Op-Amp Design

Changes on-chip op-amp

$g_m$ for input stage: $g_m = \sqrt{\frac{2(20 \mu A)(2.6E-5)}{10}}$

$g_m = 200 \mu A/V$

Predicted $f_T$: $g_m = \frac{200 \mu A/V}{2\pi C_c}$ = 1.06 MHz

Open Loop Test Simulation

DC sweep

AC magnitude = 1
Open Loop DC response

Systematic Offset Voltage: -153 μV
Average DC gain = 8.014V / 1.32mV = 6070

Open Loop AC response

$20 \log_{10}(6070) = 75.6 \text{ dB}$

Phase margin: $-99 - (-180)$
81° $\phi$ MARGIN
√ STABLE
Closed Loop Simulations

UNITY GAIN FEEDBACK

Closed Loop DC Sweep

Dec 6, 2013

DC Response

UNITY GAIN

\[ \approx 300 \text{mV} \]

\[ \sim 3.5 \text{V} \]

\text{INPUT CM RANGE CRASH}
Closed Loop Transfer Function (Unity Gain)

Closed Loop Step Response (Large Signal)

Rising slew rate $4V / 3.31\mu s = 1.21 V / \mu s$

Falling slew rate $4V / 3.72\mu s = 1.08 V / \mu s$

Prediction:

$$\frac{I_D}{C_C} = \frac{40 \text{mA}}{30 \text{pF}} = 1.33 \text{ V/\mu s}$$

2 differences: smaller $\uparrow$, different \rightleftharpoons parasitics
OPEN LOOP GAIN: HOW TO INCREASE?

2 STAGE OP-AMP

\[ A: \quad G_{m1} \frac{R_0}{g} \quad G_{m2} \left( \frac{R_{II}}{R_L} \right) \]  \{ INCREASE? \}

\[ \frac{R_{II}}{R_L} \]

INCREASE IMPEDANCE
AT 1st STAGE OUTPUT
NODE *

LOOK INTO CURRENT MIRROR

\[ \frac{G_{m1}, f_T, C_c \text{ RELATIONSHIP}}{\text{LIMITED FLEXIBILITY}} \]

\[ G_{m1}, G_{m2} \uparrow : \text{POWER COST} \uparrow \]

\[ \uparrow \quad \frac{R_{II}}{R_L} \]

\[ \models \text{INCREASING} \quad R_{0I}, R_{0II} \]

* MOST CONTROL
CASCODE CURRENT SOURCE DEVELOPMENT

**Simple Mirror**

\[ I_{out} = I_{out1} \approx 100\, k\Omega \]

**Source Degeneration**

\[ R_{out} = R_{out1} \approx 10\, M\Omega \]

**Problem**

\[ I_{out} = I_{D2} = \frac{M_{ox} W}{2} (V_{GS} - V_{TH})^2 + \lambda V_{DS} \]

**What to Do to Fix Change in I_{out} Caused by Change in V_{GS}?**

\[ V_{DS} \uparrow \Rightarrow I_{D2} \uparrow \Rightarrow V_{GS} \downarrow \]

Look at I_{out} (somehow) counteract with change in V_{GS}

**KVL for V_{GS}**

\[ V_{GS} = V_{G} - I_{out} R_{S} \]

**Negative Feedback**

\[ I_{out} \uparrow \Rightarrow V_{GS} \downarrow \Rightarrow I_{out} \downarrow \]

\[ \sqrt{R_{out}} \text{ increased} \]

**Headroom Cost**

**What to Do?**

Do not let V_{DS} change.

M_{4} "Cascode" device

\[ M_{4} \text{ "Cascode" device} \]
Small Signal Model

\[ i_x = g_m V_{gs} \frac{V_x - V_S}{r_{o2}} \quad [1] \]

KCL

\[-V_{gs} = V_S \Rightarrow V_{gs} = -V_S \quad [2] \]


\[ i_x = -g_m V_S + \frac{V_x}{r_{o2}} - \frac{V_S}{r_{o2}} \]

\[ i_x = -V_S \left( g_m + \frac{1}{r_{o2}} \right) + \frac{V_x}{r_{o2}} \quad [3] \]

* \( i_x R_s \)

Routing Looking Into Drain

\[ R_{out} = \frac{V_x}{i_x} \]

\[ R_{out} = r_{o2} \left[ 1 + g_m R_s \right] \]

Rewrite [3]

\[ i_x \left[ 1 + g_m R_s + \frac{R_s}{r_{o2}} \right] = \frac{V_x}{r_{o2}} \]

\[ \frac{V_x}{i_x} = r_{o2} \left[ 1 + g_m R_s + \frac{R_s}{r_{o2}} \right] \]
ID vs. V_DS SWEEP COMPARISON: SIMPLE MIRROR - SOURCE DEGENERATED - CASCODE

DC Response

- /MN2/D
- /MN1/D
- /MN3/D

SIMPLE MIRROR CRASH @ V_DS ~ 0.5V
SOURCE DEGENERATED
CASCODE CRASH @ V_DS ~ 1.3V

SIMPLE MIRROR
worse Rout
better Rout
SIMPLE MIRROR

best Rout
SOURCE DEGENERATED
CASCODE