGES GENERALLY PRODUCE A DOMINANT POLE (POLE-SPLITTING OCCURS)

TWO-STAGE MOS AMPLIFIER COMPENSATION



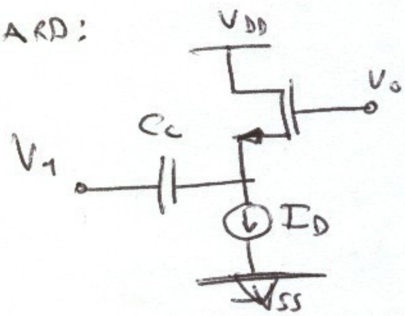
PROBLEM: $Z = \frac{g_{m6}}{C}$ SOMETIMES BELOW ω_{0dB}

- ZERO IN POSITIVE HALF PLANE ⇒ REDUCES PHASE MARGIN



EXPLANATION: C_c ACTS AS A SHORT THAT BYPASSES M_6 AT HIGH FREQ ⇒ ~~MAKES~~ ADDS 180° PHASE SHIFT.

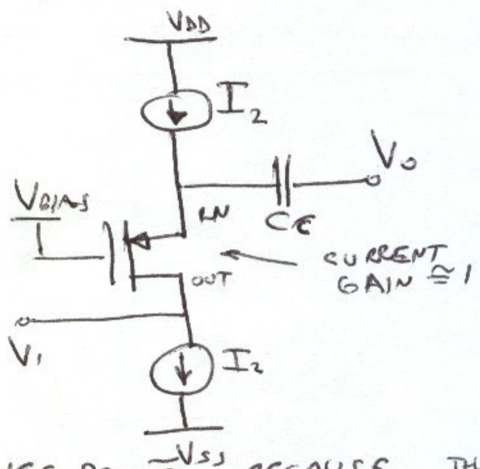
SOLUTIONS: 1) USE SOURCE-FOLLOWER TO BLOCK CURRENT FEED-FOWARD:



(ELIMINATES ZERO)

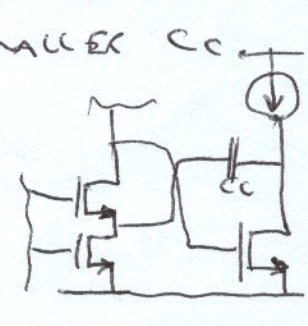
PROBLEMS:
- EXTRA BIASING CURRENT → NOT IF OUTPUT STAGE IS USED
- REDUCED SWING

2) USE COMMON-DRAIN STAGE:

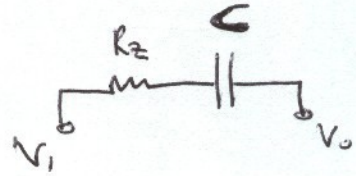


ELIMINATES ZERO AND MOVES P2 UP, BECAUSE THE INPUT IS NO LONGER LOADED BY C_c → CAN USE SMALLER C_c.

- CASCODE AMPLIFIERS DO NOT NEED EXTRA BRANCH.



3) ADD RESISTOR IN SERIES WITH C_c :



$$P_1 \cong -\frac{1}{g_{m6} R_2 R_1 C}$$

$$P_2 \simeq -\frac{g_{m6}}{C_1 + C_2}$$

$$\underbrace{P_3 \simeq -\frac{1}{R_z C_1}}$$

TYPICALLY
VERY HIGH FREQ
SINCE R_z, C_1
SMALL.

$$z = \frac{1}{\left(\frac{1}{g_{m6}} - R_z\right) C}$$

$R_z = \frac{1}{g_{m6}} \Rightarrow z \to \infty$

$R_z > \frac{1}{g_{m6}} \Rightarrow$ NEGATIVE SEMIPLANE ZERO HELPS WITH PHASE MARGIN..

EXAMPLE: COMPENSATE ~~TO~~ SAMPLE O.A. DESIGNED BEFORE FOR $PM = 45°$, $C_L = 5\,pF$, UNITY FEEDBACK (PAGE 650)

IF $P_1 \ll P_2 \Rightarrow$ MOVE P_1 DOWN TO MAKE ω_{0dB} COINCIDENT WITH P_2. BETWEEN P_1, P_2 WE HAVE $-40\frac{dB}{dec}$.

$$a_0 |P_1| = \overset{0(\omega_{0dB})}{1}\, |P_2|$$

$$a_0 \simeq g_{m1} (r_{o1} \,//\, r_{o4})\, g_{m6} (r_{o6} \,//\, r_{o7}) = g_{m1} R_1 g_{m6} R_2$$

