TWO-STAGE CMOS OPAMP

\[ \frac{W/L_6}{W/L_4} = 2 \frac{W/L_7}{W/L_5} \]
RECALL FOR ACTIVE REGION

N莫斯

\[ V_{Ds} \geq V_{GS} - V_{tn} \]

\[ V_D \geq V_G - V_{tn} \]

\[ V_G \leq V_D + V_{tn} \]

PMOS

\[ V_{SD} \geq V_{SG} - 1V_{tp} \]

\[ -V_D \geq -V_G - 1V_{tp} \]

\[ V_D \geq V_D - 1V_{tp} \]

INPUT COMMON-MODE RANGE

TIE \( V^+ \) TO \( V^- \) + CONNECT TO \( V_{ICM} \)

\[ \min V_{ICM} \Rightarrow \text{KEEP M1 \& M2 ACTIVE} \]

\[ V_{ICM} \geq -V_{SS} + V_{tn} + V_{ou3} - 1V_{tp} \] ①

\[ \max V_{ICM} \Rightarrow \text{KEEP M5 ACTIVE} \]

\[ V_{ICM} + |V_{tp}| + |V_{ou1}| \leq V_{DD} - |V_{ou5}| \] ②
COMBINING (1) AND (2) WE HAVE

\[-V_{SS} + V_{tn} + V_{ov3} - |V_{tp}| \leq V_{Icm} \leq V_{DD} - |V_{tp}| - |V_{ov1}| - |V_{ov5}|\]

IF \( V_{tn} \leq |V_{tp}| \)

\[-V_{SS} + V_{ov3} \leq V_{Icm} \leq V_{DD} - |V_{tp}| - |V_{ov1}| - |V_{ov5}|\]

CAN BE CLOSER TO \(-V_{SS}\) THAN \(V_{DD}\)

OUTPUT VOLTAGE SWING

\[-V_{SS} + V_{ov6} \leq V_o \leq V_{DD} - |V_{ov7}|\]

WITHIN ONE \(V_{ov}\) OF EACH POWER SUPPLY.
**VOLTAGE GAIN**

\[ \Delta_{id} = N^+ - N^- \]

\[ A_i = \frac{\Delta_i}{\Delta_{id}} = -g_m \left( \frac{1}{\frac{R_o2}{1} \frac{1}{R_o4}} \right) \]

WHERE \[ g_m = \frac{2I_D}{V_{OV1}} = \frac{2}{V_{OV1}} = \frac{I}{V_{OV1}} \]

\[ R_{o2} = \frac{V_{A2I}}{I_{2}} \quad R_{o4} = \frac{V_{A4}}{I_{2}} \]

\[ A_i = -\frac{2}{V_{OV1}} \left( \frac{1}{V_{A2I}} + \frac{1}{V_{A4}} \right) \]

**FOR A GIVEN I = 2 TO INCREASE A1,**

DECREASE \( V_{OV1} \) AND INCREASE \( \left( \frac{V_{A2I}}{V_{A4}} \right) \)

(LARGER \( W/L \)) (LONGER \( L \))
\[ A_2 = \frac{v_b}{v_i} = -q_{m6} \left( r_{06} || r_{07} \right) \]

\[ \text{WHERE } q_{m6} = \frac{2 I_{06}}{V_{0V6}} \]

\[ r_{06} = \frac{V_{A6}}{I_{06}} \quad r_{07} = \frac{1}{I_{06}} \quad \text{since } I_{07} = I_{06} \]

\[ A_2 = -\frac{2}{V_{0V6}} \left( \frac{1}{V_{A6}} + \frac{1}{1/V_{A7}} \right) \]

To increase \( A_2 \) =) Decrease \( V_{0V6} \)
\( \text{(LARGE } W/L) \)

Increase \( V_{A6} , V_{A7} \)
\( \text{(LONGER } L) \)

\[ A_\nu = A_1 A_2 \]

\[ A_\nu = q_{m1} \left( r_{02} || r_{04} \right) q_{m6} \left( r_{06} || r_{07} \right) \]
OUTPUT RESISTANCE

\[ R_o = R_{06} || R_{07} \]

IF IN FEEDBACK WITH \( \beta = 1 \)

THEN

\[ R_{OF} = \frac{R_0}{1 + A_0 \beta} \approx \frac{R_{06} || R_{07}}{g_m 1 (r_{01} || r_{02}) g_m 6 (r_{05} || r_{07})} \]

\[ R_{OF} \approx \frac{1}{g_m 6 g_m (r_{01} || r_{02})} \]
FREQ RESPONSE

Can model OPAMP as

\[ V_0 = \frac{G_{m1} V_{in}}{R_1} + \frac{G_{m2} V_{in}}{R_2} \]

\[ C_1 = C_{gd2} + C_{db2} + C_{gd4} + C_{db4} + C_{gd6} \]

\[ C_2 = C_{db6} + C_{db7} + C_{gd2} + C_L \]

\[ C_C \quad \text{added compensation capacitor that includes } C_{gd6} \]
FROM BEFORE WE FOUND

\[ f_{p1} \approx \frac{1}{2 \pi R_1 C_m R_2 C} \quad \text{Dominant Pole} \]

\[ f_{p2} \approx \frac{G_m}{2 \pi C_2} \quad \text{Non-Dominant Pole} \]

\[ f_2 \approx \frac{G_m}{2 \pi C_C} \quad \text{Zero} \]

\[ f_t = |A_m| + f_{p1} = \frac{G_m}{2 \pi C_C} \quad \text{Unity Gain Freq} \]

TO ENSURE REASONABLE STABILITY WITH \( \beta = 1 \)

REQUIRE \( f_t \leq f_{p2} + f_t \leq f_2 \)

\[ \frac{G_m}{C_C} \leq \frac{G_m}{C_2} \quad (f_{p2} \text{ Requirement}) \]