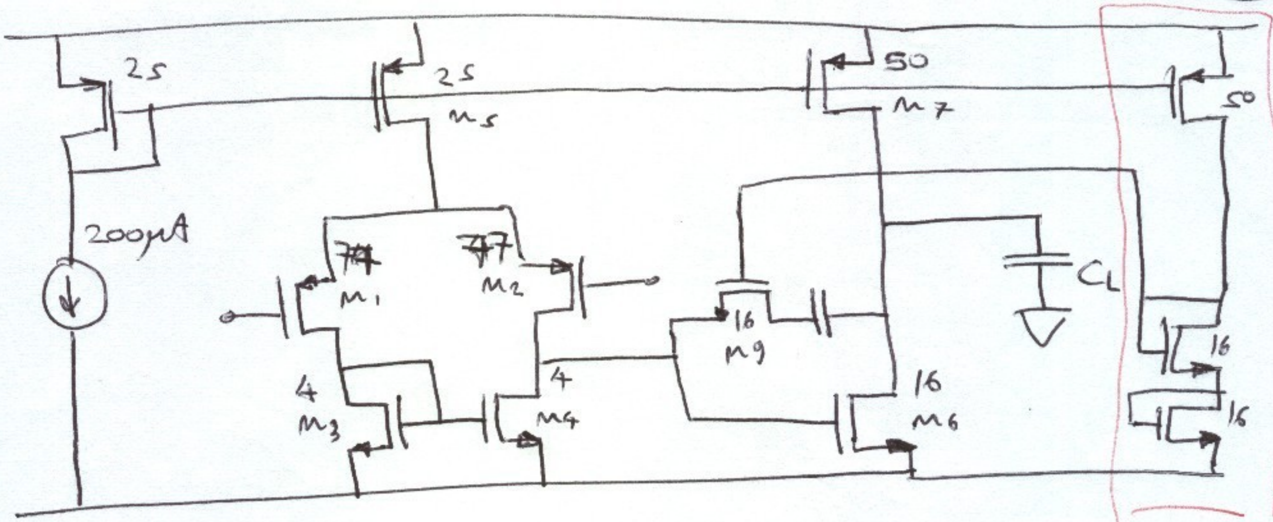
$$\therefore\ g_{m1} \cancel{R_1} \cancel{g_{m6}} \cancel{R_2} \cdot \frac{1}{\cancel{g_{m6}} \cancel{R_2} \cancel{R_1} C} = \frac{g_{m6}}{C_1 + C_2}$$

$C_L = 5pF \gg$ PARASITIC CAPS.

$$\frac{g_{m1}}{C} \simeq \frac{g_{m6}}{C_L}$$

$$\left.\begin{aligned} g_{m1} &= 1 \frac{mA}{V} \\ g_{m6} &= 1.55 \frac{mA}{V} \end{aligned}\right\} \Rightarrow \boxed{\begin{aligned} C &= 3.2\,pF \\ R_z &= \frac{1}{g_{m6}} = 645\,\Omega \end{aligned}}$$

SHOW FIG. 9.29
PAGE 653



REPLICA BIASING (EXTRA CURRENT)

$A_{dm} = 7471$

$$\omega_{0dB} = \begin{cases} \simeq 350\,\text{MHz} & \text{BEFORE COMP. (UNSTABLE)} \\ \simeq 35\,\text{MHz} & \text{AFTER COMP.} \end{cases}$$

NOTE THAT CONST = GAIN x BANDWIDTH CAN NOT BE USED IF THE DOMINANT POLE IS NOT THE ONLY ONE UNTIL ω_{0dB}

- OBSERVATION: IF A CLASS AB OUTPUT STAGE IS USED, THERE IS NO NEED FOR RESISTOR. SINCE THE ZERO IS ELIMINATED WITH METHOD (1).

$$r_{ds16} = \frac{1}{\frac{\partial I_{ds16}}{\partial V_{ds}}} \quad , \quad \frac{\partial I_{ds16}}{\partial V_{DS}} = \frac{k'}{2}\frac{W}{L}\left(2V_{ov} - 2V_{DS}\right)$$

$$\simeq k'\frac{W}{L}V_{ov} \quad \text{if } V_{DS} \ll V_{ov}$$

$$\therefore \quad r_{ds16} = \frac{1}{g_{m6}} \quad \text{IF} \begin{cases} \left(\frac{W}{L}\right)_{16} = \left(\frac{W}{L}\right)_{6} \\ \text{AND} \\ V_{ov16} = V_{ov6} \end{cases}$$

$C_{MIM} \approx 1\frac{fF}{\mu m^2}$