AND \( G_m \leq G_m \quad (f_2 \text{ Requirement}) \)
PHASE MARGIN (ASSUME $\beta = 1$)

$\theta = AB = A$

$\omega_1$  $\omega_2$

$\theta = -\tan^{-1}\left(\frac{\omega}{\omega_2}\right) \leq \Delta \omega$ due to $\omega_2$

$\theta = -\tan^{-1}\left(\frac{\omega}{\omega_2}\right) \leq \Delta \omega$ due to $\omega_2$
So phase AT \( f_T \to \phi_{\text{total}} \)

\[
\phi_{\text{total}} = -90^\circ - \tan^{-1}\left(\frac{f_T}{f_p}\right) - \tan^{-1}\left(\frac{f_T}{f_z}\right)
\]

Phase Margin \( \phi_M = \phi_{\text{total}} - (-180^\circ) \)

\[
\phi_M = 90 - \tan^{-1}\left(\frac{f_T}{f_p}\right) - \tan^{-1}\left(\frac{f_T}{f_z}\right)
\]

So right half plane zero causes worse phase margin.

\[
\left(\text{Note a left half plane zero would help improve phase margin}\right)
\]
LHP + RHP ZERO

**CONSIDER NUMERATOR**

\[
(1 + \frac{S}{W}) \Rightarrow S = -W
\]

**IF** \( W > 0 \) **LHP ZERO**

\[
\angle \left(1 + \frac{jW}{W^2}\right) = \angle \tan^{-1}\left(\frac{W}{W^2}\right)
\]

**IF** \( W = W^2 \Rightarrow \text{PHASE} = 45^\circ \),

\[
\left(\tan^{-1}(1)\right)
\]

**IF** \( W < 0 \) **RHP ZERO**

\[
\angle \left(1 + \frac{jW}{W^2}\right) = \angle \tan^{-1}\left(\frac{W}{W^2}\right)
\]

**IF** \( W = -W^2 \Rightarrow \text{PHASE} = -45^\circ \),

\[
\left(\tan^{-1}(-1)\right)
\]
Zero occurs where $\frac{v_o}{v_{id}} = 0$

So to find zero can assume $v_o = 0$

And write

$$\frac{v_{id}}{v_{id}} = G_{m2}v_{i2} \Rightarrow s = \frac{1}{C_C \left(\frac{1}{G_{m2}}\right)}$$

RHP

$$\omega_2 = \frac{1}{C_C \left(\frac{1}{G_{m2}}\right)}$$

$$\alpha_2 = \frac{1}{2\pi C_C \left(\frac{1}{G_{m2}}\right)}$$
Now \[ \frac{V_{i2}}{R + \frac{1}{SCc}} = Gm_2 V_{i2} \]

\[ S = \frac{1}{Cc \left( \frac{1}{Gm_2} - R \right)} \]

\[ w_2 = \frac{1}{Cc \left( \frac{1}{Gm_2} - R \right)} \]

If \( R = \frac{1}{Gm_2} \)

\( w_2 \rightarrow \infty \)

Much better phase margin

If \( R > \frac{1}{Gm_2} \) zero in left half plane and improves phase margin

(limit to this as there are other poles as well)
SIMPLIFIED HIGH FREQUENCY MODEL

\[ f_t = \frac{Gm_1}{2\pi f_c C_C} \]

valid for \( f \gg f_{p1} \)

(but not realistic output impedance)
SLEW-RATE

\[ V_I \rightarrow V_O \]

\[ V_I \quad 0 \rightarrow t \]

\[ V_O \quad 0 \rightarrow t \]

\[ \text{SLEW-RATE LIMIT} \quad \text{MAX} \quad \frac{dV_O}{dt} \]

SLEW-RATE LIMIT OCCURS WHEN \( I \)

OF INPUT DIFF PAIR ALL GOES ONE SIDE OF DIFF PAIR AND CHARGE/DISCHARGES CC
Due to either
\[ \begin{cases} \frac{dQ}{dt} = I \\ i_{id2} = 0 \end{cases} \]

or
\[ \begin{cases} i_{id2} = I \\ i_{id4} = 0 \end{cases} \]

\[ q = CV \Rightarrow \frac{dq}{dt} = C \frac{dv}{dt} \Rightarrow I = C \frac{dv}{dt} \]

Here
\[ v_o(t) = \frac{I}{C_C} t \]

\[ SR = \frac{I}{C_C} \]
RELATIONSHIP BETWEEN SR & \( f_t \)

\[
G_m = g_m = \frac{2I_{01}}{V_{OV1}} = \frac{2\left(\frac{I}{2}\right)}{V_{OV1}} = \frac{I}{V_{OV1}}
\]

\( I = G_m \cdot V_{OV1} \)

\[
SR = \frac{G_m \cdot V_{OV1}}{C_C} + f_t = \frac{G_m}{2\pi f_t C_C}
\]

\[
\Rightarrow G_m = 2\pi f_t C_C
\]

\[
SR = 2\pi f_t V_{OV1} \quad \text{&} \quad \omega = 2\pi f_t
\]

\[
SR = \omega \cdot V_{OV1}
\]

So to obtain a high slew rate, increase \( V_{OV1} \) & \( \omega \)

Should choose \( PMOS \) input stage due to \( NMOS \) \( \Rightarrow \) increases \( \omega \)

\( V_{OV1} \) higher for same \( I \)
Finally recall from Chapter 2

If output step size is $\hat{V}_0$

then will not slew-rate limit if

$$\hat{V}_0 \leq SR = \hat{V}_0 V_{ou1}$$

If step output has

$$\hat{V}_0 \leq V_{ou1}$$ then will not slew-rate limit and will settle as exponential